TROPICAL CLIMATOLOGY, METEOROLOGY AND HYDROLOGY *IN MEMORIAM* FRANZ BULTOT (1924-1995)

Brussels, 22-24 May, 1996

Royal Meteorological Institute of Belgium

Royal Academy of Overseas Sciences

Guest Editors : G. Demarée, J. Alexandre, M. De Dapper

1998

International Conference on

TROPICAL CLIMATOLOGY, METEOROLOGY AND HYDROLOGY *IN MEMORIAM* FRANZ BULTOT (1924-1995)

Brussels, 22-24 May, 1996



Royal Meteorological Institute
of Belgium



Royal Academy
of Overseas Sciences

Guest Editors : G. Demarée, J. Alexandre, M. De Dapper

1998

Royal Meteorological Institute
of Belgium
av. Circulaire/ Ringlaan 3
B-1180 Brussels (Belgium)
Tel. : (02) 373 05 01
Fax : (02) 375 12 59

Royal Academy
of Overseas Sciences
rue Defacqzstraat 1/3
B-1000 Brussels (Belgium)
Tel. : (02) 538 02 11
Fax : (02) 539 23 53

D/1998/0149/4

INHOUDSTAFEL — TABLE DES MATIERES — CONTENTS

Woord vooraf — Avant-propos — Foreword ..... 7 ; 9 ; 11
Introduction 13

Academic Opening Session

Opening Addresses :

H. R. H. Prince Laurent of Belgium, President of the Royal Institute for Sustainable Management of Natural Resources and Promotion of Clean Technology 19
F. Demeyere, Chef de Cabinet Adjoint, Ministry of Science Policy 22
G. Obasi, Secretary General of the World Meteorological Organization 25
A. Szöllösi-Nagy, Director Division of Water Sciences, UNESCO 30
E. Bernard, L'œuvre de Franz Bultot en météorologie et en climatologie tropicales 35
G. Demarée, A Bibliography of Franz Bultot 42

Palaeoclimatology

N. Petit-Maire & R. Bryson, Holocene Climatic Change and Man in the Sahara 51
R. Michel, Palaeoenvironmental Evidence for Synchronous Changes in Calcite Flowstones Formation, Speleothems Erosion and/or (Re)Dissolution and Equatorial Wetter Conditions in the Tropical Karst of Mount Hoyo (N.E. Zaire) 68
J. Moeyersons, Absence of Arid Conditions at Shum Laka Rock Shelter (Bamenda-Western Cameroon) since 30,000 yr B.P 86
J. Jelínek, Climate as Reflected in Rock Art. Example from Central Saharan Fezzan 103
E. Roche, Evolution du paléoenvironnement holocène au Rwanda. Implications climatiques déduites de l'analyse palynologique de séquences sédimentaires 108
H. Pajunen, Peat Accumulation Rate in Rwanda and Burundi. An Indicator of Long-term Climatic Changes? 128
E. van Overloop & R. Paepe, The Quaternary Geology around the Great Lakes in Central Africa. Pluvials and Interpluvials are not the Equivalent of Glacials and Interglacials 142

Climatology

C. Mbaye, Etudes des fluctuations de la température de l'air et des précipitations au Sénégal de 1854 à 1990 179
A. Venäläinen & M. Mhita, The Variability of Rainfall in Tanzania 191
R. Morel, Début de la sécheresse en Afrique de l'Ouest 200
P. Ozer, Lithometeors and Wind Velocity in Relation with Desertification during the Dry Season from 1951 to 1994 in Niger 212
P.-D. Plisnier, Lake Tanganyika : Recent Climate Changes and Teleconnections with ENSO 228
A. Santiago-Jegaden & J. Suchel, Etude du lien relief-convection dans l'Ouest-Cameroun, analyse d'images Météosat 251
B. Van Gompel & H. Decleir, Further Characteristics of Climate Change in the Sahel Region and West Africa 263
K. Olszewski, Bioclimatic Regions of Nigeria 279
T. Ridder, Rainfall and Sunshine in Irian Jaya (New Guinea) 288
C. van Scherpenzeel, Rainfall in the Northern Part of Surinam (South America) 292

Meteorology

O. Brasseur, C. Tricot, V. Ntezimana, H. Gallée & G. Schayes, Importance of the Convective Adjustment Scheme in the Simulation of the Diurnal Cycle of Convective Activity in Africa 299
A. Colman, Predictions of Precipitation from Two Global Circulation Models and an Empirical Technique 313
D. Guschchina, E. Semenov & S. Lakeev, The Evolution of Atmosphere Circulation Anomalies during El Niño-Southern Oscillation 328
E. Cayanan & C. Lao, Statistical Method of Forecasting the Probability of Tropical Cyclone Recurvature in the Philippines 341
S. Lakeev, D. Guschchina & N. Astafyeva, Spectral and Wavelet Analysis of Circulation Processes during the ENSO 355
E. Semenov, The Empirical Model of Global-Scale Circulation in Tropical Atmosphere 363

Remote Sensing

P. Boekaerts, D. Crommelynck & J. Cornelis, Sub-Pixel Scene Identification in ScaRaB Broad-Band Data of the Tropical Hurricane Kelvina by Collocation with High-Resolution Meteosat Data for the Study of Angular Dependency Models of Radiation Fields 373

S. Dewitte, N. Manalo-Smith, D. Crommelynck & J. Cornelis, Determination of Tropical Radiation Budget at High Time and Space Resolution by Combination of Geostationary and Polar Satellite Measurements 390
T. Dinku, Satellite Rainfall Estimation and its Applications in Ethiopia 414
S. Griguolo & P. Santacroce, Eco-Geographic Classifications Based on Time Series of HRPT NDVI Images 422
G. Hendrickx, A. Napala, D. Rogers & J. Slingenbergh, Contribution des satellites à la lutte contre la trypanosomose animale africaine 441

Hydrology

J. Sircoulon, Cinquante ans d'études hydrologiques en Afrique de l'Ouest 457
A. Grove, Variability of African River Discharges and Lake Levels 470
H. Vermeulen, P. Van Damme, F. De Troch & P. Troch, Influence of Small Dams on the Water Table Level in Northern Togo 479
J. Charlier, Pourra-t-on sauver les connaissances hydrologiques du bassin congolais/zaïrois? 492
M. Daouda, P. Ozer & M. Erpicum, Conséquences de la sécheresse sur la longueur et l'amplitude de la saison des pluies au Niger 497
G. Demarée, S. Derasse & A. Assani, Extreme Value Distributions of the Rainy Season Maximum Daily Precipitation Depths at Lubumbashi (Shaba), Zaire 507
Y. Seleshi & G. Demarée, Identifying the Major Cause of the Prevailing Summer Rainfall Deficit over the North-Central Ethiopian Highlands since the Mid-60s 516
F. Moreda, G. Vandewiele, G. Demarée & W. Bauwens, Application of Pure Run-off Models in Low Flow Analysis of Awash River Basin in Ethiopia 532
B. Tychon & G. Wollenweber, Estimation of Latent Heat Fluxes with a Modified Jackson Model Applied to Sparse Vegetation : Application to the Hapex Sahel Experiment 556
S. Vannitsem & C. Nicolis, Non-Markovian Processes and the Statistical Prediction of River Flows 582
A. Laraque & J.-C. Olivry, Deux systèmes hydrologiques mitoyens mais opposés du bassin du Congo-Zaïre : la Cuvette congolaise et les plateaux Tékés 593
E. Servat, M. Sakho, G. Ale, A. Afouda & J. Fritsch, Le projet FRIEND en Afrique de l'Ouest et centrale : l'expérience d'un réseau de recherche en partenariat dans le domaine de l'hydrologie régionale 607

L. Bergonzini, Les fluctuations du niveau du lac Tanganyika et les termes de surface de son bilan hydrique 613
J. Berlamont, The Hydraulics Laboratory of U.M.S.S. at Cochabamba, Bolivia, and its Contribution to the Remediation of Topsoil Erosion 638
B. Olechnowicz-Bobrowska, N. Can & S. Wahab, Bilan hydrique climatique de la zone aride et de la zone de mousson en Asie 641

Agrometeorology

R. Gommes, Some Aspects of Climate Variability and Food Security in Sub-Saharan Africa 655
R. Ahmed, Monsoon Prediction in Bangladesh : a Preliminary Study 674
V. Tonnard & B. Tychon, L'enseignement en agrométéorologie pour les ressortissants des pays en voie de développement 685
D. Dabi & W. Anderson, Water Scarcity and Sustainable Agricultural Development in the Drought-prone Semi-Arid Zone of West Africa 693

Sustainable Development

J. Van Goethem, The Convention on Biological Diversity and the Role of the Royal Belgian Institute of Natural Sciences in Biodiversity Research 713
G. Baert & E. Van Ranst, Importance of Organic Matter for Sustainability of Agro-Ecosystems in Lower Zaire 730
M. Akhtar, Desertification in the Republic of Sudan. Some Recommendations for the Sustainable Utilization of Sahelian Resources 745
L. Hens, The Implementation of the Rio Conventions and Agenda 21 in the European Union and in Belgium 752
Z. Kundsewicz, Water for Sustainable Development in Tropical Areas 768

List of contributors 787

List of participants 795

WOORD VOORAF

De internationale conferentie over „Tropische Klimatologie, Meteorologie en Hydrologie (TCMH-96)" werd gehouden *in memoriam* professor Franz Bultot (1924-1995) die een groot gedeelte van zijn wetenschappelijke loopbaan gewijd heeft aan de studie van de klimatologie, meteorologie en hydrologie van Centraal-Afrika. Zijn onderzoek op dat terrein culmineerde in de publicatie tussen 1971 en 1977 van het monumentale vierdelige werk *Atlas Climatologique du Bassin Congolais/ Zaïrois*. Franz Bultot was ook de auteur van een vijftigtal publicaties in bovenvermelde gebieden.

De internationale conferentie TCMH-96 werd gezamenlijk georganiseerd door de Koninklijke Acdemie voor Overzeese Wetenschappen (KAOW/ARSOM) en het Koninklijk Meteorologisch Instituut van België (KMI/IRM) en greep plaats onder de hoge bescherming van Z.M. Koning Albert II van België. Verder werd ze gecopatroneerd door het Koninklijk Instituut voor het Duurzame Beheer van de Natuurlijke Rijkdommen en de Bevordering van Schone Technologie (KINT/IRGT), de Wereld Meteorologische Organisatie (WMO/OMM) en het Internationaal Hydrologisch Programma van de UNESCO (IHP, Thema 6, Hydrologie en Schatting van het Watervoorkomen in de Vochtige Tropische Zones). Daarenboven werd de conferentie ook gesponsord door de Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden (DWTC/SSTC), het *Fonds National de la Recherche Scientifique* (*FNRS*), het *Ministère de l'Education et de la Formation*. Beurzen werden verleend door het Algemeen Bestuur van de Ontwikkelingssamenwerking (ABOS/AGCD) en het *Technical Centre for Agricultural and Rural Co-operation* (*CTA*) te Wageningen. Een wetenschappelijk kerncomité bestaande uit Dr. Gaston Demarée en de professoren Jean Alexandre en Morgan De Dapper leidde en was verantwoordelijk voor de wetenschappelijke aspecten van TCMH-96.

De Academische Openingsceremonie werd gehouden in het Paleis der Academiën op woensdag 22 mei 1996 in aanwezigheid van Z.K.H. Prins Laurent van België, Voorzitter van het KINT/IRGT. Professor Ivan Beghin, Voorzitter van de Koninklijke Academie voor Overzeese

Wetenschappen, en Dr. Henri Malcorps, Directeur van het KMI/IRM, namen het voorzitterschap van de openingsceremonie waar. Lezingen werden gegeven door Prins Laurent van België, M. Frank Demeyere, vertegenwoordiger van de Minister voor Wetenschapsbeleid, professor G.O.P. Obasi, Secretaris-generaal van de WMO, en professor András Szöllösi-Nagy, Directeur van de Divisie voor Waterwetenschappen van de UNESCO. Professor Etienne Bernard belichtte de loopbaan van Franz Bultot in het domein van TCMH. Meer dan tweehonderd belangstellenden — vertegenwoordigers van het diplomatieke korps, van nationale en internationale organisaties, en wetenschappers — waren op de openingsceremonie aanwezig. Op deze ceremonie volgde een receptie in de Marmeren Zaal. Op donderdag 23 en vrijdag 24 mei 1996 grepen de wetenschappelijke zittingen plaats op het Koninklijk Belgisch Instituut voor Natuurwetenschappen.

Prof. Dr. Yola VERHASSELT
Vast Secretaris
Koninklijke Academie
voor Overzeese Wetenschappen

Dr. Henri MALCORPS
Directeur
Koninklijk Meteorologisch
Instituut van België

AVANT-PROPOS

La conférence internationale «Climatologie, Météorologie et Hydrologie tropicales (TCMH-96)» a été tenue en mémoire du professeur Franz Bultot (1924-1995) qui a consacré une grande partie de sa carrière scientifique à l'étude de la climatologie, de la météorologie et de l'hydrologie de l'Afrique centrale. Le point culminant de ses recherches dans ce domaine fut la publication du monumental *Atlas Climatologique du Bassin Congolais/Zaïrois* paru en quatre tomes entre 1971 et 1977. Franz Bultot est aussi l'auteur de plus de cinquante publications scientifiques sur les sujets mentionnés ci-dessus.

La conférence internationale TCMH-96 a été organisée conjointement par l'Académie Royale des Sciences d'Outre-Mer (ARSOM/KAOW) et l'Institut Royal Météorologique de Belgique (IRM/KMI) et placée sous le haut patronage de S.A.R. le Roi Albert II de Belgique. En outre, elle a été co-patronnée par l'Institut royal pour la Gestion durable des Ressources naturelles et la Promotion des Technologies propres (IRGT/KINT), l'Organisation Météorologique Mondiale (OMM) et le Programme International Hydrologique de l'UNESCO (IHP, Thème 6, Hydrologie et Inventaire des Ressources en Eau dans les Zones tropicales humides). Finalement, la conférence a été co-sponsorisée par les Services fédéraux des Affaires scientifiques, techniques et culturelles (SSTC/DWTC), le Fonds National de la Recherche Scientifique (FNRS), le Ministère de l'Education et de la Formation. Des bourses ont été attribuées par l'Administration Générale de la Coopération au Développement (AGCD/ABOS) et le *Technical Centre for Agricultural and Rural Co-operation* (*CTA*) à Wageningen, Pays-Bas. Un comité scientifique restreint, constitué du Dr Gaston Demarée et des professeurs Jean Alexandre et Morgan De Dapper, a guidé et pris en charge les aspects scientifiques de la conférence TCMH-96.

La Cérémonie d'ouverture s'est déroulée au Palais des Académies le mercredi 22 mai 1996 en présence de S.A.R. le Prince Laurent de Belgique, Président de l'IRGT/KINT. Elle a été présidée par le professeur Ivan Beghin, Président de l'Académie Royale des Sciences d'Outre-Mer, et le Dr Henri Malcorps, Directeur de l'IRM/KMI. Des allocutions d'ouverture ont été prononcées par le Prince Laurent de

Belgique, M. Frank Demeyere, représentant du Ministre de la Politique scientifique, le professeur G.O.P. Obasi, Secrétaire général de l'OMM, et le professeur András Szöllösi-Nagy, Directeur de la Division des Sciences de l'Eau de l'UNESCO. Le professeur Etienne Bernard a mis en exergue la carrière scientifique de Franz Bultot en matière de TCMH. Plus de deux cents participants — représentants du corps diplomatique, des organisations nationales et internationales, ainsi que des scientifiques — ont rehaussé la cérémonie d'ouverture de leur présence. Une réception dans la Salle de Marbre a suivi la cérémonie d'ouverture. Le jeudi 23 et le vendredi 24 mai 1996, les séances scientifiques ont eu lieu à l'Institut Royal des Sciences Naturelles de Belgique.

Prof. Dr Yola VERHASSELT
Secrétaire perpétuelle
Académie Royale des Sciences
d'Outre-Mer

Dr Henri MALCORPS
Directeur
Institut Royal Météorologique
de Belgique

FOREWORD

The international conference on "Tropical Climatology, Meteorology and Hydrology (TCMH-96)" was held *in memoriam* of professor Franz Bultot (1924-1995), who dedicated a large part of his scientific career to the study of the climatology, meteorology and hydrology in Central Africa. His research in that field culminated into the publication of the monumental four-volume "Atlas Climatologique du Bassin Congolais/Zaïrois" published between 1971 and 1977. Franz Bultot was also the author of about fifty papers on the above-mentioned subjects.

The international conference TCMH-96 was jointly organized by the Royal Academy of Overseas Sciences (KAOW/ARSOM) and the Royal Meteorological Institute of Belgium (KMI/IRM) and took place under the high patronage of H.M. King Albert II of Belgium. Furthermore, it was co-patronized by the Royal Institute for Sustainable Management of Natural Resources and Promotion of Clean Technology (KINT/IRGT), the World Meteorological Organization (WMO/OMM) and the International Hydrological Programme of UNESCO (IHP, Theme 6, Hydrology and Water Resources Assessment in the Humid Tropical Zones). Finally, the conference was co-sponsored by the Federal Services for Scientific, Technical and Cultural Affairs (OSTC), the "Fonds National de la Recherche Scientifique (FNRS)" the "Ministère de l'Education et de la Formation" and scholarships were provided by the Belgian General Administration for Cooperation for Development (ABOS/AGCD) and the Technical Centre for Agricultural and Rural Cooperation (CTA) at Wageningen, the Netherlands. A core scientific committee consisting of professor Jean Alexandre, professor Morgan De Dapper and Dr Gaston Demarée guided and was responsible for the scientific aspects of TCMH-96.

The Academic Opening Ceremony was held at the "Palais des Académies" on Wednesday 22 May 1996 in the presence of H.R.H. Prince Laurent of Belgium, President of KINT/IRGT. The opening ceremony was under the presidency of professor Ivan Beghin, President of the Royal Academy of Overseas Sciences, and of Dr Henri Malcorps,

Director of the KMI/IRM. Speeches were given by Prince Laurent of Belgium, Mr Frank Demeyere, representative of the Minister of Science Policy, professor Godwin Obasi, Secretary general of the WMO, and professor András Szöllösi-Nagy, Director Division of Water Sciences of UNESCO. Mr Etienne Bernard highlighted the career of Franz Bultot in the field of TCMH. More than two hundred representatives of the diplomatic corps, of national and international organizations, and scientists were present at the opening ceremony. A reception followed the Academic Opening Ceremony in the "Salle de Marbre". On Thursday 23 and Friday 24 May 1996, the Royal Belgian Institute of Natural Sciences hosted the scientific sessions.

Prof. Dr Yola VERHASSELT
Permanent Secretary
Royal Academy
of Overseas Sciences

Dr Henri MALCORPS
Director
Royal Meteorological Institute
of Belgium

INTRODUCTION

The international conference "Tropical Climatology, Meteorology and Hydrology 1996" (TCMH-96) has been jointly organized by the Royal Academy of Overseas Sciences and the Royal Meteorological Institute of Belgium (RMIB) to honour the memory of Professor Dr Franz Bultot (1924-1995). Previously to his scientific career at the Royal Meteorological Institute, Professor Bultot had been heading quite a long time the "Bureau Climatologique" of the "Institut national pour l'étude agronomique du Congo belge" (INEAC) located in Brussels. There he met the late Professor Etienne A. Bernard (1917-1998), who was the Head of the "Division de climatologie de l'INEAC". It was the origin of a long-lasting scientific collaboration and friendship. It was also Etienne Bernard who has drawn the contribution of Professor Bultot in the fields of tropical climatology and meteorology (see this volume).

When in an unfortunate move in the decolonization process the "Institut Belge pour l'Encouragement de la Recherche scientifique Outre-Mer" (IBERSOM/BIBWOO), the ephemerous successor of INEAC, was dissolved, both scientists, together with a few others, found a new scientific home at the Royal Meteorological Institute of Belgium. Finally, Professor Bultot remained at the RMIB until his retirement mid-1989 and continued to serve until his death. It was at the Institute that he completed between 1971 and 1977 the monumental four-volume "Atlas climatologique du Bassin congolais". Tropical climatology never completely disappeared from Professor Bultot's scientific interests. In some of his last publications (see his bibliography in this volume), he returned to the subject. He wrote a comment on a published paper dealing with the evaporation of Lake Tanganyika and co-authored a paper on the statistical analysis of rainfall in Rwanda.

The scientific career of Professor Bultot brought him, among others, to accept responsibilities within bodies of the United Nations such as the Department of Hydrology and Water Resources (HWR) of the World Meteorological Organization (WMO) (see the contribution of Professor Obasi) and the International Hydrological Programme (IHP) of UNESCO (see the contribution of Professor Szöllösi-Nagy).

In many of the contributions in this volume, reference is made to the scientific work of Professor Bultot related to tropical climatology, meteorology and hydrology (see GROVE, DEMARÉE *et al.*, VANNITSEM & NICOLIS, LARAQUE & OLIVRY, BERGONZINI, OLECHNOWICZ *et al.*, GOMMES). This is particularly the case for the climatology of Congo because, for various reasons, few climatological data covering the last decades have been made available to the international scientific community for research.

The scientific contributions of TCMH-96 were classified into different sessions according to the following themes (in brackets are the selected chairpersons) : Palaeoclimatology (Professor Morgan De Dapper), Climatology (Professor Nicole Petit-Maire and Professor Hugo Decleir), Meteorology (Professor Alfred Quinet), Remote Sensing (Dr Anne Osterrieth and Professor André Ozer), Hydrology (Professor Jean Alexandre, Professor Alfred Grove and Dr Jean Sircoulon), Agrometeorology (Professor Victor Thonnard and Dr René Gommes) and Sustainable Development (Professor Jules d'Hoore). For each division, one or two keynote speakers brought the state of the art in their field and introduced the presentations withheld by the scientific committee. About 70 lectures and 15 posters were presented during the 2 ½ days of the scientific meetings which were attended by more than 150 scientists. Participants in TCMH-96 originated from more than 10 European countries ; furthermore, the attendance to TCMH-96 consisted of several representatives from international organizations, 4 Asian participants, 2 from the USA, 1 from Central America and about 15 African participants. Most of the latter were given a scholarship by the General Administration for Cooperation Development (ABOS/AGCD) or by the Technical Centre for Agricultural and Rural Cooperation (CTA) at Wageningen, the Netherlands. TCMH-96 also captured a large attendance from Belgian universities and research institutes such as the "Fondation Universitaire Luxembourgeoise" (FUL) at Arlon.

The international conference has proved to be successful ; indeed, it attracted many European scientists and, at the same time, demonstrated the interest for the conference themes. The very large national response has shown that the subject remains much alive in the Belgian scientific community although no formal permanent structures such as research institutes dealing with the items of this conference exist. This vacuum has been partly filled by the dynamic approach of the Royal Academy of Overseas Sciences.

At the same time, an effort was made to provide a meeting for scientists from north and south to enable them to discuss in an open forum matters on the conference themes. It is encouraging that presentations by African scientists did indeed receive a large interest from the audience. One of the repeated messages from the conference pointed towards a general lack of recent scientific data from the target area.

It was noted that several presentations were parts of a larger international co-operative effort like the "International Decade for the East African Lakes" and "Flow Regimes from International and Experimental Networks Data" (FRIEND AOC) for West and Central Africa.

The large response of the sections on "Remote Sensing" and "Sustainable Development" underline the efforts deployed by the Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC) of the Ministry of Science Policy in its research programme on Sustainable Development (see opening speech by Mr Frank Demeyere in this volume).

The success of the international conference TCMH-96 has led the initiators to consider a new edition of it in May 2000. The Organizing Committee bid you already a hearty welcome to Brussels on the occasion of TCMH-2000.

The Guest Editors

ACADEMIC OPENING SESSION

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 19-21 (1998)

Opening Speech

by

H. R. H. Prince Laurent of Belgium *

Ladies and Gentlemen,
Mesdames et Messieurs,
Dames en Heren,

It is an honour and a pleasure to take the floor on this International Conference on "Tropical Climatology, Meteorology and Hydrology" *in memoriam* Professor Bultot. I am truly delighted that you have given me the opportunity to share with you an important environmental message and to explain to you the objectives of the Royal Institute for Sustainable Management of Natural Resources and Promotion of Clean Technology, for which I am responsible.

For the last decades, environmental degradation has continued with increasing speed. The multiple threats to the natural environment have become a problem of global dimension. The disastrous floods in different parts of the world are an example that illustrates extraordinarily well how vulnerable natural equilibria are, when faced with a non-sustainable management. One could just as well mention deforestation, unsustainable agricultural practices, urbanization, drainage, straightening and canalization of rivers or deficient land-use planning in general, to illustrate the point. An increase in flood frequency may be an indicator of human-induced climatic changes. These climate changes are primarily driven by land-use changes on the lower latitudes and industrial greenhouse gas emissions on the higher latitudes. The uncertainties on the hydrological consequences of global warming must still be resolved.

In the long term, anthropogenic global changes are not expected to have a more dramatic impact on the biosphere than, for example, the last glaciation or prehistorical volcano eruptions. However, even if the thermodynamics of this human-induced process are not excep-

* President of the Royal Institute for Sustainable Management of Natural Resources and Promotion of Clean Technology, E. Jacqmainlaan 157, B-1210 Brussels (Belgium).

tional on a geological time-scale, its kinetics are expected to be exceptionally high. Moreover, even if life is not threatened with extinction, the structure and stability of human society is in danger.

The remaining uncertainties should not be used as a reason to do nothing. On the contrary, we should follow the precautionary principle. This means that we should pursue a no-regret policy, and work out preventive measures. We should start it now, even before complete certainty of changes can be achieved.

Le génie humain est tel que nous comprenons de mieux en mieux le processus complexe des changements globaux. Mais pourrons-nous faire face à ce défi? Avons-nous des systèmes de développement durable qui soient capables de ralentir ou de contrer ces changements? Sommes-nous prêts à utiliser les ressources naturelles avec plus d'efficacité et plus d'équité entre les différentes parties du monde?

Jusqu'à présent, il me semble que dans la société humaine une certaine inertie au sens scientifique du mot domine la force de l'intelligence. Celle-ci est la conséquence du manque de responsabilité individuelle ou encore de la prédominance des intérêts personnels.

Het gevolg hiervan is dat ons antwoord op deze bedreigingen al te zeer gericht is op *herstellen* in plaats van *voorkomen*, op symptoombestrijding in plaats van daadwerkelijk beheer. Ons beleid wordt in de meeste gevallen gedomineerd door het hoogdringende, ten koste van preventie en duurzaamheid. Deze *end of pipe*-aanpak herleidt onze inbreng tot een rol van brandweerlieden die achter steeds grotere branden aanlopen.

Om een voorspoedige toekomst van de planeet Aarde te verzekeren, is het van kapitaal belang dat we onze inspanningen tot duurzaamheid verhogen. Actie is zowel vereist op het internationale, nationale, regionale als lokale niveau. In het algemeen kader van duurzame ontwikkeling wil het Instituut de inspanningen bundelen die kunnen leiden tot een herstel van de milieukwaliteit en dit door het accent te leggen op een tweevoudige aanpak : het duurzame beheer van de natuurlijke rijkdommen en de bevordering van schone technologie.

Sustainable management of natural resources demands a respectful relationship between the socio-economic development and the vital components of our planet : energy, air, water, soil, plants, animals and their biotopes. The term "management" is essential and refers to the central role of human beings in the ecosystem. There is no sustainable development without management. A sustainable management of natural resources must create a worthwhile existence for mankind, but

without depletion or irreversible degradation of the resources that will also be needed by future generations. In other words, sustainable management of natural resources has an ecological and a socio-economic component.

If we want to promote *clean technology*, we must develop techniques which will lead to a further enhancement of the quality of life, while preventing further degradation. Technology must provide ways to restore and avoid environmental damage, while simultaneously ensuring a satisfactory level of human welfare and well-being, as well as respecting the environment of animals and plants.

The question on how to implement these two fundamental elements of sustainable development gives rise to many ideas and controversies. The latter are frequently due to the lack of a common language to speak about environmental problems. Dialogue and reciprocal understanding between people and nations, therefore, need to be better defined, and a uniform terminology should be used. The Institute tries to contribute to the uniformization of language, and the convergence and harmonization of efforts directed towards problems with the environment. It aims to be the spark that lights the imagination, it wants to be a bridge between different ideas and parties, and also a forum for everyone involved in these problems, where they can meet, share ideas and build up a common future. The Institute tries to build concrete action on a solid philosophical basis.

The only successful answer to the problems of global change will lie in a responsabilization of every single individual. There is need for *a global change in mentality*. This is only possible by means of education. We must develop better ways to translate objective scientific information into unbiased messages for the public.

In conclusion, I would like to remind you that humanity and humility are two words with the same etymological origin. It means that, in spite of the impressive technological development, humans should keep a certain modesty. Our society is very vulnerable because of its complexity and its dependence on technology. Better understand the world in order to manage it better, communicate better for a better understanding of each other, these are ambitious and passionating objectives. The Institute invites you all to contribute to this valuable goal.

Ladies and Gentlemen, Mesdames et Messieurs, Dames en Heren, thank you very much for your attention.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 22-24 (1998)

Opening Speech

by

Frank DEMEYERE *

Monseigneur,
Madame Bultot,
Mesdames, Messieurs,

Het is voor mij een bijzonder genoegen om in naam van Minister Yvan Ylieff, Federaal Minister van Wetenschapsbeleid, het woord tot U te kunnen richten op deze academische openingszitting van de Internationale Conferentie „Tropische Klimatologie, Meteorologie en Hydrologie".

C'est aussi un honneur, car cette conférence scientifique de haut niveau témoigne, une fois de plus, de l'importance de nos établissements scientifiques fédéraux sur le plan scientifique. Cela est aujourd'hui illustré non seulement par les organisateurs de cette conférence, à savoir l'Académie Royale des Sciences d'Outre-Mer et l'Institut Royal Météorologique de Belgique, deux établissements relevant de la compétence du Ministre fédéral de la Politique scientifique, Yvan Ylieff, mais également, lors des diverses sessions, par plusieurs intervenants employés soit dans nos établissements scientifiques fédéraux, soit aux Services fédéraux des Affaires scientifiques, techniques et culturelles, l'administration du département politique scientifique.

Madame Bultot,

Cette conférence internationale se tient, à juste titre, en mémoire du professeur Franz Bultot, dont le nom a été donné récemment à la Section Hydrologie de l'Institut Royal Météorologique de Belgique. En effet, le professeur Bultot a été un des pionniers des sciences tropicales. La liste de ses publications comptant environ cinquante sujets ayant trait à la climatologie, à la météorologie ou à l'hydrologie,

* Chef de Cabinet Adjoint, Ministry of Science Policy, rue de la Loi 66, B-1040 Brussels (Belgium).

en témoigne. Entre autres pour cette raison, je crois pouvoir dire, Madame Bultot, que votre mari a sans aucun doute contribué d'une façon remarquable au rayonnement scientifique mondial de l'Institut Royal Météorologique de Belgique.

Monseigneur,
Mesdames, Messieurs,

Les organisateurs ont bien fait de situer cette manifestation scientifique internationale dans le cadre de la recherche scientifique selon les lignes du «développement durable», de la «biodiversité» et des «sources d'énergie renouvelables», forces agissantes de la Conférence des Nations Unies sur l'Environnement et le Développement de Rio de juin 1992.

Les instruments ou moyens d'action fournis par ladite conférence sont compris dans :

— La Déclaration de Rio et son Agenda 21 ;
— La Convention sur la diversité biologique ;
— La Convention-cadre sur le changement climatique ;
— La Convention sur les principes de la conservation forestière ;
— La Convention internationale de la lutte contre la désertification.

Permettez-moi de vous rappeler à cet égard que le Ministre de la Politique scientifique a été chargé, au sein de l'actuel Gouvernement, de la mise en œuvre d'un appui scientifique aux politiques de développement durable. A cet effet, un Plan d'appui scientifique aux politiques de développement durable a été préparé qui représente un montant de plus de 2,5 milliards de francs pour les années à venir.

Ladies and Gentlemen,

In the context of a policy oriented towards a sustainable development, both at international and Belgian level, the Plan for Scientific Support of a Policy oriented towards a Sustainable Development has to encourage the integration of a strictly scientific approach of the strategic concerns. The research that will be conducted :

— Fits in with the options of the recent government policy statement ;
— Supports the commitments of Belgium within the framework of the international agreements (conference of Rio, the Treaty on Antarctica, The Council for Sustainable Development of the UNO) ;
— Integrates the recommendations of the National Council for Sustainable Development by laying the emphasis on the development

of indicators and instruments (crossroads of information) in order to encourage the interdisciplinarity and on the observance of both the social and scientific aspects.

In the light of these general requirements, the actions cannot pass over the less goal-oriented studies that can develop new ways of thinking in the future, given the evolving and vaguely defined character of the concept of "sustainable development".

The research that will be conducted within the framework of the Plan for Scientific Support of a Policy oriented towards a Sustainable Development has to correspond to the following objectives :

— Development of a solid basis of scientific and technological assessment, including the appropriate methods and instruments, in order to correspond better to the objectives of a sustainable development by simplifying the integration of data ;
— Scientific and technological support of the political actions in order to find a solution to the problems at federal and international level (preparation and implementation of conventions, guidelines, protocols, ...) ;
— Integration of research teams in action frameworks at international level, not only to exchange data and knowledge but also to contribute to a sustainable development exceeding our borders and even our continent.

The Plan for Scientific Support of a Policy oriented towards a Sustainable Development meets this objective. Its most important pillars are : Global Change, the Sustainable Management of the North Sea, Antarctica, the Sustainable Mobility, the Food Standards and the Driving Forces of a Policy oriented towards a Sustainable Development.

It is clear that the Plan for Scientific Support must constitute a whole. Its various programmes have to be carried out in close collaboration in order to encourage the mutual and permanent exchange of information and results.

Monseigneur,
Mesdames, Messieurs,

Il ne me reste plus qu'à vous souhaiter une conférence fructueuse et à exprimer le désir que vos activités puissent contribuer à la concrétisation d'une politique de développement durable.

Je vous remercie de votre attention.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 25-29 (1998)

Opening Address

by

Godwin Obasi *

Your Royal Highness, Prince Laurent,
Mr Chairman,
Excellencies,
Ladies and Gentlemen,

It is indeed an honour and a privilege for me to address you today at the opening of the International Conference on "Tropical Climatology, Meteorology and Hydrology" in memory of professor Franz Bultot. On behalf of the World Meteorological Organization (WMO) and on my own, I wish to express my sincere thanks to the Government of Belgium for the kind invitation to me to address this ceremony. I wish also to thank Dr H. Malcorps, Director of the Royal Meteorological Institute of Belgium (IRM) and Permanent Representative of Belgium with WMO, for all the arrangements for the Conference and for my own participation here today.

This Conference offers an opportunity for me, on behalf of the World Meteorological Organization, to pay tribute to professor Bultot, as well-known scientist who passed away in 1995, after having dedicated a large part of his career to the well-being of his countrymen and in several ways in service to humanity. Professor Bultot's work covered a broad spectrum of specialities, which contributed to the fame he was to enjoy. I will not go through his entire career, but I would like to touch on those aspects which, in my mind, are relevant to the programmes of WMO and are of interest to the world meteorological and hydrological communities.

The early period of his professional career, between 1947 and 1962, was at the National Institute for Agronomic Study of the Congo

* Secretary-General of the World Meteorological Organization, 41 avenue G. Motta, Case Postale no. 2300, CH-1211 Geneva 2 (Switzerland).

(INEAC) where he was in charge of the Bureau of Climatology, a period during which he expended considerable effort on studying the meteorology and climatology of Central Africa. This culminated in the authoritative four-volume *Atlas Climatologique du Bassin Congolais/Zaïrois*. I recall his work very well, for in the sixties, I myself read most of professor Bultot's papers and I used some of his results in my own tropical meteorological research in Western Africa. Professor Bultot also widened his interest from meteorology and climatology to hydrological matters. He studied precipitation processes and pursued his theories on the close relationship between atmospheric and hydrological processes. In 1962, a couple of years after the independence of the Congo, now Zaire, professor Bultot joined the Royal Meteorological Institute where he was put in charge of the Hydrology Section in 1969, and then in 1985, he became Head of the Department of Climatology. The results of his research in hydrology and his hydrological-oriented activities while at IRM made his name quite famous in both the operational and scientific hydrological communities.

Over the past decades, professor Bultot actively participated in the work of several WMO bodies related to hydrology. He was very active as the Hydrological Adviser to the President of WMO's Regional Association VI for Europe, and as Chairman of the Association's Working Group on Hydrology from 1986 until his untimely death in 1995. The accomplishment of the Working Group under his leadership, served as a good example for similar Working Groups. Professor Bultot was also actively involved in the global work of WMO's Commission for Hydrology (CHy). He was the instigator and subsequent director of a project to adapt the existing Belgian hydrological database for use in microcomputers, for international distribution in several languages, through the WMO Hydrological Operational Multipurpose System (HOMS). This project provides several of the most widely used HOMS components. He also participated in most WMO and UNESCO conferences and meetings concerning hydrology over the last fifteen to twenty years, either as a delegate for Belgium or as an invited expert. It was his dedication to the many important duties he discharged in various national and international committees, in particular with WMO, that led to his worldwide recognition. Therefore in 1993, professor Bultot received the *President's Award* during the ninth session of the Commission for Hydrology in Geneva, for his exceptional contribution to science through the work of the Commission.

Mr Chairman,

A significant contribution of professor Bultot relates to the ongoing international activities on the state of the world's environment. Franz Bultot was the leader of a team of scientists studying the impacts of climate change on the water cycle and on the water balance. A conceptual hydrological model developed at the Royal Meteorological Institute was found to be applicable in climate change studies, and to be able to simulate such hydrological elements as evapotranspiration, soil moisture, snow cover, groundwater storage and the components of flow in a *warmer* climate, as a consequence of a doubling of carbon dioxide (CO_2) in the atmosphere. The results of the studies on this subject by professor Bultot and his colleagues have been subject to a large number of citations worldwide; they are reflected in authoritative works such as the scientific assessments of the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC), which form the basis for actions being undertaken by Governments worldwide to combat the human effects on climate, as part of the United Nations Framework Convention on Climate Change.

In view of the work carried out by professor Bultot and his colleagues in the area of climatology and hydrology in support of activities in Central Africa, it is appropriate for me to highlight here the efforts deployed by the World Meteorological Organization since the independence of Zaire, to establish and develop adequate meteorological and hydrological facilities in that country and others in Central Africa.

In the first few years, WMO launched a major UN Special Fund project for the development of the Meteorological Service of Zaire. That project included expert services, the provision of meteorological equipment, fellowships and training services. In particular, the project assisted in the establishment of a training school for meteorological personnel at various levels, the establishment of the surface and upper-air meteorological networks, and the forecasting and data collection system of the country. I am sure that this initiative must have pleased professor Bultot. Unfortunately, by the middle of the seventies, the situation in that region continued to deteriorate.

In 1982 therefore, WMO sent special missions to Zaire to reassess the status of the meteorological and hydrological infrastructure, as well as the human resources requirements, to further develop these services. Thereafter, several project proposals were formulated, and assistance was received to support the rehabilitation of the aeronautical meteo-

rology facilities at the main airports and the training of nationals in various fields.

In addition, further efforts were made in the early nineties to develop new projects at national and regional levels for Zaire and the riparian countries of the Congo river. However, due to the prevailing situation in the countries of Central Africa, it was not possible to successfully accomplish these tasks. This is to be regretted. Nevertheless, WMO continued to work with the development partners to assist the countries concerned. In this context, WMO has now developed a regional meteorological programme for the Member States of the Economic Community of the Great Lakes Countries (GEPGL), comprising Burundi, Rwanda and Zaire. Recently, WMO has been negotiating with the World Bank for the development and implementation of a meteorological and hydrological project covering the Congo basin area, within the framework of a World Bank Environment Information Database for the region.

Your Excellencies,

The Government of Belgium did not sit idly by to watch the deterioration of the meteorological situation of Zaïre. Indeed, the Government of Belgium had made significant contributions towards the development of meteorology and operational hydrology, especially in Zaïre, Burundi and Rwanda, and indeed in many other developing countries, much of which is itself tied up with the life of Franz Bultot. Following the severe and persistent drought in the Sahel in the late sixties and early seventies, the Belgian Government funded a Data Rescue Project (DARE) aimed at microfilming the original data manuscripts in several Sahelian countries. By the end of 1995, an International Data Rescue Coordination Centre (IDCC), which was established in Brussels to coordinate the project, had compiled nearly five million records on microfilm. A similar project is being implemented for Central American countries. The Belgian Government also provides support to other WMO initiatives in Africa, including regional centres such as the African Centre for Meteorological Applications for Development (ACMAD) and the AGRHYMET Centre.

In the area of capacity building, the HOMS Microcomputer Project, which offers useful training to relevant personnel, has benefited many developing countries, especially those of Latin America and the Newly Independent States (NIS). In addition, the Government of Belgium

has, since 1979, funded eight fellowships per year for training in Belgium of agrometeorologists from developing countries. Over one hundred sixty from forty countries have benefited so far from these courses. These examples demonstrate the role that Belgium continues to play in the international co-operation in meteorology and operational hydrology in support of the goals and objectives of WMO.

Mr Chairman,

The humid tropic is a region of special importance to meteorology, hydrology and global water resources, a fact that has become increasingly understood for the last few decades. A lingering problem in many countries of the tropics is the need for sufficient trained staff and the funds to install and maintain adequate networks of meteorological and hydrological stations and flood forecasting systems. The key to this issue continues to be capacity building, which professor Bultot promoted and understood quite well. I therefore look forward to further collaboration with the Belgian authorities, especially for the development of projects to enhance the capabilities of national meteorological and hydrological services in the developing countries. Regional programmes such as the Drought Monitoring Centre and ACMAD in Africa should also be supported. This is the greatest tribute that can be paid to the late professor Bultot. On our part, I wish to give the assurance of WMO's commitment to continue to collaborate with the Belgian Government in its efforts to foster international co-operation in meteorology and operational hydrology.

Your Royal Highness, Excellencies, Ladies and Gentleman,

In conclusion, I wish once more to express my appreciation to the Belgian Government for enabling me to pay this tribute to professor Franz Bultot, on behalf of all who were associated with him in WMO and in the meteorological and hydrological communities around the world. The little I have said does not adequately catalogue his contribution. As a man of science endowed with great charm and diplomacy, he set fine examples of dedication to international co-operation which is worthy of emulation, and for which he shall always be remembered.

Thank you very much.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 30-34 (1998)

Opening Address

by

András Szöllösi-Nagy *

Your Royal Highness, Prince Laurent,
Madame Bultot,
Professor Beghin, President of the Royal Academy of Overseas Sciences,
Dr Malcorps, Director of the Royal Meteorological Institute,
Professor Obasi,
Ladies and Gentlemen,
Dear Colleagues,

It is indeed a great honour for me to address you this morning on behalf of the Director General of UNESCO, Mr Federico Mayor, and also on my own behalf as the Secretary of the International Hydrological Programme of UNESCO at the academic opening ceremony of the International Conference on "Tropical Climatology, Meteorology and Hydrology" dedicated to the late professor Franz Bultot, the eminent Belgian hydrologist and climatologist.

It gives me additional pleasure to see that the Conference is a contribution from Belgium to the Humid Tropics Hydrology Programme of the I.H.P. I should like to add a very personal remark and that is that I am deeply touched that this important meeting is being organized *in memoriam* Franz Bultot, a long-standing friend who helped me a great deal in finding my way through the jungles of international hydrological cooperation.

Ladies and Gentlemen,

As you may know, the hydrology and water management of the humid tropical regions has been and is one of the priorities of I.H.P.

* Secretary of the International Hydrological Programme, United Nations Educational, Scientific and Cultural Organization, 7, Place de Fontenoy, F-75352 Paris 07 SP (France).

The origins of the Humid Tropics Hydrology Programme date back to 1987, coinciding with an I.H.P. Working Group meeting held at the University of Hawaii's Water Resources Center. In recognition of the escalating socio-economic problems of the humid tropics and the urgency of the need to address associated water management issues, it was proposed that a more comprehensive programme needed to be developed under the auspices of I.H.P. An international meeting was suggested to formulate the directions of this programme. Subsequently, this was held at the James Cook University of Townsville, Australia, in 1989, entitled „International Colloquium on the Development of Hydrologic and Water Management Strategies in the Humid Tropics". A series of recommendations on follow-up actions emanated from that Colloquium which are currently being implemented in member states and form the backbone of UNESCO's Humid Tropics Programme.

During the Fourth Phase of I.H.P. which ended last December, the Humid Tropics Hydrology Programme grew and expanded into various regional activities while supporting the development of improved methodologies to model the land-phase of the hydrological cycle that represents a major feed-back in the climate system. Still, if someone looks at how this land-phase is generally handled in global-scale models the picture is rather disturbing. Areas of continental size are often represented by simple elementary reservoirs. Therefore, the hydrological uncertainties and risks associated with different climate change scenarios are still too great — as Prince Laurent has already mentioned —, not only due to our limited understanding but also due to the very limited data available. Again, there are continents where there are less hydrological data than in a medium-sized industrialized country. Thus, it is an extremely important mission to build up and maintain endogenous hydrological science capacities in the developing world. This is not only a moral obligation but also a rational must. Take, for example, Africa, where the hydrological capacity is less than it was fifteen years ago. There are more data on the hydrology of Africa outside the continent than inside. So, how can we talk of understanding and modelling global processes if the sample data sets refer almost exclusively to the developed world? Any conclusion drawn from such data is necessarily biased and subject to huge uncertainties. We need to focus all our efforts on changing this bad situation. Of course, it is primarily not the global modelling that necessitates smoothly running operational data collection services, but rather the dire needs of the

countries concerned. This is one of the points Franz Bultot never stopped emphasizing.

A host of activities have recently taken place concerning humid tropics hydrology in Latin America and the Caribbean. With the launching of the UNESCO-sponsored Regional Center for Humid Tropics Hydrology in Panama City, with the strong support of the Panamanian and US Governments, activities took a new momentum. In the meantime a large-scale field experiment in the Amazon basin, known as LAMBADA which stands for : Large-Scale Atmospheric Moisture Balance of Amazonia using Data Assimilation, is being planned in conjunction with the biohydrological core project of the International Geosphere/Biosphere Programme of ICSU. The establishment of a Regional Humid Tropics Hydrology Centre for South-East Asia and the Pacific is currently being negotiated.

All these I.H.P. centres will ultimately be devoted to assist sustainable development as it is absolutely clear that the growing population in the humid tropics obviously requires that future actions must be carried out in terms of sustainable development. Several reasons have encouraged some clearly unsustainable development policies and practices concerning water management in developing nations of the humid tropics. Environmentally unsound development of the water and related sources has been further aggravated by the rapid economic, social and political changes resulting from the rapidly growing tropical urban populations. This complex social structure, combined with a lack of knowledge of hydro-ecological relationships of the natural systems, clearly show that the humid tropics are an extremely vulnerable environment that, acting as a boiler for the climate system, is also of great importance from a global change perspective.

It has been estimated that by the year 2000 the countries within the humid tropics and the other warm humid regions will represent almost one third of the total world population. This proportion will continue to rise in the twenty-first century. The humid tropics regions are quite clearly the zones which are potentially facing the most serious social and economic problems. For example, it is common knowledge that small tropical islands are particularly subject to an ever-increasing risk concerning their water management.

The pertinent question to ask is : what is special about tropical islands in terms of their hydrology and water management? The *low* or *atoll* islands present a distinctive physical basis for the occurrence of

groundwater, the so-called *freshwater lenses*. In fact the term *freshwater lens* is a misnomer because there is no distinct freshwater body floating on sea water. In reality there is a gradual transition from the freshest water at the water table to sea water at depth. Comprehensive knowledge of the physical basis of such water bodies, application of the most appropriate groundwater models, and in turn, their management to avoid their temporary or even irreversible destruction by sea-water intrusion poses major problems. Otherwise there is nothing special about tropical islands — the problems highlighted are as much a concern to other coastal areas as well, e.g. water quality/pollution issues of both surface and subsurface water bodies, hydrological impacts from the conversion of forests (on high islands), coastal saline intrusion of groundwater aquifers connected with high islands and, last but not least, possible impact of sea level rise. What enhances the environmental focus of attention on islands in general is their sheer limited size which makes their natural resources extremely vulnerable to environmental mismanagement in response to socio-economic pressures for development. Their limited areas and the conflicting as well as competing demands on natural resources, such as a limited water supply, are further aggravated by the escalation in population densities in many islands.

Paradoxically, at a time when potable water demands are increasing in response to population and tourism pressures, the limited freshwater resource is the ultimate recipient of all the pollution resulting from various socio-economic activities associated with urbanization, agriculture, conversion of native vegetation.

It is urgent to question whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources of the humid tropics and other warm humid regions. The analysis of humid tropical hydrological phenomena on different scales is of utmost importance and as a matter of urgency, particularly in light of the critical role the humid tropics play in the global atmospheric and hydrological processes. As already mentioned, with the present level of data availability in the humid tropics there is no hope of reducing uncertainties in any global consideration.

Some of the most urgent hydrological and water resources management problems that need to be addressed from an integrated environmental and socio-cultural perspective include the issues of :

— Population, food and agriculture ;
— Population, deforestation and reforestation ;
— Rural/urban water pollution, urban drainage, water treatment, water supply and health :
— River systems, natural and man-made lakes ;
— Interaction between ocean-atmosphere-water-man's activities ;
— Special problems associated with tropical islands.

The General Conference of UNESCO, held last October, approved the continuation of the International Hydrological Programme into its fifth phase which will be devoted to "Hydrology and water resources development in a vulnerable environment" and will lead us into the next century. Out of the eight themes of I.H.P.-V one theme is dealing with humid tropics problems with the basic aims of : first, assessing the vulnerability of the humid tropical environment with respect to different water and land-use techniques to assure sustainable development on short-term and long-term scales ; secondly, developing networks of water and water-related experts and research organizations involved in warm humid regions hydrology and water management studies ; thirdly, evaluating, understanding and defining the spatial and temporal variability of key hydrological variables along with the modelling of hydrologic processes in the tropics on different scales ; fourthly, evaluating the impact of human activities on the hydrological cycle of the tropical forests to better understand the global climate system.

As you see, to reach these goals interdisciplinary co-operation is required between tropical hydrologists, climatologists and meteorologists — in the same way you set out to do in the coming days. We are very grateful to the organizers, the Belgian authorities and the various sponsoring agencies to make this event, which is an extremely important contribution to I.H.P., possible. Special thanks also go to Dr Gaston Demarée for the enormous amount of work he put into this venture. I am sure if Franz Bultot was with us he would approve the agenda and would certainly help us in the evening to get around the tropical jungle of Belgian jokes of which he was a master beside his brilliant scientific mind.

Finally, may I wish you, Ladies and Gentlemen, much success in your deliberations as well as a pleasant stay in this marvellous city. Thank you.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 35-41 (1998)

L'œuvre de Franz Bultot en météorologie et en climatologie tropicales

par

Etienne BERNARD *

Il m'appartient dans cette séance d'ouverture de notre Conférence, à la mémoire de Franz Bultot, de résumer ce que furent sa carrière et son œuvre scientifiques dans sa spécialité d'origine : la météorologie et la climatologie tropicales et, plus particulièrement, celles du Zaïre et de l'Afrique.

J'ai été appelé à faire cet exposé parce que Bultot et moi, nous avons été durant treize ans au service d'une même Institution, mais dans des fonctions différentes, moi au siège africain de l'Institution en un lieu appelé Yangambi, Bultot au siège de Bruxelles.

On ne peut comprendre l'œuvre de Bultot, à qui nous rendons hommage, qu'en rappelant ce que fut l'Institution où il s'est formé et l'esprit qui l'animait.

L'organisme était de statut parastatal comme nous disons en Belgique. Il s'appelait «Institut National pour l'Etude Agronomique du Congo belge», en abrégé l'INEAC. Il avait été créé en 1933 pour promouvoir le développement de l'agriculture du Congo belge et du Ruanda-Urundi par la science et la technique. Le duc de Brabant, futur Léopold III, et son conseiller scientifique Victor Van Straelen, directeur de l'Institut royal des Sciences naturelles, avaient effectué un voyage d'étude aux Indes néerlandaises, accompagnés de la Princesse Astrid.

Inspirés par l'expérience hollandaise en agronomie tropicale, ils firent créer l'INEAC à partir des établissements de la Régie des Plantations, organisme déjà vieilli qui remontait à 1910.

---

* Membre de l'Académie ; ancien Directeur du Centre de Recherches de l'INEAC à Yangambi († 7 juin 1998).

Par ses succès croissants, l'INEAC a toujours disposé de grands moyens matériels, financiers et humains. En 1960, à l'indépendance du Zaïre, l'INEAC formait un vaste ensemble de réalisations : 1) trente établissements couvrant les grandes régions écologiques des Territoires, 2) un Centre de recherches disposant d'une centaine de chercheurs répartis sur vingt divisions et couvrant 5 000 hectares de plantations expérimentales. Le vaste Domaine de ce Centre se situait à Yangambi : au cœur de la forêt équatoriale et sur la rive droite du fleuve Congo, à 100 km en aval de Stanleyville, l'actuelle Kisangani. Les rendements des cultures industrielles et vivrières avaient été multipliés par des coefficients de 3 à 6. L'agriculture était prospère, représentant 40 % du Produit National Brut d'un pays aux richesses minières pourtant considérables.

Je suis heureux de rappeler ici, devant le Prince Laurent qui nous honore de sa présence, que c'est son père, notre Roi actuel Albert II, qui assuma la présidence de l'INEAC durant ses cinq dernières années d'existence, années où l'énorme capital investi dans la recherche à long terme rendait ses plus hauts intérêts de progrès.

Je peux expliquer maintenant le rôle que joua Franz Bultot dans cette grande institution.

Après la guerre, de 1945 à 1947, la politique des éminents savants qui dirigeaient l'INEAC fut de créer et de développer les divisions des sciences de l'environnement des cultures : une division d'agrologie-pédologie pour les sols, une division de botanique pour la végétation naturelle, une division de climatologie pour le milieu atmosphérique. En bref, l'abc de l'agriculture à rationaliser par la connaissance du milieu.

La recette pour bénéficier de cultures à haut rendement est simple mais l'application est exigeante en moyens. Voici la recette. Créez par la sélection un potentiel de bons gènes, capables de programmer des fonctions physiologiques de croissance bien actives. Cultivez dans un milieu écologique de climat et de sol en harmonie avec les besoins de ces fonctions. Luttez conte les pestes, les insectes et les prédateurs. Vous obtiendrez de hauts rendements surtout si vous améliorez le milieu par des techniques culturales.

Ainsi, il y a cinquante ans, tous les chercheurs de l'INEAC faisaient de l'écologie, mais en le sachant et en réalisant des programmes d'action à long terme, convenus entre les agronomes et les spécialistes. Ils appliquaient la définition de l'écologie, à sa création par Haeckel en

1866 : la science des rapports mutuels entre les êtres vivants et leur milieu d'existence.

J'étais responsable depuis 1945 de la nouvelle division de climatologie. Ma mission prioritaire avait été d'organiser un réseau moderne de stations climatologiques basé sur les établissements de l'INEAC. D'autre part, le Service météorologique du Gouvernement général avait développé un réseau de quatre-vingt stations synoptiques parfaitement coordonnées avec celles de l'INEAC dans l'équipement comme dans les méthodes d'observation. La riche moisson de données, traitées en Afrique, exigeait l'existence, au siège de l'INEAC à Bruxelles, d'un Bureau climatologique. Il fut chargé de centraliser les données, d'en publier l'annuaire, de les exploiter en études de synthèse et d'informer tous les utilisateurs.

Bultot fut choisi comme Chef de ce Bureau. Il terminait à cette époque, en 1947, sa thèse de Docteur en Sciences à l'Université Libre de Bruxelles, sous la direction d'un grand théoricien de la dynamique atmosphérique, le professeur Jacques Van Mieghem, futur directeur de l'Institut Royal Météorologique.

Le titre de sa thèse était : «Les surfaces de discontinuité dans l'atmosphère». Licencié en sciences mathématiques, il venait par ailleurs de terminer une licence en sciences actuarielles. Par ces études complémentaires, il prendra goût à l'analyse statistique où il excellera dans tous ses travaux. Il sera Vice-Président de la Société belge de Statistique de 1957 à 1959. Cette société lui décernera son Prix quinquennal pour la période 1954-1958.

Franz Bultot a accompli sa tâche à l'INEAC avec passion et compétence. Sans désemparer et avec une tranquille ardeur, parce que c'était le devoir de ses fonctions, il signera de belles publications de synthèse qui se succéderont durant quatorze années. Il faut ajouter à ces travaux de synthèse les dix *Bulletins climatologiques* annuels du Congo belge et du Ruanda-Urundi qu'il publie anonymement de 1950 à 1959.

Je veux souligner maintenant l'originalité, quant au fond, des *Bulletins* annuels et des publications de Franz Bultot en climatologie tropicale, fond de principes et de méthodes qu'il reçut dès son engagement et qu'il développera dans tous ses travaux.

La réorganisation du réseau climatologique colonial avait été fondée sur une conception très neuve en 1947 de la climatologie et de l'hydrologie, conception qui les réunissait dans une synthèse unificatrice.

Les processus atmosphériques au-dessus d'un bassin hydrologique,

d'une surface naturelle ou d'un champ cultivé obéissent, par leurs termes, à deux équations simples. Chacune exprime un bilan de conservation : un bilan des termes qui répartissent l'énergie solaire incidente, un bilan des termes qui distribuent l'eau des pluies reçues par la surface. Bilans comptables élémentaires : la quantité qui entre dans le système sol-végétation moins celle qui le quitte est égale à celle qui reste.

L'évapotranspiration de la surface naturelle ou cultivée, impossible à observer, était déterminée dans cette méthode par la chaleur latente consommée, terme résiduel du bilan d'énergie. Terme essentiel, représentant pour le bassin congolais 70 % des pluies. Il unissait les deux bilans en un système de termes mesurables ou fonction de lois physiques. Les réseaux, par leur équipement, fournissaient l'observable et la théorie achevait la connaissance des bilans. Par leur union, la climatologie et l'hydrologie étaient ainsi promues, du rang de sciences descriptives et statistiques, au rang de sciences rationalisables.

Ces conceptions paraissent bien évidentes aujourd'hui. Il y a cinquante ans, il a fallu y réfléchir beaucoup et convaincre par l'expérimentation.

La seconde carrière de Franz Bultot commence en 1962 à l'Institut Royal Météorologique. Il y est engagé, après la suppression de l'INEAC dans son statut métropolitain, en conséquence de l'indépendance du Congo devenu le Zaïre. Il retrouve à l'I.R.M. son ancien professeur, devenu Directeur de l'Institut, Jacques Van Mieghem. Leurs vues se rencontrent sur la nécessité de créer une nouvelle section d'hydrologie au Département de Climatologie de l'I.R.M. Elle est créée en 1965 et Bultot l'organise. Notons que l'hydrologie opérationnelle n'est devenue responsabilité de l'Organisation Météorologique Mondiale qu'en 1975. On sait avec quel succès Bultot accomplira son œuvre d'hydrologue de la Belgique, puis de l'Europe dans le cadre de l'O.M.M.

Par ses acquis à l'INEAC, la conversion de Franz Bultot à l'hydrologie ne fut que l'adoption d'un point de vue différent au sein d'une même unité de connaissances.

Franz Bultot a consacré une grande part de ses activités à l'enseignement supérieur. Il a notamment donné les cours «Bilan d'énergie et Bilan d'eau» à l'option «Agrométéorologie» de la Fondation Universitaire Luxembourgeoise à Arlon, fondation chargée des sciences de l'environnement. L'option fonctionne avec l'aide de la coopération belge, en coordination avec l'O.M.M. Elle a formé à ce jour un grand nombre de météorologistes-boursiers venus des pays en voie de développement.

Ainsi, l'intérêt de Franz Bultot pour le monde tropical n'a jamais décliné au cours de sa carrière entière, commencée en 1947 et achevée en 1989, lors de sa mise à la retraite. Je dois citer à cet égard deux travaux de longue haleine qu'il mena à bon terme avec ses collaborateurs.

Le premier de ces travaux est l'«Atlas climatologique du Bassin congolais». La publication d'un tel atlas était une vieille idée dont j'entretenais Bultot à chacun de mes retours d'Afrique. L'atlas devait être le couronnement des activités de la division de climatologie, mais il compléterait aussi l'œuvre écologique de l'INEAC en cartographie des sols et de la végétation. En 1958, Bultot entreprit la tâche. Il publia l'Atlas en quatre volumes de grand format de 1974 à 1977.

Le dernier volume paru a pour titre «Atlas climatique du Bassin zaïrois». Ainsi, dix-sept ans après notre départ de l'Afrique, l'INEAC et Franz Bultot dotaient le Zaïre d'un des atlas climatologiques les plus complets des pays en voie de développement !

Le titre du second travail a aujourd'hui une résonance douloureuse dans nos cœurs : «Evolution du Climat et des Ressources en Eau du Rwanda». Le projet fut entrepris à la demande de notre regretté Jean-Paul Harroy, ancien Résident général du Ruanda-Urundi. Il fut mené de 1982 à 1992 dans le cadre de la coopération Belgique-Rwanda. Le résumé du rapport complet a été publié par notre Académie sous le titre : «Sur le caractère stationnaire et cyclique des précipitations au Rwanda».

Beaucoup de pays en voie de développement devraient s'inspirer de cette étude exemplaire. Car il importe de répondre à la question : comment le lent réchauffement planétaire, observé depuis un siècle aux hautes et moyennes latitudes, a-t-il modifié les climats de la zone tropicale?

Mesdames et Messieurs,

La valeur de l'œuvre accomplie par Franz Bultot tient à l'ensemble de ses qualités : rigueur et méthode, ampleur des connaissances, ardeur au travail, esprit rationnel et de synthèse. Mais elle tient aussi au fait qu'il a toujours pu disposer pour exercer ces qualités d'une masse importante de données fiables, recueillies en réseaux bien opérationnels. Qu'il s'agisse, dans la première partie de sa carrière, des réseaux des Territoires d'Afrique ou, dans la seconde, des réseaux de la Belgique.

Et ceci m'amène à conclure en vous livrant deux réflexions. Elles sont le résultat, la conclusion des fonctions diverses que j'ai exercées en Afrique en y séjournant plus de vingt années. Ces idées sont devenues convictions dans mes fonctions au siège du Programme des Nations Unies pour le Développement, le PNUD. Comme conseiller pour les projets de renforcement des services météorologiques et hydrologiques, j'ai visité beaucoup de pays et vu l'état de leurs réseaux. Voici ces convictions dans la ligne des buts de cette Conférence.

1. Les premières ressources naturelles et renouvelables des pays tropicaux sont celles de leurs climats. Ils leur apportent la lumière, la chaleur et l'eau douce des sols, des lacs et des fleuves. L'exploitation rationnelle de ces ressources par l'agriculture intensifiée est le fondement de l'essor économique de ces pays, dont la population croît rapidement, population qu'il faut mieux nourrir en lui assurant une meilleure qualité de vie. Le potentiel de production de l'Afrique, par exemple, est énorme. Et cependant, tant d'eau précieuse s'évapore ou coule à l'océan en n'ayant produit aucune des richesses agricoles si nécessaires.

2. Pour exploiter ces ressources d'origine atmosphérique, il faut que les pays disposent de services nationaux en météorologie et en hydrologie, capables de gérer des réseaux d'observation bien opérationnels et couvrant des territoires souvent immenses. Bien mesurer la pluie est le premier devoir d'un bon service météorologique tropical et ce devoir exigera toujours de bons réseaux pluviométriques. Mais que de difficultés à vaincre pour sortir de l'indigence opérationnelle tel réseau pluviométrique ou hydrologique !

A l'unité des processus météorologiques et hydrologiques doit correspondre une unité de gestion des réseaux. Toute séparation administrative est une faiblesse qu'il faut payer par une coordination difficile.

Le fonctionnement opérationnel des réseaux en équipement, maintenance, coût, inspection, transmission des données, ne peut être assuré que, soutenu sur place, par une coopération internationale, vigilante et permanente. Car la haute technicité de la météorologie et de l'hydrologie modernes est à la mesure des pays riches qui la conçoivent et qui l'exploitent. Et désormais, c'est à l'échelle planétaire que l'évolution de l'atmosphère est à suivre et à prédire, de l'équateur aux pôles.

Pour prédire l'évolution du temps sur l'Europe, à l'échéance de quelques jours, les meilleurs services météorologiques ont dû unir leurs

forces en un puissant Centre européen réalisé à Reading. Ce n'est pas un problème moins exigeant en moyens que de prédire le retour de la saison des pluies au Sahel, d'en suivre l'évolution et d'en informer vingt-cinq millions de paysans qui, chaque jour, observent le ciel avec inquiétude. Les fluctuations des courants chauds et froids de l'Atlantique tropical sont très impliquées dans ce problème, ce qui ne le simplifie pas.

L'expression nouvelle est maintenant «développement durable». Il n'y aura pas de développement durable sans des centres permanents qui assureront la durée et d'où rayonnera l'idéal à maintenir.

Il faudra bien qu'un jour les pays riches réalisent que les progrès de la météorologie nécessitent des «Readings tropicaux» pour que s'optimise enfin l'usage mondial des ressources de l'atmosphère.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 42-48 (1998)

A Bibliography of Franz Bultot

compiled by

Gaston DEMARÉE *

Régimes normaux et cartes des précipitations dans l'est du Congo belge. *Publ. INEAC*, Coll. in-4, 56 pp., 13 fig., Bruxelles, 1950.

Carte des régions climatiques du Congo belge établie d'après les critères de Köppen. *Publ. INEAC*, Coll. in-4, 16 pp., 1 carte, Bruxelles, 1950.

Sur la courbure des surfaces de discontinuité de l'atmosphère. *Acad. R. de Belgique, Bull. Cl. des Sciences* (1re comm. pp. 977-985, 2e comm. pp. 1081-1092), Bruxelles, 1950.

Circulation horizontale de l'air au passage d'une zone frontale. *Jl Sci. de la Mét.*, pp. 113-123, Paris, 1951.

Sur le caractère organisé de la pluie au Congo belge. *Publ. INEAC*, Coll. in-4, 16 pp., 8 cartes, Bruxelles, 1952.

Saisons et périodes sèches et pluvieuses au Congo belge et au Ruanda-Urundi. *Publ. INEAC*, Coll. in-4, 70 pp., 1 fig., 7 cartes, Bruxelles, 1954.

Notice de la carte des zones climatiques du Congo belge et du Ruanda-Urundi. *In*: Atlas Général du Congo (fasc. 33). Publ. Acad. R. Sci. colon., Bruxelles, 1954.

Inférence statistique et échantillonnage en climatologie. *Bull. Soc. b. Stat.*, pp. 9-23, Bruxelles, 1955-1956.

Etude statistique des pluies intenses en un point et sur une aire au Congo belge et au Ruanda-Urundi. *Publ. INEAC*, Coll. in-4, 90 pp., Bruxelles, 1956.

Risques d'années sèches et pluvieuses au Congo belge et au Ruanda-Urundi. *Publ. INEAC*, Coll. in-4, 22 pp., 5 cartes, Bruxelles, 1957.

Distribution conjointe de la température et de l'humidité de l'air au Congo belge. *Publ. INEAC*, Coll. in-4, 32 pp., Bruxelles, 1957.

La masse spécifique de l'air dans la Cuvette centrale congolaise. *Bull. Acad. R. Sci. colon.*, **3** (4) : 956-962, Bruxelles, 1957.

Existe-t-il un cycle pluviométrique de 11 ans au Congo belge? *Bull. Acad. R. Sci. colon.*, **3** (2) : 470-479, Bruxelles, 1957.

* Chief of the Hydrology Section, Royal Meteorological Institute of Belgium, av. Circulaire 3, B-1180 Brussels (Belgium).

Quelques aspects de la climatologie du Bas et du Moyen-Congo. *Bull. Acad. R. Sci. colon.*, **4** (2) : 508-530, Bruxelles, 1958.

A propos de l'ouvrage de F.W. Lockermann intitulé «Zur Flusshydrologie der Tropen und Monsunasiens». *Bull. Acad. R. Sci. colon.*, **4** (6) : 1266-1267, Bruxelles, 1958.

Etude statistique des chutes de grêle au Congo belge et au Ruanda-Urundi. *Publ. INEAC*, Coll. in-4, 43 pp., 6 fig., Bruxelles, 1959.

Sur le régime des rivières du bassin congolais. *Bull. Acad. R. Sci. colon.*, **5** (2) : 442-456, Bruxelles, 1959.

Cotes hydrométriques et débits maxima et minima probables de quelques cours d'eau congolais. *Bull. Acad. R. Sci. colon.*, **5** (4) : 992-1011, Bruxelles, 1959.

Estimation à partir d'un nombre limité de mesures, des moyennes vraies journalières, diurnes et nocturnes de la température et de l'humidité de l'air au Congo, au Ruanda et au Burundi. *Publ. INEAC*, Coll. in-4, 97 pp., 16 planches, Bruxelles, 1961.

Eléments de mécanique rationnelle à l'usage des électroniciens. Gauthier-Villars et Cie, Paris, 1961, 279 pp.

Pour une exploitation rationnelle des indices bioclimatiques. *Revue belge de Statistique et de Recherche opérationnelle*, **3** (1) : 23-38, Bruxelles, 1962.

Météorologie et Climatologie. *In* : Apport scientifique de la Belgique en Afrique centrale. *Publ. Acad. R. Sci. Outre-Mer*, Livre blanc, Tome II, pp. 615-624, Bruxelles, 1962 (en coll. avec BERNARD, E.).

Sur la détermination des moyennes mensuelles et annuelles de l'évaporation réelle et de l'écoulement dans le bassin congolais. *Bull. Acad. R. Sci. Outre-Mer*, **8** (4) : 816-838, Bruxelles, 1962.

Etude de la diffusion atmosphérique des effluents radioactifs - modèle mathématique. *Publ.* IRM, note interne, 25 pp., Bruxelles, 1963.

Sur la délimitation de la zone tropicale humide. *Bull. Acad. R. Sci. Outre-Mer*, **1964**-2 : 406-412, Bruxelles.

Elements of Theoretical Mechanics for Electronic Engineers. Pergamon Press, Oxford, 260 pp., 1965.

A propos de l'évaporation du lac Tanganyika. *Bull. Acad. R. Sci. Outre-Mer*, **1965**-4 : 1226-1241, Bruxelles.

Le programme hydrométéorologique de l'Institut Royal Météorologique. *Ciel et Terre*, **81** (11-12) : 3-19, Bruxelles, 1965.

Comparaison des climats congolais sous l'angle de l'effort imposé à l'organisme humain. *Bull. Acad. R. Sci. Outre-Mer*, **1966**-6 : 1113-1125, Bruxelles.

Le bac évaporatoire en usage dans le réseau hydrométéorologique belge. *Bull. Ass. Int. Hydr. Scient.*, **13** (2) : 163-168, Gentbrugge, 1968 (en coll. avec DUPRIEZ, G. L.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, I. Bassin de la Semois. *Publ. IRM*, Série A, **64** : 74 pp., Bruxelles, 1968 (en coll. avec DUPRIEZ, G. L.).

Lectrice semi-automatique pour le dépouillement des diagrammes climatologiques conventionnels. *In* : Data processing for climatological purpose. Publ. World Meteorological Organization, Techn. Note No. 100, pp. 46-48, Genève, 1969 (en coll. avec DUPRIEZ, G. L.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, II. Bassin du Viroin, *Publ. IRM*, Série A, **70** : 70 pp., Bruxelles, 1971 (en coll. avec DUPRIEZ, G. L. & BLEIMAN, N.).

Atlas climatique du Bassin congolais (Première partie : les composantes du bilan de rayonnement). *Publ. INEAC*, 104 cartes, 26 fig., 8 tab., Bruxelles, 1971.

Atlas climatique du Bassin congolais (Deuxième partie : les composantes du bilan d'eau). *Publ. INEAC*, 98 cartes, 19 fig., 19 tab., Bruxelles, 1971.

The equatorial wet zone. *In* : World Survey of Climatology (Vol. 10 : Climates of Africa), pp. 259-311, Elsevier Publ. Cy, Amsterdam, 1971 (in co-operation with GRIFFITHS, J. F.).

Rwanda and Burundi. *In* : World Survey of Climatology (Vol. 10 : Climates of Africa), pp. 349-368, Elsevier Publ. Cy, Amsterdam, 1971.

Comparaison d'instruments de mesure de l'humidité de l'air sous abri. *Arch. Met. Geoph. Biokl.*, Série B, **19** : 53-67, Vienne, 1971 (en coll. avec DUPRIEZ, G. L.).

Contrôle des cotes hydrométriques journalières - test du rapport des cotes réduites. *Bull. Int. Ass. Sc. Hydr.*, **16** (4) : 73-82, Budapest, 1971 (en coll. avec DUPRIEZ, G. L. & SEYVERT, J.).

Machine processing of hydrological data. *In* : Machine processing of hydrometeorological data, Publ. World Met. Organization, Techn. Note No. 115, pp. 51-79, Geneva, 1971 (in co-operation with DUPRIEZ, G. L.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, III. Bassin de l'Ourthe. *Publ. IRM*, Série A, **72** : 69 pp., Bruxelles, 1972 (en coll. avec DUPRIEZ, G. L. & BLEIMAN, N.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, IV. Bassin de la Lesse. *Publ. IRM*, Série A, **76** : 69 pp., Bruxelles, 1972 (en coll. avec DUPRIEZ, G. L. & BLEIMAN, N.).

Atlas climatique du Bassin congolais (Troisième partie : température et humidité de l'air, rosée, température du sol). *Publ. INEAC*, Bruxelles, 1972.

Interception de la pluie par la végétation forestière. Estimation de l'interception journalière à l'aide d'un modèle mathématique. *Jl. of Hydrology*, **17** (3) : 193-223, Amsterdam, 1972 (en coll. avec DUPRIEZ, G. L. & BODEUX, A.).

A propos de l'évapotranspiration potentielle et réelle en climat tropical. *In* : Comptes-rendus Semaine d'Etude Probl. Intertrop., Fac. Sci. Agron. Gembloux, 1973.

L'évaporation d'un bac d'eau libre - sa signification restreinte. *Jl. of Hydrology*, **20** : 83-95, Amsterdam, 1973 (en coll. avec DUPRIEZ, G. L.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, V. Bassin de l'Amblève. *Publ. IRM*, Série A, **79** : 62 pp., Bruxelles, 1973 (en coll. avec DUPRIEZ, G. L. & BLEIMAN, N.).

Exemples de situations atmosphériques caractérisées par des pluies abondantes en Belgique. *Publ. IRM*, Miscellanea, Série A, **4** : 14 pp., *ca.* 100 planches, Bruxelles, 1973 (en coll. avec VAN UFFELEN, J.).

Les progrès de la connaissance en climatologie générale et tropicale. *Publ. Acad. R. Sci. Outre-Mer*, **1973**-4 : 647-665, Bruxelles.

L'évapotranspiration potentielle des bassins hydrographiques en Belgique. *Publ. IRM*, Série A, **85** : 61 pp., Bruxelles, 1974 (en coll. avec DUPRIEZ, G. L.).

Estimation des valeurs journalières de l'évapotranspiration potentielle d'un bassin hydrographique. *Jl. of Hydrology*, **21** : 321-338, Amsterdam, 1974 (en coll. avec DUPRIEZ, G. L.).

Les dix premières années d'activités de la section d'hydrologie. *In* : Hommage à J. Van Mieghem, *Publ. IRM*, Série A, **91** : 67-81, Bruxelles, 1975 (en coll. avec DUPRIEZ, G. L. & DUMOULIN, J.).

Etude hydrométéorologique des précipitations sur les bassins hydrographiques belges, VI. Bassin de la Vesdre. *Publ. IRM*, Série A, **93** : 72 pp., 1975 (en coll. avec DUPRIEZ, G. L. & BLEIMAN, N.).

Bilans hydriques et données hydrologiques pour la conception de projets de mise en valeur des ressources en eau dans les bassins hydrographiques belges, I. Bassin de la Semois. *Publ. IRM*, Série A, **96** : 147 pp., Bruxelles, 1976 (en coll. avec DUPRIEZ, G. L.).

Les ressources d'eau souterraine en Belgique - réserve, régime et exploitabilité des aquifères, I. Bassin versant de la Dyle à Wavre. *Publ. IRM*, Série A, **97** : 45 pp., Bruxelles, 1976 (en coll. avec DUPRIEZ, G. L. & LAURENT, E. - Ministère de la Santé Publique).

Conceptual hydrological model for an average-sized catchment area. *Jl. of Hydrology*, **29** : 251-292, Amsterdam, 1976 (in co-operation with DUPRIEZ, G. L.).

Interception potentielle journalière de la pluie par divers peuplements forestiers. *Jl. of Hydrology*, **31** : 381-392, Amsterdam, 1976 (in co-operation with DUPRIEZ, G. L. & BODEUX, A.).

Simulation of a series of daily areal mean rainfalls at a basin using rainfall observations at a reference station located outside the basin. *Bull. des Sciences Hydrologiques*, **21** (4) : 569-585, Wallingford, 1976 (in co-operation with DUPRIEZ, G. L.).

Atlas climatique du Bassin zaïrois (Quatrième partie : pression atmosphérique, vents en surface et en altitude, température et humidité de l'air en altitude, nébulosité et visibilité, propriétés chimiques de l'air et des précipitations et classifications climatiques). *Publ. INEAC*, 193 cartes, 11 fig., 35 tab., Bruxelles, 1977.

Organization of hydrological services in Belgium. *In* : Casebook of examples of organization and operation of Hydrological Services. Operational Hydrology Report No. 9 (WMO-No. 461), pp. 15-29, Geneva, 1977.

Cours d'hydrométéorologie et compléments d'hydrométéorologie. Remis à jour annuellement depuis 1979 dans le cadre des enseignements dispensés à la FUL et à l'ULB (env. 600 pp.).

L'inventaire des ressources en eau - sa problématique. *In* : Problématique et gestion des eaux intérieures, tome I. Colloque intern. de Liège, 1978, pp. 13-39, Ed. Derouaux, Liège, 1979. *Ciel et Terre*, **96** (6) : 343-354, Bruxelles, 1980.

Exploitation des eaux de surface dans les bassins hydrographiques belges. Données hydrologiques pour la conception de résevoirs d'épargne - Bassin de la Lasne. *In* : Monographie du Bassin de la Dyle, 3e partie. Publ. du Ministère de la Santé Publique et de l'Environnement, Noyau de l'eau, Commission Dyle, pp. 255-284, Bruxelles, 1980 (en coll. avec DUPRIEZ, G. L.).

Exploitatie van het oppervlaktewater van de Belgische stroombekkens. Hydrologische gegevens voor het ontwerp van spaarbekkens - Bekken van de Lasne. *In* : Monografie van het Dijlebekken, Derde deel, Ministerie van Volksgezondheid en Leefmilieu, Kerngroep Water, Commissie Dijle, pp. 221-249, Brussel, 1980 (met medewerking van DUPRIEZ, G. L.).

Bilans hydriques et données hydrologiques pour la conception de projets de mise en valeur des ressources en eau dans les bassins hydrographiques belges, II. Bassin de la Dyle. *Publ. IRM*, Série A, **107** : 149 pp., Bruxelles, 1981 (en coll. avec DUPRIEZ, G. L. & BASIAUX, A.).

Hydrological data management in relation to the World Climate Programme. *In* : Report of the Informal Planning Meeting on WCP Data Management (Geneva, 16-20 November 1981), WMO, WCP-17, Appendix 7, pp. 1-7, Geneva, 1981.

The Belgian national hydrological data bank - planning, development and organization. *In* : Case studies of national hydrological data banks. Operational hydrology Report No. 17, WMO-No. 576, pp. 17-28, Geneva, 1981.

The automatic recording station of the Belgian hydrometeorological network. *In* : Proceedings of the International Symposium on Hydrological Research Basins and their Use in Water Resources Planning (Bern, September 1982), Vol. 1, pp. 41-46. Office fédéral de la protection de l'environnement, Berne, 1982.

Estimation de l'évapotranspiration potentielle en Belgique (Procédure révisée). *Publ. IRM*, Série A, **112**, Bruxelles, 1983 (en coll. avec COPPENS, A. & DUPRIEZ, G. L.).

Incidences d'ordre climatique et hydrologique de modifications des caractéristiques d'un bassin hydrographique. Rapp. techn. n° 1, 63 pp., CCE, 1984 (en coll. avec DUPRIEZ, G. L.).

Régime annuel estimé des composantes du bilan d'énergie et de l'évapotranspiration potentielle d'une surface naturelle dans l'hypothèse d'un doublement du CO_2 atmosphérique. Rapp. techn. n 3, 23 pp., CCE, 1984 (en coll. avec DUPRIEZ, G. L. & GELLENS, D.).

Puissance d'une averse. *Bull. des Sciences hydrologiques*, **30** (3) : 361-369, Wallingford, 1985 (en coll. avec COPPENS, A.).

Sur le caractère stationnaire et cyclique de la variabilité des précipitations au Rwanda. Rapp. techn. n° 1, 83 pp., A.G.C.D., 1985 (en coll. avec GELLENS, D.).

Les activités du Comité national belge pour le PHI. *In* : VAN DER BEKEN, A. (éd.), The International Hydrological Programme, VUB - Hydrologie (12), Bruxelles, 1985.

Daily effective evapotranspiration from a river basin. *In* : Casebook on Operational Assessment of Areal Evaporation. Operational Hydrology Report no. 22 (WMO-No. 635), pp. 80-105 Geneva, 1985 (in co-operation with DUPRIEZ, G. L.).

Niveaux et débits du fleuve Zaïre à Kinshasa (régime - variabilité - prévision). *Publ. ARSOM*, Classe des Sciences techniques, Mémoire in-4, **6** (2) : 79 pp., 2 cartes, 15 fig., 15 tab., Bruxelles, 1987 (en coll. avec DUPRIEZ, G. L.).

Impact of a climatic change induced by a doubling of atmospheric CO_2 on the water cycle and on the water balance. *In* : COTTENIE, A. & TELLER, A. (eds.), Belgian Research on Global Change IGBP, Proceedings of a Symposium held in Brussels on 22 April 1988, pp. 213-231. Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique (in co-operation with GELLENS, D.).

Land-surface management and its impact on climate and water balance. *In* : COTTENIE, A. & TELLER, A. (eds.), Belgian Research on Global Change IGBP. Proceedings of a Symposium held in Brussels on 22 April 1988, pp. 232-241. Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique.

Estimated annual regime of energy-balance components, evapotranspiration and soil moisture for a drainage basin in the case of a CO_2 doubling. *Climatic Change*, **12** : 39-56, Amsterdam, 1988 (in co-operation with DUPRIEZ, G. L. & GELLENS, D.).

Repercussions of a CO_2 doubling on the water cycle and on the water balance - a case study for Belgium. *Jl. of Hydrology*, **99** : 319-347, Amsterdam, 1988 (in co-operation with COPPENS, A., DUPRIEZ, G. L., GELLENS, D. & MEULENBERGHS, F.).

Simulation of the impact of atmospheric CO_2 doubling on precipitation and evapotranspiration - study of the sensitivity to various hypotheses. *In* : Proceedings of the Conference on Climate and Water, Helsinki, 11-15 September 1989, pp. 73-92 (in co-operation with GELLENS, D.).

Simulation of land-use changes and impacts on the water balance - a case study for Belgium. *Jl. of Hydrology*, **114** : 327-348, Amsterdam, 1990 (in co-operation with DUPRIEZ, G. L. & GELLENS, D.).

Informatique et hydrologie. *In* : Compte-rendus Symposium «Impact de l'informatique dans le Tiers-Monde» (Acad. R. Sci. Outre-Mer, décembre 1988), Bruxelles, 1990, pp. 73-93.

Climat et Eau. *In* : Contributions à l'Etude des Changements de Climat. *Publ. IRM*, Série A, **124** : 55-67, Bruxelles, 1990 (en coll. avec DEMAREE, G. R., GELLENS, D. & MEULENBERGHS, F.).

Repercussions of a CO_2 doubling on the water balance - a case study in Switzerland. *Jl. of Hydrology*, **137** : 199-208, Amsterdam, 1992 (in co-operation with GELLENS, D., SPREAFICO, M. & SCHADLER, B.).

Evaporation from a tropical lake : comparison of theory with direct measurements - comment. *Jl. of Hydrology*, **143** : 513-519, Amsterdam, 1993.

Sur le caractère stationnaire et cyclique des précipitations au Rwanda. *Publ. ARSOM*, Classe des Sciences techniques, Mémoire in-8, **19** (1) : 53 pp., 8 tab., 8 fig., Bruxelles, 1994 (en coll. avec GELLENS, D.).

Effects of Climate change on snow accumulation and melting in the Broye catchment (Switzerland). *Climatic Change*, **28** : 339-363, Amsterdam, 1994 (in co-operation with GELLENS, D., SCHADLER, B. & SPREAFICO, M.).

Preface. *In* : Climate and water in Europe ; some recent issues. Technical Report of Rapporteurs. World Meteorological Organization, Regional Association VI (Europe), Working Group on Hydrology (by KUUSISTO, E., LEMMELA, R., LIEBSCHER, H. & NOBILIS, F.), Helsinki, 1994.

PALAEOCLIMATOLOGY

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 51-67 (1998)

Holocene Climatic Change and Man in the Sahara

by

Nicole PETIT-MAIRE * & Robert BRYSON **

KEYWORDS. — Climate ; Holocene ; Lakes ; Migrations ; Sahara.

ABSTRACT. — The activity and range of the African monsoon, as well as the penetration of Atlantic cyclones and Mediterranean winter rainfall over the present-day Sahara desert, highly increased during the Holocene, between 9.5 and 7 ka and 5.5 and 5 ka. The desert belt then considerably shrank, although arid biotopes persisted around the Tropic of Cancer. Human Neolithic groups could then live sedentarily around the permanent lakes or swamps ; they migrated from the aridified lowlands between 4.5 and 4 ka.

MOTS-CLES. — Climat ; Holocène ; Lacs ; Migrations ; Sahara.

RESUME. — *Changements climatiques et peuplement au Sahara holocène.* — L'activité et la portée de la mousson africaine, ainsi que la pénétration des cyclones atlantiques et des pluies méditerranéennes sur le Sahara actuel, ont été beaucoup plus fortes pendant l'optimum climatique holocène, entre 9,5 et 7 ka et entre 5,5 et 5 ka. La ceinture désertique latitudinale rétrécit considérablement, bien que des biotopes arides aient persisté autour du Tropique du Cancer. Des populations néolithiques ont pu alors vivre de graminées sauvages et de gros gibier autour de lacs ou de zones marécageuses permanentes ; elles ont émigré hors des bassins devenus arides entre 4,5 et 4 ka.

TREFWOORDEN. — Klimaat ; Holoceen ; Meren ; Migraties ; Sahara.

SAMENVATTING. — *Holocene klimaatveranderingen en de Mens in de Sahara.* — De activiteit en draagwijdte van de Afrikaanse moesson evenals de invloed van Atlantische cyclonen en Mediterrane winterneerslag over de huidige Sahara waren meer uitgesproken tijdens het Holoceen, tussen 9,5 en

* URA 164, C.N.R.S., MMSH, BP 647, 13094 Aix-en-Provence. Cedex 2 (France).
** Archaeoclimatology Consultant ; P.O. Box 2084, Davis, CA 95617 (U.S.A.).

7,5 ka en 5,5 en 5 ka. Toen is het woestijngebied sterk afgenomen in oppervlakte, niettegenstaande nog steeds aride biotopen rond de Kreeftskeerkring bleven bestaan. Menselijke Neolithische gemeenschappen konden toen sedentair overleven in de omgeving van permanente meren en moerassen met hun wilde grassen en groot wild ; ten slotte migreerden deze gemeenschappen uit de aride laaglanden tussen 4,5 en 4 ka.

Introduction

The Sahara is the largest desert in the world, covering more than 9,000,000 km^2. The boundary between the present-day desert and the semi-arid transitional zones on its margins (the Sahel to the south and the Mediterranean region to the north) generally corresponds with the 100-150 mm isohyets which, with the exception of mountainous areas and oases, in turn also roughly coincide with the limit of active sand dunes and of sedentary human habitations. Between these transition zones and the desert core, the precipitation gradient is very steep (fig. 1). For example, in the south, precipitation decreases approximately by 1 mm each 1.4 km from the Sahel to the Tropic of Cancer, where the precipitation/evaporation (P/E) ratio approaches zero, owing to potential evaporation ranging between 5 and 8 m/yr and an average annual rainfall under 5 mm.

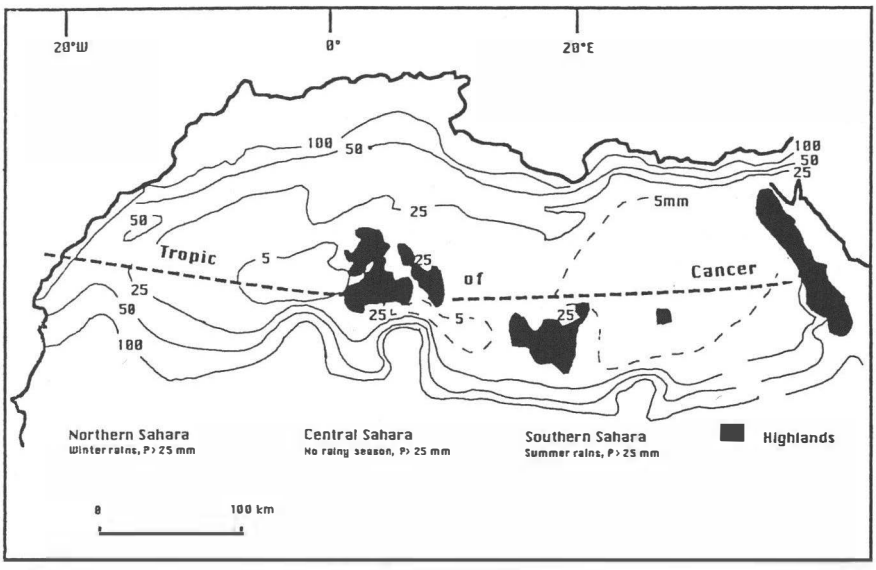


Fig. 1. — Present-day climate in the Sahara. (From Le Houerou 1989.)

Rainfall in the two transition zones differs in both its origin and season. In the north, winter precipitation generated in cyclonic storms carried by the westerlies predominates. In contrast, summer precipitation deriving from monsoonal flow off the Gulf of Guinea provides virtually all of the effective moisture for the Sahel to the south. Changes in degree to which these two regimes penetrate into the current Saharan area would shift the latitude of the respective desert boundaries and thus increase or decrease the size of the desert. Clearly the locations of the northern and southern desert boundaries have changed on both short and long temporal scales and this has been critical to cultures and biota in the transition zones.

Evidence for Holocene Climatic Change

For the last twenty years, many new observations combined with analysis of geological records have yielded a great deal of information on major palaeoenvironmental and climatic changes throughout the present-day desert up to its most desolate core along the Tropic. The Holocene has been particularly well studied. About 2,000 radiocarbon assays provide dates, mostly ranging between 10,000 and 3,000 years B.P., for a wide range of palaeoenvironmental proxies (VERNET & AUMASSIP 1992) and some continuous lacustrine sections (PETIT-MAIRE (ed.) 1991) and thus allow a meaningful analysis of regional palaeoenvironmental evolution to be made (a major part of the corresponding research was provided by members of former IGCP 252 „Evolution of Deserts : Past, Present, Future").

A recently produced palaeomap (PETIT-MAIRE *et al.* 1993) has synthesized the currently available information. The general scheme represented by these data suggests an assessment that a significant increase in the P/E ratio over the whole currently Saharan area began in the early Holocene. Major environmental changes taking place as early as 9,500 yrs B.P. produced conditions such that freshwater lakes and sahelian vegetation and fauna existed even in the most continental, hydrologically isolated lowlands at the latitude of the Tropic. A hydrological maximum appears to have been reached between 9,000 and 4,500 yrs B.P., with a significant, although slight, decrease between 7,000 and 5,500 B.P. (PETIT-MAIRE & GUO 1996). Since 4,500 yrs B.P., another expansion of the Sahara over the early Holocene semi-arid zones has resulted in the desert reaching its present-day extension between 3,000 and 2,000 years ago. Explanations offered for these

processes have related them to astronomically forced global changes in oceanic and atmospheric circulation (BERGER 1992, IMBRIE *et al.* 1993) coinciding with a strong increase in monsoon activity and range after the end of the Younger Dryas, and a decrease of the same after 7,000 yrs B.P. due to the reduction of insolation at that time (PETIT-MAIRE 1994, YAN & PETIT-MAIRE 1994).

BRYSON (1992) has convincingly demonstrated a relationship between the Holocene positions of the intertropical convergence and jetstream and rainfall in the Saharan region. This analysis establishes that significant changes in the latitude of the intertropical convergence zone (ITCZ) took place during the Holocene, and that these were accompanied by concomitant shifts in the mean northern extent of sub-Saharan rainfall (fig. 2). During the early to mid-Holocene, the seasonal contrast was greater than in subsequent periods, with colder winters and warmer summers prevailing. With the latitude of the ITCZ further to the north and the jetstream further to the south during that time, the northward penetration of summer monsoonal rainfall and the southward extent of winter rainfall were increased. This resulted into respective shifts in the desert boundaries and a reduction in the size of the Sahara. The modelled late Holocene reduction of the seasonal contrast had the reversed effect. These general trends were accompanied by significant short-term variances in the positions of both circulation features, and, hence, in rainfall over the area.

No desertification by humans was involved at such latitudes during the mid- to late-Holocene. Indeed, it is hard to imagine severe environmental impacts caused by small Neolithic groups which were probably as cautious about protecting the environment they fed on as were present-day semi-nomads before modern socio-economic and political patterns changed their traditional ways.

The data bank used for preparing the map "The Sahara in the Holocene" (PETIT-MAIRE *et al.* 1993) was compiled from literature published over the last twenty years and from earlier compilations (COMMELIN & PETIT-MAIRE 1979, VERNET & AUMASSIP 1992). Only radiocarbon dated information was used, thereby eliminating a good number of observations, most of them from literature prior to 1970. Data associated with 1890 radiocarbon ages have thus been considered. These cover two types of information :

a) Proxy markers for humidity, implying local precipitation or aquifer rise :

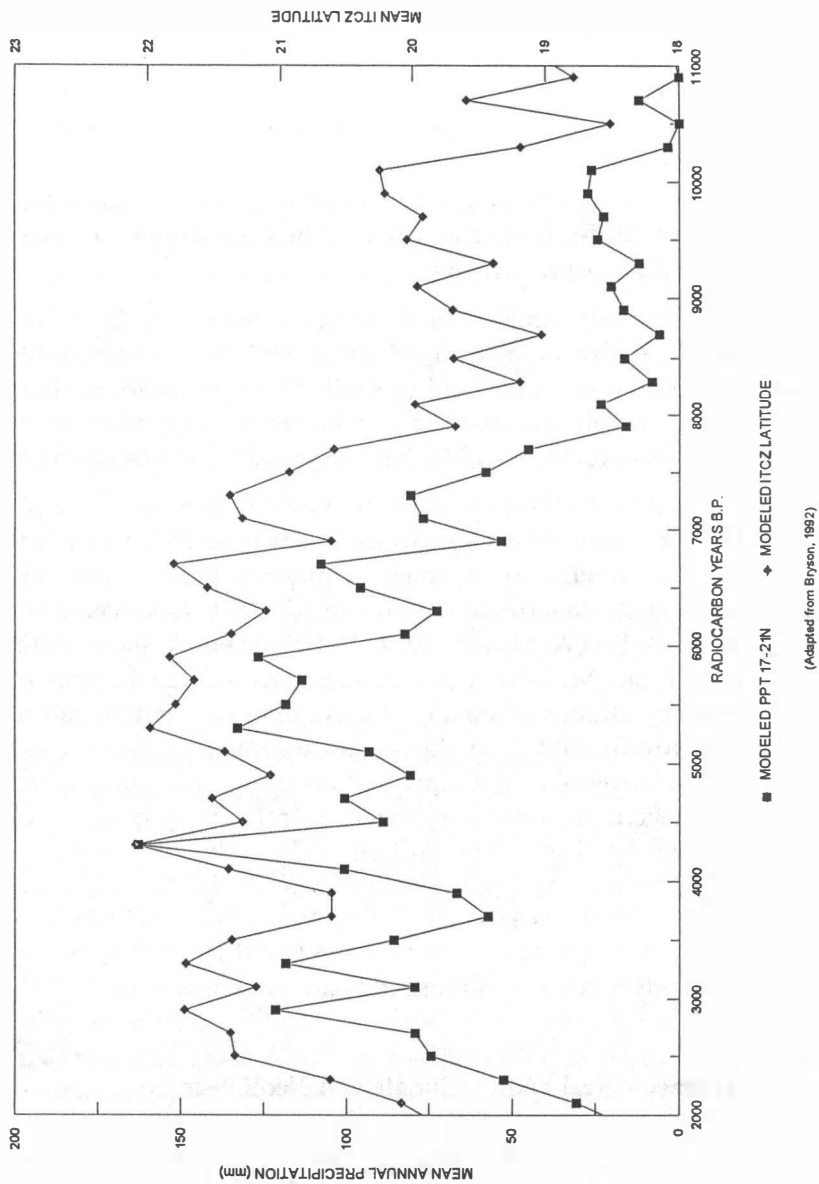


Fig. 2. — Modelled precipitation *vs* modelled mean ITCZ latitude.

— Surface water : lakes, swamps (generally dated from shells of freshwater molluscs) ;
— Dissolution processes : calcretes, travertines ;
— Vegetal cover : organic matter in palaeosols, pollen and charcoal in lake sediments ;
— Skeletal remains of aquatic or semi-aquatic animals : fish, crocodiles, hippopotamus ;
— Skeletal remains of large mammals (elephants, rhinoceros, antelopes, etc.) implying both freshwater accessibility and a grassland, or even a wooded grassland (giraffes) cover.

b) Prehistoric habitats : archaeological sites, burials and artifacts, also implying the possibility of a semi-sedentary life, that is, accessible freshwater and food (both game and vegetal). The significance of these proxies has been widely discussed in the literature (PETIT-MAIRE & RISER 1983, HAYNES & MEAD 1987, NEUMANN 1989, SCHULTZ 1991).

In the paragraphs which follow, we rely on this data bank to couple significant Holocene climatic changes towards wetter or drier conditions with two general trends. First, human migrations *into* the late Pleistocene hyperarid Sahara (MAINGUET *et al.* 1980, ROGNON 1980, TALBOT 1984, OUSSEINI & MOREL 1989, PETIT-MAIRE & PAGE 1992) and the onset of the Neolithic civilization are considered in light of generally wetter conditions. Secondly, we examine the relationship of climatic trends towards drier conditions with human migrations *out of* the early to mid-Holocene, semi-arid Sahara at the end of the human phase and consider these various movements from the perspective of three Saharan regions. The full repartition of the proxy data is shown on the published palaeomap (PETIT-MAIRE *et al.* 1993). The frequency of surface freshwater occurrence according to age and latitude (figs 3a, 3b) is shown in PETIT-MAIRE & GUO 1996 and in GUO & PETIT-MAIRE (1996). Only a portion of those data are presented here.

Archaeological Data : Climate and Neolithisation

A subset of the overall database, comprising 396 dates on proxy indicators of wet conditions recovered from 17°-21° N between the longitudes of 10° W and 30° E, was produced to facilitate comparison with changes in the northward extent of the ITCZ (fig. 4). In general, the fit between the modelling results and the proxy record is quite

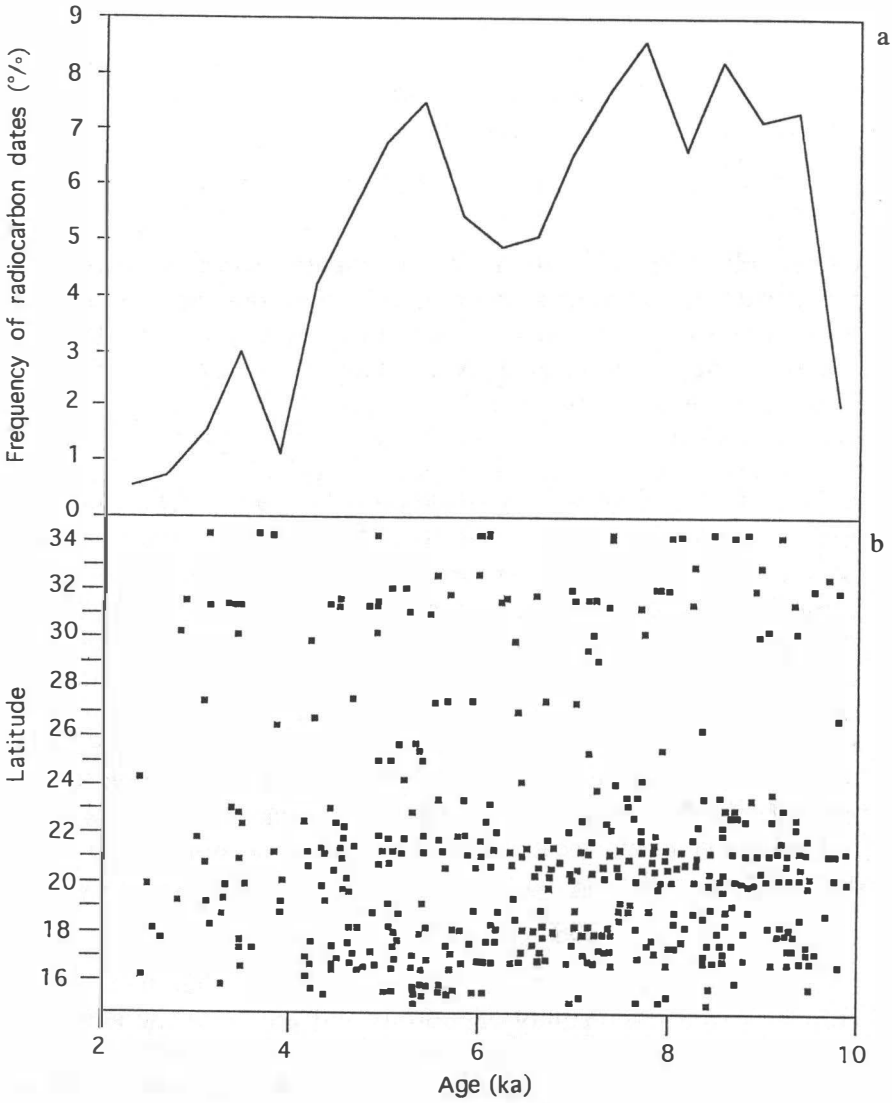


Fig. 3a. — Frequency (%) of surface freshwater in the Sahara during the Holocene. (From PETIT-MAIRE & GUO, 1996.)

Fig. 3b. — Individual data for freshwater in the Sahara according to latitude and age. The range of the monsoonal rains, to the South, and the range of the Mediterranean rains, to the North, appear clearly. Most dots at latitudes *ca.* 25-28 N correspond to data in the mountainous or coastal areas (from GUO & PETIT-MAIRE, in press), which testifies to the persistence of a narrow arid belt between *ca.* 26 and 28 N.

good. By about 8,000 B.P. it appears that the environmental proxy record no longer lags behind modelled shifts in the monsoon.

In figure 5, the frequency distribution of 1,175 radiocarbon dates for archaeological sites in the Sahara, grouped by age in 200 years intervals, is compared with the modelled mean latitude of the ITCZ at the same time intervals. Although the modelled ITCZ latitude has been related by BRYSON (1992) to rainfall in the Sahel alone, the dated sites are geographically distributed throughout the Sahara. Further, the number of Neolithic sites reported in figure 5 widely underestimates the actual occurrence of such evidence throughout the present desert because at least twice as many are described in literature, but have not been radiocarbon dated. Nonetheless, it is clear that peaks in Holocene rainfall in the Sahel (*i.e.*, when the ITCZ reached its most northern extent) anticipate evidence for human occupation by *ca.* 400-500 years, or more. After the onset of significant precipitation, the time needed for a full biological response in a region which had been hyperarid during the preceding 10,000 years (cf. BRYSON 1992), in particular the migrative response of vegetation, game, and man (probably following the latter), logically accounts for the lag between the onset of each wet episode and a corresponding increase in the number of dated archaeological sites. As seen in figures 4 and 5, the biological response to changing precipitation regimes, once initiated in the early Holocene, did not lag as significantly behind those changes as did the cultural response. It is further interesting to note that, in general, the field evidence suggests that archaeological sites in the Sahara were typically located *around* the lakes between 9,000 and 5,000 B.P., but *upon* the dry lake beds, generally the centres of the topographical depressions, after *ca.* 5,000 yrs B.P.

The development of the Neolithic civilization in the Sahara is clearly related to climatic change. The wide extension of a Gramineae cover correlates with the ubiquity of mortars and grinders. The abundance of large fish in shallow lakes is related to the development of bone hooks and harpoons. For instance, 115 harpoons were found in a single, roughly 200 m² site at 19°15'N (DECOBERT & PETIT-MAIRE 1985). The possibility of sedentary life around clayey pans apparently allowed the invention and expansion of a rich ceramics industry (COMMELIN 1984, ROSET 1988). The variety and quality of pottery decoration and of stone and bone adornments (CAMPS-FABRER *et al.* 1982, CAMPS-FABRER 1983) suggest spare time for refinement, a development

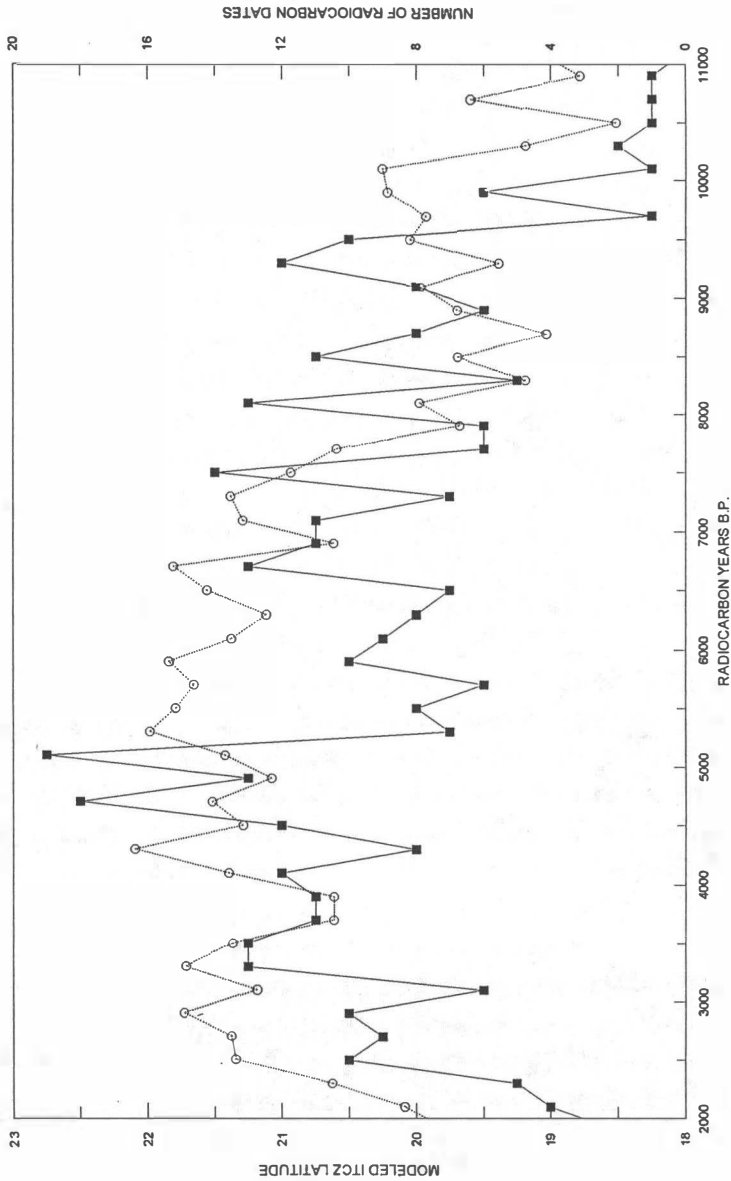


Fig. 4. — Modelled ITCZ latitude *vs* number of humidity markers dates.

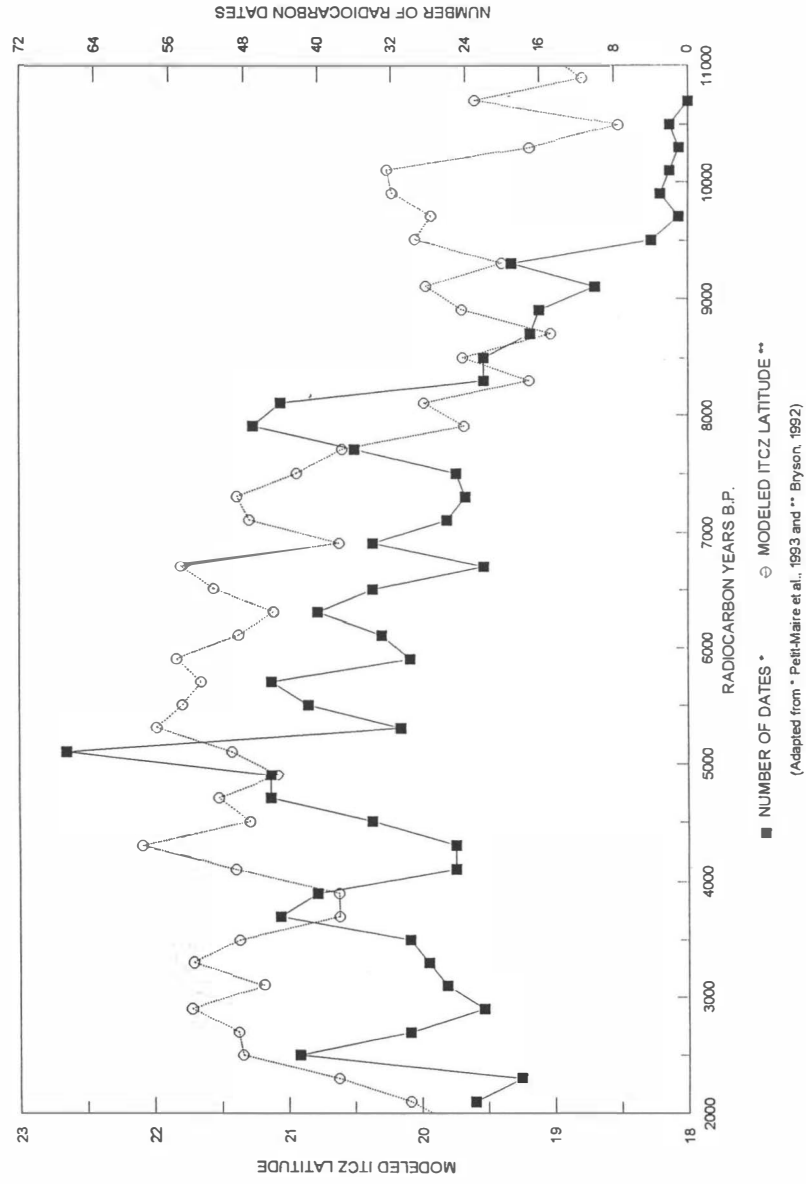


Fig. 5. — Modelled ITCZ latitude *vs* number of radiocarbon dated archaeological sites.

incompatible with a presumed hard struggle for life in a hostile environment.

In order to increase the specificity of these observations, one can compare the climatic and archaeological changes in three units of the Sahara, the geographical settings of which are liable to have influenced both the hydrological balance and human life. These include the wetter mountainous areas (the Hoggar and Tibesti) and oceanic borders, and the drier continental lowlands which still constitute the hyperarid core of the desert (fig. 6).

The maximal occupation period in the lowlands was coeval with the mid-Holocene hydrological maximum. Following this period, the frequency of dated occupations then decreases, with only the lowest latitudes being occupied after 4,000 yrs B.P. Archaeological sites are steadily present in the highlands, although they are scarcer for the periods before 9,000 yrs B.P. and after 3,000 yrs B.P.

The Atlantic coast has been wet since 9,500 yrs B.P., but human settlements were not present here until rainfall declined following its mid-Holocene peak. This "colonization" of the ocean margins of the desert was maximal after 4,000 yrs B.P. and lasted until 2,000 yrs B.P. or perhaps later. It is not surprising that coastal subsistence patterns during this period were largely based on sea resources, as testified to by the thick, nearly continuous shell middens lining the coast from 28° to 17° N (Petit-Maire 1979, 1980).

It is reasonable to conceive that humans migrated to the nearest areas still remaining wet when the continental lowlands became too dry to provide accessible freshwater, substantial vegetal food and game. Namely, this process included migrations to the shores of large rivers, such as the Niger, Nile and Senegal, to the highlands, and to oceanic margins where atmospheric humidity and freshwater still remained sufficient to support life. It has been shown (Petit-Maire 1979, Guerin & Faure 1983) that large game also migrated into those areas, probably followed by its hunters.

The case of the monsoonal changes in the southern Sahara is particularly well illustrated by the data from the Sahara in Mali (17° to 24° N), where a large number of observations on a variety of palaeoenvironmental proxies were made between 1980 and 1988 (Petit-Maire 1986, Petit-Maire & Riser 1983, 1988). Anthropological studies providing thorough descriptions of numerous human remains from burials between 20° and 16° N, including their archaeological context (Petit-Maire & Dutour 1987, Dutour 1989, Raimbault

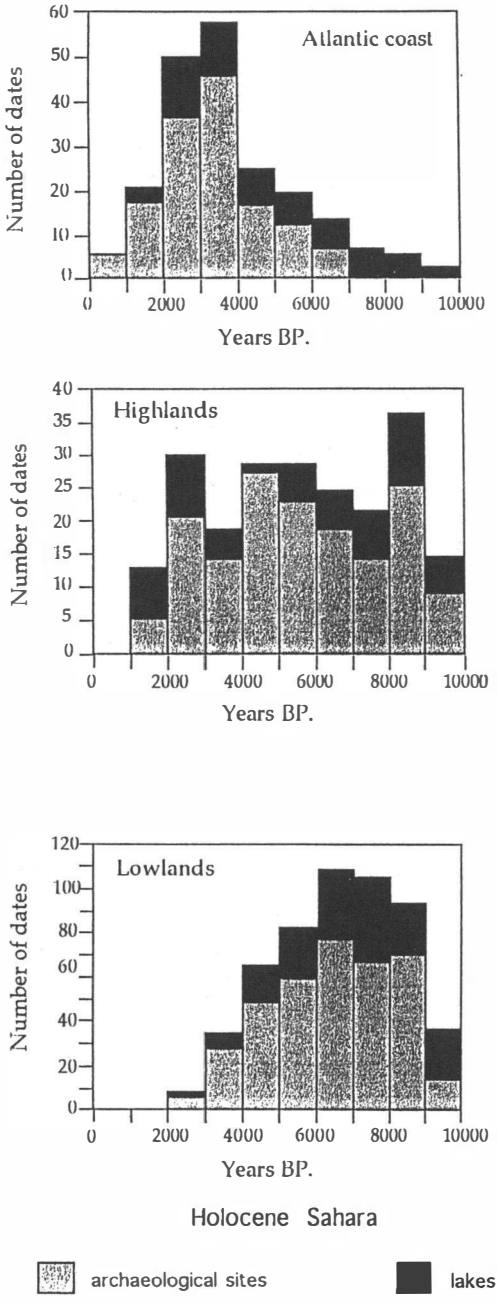


Fig. 6. — Human migrations in the holocene Sahara, as shown by frequency of archaeological sites in relation with presence of surface freshwater.

& DUTOUR 1990, RAIMBAULT 1994), have shown a southward migration of the same population after the palaeolakes at 19° N dried up (PETIT-MAIRE & GAYET 1984, PETIT-MAIRE & RISER 1987).

Figure 7 shows the age of maximal human occupation in relation to latitude. The maximal occupation around the 24th parallel also corresponds to the highlands, the Atlantic coast, and the Nile valley.

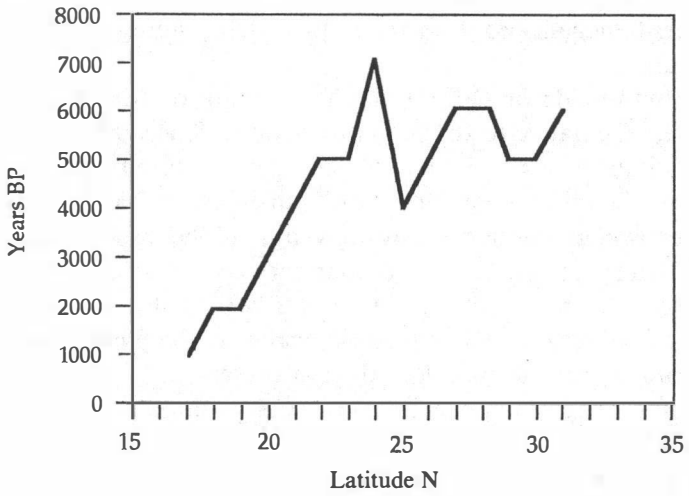


Fig. 7. — Repartition of the ages of the ultimate archaeological sites according to latitude (N).

Conclusion

Primarily due to changes in the locations of two major atmospheric circulation features (*i.e.*, the jetstream and ITCZ latitudes), which are in turn related to global boundary conditions, both monsoon activity and range and penetration of Atlantic cyclones have been variable through time. The arid/semi-arid belt in northern Africa is thus prone to acute environmental changes which have been documented by numerous palaeoenvironmental proxy data.

During the early Holocene, the arid belt around the Tropic of Cancer practically disappeared (PETIT-MAIRE *et al.* 1993) and was replaced by (steppic, sahelian, and sudanian) semi-arid environments. This development appears to have been related to the southward shift of the jetstream and the northern movement of the ITCZ during this

period. The temporal and spatial distribution of a large body of palaeoenvironmental proxy data from a wide range of sources throughout the currently hyperarid area of the Sahara shows how sensitive human populations have been to the climatic evolution of this region. Both the onset of hydrologically viable conditions during the early Holocene and their progressive deterioration after the mid-Holocene induced wide migrations into and out of a territory covering several million km^2, while the highlands, the Atlantic coast, and the shores of the Niger, Senegal, and Nile rivers provided a refuge until about 2,000 years ago.

If a new man-made or natural global warming occurs and reaches + 1 °C to + 2 °C relative to the present (WIGLEY & RAPER 1990), that is, a value similar to the Holocene summer maximum, it may be expected that the climatic conditions in sub-Saharan northern Africa will again evolve in the same way they did in the past in response to natural changes in climatological boundary conditions, and that the environments will once again become more hospitable to human life. Of course, to be very similar climatologically to the early Holocene, the winters would have to be colder than at present.

Models of Holocene changes in the ITCZ position and associated monsoonal rainfall show a tendency for the calculated rainfall increases to precede the advent of wetness indicators by hundreds of years at least (BRYSON 1992) and of cultural indicators by longer periods, perhaps of the order of 400-500 years or more. It is doubtful that modern technologies can hurry this pace to the much shorter span of perhaps decades or a century.

REFERENCES

BERGER, A. 1992. Le climat de la Terre. Un passé pour quel avenir? — De Boeck-Wesmael, Bruxelles, 447 pp.

BRYSON, R. A. 1992. A macrophysical model of the Holocene intertropical convergence and jetstream positions and rainfall for the Saharan region. — *Meteor. and Atmos. Phys.*, **47** : 247-258.

CAMPS-FABRER, H. 1983. Parures et engins de pêche. — *In* : PETIT-MAIRE, N. & RISER, J (éds), Sahara ou Sahel? Quaternaire récent du Bassin de Taoudenni, C.N.R.S., Marseille, pp. 367-401.

CAMPS-FABRER, H., COMMELIN, D. & PETIT-MAIRE, N. 1982. Objets rares et parures néolithiques du Sahara malien. — Travaux du Laboratoire d'Anthropologie des Pays de Méditerranée Occidentale, Aix-en-Provence, pp. 1-19.

COMMELIN, D. 1984. La céramique néolithique dans le Bassin de Taoudenni (Sahara malien). — Thèse, Université de Marseille.

COMMELIN, D. & PETIT-MAIRE, N. 1979. Chronologie isotopique saharienne pour les derniers 10 000 ans. Essai d'interprétation : migrations humaines et paléoclimatologie. — *Bulletin du Musée d'Anthropologie préhistorique de Monaco*, **23** : 37-88.

DECOBERT, M. & PETIT-MAIRE, N. 1985. An early Neolithic midden and necropolis in the Malian Sahara. — *Nyame Akuma*, **26** : 26-32.

DUTOUR, O. 1989. Hommes fossiles du Sahara : peuplement holocène du Mali septentrional. — Editions du C.N.R.S., Marseille, 342 pp.

GUERIN, C. & FAURE, M. 1983. Mammifères. — *In* : PETIT-MAIRE, N. & RISER, J. (éds), Sahara ou Sahel? Quaternaire récent du Bassin de Taoudenni (Mali), C.N.R.S., Marseille, pp. 239-272.

HAYNES, C. V. & MEAD, A. R. 1987. Radiocarbon dating and paleoclimatic significance of subfossil Limicolaria in northwestern Sudan. — *Quaternary Research*, **28** : 86-99.

IMBRIE, J., BERGER, A., BOYLE, E. A., CLEMENS, S. C., DUFFY, A., HOWARD, W. R., KUKLA, G., MARTINSON, D. G., MCINTYRE, A., MIX, A. C., MOLFINO, B., MORLEY, J. J., PETERSON, L. C., PISIAS, N. G., PRELL, W. L., RAYMO, M. E., SHACKLETON, N. J. & TOGGWEILER, J. R. 1993. On the structure and origin of major glaciation cycles : The 100,000 years cycles. — *Paleoceanography*, **8** (6) : 699-735.

LE HOUEROU, H. N. 1989. Classification écoclimatique des zones arides (s. l.) de l'Afrique du Nord. — *Ecologia Mediterranea*, **15** (314) : 95-144.

MAINGUET, M., CANON, L. & CHEMEN, M. C. 1980. Le Sahara : géomorphologie et paléomorphologie éoliennes. — *In* : WILLIAMS, M. & FAURE, H. (éds), The Sahara and the Nile. Balkema, Rotterdam, pp. 17-35.

NEUMANN, K. 1989. Holocene vegetation of the eastern Sahara : charcoal in prehistoric sites. — *African Archaeological Review*, **7** : 97-116.

OUSSEINI, I. & MOREL, A. 1989. Utilisation de formations alluviales pour l'étude des paléoenvironnements du Pléistocène supérieur et de l'Holocène au Sud du Sahara : l'exemple de la Vallée du fleuve Niger dans le Liptako nigérien. — *Bulletin de la Société Géologique de France*, (**8**) 5/1 : 85-90.

PETIT-MAIRE, N. (éd.) 1979. Le Sahara atlantique à l'Holocène. Peuplement et écologie. — Mémoire 28, CRAPE, Alger, 340 pp.

PETIT-MAIRE, N. 1980. Holocene biogeographical variations along the northwestern African coast (28-19 N) : Paleoclimatic implications. — *In* : SARNTHEIN, M., SEIBOLD, E. & ROGNON, P. (eds.), The Sahara and the Surrounding Seas. Balkema, Rotterdam, pp. 365-377.

PETIT-MAIRE, N. 1986. Paleoclimates in the Sahara of Mali : A multidisciplinary study. — *Episodes*, **9**(1) : 7-16.

PETIT-MAIRE, N. (éd.) 1991. Paléoenvironnements du Sahara : Lacs holocènes à Taoudenni (Mali). — Editions du C.N.R.S., Marseille-Paris, 239 pp.

PETIT-MAIRE, N. 1994. Natural variability of the Asian, Indian and African monsoons over the last 130 ka. — *In* : DESBOIS, M. & DESALMAND, F. (eds.), Global Precipitation and Climate Change, NATO ASI Series, **17** (26) : 3-26.

PETIT-MAIRE, N. & DUTOUR, O. 1987. Holocene populations of the Western and Southern Sahara. Mechtoids and paleoclimates. — *In* : CLOSE, A. E. (ed.), Prehistory of Arid North Africa. Southern Methodist University, Dallas, pp. 259-286.

PETIT-MAIRE, N. & GAYET, M. 1984. Hydrographie du Niger (Mali) à l'Holocène ancien. — *C.R. Acad. Sci. Paris*, II, **298** : 21-23.

PETIT-MAIRE, N. & GUO, Z. T. 1996. Mise en évidence de variations climatiques holocènes rapides en phase au Sahara et dans les déserts du nord de la Chine. — *C. R. Acad. Sci. Paris*, II A, **322** (10) : 847-851.

PETIT-MAIRE, N. & PAGE, N. 1992. Remote sensing and past climatic changes in tropical deserts : the case of the Sahara. — *Episodes*, **15** (2) : 113-117.

PETIT-MAIRE, N., PAGE, N. & MARCHAND, J. 1993. The Sahara in the Holocene : Map 1/5,000,000. — Unesco, C.G.M.W., Paris.

PETIT-MAIRE, N. & RISER, J. (éds). 1983. Quaternaire récent du Bassin de Taoudenni (Mali) : Sahara ou Sahel? — Editions du C.N.R.S., Marseille, 473 pp.

PETIT-MAIRE, N. & RISER, J. 1987. Holocene palaeohydrology of the Niger. — *Palaeoecology of Africa*, **18** : 135-141.

PETIT-MAIRE, N. & RISER, J. 1988. Le Sahara à l'Holocène (Mali) : Map 1/1,000,000. — C.G.M.W., Paris.

RAIMBAULT, M. 1994. Sahara malien : environnement, populations et industries préhistoriques. — Thèse, Université de Provence, Marseille, 3 vol.

RAIMBAULT, R. & DUTOUR, O. 1990. Découvertes de populations méchtoïdes dans le néolithique du Sahel malien (gisement lacustre de Kobadi) ; implications paléoclimatiques et paléoanthropologiques. — *C. R. Acad. Sci. Paris*, III, **310** : 631-638.

ROGNON, P. 1980. Une extension des déserts (Sahara et Moyen-Orient) au cours du tardiglaciaire (18 000-10 000 ans BP). — *Revue de Géologie dynamique et Géographie physique*, **22** : 313-328.

ROSET, J. P. 1988. Paleoclimatic and cultural conditions of Neolithic development in the Early Holocene of Northern Niger (Air and Tenere). — *In* : CLOSE, A. E. (ed.), Prehistory of Arid North Africa. S.M.U., Dallas, pp. 211-234.

SCHULTZ, E. 1991. Les pollens des lacs de Taoudenni-Agorgott. — *In* : PETIT-

MAIRE, N. (éd.), Paléoenvironnements du Sahara : lacs holocènes à Taoudenni (Mali). Editions du C.N.R.S., Marseille-Paris, pp. 141-146.

TALBOT, M. 1984. Late Pleistocene rainfall and dune building in the Sahel. — *Palaeoecology of Africa*, **16** : 203-214.

VERNET, R. & AUMASSIP, G. 1992. Le Sahara et ses marges. Paléoenvironnement et occupation humaine à l'Holocène. Inventaire des datations ^{14}C. — Editions du C.N.R.S., Meudon-Paris, 107 pp.

WIGLEY, J. M. L. & RAPER, S. C. 1990. Natural variability of the climate system and detection of the greenhouse effect. — *Nature*, **344** : 324-327.

YAN, Z. W. & PETIT-MAIRE, N. 1994. The last 140 ka in the Afro-Asian climatic transitional zone. — *Palaeogeography, Palaeoclimatology, Palaeoecology*, **110** : 217-233.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 68-85 (1998)

Palaeoenvironmental Evidence for Synchronous Changes in Calcite Flowstones Formation, Speleothems Erosion and/or (Re)Dissolution and Equatorial Wetter Conditions in the Tropical Karst of Mount Hoyo (N.E. Zaire)

by

Raymond MICHEL *

KEYWORDS. — Zaïre ; Tropical Karst ; Flowstones ; Clay and Carbonate Minerals ; Palaeoenvironments.

ABSTRACT. — Speleothems and detrital sediments from Mount Hoyo (1.5 N, 30 E) caves reveal clay mineral assemblages and relative pollen composition indicating important changes in tropical karst palaeoenvironments in the past 150 ky B.P. This multidisciplinary study shows a correlation between : three calcite flowstone levels and equatorial mountainous or rain forest conditions ; aragonite speleothem formation and open herbaceous wooded savanna ; gravel deposits covered by sulfate gypsum and dry-cold grassland and/or afromountainous taxa. Present climatic and edaphic conditions of the pollen taxons observed in these deposits suggest palaeotemperatures oscillating between ($\leq +2$ °C for the optimum of Holocene and (≥ -4 °C during the hypothermal of Pleistocene period from modern (23 °C) external value. These geomorphological phenomena are thus very interesting climatic indicators for understanding the karst dynamics and tropical palaeoenvironments.

MOTS-CLES. — Zaïre ; Karst tropical ; Planchers stalagmitiques ; Minéraux argileux et carbonates ; Paléoenvironnements.

RESUME. — *Mise en évidence d'une corrélation entre la formation de planchers stalagmitiques composés de calcite, l'érosion et/ou la (re)dissolution*

* Ministère de la Région wallonne, Direction générale de l'aménagement du territoire, du logement et du patrimoine, rue des Brigades d'Irlande 1, B-5100 Namur (Belgium).

de concrétions stalagmitiques et l'existence de conditions de climat humide équatorial dans le karst tropical du Mont Hoyo (N.E. Zaïre). — Les concrétions et les dépôts détritiques des grottes du Mont Hoyo (1,5 N, 30 E) révèlent par leur composition minéralogique et pollinique des indices d'une modification importante du paléoenvironnement karstique tropical depuis près de 150 ka. Cette étude multidisciplinaire montre qu'il existe une corrélation entre : la formation de trois niveaux de planchers stalagmitiques composés de calcite et l'existence d'un milieu de forêt dense ; la formation de concrétions composées d'aragonite et un assèchement du climat propice au développement d'une végétation de milieu ouvert de type savane arbustive ; le dépôt de cailloutis concrétionné par du gypse et le développement d'un milieu sec et froid de type afro-montagnard. Les conditions climatiques et édaphiques actuelles des différents taxons polliniques observés dans ces dépôts suggèrent des paléotempératures oscillant entre ($\leq +2°C$ pour l'optimum de l'Holocène et ($\geq -4°C$ lors de l'hypothermal du Pléistocène par rapport à la moyenne (23°C) de la température externe actuelle. Dès lors, ces phénomènes géomorphologiques constituent des indicateurs climatiques d'un grand intérêt pour la connaissance de la dynamique du karst et des paléoenvironnements tropicaux.

TREFWOORDEN. — Zaire ; Tropische karst ; Vloeistenen ; Klei- en karbonaatmineralen ; Paleo-omgevingen.

SAMENVATTING. — *Paleo-omgevingsevidentie voor synchrone veranderingen in de vorming van calciethoudende vloeistenen, speleothemerosie en/of (her)-dissolutie en equatoriale weercondities in de tropische karst van de Hoyo Berg (N.-O.-Zaire).* — De concreties en de detritische sedimenten van de grotten van Mount Hoyo (1,5 N, 30 E) geven, door hun mineralogische en pollensamenstelling, belangrijke veranderingen aan in de paleo-omgeving van de tropische karstverschijnselen gedurende ongeveer 150 ka. Deze multidisciplinaire studie toont een correlatie aan tussen de vorming van drie niveaus van calciethoudende vloeistenen en het bestaan van equatoriale berg- of regenwoudcondities, de vorming van aragonietconcreties en een milieu van een open savanne met heesters, de aanwezigheid van een gegipsifieerde grindafzetting samengaand met de ontwikkeling van grasland in een droog en koud milieu in Afrikaans-bergachtige klimaatcondities. De huidige klimatische en edafische condities van de verschillende pollentaxa, geobserveerd in de bovenvermelde afzettingen, wijzen op paleotemperaturen die schommelen tussen $\leq +2$ °C voor het optimum van het Holoceen en ≥ -4 °C gedurende het hypothermale deel van het Pleistoceen in vergelijking met de huidige gemiddelde (23 °C) externe temperatuur. Deze geomorfologische fenomenen zijn bijgevolg zeer belangrijke klimatologische indicatoren om een beter inzicht te verkrijgen in zowel de dynamiek van karstverschijnselen als van tropische paleo-omgevingen.

Introduction

Pollen spectra, plant and animal fossils in lakes and marshes, ancient lake shorelines, abandoned glacial moraines, ancient sand dunes and alluvial deposits have provided evidence of changes in the climate in Central Africa during the late Quaternary period (LIVINGSTONE 1962, HARVEY 1976, VAN NOTEN 1977, STOFFERS & SINGER 1979, ALEXANDRE & STREEL-POTELLE 1979, VAN ZINDEREN BAKKER 1982, VAN NEER 1984, POKRAS *et al.* 1985, COHEN 1987, HOOGHIEMSTRA & AGWU 1988, BONNEFILLE & VINCENS 1989, ELENGA 1992, MAHANEY 1989, BROOK *et al.* 1990, LEZINE & HOOGHIEMSTRA 1990, BENGO & MALEY 1991, MALEY 1989, MICHEL 1991a, d, ROELAND 1991, ROCHE 1991, VINCENS *et al.* 1991, SOWUMNI 1991, BONNEFILLE *et al.* 1992, ROBERTS *et al.* 1993, SSEMMANDA & VINCENS 1993, RUNGE 1995).

In general, main studies suggest that glacial maxima at higher latitudes corresponded to phases of a more arid climate in tropical Africa while interglacials have been periods of interstadial wetter climate.

Long periods of tropical palaeoenvironments (to 135 ky B.P.) have been obtained from Atlantic ocean core sediments (POKRAS *et al.* 1985, BENGO & MALEY 1991) but there are no comparable long-dated records for terrestrial sites.

East African lakes and marsh sediments have the potential to provide long records, although data on these palaeoenvironments are restricted in time because absolute radiometric ^{14}C dating beyond 40 ky is impossible and clastic sediments are more easily removed by geomorphological and/or tectonic phenomena.

However, sources for palaeoenvironmental data can be obtained from caves by documenting phases of speleothems deposition and erosion (MICHEL 1991a, d) or (re)dissolution (BROOK *et al.* 1990).

Therefore, it may be possible to obtain a long-term vegetation, soil and climatic reconstruction from clay minerals, pollen spectra and isotopic $^{230}Th/^{234}U$ dated speleothems, particulary in flowstones.

This paper reports the results from a multidisciplinary study of the palaeoenvironments in Mount Hoyo caves (Matupi and Kabambi) in the Ituri region of north-eastern Zaire.

Method

Multidisciplinary (geomorphological, mineralogical, palynological) studies of the Matupi (MAT) and Kabambi (KAB) caves were undertaken to establish the history of sediment deposition and erosion in these caves.

Eight samples of detrital material were collected in Matupi cave and clay minerals DRX and pollens were analysed. Five samples of speleothems from Matupi cave were ^{14}C radiometric dated along with five others from Kabambi cave dated by isotopic $^{230}TH/^{234}U$. DRX mineral and pollen analysis of these speleothems was also carried out. One soil sample from the slope below the Kabambi cave entrance and one sample of dolomitic and shale bedrock were taken for DRX and optic mineral analysis.

Pollens were extracted from the speleothem sample by a combination of methods from two sources. The calcite matrix was first treated in HCl, as described in BASTIN (1990). Clastic humic and clay minerals were then removed in HF using Professor Streel's method developed at the Palynology Laboratory, Liège. The XRD analysis of clay minerals has identified diffraction peaks for the N-EG-500 °C tests using the method described in THOREZ (1976, 1985).

Radiometric ^{14}C dating speleothems were carried out in the CEN/SCK Mol (Hurtgen laboratory) with a method combining two sources (FONTES 1971, GEWELT 1983). Apparent ^{14}C Ages are corrected with a bedrock carbonate dilution factor $q = 0.85$ used by GEWELT (1983b, 1985). Each detector was connected to a Tricarb 2250CA-channel Beta spectrometer.

Isotopic $^{230}Th/^{234}U$ dating speleothems were analysed in CEN/SCK Mol with a method described in HURTGEN *et al.* (1985). Each detector was connected to and housed with a Camberra model 7404-channel Alpha spectrometer.

Mount Hoyo Caves

Mount Hoyo (1.5 N, 30 E) is located 50 km SW of Lake Mobutu in eastern Zaïre (fig. 1). This mountain reaches an altitude of 1,450 m. Climatic statistics indicate a mean annual precipitation close to 1,700 mm (RUSCART 1951) and a mean annual temperature of 20 °C in the caves (MICHEL 1991a). The rainfall distribution shows a peak in September, equal distribution during the March-August period and

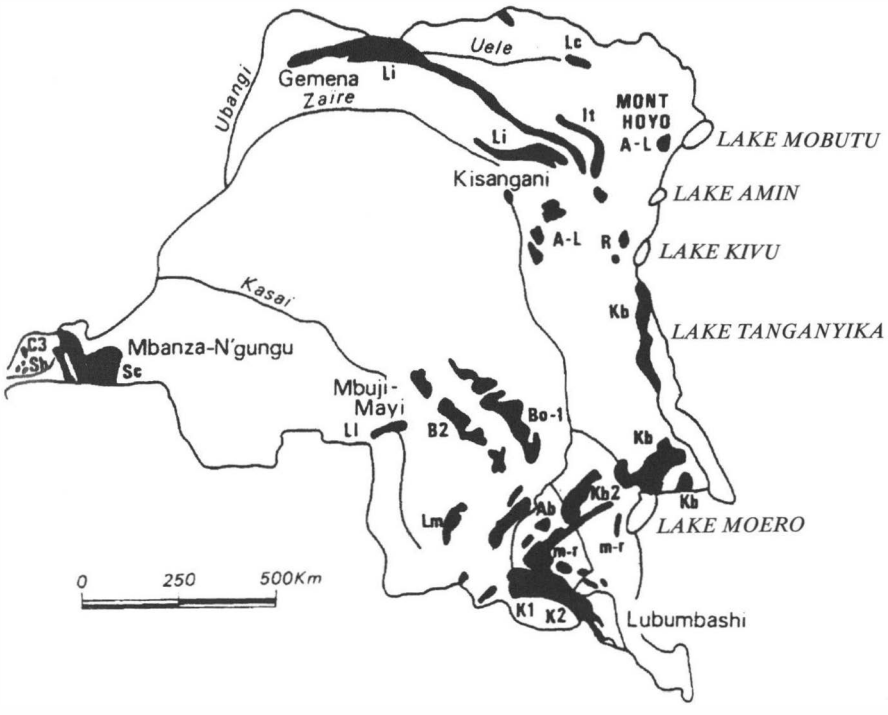


Fig. 1. — Carbonate formations of Zaïre.

a dry interval in January-February. Fourteen maze caves were recorded, mostly developed at an altitude of 1,100 m in the horizontal dolomitic limestones, strongly faulted from Precambrian Age (Lindian?) (MICHEL 1991). Vegetation at the main caves level is a rich equatorial rain forest recently removed by human activity and including *Cynometra*, *Ficus*, *Fagara*, *Chorophera*, ... (RUSCART 1951).

The closed forest thins eastwards and becomes savanna on the summit of the mountain and its eastern slope where the Semliki River flows into Lake Mobutu located in the Rift valley.

Matupi and Kabambi (fig. 2, fig. 3) caves contain large chambers, channels and galleries. The stream in the Kabambi cave was active after heavy rain. Galleries have been developed on several levels. The keyholes or pressure passages show evidence of origin under phreatic conditions previous to the fault escarpment bounding Mount Hoyo and the morphology of this area. Nevertheless, vadose conditions prevailed during the mid- and late Quaternary levels.

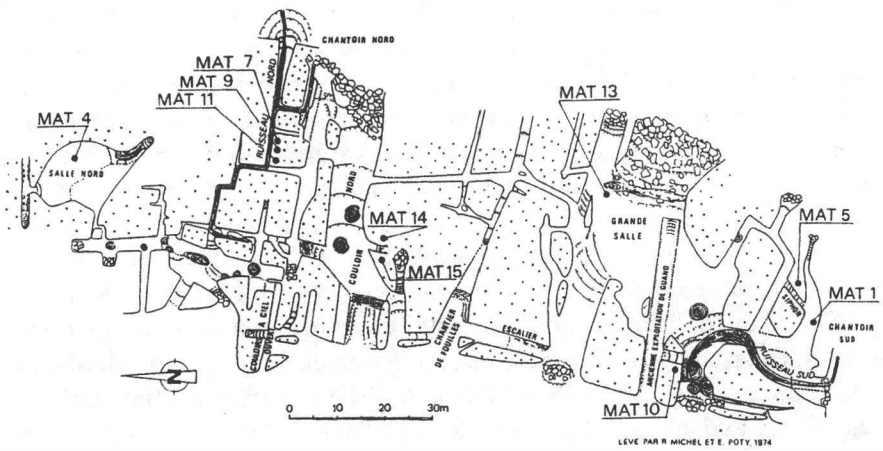


Fig. 2. — Map with the localization of the studied deposits and concretions in the Matupi cave.

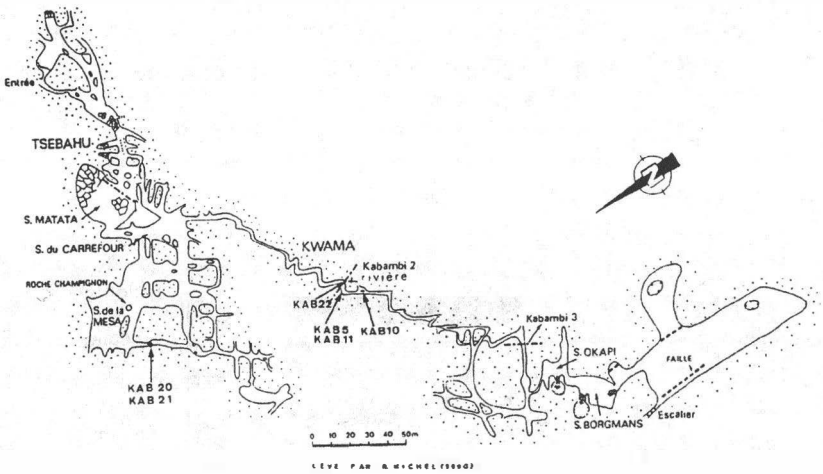


Fig. 3. — Map with the localization of the studied deposits and concretions in the Kabambi cave.

Several speleothems were eroded (MICHEL 1991) by stream action or (re)dissolved by water infiltration (BROOK *et al.* 1990). Fresh and ancient bat guano deposits rich in P_2O_5 covered speleothems and the floor of the large cavities ; up to 6 m of bat guano was observed ; about 350,000 tonnes were buried in the "Grande Salle" of the Matupi cave.

Results

The plans of Matupi and Kabambi caves show a network of joint-controlled passages. The most common orientations are in relation to main lineaments (NS, NNW-SSE and WE) revealed by the study of satellite (Landsat 5) imagery of this area (MBULOYO & LAVERAU 1989, MICHEL 1991).

Data from Matupi (VAN NOTEN 1977, 1982 ; BROOK 1990 ; MICHEL 1991) and Kabambi (MICHEL 1991) caves indicate that pollens, carbonate and clay minerals in clastic sediments and speleothems can provide interesting information on past vegetation and soil characteristics.

XRD analysis of clay minerals (fig. 4) indicates : higher (24 %) percentage of kaolinite well crystalled in the silt deposits (MAT5) and flowstone levels (MAT14) (8 %), vermiculite and mixed layer (10-14V) (11 %) and in the calcite flowstone levels (MAT14) ; smectite (7 %) and mixed layer (10-14Sm) (10 %) in the gravels (MAT9) ; illite in all samples and specially in the gravels (79 %) and in the dolomitic bedrock (MH3) and in the shales (MH2) located upon the caves.

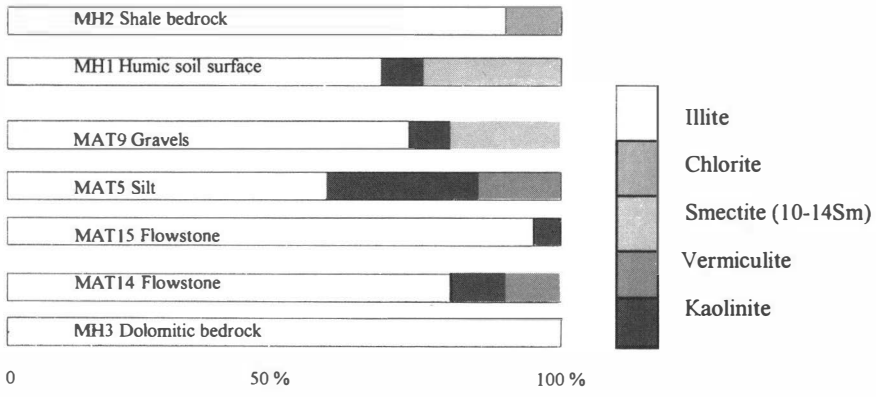


Fig. 4. — Clay mineral analysis in typical sequence of Matupi cave.

The optic and XRD analysis of the karst concretions reveals two calcium carbonate minerals : the calcite shows a d hkl peak at 3.03 Å in the flowstone levels (MAT14, MAT15) and in several speleothems (KAB21) ; the aragonite (KAB20) is characterized by a fibro-radial structure and two reflexion peaks (3.39 Å and 1.97 Å).

Sulfate gypsum has been observed in several speleothems (KAB22, KAB20, KAB10) showing a d hkl peak at 7.65 Å. The KAB22 sample corresponds to a flowstone covering the gravels also observed in Matupi cave (MAT9).

The palynological results (fig. 5) show : pollens of secondary forest and/or forest gallery (MAT5 : *Celtis*, *Cissus*, *Carapa*, *Pavetta*) (18 %) in the silt deposits and pollens of equatorial mountainous forest and/or rain forest (MAT15 : *Trichilia*, *Khaya*, *Allophyllus*, *Dracaenia*, *Fagara*, *Canthium gloriosa superba*, maximum percentage of the spores of monolete *Pteridophytae*) (39 and 57 %) in the calcite flowstones ; pollens of grassland and open marsh, open herbaceous savanna with wooded formations and/or afromountainous taxa (MAT1, MAT9 : 69 % *Gramineae*, *Leguminoseae*, *Euphorbiaceae*, *Lobelia*, *Chenopodiaceae*, *Hypericum*, *Dombeya* and maximum percentage of *Pteridium*) in the gravels.

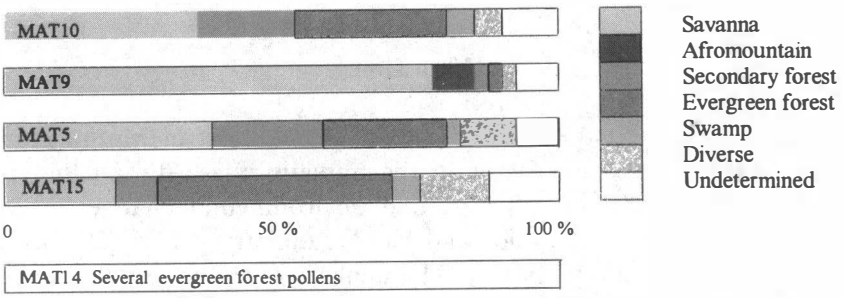


Fig. 5. — Pollen taxons in typical sequence of Matupi cave.

Isotopic and radiometric $^{230}TH/^{234}U$ and ^{14}C dated speleothems from Matupi and Kabambi caves produced a record of four wetter phases during the last 150 ky B.P. : Interglacial Teliki-Liki (115 ± 7 to 165 ± 15 B.P.), Kalambo Interstadial (28.7 ± 0.5 ky B.P.), Optimum Holocene (6.2 ± 0.5 ky B.P.) and the last long wet phase of Holocene (2.2 ± 0.2 ky B.P.).

Table 1

Results of ^{14}C analysis from Matupi cave

Sample	Rough ^{14}C Age *(y B.P.)* $\pm \sigma$	Apparent ^{14}C Age *(y B.P.)* $\pm \sigma$	Corrected ^{14}C Age *(ky B.P.)*; $q = 0.85$	Type of deposit
MAT 10	3,173 ± 39	3,450 ± 65	2.1 ± 0.5	flowstone
MAT11	3,226 ± 51	3,500 ± 70	2.2 ± 0.5	speleothem
MAT13	3,440 ± 40	3,610 ± 70	2.3 ± 0.5	flowstone
MAT14	29,700 ± 450	29,980 ± 460	28.7 ± 0.5	flowstone
MAT15	7,276 ± 68	7,550 ± 85	6.2 ± 0.5	flowstone

q = bedrock carbonate dilution factor.

Table 2

Results of U and Th analysis from Kabambi and Matupi caves

Sample	[U] ppm ± *1σ*	$^{230}Th/^{234}U$ ± *1σ*	Age $^{230}Th/^{234}U$ *(ky)*	Type of deposit
MAT 13	*4.438* ± 0.032	*0.021* ± 0.001	2.2 ± 0.2	flowstone
KAB10	4.488 ± 0.064	0.220 ± 0.006	26.8 ± 1.1	speleothem
KAB11	0.458 ± 0.009	1.145 ± 0.034	> 350	flowstone
KAB20	1.097 ± 0.016	0.673 ± 0.018	115 ± 7	speleothem (1)
KAB21	3.268 ± 0.048	0.820 ± 0.021	165 ± 15	speleothem (2)

Discussion

The weathering and erosion of the dolomitic karst of Mount Hoyo is a result of a tectonic factor in the phreatic phase during the end of the Tertiary (Miocean?) Age and environmental changes in the vadose phase during the mid- and late Quaternary period (Ollier & Harrop 1963, Michel 1991a). The analysis of the cave palaeoenvironments indicates a relationship between extended flowstone levels, eroded or (re)dissolved speleothems and wetter conditions.

Kaolinite is an important component of the clay assemblage of the silt deposits and the flowstone levels. The presence of kaolinite indicates that this area experienced a warm humid climate with high rainfall increasing chemical weathering (Stoffers & Singer 1979, Robert & Kennets 1992). The relative representation of the tropical forest elements reached high values. The main factor controlling the presence of the tropical forest is continuous high rainfall, rather than high temperature.

Smectite and illite dominate in the detrital gravels. Pedogenic smectite suggests a globally warm climate and alternating wet and dry seasons (ROBERT & KENNETS 1992). An abundance in illite indicates the development of more poorly weathered soils. During this gravel deposit period, the decrease in tropical vegetation is mainly compensated by an increase in Gramineae, woodland and afromountainous taxa dominated by savanna vegetation under drier and cooler conditions.

Aragonite suggests a high value of Mg/Ca ratio in water percolation (FOLK & ASSERETO 1976) and/or in ion strontium (HILL *et al.* 1986) and dry conditions promoting rapid CO_2 loss and a high rate of evaporation favourable to supersaturation in Mg. The temperature factor on the precipitation of aragonite has not been established by the researchers though RICHARD (1983) advocated warm conditions.

Gypsum formation corresponds to dry conditions (HILL & FORTI 1986) favourable to the evaporation of small surface water oversaturated in sulfates issuing from the weathering of the galene included in the dolomitic bedrock. As this mineral is associated with aragonite in some concretions, we suggest a development under dry conditions. In terms of the influence of environmental factors on the karst dynamics, it is clear that climate through its temperature and rainfall regimes, soils and vegetation cover and availability of carbon dioxide are the primary factors to be considered.

Rainfall controls soil moisture levels and influences run-off rates which govern the supply of water and solution reactants over rock surfaces and the removal of solution products (FORD & WILLIAMS 1989).

Soil cover is a reservoir for carbon dioxide (EK & GEWELT 1988), for organic acids (SCHOELLER 1962, JAKUCS 1977) and a store of percolating rainwater.

Soil temperature has an important effect on organic matter decomposition (DRAKE & WIGLEY 1975) and together with soil moisture controls the supply of soil dioxide. On the other hand, higher temperatures increase evaporation which reduces the store of percolating rainwater and the formation of speleothems by the evaporation of dripwater. Nevertheless, evidence of relationships was found between these key variables.

Bat guano deposits in the Matupi cave contain a mean percentage of P_2O_5 above 15 %. Several values for 100 % have been obtained just above the dolomitic bedrock (RUSCART 1951). The weathering action of speleothems by strongly concentred P_2O_5 water must also be envisaged.

According to BROOK *et al.* (1990) several speleothems in the Matupi cave have stopped growing by insufficient degassing of CO_2 from cave dripwaters. Cessation of carbonate calcite deposition implies insufficient rainfall percolation and reduced vegetation cover. These drier conditions suggest higher evaporation favourable to sulfate gypsum deposition (HILL *et al.* 1986) and lower levels pCO_2 favourable to carbonate aragonite deposition (ROQUES 1995).

According to BROOK *et al.* (1990), many speleothems were (re)dissolved by dripwaters undersaturated with respect to calcite. This phenomenon occurred at the time of environmental change towards a warmer and wetter climate when vegetation cover reduced, increasing soil erosion which allowed the widening of the percolation routes and velocity water into the cave, but did not allow time for water to become saturated in calcite.

However, widening percolation routes and higher levels of pCO_2 were required to dissolve the dolomitic bedrock. This is difficult under dry conditions because dolomitic limestones contain more than 85 % of $MgCO_3$ (MICHEL 1991). Thus, eroded speleothems observed in the Mesa chamber of the Kabambi cave suggest a stream action under wetter conditions.

Finally, the hiatus observed between KAB20 and KAB21 speleothem samples is dated for the Interglacial Teleki-Liki (115 ± 7 to 165 ± 15 ky B.P.) (Eemian?) revealed by MAHANEY (1989) and DRX mineral analysis of KAB20 indicates carbonate aragonite and sulfate gypsum suggesting drier conditions after 115 ± 7 ky B.P. and not the wetter conditions suggested by BROOK *et al.* (1990) concerning the (re)dissolution sequence of several speleothems from Matupi cave.

Conclusions

Relative pollen composition and clay mineral assemblages recorded from speleothems and detrital deposits in the Mount Hoyo caves lead to the following reconstruction of changes in the north-east Zaïrean vegetation and climatic conditions during the middle and the late Quaternary period.

The tropical rain forest had maximally expanded between 115 ± 7 and 165 ky ± 15 B.P. (Interstadial Teleki-Liki), around 28.7 ky ± 0.5 B.P. (Kalambo Interstadial), around 6.2 ky ± 0.5 B.P. (Thermal and Pluvial Optimum of Holocene) and around 2.2 ky ± 0.2 B.P. (the last long wet phase of Holocene).

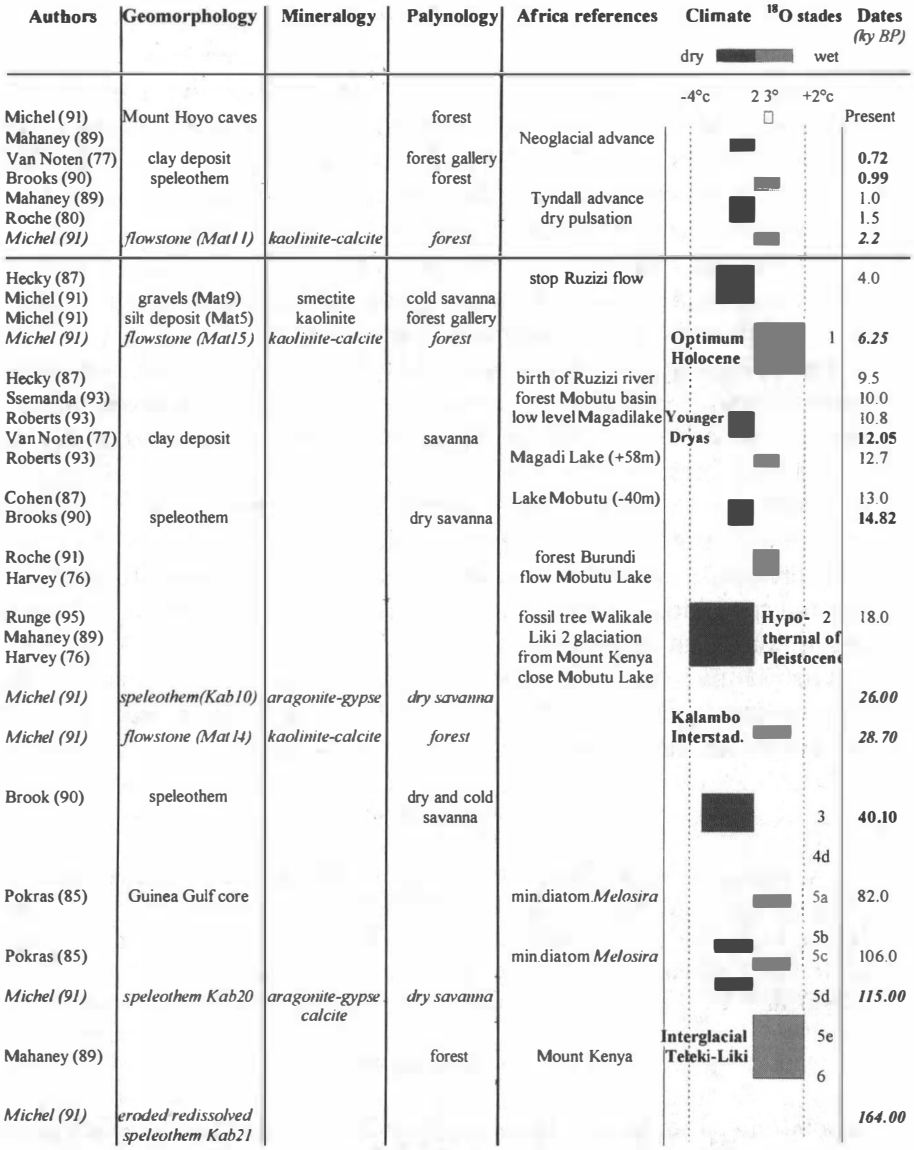


Fig. 6. — Palaeoenvironments of Mount Hoyo. Dates of the speleothems and East Africa references. Idealized diagrammatic representation of Mount Hoyo (1.5 N, 30 E, 1,100 m) cave palaeoenvironments during the past 150,000 years. Minor differences in amplitude of vegetational shifts are not considered. Maximum amplitude values of temperatures are deduced from the geographical position (altitude, latitude) where the typical taxons observed in the detrital and calcium carbonate deposits of these caves are located now. Several climatic interpretations are the result of research developed in East African palaeoenvironments. Pollen-derived estimated palaeotemperatures indicate differences, from modern values (23 °C) of $\leq +2$ °C for Holocene and ≥ -4 °C during the Hypothermal Pleistocene period, sufficient to change potential evaporation and diminish palaeoprecipitations at the caves [entry by > 40 % from present values (1,700 mm)].

Contractions of the tropical rain forest correspond to the expansion of gallery (secondary) forest and then grassland dry savanna after 115 ky B.P., around 40 ky B.P. (Early Stone Age), between 26 and 12 ky B.P. (Hydrothermal of Mount Kenya) and around 4 ky B.P. (flow of the Ruzizi River stopped).

The general picture which emerges from vegetation, pedologic and thus climatic changes in Central Africa during the last 150 ky B.P. is shown in an idealized schematic diagram (fig. 6).

Palynological and XRD mineralogical results of the flowstone analysis and (re)dissolved speleothem phenomena observed in the Mount Hoyo caves reveal a development under wetter conditions and closed rain forest.

Aragonite carbonate and gypsum sulfate depositions of several speleothems suggest a development under dry conditions.

Therefore, it can be argued that a new base has been provided for the interpretation of karst dynamics in tropical areas by analysing a vegetational and climatic history.

Further investigations in the same phytogeographical domain of the tropical karst in Central Africa should be undertaken in order to shed more light on the findings presented in this paper.

ACKNOWLEDGEMENTS

The author wishes to thank Mr Hurtgen (CEN/SCK Mol) and Mr Gewelt (ULG, Liège) for the ^{14}C and the $^{230}TH/^{234}U$ speleothem data, J. Thorez (ULG, Liège) for the clay mineral analysis, E. Roche (Musée royal d'Afrique centrale, Tervuren) for pollen identification, and J. Alexandre, C. Ek (ULG, Liège) and R. Tuffs (ULB, Brussels) for critically reading the manuscript.

REFERENCES

ALEXANDRE, J. & STREEL-POTELLE, A. 1979. Les alluvions anciennes de la Lupembashi inférieure (Shaba, Zaïre) et l'évolution d'une plaine alluviale de la région intertropicale à saison sèche pendant le Quaternaire. — *Geo-Eco-Trop.*, **3** (3) : 169-184.

BASTIN, B. 1990. L'analyse pollinique des concrétions stalagmitiques : méthodologie et résultats en provenance des grottes belges. — *Karstologia*, **2** : 3-10.

BASTIN, B. & GEWELT, M. 1986. Analyse pollinique et datation ^{14}C de concrétions stalagmitiques holocènes : apports complémentaires de deux méthodes. — *Géographie physique et Quaternaire*, **40** (2) : 185-196.

BENGO, M. & MALEY, J. 1991. Analyse des flux pollinitiques sur la marge sud du Golfe de Guinée, depuis 135 000 ans. — *C.R. Acad. Sci. Paris*, 313, **2** : 843-849.

BERGER, A.L. 1978. Long-term variations of caloric insolation resulting from the Earth's orbital elements. — *Quat. Res.*, **9** : 139-167.

BONNEFILLE, R., CHALIE, F., GUIOT, J. & VINCENS, A. 1992. Quantitative estimates of full glacial temperatures in Equatorial Africa dm palynological data. — *Climate Dynamics*, **6** : 251-257.

BONNEFILLE, R., ROELAND, J. C. & GUIOT, J., 1990. Temperature and rainfall estimates for the past 40,000 years in Equatorial Africa. — *Nature*, **346** : 347-349.

BONNEFILLE, R. & VINCENS, A. 1989. Palynologie africaine. — *Géochronique*, **31**, 3.

BROOK, G. A., BURNEY, D. & COWART, J. 1990. Paleoenvironmental Data for Ituri, Zaïre, from sediments in Matupi Cave, Mt. Hoyo. — *Virginia Mus. Nat. Hist. Memoir*, **1** : 49-70.

CLARK, J. D. & VAN ZINDEREN-BAKKER, E. M. 1962. Pleistocene climates and cultures in North-Eastern Angola. — *Nature*, **196** (4855) : 639-642.

CLARK, J. D. & VAN ZINDEREN-BAKKER, E. M. 1964. Prehistoric cultures and Pleistocene vegetation at the Kalambo Falls, Northern Rhodesia. — *Nature*, **210** : 971-975.

COETZEE, J. & VAN ZINDEREN-BAKKER, E. 1984. Palaeoecology of Africa and the surrounding Islands. — Rotterdam, Balkema, **16**, 170 pp.

COHEN, A. S. 1987. Fossil ostracodes from Lake Mobutu (Lake Albert) : Palaeoecologic and taphonomic implications. — *Palaeoecol. Afr.*, **18** : 271-281.

DRAKE, J. & WIGLEY, T. 1975. The effect of climate on the chemistry of carbonate groundwater. — *Water Resources Res.*, **11** : 958-962.

EK, C. & GEWELT, M. 1988. Les concrétions carbonatées des grottes : aperçu synthétique. — *Ann. Soc. Géol. de Belgique*, **111** : 9-19.

ELENGA, H., SCHWARTZ, D. & VINCENS, A. 1992. Changements climatiques et action anthropique sur le littoral congolais au cours de l'Holocène. — *Bull. Soc. Géol. France*, **163** (1) : 83-90.

ELENGA, H. & VINCENS, A. 1990. Paléoenvironnements quaternaires récents des plateaux Bateke (Congo) : étude palynologique des dépôts de la dépression du bois de Bilanko. — *In* : Paysages quaternaires de l'Afrique centrale atlantique, Orstom, pp. 271-282.

FOLK, R. & ASSERETO, R. 1976. Comparative fabrics of length-slow and length-fast calcite and calcitized aragonite in a holocene speleothem Carlsbad caverns. New Mexico. — *J. sedem. Petrol.*, **46** : 486-496.

FONTES J. C. 1971. Un ensemble destiné à la mesure de l'activité du radiocarbone naturel par scintillation liquide. — *Revue de géographie physique et de géologie dynamique*, **13** (1) : 67-86.

FORD, D. & WILLIAMS, P. 1989. Karst geomorphology. — London, Unwin Hyman Ltd, 601 pp.

GEWELT, M. 1981. Les variations isotopiques du carbone et de l'oxygène dans une stalagmite de la grotte de Remouchamps (Belgique). Méthodes et premiers résultats. — *Ann. Soc. Géol. de Belgique*, **104**.

GEWELT, M. 1983a. Datations ^{14}C de coquilles marines prélevées près de Kuujjuaq (Fort Chimo, Québec). — *Bull. Soc. Géogr. Liège*, **19** : 133-137.

GEWELT, M. 1983b. Nouvelle datation d'une couche de tourbe d'une butte périglaciaire fossile de la Konnerzvenn (Hautes-Fagnes, Belgique). — *Ann. Soc. Géol. de Belgique*, **106** : 331-333.

GEWELT, M. 1985. Cinétique du concrétionnement dans quelques grottes belges : apport des datations ^{14}C et $^{230}Th/^{234}U$. — *Ann. Soc. Géol. de Belgique*, **108** : 267-273.

GIRESSE, P. *et al.* 1984. Les climats et les océans de la région congolaise pendant l'Holocène - Bilans selon les échelles et les méthodes d'observations. — *Paléoecol. Afr.*, **16** : 77-88.

HABERYAN, K. A. & HECKY, R. E. 1987. The late Pleistocene and Holocene stratigraphy and paleolimnology of Lakes Kivu and Tanganyika. — *Paléogéogr., Paléoclimatol., Paléoécol.*, **61** : 169-197.

HAMILTON, A. C. 1982. Environmental History of East Africa. — Academic Press, London, 328 pp.

HARVEY, T. J. 1976. The paleolimnology of Lake Mobutu Sese Seko, Uganda-Zaïre : the last 28,000 years. — Thesis. Duke Univ. Durham, N.C., 104 pp.

HECKY, R. E. 1978. The Kivu-Tanganyka basin : the last 14,000 years. — *Pol. Arch. hydrobiol.*, **25** (1-2) : 159-165.

HILL, C. & FORTI, P. 1986. Cave minerals of the world. — National Speleogical Society, Hunsville, Alabama, U.S.A., 238 pp.

HOOGHIEMSTRA, H. & AGWU, C. O. C. 1988. Changes in the vegetation and trade winds in equatorial northwest Africa 140,000-70,000 yr BP as deduced from two marine pollen records. — *Palaeogeography, Palaeoclimatology, Palaeoecology*, **66** : 173-213.

HURTGEN, C., GEWELT, M. & HOFKENS, K. 1985. A new radiochemical procedure for U-series dating of speleothems. — Paper presented at the Karlsruhe International Conference on Analytical Chemistry in Nuclear Technology (June 3-6, 1985). Abstract + 8 pp.

IVANOVITCH, I. & HAARMON, R. S. (eds.) 1982. Uranium Series Desequilibrium : Applications to Environmental Problems. — Clarendon Press, Oxford, 571 pp.

JAKUCS, L. 1977. Morphogenetics of karst regions. — Adam Hilger, Bristol Ed., 284 pp., 100 figs.

LASESKI, R. A. 1983. Modern pollen data and Holocene climate change in Eastern Africa. — Thesis, Brown University, Providence, R.I.

LEBRUN, J. 1934. Rapport sur un voyage d'études botaniques dans le district du Kibali-Ituri. — *Bull. agron. du Congo belge*, **25** (3) : 386-437.

LEZINE, A. M. & HOOGHIEMSTRA, H. 1990. Land-sea comparisons during the last glacial-interglacial transition : pollen records from West tropical Africa. — *Palaeogeogr., Palaeoclimat., Palaeoecol.*, **79** : 313-331.

LITTMAN, T. 1989. Climate change in Africa during the last glacial : facts and problems. — *Paleoecol. Afr.*, **20** : 163-179.

LIVINGSTONE, D. A. 1962. Age of deglaciation in the Ruwenzori Range, Uganda. — *Nature*, **194** : 859-860.

LIVINGSTONE, D. A. 1967. Postglacial vegetation of the Ruwenzori Mountains in equatorial Africa. — *Ecol. Monogr.*, **37** : 25-52.

LIVINGSTONE, D. A. & CLAYTON, W. D. 1980. An altitudinal cline in tropical African grass floras and its paleoecological significance. — *Quat. Res.*, **13** : 392-402.

MAHANEY, W. 1989. Quaternary glacial geology of Mount Kenya. — *In* : MAHANEY (ed.), Quaternary Environmental Research on East African Mountains, pp. 121-140.

MAHANEY, W. 1990. Cadre stratigraphique, géochronologique et paléoclimatique de la fin du Pléistocène et de l'Holocène dans les régions montagneuses de l'Est africain. — *L'anthropologie*, **94** (2) : 221-228.

MALEY, J. 1989. Palaeoclimatology and palaeometeorology : modern and past patterns of global atmospheric transport. — *Nato asi*, Series C, **282** : 585-614.

MBULUYO, M. & LAVREAU, J. 1989. Apport de la télédétection à la connaissance de grands traits structuraux du Bassin du Haut-Ituri (N-E Zaïre). — Mus. R. Afr. Centr., Tervuren, Dept Géol. Min., Rapp. ann., 1987-1988 :165-172.

MICHEL, R. 1991a. Le massif du Mont-Hoyo (N.E. Zaïre) : karst et paléoenvironnement. — Mémoire de Maîtrise en Géologie des terrains superficiels. Inédit, Univ. Liège, 119 pp.

MICHEL, R. 1991b. Le karst tropical humide. Essai de synthèse. L'exemple du Zaïre. — *Bull. Soc. Géog. Liège*, **27** : 3-22.

MICHEL, R. 1991c. Le massif karstique du Mont-Hoyo (N.E. Zaïre). Hommage au Professeur Alexandre. — *Bull. Soc. Géog. Liège*, **27** : 23-28.

MICHEL, R. 1991d. Les grottes du Mont-Hoyo (N.E. du Zaïre). Un paléoenvironnement karstique de plus de 150 000 ans. — *Geo-Eco-Trop*, **15** (1-2) : 59 pp.

MICHEL, R. & POTY, E. 1974. Plan de la grotte Matupi (N-E Zaïre). — Univ. Liège (inédit).

MOEYERSONS, J. & ROCHE, E. 1982. Past and present environments. — *In* :

VAN NOTEN, F. (ed.), The Archaeology of Central Africa. Graz. Akademische Druck- und Verlagsanstalt, 26 pp.

OLLIER, C. D. & HARROP, J. F. 1963. The caves of Mount Hoyo, Eastern Congo Republic. — *Nat. Speleolog. Sci. Bull.*, **25** (2) : 73-78.

POKRAS, E. & MIX, A. 1985. Eolian evidence for spatial variability of late Quaternary climates in tropical Africa. — *Quaternary Research*, **24** : 137-149.

POKRAS, E. *et al.* 1987. Earth 81's precession cycle and Quaternary climatic in tropical Africa. — *Nature*, **326** (6112) : 486-487.

PREUSS, J. 1990. L'évolution des paysages du bassin intérieur du Zaïre pendant les quarante derniers millénaires. — *In* : LANFRANCHI, R. & SCHWARTZ, D. (éds), Paysages quaternaires de l'Afrique centrale et atlantique. Orstom, pp. 260-271.

ROBERT, C. & KENNETT, J. P. 1992. Paleocene and Eocene kaolinite distribution in the South atlantic and Southern Ocean : Antarctic climatic and paleoceanographic implications. — *Marine Geology*, **103** : 99-110.

ROBERTS, N., TAIEB, M., BARKER, P. R., DAMNATI, B. & ICOLE, M. 1993. Timing of Younger Dryas event in East Africa from lake level changes. — *Nature*, **366** (6451) : 146-148.

ROCHE, E. 1985. Analyse palynologique de quatre sondages effectués dans les dépôts de surface quaternaires au Rwanda. Interpréation paléoclimatique. — *Mus. R. Afr. Centr., Dpt Géol. Min., Rapport annuel,* **83-84** : 153-159.

ROCHE, E. 1991. Evolution des paléoenvironnements en Afrique centrale et orientale au Pléistocène supérieur et à l'Holocène. Influences climatiques et anthropiques. Une synthèse. — *Bull. Soc. Géog. Liège*, **27** : 187-208.

ROELAND, J. C. 1991. Méthode de reconstitution paléoclimatique en Afrique centrale. Application à la séquence pollinique de Kashiru, Burundi. — *Palynosciences*, **1** : 187-198.

ROQUES, H. 1995. Réflexions sur le calcul des équilibres calco-carboniques. — *Tribune de l'eau*, **575** (3) : 43-50.

RUNGE, J. 1995. New results on Late Quaternary landscape and vegetation dynamics in eastern Zaire (Central Africa). — *Z. Geomorph.*, N.F., suppl., **99** : 65-74.

RUSCART, D. 1951. Les homas du Mont-Hoyo. — Ministère des Colonies, 66 pp.

SCHOELLER, H. 1962. Les eaux souterraines. — Masson & Cie, Paris, 642 pp.

SINGER, A. 1980. The paleoclimatic interpretation of clay minerals in soils and weathering profiles. — *Earth Sci. Rev.*, **15** : 303-326.

SOWUNMI, M. A. 1991. Late Quaternary environments in Equatorial Africa. Palynological evidence. — *Palaeoecol. Afr.*, **22** : 213-238.

SSEMMANDA, I. & VINCENS, A. 1993. Végétation et climat dans le bassin

du lac Albert (Ouganda, Zaïre) depuis 13 000 ans : apport de la palynologie. — *C.R. Acad. Sci. Paris*, **316** : 561-567.

STOFFERS, P. & SINGER, A. 1979. Clay minerals in Lake Mobutu Sese Seko (Lake Albert), their diagenetic changes as an indicator of the paleoclimate. — *Geol. Rundsch.*, **68** : 1009-1024.

STUIVER, M. & POLACH, A. 1977. Discussion reporting of ^{14}C data. — *Radiocarbon*, **19** (3) : 355-363.

TAIEB, M., BARKER, P., BONNEFILLE, R., DAMUATI, B., GASSE, F., GOETZ, C., HILLAIRE-MARCEL, C., ICOLE, M., MASSAULT, M., ROBERTZ, N., VINCENS, A. & WILLIAMSON, D. 1991. Histoire paléohydrologique du lac Magadi (Kenya) au Pléistocène supérieur. — *C.R. Acad. Sc. Paris*, **313** (2) : 339-346.

THOREZ, J. 1976. Practical Identification of Clay Minerals. — Lelotte, Dison, Belgique, 90 pp.

THOREZ, J. 1985. Qualitative clay mineral analyses biased by sample treatments. — 5th European Clay Group Meeting, Prague 1983, pp. 383-389.

VAN NEER, W. 1984. Faunal remains from Matupi cave, an iron age and late stone age site in Northeastern Zaïre. — *Meded. K. Acad. Wet. Lett. Schone Kunst. Belg.*, Kl. Wet., **46** (2) : 57-76.

VAN NEER, W. 1990. Les faunes de vertébrés quaternaires en Afrique centrale. — *In* : LANFRANCHI, R. & SCHWARTZ, D. (éds), Paysages quaternaires de l'Afrique centrale atlantique, Orstom, pp. 195-212.

VAN NOTEN, F. 1977. Excavations at Matupi cave. — *Antiquity*, **61** : 33-40.

VAN NOTEN, F. 1982. The Stone Age in the North and East. — *In* : The Archaeology of Central Africa, Graz, pp. 27-40.

VAN ZINDEREN BAKKER, E. M. 1974. Tentative vegetation maps of Africa south of the Sahara during a glacial and an interglacial maximum. — *Palaeoecol. Afr.*, **9** (IV).

VAN ZINDEREN BAKKER, E. M. 1982. African paleoenvironments 18,000 B.P. — *Palaeoecol. Afr.*, **15** : 77-99.

VERBEEK, T. 1970. Géologie et lithologie du Lindien (Précambrien supérieur au nord de la République démocratique du Congo). — *Ann. Mus. R. Afr. Centr.*, **70** : 309 pp.

VINCENS, A. 1989. Early Holocene pollen data from an arid East African region, Lake Turkana (Kenya) : botanical and climatic implications. — *Palaeoecol. Afr.*, **20** : 87-97.

VINCENS, A. 1989. Paléoenvironnement du bassin du nord Tanganyika (Zaïre, Burundi, Tanzanie) au cours des 13 derniers mille ans : rapport de la palynologie. — *Review of Palaeobotany and Palynology*, **61** : 69-88.

VINCENS, A., BONNEFILLE, R. & BUCHET, G. 1991. Etude palynologique du sondage Magadi NF1 (Kenya). Implications paléoclimatiques. — *Geobios*, **24** (5) : 59-558.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 86-102 (1998)

Absence of Arid Conditions at Shum Laka Rock Shelter (Bamenda-Western Cameroon) since 30,000 yr B.P.

by

Jan MOEYERSONS *

KEYWORDS. — Cameroon ; Erosion Susceptibility Index ; Geomorphology ; Palaeoclimate ; Rock Shelter.

ABSTRACT. — It is generally accepted that the southern border of the Sahara shifted far to the south during the last glacial maximum in Europe. However, at Shum Laka rock shelter (Western Cameroon), geomorphological and palaeobotanical evidence confirms the absence of arid conditions between 30,000 and 12,000 yr B.P. Instead, this mountainous area (1,650-2,000 m ASL) carried an open mountain forest, with galleries along the water courses and grassy patches on the interfluves. Temperature did not fall significantly below freezing point. Annual precipitation values were not very different from today : they lowered slightly after 20,000 yr B.P. and have risen again since about 13,000 yr B.P. The absence of arid conditions during this period might be explained by the localization of the site on a south-westward looking 800 m high escarpment zone.

MOTS-CLES. — Cameroun ; Index de susceptibilité à l'érosion ; Géomorphologie ; Paléoclimat ; Abris sous roche.

RESUME. — *Absence de conditions arides à l'abri sous roche de Shum Laka (Bamenda-Ouest-Cameroun) depuis 30 000 ans B.P.* — On sait que la bordure méridionale du Sahara se déplaça considérablement vers le sud pendant la dernière glaciation en Europe. Mais autour de l'abri sous roche de Shum Laka (Cameroun occidental), l'évidence géomorphologique et paléobotanique indique une absence totale de conditions désertiques entre 30 000 et 12 000 ans B.P. Cette région montagneuse (1 650-2 000 m d'altitude) connaissait une

* Royal Museum of Central Africa, Leuvensesteenweg 13, B-3080 Tervuren (Belgium).

forêt de montagne ouverte, des forêts de galeries et des ouvertures herbeuses sur les interfluves. La température restait essentiellement au-dessus du point de congélation. Le taux de précipitation annuel était semblable à celui d'aujourd'hui, avec une légère baisse après 20 000 ans B.P. et une remontée à partir de 13 000 ans B.P. L'absence de conditions arides s'explique peut-être par la localisation du site sur un escarpement, haut de 800 m, exposé au sud-ouest.

TREFWOORDEN. — Kameroen ; Erosiegevoeligheidsindex ; Geomorfologie ; Paleoklimaat ; Grot.

SAMENVATTING. — *Afwezigheid van aride condities in de Shum Laka grotschuilplaats (Bamenda-West-Kameroen) sinds 30 000 jaar B.P.* — Het is bekend dat de zuidrand van de Sahara zich ver naar het zuiden verplaatst heeft tijdens de laatste ijstijd in Europa. Nochtans zijn er geomorfologische en paleobotanische aanduidingen dat rond de grot van Shum Laka (West-Kameroen) geen perioden van grote droogte zijn voorgekomen tussen 30 000 en 12 000 jaar B.P. Dit bergachtig gebied (1 650-2 000 m hoogte) kende een open bergwoud met galerijwouden en open plaatsen met gras op de interfluvia. De temperatuur kwam nauwelijks onder het vriespunt. De jaarlijkse neerslag benaderde die van vandaag met een lichte daling sinds 20 000 jaar B.P. en opnieuw een stijging vanaf 13 000 jaar B.P. De lokalisatie van de site, op een 800 m hoge steilrandzone die naar het zuidwesten gekeerd staat, is een mogelijke verklaring voor de afwezigheid van droge levensomstandigheden daar.

1. Introduction

It is quite well established that during the last glacial maximum in Europe, the southern border of the Afro-Asian deserts shifted considerably southwards (PETIT-MAIRE *et al.* 1995). As far as Africa is concerned, the southern border of the Sahara was about 500 km to the south of its present position (PETIT-MAIRE 1993). As a matter of fact, the whole West African subcontinent seems to have been much drier than today (SERVANT & SERVANT-VILDARY 1980) and even in the tropical African lowlands, annual precipitation fell by 59 % - 79 % of the present-day level (SHINODA 1994). Studies (TALBOT *et al.* 1984) showed that the moist tropical rain forest did not survive in Ghana at less than 150 km from the coast. In fact, whole tropical Africa, from the southern Sahara to the Zaire basin and from the Atlantic Ocean coast to the Indian Ocean coast, suffered from drastic aridity (KADOMORA 1986). However, some isolated areas are believed to have remained rather humid during this general aridification phase. MALEY

(1989) cited two forest refugia in Western Africa for the period around 18,000 yr B.P. : the Loma interfluve area and the southern part of the West Cameroonian volcanic line. The latter indication resulted from his study at Barombi Mbo (GIRESSE *et al.* 1994) : in this site, at 301 m ASL and about 55 km from the coast, the rain forest persisted during the period considered.

This article aims to add new palaeoenvironmental and palaeoclimatic evidence from Shum Laka rock shelter for the period contemporaneous with the last glaciation period in Europe.

2. General Information about Shum Laka Rock Shelter

Shum Laka rock shelter is a 20 m deep and 50 m wide perched cliff recession, at 5°51'37" N and 10°04'44" E, located ca. 15 km to the SE of Bamenda (fig. 1). Like Barombi Mbo Lake, the site lies on the Cameroonian volcanic line, but 1,650 m ASL and more than 200 km inland. Archaeological excavations in the Shum Laka rock shelter (DE MARET *et al.* 1987) entrance revealed the existence of a more than 3 m thick infill, dated by ^{14}C between ca. 31,000 yr B.P. and the present. Such a long and continuous sequence is rather exceptional in Western Africa. The presence of archaeological remains throughout the whole sequence makes the site still more attractive.

Stratigraphy, geology and geomorphology of the shelter were studied by MOEYERSONS (1996). The shelter looks over the bottom of the Bafochu Mbu Caldera, drained by the Matongwe river. The Laka, a tributary of the latter, falls from the cliff and forms a small waterfall in front of the shelter. The upper 20 m of the cliff consist of rather massive, fissured and partly weathered welded tuffs, belonging to the middle volcanic series, described by GEZE (1943). At about 1 m above the actual shelter floor, the top of a much more weathered volcanic breccia appears.

The deposits at the entrance of the shelter are more than 3 m thick and comprise, from old to young, the following layers : P-deposits, S-deposits and T-deposits (fig. 2). A thin superficial layer is in the stage of development today and covers the other stratigraphical members. A high number of ^{14}C dates document this sequence and some of these dates come from the section shown (fig. 2). It appears that the so-called S-deposits are dated between 31,700 ± 750 yr B.P. and about 11,000 yr B.P. Thus the S-deposits cover the period of the last glacial maximum in Europe.



Fig. 1. — Localization map of Shum Laka rock shelter with approximate position of isohyetes.

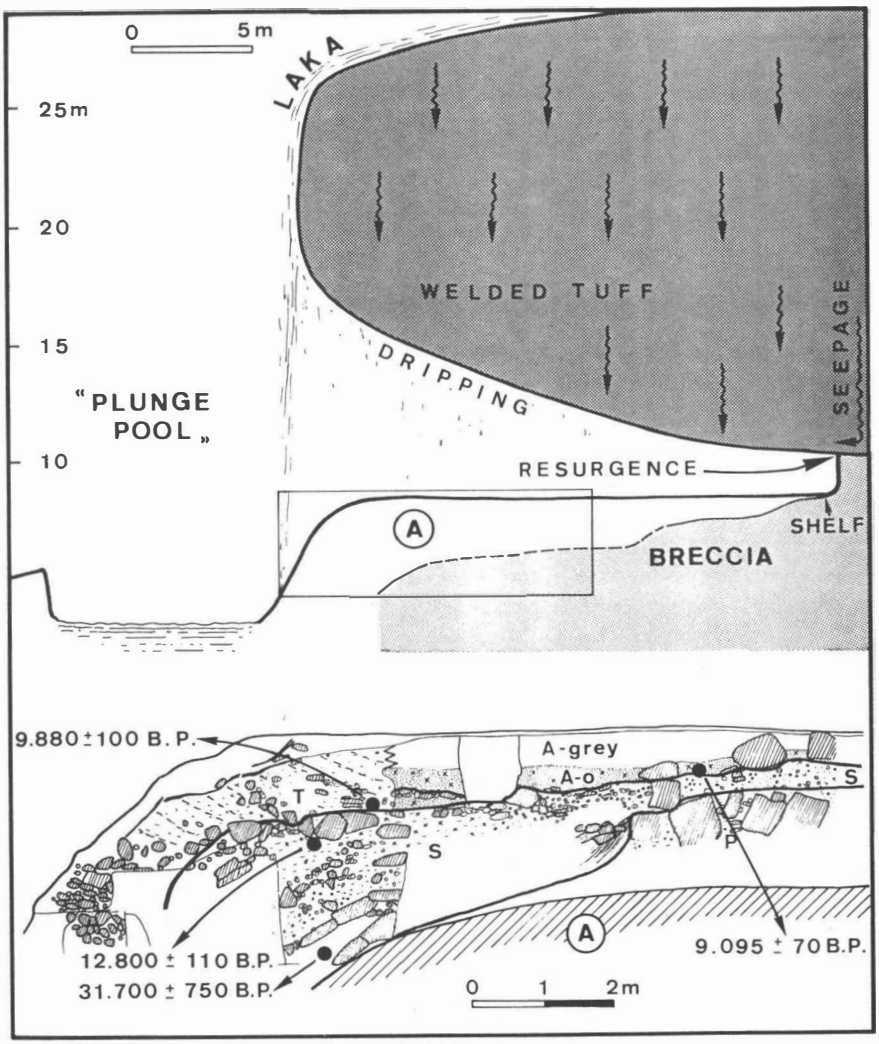


Fig. 2. — Geology and stratigraphy of Shum Laka rock shelter.

3. Nature of the S-deposits

3.1. Origin of the Sand-loam Fraction below 0.002 m

The S-deposits are the oldest dated sediments at the entrance of the shelter. They are about 2 m thick and fill an ancient depression, probably an old plunge pool, scoured out in the bedrock and part of the P-deposits and extending several meters deep into the shelter. They form a complex of sand-loam material, intermingled with rock debris of very variable size, ranging from 0.002 m to 2 m. The latter are considered as rockfall from the roof of the shelter.

The sand-loam material shows lamination structures over the whole depth of the complex. Running water has clearly played a role in its deposition. However, the competence of the water flow seems to have been rather low and probably was more characteristic for run-off than for river flow. This can be deduced from the fact that the dipping of the long axis of rockfall fragments most closely corresponds to the dipping of laminae in the fines : rock fragments, longer than 3 cm, have never been displaced by water currents after their fall and, therefore, never show an imbrication structure.

The sand-loam matrix of the S-deposits shows clear affinities with the superficial layer, mentioned above to be in the stage of development. The latter is transported and finally deposited in the lower part of the shelter by run-off with a double origin. Firstly, water from the Laka valley above the shelter seeps along fissures and joints through the welded tuffs and resurges on top of the breccia in the south-eastern and part of the eastern shelter wall (fig. 2). Desquamation and detachment of small rock flakes seem to be especially active in this resurgence belt and is a factor of shelter widening (fig. 3) and a source for fine sediments. Secondly, run-on from the south-eastern part of the entrance (fig. 4) joins the resurgence water and provides fine material from outside the shelter. Both flows feed the actual run-off trajectories in the shelter along which sediments are conveyed.

Wide and shallow run-off channels in the fines of the S-deposits at the shelter entrance suggest a pattern of conveyor paths (fig. 4), comparable with the actual one, described above. The much stronger curvature of the conveyor paths in the S-deposits confirms the idea (Moeyersons 1996) that, somewhat later than 30,000 yr B.P., the shelter was about 10 m less wide than today. The estimated localization of the south-eastern wall around 30,000 yr B.P. is indicated (fig. 4).

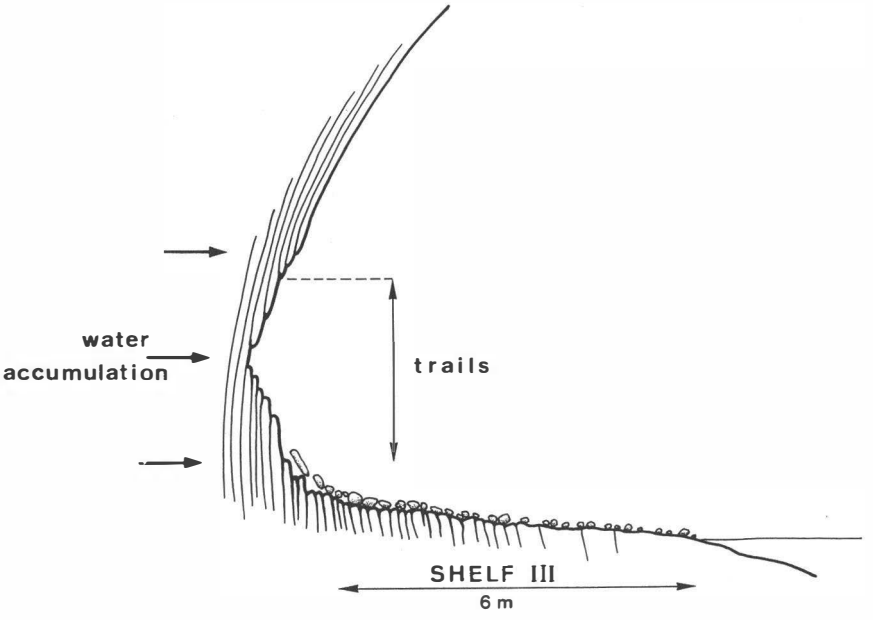


Fig. 3. — Flaking and the resultant wall retreat and shelf development as occurring along the south-eastern wall of Shum Laka rock shelter (MOEYERSONS 1996). Trails are black coatings on the wall due to water films of resurgence water.

3.2. ROCKFALL AND "STONE-LINES"

Abundant presence of rockfall is typical for the late Pleistocene S-deposits. On the contrary, rockfall in primary stratigraphical context is rare in the overlying sediments. Because post-rockfall reworking of the rock debris seems unimportant in the S-deposits, the numerous discontinuous "stone-lines" should represent temporary accumulation surfaces within the S-infill. This enabled us to recognize more easily the different phases of their deposition. Two units can be distinguished.

The lower one shows vertical accretion, the basal and two lower stone-line complexes reflecting more or less the form of the bottom of the ancient plunge pool.

The upper unit is characterized by a summital stone-line, dipping to the outside of the shelter at 5 to 10°. Two secondary stone-lines start from this summital level and plunge steeply to the shelter outlet at an angle of 30 to 35° ! This picture is reminiscent of deltaic deposits with a top set bed layer, covering a member of foreset beds. The two

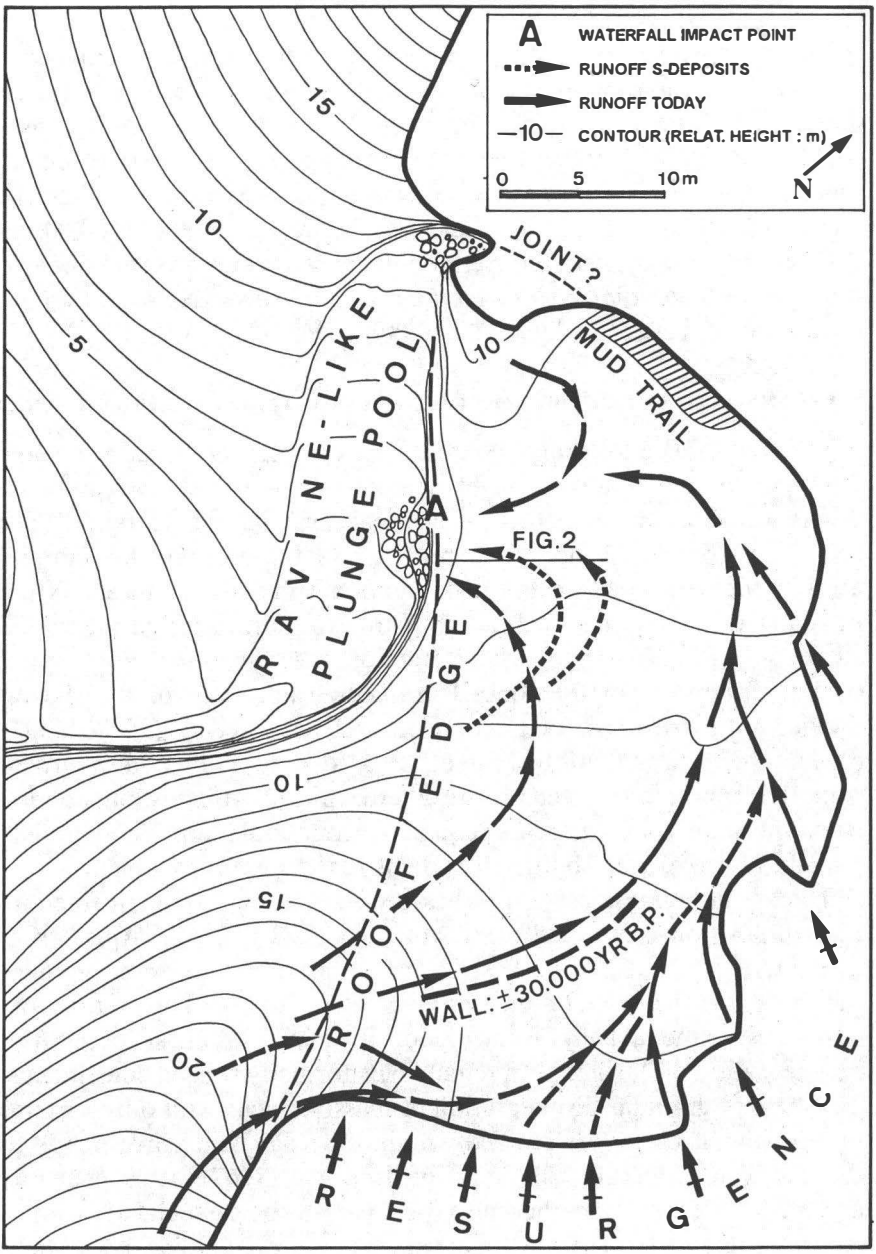


Fig. 4. — Topographical map of Shum Laka rock shelter with the localization of resurgence water, run-on, actual conveyor paths and conveyor paths during the S-deposits period.

steeply inclined stone-lines in these so-called "foresets" should represent rather short events, while the summital stone-line might be polygenic.

This change in dynamics from vertical to lateral accretion has been dated by interpolation at ca. 20,000 yr B.P. A clear relation between rockfall intensity and the system of infill appears to exist. Rockfall, especially active during vertical accretion, occurred shortly after the incision of the old plunge pool and also between 30,000 and 20,000 yr B.P. During the subsequent period of lateral accretion, rockfall was much more sporadic, but an increase can be observed near the end of the period, between 12,000 and 10,000 yr B.P.

3.3. Textural and Morphoscopic Characteristics of the Fines

The textural and morphoscopic analysis of the fraction below 2,000 μm of a column of eight samples does not show significant differences between the belt of vertical and lateral accretion, nor between "stone-lines" and finer portions in the section. All samples are bimodal and badly calibrated. Bimodality results from a mixture of coarse sand or gravel with a population of grains around the modal value of ± 16 μm. In the sand fraction (2,000-63 μm), all samples contain fragments of the rocks from ceiling and roof of the shelter. Welded tuffs are hummocky rounded and hollowed out, reflecting a certain chemical alteration. Present are also some individual quartzes, some feldspar crystals and a rare altered mica, probably phenocrists from the cave rock. Allochtoneous elements could not be identified. An admixture of wind-blown material is therefore improbable.

The silt population (63-2 μm) has been tested in the 32 μm fraction. Its composition is very different from the sand fraction. Apart from a few quartz grains, some felspar and a sanidine and some pumice, the bulk of the population contains glass shards and saccharoid structures, cimented by iron oxide. In fact, we assist here at a desintegration of the ignimbritic rock in its formerly welded constituents. This type of granular disintegration of massive rocks with only a minor production of clays was studied a long time ago and corresponds to the sandy deep weathering type of Bakker (1967). It is generally accepted that this weathering type has to be associated with a subtropical climate, whereby the circulation of iron colloids in the rocks is responsible for their desquamation along shells and their further breakdown in their granular constituents (Schnütgen & Späth 1983, Schnütgen 1992).

4. Environmental Evidence from the S-Deposits

4.1. Evidence from the Fines and the Botanical Remains

In spite of the total absence of pollen, the fines and their inclusions of botanical remains contain a lot of environmental information for the period between ± 31,000 yr B.P. and ± 11,000 yr B.P.

As mentioned above, the composition of fines below 63 µm might indicate subtropical weathering conditions.

Further, the fines in the S-deposits have been transported by run-off. Part of this runoff came from outside the shelter. Of course, run-off is not a clear climate indicator : the process occurs in deserts as well as in tropical regions. However, it points to the incomplete soil protective nature of the vegetation of that time and/or the existence of open ground patches.

On the other hand, the presence of vegetation is attested by the high organic content (to over 8 % of the total weight), mostly of vegetational nature, of the fines.

Moreover, charcoal pieces are scattered throughout the entire sequence. Amazingly enough, the numerous determinations could not reveal the presence of much woody plants other than *Protea mad. sp.* The ecological conditions of this species (Beard 1992), imported or left behind either by man or by natural processes, confirm the idea that the surroundings of the site during all that time neither were really dry like a desert, nor extremely hot and wet like a tropical forest and that temperatures never dropped significantly below zero for periods of several days.

A few charcoal remains of *Kigelia cfr. africana*, *Drypetes sp.*, *Triumphetta sp.* and *Hypericum sp.* point to a montane forest with open patches and gallery forest. As a matter of fact, the species found in the charcoal also occur still today in the study area.

4.2. Indirect Evidence from the Rockfall

Rockfall in the shelter might have some palaeoenvironmental significance. Two hypotheses concerning its origin are to be excluded.

The first hypothesis, namely that rockfall might result from frost action, has to be rejected on the following grounds : firstly, frost wedges or cryoturbation structures are apparently absent in the deposits ; secondly, *Protea mad. sp.* seems unlikely to support numerous important temperature drops below 0 °C.

The second hypothesis was that earthquakes might have induced rockfall during the S-period. But also this hypothesis cannot be withheld : according to information from the local habitants, the region actually undergoes rather heavy earthquakes at regular times, accompanied by the fall and cascade of rocky debris from steep slopes. But inside the shelter, no traces of important rockfall are visible in the stratigraphic layers for the period of the last 9,000 years. Moreover, the actual morphology of the shelter roof does not display any clear negatives of the numerous big boulders and massive exfoliation plates, sometimes more than 0.5 m thick, and so abundantly present in the S-deposits. Instead, roof and walls are smoothened and garned by a weathering zone, in some places at least 50 cm thick, consisting of bundles of 1 mm to more than 1 cm thick lamellae and shells. Massive rock detachment from the roof seems to be an old phenomenon, not occurring any more for a long time.

It seems therefore appropriate to attribute rockfall during the S-period to specific seepage regimes of water through the shelter roof, a combination of hydrolytic weathering and hydrostatic pressure contributing to the opening of existing joints and the breakdown of the edges of massive exfoliation slabs. The occurrence of seepage during the periods of rockfall is further attested by pitting (WATSON & PYE 1985) of the upper faces of rock debris and boulders. The phenomenon is visible on buried as well as free rock surfaces. This confirms that many blocks are still in their original position, acquired immediately after their fall, and that the deposits were not laid down under water.

It has been mentioned above that rockfall is not evenly spread in time during the S-deposits : there is a slow-down in the rate of rockfall production between ±20,000 yr B.P. and ±13,000 yr B.P. This is a possible indication for a decrease in seepage, reflecting somewhat drier conditions in the Laka valley above the shelter.

4.3. ESTIMATION OF SEEPAGE RATE BY APPLICATION OF THE ES-MODEL

The model of erosional susceptibility, Es, elaborated by DE PLOEY (1990), allows an estimation of seepage discharges during the S-deposits period. As far as seepage discharge might be related to precipitation, an exercise to compare past with actual discharge rates might be useful. Detailed information about the application of the Es model can be found in DE PLOEY (1990) and DE PLOEY *et al.* (1995).

The basic idea behind the application of the Es model at Shum Laka is that the during S-deposits period, the south-eastern wall receded

about 4 m (MOEYERSONS 1996) : water, seeping out of this wall, contributed to the evacuation of rock, accumulating in front of this wall in the form of disintegrated fine earths. So, the erosion process involved consists of rill and interrill erosion, provoked by resurgence water along the wall with splash effect during the extreme events. For rill and interrill erosion, the erosional susceptibility is of the order of 10^{-3} s^2/m^2 and is given by the equation (DE PLOEY *et al.* 1995) :

$$Es = V/A.P.g.h \qquad (1)$$

Where :

Es = the erosional susceptibility, 10^{-3} s^2/m^2.

V = total volume (m^3) eroded within a surface area A. As the wall is about 20 m long, about 5 m high and receded over about 4 m, the eroded volume is of the order of 400 m^3.

A = the planimetric size (m^2) of the considered area, representing a hydrological unit. It consists here of a belt, maybe 1 m wide and as long as the wall.

P = the total volume of water, precipitated per m^2 during the period considered. In the case worked out here, it concerns resurgence water per m^2 of an unknown volume. The product A.P represents the total volume of water which resurged along the south-eastern wall during a period of 20,000 years.

g = the gravitational acceleration, 10 m/s^2.

h = the elevation head loss in m, here represented by the rill depth, which has been estimated at 0.1 m.

Introducing these values in (1) gives :

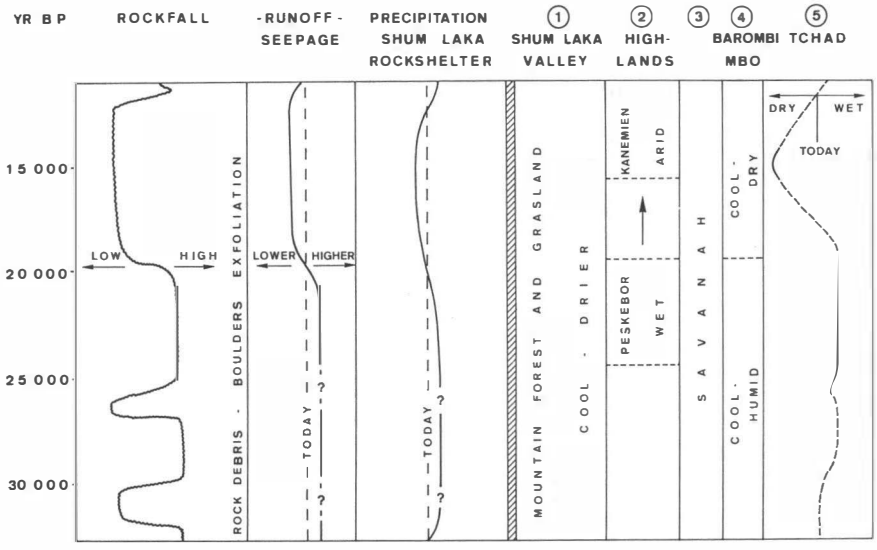
$$A.P\ (20{,}000\ \text{years}) = \frac{400\ m^3}{10^{-3}\ s^2/m^2 . 10\ m/s^2 . 10^{-1}\ m} \qquad (2)$$

A.P (annual) = 20 m^3 resurgence water.

According to our measurements and estimations during the dry season in 1991/1992 and 1994, annual seepage along the south-eastern wall should be of the order of something more than 18 m^3. The good agreement of this result with (2) leads to the conclusion that throughflow through the roof of the shelter between 30,000 and 10,000 yr B.P. did not differ very much from now. Again, we are confronted with late Pleistocene conditions, this time conditions of infiltration, much alike those of today (table 1).

Table 1

Geomorphological processes and their palaeoenvironmental significance at Shum Laka Rock shelter. Period between 30,000 and ± 11,000 yr B.P. Comparison with : 1 : KADOMURA & KIYONAGA (1994) ; 2 : MORIN (1989) ; 3 : HORI (1984) ; 4 : GIRESSE *et al.* (1994) ; 5 : SERVANT & SERVANT-VILDARY (1980)



5. Discussion

Information from sedimentological, geomorphological, stratigraphical and botanical nature leads to the conclusion that the area in the vicinity of Shum Laka rock shelter enjoyed climatic and environmental conditions which were not so different from those from today. Although a lowering of precipitation can be observed between ± 20,000 yr B.P. and 13,000 yr B.P., the area never suffered from long-lasting aridity, even not during this period. A number of questions arise from this conclusion.

5.1. REPRESENTATIVITY OF THE RESULTS

First of all, there is the question about the representativity of the data from Shum Laka. Figure 1 shows that the study area comprises two physiographic entities. South-west of Bamenda, in the north-western part of the map, lies the Bali-Bamenda plain (± 1,200 m ASL).

The south-eastern corner of the area is occupied by the Bamenda highlands (± 2,000 m ASL, but slowly dipping in eastward direction). Both physiographical regions are separated by a double escarpment, embracing an intermediate level at ± 1,650 m ASL. Part of the Laka basin, upstream from the shelter, drains about 2 km² of this intermediate level. Variations in seepage and other changes in the cave would, therefore, reflect in some way the situation on this topographic level. On the precipitation map of the area (CHAMPEAUD 1973), the south-south-west oriented double escarpment belt receives in the south about the same annual precipitation (2,000-2,500 mm) as in the north (fig. 1). It is plausible that this constancy from south to north, well known to occur along the whole western escarpment zone of the Bamboutos (MORIN 1988), has always existed on the intermediate level, even in climatic contexts, differing from those from today. Therefore, it is thought that the climatic environmental data from Shum Laka are essentially representative for this belt at ± 1,650 m ASL along the western border of the massif.

5.2. THE SIGNIFICANCE OF THE RESULTS

Environmental conditions on the western border are clearly not univocal indicators for the environmental conditions in the adjoining Bamenda-Bali plain and Bamenda highlands. As the rains on the escarpment are highly orographic in nature (MORIN 1988), precipitation there might remain the same or might decrease only slightly, while plain and/or highlands become considerably drier. In fact, the small decrease in precipitation at Shum Laka coincides with the period, believed to be the driest part of the last big aridification period in the surrounding areas and Western Africa (KADOMURA & KIYONAGA 1994, MORIN 1989, HORI 1984, GIRESSE *et al.* 1994, SERVANT & SERVANT-VILDARY 1980). Table 1 illustrates this convergent view. The only thing we know for sure is that during that period mountain forest survived on the escarpment at 1,650 m ASL. The results from Shum Laka rock shelter confirm and refine the palynological information, gathered from the Matongwe valley, 2 km downstream of Shum Laka and about 300 m below the rock shelter (KADOMURA & KIYONAGA 1994). The combined results of both studies indicate that at least the western escarpment border of the volcanic line, south of Bamenda, is a valuable candidate as a mountain forest refuge area during aridity which occurred in Western Africa during the last glacial maximum

in Europe. During the same period, the lowland rain forest survived on the lake Barombi Mbo shores (MALEY 1991). It seems, therefore, that on the Cameroon line refuge a geographical and altitudinal botanical spreading existed.

ACKNOWLEDGEMENTS

This study is part of an archaeological research project at Shum Laka (Bamenda-Western Cameroon), in collaboration with the University of Yaoundé (Cameroon), the "Université Libre de Bruxelles" (Belgium) and the Royal Museum of Central Africa of Tervuren (Belgium). The project was financed by these institutions and by funds from the "Loterie Nationale" (Belgium), the "Fonds National de la Recherche Scientifique" (Belgium), the "Nationaal Fonds voor Wetenschappelijk Onderzoek" (Belgium) and the L.S.B. Leakey Foundation (U.S.A.). Determinations of floristic and faunal macro-remains have been done by H. Doutrelepont and W. Van Neer. We thank J. Maley and P. Giresse for fruitful discussions in the field and J. Maley for his inspection of soil samples on pollen. Further aid provided by H. Beeckman. Drawings by Y. Paquay.

REFERENCES

BAKKER, J. P. 1967. Weathering of granites in different climates, particularly in Europe. — Les Congrès et Colloques de l'Université de Liège, **40** (L'évolution des versants) : 51-68.

BEARD, J. S. 1992. The *Proteas* of Tropical Africa. — Kangaroo Press, Hong Kong, book 144, 112 pp.

CHAMPAUD, J. 1973. Atlas régional Ouest 2 de la République unie du Cameroun. Milieu physique : précipitations. — O.R.S.T.O.M., Centre de Yaoundé.

DE MARET, P., CLIST, B. & VAN NEER, W. 1987. Résultats des premières fouilles dans les abris de Shum Laka et d'Abéké au nord-ouest du Cameroun. — *L'Anthropologie*, **91** : 559-584.

DE PLOEY, J. 1990. Modelling the erosional susceptibility of catchments in terms of energy. — *Catena*, **17** : 175-183.

DE PLOEY, J. (†), MOEYERSONS, J. & GOOSSENS, D. 1995. The De Ploey erosional susceptibility model for catchments, Es. — *Catena*, **25** : 269-314.

GEZE, B. 1943. Géographie physique et géologie du Cameroun occidental. — *Mém. Inst. Hist. Nat.*, Paris, **17** : 273 pp.

GIRESSE, P., MALEY, J. & BRENAC, P. 1994. Late Quaternary palaeoenvironments in the Lake Barombi Mbo (West Cameroon) deduced from

pollen and carbon isotopes of organic matter. — *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107** : 65-78.

HORI, N. 1984. Formation and chronology of superficial deposits in the forested Southern Cameroon. — *In* : KADOMURA, H. (ed.), Geomorphology and environmental changes in the forest and savannah Cameroon. Preliminary report of the tropical African geomorphology and late Quaternary palaeoenvironments research project 980/1981, Sapporo, Japan, pp. 13-27.

KADOMURA, H. 1986. Late Glacial - early Holocene environmental changes in tropical Africa : a comparative analysis with deglaciation history. — Geographical Reports of Tokyo Metropolitan University, **21** : 1-21.

KADOMURA, H. & KIYONAGA, J. 1994. Origin of grassfields landscapes in the West Cameroon highlands. — *In* : KADOMURA, H. (ed.), Savannisation processes in tropical Africa, II. Dept. Geogr. Tokyo Metropol. Univ., Tokyo, pp. 47-85.

MALEY, J. 1989. Late quaternary climatic changes in the African rain forest : forest refugia and the major role of sea surface temperature variations. — *In* : LEINEN, M. & SARNTHEIM, M. (eds.), Paleoclimatology and paleometeorology : modern and past patterns of global atmospheric transport. NATO ASI, Series C : Mathematical and Physical Sciences, **282** : 585-616.

MALEY, J. 1991. The African rain forest vegetation and palaeoenvironments during late Quaternary. — *Climatic Change*, **19** : 79-98.

MOEYERSONS, J. 1996. Rock shelter collapse as a possible reason for waterfall retreat in the Bafochu Mbu caldeira, Western Cameroon. — *Z. Geomorph.*, N.F. (Suppl.-Bd.), **103** : 354-358.

MORIN, S. 1988. Les dissymétries fondamentales des Hautes Terres de l'Ouest-Cameroun, l'exemple des monts Bambouto. — L'Homme et la montagne tropicale, SEPANRIT, Bordeaux, pp. 35-56

MORIN, S. 1989. Hautes terres et bassins de l'Ouest-Cameroun. Etude géomorphologique. — Thèse doct. Etat, Univ. Bordeaux III : 2 tomes, 1190 pp., 1 atlas, 17 cartes h.t.

PETIT-MAIRE, N. 1993. Past global climatic changes and the tropical arid/semi-arid belt in the north of Africa. — *In* : THORNWEIHE & SCHANDELMEIER (eds.), Geoscientific Research in North-East Africa, Balkema, Rotterdam, pp. 551-560.

PETIT-MAIRE, N., SANLAVILLE, P. & ZHONGWEI, Y. 1995. Oscillations de la limite nord du domaine des moussons africaine, indienne et asiatique, au cours du dernier cycle climatique. — *Bull. Soc. Géol. France*, **166** (2) : 213-220.

SCHNUETGEN, A. 1992. Spheroidal weathering, granular disintegration and loamification of compact rock under different climatic conditions. — *Z. Geomorph.*, N.F. (Suppl.-Bd.), **91** : 79-94.

SCHNUETGEN, A. & SPAETH, H. 1983. Mikromorphologische Sprengung von Quarzkörnern durch Eisenverbindungen in tropischen Böden. — *Z. Geomorph.*, N.F. (Suppl.-Bd.), **48** : 17-34.

SERVANT, M. & SERVANT-VILDARY, S. 1980. L'environnement Quaternaire du bassin du Tchad. — *In* : WILLIAMS, A. J. & FAURES, H. (eds.), The Sahara and the Nile, Balkema, Rotterdam, pp. 133-162.

SHINODA, M. 1994. Annual precipitation estimates over tropical Africa for 18,000 yr B.P. — *In* : KADOMURA, H. (ed.), Savannization processes in tropical Africa II. Dept. Geogr. Tokyo Metropol. Univ., Tokyo, pp. 229-247.

TALBOT, M. R., LIVINGSTONE, D. A., PALMER, P. G., MALEY, J., MELACK, J. M., DELIBRIAS, G. & GULLIKSEN, S. 1984. Preliminary results from sediment cores from Lake Bosumtwi, Ghana. — *Palaeoecology of Africa*, **16** : 173-192.

WATSON, A. & PYE, K. 1985. Pseudokarstic microrelief and other weathering features on the Mswati granite (Swaziland). — *Z. Geomorph.*, N.F., **29** : 285-300.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 103-107 (1998)

Climate as Reflected in Rock Art. Example from Central Saharan Fezzan

by

Jan JELÍNEK *

KEYWORDS. — Climate ; Rock Art ; Fezzan.
ABSTRACT. — The climatic evolution of the Fezzan region in the Central Sahara is described as witnessed through the rock art.

MOTS-CLES. — Climat ; Art rupestre ; Fezzan.
RESUME. — *Le climat à travers l'art rupestre. Exemple de la région du Fezzan dans le Sahara central.* — L'évolution climatique de la région du Fezzan dans le Sahara central est décrite par le témoignage produit par l'art rupestre.

TREFWOORDEN. — Klimaat ; Rotskunst ; Fezzan.
SAMENVATTING. — *Het klimaat gezien door de rotskunst. Voorbeeld uit Fezzan in de centrale Sahara.* — De klimaatevolutie van Fezzan in de centrale Sahara wordt beschreven aan de hand van getuigenissen uit de rotskunst.

*
* *

In my contribution I would like to illustrate how the extreme climatic conditions and their changes are reflected in faunal and human occurrence, especially in the human colonization of the Sahara, the world's largest desert.

Before considering the limited region of Fezzan, that is of the north-eastern part of Central Sahara, it would be probably interesting to summarize orographical saharan differentiation and to clarify the position of Fezzan. Observing the map of North Africa we see the Mediterranean sea in the north and the Atlantic Ocean in the north-west. Both these water masses have influenced the humidity and

* Moravske Museum, Preslova 1, 602 00 Brno (Czech Republic).

temperature of winds coming from those directions. The North African climate was influenced in pleistocene times also by the glacial oscillations of the European continent. They lowered the temperature simultaneously with the lowering of the sea level. The oscillating influences coming from the north have brought as a consequence the oscillation of the northern limits of the saharan desert which was not stable, neither in pleistocene times nor in postpleistocene neolithic times which are of special interest to us. Periods with a northern advance of the desert alternated with periods of retreat as was demonstrated by VERNET (1995) in his summarizing study of saharan palaeoclimatology.

In a similar way also the southern monsoon influence was not stable and its oscillations were reflected in changes of the southern limits of the Sahara. Through cartographical study we can learn that the orography of the vast saharan territory was diversified. While in the east we find only two limited and not too high mountainous regions, Gilf Kebir and Djebel Uenat, in Central Sahara we find the outstanding volcanic massives of Ahaggar and Tibesti, more than 3,000 m high and also other lower massives and high plains, e.g. Tassili, Acacus, Messak in southern Fezzan or Djado.

In neolithic times in which we consider two principal humid oscillations — one earlier and more important called the Great humid oscillation (Holocene Climatic Optimum) between 10,000 and 6,500 B.P. and another later and weaker called Neolithic humid oscillation.

The Great humid oscillation precedes (in a Europocentric view) by its larger part the neolithic cultural period and only its final part coincides with the early Neolithic of the European continent. But such an application of the chronology of the European cultural development into Saharan climatic conditions is by no doubt one of the simplified erroneous aspects of the first half of this century. Different climatic conditions were evidently in different chronological sequences but there was even a different composition of cultural components. The Saharan region did not know such an agriculture as we know in Europe and at least two cultural features usually considered as neolithic — ceramics and cattle domestication — appear in Sahara without any relation with agriculture and most probably earlier than in Europe.

The mountains and the 1,000 m and higher plains above the sea level have allowed human existence in Early Holocene. Ahaggar and Tibesti, high mountainous regions, were fully different from the surrounding desert. While the lower regions were already strongly arid, the climate of the mountains was characterized by humidity, which

was stronger and earlier at the beginning. Sahara is evidently not a climatically homogeneous region. We can recognize the northern and southern marginal territories with their specific climatic oscillations and a different climatic situation in mountainous areas making human existence possible in times when surrounding desert areas changed these mountains into isolates of human occupation, eventually into refugia. And certainly there was another climatic difference between the western and eastern Sahara.

As a consequence of this situation demanding specific ways for human adaptations, it is not surprising that opposite to Europe we can find here hunting economy together with pastoralism, that means together with the developed knowledge of cattle domestication. It is also misleading to suppose *a priori* the same way of domestication as in Europe, that means such a use of milk, meat and drought force of domesticated cattle. Many important rock art figures in Central Sahara demonstrate the important use of bulls, or better of oxen for transport of burdens or people. It would be erroneous to presume the same age for those features in Sahara as in Europe.

But let us consider the distribution or dislocation of the earliest engravings which are so numerous in Messak. Their unusual number together with rich archaeological findings (stone tools, their workshops, living sites with or without pottery, stone constructions, etc.) document a concentrated stay.

Interesting information brings us the analysis of kinds of animals represented in rock art. We know that we face here a distorted picture of that time fauna and not an objective illustration of living animals. First, human interest was focused to some animals for different reasons and those animals could be even rare or extinct when compared with other represented species. The engraved figures with the darkest patina represent frequently those animals which need water, often even deep and permanent water to survive : hippopotamus, crocodile, *Pelorovis antiquus*, *Syncerus cafer*, etc. These species we find represented in the Messak galleries but not in Northern Fezzan. The nearest comparable fauna we can find in wadi Djerat which is west of Messak, not north. This means, that hippopotamus, crocodile, *Pelorovis antiquus* and *Syncerus cafer* were not living north of southern Fezzan in neolithic times (but see *Pelorovis antiquus* in northern Algeria).

True, we must be prudent when considering some represented species as "leitfossilien" (e.g. *Pelorovis antiquus*). These occurrences in different isolates were often not synchronous as demonstrates the example of

the last crocodile killed in Tassili in 1934, or the survival of the last North African lion in the Atlas mountains up to this century. Similar situation, the rare survival, can be reflected in some inaccurate engravings of *Pelorovis* with a long cattle-like tail and with wrong shape of the body (and sometimes with a weaker patina) which signals the lack of good knowledge of this animal. It could be an inaccurate copy of some earlier engravings (JELÍNEK 1993).

Other important climatic markers are animals living under arid conditions like the fennec and adax antelope. The fact that we find them sometimes synchronous in Messak Settafet with the savannah fauna like elephant, giraffe, aurochs and domesticated cattle proves that adax and fennec were well-known to neolithic people and that more arid environment typical of fennec and adax ought to be nearby. The adax figures continue frequently into the later "horse" period and geographically we find them also more north, that is in Northern Fezzan. Evidently they correspond to advancing aridity (MUZZOLINI 1995).

The hydrographical situation during neolithic period is sometimes illustrated by the distribution of the engraved figures on the floor of the wadi. In Galghien on the southern margin of Messak Settafet we find in the middle of the riverbed (today dry) large flat stone reefs with engraved figures of *Syncerus cafer* (JELÍNEK 1984, figs 10-11). There were rapids here when the water was flowing and the stony reefs were, at least some time during the year, dry and accessible.

In Northern Fezzan we find another illustrative example in wadi-Zreida (wadi Deb-deb) (GRAZIOSI 1981, JELÍNEK 1982, LE QUELLEC 1987). Its upper, northern part is narrow and rocky and we find here neolithic living sites. One is situated on the flat gravel-terrace some two metres above the floor of the wadi. This means that the water was in the wadi only in some parts of the year or that it was only in the guelta nearby (today dry as well as the wadi). Directly in the floor of the riverbed we find postneolithic engravings on a flat horizontal rock face. There was no more water here at the times of the origin of these rock art figures. The wadi was already dry.

The southern part of this wadi is broader, more open and with lower cliffs. We find here mostly late, that is postneolithic, engravings. Figures of elephants are missing here (they are only in the northern part of the wadi). We find only engraved figures of giraffes, adax antelopes, some simple cattle, horse and camel figures. There are no archaeological living sites proving longer stay of humans and the domesticated animals

were here for daily pasture only. Human habitations were elsewhere. This change, which can be followed in rock art, can be easily explained by the development of corresponding human groups and as a human reaction to the changed hydrological situation.

Also in Messak we do not find traces of longer human stay in postneolithic times. The postneolithic engravings are rare with the exception of some tifinag inscriptions. These are traces of sporadic visits, not of the stay. The everyday life was concentrated round permanent water springs in large wadis (wadi Ajal, wadi Sciatti) and in adjacent oasis.

In this short paper, I have tried to demonstrate how climatic change is reflected in human stay or colonization of the Central Saharan region and how the climate can be followed with the help of rock art, its kind, its distribution and the animals represented.

REFERENCES

GRAZIOSI, P. 1981. L'arte rupestre dell'Uadi Zreda presso Brach, nell Fezzan. — *Rivista di Science Preistoriche*, **36** (1-2), 23 pp.

JELÍNEK, J. 1982. Wadi Zreida, a north Fezzanese rock art site. — *Anthropologie*, **20** (3) : 219-245.

JELÍNEK, J. 1984. Mathrndush, In Galghien, two important fezzanese rock art sites. Part II. — *Anthropologie*, **22** (3) : 237-266.

JELÍNEK, J. 1993. Some ideas on the possibilities and traps of the Saharan rock art chronology. — *In* : CALEGARI, E. (ed.), L'arte e l'ambiente del Sahara prehistorice : dati e interpretazioni, Milan, pp. 293-295.

LE QUELLEC, J. L. 1987. L'art rupestre du Fezzan septentrional/Libye. — BAR. IS. 365, Cambridge, p. 402.

MUZZOLINI, A. 1995. Faunes holocènes du Maroc et variations des aires de distribution de certaines espèces sauvages dans le nord de l'Afrique. L'expansion récente de l'Oryx dammah. — Actes du 2e Congrès International de Ceuta, Ed. Ripoll Perello, pp. 215-244.

VERNET, R. 1995. Climats anciens du nord de l'Afrique. — Ed. L'Harmattan, Paris, 180 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 108-127 (1998)

Evolution du paléoenvironnement holocène au Rwanda. Implications climatiques déduites de l'analyse palynologique de séquences sédimentaires

par

Emile Roche *

Mots-cles. — Rwanda ; Holocène ; Climat ; Paléoenvironnement.

Resume. — L'analyse palynologique de trois sondages dans des dépôts sédimentaires tourbeux de haute altitude au Rwanda révèle divers épisodes marquants caractérisant l'évolution du climat au cours de l'Holocène. De *ca.* 12 000 à *ca.* 7 000 ans B.P. : passage progressif du climat froid et sec de la fin du Pléistocène vers un stade plus chaud et humide. Une oscillation froide, *ca.* 9 000 B.P., interfère dans cette progression ; optimum chaud-humide *ca.* 6 000 ans B.P. attesté par une expansion maximale de la forêt ombrophile montagnarde, pic d'aridité *ca.* 4 000 ans B.P., puis évolution vers un climat à nouveau plus humide, semblable à l'actuel. Ce stade est atteint à *ca.* 2 000 ans B.P. Au cours des deux derniers millénaires, deux pulsations sèches se manifestent encore : l'une, assez brève, *ca.* 500 A.D. ; l'autre vers les 16e-17e siècles.

Trefwoorden. — Rwanda ; Holoceen ; Klimaat ; Paleo-omgeving.

Samenvatting. — *Evolutie van de holocene paleo-omgeving in Rwanda. Klimaatgevolgen getrokken uit de palynologische analyse van sedimentsequenties.* — Palynologisch onderzoek van drie sedimentaire veenafzettingen afkomstig van een bergachtig gebied in Rwanda tonen verschillende belangrijke klimatologische periodes aan gedurende het Holoceen. Van *ca.* 12 000 tot 7 000 B.P. veranderde een koud en droog klimaat geleidelijk in een warmer en vochtiger. Het optimum van de vochtige periode, bereikt rond 6 000 B.P., begunstigde een grote uitbreiding van bossen tijdens deze periode. Na een nieuwe aride piek in het klimaat (*ca.* 4 000-3 000 B.P.), evolueerde het klimaat naar zijn huidige toestand, warmer en vochtiger. Nochtans, gedurende de laatste twee millenia, kwamen opnieuw twee drogere fases voor : de eerste *ca.* 500 A.D. ; de tweede rond de 16de-17de eeuw.

* Musée de l'Afrique centrale, Leuvensesteenweg 13, B-3080 Tervuren (Belgique).

KEYWORDS. — Rwanda ; Holocene ; Climate ; Palaeo-environment.

ABSTRACT. — *Evolution of the Holocene Palaeoenvironment in Rwanda. Climatic Implications deduced from the Palynological Analysis of Sedimentary Sequences*. — Palynological analysis of three sedimentary sequences coming from mountainous peatbogs of Rwanda reveals that some important climatic events occurred during the Holocene period. From *ca.* 12,000 until *ca.* 7,000 years B.P. a cold and dry climate became gradually warmer and wetter. The optimum of humidity, having reached *ca.* 6,000 yr B.P., favoured a large extension of forests at that time. After a new aridity peak (*ca.* 4,000-3,000 B.P.), climate had evolved to its present situation, warmer and wetter. However, during the last two millenia, two dry phases occurred again : the first one, *ca.* 500 A.D. ; the second one around 16th-17th centuries.

Introduction

Sur base de l'analyse de séquences sédimentaires holocènes relevées dans des dépôts tourbeux de haute altitude au Rwanda (situation géographique : fig. 1), on peut proposer un schéma évolutif forestier montagnard et mettre en évidence les phénomènes climatiques marquants survenus au cours des dix derniers millénaires.

La végétation naturelle qui subsiste encore sur la crête bordière orientale du lac Kivu et sur les flancs de la chaîne volcanique des Birunga présente la zonation suivante : les hauts-reliefs, au-dessus de 2 800 m, sont le domaine de formations sclérophylles afro-alpines et afro-subalpines. Entre 2 800 et 2 000 m se développe la forêt ombrophile de montagne ; celle-ci, aux altitudes plus basses (1 800-1 600 m) fait place à des ensembles forestiers à caractère mésophile assurant la transition vers des savanes tropophiles plus ou moins densément boisées dans la région des collines au centre du pays et vers des formations sclérophylles submontagnardes sur la plaine de lave du nord.

La dynamique forestière est intimement liée aux changements climatiques : ceux-ci se traduisent par des modifications de constitution des milieux forestiers et, en altitude, par des mouvements des zones de végétation à flanc de montagne. Ces faits sont inscrits dans les spectres polliniques que révèlent les dépôts sédimentaires. Les variations que ces spectres subissent au cours du temps sont indicatrices des changements environnementaux et des fluctuations climatiques qui les ont induits.

Trois séquences sédimentaires sont analysées dans le cadre de la présente étude : les deux premières (Rugezi I et Kiguhu II) couvrant

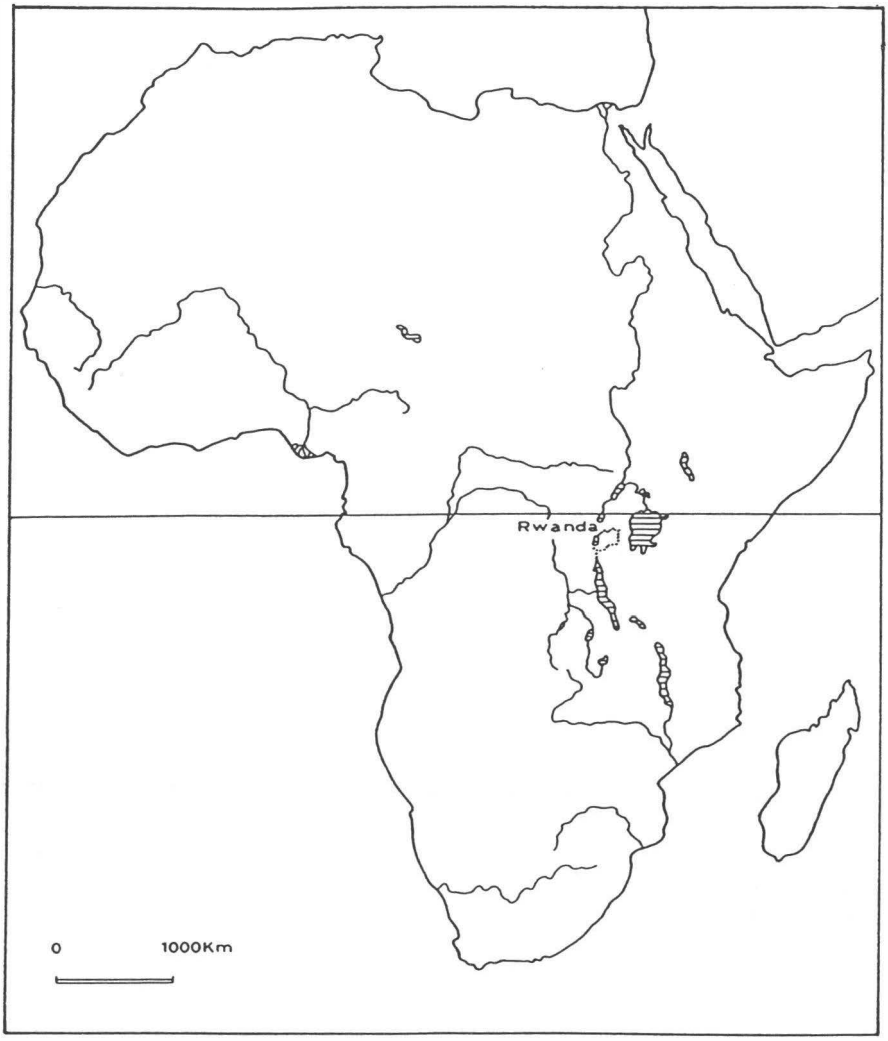


Fig. 1. — Situation géographique du Rwanda.

toute la période holocène (± 11 000 ans) proviennent de la région des volcans au nord ; la troisième (Gasare), temporellement plus limitée (2 500 ans), a été relevée dans un marais situé en forêt de Nyungwe au sud-ouest (fig. 2).

Sites étudiés

Au Rwanda, les tourbières sont dispersées un peu partout à des altitudes très variées : la morphologie particulière du pays et le réseau hydrologique complexe qui en est la conséquence ont favorisé la formation, tant en altitude que dans les dépressions orientales, de milieux particuliers propices à la genèse de dépôts sédimentaires tourbeux.

Il existe cependant une plus forte densité de tourbières en haute altitude car, au-dessus de 1 700 m, la tourbe se forme normalement dans tous les milieux humides.

A l'ouest, sur la crête Zaïre-Nil, de petites tourbières où l'épaisseur des dépôts excède rarement 3 m, se développent généralement à proximité des têtes de sources et dans le cours supérieur des rivières.

Au nord, dans la région des volcans, des marécages faisant partie d'un grand complexe fluvio-lacustre entourant les lacs Bulera et Ruhondo renferment des dépôts de tourbe considérables.

Rugezi I (Marais de Rwagambavu)

Le marais de Rugezi est une vaste tourbière couvrant une superficie de quelque 40 km². Sur plus de 30 km de long, il occupe une dépression schisteuse fermée par un seuil quartzitique. Surplombant le lac Bulera, il y déverse ses eaux par une série de chutes franchissant une dénivellation de 200 m.

Les sédiments que renferme le marais sont de nature essentiellement tourbeuse en son centre mais à caractère plus argileux à sa périphérie et dans les vallées latérales. Le sondage RUG. I a été réalisé dans une de ces vallées, celle de Rwangambavu, affluent de droite de la Rugezi, proche des chutes.

Altitude du site : 2 050 m.
Coordonnées géographiques : 1°24′ S : 29°50′ E.
Epaisseur de la séquence : 3,30 m.
Datations C_{14} : – 0,60 m : 1 315 ± 110 B.P. (Hv. 12 928).
– 1,90 m : 5 770 ± 75 B.P. (Hv. 11 596).

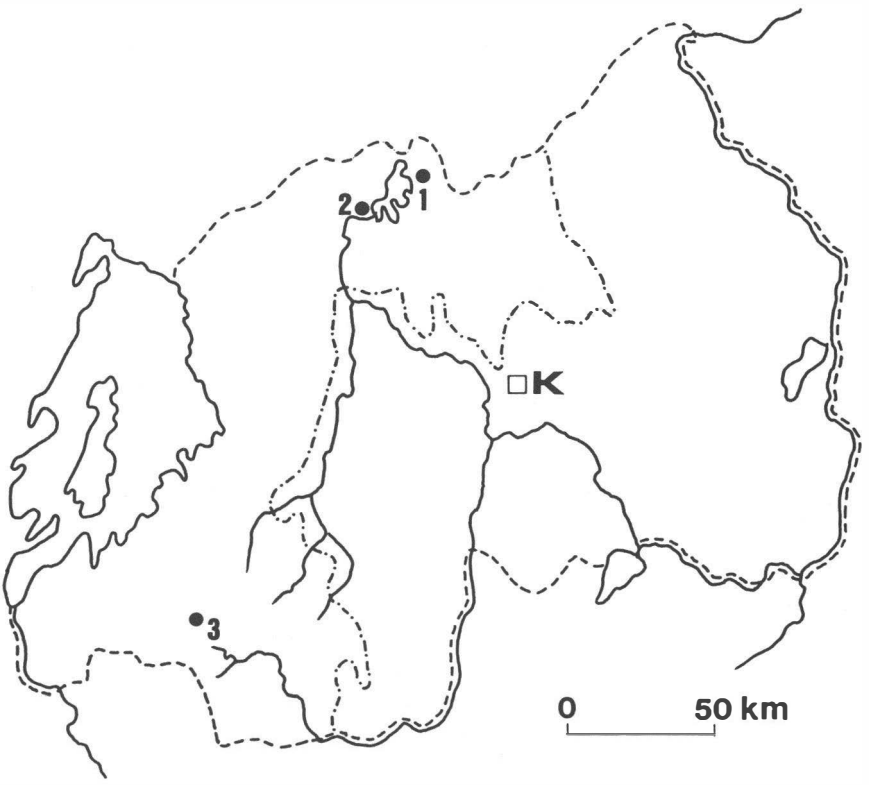


Fig. 2. — Localisation des sites (●) : 1. Rugezi; 2. Kiguhu ; 3. Gasare. – · – · – : limite orientale des zones forestières montagnardes.

KIGUHU II

Le marais de Kiguhu, inséré dans des collines surplombées par le volcan éteint Muhabura (4 127 m) est situé à proximité du lac Ruhondo vers lequel il déverse ses eaux par un exutoire étroit. Le marais recèle un important dépôt tourbeux.

La nature des sédiments qui constituent la séquence de Kiguhu revêt un caractère relativement homogène. Il s'agit d'un matériau tourbeux de couleur brun noir à débris herbacés ou ligneux devenant plus compact et argileux dans la partie inférieure du profil. A la base de celui-ci, à la zone de contact avec le socle rocheux, des particules sableuses se mélangent à l'argile tourbeuse.

Altitude du site : 1 800 m.
Coordonnées géographiques : 1°29′ S ; 29°43′ E.
Epaisseur de la séquence : 5,30 m.

Datations C_{14} : – 0,60 m : 1 145 ± 130 B.P. (Hv. 12 115) ;
– 1,20 m : 2 250 ± 90 B.P. (Hv. 12 116) ;
– 1,80 m : 3 915 ± 375 B.P. (Hv. 12 118) ;
– 3,20 m : 8 800 ± 120 B.P. (Lv. 1 826) ;
– 5,10 m : 11 270 ± 120 B.P. (Lv. 1 827).

Gasare

Le marais de Gasare, de faible superficie, se situe en pleine forêt de Nyungwe, seul grand massif forestier subsistant encore dans le sud-ouest du Rwanda. Alimenté par un ruisseau, il occupe une petite dépression sur la crête Zaïre-Nil à plus de 2 000 m d'altitude.

Le profil relevé pour l'analyse est constitué d'une tourbe argileuse contenant des fragments végétaux herbacés ou ligneux. Sa portion superficielle, couverte de végétation, est un sol organique gris noir tandis que la séquence de fond est constituée par du sable tourbeux devenant très grossier et fortement micacé à la base.

Altitude du site : 2 300 m.
Coordonnées géographiques : 2°28′ S ; 29°14′ E.
Epaisseur de la séquence : 3,20 m.
Datations C_{14} : – 3,00 m : 2 360 ± 70 B.P. (Lv. 1 807).

Analyse des diagrammes palynologiques

Les diagrammes palynologiques (figs. 3 à 5) synthétiques présentés ici résultent d'une analyse des séquences basée sur un regroupement des taxons polliniques en assemblages représentatifs des groupements végétaux caractéristiques des zones d'altitude bordières de la branche occidentale du rift africain :

— Groupements afro-alpins et afro-subalpins à *Alchemilla*, *Lobelia*, *Ericaceae*, *Hypericum*.
— Forêt ombrophile de montagne à *Podocarpus*, *Cassipourea*, *Ekebergia*, *Ficalhoa*, *Ilex*, *Syzygium*, ...
— Forêts mésophiles ou secondaires à *Hagenia*, *Macaranga*, *Albizia*, *Croton*, *Maesa*, *Neoboutonia*, *Polyscias*, *Trema*, ...
— Milieux de savanes à *Acacia*, *Euphorbia*, *Protea*, *Gramineae*, ...
— Milieux marécageux à *Cyperaceae*.

Les modifications subies par ces différents assemblages dans les diagrammes sont révélatrices des variations que l'environnement a

connues au cours du temps et des fluctuations climatiques qui en ont été responsables.

RUGEZI I (fig. 3)

Zone 1 : – 3,30 à – 2,50 m.

Les taxons recensés dans cette zone pollinique attestent l'occupation du terrain par des formations boisées hétérogènes ombro-mésophiles dont les principaux représentants étaient *Podocarpus*, *Olea*, *Syzygium*, *Myrica*, *Trema*.

L'existence de milieux plus ouverts est attestée par une présence marquée de *Gramineae* et d'éléments sclérophylles subalpins comme les *Ericaceae* et *Hypericum*.

Durant cette période que l'on peut estimer correspondre au début de l'Holocène avant l'amorce, *ca.* 9 000 ans B.P., de la phase d'expansion de la forêt ombrophile montagnarde, le climat devait être plus froid et plus sec que l'actuel, ce qui explique l'intrusion sensible d'éléments sclérophylles dans l'étage montagnard.

Zone 2 : – 2,50 à – 2,00 m.

Cette zone se caractérise par une progression des taxons de forêt ombrophile de montagne, tant en fréquence qu'en densité. A l'inverse, les fréquences des taxons du milieu afro-subalpin (*Ericaceae-Hypericum*) et ceux d'autres milieux ouverts (*Gramineae-Cyperaceae*) régressent.

Aux taxons ombrophiles les plus fréquemment présentés (*Podocarpus*, *Olea*, *Cassipourea*, *Ilex*, *Pygeum*, *Symphonia*, *Syzygium*) sont associées significativement certaines essences mésophiles telles *Hagenia*, *Macaranga*, *Trema*.

Ce développement forestier n'a pu se produire que sous un climat favorable à son expansion, c'est-à-dire en évolution vers un optimum chaud et humide.

Zone 3 : – 2,00 à – 1,65 m.

L'optimum chaud-humide favorable à l'extension de l'élément ombrophile montagnard est atteint à *ca.* 6 000 ans B.P. (datation C_{14} à – 1,90 m : 5 770 ± 75 B.P.). A ce niveau, la forêt de montagne est à un stade de diversification maximal et connaît sa plus grande extension holocène. Les milieux ouverts à *Gramineae* et *Cyperaceae* sont en nette régression tout comme le sont les éléments mésophiles ou à tendance sclérophylle (*Podocarpus*) au sein même de la forêt.

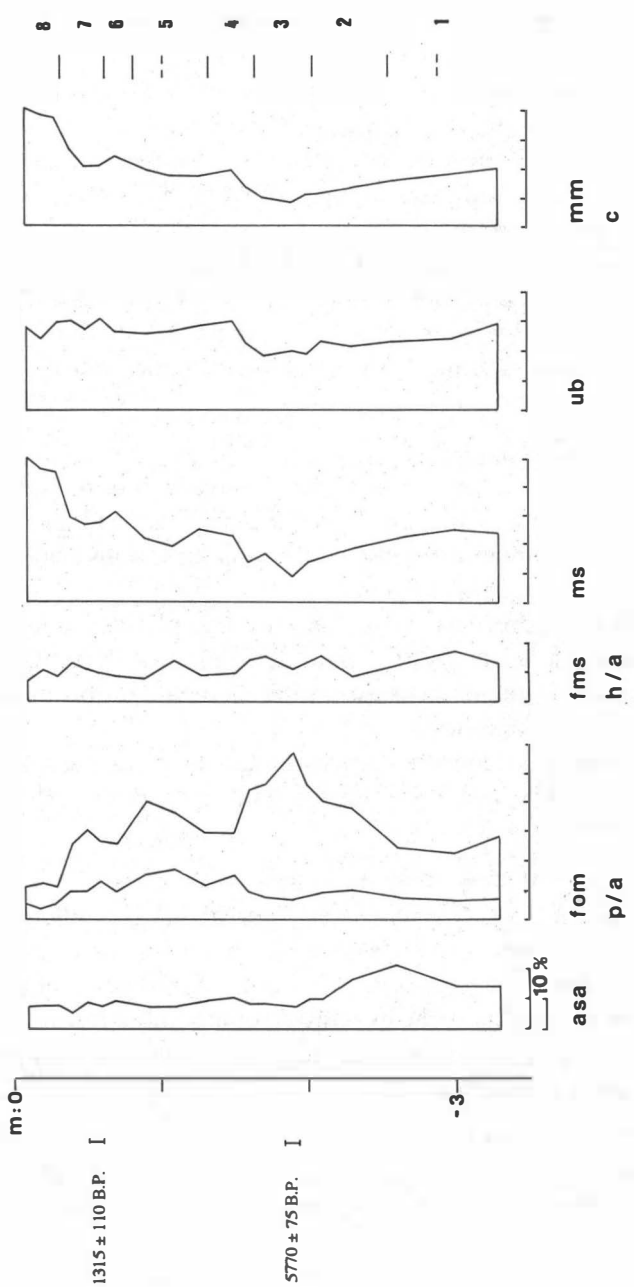


Fig. 3. — Rugezi I. Altitude : 2 050 m ; coordonnées : 1°24' S, 29°50' E.

Zone 4 : – 1,65 à – 1,40 m.

Un important recul forestier affectant formations ombrophiles et mésophiles se manifeste ici. Ce recul très net correspond à une phase d'aridité qui traduirait une diminution sensible des précipitations, mais celle-ci ne serait pas nécessairement concomitante d'un recul de la température. On constate en effet une progression des *Gramineae* attestant une extension des milieux ouverts, mais ceux-ci ne semblent guère colonisés par les éléments afro-subalpins dont le pourcentage dans les diagrammes augmente à peine. Ce fait exclurait une diminution sensible de la température. Par ailleurs, la progression de *Podocarpus* au sein du massif forestier permet de supposer le maintien d'une certaine humidité atmosphérique, mais non édaphique, entretenue par des brouillards.

Zone 5 : – 1,40 à – 0,85 m.

Dans cette zone, on constate une nouvelle progression de la forêt de montagne et une expansion lente mais continue du milieu marécageux alors que les pourcentages en graminées et en taxons sclérophylles subalpins régressent quelque peu.

L'expansion forestière s'effectue en deux phases : une première où *Podocarpus* est l'élément dominant associé à des éléments mésophiles ; une seconde où une diversification des éléments ombrophiles, toujours en expansion, se manifeste.

Cette évolution marque vraisemblablement le passage du climat humide (*ca.* 2 000 ans B.P.) qui n'atteint cependant pas l'optimum de *ca.* 6 000 B.P.

Zone 6 : de – 0,85 à – 0,55 m.

Les fréquences en *Gramineae* et *Cyperaceae* deviennent plus élevées à ce niveau alors qu'on assiste à un recul assez sensible mais temporellement peu important des taxons forestiers ombrophiles. Une oscillation climatique sèche et plutôt froide semble responsable de cette modification environnementale qui a été datée ailleurs au Rwanda (Butare) de *ca.* 500 A.D.

Zone 7 : de – 0,55 à – 0,35 m.

La zone pollinique 7 révèle un regain des taxons forestiers ombrophiles et mésophiles accompagné d'une légère régression des *Gramineae* et des *Cyperaceae.* Il semble que le climat redevienne favorable à une nouvelle expansion de la forêt semblable à celle qui a précédé le pic d'aridité de la zone 6 mais qu'une incidence d'origine anthropique freine la recolonisation du milieu.

Zone 8 : de – 0,35 à – 0,10 m.

Une importante expansion de la végétation herbacée (*Gramineae* ; *Cyperaceae*) souligne cet effet anthropique dans la partie supérieure du profil (*post* 1 000 B.P.), tandis que les formations boisées primaires et secondaires subissent un recul prononcé.

Le profil Rugezi I révèle l'évolution holocène de l'environnement en milieu montagnard. Au début de la séquence, on observe le développement d'une forêt hétérogène méso-ombrophile teintée d'éléments sclérophylles afro-subalpins qui attestent l'existence d'un climat relativement froid et sec. On assiste ensuite (*ca.* 6 000 ans B.P.) à une expansion très importante de la forêt ombrophile de montagne au sein de laquelle les éléments mésophiles et sclérophylles sont marginalisés. Cet épisode est dû à l'installation d'un optimum climatique humide et chaud. Après un pic d'aridité responsable d'un recul sensible du milieu forestier, celui-ci manifeste un regain de colonisation du milieu favorisé par un climat redevenu plus humide mais présentant encore une petite oscillation sèche à *ca.* 1 300-1 400 B.P. Au sommet de la séquence, les formations ouvertes à *Gramineae* et *Cyperaceae*, qui acquièrent de l'importance au détriment des ensembles forestiers, reflètent l'importance de l'influence humaine sur l'environnement.

KIGUHU II (fig. 4)

Le diagramme établi sur cette séquence de 5,30 m permet de distinguer 9 zones polliniques majeures :

Zone 1 : – 5,30 à – 3,85 m.

Les assemblages polliniques relevés dans cette première zone dont la base se situe à *ca.* 11 000 ans B.P. reflètent l'existence de formations boisées hétérogènes méso-ombrophiles teintées d'éléments sclérophylles afro-subalpins.

Durant cette période du début de l'Holocène, l'environnement forestier évolue en deux phases : la première, la plus importante, se caractérise par une dominance de taxons sclérophylles et mésophiles parmi lesquels on remarque surtout la présence d'*Ericaceae*, d'*Hypericum* et de *Hagenia* ; la seconde, à l'inverse, voit une progression des taxons ombrophiles avec *Podocarpus* comme genre dominant.

Cette première zone souligne l'évolution du climat : à l'origine plutôt froid et sec, vers un stade de léger réchauffement sous atmosphère plus humide.

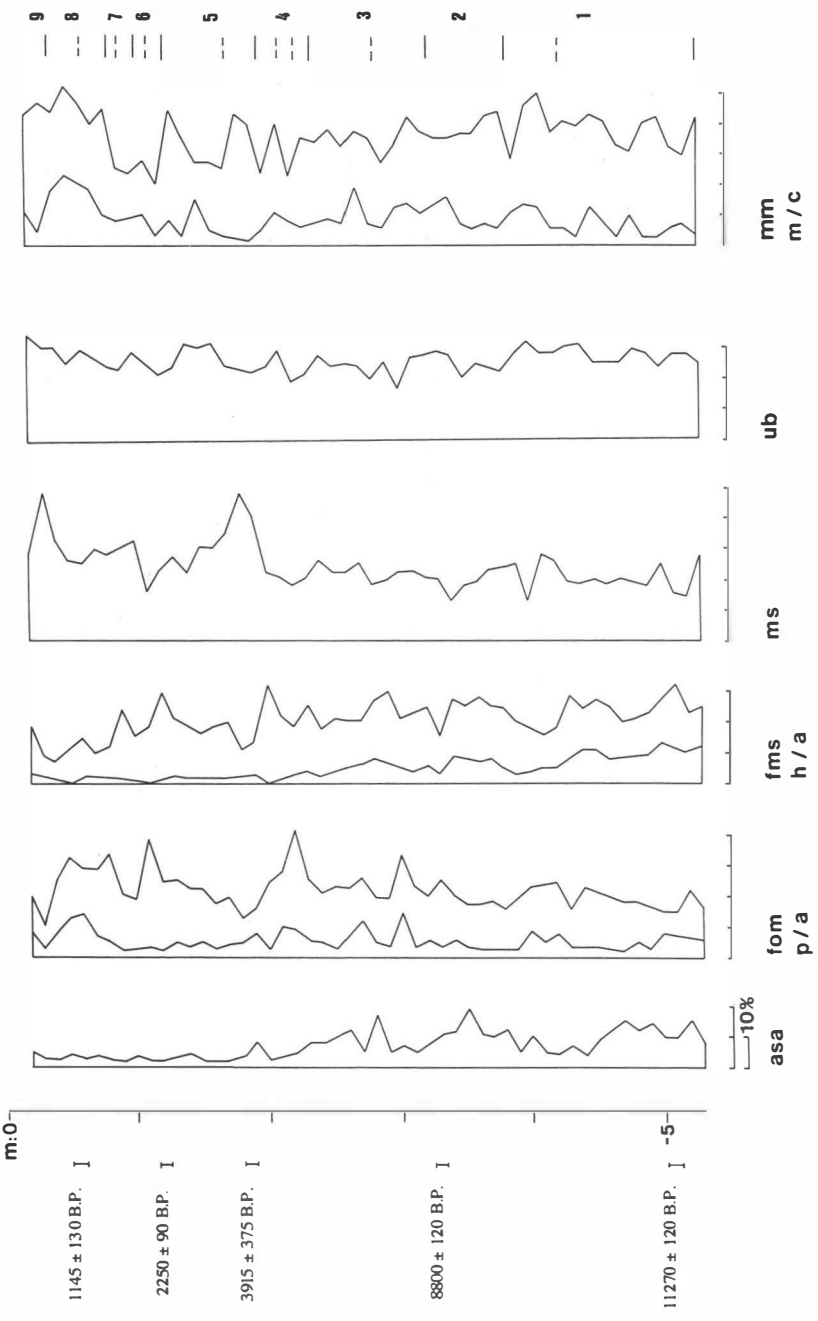


Fig. 4. — Kigihu II. Altitude : 1 800 m ; coordonnées : 1°29' S, 29°43' E.

Zone 2 : – 3,85 à – 3,25 m.

Dans cette partie de la séquence, les taxons mésophiles et sclérophylles reprennent de l'extension au détriment des ombrophiles. On observe un regain de *Hagenia* et une poussée sensible des *Ericaceae*, ce qui semble indiquer que le climat connaît à nouveau une oscillation plus froide. La fin de la zone est datée de *ca.* 9 000 ans B.P.

Zone 3 : – 3,25 à – 2,35 m.

Cette zone est marquée par une progression des éléments forestiers ombrophiles et mésophiles qui présentent une plus grande diversité floristique que précédemment.

Après, au début de la période où *Ericaceae* et *Hagenia* occupent encore une place marquante au sein des spectres polliniques, ces taxons connaissent une régression progressive. Ce fait atteste un climat de transition évoluant régulièrement vers un stade plus chaud et plus humide.

La dominance en alternance des *Ericaceae* et de *Podocarpus* à la base de la zone indique que le climat a connu des oscillations plus fraîches avant d'évoluer plus franchement vers le réchauffement.

Dans toute la partie (trois premières zones) de la séquence Kiguhu II correspondant à la période de l'Holocène qu'on peut estimer antérieure à *ca.* 7 000 ans B.P., la présence nettement marquée des *Ericaceae* et de *Hagenia* dans les assemblages polliniques est révélatrice d'une descente des zones de végétation à flanc de montagne favorisée par un climat qui, à des degrés divers au cours du temps, était plus froid et vraisemblablement plus sec que l'actuel.

Zone 4 : – 2,35 à – 1,95 m.

Les assemblages polliniques de cette zone soulignent une importante expansion forestière qui se déroule en trois phases : une phase de développement marqué de la forêt ombrophile de montagne dans laquelle *Podocarpus* est un élément important, précédée et suivie par des périodes favorables à l'expansion des taxons forestiers mésophiles. Durant la première de ces périodes, *Hagenia* et certains genres sclérophylles afro-subalpins sont encore présents dans l'environnement ; en fin de seconde période, ils ont quasi disparu.

Il résulte de ces constatations que le climat se caractérise ici par une augmentation sensible de la température et des précipitations qui, vraisemblablement, sont à leur optimum.

Dans les périodes initiale et terminale, les températures devaient être assez élevées mais les précipitations un peu moins importantes que dans

la période intermédiaire au cours de laquelle devaient régner des conditions climatiques plus fraîches en altitude entretenues par une humidité atmosphérique persistante.

Zone 5 : – 1,95 à – 1,25 m.

L'analyse pollinique révèle à ce niveau d'importants changements dans l'environnement consécutifs à une dégradation sensible des conditions climatiques. Celle-ci se traduit (*ca.* 4 000 ans B.P.) par un pic d'aridité entraînant un recul prononcé des taxons forestiers ombrophiles et mésophiles et une progression des milieux ouverts de savanes attestée par une augmentation importante du pourcentage des *Gramineae*. Cette aridité était due probablement à une diminution des précipitations alors que la température n'a pas dû connaître de recul significatif comme le laisse supposer la faible avancée des éléments sclérophylles afro-montagnards et de *Hagenia*.

A la suite de cet événement plutôt limité dans le temps, des formations forestières hétérogènes méso-ombrophiles réoccupent progressivement le terrain à la faveur d'un climat de transition évoluant à nouveau vers un stade plus humide. Ces nouvelles conditions se traduisent également par une extension du marécage (*Cyperaceae*) et une réduction des milieux de savanes (*Gramineae*).

Zone 6 : – 1,25 à – 1, 05 m.

L'expansion forestière amorcée dans la zone 5 atteint son optimum dans la zone 6.

L'ensemble forestier voit progresser successivement sa composante mésophile à dominance de *Macaranga*, puis sa composante ombrophile à *Olea* (type *hochstetteri*), tandis que les milieux ouverts de savane à *Gramineae* et le marécage à *Cyperaceae* régressent. A ce niveau s'amorce une colonisation des bords de marais par *Mitragyna*.

Cette extension des milieux forestiers est due à une nouvelle phase climatique chaude et humide qui n'atteint cependant pas en intensité celle qui s'est développée antérieurement à *ca.* 6 000 B.P.

Zone 7 : – 1,05 à – 0,85 m.

Une oscillation sèche temporellement limitée (*ca.* 500 A.D. : *cf.* Rugezi I) se traduit par un recul assez sensible des taxons ombrophiles et mésophiles, puis par une reprise des mésophiles uniquement quand les *Gramineae* sont de nouveau en expansion.

Zone 8 : – 0,85 à – 0,35 m.

Après la pulsation sèche précédente, le milieu forestier progresse à

nouveau mais on constate que cette progression n'affecte que les éléments ombrophiles alors que les taxons mésophiles sont en recul.

La situation climatique semble pourtant favorable à un développement forestier comme le prouve par ailleurs l'extension de *Mitragyna*, composante de la végétation galerie du marécage.

Il faut admettre qu'une cause autre que climatique, après 1 200 B.P. (datation C_{14} à – 0,60 m : 1 145 ± 130 B.P.), a provoqué la régression de la végétation mésophile occupant les zones de basse altitude sur la chaîne des Birunga.

Cette cause doit être de nature anthropique. On sait en effet que vers les x^e^-xi^e^ siècles de notre ère, la région a été occupée par des populations de chasseurs-pasteurs venus du nord-est. La déforestation observée résulte en partie des activités pastorales mais aussi des feux courants qui nuisent à la stabilité du couvert végétal.

La composition de la forêt ombrophile de montagne, qui ne semble pas avoir été affectée ici par l'impact anthropique, permet d'émettre un avis sur l'évolution climatique à cette époque.

L'extension du milieu afro-montagnard a été favorisée par une nouvelle phase humide qui s'est manifestée après la pulsation sèche de *ca.* 500 A.D. Chaude à son origine, celle-ci a évolué vers un stade plus frais comme le montre la progression de *Podocarpus* au sein de la forêt ombrophile de montagne.

Zone 9 : – 0,35 à – 0,25 m.

La zone terminale du profil indique qu'après la forêt mésophile, la forêt ombrophile elle-même est réduite par l'effet anthrophique. La secondarisation du milieu provoque une importante expansion des *Gramineae*. Celle-ci affecte aussi l'environnnement proche du marécage comme l'atteste le recul de *Mitragyna*.

Vers le sommet de la séquence, on observe toutefois un regain forestier qui pourrait résulter d'un abandon relatif du milieu par les populations après épuisement de l'environnement local.

L'analyse palynologique de la partie supérieure de la séquence Kiguhu II (zones 4 à 9) révèle que les variations climatiques y sont plus contrastées que dans sa partie inférieure : après l'optimum chaud-humide de *ca.* 6 000 B.P., une aridification du milieu intervient. Vive au début, elle s'atténue progressivement jusqu'à *ca.* 2 500 ans B.P. Une phase humide et chaude se développe ensuite, coupée à *ca.* 500 ans A.D. par une oscillation sèche. En fin de séquence (*ca.* 1 000 B.P.), un impact

anthropique interfère dans les conditions climatiques qui, jusqu'alors, régissaient l'évolution de l'environnement.

Dans la séquence de Kiguhu qui couvre toute la période holocène, on constate que, de *ca.* 11 000 ans B.P. à 7 000 ans B.P., le milieu est occupé par des formations forestières hétérogènes de tendance mésophile à dominance de *Hagenia* et de taxons sclérophylles afro-subalpins intrusifs se situant en dessous de leur limite de distribution altitudinale actuelle.

Par la suite (*post* 7 000 B.P.), Hagenia et les éléments sclérophylles régressent et une forêt montagnarde à caractère ombrophile plus marqué s'installe qui présente toutefois deux phases régressives : la première à *ca.* 4 000 ans B.P. ; la seconde à *ca.* 500 ans A.D.

Les deux épisodes environnementaux principaux constatés dans le profil sont le fait d'incidences climatiques : climat plus froid et plus sec de *ca.* 11 000 à *ca.* 7 000 ans B.P. ; climat plus chaud et plus humide de *ca.* 7 000 B.P. à la période actuelle entrecoupé d'un pic d'aridité très net à *ca.* 4 000 B.P. et d'une pulsation sèche de moindre amplitude et de faible durée à *ca.* 500 A.D. Le recul subrécent des éléments forestiers mésophiles est une conséquence de l'action anthrophique.

GASARE (fig. 5)

Cette séquence relevée en forêt de Nyungwe (sud-ouest du Rwanda) indique que, depuis vingt-quatre siècles, une forêt montagnarde à *Podocarpus*, *Olea*, *Cassipourea*, *Ilex*, *Syzygium*, *Macaranga*, ... couvre les hauteurs avoisinant le marais de Gasare.

Zone 1 : – 3,20 à – 2,85 m.

En début de période (*ca.* 2 400 ans B.P.), la végétation à dominance de taxons ombrophiles se développe sous un climat relativement froid et peu humide comme en témoigne la présence marquée d'associations à *Ericaceae* - *Hypericum.*

Zone 2 : – 2,85 à – 1,85 m

Le recul des formations sclérophylles à *Ericaceae* concomitant d'un développement de la forêt montagnarde traduit des conditions climatiques devenues plus humides mais demeurant fraîches comme le laisse présumer la persistance de *Podocarpus* dans le milieu forestier. La progression de la composante mésophile et un regain des éléments afro-subalpins à la fin de cette séquence sont le signal de l'amorce d'une détérioration climatique.

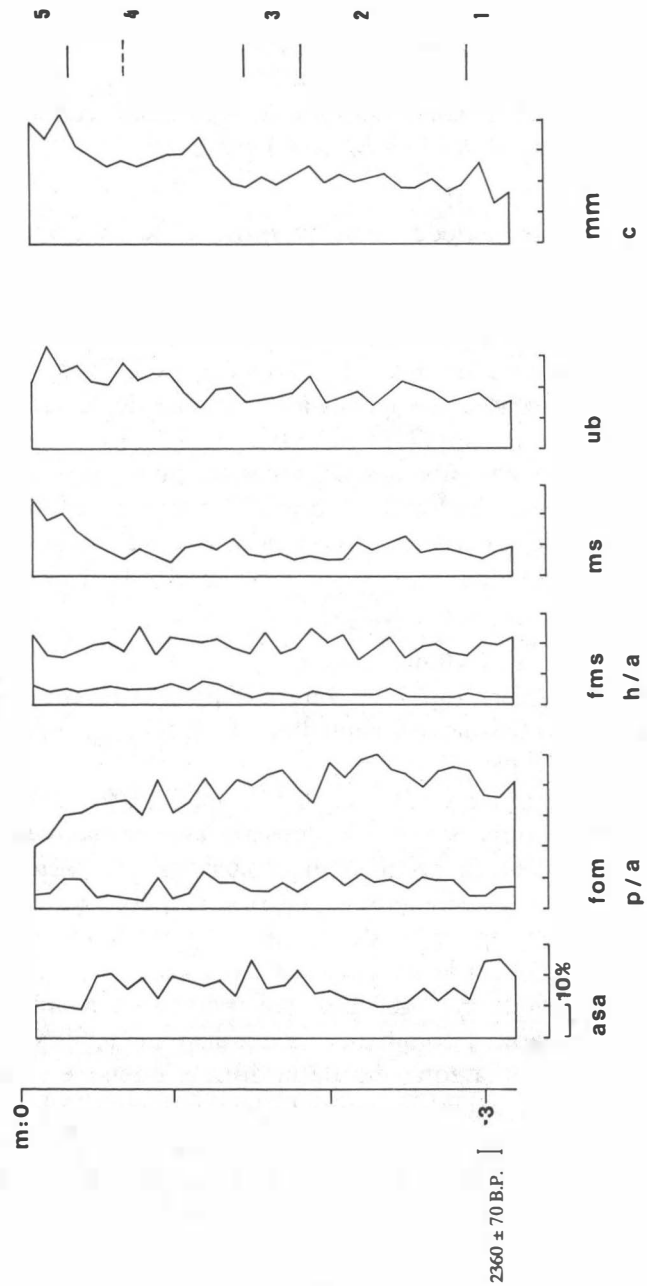


Fig. 5. — Gasare. Altitude : 2 300 m ; coordonnées : 2°28′ S, 29°14′ E.

Zone 3 : – 1,85 à – 1,45 m.

Une pulsation sèche de courte durée se manifeste à ce niveau. Elle est attestée par une progression de *Macaranga* et des formations sclérophylles à *Ericaceae* ainsi que par le recul des *Cyperaceae.*

Cet épisode serait contemporain de la phase climatique sèche observée ailleurs au Rwanda à *ca.* 1 400 ans B.P.

Zone 4 : – 1,45 à – 0,45 m.

Après la courte période sèche précédente, le milieu forestier où *Podocarpus* acquiert à nouveau de l'importance (du moins dans un premier temps) est conquis par *Hagenia.* Cela traduit le retour de conditions d'un climat relativement humide et froid.

On assiste ensuite au recul de *Podocarpus* et aux progressions successives des essences mésophiles à dominance de *Macaranga* et des formations afro-subalpines à *Ericaceae.*

Cette deuxième extension des *Ericaceae* accompagnée d'une progression des *Gramineae* traduit le retour de conditions climatiques plus sèches et froides qui correspondraient à la petite glaciation (16e-17e s.) caractérisée en Afrique de l'Est par une réactivation des glaciers en haute montagne.

Zone 5 : – 0,45 à – 0,10 m.

Dans cette dernière zone, une nouvelle progression de *Podocarpus* et le recul des taxons sclérophylles traduisent la phase actuelle d'humidité climatique.

Au sommet du profil, on remarque un recul des essences ombrophiles au profit des mésophiles parmi lesquelles *Hagenia* maintient son taux de présence antérieur. La progression sensible des *Gramineae* indiquerait une action anthropique (actions pastorales, feux courants, ...) qui expliquerait le développement de formations secondaires et de pelouses encore actuellement sur le versant sud du marais.

Durant la période de 2 400 ans que présente le profil de Gasare, la forêt montagnarde à dominance de taxons ombrophiles est présente en pemanence dans la zone sud de la dorsale orientale du Kivu. Les modifications intervenues au cours du temps dans la composition du couvert forestier (fluctuations des composantes ombrophile, mésophile et sclérophylle) relèvent des variations du climat qui, généralement plus humide et frais, a connu deux épisodes plus froids et plus secs, l'un qui se situerait à *ca.* 500 ans A.D., l'autre vers les 16e-17e siècles. Dans la moitié supérieure du profil, l'expansion de *Hagenia* est liée à

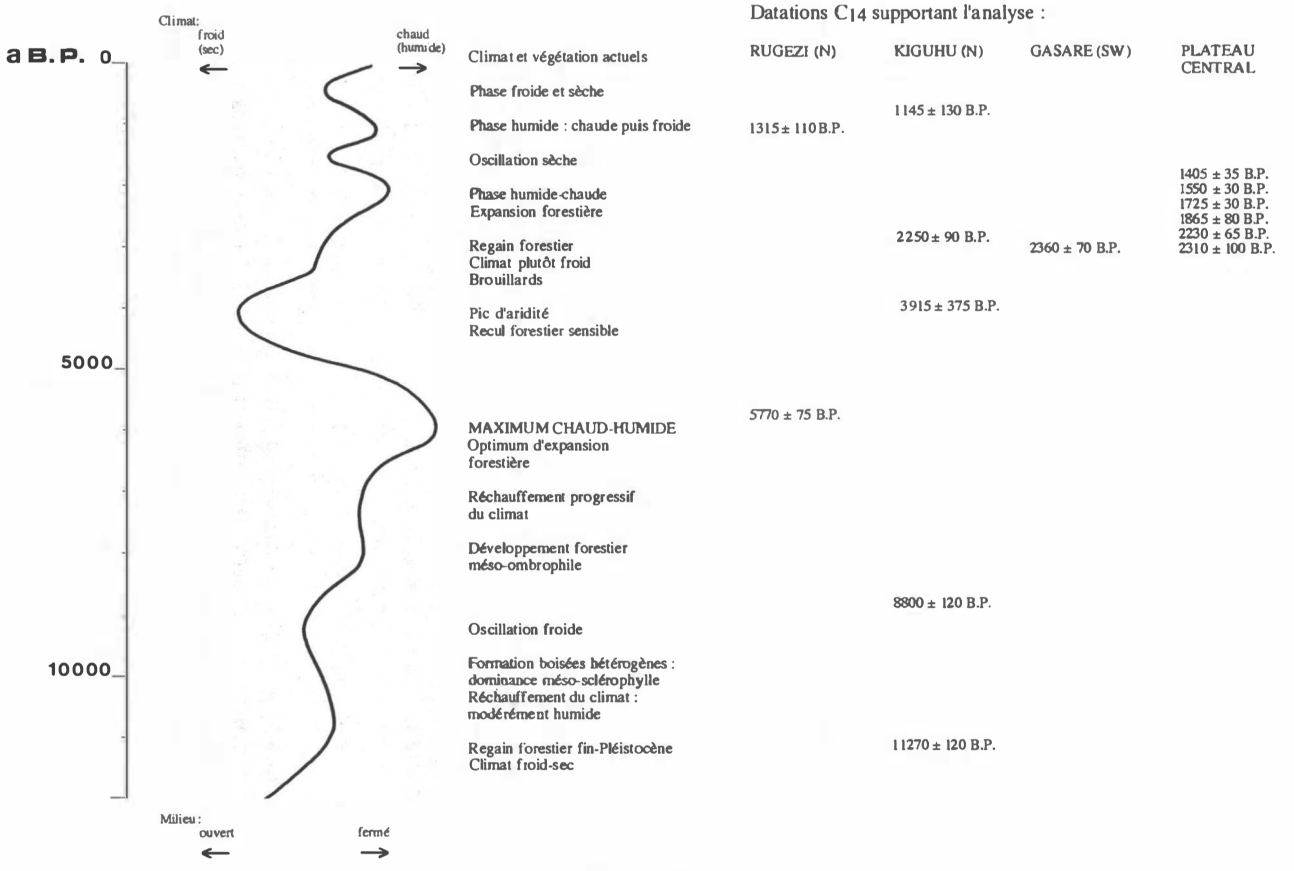


Fig. 6. — Rwanda : évolution du paléoenvironnement et du paléoclimat à l'Holocène.

l'évolution climatique mais aussi, à la fin de la séquence, à une altération d'origine anthropique.

Synthèse

L'analyse globale des épisodes environnementaux relevés par les trois séquences sédimentaires (Rugezi I, Kiguhu II, Gasare) relevées dans les régions montagneuses du Rwanda permet de dégager, sur base de datations C_{14}, l'évolution que le paléoclimat a connue au cours de l'Holocène (fig. 6).

On constate tout d'abord que la forêt afro-montagnarde a, en permanence, été présente sur les reliefs durant les dix derniers millénaires, même au cours des phases d'aridité qui ont marqué cette période. Ce sont donc les modifications qui apparaissent au sein même du milieu forestier qui sont le reflet des épisodes climatiques survenus depuis la dernière glaciation.

A la fin du Pléistocène (*ca.* 12 000 ans B.P.), des formations boisées hétérogènes méso-ombrophiles fortement teintées d'éléments sclérophylles occupent le milieu montagnard attestant l'existence d'un climat froid et sec.

Au début de l'Holocène et jusqu'à *ca.* 7 000 ans B.P., le couvert forestier évolue au cours du temps, les taxons ombrophiles y prenant progressivement une place prépondérante. Ce phénomène est révélateur d'un climat devenant petit à petit plus chaud et plus humide. Le réchauffement observé marque un temps d'arrêt, *ca.* 9 000 ans B.P., ponctué par une oscillation froide.

L'optimum chaud-humide atteint à *ca.* 6 000 ans B.P. se traduit par une extension maximale des taxons ombrophiles au sein de la forêt et par une marginalisation des éléments sclérophylles et même, au-dessus de 2 000 m, des genres mésophiles. Dans les milieux ouverts, Graminées et Cypéracées régressent sensiblement.

A cet optimum succède un important recul forestier attestant un pic d'aridité particulièrement sensible à *ca.* 4 000 ans B.P. Ensuite, on assiste à une réoccupation du terrain par des formations hétérogènes méso-ombrophiles. Celle-ci a dû s'opérer sous un climat plutôt frais présentant une humidité relative, principalement atmosphérique, entretenue par des brouillards en altitude.

Vers 2 000 B.P., une phase climatique chaude-humide est soulignée par une nouvelle progression de la composante forestière ombrophile. Elle est suivie, *ca.* 500 A.D., par une oscillation sèche de courte durée.

Ces faits sont corroborés par des observations archéo-environnementales effectuées par ailleurs sur le Plateau central (1 500-1 800 m d'altitude) du Rwanda.

A cette oscillation succède une phase humide, d'abord chaude, puis plus froide, précédant une nouvelle pulsation sèche qui se situerait vers les XVI^e^-XVII^e^ siècles et qui correspondrait au Petit Age glaciaire.

L'évolution vers l'environnement et le climat actuels se poursuit ensuite mais une action anthropique de plus en plus incisive interfère dans les phénomènes naturels.

BIBLIOGRAPHIE

HABIYAREMYE, F. X., ROCHE, E. & NTAGANDA, C. 1995. Le *Hagenietum abyssinicae* sur la dorsale orientale du Lac Kivu ; interprétations palynologiques et écologiques. — CIFEG-Orléans, P.O. 95/31, pp. 123-144.

LEWALLE, J. 1972. Les étages de végétation du Burundi occidental. — *Bull. Jard. Bot. Nat. Belg.*, **42** : 1-247.

LIBEN, L. 1962. Nature et origine du peuplement végétal (spermatophytes) des contrées montagneuses du Congo oriental. — Acad. R. Belg., Cl. Sci., Mém. in-4°, sér. 2, **15** (3) : 195 pp.

MOEYERSONS, J. & ROCHE, E. 1977. Evolution paléogéographique et phytosociologique en Afrique centrale durant le Pléistocène supérieur. Interprétation des données géomorphologiques, botaniques et palynologiques. — *Etudes d'Histoire africaine*, Lubumbashi, **XI-X** : 37-48.

ROCHE, E. 1991. Evolution des paléoenvironnements en Afrique centrale et orientale au Pléistocène supérieur et à l'Holocène. Influences climatiques et anthropiques. — *Bull. Soc. géographique de Liège*, **27** : 167-176.

ROCHE, E. 1996. L'influence anthropique sur l'environnement à l'Age du Fer dans le Rwanda ancien. — *Geo-Eco-Trop,* **20** (1-4) : 73-89.

ROCHE, E. & VAN GRUNDERBEEK, M. C. 1987. Apports de la palynologie à l'étude du Quaternaire supérieur au Rwanda. — Mém. Trav. E.P.H.E., Inst. Montpellier, **17** : 111-127.

ROCHE, E., BIKWEMU, G. & NTAGANDA, C. 1988. Evolution du paléoenvironnement quaternaire au Rwanda et au Burundi : analyse des phénomènes morphotectoniques et des données sédimentologiques et palynologiques. — Institut français de Pondichéry, Trav. sci. et techn., Pondicherry (India), **XXV** : 105-123.

VAN NOTEN, F. 1983. Histoire archéologique du Rwanda. — MRAC-KMMA (Tervuren), *Annales Sciences humaines*, Sér. in-8, **112** : 174 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 128-141 (1998)

Peat Accumulation Rate in Rwanda and Burundi. An Indicator of Long-term Climatic Changes?

by

Hannu PAJUNEN *

KEYWORDS. — Bogs ; Peat ; Sedimentation Rates ; Climatic Change ; Radiocarbon Dating ; Rwanda ; Burundi.

ABSTRACT. — The time of mire initiation and the accumulation rate of peat and carbon were studied in the Akanyaru swamp complex and in two smaller peat deposits situated in the western rift valley. The time of mire initiation varies from 20,200-1,600 B.P. The oldest peat deposits are in the southern part of the Akanyaru swamp complex and the youngest are in the rift valley region.

During the last glacial stage the climate was mainly dry and peat accumulation rates remained low. Increasing humidity in the early Holocene made conditions favourable for accumulation of peat and increasing dryness after mid-Holocene made them again unfavourable. The increased dryness of the climate is more clearly distinguishable in the accumulation rates than the increasing humidity. In most of the mires there were periods with high accumulation rates during the last two millennia, caused by the increased humidity of the climate and by non-climatic factors. The effect of human activities on the peat accumulation rate becomes more significant the closer we get to the present, and it may totally obscure the effect of small climatic changes.

MOTS-CLES. — Marécage ; Tourbière ; Vitesse de sédimentation ; Changement climatique ; Datation C_{14} ; Rwanda ; Burundi.

RESUME. — *Taux d'accumulation de la tourbe au Rwanda et Burundi. Un indicateur de changements de climat à long terme.* — Le temps nécessaire à l'apparition d'une tourbière et la vitesse d'accumulation de la tourbe et du carbone ont été étudiés dans le complexe de l'Akanyaru ainsi que dans

* Geologist ; Geological Survey of Finland, P.O. Box 1237, FIN-70211 Kuopio (Finland).

deux dépôts plus modestes du Rift. Le premier varie entre 20 200 et 1 600 B.P. La tourbe la plus ancienne se trouve dans le sud du complexe de l'Akanyaru et la plus récente dans le Rift. Pendant le dernier âge glaciaire, le climat était plutôt sec et le taux d'accumulation de la tourbe est resté bas. L'humidité croissante au début de l'Holocène a donné des conditions favorables à l'accumulation de la tourbe tandis que la sécheresse croissante de l'Holocène moyen a de nouveau dégradé ces conditions. Une sécheresse croissante se distingue plus clairement dans les taux d'accumulation qu'une croissance d'humidité. Dans la plupart des tourbières, il s'est produit des périodes avec forte accumulation durant les deux derniers millénaires ; celles-ci sont dues à une humidité croissante et à des facteurs non climatiques. Les effets de l'activité humaine sur l'accumulation sont devenus plus significatifs, à mesure que l'on s'approche de la période actuelle ; ils ont même pu masquer complètement les effets de petits changements climatiques.

TREFWOORDEN. — Moeras ; Veen ; Sedimentatiesnelheid ; Klimaatverandering ; C_{14} datering ; Rwanda ; Burundi.

SAMENVATTING. — *Veenaccumulatiesnelheid in Rwanda en Burundi. Een indicator van klimaatveranderingen op lange termijn ?* — De periode van opbouw van drasland en veen- en koolstofaccumulatie werd bestudeerd in het Akanyaru moerascomplex en in twee kleinere veenafzettingen gesitueerd in de westelijke riftvallei. De periode van vorming van drasland varieert van 20 200-1 600 B.P. De oudste veenafzettingen bevinden zich in het zuidelijk deel van het Akanyaru moerascomplex en de meest recente in het riftvalleigebied. Gedurende de laatste ijstijd was het klimaat voornamelijk droog en was de veenaccumulatie laag. Toenemende vochtigheid in het vroege Holoceentijdperk creëerde gunstige condities voor veenaccumulatie ; de toenemende droogte na het midden-Holoceen was dan weer de oorzaak voor ongunstige condities. De toegenomen droogte van het klimaat is duidelijker waarneembaar in de accumulatiesnelheid in vergelijking met de toegenomen vochtigheid. In de meeste draslanden zijn er periodes geweest met een hoge accumulatiesnelheid gedurende de laatste twee millenia en dit ten gevolge van de toegenomen vochtigheid van het klimaat en tevens door niet-klimatologische factoren. De menselijke invloed op de veenaccumulatiesnelheid wordt belangrijker naarmate het heden nadert en kan op die manier het effect van kleinere klimaatveranderingen verbergen.

Introduction

The majority of present peatlands are situated in glaciated, high latitude areas, where the maximum age of peat is limited by deglaciation or shoreline displacement. Such limiting factors are missing in Rwanda

and Burundi and data recorded by their peat deposits can extend beyond the last glacial/postglacial transition. Palynological studies carried out in Rwandan and Burundian highlands confirm that certain mires had already started accumulating peat before 30,000 B.P. (HAMILTON 1982, BONNEFILLE & RIOLLET 1988).

In Rwanda and Burundi the most extensive peat deposits are situated in river valleys (fig. 1). In the highland area numerous small peat deposits occur along the main watershed. In the 1980s a peat project, aimed at finding domestic fuel for the processing of the Musongati nickel ore, was carried out in Burundi and in the 1990s the "peat master plan study" was carried out in Rwanda. The data collected during these projects included, for example, descriptions of peat stratigraphy and dry bulk density. Later it was possible to supplement the data with age determinations and to calculate peat accumulation rates. The stratigraphy of the deposits was discussed in detail in a previous paper (PAJUNEN 1996). In this paper peat accumulation rates from six cores were discussed. Four of them are situated in the Akanyaru swamp complex, one in the Gishoma swamp and one in the Mashya bog.

During recent years, the role of peatlands as a sink or as a source of atmospheric carbon has been of great interest (e.g. GORHAM 1991, MALTBY & IMMIRZI 1993, FRANZEN 1994). Growth models for peat deposits have been presented and peat accumulation rates studied. The published data deals mainly with peatlands of boreal areas. Accumulation data from tropical environment is limited to few countries.

Methods

The botanical composition and the decomposition degree of peat were determined in the field. Samples for laboratory analyses were taken with a Russian type sampler and with a volumetric piston sampler. Determinations of dry bulk density were based on volumetric samples. Samples taken to the laboratory were analysed for water content, dry bulk density, ash content and carbon content. Peat deposits having ash content higher than 30 % were excluded.

Altogether thirty-three samples were dated at the radio carbon laboratory of the Geological Survey of Finland. The ^{14}C ages were converted to calendar years for calculation of average thickness increment and dry matter accumulation rates. The age calibration was done with a computer program (STUIVER & REIMER 1993). The

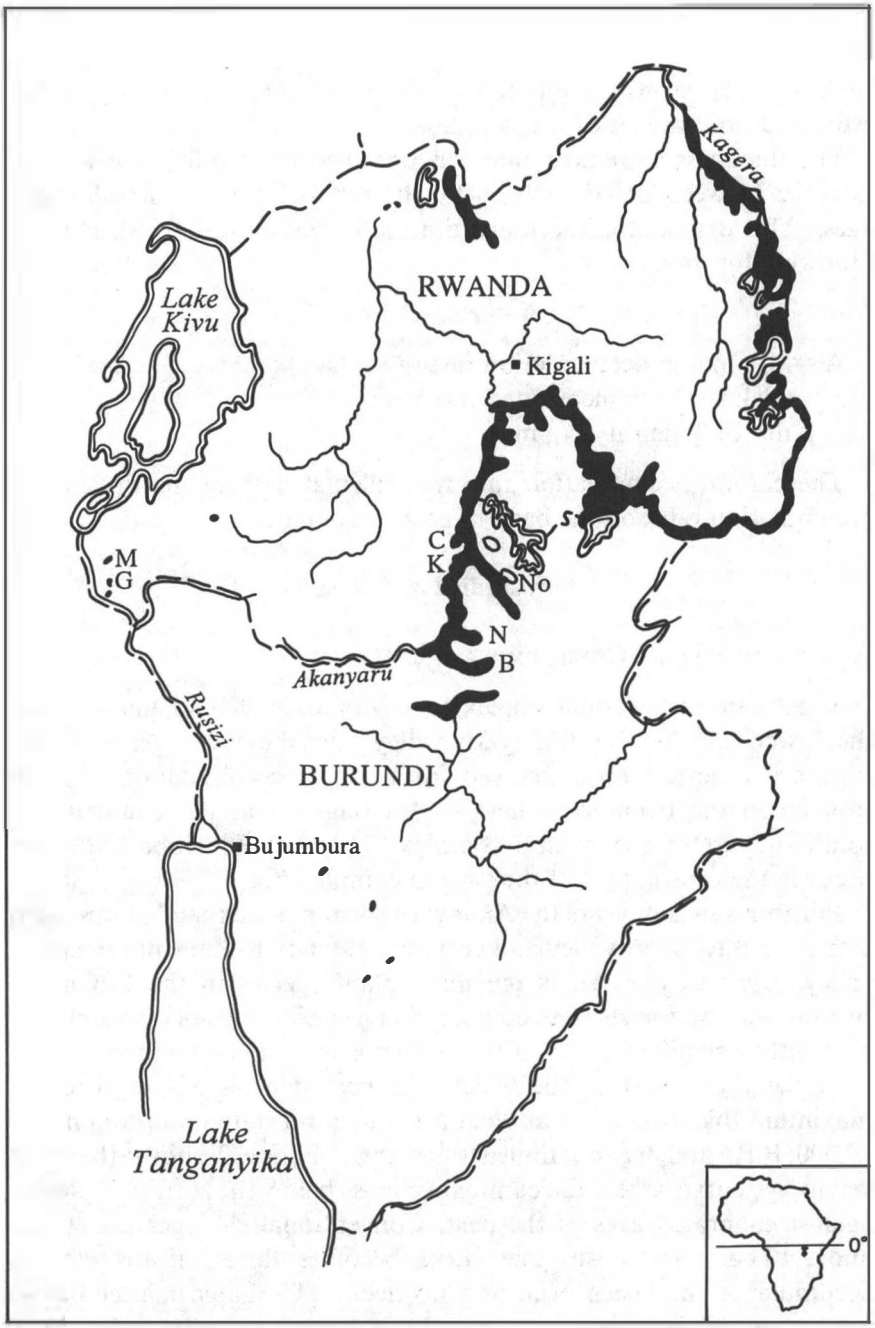


Fig. 1. — Black areas indicate the location of peat deposits in Rwanda and Burundi. Peat accumulation data is available from the swamps of Buyongwe (B), Ndurumu (N), Kinamba (K) and Cyili (C) within the Akanyaru swamp complex and from the Gishoma swamp (G) and Mashya bog (M) in the rift valley region. The location of the Nyavyamo swamp is indicated by No.

calibration curve was smoothed to an extent commensurate with the estimated time-widths of the samples.

The thickness increment rate was obtained by dividing the vertical distance between dated samples by the difference between calibrated ages. The dry matter accumulation rate was calculated using the following formula :

$$A = r \rho, \text{ where :}$$

A = dry matter accumulation rate (g m^{-2} a^{-1}) ;
r = thickness increment rate (mm a^{-1}) ;
ρ = dry bulk density (kg m^{-3}).

The carbon accumulation rate was calculated from the dry matter accumulation rates on the basis of carbon content.

Areas studied and Results

Akanyaru Swamp Complex

The Akanyaru swamp complex covers about 25,900 ha and occupies the lower part of the Akanyaru valley and the lower parts of the tributary valleys. Cores surveyed for the peat accumulation rate are situated in the tributary valleys of Buyongwe and Ndurumu in the southern part of the swamp complex. Those at Kinamba and Cyili occur in the central part of the swamp complex (fig. 1).

For thousands of years the Akanyaru swamp has expanded upstream along the Buyongwe valley and currently extends 15 km from the main valley. *Cyperus papyrus* is the main plant species in the Buyongwe swamp. Swamp forests were common in an earlier stage of development. Currently a significant part of the swamp is used in agriculture.

In the lower part of the valley, the peat deposit has reached the maximum thickness of 29 m. Peat accumulation started approximately 12,000 B.P., and has continued since then. Figure 2 shows the mass versus age curve, where the cumulative mass below the surface is plotted against calibrated ages of the peat. Conventional ^{14}C ages are shown above. The mass versus age curve becomes linear, if the rate of accumulation has been even and no decay of organic matter occurs in the anaerobic part of the peat layer, called catotelm. The decay of the organic matter in the catotelm or increasing accumulation rate makes the curve concave. A decreasing accumulation rate makes the curve convex, provided that there is no decay of organic matter in

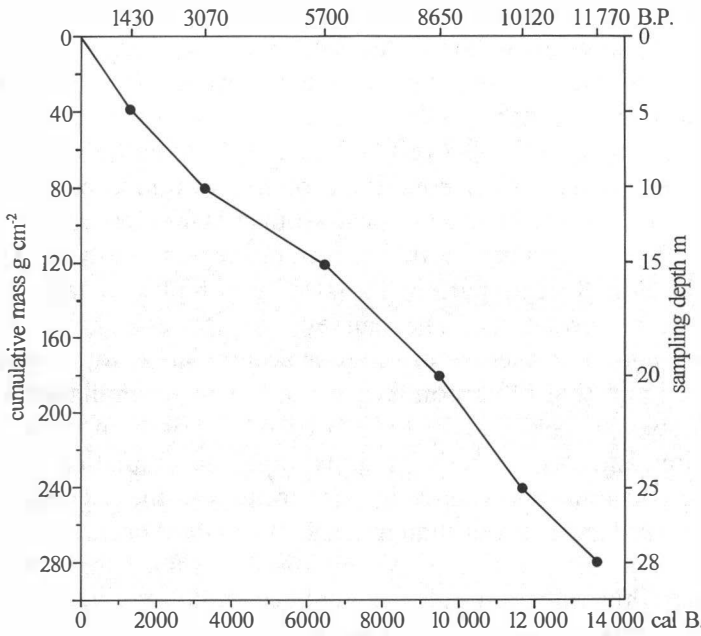


Fig. 2. — Cumulative mass of total dry matter below the surface plotted against calibrated ages of the peat in the Buyongwe swamp.

the catotelm. In the mass versus age curve for the Buyongwe swamp there is a slightly convex section formed during the early Holocene and a slightly concave section formed after the middle of the Holocene.

On an average, the dry matter accumulation rate has been 201 g m^{-2} a^{-1} and that of carbon 104 g m^{-2} a^{-1}. The rate of dry matter accumulation has been at its maximum during the early Holocene, 10,000-9,000 B.P. The lowest accumulation rates occur after the mid-Holocene. In the uppermost part of the deposit, formed after 1,400 B.P., the rate of dry matter accumulation is almost as high as it was during the early Holocene.

In the southern part of the Ndurumu swamp, *Miscanthidium* grass occurs with species of *Cyperus* and ferns. The peat deposit has low bulk density and ash content, and has a maximum thickness of 32 m. Peat has accumulated for 20,000 years, the peat stratigraphy indicating that this process has been uninterrupted. The average dry matter accumulation rate has been 108 g m^{-2} a^{-1} and that of carbon 56 g m^{-2} a^{-1}. There is a long time interval between the two lowermost samples

and therefore late Pleistocene/early Holocene variations cannot be identified. The lowermost layer (20-32 m) probably includes notable variations in the accumulation rate. In the uppermost 20 m deep layer, which was formed after 7,380 B.P., the minimum rate of peat accumulation occurred 4,640-2,060 B.P. and the maximum rate 2,060-1,410 B.P. The hydrological conditions of the swamp became more favourable for the accumulation of peat around 2,000 B.P.

C. papyrus reed swamp is the prevailing vegetation type in the Kinamba swamp. In this part of the swamp complex, a lake phase preceded mire formation. The survey site terrestrialized about 10,000 years ago. The average dry matter accumulation rate has been 124 g m^{-2} a^{-1} and that of carbon 68 g m^{-2} a^{-1}. The accumulation rates vary from layer to layer. There have been two periods of quite slow accumulation and two periods of quite rapid accumulation (fig. 3). During the two millennia following mire formation the accumulation rates were considerably lower than average, the highest occurring 8,300-6,500 B.P. After this period the accumulation continued for 800 more years at nearly the same rate. The smallest accumulation rates occurred 5,700-1,700 B.P. The accumulation rates in the uppermost layer, formed after 1,700 B.P., again exceed average values.

Cladium reed swamp prevails in the lower part of the Cyili valley. The peat deposit is about 10 m deep. The peat formation initiated approximately 2,500 years ago. Since then, the peat deposit has grown

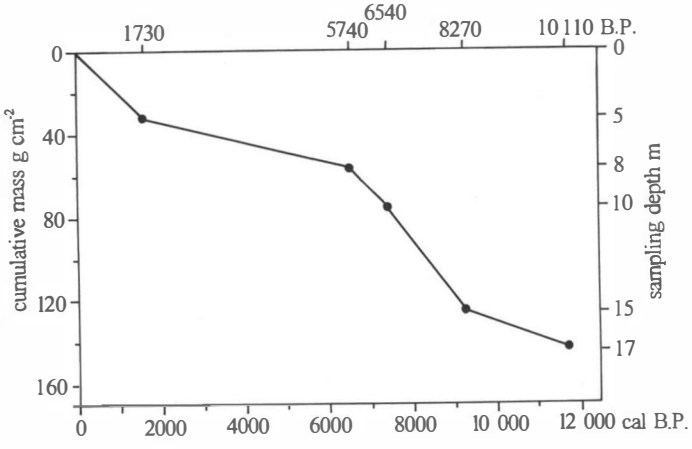


Fig. 3. — Cumulative mass of total dry matter below the surface plotted against calibrated ages of the peat in the Kinamba swamp.

by an average of 3.48 mm a^{-1}. The surface part is very watery and slightly decomposed. Therefore volumetric samples are not available and it was not possible to calculate accumulation rates for the uppermost 2 m deep layer. The average dry matter accumulation rate during the period 2,495-190 B.P. was 209 g m^{-2} a^{-1} and that of carbon 113 g m^{-2} a^{-1}. The maximum rates occurred 1,370-950 B.P.

Rift Valley Region

The Gishoma swamp is situated in the rift valley region at an elevation of 1,620 m. Part of the deposit has been used for fuel and currently the swamp is used in agriculture. The bedrock of the drainage basin has been broken by tectonic faults into several blocks (Pajunen & Karega 1994), and the mire basin has been formed as a consequence of the vertical movements of these blocks. In the main basin a lake was formed and later terrestrialized.

The age of a sample series from the southern part of the main basin and two basal peat samples were determined. The time of peat initiation was 2,000-1,440 B.P. The southern part of the main basin terrestrialized about 1,600 B.P., at the beginning of a short dry phase detected by palynological studies in the Burundian highlands (Roche & Bikwemu 1989). This dry phase may have lowered the water surface in the Gishoma basin and thus favoured the filling-in of the water body (Korhola 1992).

Since terrestrialization, the accumulation has continued uniformly until the present day. In the southern part of the main basin, the average dry matter accumulation rate is 153 g m^{-2} a^{-1} and that of carbon 86 g m^{-2} a^{-1}. The average accumulation rates indicate that there are only small areal variations. However, time periods indicate that variations in accumulation rates are more than twofold. The highest rates occurred 1,375-1,170 B.P. and the lowest after 285 B.P.

Mashya is a small bog covering about 30 ha and lying at an elevation of 1,700 m. The bog has a slightly domed surface. *Syzygium* trees and *Sphagnum* moss prevail in the central part and *Cyperus* species in the marginal zone. The peat deposit is more than 4 m deep. Wood remains are common and the decomposition degree varies according to the layers. A well-decomposed peat layer lies at the depth of 0.7-1.0 m. The layer extends all over the bog and includes charcoal. Mineral matter, washed down from the drainage basin, has been deposited in

the marginal zone. In the central part of the bog the ratio of mineral matter is extremely small.

Peat started to accumulate about 1,900 B.P. during a short humid phase (ROCHE & BIKWEMU 1989) and has continued since then without interruptions (fig. 4). The upper part of the cumulative mass versus age curve is somewhat convex, indicating a slight decrease in the accumulation rate during the last millennia. The average dry matter accumulation rate is 163 g m^{-2} a^{-1} and that of carbon 91 g m^{-2} a^{-1}. The maximum rate occurred 1,305-980 B.P. and the minimum rate after 510 B.P. The uppermost layer, formed after 510 B.P., probably includes notable variations in the accumulation rate, but they are not possible to detect in this data.

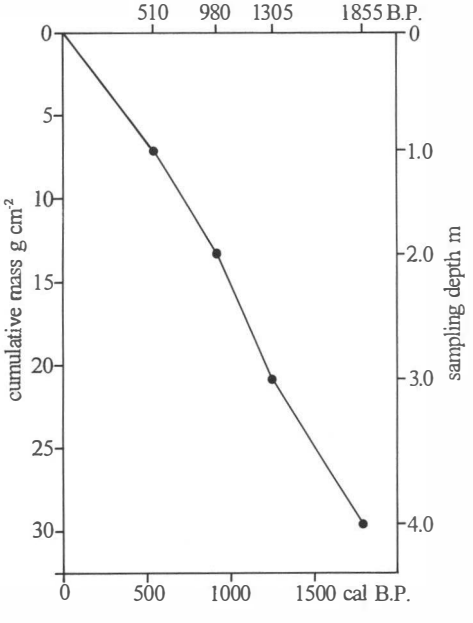


Fig. 4. — Cumulative mass of total dry matter below the surface plotted against calibrated ages of the peat in the Mashya bog.

Discussion

The changes in peat accumulation rates are due to changes either in the production of biomass or in the activity of decay organisms. Primary production may vary with the normal development of the

mire, so that the productivity changes with variations in the peat-forming vegetation. The decay process again is affected by numerous factors, e.g. pH, nutrient content, the type of plant matter and the hydrology of the mire. Since the accumulation percentage of the peat is the result of several factors, the changes in accumulation rate may also be due to a number of reasons. It is hard to distinguish between these various factors (FRENZEL 1983).

The changes in plant material decay rate are, however, more significant than the changes in biomass production. In many peat deposits there are large changes in accumulation rate without notable changes in vegetation. According to DAMMAN (1979), the accumulation of peat is mainly controlled by the slow decay of organic material, not by rapid production. The changes in efficiency of the decay process are mainly due to changes in the hydrology of the mire, which may in turn be due to climatic changes or non-climatic reasons.

It is generally accepted that increasing soil moisture is a prerequisite for the onset of mire formation and for the accumulation of peat deposits. Wateriness of a basin may increase for numerous reasons. Some are related to climatic changes, others to geological processes and human activities. Increasing precipitation and decreasing temperature are the most important climatic factors favouring mire formation.

The most significant Holocene climatic changes in the study area occurred about 10,000 B.P. and 4,500 B.P. If the increased humidity had led to expansion of the mire areas, the times of peat initiation would be concentrated in the early Holocene. As shown by the material here this is not, however, the case. The Ndurumu basin started accumulating peat during the last ice age, just before the aridity maximum, the Buyongwe basin during the late Pleistocene and the Kinamba basin at the beginning of the Holocene. The basins of Cyili, Gishoma and Mashya started accumulating peat during the late Holocene.

If it is assumed that the increasing humidity made the conditions favourable for accumulation of peat and increasing dryness made them unfavourable, the periods of high accumulation rates should be concentrated in the early Holocene and those with low accumulation rates should occur after the mid-Holocene. The swamps of Buyongwe, Ndurumu and Kinamba had high accumulation rates during the early Holocene, but according to the present data they are not synchronous (fig. 5). All these three swamps had minimum rates after the mid-Holocene. The increased dryness of the climate is more clearly

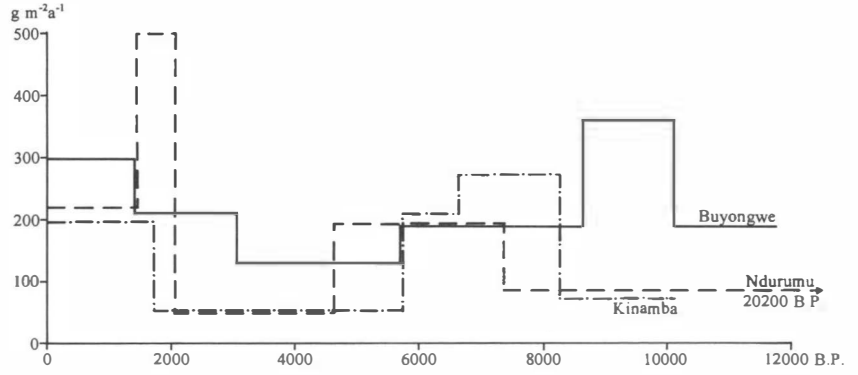


Fig. 5. — Variations in the dry matter accumulation rate in the Buyongwe, Ndurumu and Kinamba peat deposits.

distinguishable in the accumulation rates than the increasing humidity. In most of the mires there were periods of high accumulation rates during the last two millennia, caused by the increased humidity of the climate and also by non-climatic factors. Most of these factors are related to increasing human activities.

Late Holocene variations in the peat accumulation rate are more easily seen in the profiles of Cyili, Gishoma and Mashya. All these mires had maximum rates at 1,400-1,000 B.P. (fig. 6). The reasons to these maximum rates are most probably climatic. According to HABERYAN & HECKY (1987), Kivu was a closed lake between 3,500 and 1,400 B.P. The reopening of Ruzizi around 1,400 B.P. is synchronous

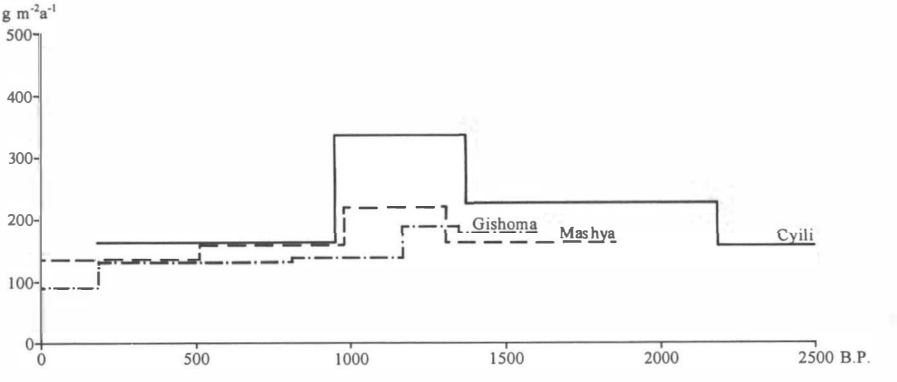


Fig. 6. — Variations in the dry matter accumulation rate in the Cyili, Gishoma and Mashya peat deposits.

with increasing accumulation rates. Both indicate increasing climatic humidity. The period of high accumulation rates is slightly older than the "Medieval Warm Period", which occurred in Europe around 1,080-1,180 A.D. (GOUDIE 1992). The highly decomposed peat layer of the Mashya bog formed after 510 B.P. and is synchronous with the "Little Ice Age".

Besides climatic factors there are many other factors changing the hydrology of the mire and thus affecting the accumulation rates. In the Akanyaru area the crust is inclined towards the south-east. The topography and the thickness of the peat deposits indicate that the northern part of the present swamp complex must have risen more rapidly than the southern part. The inclination of the crust towards the south-east is also reflected by the gentle gradient of, and extremely wet peat deposit in the Nyavyamo swamp extending south-east from the main valley.

The inclination of the Earth's crust has caused the swamp complex to expand further in the eastern than in the western tributary valleys of Akanyaru (fig. 1). Since the water level rises faster in the bays extending eastwards than in those extending westwards, it is also probable that the peat accumulation rates are higher in the former than in the latter. Accordingly, the peat accumulation rates in the southern part of the swamp complex should be higher than in the northern part. The present data are from the central and southern part near the main river valley, and thus do not prove the effect of the tectonic inclination on the variation in accumulation rates.

Human activities in the drainage basin have influenced the hydrology of the rivers in the present study area. The decrease of forests in the drainage basin has increased the discharge and its seasonal fluctuations. The conditions have turned more favourable for the accumulation of peat due to the increased wateriness. Occasionally, the increased wateriness has led to the decrease of the swamp forests. The influence of human activities is limited to the time after the beginning of the Iron Age which occurred approximately 2,000 B.P. (VAN GRUNDERBEEK *et al.* 1983). The production of iron implements made it possible to expand cultivation. In addition the production of iron required abundant charcoal, which contributed to the diminishing of the forests. Changes in land use have affected the swamp development. This is especially clear in the Akanyaru swamp complex where, since the beginning of the Iron Age, the area of swamp forest has decreased

and the accumulation rate of peat increased. Further, there has been marked increase in silting during this century.

Conclusions

The changes in the macro-climate have affected the hydrological conditions in the river valleys and thus the accumulation rate of peat. Synchronous changes with the same increasing or decreasing trends may be interpreted to be a response to the climate. However, changes to a drier climate are more pronounced than those to a wetter climate. This is understandable, because dry conditions are extremely crucial for the existence of tropical peat deposits. Besides climatic reasons, numerous other factors have affected the accumulation rate of peat in Rwanda and Burundi. Some of these are related to geological processes, others to human activities. Local non-climatic reasons have confused, and in some basins totally obscured, the main trends determined by changes in the macro-climate.

REFERENCES

BONNEFILLE, R. & RIOLLET, G. 1988. The Kashiru pollen sequence (Burundi) palaeoclimatic implications for the last 40,000 yr B.P. in tropical Africa. — *Quaternary Research*, **30** : 19-35.

DAMMAN, A. W. H. 1979. Geographic patterns in peatland development in eastern North America. — *In* : Proceedings of Symposium on Classification of peat and peatlands (International Peat Society, Hyytiälä, Finland, September 17-21, 1979), University of Helsinki Printing Services, Helsinki, pp. 42-57.

FRANZEN, L. G. 1994. Are Wetlands the Key to the Ice-age Cycle Enigma? — *Ambio*, **23** : 300-308.

FRENZEL, B. 1983. Mires - repositories of climatic formation or self-perpetuating ecosystems? — *In* : GORE, A. J. P. (ed.), Mires : swamp, bog, fen and moor, General Studies. Ecosystems of the World 4A, Elsevier, Amsterdam, pp. 35-65.

GORHAM, E. 1991. Northern peatlands : role in the carbon cycle and probable responses to climatic warming. — *Ecological Applications*, **1** : 182-195.

GOUDIE, A. 1992. Environmental Change. Contemporary Problems in Geography. — Oxford University Press, New York, 329 pp.

HABERYAN, K. A. & HECKY, R. E. 1987. The Late Pleistocene and Holocene stratigraphy and paleolimnology of lakes Kivu and Tanganyika. — *Palaeogeography, Palaeoclimatology, Palaeoecology*, **61** : 169-197.

HAMILTON, A. C. 1982. Environmental history of East Africa : A study of the Quaternary. — Academic Press, London, 328 pp.

KORHOLA, A. 1992. Mire induction, ecosystem dynamics and lateral extension on raised bogs in the southern coastal area of Finland. — *Fennia*, **170** (2) : 25-94.

MALTBY, E. & IMMIRZI, P. 1993. Carbon dynamics in peatlands and other wetland soils, regional and global perspectives. — *Chemosphere*, **27** : 999-1023.

PAJUNEN, H. 1996. Mires as late Quaternary accumulation basins in Rwanda and Burundi, Central Africa. — *Bulletin Geological Survey of Finland*, **384** : 104 pp.

PAJUNEN, H. & KAREGA, E. 1994. Accumulation of peat and energy in a tropical mire in south-western Rwanda. — *In* : Wetland Environment and Peatland Utilization. Proceedings of the International Conference 1994 on Wetland Environment and Peatland Utilization (Changchun, P.R. China, August 9-11, 1994), Jilin People's Publishing House, Changchun, pp. 147-156.

ROCHE, E. & BIKWEMU, G. 1989. Palaeoenvironmental change on the Zaire - Nile ridge in Burundi ; the last 20,000 years : An interpretation of palynological data from the Kashiru Core, Ijenda, Burundi. — *In* : MAHANEY, W. C. (ed.), Quaternary and Environmental Research on East African Mountains. York University, Balkema, Rotterdam, pp. 231-242.

STUIVER, M. & REIMER, P. J. 1993. Extended ^{14}C data base and revised calib 3.0 ^{14}C age calibration program. — *Radiocarbon*, **35** : 215-230.

VAN GRUNDERBEEK, M.-C., ROCHE, E. & DOUTRELEPONT, H. 1983. Le premier âge du fer au Rwanda et au Burundi, archéologie et environnement. — Institut national de Recherche scientifique, Butare, République Rwandaise, Publication **23** : 57 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 142-175 (1998)

The Quaternary Geology around the Great Lakes in Central Africa. Pluvials and Interpluvials are not the Equivalent of Glacials and Interglacials

by

Elfi VAN OVERLOOP * & Roland PAEPE **

with the collaboration of Members of the Centre for Quaternary Research
in the African Rift and Olduvai CEQUARO, Lutumba P. ILUNGA (Zaire, Burundi),
Symphorien KASEBA (Zaire), Peter KAFUMU DADALI (Tanzania) &
Jack H. MUSISI (Uganda)

KEYWORDS. — Palaeoclimatic Cycles ; Fossil Soils ; Central Africa ; Pluvials and Interpluvials.

ABSTRACT. — The Pluvial Theory in which Pluvials and Interpluvials were considered by LEAKEY (1959) to indicate in the Tropics the equivalents of Glacials and Interglacials of the Temperate Belt was a first attempt to correlate Tropical with Nordic Boreal climatic Stages. Pluvials were thought to be the result of a humidity increase in the tropical belt during periods corresponding to glaciation in the temperate belt. Interpluvials were then simply considered as interperiods between two pluvials with a climate similar to the tropical climate today. This was far too great a simplified statement which led to a number of misinterpretations. Since the 1980s detailed quaternary stratigraphic research has been enhanced by the Department for Quaternary Research (Paepe) of the VUB together with research students of the International postgraduate training course on Fundamental and Applied Quaternary Geology-IFAQ (Van Overloop) in the Great Lake Region respectively between Lake Tanganyika, Kivu, George and Albert namely : in the Ruzizi (ILUNGA 1984), Rutshuru (YAMBA TSHISUNGU 1993) and Semliki (GAUTIER 1967) River Plains on the border between Zaire, Uganda, Rwanda and Burundi and along the Kazinga Channel in Uganda (MUSISI 1991).

* International postgraduate training course on Fundamental and Applied Quaternary Geology IFAQ, Earth Technology Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussel (Belgium).

** Belgian Geological Survey and Department Quaternary Geology and Department Applied Geology, Earth Technology Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussel (Belgium).

Recently there was also a new attempt in the Olduvai Gorge, Tanzania (KAFUMU 1995). The recording of several geo-soil (palaeosoil) sequences with geo-soils interfering with either lake or river sediments led to the identification of a number of humid tropical forest phases (indicated by the geo-soils) and relatively dryer phases in-between (indicated by the clastic sediments). Furthermore, the number of geo-soils could be correlated with land-series of geo-soil sequences elsewhere such as in the Loess deposits of China and in the loessoid deposits in Greece, thus attesting the global character of their cyclicity. Moreover, the geo-soil sequences in all of the studied places showed perfect correlation with the odd isotopic stages of the deep-sea cores (PAEPE 1995) in both number and stratigraphic position. Thus, it was proved that warm humid phases of the tropics corresponded to warm humid phases of the temperate and boreal belts. Henceforth, boreal interglacials do equally correspond to warmer and more humid phases in the tropics. By no means should a wet warm Pluvial be correlated with a Glacial! Another important conclusion resulting from this is the global synchronism of drought and wet phases throughout the long-term 2.6 Ma timespan of the Quaternary. Also, considering the middle-term cycle of the Last Interglacial/Glacial Cycle or last 130 Ka, it is found that phases of drought and more especially the cold/drought maximum of about 20,000 years ago as well as the Younger Dryas of about 11,000 years ago are synchronous and enhanced desertification all over the globe : polar desert in Belgium (PAEPE 1963), expansion of the Sahara (PETIT-MAIRE 1990), drought on the African equator (ILUNGA 1984, MUSISI 1991, KAFUMU 1995, KASEBA 1996). Even the short-term cycle of the Holocene or current interglacial of the last 10,000 years is attesting at least 20 cycles of drought with a periodicity of 1,000 years of which the so-called Sahel drought is most probably the last phase, thus pointing at a possible naturally induced desertification rather than a man-made Greenhouse Effect. The well-known carbon dioxide cycle of 2,500 years (the so-called Suess cycle) stands for the fourfold subdivision of the Holocene in Boreal, Atlantic, Sub-Boreal and Sub-Atlantic subphases, which phases perfectly tally with the Neolithic, Bronze Age and Historic Times in the Greek Mediterranean Regions (PAEPE *et al.* 1995). Finally, the afore clearly reflects that changes in the environment at one specific spot of the Earth's surface have an almost immediate global response simultaneously using the atmosphere as a catalyst as seems experienced in today's depletion of the Amazone Tropical Forest.

MOTS-CLES. — Cycles paléoclimatiques ; Sols fossiles ; Afrique centrale ; Pluviaux et Interpluviaux.

RESUME. — *La géologie quaternaire autour des Grands Lacs en Afrique centrale. Les Pluviaux et Interpluviaux ne sont pas les équivalents des Glaciaires et des Interglaciaires.* — La théorie pluviale, par laquelle les Pluviaux et Interpluviaux furent introduits par LEAKEY (1959) pour indiquer

les équivalents des Glaciaires et Interglaciaires, fut une première tentative de corréler les étages des Tropiques avec ceux du Nord boréal. Les Pluviaux furent considérés comme le résultat d'une hausse de l'humidité dans la zone tropicale pendant des périodes correspondant aux glaciations des régions tempérées. Les Interpluviaux furent considérés comme une simple période intermédiaire entre deux pluviaux caractérisés par un climat très semblable à celui d'aujourd'hui dans les tropiques. Ce concept trop simplifié conduit à un grand nombre d'opinions erronées. Depuis 1980, des recherches détaillées de stratigraphie quaternaire détaillée ont été entamées par le Département de Géologie du Quaternaire (Paepe) de la VUB en liaison avec les chercheurs du «International postgraduate training course on Fundamental and Applied Quaternary Geology-IFAQ» (Van Overloop) dans la Région des Grands Lacs, respectivement entre les lacs Tanganyika, Kivu, George (Idi Amin) et Albert (Mobutu) notamment : dans les plaines de la Ruzizi (ILUNGA 1984), Rutshuru (YAMBA TSHISUNGU 1993) et Semliki (GAUTIER 1967) sur la frontière entre le Zaïre, l'Ouganda, le Rwanda et le Burundi ainsi que le long du Canal de Kazinga en Ouganda (MUSISI 1991). Le levé de plusieurs séquences de géosols (paléosols) avec intermittence de géosols et de dépôts de lacs et de rivières permettait la détermination de multiples phases de forêt humide tropicale (géosols) et de phases intermédiaires plutôt sèches. Le nombre de géosols relevés a pu être corrélé avec celui des séries de géosols trouvées ailleurs comme dans les dépôts de loess de Chine ou encore dans les dépôts loessoïdes de Grèce attestant ainsi la présence synchrone de ces cycles dans le monde entier. Par ailleurs, ces séquences de géosols démontrent dans toutes les régions étudiées une corrélation parfaite avec les étages d'isotopes stables impairs de séquence du fond océanique (PAEPE *et al.* 1995) tant par leur nombre que par leur position stratigraphique. Ainsi fut démontré que les phases chaudes humides des tropiques correspondent aux phases chaudes humides des régions tempérées et boréales. En conséquence, les interglaciaires boréaux coïncident de même avec les phases chaudes et plus humides des tropiques. En aucun cas on ne peut donc corréler un Pluvial chaud-humide avec un Glaciaire! Une deuxième conséquence qui en émane vise le synchronisme des phases sèches et humides dans le courant de la longue série temporelle de 2,6 Ma dans l'intervalle du Quaternaire. Même si on considère la série temporelle moyenne du cycle Dernier Interglaciaire/Glaciaire ou derniers 130 Ka, il faut constater que les phases de sécheresse, et plus exactement la phase de froid-sec maximal d'environ 20 000 ans ainsi que le pic froid du Dryas supérieur, sont synchrones tout en introduisant la désertification dans le monde entier : désert polaire en Belgique (PAEPE 1963), expansion du Sahara (PETIT-MAIRE 1990) et sécheresse dans la région tropicale africaine (ILUNGA 1984, MUSISI 1991, KAFUMU 1995, KASEBA 1996). Enfin, la courte série temporelle de l'Holocène ou de l'Interglaciaire actuel des 10 000 dernières années témoigne d'au moins vingt cycles de sécheresse d'une périodicité de 1 000 ans dont

la sécheresse actuelle du Sahel pourrait bien représenter la dernière phase ; cela indiquerait qu'il soit possible d'attribuer la désertification actuelle à une origine naturelle plutôt qu'à un Effet de Serre dû à l'action de l'homme. Le cycle d'oxyde de carbone de 2 500 ans (connu sous le nom de Cycle de Suess) est responsable de la subdivision quadripartite de l'Holocène en sous-phases de Boréal, d'Atlantique, de Sous-Boréal et de Sous-Atlantique qui d'ailleurs coïncident parfaitement avec les Périodes du Néolithique, de l'Age du Bronze et de la Période Historique dans les régions gréco-méditerranéennes (PAEPE *et al.* 1995). Enfin, de ce qui précède on peut déduire que les changements de l'environnement à un point déterminé du globe, via l'interférence de l'atmosphère agissant comme catalyseur, ont une répercussion quasi immédiate sur tout autre endroit de la terre ainsi que le défrichement de la forêt tropicale d'Amazonie semble le prouver aujourd'hui.

TREFWOORDEN. — Paleoklimaatcycli ; Fossiele bodems ; Centraal-Afrika ; Pluvialen en Interpluvialen.

SAMENVATTING. — *De Kwartairgeologie rond de Grote Meren in Centraal-Afrika. De Pluvialen en Interpluvialen zijn niet de equivalenten van de Glacialen en Interglacialen.* — De Pluviale Theorie waarin Pluvialen en Interpluvialen door LEAKEY (1959) ingevoerd werden om in de Tropen de equivalenten van Glacialen en Interglacialen aan te duiden, was een eerste poging tot correlatie van Tropische met Noordelijke Boreale etages. Pluvialen werden hierbij beschouwd als het resultaat van een verhoging van de vochtigheid in de tropische gordel gedurende de periodes die met de glaciaties overeenstemden in de gematigde streken. Interpluvialen waren dan simpelweg beschouwd als tussenperiodes tussen twee pluvialen met een klimaat dat sterk gelijkt op dit van vandaag in de tropen. Dit was uiteraard een veel te sterk vereenvoudigde opvatting die leidde tot een groot aantal misvattingen. Sinds 1980 werd met een detail kwartair stratigrafisch onderzoek aangevangen door het departement Kwartairgeologie (Paepe) van de VUB samen met de onderzoeksstudenten van de „International postgraduate training course on Fundamental and Applied Quaternary Geology-IFAQ" (Van Overloop) in het Grote Meren Gebied tussen respectievelijk de Tanganyika, Oeganda, Kivu, George (Idi Amin) en Albert (Mobutu) Meren, namelijk : in de valleien van de Ruzizi (ILUNGA 1984), Rutshuru (YAMBA TSHISUNGU 1993) and Semliki (GAUTIER 1967) rivieren op de grens tussen Zaïre, Rwanda en Burundi en langsheen het Kazinga Kanaal in Uganda (MUSISI 1991). Zeer onlangs was er ook een nieuwe poging in de Olduvai Gorge, Tanzania (KAFUMU 1995). De opname van verschillende geosol-(palaeosol)-sequenties met geosols afwisselend met meer- of riviersedimenten leidde tot het vaststellen van talrijke humiede tropische woudfasen (aangeduid door de geosols) en relatief drogere fasen ertussen (aangeduid door de klastische sedimenten). Het aantal optredende geosols kon gecorreleerd worden met de geosols van landseries elders

zoals in de Loessafzettingen van China en in de Loessachtige afzettingen in Griekenland waarmee het wereldwijds synchroon optreden van de cycli werd bevestigd. Bovendien vertonen de geosol-sequenties in alle bestudeerde gebieden een perfecte correlatie met de oneven stabiele isotopenetages van de diepzee-sequentie (Paepe *et al.* 1995) zowel qua aantal als stratigrafische positie. Aldus werd aangetoond dat warme humiede fasen van de tropen overeenstemmen met warme humiede fasen van de gematigde en boreale gebieden. Bijgevolg stemmen de boreale interglacialen eveneens overeen met de warmere en meer humiede fasen in de tropen. In geen geval kan een vochtig-warm Pluviaal dus met een Glaciaal gecorreleerd worden! Een andere belangrijke gevolgtrekking die hieruit voortvloeit, is het synchronisme van droge en vochtige fasen in de loop van de lange tijdreeks van 2,6 Ma over geheel het tijdsinterval van het Kwartair. Ook wanneer de middellange tijdreeks van de Laatste Interglaciaal/Glaciaal cyclus of laatste 130 Ka beschouwd wordt, wordt vastgesteld dat droogtefasen en meer bepaald de maximale droog/koude fase van omstreeks 20 000 jaren geleden evenals de Jongere Dryas koude piek van omstreeks 11 000 jaren geleden overal synchroon optreden en de desertificatie over de ganse wereld inluiden : pool-woestijn in België (Paepe 1963), expansie van de Sahara (Petit-Maire 1990) en droogte in het Afrikaans evenaarsgebied (Ilunga 1984, Musisi 1991, Kafumu 1995, Kaseba 1996). Zelfs de korte tijdreeks van het Holoceen of het huidige interglaciaal van de laatste 10 000 jaren getuigt op zijn minst van twintig droogtecycli met een periodiciteit van 1 000 jaren waarvan de Saheldroogte wellicht de laatste fase vertegenwoordigt ; hieruit zou dan verder de mogelijkheid blijken dat de hedendaagse desertificatie eerder gebonden lijkt te zijn aan een natuurlijk proces dan aan het door de mens veroorzaakte broeikaseffect. De wel bekende koolzuurcyclus van 2 500 jaar (de zogenaamde Suesscyclus) is verantwoordelijk voor de vierdelige onderverdeling van het Holoceen in subfases als Boreaal, Atlanticum, Sub-Boreaal en Sub-Atlanticum die overigens perfect overeenstemmen met het Neolithicum, de Bronstijd en de Historische tijd in de Grieks-Middellandse-Zeegebieden (Paepe *et al.* 1995). Ten slotte wijst het voorgaande er duidelijk op dat veranderingen in het milieu op een bepaald punt van de aardbol een bijna gelijktijdig effect kan hebben op elk ander punt van de wereld via de atmosfeer als katalysator zoals waarschijnlijk reeds wordt ervaren door het hedendaags wegkappen van het Amazone tropisch regenwoud.

1. Introduction

Why use this subtitle "Pluvials and Interpluvials are not the equivalent of Glacials and Interglacials"? Because today still too many scientists, apart from very few top researchers dealing with tropical environment, tropical climate, early man and landscape evolution, are dealing in most of the tropical regions with the Pluvial Theory. In

the light of Global Change and Global Climate research the Pluvial Theory has, however, become obsolete and far too inadequate for climato-geological correlations and possible predictions in the future. Nevertheless, in rejecting this theory, as will be done hereafter, its historical role in the evolution of African land quaternary correlation should not be denied completely. Yet, new research shows that it is quite possible to study land tropical palaeoclimates on basis of geological land proxydata, both lake and other land data, with the same methods and degree of accuracy as is done for the land palaeoclimatic records elsewhere as for example in Europe and in particular for the ocean and ice records. Thus, the missing African tropical link in palaeoclimatic studies of the World may be fully integrated in adapting new methods and even serve as a didactic methodology as we will also show hereafter. Therefore, it is a good place here to pay a tribute of highly estimated consideration to the former Central African IFAQ-students whose names are referred to as co-authors and who associated themselves recently in CEQUARO (Centre for Quaternary Research in the African Rift and Olduvai). They opened the path to new fields in a complete no man's land of Quaternary land climato-geology. They were spreading the new concept on "palaeo- or geosoil stratigraphy" we taught them at UNESCO's International postgraduate training course on Fundamental and Applied Quaternary geology (IFAQ) in Brussels — and brought back to us the evidence from the field.

1.1. The Concept of the "Pluvial Theory"

The "Pluvial Theory" has been used for many decades and to some extent is still being used as a tool for correlation of climatic changes over such widely spread regions of the Earth's land surface as Africa. It dates from the time when nothing was known about ocean and ice records and absolute dating was rather fragmentary. Neither could this pure theoretical approach lean on a large range of isotopic geochemical laboratory analyses bringing the terrestrial evidence close to the atmospherical changes. Milankovitch's curve of climate change (1941) was in this light a memorable exercise, yet just a mathematical approach and a confirmation of what was so far known as the Penck and Bruckner's Subdivision of the Quaternary into a fourfold multiple glaciation system of Glacials and Interglacials (1910).

The Concept of the "Pluvial Theory" can henceforth be seen as a great step forward in its attempt to make the aforementioned "Multiple

Glaciation Theory" of Penck and Bruckner applicable in regions far away from its restricted area of origin, namely the Foreland of the Alps in Bavaria (Germany). It opened the path to the concept of multiple climatic changes all over the Earth. A brief review about the origin of the "Pluvial Theory" and its almost immediate demise shortly after follows.

The "Pluvial Theory" emerged in the 1930s in Africa a quarter century later than the concept of Quaternary Multiple Climatic Change developed in Europe. Indeed investigators like LEAKEY senior (1936, 1965), WAYLAND (1934), NILLSON (1931, 1963) became aware of the fact that Lake Level Changes proved to occur frequently in Central Africa and surroundings. According to the "Pluvial Theory", wet and dry climatic periods alternated in the Tropics during the Quaternary, say the last 2.5-3.0 Million years (Ma). The wet periods of tropical Africa or Pluvials were correlated with the Glaciations of the temperate parts of the world as well as of the mountains of Eastern Africa, the dryer periods of tropical Africa like today being correlated with the Interglacials of the temperate zones.

How wonderful! Pluvials equivalent of Glacials and Interpluvials equivalent of Interglacials. Linguistically it could not sound better for the supporters of this "Pluvial Theory" and by the mid-1950s CLARK & COLE (1957) built up a formal climato-stratigraphic scheme for tropical Africa (table 1) which was simply copied from the four glacial and interglacial stages from the temperate zone as introduced by Penck and Bruckner.

Glaciations of the temperate belt were considered to coincide with "cool moist climates" in the tropics (COLE 1964). The four presumed interpluvials were climatically undefined and simply referred to as periods in-between the four pluvial periods corresponding in number to the three interglacials of the temperate zone. The ultimate interglacial or Holocene was called Postpluvial and comparable to the present-day climate of tropical Africa. More emphasis was hereby put on temperature than on humidity which higher effective precipitation during the glacial stages in the tropics was believed to be simply a result of a decrease in potential evapotranspiration. Changes in rainfall were, henceforth, generally regarded as less important by those in favour of the "Pluvial Theory". If a general synchronous global cooling during the glaciations of the temperate zone was likely to be accepted, it was far from being so with regard to humidity. Glacial drought of the temperate zone corresponded to higher moisture during the Pluvials

Table 1

Original table of correlation between tropical Africa and Europe

Tropical Africa		Europe
Postpluvial	=	Holocene
Fourth (Last) or *Gamblian* Pluvial (named after Gamble's Cave, Kenya Rift Valley)	=	Würm
Third Interpluvial	=	R/W Interglacial
Third or *Kanjeran* Pluvial (named after Kanjera, on the southern shore of the Kavirondo Gulf of Victoria Nyanza, western Kenya	=	Riss
Second Interpluvial	=	M/R Interglacial
Second or *Kamasian* Pluvial (named after the Kamasian Plateau, central Kenya)	=	Mindel
First Interpluvial	=	G/M Interglacial
First or *Kageran* Pluvial (named after the Kagera river, a western tributary to Victoria Nyanza	=	Günz

Source: CLARK, J. D. = COLE, S. 1957. Subdivision of the African Quaternary. — Proceedings of the Third Pan-African Congress on Prehistory Northern Rodesia.

and Interglacial humidity of the temperate zone to relatively "dryer" interpluvial of the tropics.

1.2. THE DEMISE OF THE "PLUVIAL THEORY" AND ITS CONSEQUENCES. THE NEED FOR A GLOBAL CORRELATION

Soon one was currently speaking in generalized terms of wet — pluvial and dry — interpluvial stages and this concept was used (or better misused) worldwide even until today in places where recent literature has not yet progressed. This was a far too simple climato-stratigraphical correlation which rapidly became severely criticized towards the end of the 1950s almost at the same time when Cole's generalized correlation with the pleistocene climatic changes of the temperate zones was published.

Intensified dating in both Africa and Europe confirmed that Lake Level stands high once attributed to the Gamblian Pluvial currently corresponding to the Postpluvial, *i.e.* the Holocene stage whereas sediments attributed to Kamasian Stage seem to belong to widely separated events in time as stated by MCCALL *et al.* (1967). Equally

there is no stratigraphic proof of the Kageran Stage whereas nothing is actually recorded about the Kanjeran Stage. Perhaps the Gamblian Stage is only safe for the part which is dealing with the Last Glacial. Therefore, the "Pluvial Theory" and its related classification has now been relegated to the realm of geological fiction. However, the demise of the "Pluvial Theory" raises immediately a new series of problems. There is a stringent need for correlation of climatic events between different parts of the world. This need is enhanced since it has been clearly established that environmental changes induced at any point of the Earth's surface will effect global climatic changes via the pollution of the atmosphere and thus in return have an impact on any other point of the Earth's surface as well. Whatever change which happens in the Tropics will enhance changes of the environment everywhere else at the surface of the Globe and vice versa. Consequently, the need for a global comprehension of the Global Climatic Cycles and their potential synchronism becomes greater than ever before.

With this regard an urgent reply must be found for the following questions :

— The global palaeoclimatic synchronism of droughts and wet climates ;
— The number of climatic changes that Mankind has been facing since Lucy ;
— The impact of increasing drought throughout the Quaternary System/Period on Man's Environment and propagation all over the World ;
— Man's position today in the Geological Cycle.

The "Pluvial Theory" cannot solve these questions which are nonetheless mandatory for the future of Mankind such as the Greenhouse Effect. It should therefore be replaced by a new "theory" or better "working method" with specific emphasis on land records leading to "land-to-land correlations" and integrated correlations with the "deep-sea ocean records" and "ice records" as well.

2. The Global Palaeoclimatic Synchronism of Drought and Wet Climates

Land records offer far better insight on the global palaeoclimatic, *i.e.* environmental evolution of the Earth's surface, than ocean records and ice cores. Both latter only provide information about the total amount and intensity of the global ice production. They tell us very

little detail about the environmental evolution on the land itself which nevertheless is the complex result of transformation of the lithosphere, biosphere and hydrosphere under direct impact of the atmosphere. This is more than an indirectly derived appreciation of temperature changes in ocean and ice records.

Nevertheless, the "land-to-land correlations", how useful they may be, are even today lagging behind the ocean and ice core studies for three essential reasons :

— Land geological sections are less continuous than ocean and ice core sequences ;
— Land records most often miss possibilities for dating by radiometric methods ;
— Land records also lack possible methods to set up geochemical isotopic parameters to compare with those of the ocean and the ice.

2.1. The Geo-Soil Stratigraphic Sequential Investigation

So far basic stratigraphical geological correlation had been the only method used on land (not lake) geological sections from which finally the "Pluvial Theory" was derived. Indeed, this land stratigraphical method had proved to be an excellent approach which permitted Charles Lyell already in 1839 to establish the first global geological stratigraphical classification which is still in use today. It is an extraordinarily precise document when dealing with the timescale of the pre-quaternary geological events. Quite astonishingly, the Quaternary Period, which is the youngest and shortest of all and hence the closest to us, was the most difficult one to seize in time. The nearer to us, *i.e.* the Pleistocene and the Present, the smaller the differences become and the more difficult it is to mark off the boundaries in time and intensity. The boundary between the Tertiary and the Quaternary is still an ongoing controversial matter as well as the subdivision of the Quaternary Period itself. And so the results of the correlation between Europe and Africa on basis of the "Pluvial Theory".

2.1.1. The Geo-Soil Stratigraphic Development and Old Land Surfaces

In the course of the 1960s geologists started to identify fossil soil or palaeosoil layers which almost readily debouched into soil stratigraphy better known today as geo-soil stratigraphy. Palaeosoils or geosoils (Morrison 1967) are dealing mainly with truncated soils on old

land surfaces representing layers of standstill in the sedimentation record. These old land surfaces, just like today's, once formed at the interface of interaction between the atmosphere and the lithosphere. The biosphere or vegetation cover transformed the upper part of the lithosphere into a pedo-sphere through the process of a soil development via plantroots and aminoacids.

The palaeosoil or pedological moment (pedogenesis) in the geological process is the last in a series of five moments namely forming together the geo-soil cycle : the palaeo-sedimentation moment of depositional aggregation ; the palaeo-geomorphological moment of land surface development ; the palaeo-botanical moment of vegetational cover growth ; the palaeo-climatical moment being the ultimate permanent driving geo-dynamic external forcing (PAEPE *et al.* 1990).

2.1.2. The Geo-Soil Stratigraphic Sequence and the Astronomical Forcing. The Soil Catena. The Soil Development Intensity. The Roving Landscape

Successive stages of geo-soil cycles will ultimately result in *the geo-soil stratigraphic sequence.* The latter is composed of different types of soil as changes due to the astronomical forcing in both solar radiation on the Earth's surface and composition of the atmosphere (PAEPE & VAN OVERLOOP 1990) intervene. This leads to different degrees of *Soil Development Intensity* although recurrences of similar soil types may also occur. Furthermore, differences of soil types also occur due to their specific position in the *Soil Catena.* The latter results from the edaphic product of vegetational, geological and hydrological conditions combined bound to their geomorphological position in the landscape (slope, plateau or valley bottom position). Both soil catena and the soil development intensity are even more complex as they are a direct consequence as well of *the mixed character of the quaternary landscapes.* Following J. BUDEL (1981), PAEPE & VAN OVERLOOP (1990) pointed out that between the equator and the poles, especially in the Northern Hemisphere, landscapes, just like the vegetation cover, were migrating permanently and simultaneously either in the direction of the equator when Boreal ice caps were growing or vice versa. These *Roving Landscapes* built up mixed landscapes at a given point along the parallel position on the Earth's surface adding even greater complexity to the different types of geo-soils and sediments in the vertical sequence. Inversely, one can read from this geo-soil/sediment sequence the various landscapes and vegetational covers (*i.e.* the environment) which

passed by at this given point through time. Sedimentary, palaeomagnetic, susceptibility and isotopic parameters derived from these geosoils and interfering sediments, express the environmental variation through time in geological proxydata. These measurable land proxydata are furthermore comparable to those obtained from deep-sea and ice core records. This new method, which is hereby opposed to the "Pluvial Theory" approach, is called the *Geo-soil Stratigraphic Sequential Investigation* as was earlier introduced by PAEPE & VAN OVERLOOP (1990).

2.1.3. The Geo-Soil Traverses of Land Records based on Regional Geo-Soil Stratotype Sections

The Geo-Soil Stratigraphic Sequential Investigation leads to the identification of *Regional Geo-Soil Stratotype Sections* from which correlation *Geo-Soil Traverses of Land Records* were obtained ultimately. They enable to correlate various latitudinal and climato-morphological regions of the world and may be readily compared to the Ocean Isotopic (SHACKLETON *et al.*, 1990) and the Ice Core Isotopic Records (DANSGAARD *et al.*, 1971) as well. Hereafter the European/ African Geo-Soil Traverse will be discussed within the framework of the validity of the Pluvial Theory.

2.2. GEO-SOIL TRAVERSES OF LAND RECORDS RELATED TO GEO-SOIL TIME SERIES OF THE LONG, MIDDLE AND SHORT TERM

As already stated before, there are three types of Geo-Soil Traverses of Land Records (fig. 1), each representing time series of different duration : the Long-Term (2.6 Ma, PAEPE & VAN OVERLOOP 1990a, PAEPE *et al.* 1995, PAEPE *et al.* 1996), the Middle-Term (127-10 Ka, PAEPE *et al.* 1990b) and the Short-Term (last 10 Ka, PAEPE *et al.* 1984, PAEPE & VAN OVERLOOP 1990a) Time Series. All three studies are a proof of the synchronous climatic evolution.

2.2.1. The Long-Term Geo-Soil Traverse and the Pleistocene 2.6 Ma Time Series

The Long-Term Time Series throughout the Pleistocene is based on the cyclic occurrence of glacials and interglacial stages with periodicities of 100 Ka and 40 Ka, sometimes 400 Ka and 60 Ka.

For linking up European and African stratigraphies in one Long-Term Geo-Soil Traverse, four African equatorial Regional Geo-Soil Stratotype Sections have been selected (fig. 2). In Zaire the section of

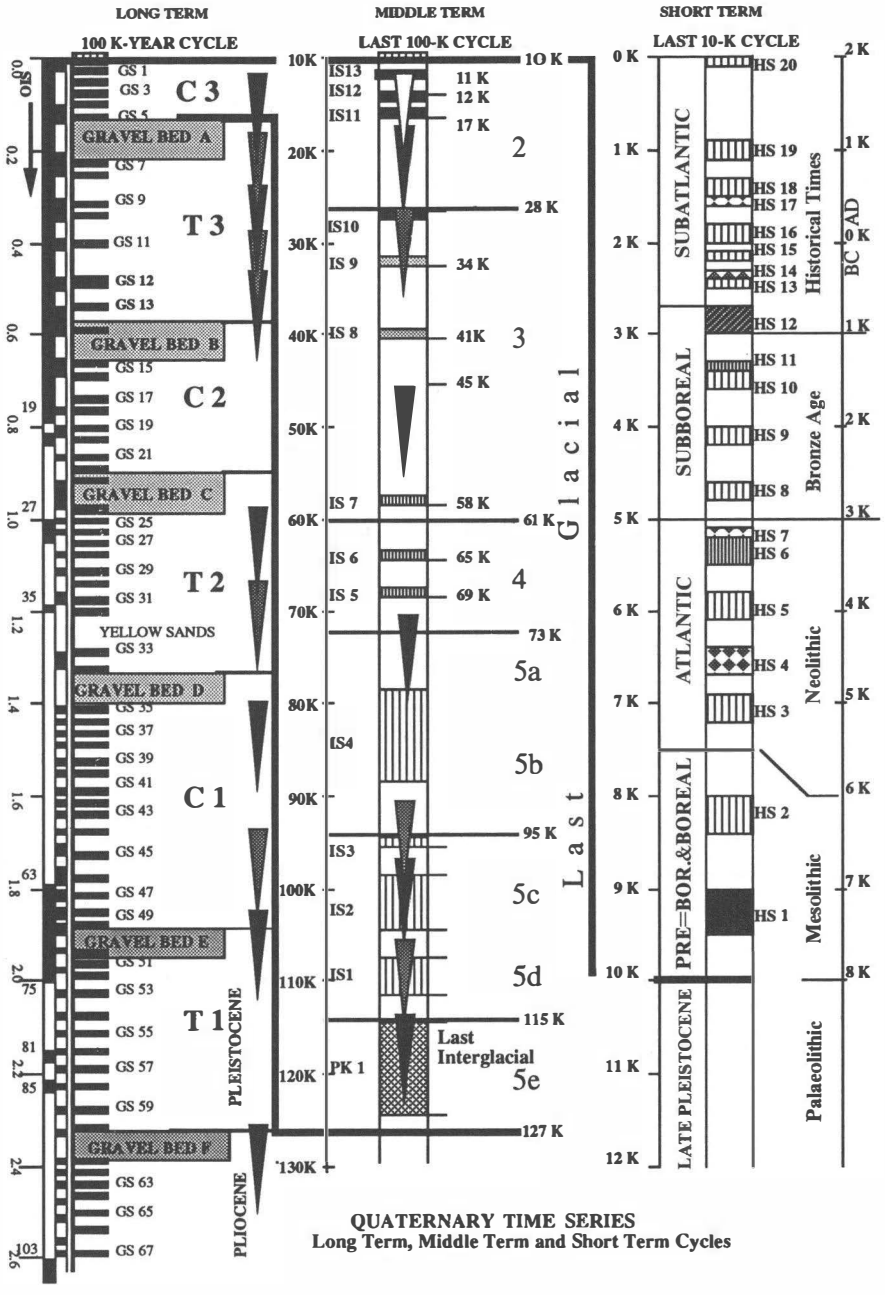


Fig. 1. — Quaternary long-term, middle-term and short-term geo-soil series.

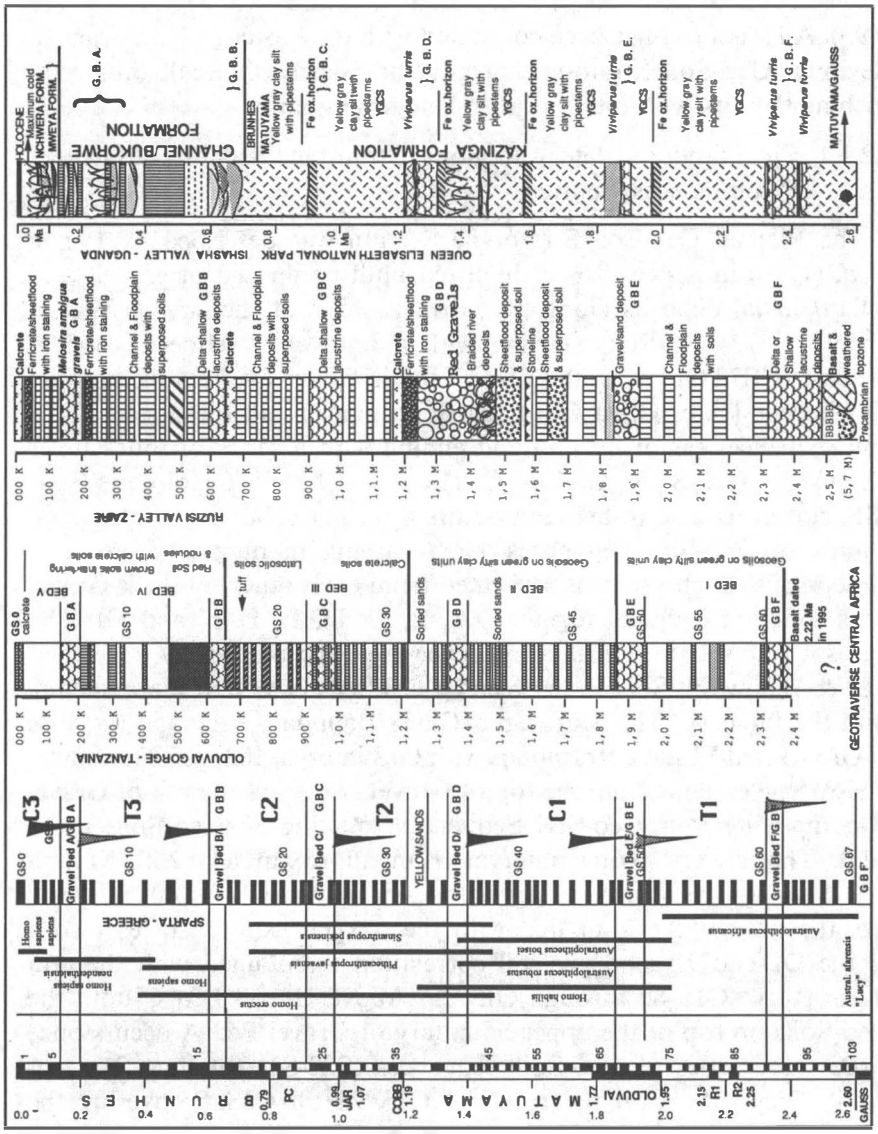


Fig. 2. — Geo-Soil Traverse of Central Africa on basis soil sequences of Olduvai, Ruzizi and Ishanshi soil sections throughout the Pleistocene compared with Sparta-Standard Section (Greece).

the Ruzizi Valley (ILUNGA 1984) was chosen as the most representative of the Semliki, Rutshuru and Ruzizi Valleys ; in Uganda the Ishasha Valley (MUSISI 1991) and in Tanzania the Olduvai Gorge (KAFUMU 1995). All sections have been connected with the Eastern Mediterranean Regional Geo-Soil Stratotype Section of Sparta (Greece), thus establishing the link with the European land stratigraphy.

2.2.1.1. The Standard Plateau Regional Stratotype Sections of Greece/ Peloponnesos/Sparta

The Plateau Geo-Soil Stratotype Section was described by PAEPE *et al.* (1996) in a steep 160 m high red bluff composed of gravels and eolian/fluvial deposits along the northern edge of the city of Sparta. There are 72 Geo-Soils starting with a Latosol of Miocene Age at the base (GS72 tallying with OIS 113, not in figure) overlain successively by Pliocene (as of GS71-GS61, partly in figure) and Pleistocene Geo-Soil sequences (as of GS 60) and ending with a series of four Upper Pleistocene Geo-Soils (GS4 — GS1) covered by eight Holocene Soils (HS, not in figure). In-between occurs a further subdivision into seven groups of Geo-Soil Sequences, each varying in number from 8 to 12 geo-soils. Each group is separated from each other by thick Gravel Beds totalling eight all together (A, B, C, D, E, F, F' and G). The Latosol below Gravel G is of Miocene Age, the intensively developed Red & Yellow Silt Soils in-between Gravel Beds G, F' and F are tallying with the Pliocene. The Matuyama/Gauss Boundary occurs at the base of Gravel Bed F' and corresponds with OIS interval 103/105.The Lower Pleistocene extends from the top of Gravel Bed F till the top of Gravel C comprising four Geo-Soil Sequences totalling 37 Geo-Soils (S60-S23). This covers a time interval from approximately 2.27 Ma till 0.91 Ma, say 1.5 Ma. inferring a dominating cyclicity of 40,000 years (*i.e.* the obliquity). Compared with the oxygen isotope stages record of the ODP 677, good geo-soil correlation is obtained with the odd warm stages OIS 89 through OIS 25. Above Gravel Bed C until the Geo-Soils on top of the upper boundary of Gravel Bed A occurs once more three series of Geo-Soil Sequences (S22-S1) totalling 21 Geo-Soils. They tally with the reach of OIS 23 till OIS 5 covering the time interval 910 Ka till 115 Ka, say 800 Ka. This points again to a dominatig cyclicity of about 40,000 years. Above follows, as stated before, the HS-soil series of the last 10,000 years or Holocene.

2.2.1.2. The Geo-Soil Traverse of Long-Term Stratotype Sections in Tropical Regions of Africa

The above-described standard section of Sparta is correlated with the Long-Term Stratotype Sections of the Tropical Regions of the West African Rift between Lakes Tanganyika, Kivu, George and Albert and the Olduvai Gorge in Tanzania.

2.2.1.2.1. The Olduvai Gorge (KAFUMU 1996) shows astonishing perfect geo-soil correlation with the standard Sparta sequence. A complete series is likely to be found throughout the Pliocene and Pleistocene Series from GS 67 through GS 7. Also the Gravel Beds occur in similar stratigraphic positions like in the Sparta sequence. The earlier introduced prehistoric subdivisions labelled as BED of the Olduvai Gorge prehistoric site are clearly bound to these gravel beds. Indeed all BED sections occupy intervals between respectively gravel beds GBF' and GBE for BED I, GBE and GBD (including sorted sands) for BED II, GBD and GBB for BED III and finally GBB and GBA for BED IV.

BED IV consists, just like in the Sparta section, of a series of Red Geo-soils at the base overlying GBB and attesting tropical conditions. It is upwards transgressing into Brown Soils interfering with calcrete horizons until GBA which point at increasingly dryer climatic conditions. Above in BED V coinciding with the Last Glacial, dry climatic conditions attested by calcrete horizons dominantly prevail indicating even much dryer conditions.

BED III shows an evolution in the other sense. Below GBB follows a series of Latosols until GBC continued downwards by a series of calcrete soils until the Upper Sorted Sands. The climate changed from tropical to semi-arid. The Complex of Upper Sorted Sands/GBD/ Lower Sorted Sands marks a definite break in the environmental system. Lacustrine green silty clay dominates BED II and BED I interfering with weakly developed geo-soils which might indicate shortly less moister periods. The latter seems to become more abundant in BED II than in BED I.

The Evolution of specific species of Early Man is bound to these BED-intervals which are covering timespans of about 600-800 Ka each. The first and last appearance data (FAD & LAD) of Early Man seem thus to be equally bound to the Gravel Bed Boundaries. *Australopithecus afarensis*, better known as Lucy, disappeared with Gravel Bed F'/GBF' inferring the extreme cold phase at the boundary of the Middle

and Upper Pliocene coinciding with the Gauss/Matuyama limit. Hereafter, *Australopithecus africanus* occupied the interval of prehistoric BED I between GBF' and GBE crossing the transition of the Tertiary/Quaternary limit at GBF about 2.4 Ma. Throughout prehistoric BED II, covering the interval between GBE and GBD (including the Sorted Sands in Olduvai and the Yellow Sands in Sparta), three new species of Early Man developed, namely *Homo Habilis*, *Australopithecus robustus* and *Australopithecus boisei*. Again in BED III, in-between GBD and GBB, new species developed as *Pithecanthropus javaensis* and *Sinanthropus pekinensis*, whereas *Homo erectus* appeared beyond GBB until the middle of BED IV. The widespread occurrence of the last mentioned species outside the African cradle may point at dramatic changes in the environment. As inferred by the massive sequence of GBD and Sorted Sands/Yellow Sands, long-lasting extreme cold conditions seem to have prevailed in the time interval of 1.4 till 1.2 Ma. Hereafter the closed forest/savanna landscape opened up and semi-arid to arid conditions became dominant in the first half of BED III. In the second half after GBC starting about the Jaramillo Event, conditions became milder and forested again as the calcrete geo-soils made place for the latosols occupying the interval in-between GBC and GBB. Both *Pithecanthropus javaensis* and *Sinanthropus pekinensis* did not survive this environmental change. After GBB was formed, the climate became even milder and probably more tropical as is attested by the Red Soils at the beginning of prehistoric BED IV. *Homo erectus* still survived in this tropical forest together with *Homo sapiens*. As conditions became gradually dryer again (Red Soils replaced by Brown Soils), both *Homo erectus* and *Homo sapiens* disappeared and were replaced by *Homo sapiens neanderthalensis*. The latter even survived the extreme cold conditions of GBA at the start of prehistoric BED V and dominated the Last Interglacial in Europe. After this initially warm phase *Homo sapiens neanderthalensis* was also replaced at the start of the Last Glacial cold by *Homo sapiens sapiens*, the maximum of which he was able to survive about 20 Ka.

2.2.1.2.2. Other Long-Term Stratotype Sections obtained from the Zaire/Burundi Ruzizi Plain (between Lake Kivu and Lake Tanganyika) and the Kazinga Channel region (Uganda) show further positive correlation.

In the Ruzizi Plain (ILUNGA 1984) the *Melosira ambigua* gravels were recognized as the base of the Last Interglacial Stage which together with the ferricrete were, henceforth, identified as the equivalent of

Gravel Bed A/GBA. Below each group of "delta shallow lacustrine deposits" occasionally linked up with "gravels and calcrete levels" up to 1.2 Ma are identified as respectively GBB (600 Ka), GBC (950 Ka) and the top of GBD (1,250 Ka or 1.2 Ma). The Geo-Soil Sequences interfering with "channel and floodplain deposits" in-between these Gravel Beds perfectly tally with the sequences of Olduvai and Sparta until the Jaramillo Event, say roughly till 1.0 Ma. Even the Red Soils of Sparta and Olduvai are also well developed and therefore important stratigraphic marker horizons occur between 500 and 600 Ka. They indicate, just as in the former two sections of Olduvai and Sparta, strongly prevailing tropical environment in the middle between two phases of less tropical conditions with "channel and floodplain deposits" interfering with weakly developed brown soils. Below, the other marker horizon is formed by the thick corpus of Red Gravels which form the bulk of GBD. They attest braided river patterns covering the time interval of 1.2 till 1.5 Ma and may be identified with the series of Olduvai composed of the Complex Upper Sorted Sands/GBD/Lower Sorted Sands in Olduvai and GBD/Yellow Sands in Sparta. Just like the two former sections the sedimentation below changes dramatically into a series of sheetflood and stoneline deposits interfering with moderately developed geo-soils. The latter points at periodic short periods of drought. Between GBE and GBF the environment was more tropical again with "Channel and Floodplain deposits" interfering with better developed geo-soils attesting generally prevailing tropical conditions.

In the Ishasha Valley (Musisi 1991) in Uganda one is dealing with basin deposits at the base of the mountain range dominated by the Ruwenzori. The influence of the latter is felt in the nature of the deposits of the Middle and Upper Pleistocene. Gravel Beds, weak geo-soils and pebble bands (sometimes stonelines) with well-developed dry cracks build up these deposits. The Last Interglacial is composed of gravels belonging to the Mweya Formation followed upwards by the yellow eolian sands of the Nchwera Formation which culminate in a dry crack horizon corresponding with the maximum of the cold of the Last Glacial at about 18 Ka. Underneath gravels and sands of the Channel/Bukorwe Formation occur. The upper part consists of two series of gravels and sands mixed with faint geo-soil layers which are identified as GBA. In fact, it is split in the middle by an important dry crack horizon filled in with eolian sands. The latter infers severe conditions of drought that must have dominated with a maximum at the level

of the dry cracks. The lower and second part of thick latosol developments just above the GBB are equal to those of the same stratigraphical position in Olduvai at the base of BED IV, above the Delta lacustrine deposits in the Ruzizi and at the base of T3 in Sparta. These deposits entirely differ from the monotonous series of "Yellow gray clay silts with pipestems-YGCS" occurring below. The latter indicates similarly an extremely shallow water sedimentation over a long interval of time from 2.6 Ma (Matuyama/Gauss Boundary) through 700/800 Ka (Brunhes/Matuyama Boundary) as revealed from the palaeomagnetic record. It builds up the Kazinga Formation which covers the whole of the Lower Pleistocene and Upper Pliocene and probably does extend into the Middle and Lower Pleistocene as well. The few interruptions which occur represent important bench marks. The first interruption down from GBB, nearby which lower limit the Brunhes/Matuyama boundary was detected, happens at the very first occurrence of the *Viviparus turris* level together with a gravel bed, an Fe-oxide layer sealing off a dry crack horizon filled up with yellow probably eolian sands. It is a serious benchmark which undoubtedly indicates a major climato-environmental break in the monotonous homogeneous sedimentation pattern of the clay silt. Yet, two other *Viviparus turris* levels together with gravels and sands are found further below in the lower part of the "Yellow gray clay silts with pipestems-YGCS" : one in the middle and another one at the base nearby the level where the Matuyama/Gauss boundary has been found. It is believed that the lower most *Viviparus turris* bearing gravels correspond to the GBF level at the beginning of the Pleistocene/Quaternary and the next higher one with the GBE level occurring about the Olduvai Event. Thus it is concluded that again the next higher one attesting the great drought with the dry cracks tallies with the GBD level nearby the Cobb Mountain Event. All three levels occur together with Fe-oxidation horizons which in the other sections of Olduvai and the Ruzizi correspond to gravelly ferricretes associated with the complex of the gravel beds. Therefore, it is assumed that the Fe-oxidation horizon halfway the upper most "Yellow gray clay silts with pipestems-YGCS" starting from the Brunhes/Matuyama Boundary may be indicative of the climatic environmental change coinciding with the GBC in the sections of Olduvai, Ruzizi and Sparta. It is assumed here that the Fe-oxidation horizons correspond to dry-breaks in the lacustrine sedimentation.

2.2.1.3. First Intermediate Conclusive Remarks

Below an attempt is made to summarize the climatic evolution of Equatorial Central Africa during the Pleistocene in some conclusive remarks :

1. There is possible correlation on basis of the presence of the six Gravel Beds (A, B, C, D, E, F) in the Pleistocene between the African Regional Stratotype Section of Olduvai (Tanzania), the Ruzizi Plain (Zaire, Burundi) and the Ishasha Valley (Uganda). These Gravel Beds correlate with those observed in the Eastern Mediterranean Geo-Soil Standard Stratotype Section of Sparta (Greece). They occur with a periodicity of intervals of 400 Ka.

2. There is even a better possible correlation on basis of geo-soils of the Eastern Mediterranean Geo-Soil Standard Stratotype Section of Sparta (Greece) which correlate perfectly with the Olduvai Gorge Geo-Soil Standard Stratotype Section. There is indeed perfect accordance as to the number of geo-soils and their degree of development up to GS 50 which is located in the GBE at the time of the Olduvai event. Considering the new dating of this event one may conclude to a continuous Geo-Soil Sequence for about the last 2.0 Ma. Henceforth, there is an equal evolution of the climate in the Equatorial African Belt and the Eastern Mediterranean at the 100 Ka.

3. Via comparison with the odd numbers of the OIS (oxygen isotopic stages) of the deep-sea record, the "warm" periods of the Ocean correlate perfectly with the geo-soil tropical phases of the Equatorial belt in Central Africa. Warm/humid phases in Europe and Central Africa occur simultaneously as well as the periods of greater drought and aridity in between. The 400 Ka periodicity seems to control the Gravel Beds, *i.e.* Cryomers and Thermomers.

4. The synchronism of Cold Glacial Stages in the Boreal Region with cooler periods of drought in the Equatorial Regions at the level of Glacial/ Interglacial Stages is hereby irrevocably demonstrated.

2.2.2. Middle-Term Geo-Soil Traverse and the Last Interglacial/Last Glacial (127-10 Ka) Time Series

The complete Geo-Soil Sequence of the Last Interglacial/ Last Glacial Cycle, the so-called Middle-Term Time Series (Paepe & Van Overloop 1990), was the first studied series. It gave access to the study of interstadials and stadials of the last 100 Ka interval of the Long-Term Time Series. To some extent it was also within the reach of radiocarbon

dating which offered good bench marks in the 60s. The question then is whether, at this level, global correlation was still possible.

2.2.2.1. The Standard Regional Middle-Term Stratotype Sections of Europe and Africa

The Regional Stratotype Section of Zelzate/Moershoofd on the Belgian-Dutch border was the first to yield a climatic curve of the Last Interglacial - Last Glacial Cycle (PAEPE 1963, ZAGWIJN & PAEPE 1968, PAEPE & ZAGWIJN 1970) (fig. 3). At least 13 interstadial soils have been recorded between the Upper Pleistocene Last Interglacial Rocourt Soil and the Holocene Current Interglacial Soil. The interstadial soils correlate perfectly with the warm peaks of the pollen-based and well-dated climatic curve of La Grande Pile (WOILLARD *et al.* 1982) in north-eastern France and with the warm peaks in the ice core record for the same period obtained from Camp Century in Greenland (DANSGAARD *et al.* 1969).

2.2.2.2. The Geo-Soil Traverse of Middle-Term Stratotype Sections in Tropical Regions of Africa

Based on the Geo-Soil Traverse (fig. 4) one can establish a perfect geo-soil correlation from the Netherlands through Belgium (52 NL) and France (50 NL) and further down to Sardinia (42 NL) till the very southern part of the continental Greece at Koroni. The latter section of Koroni (28 NL) compares readily with the section of Gihungwe on the Ruzizi (40 SL, Zaire/Burundi border), with the section of Nchwera in the Ishasha Valley in the Elisabeth Park of Uganda (right on the equator) as well as with Sumbi (Lower Zaire 5 SL). Quite extraordinary is the presence in the Gihungwe and Nchwera sections of six interstadial geo-soils most probably of the Middle Last Glacial. Actually they occur under a triple series of eolian yellowish sands separated by two rows of dry cracks. The lower most row is composed of the largest wedges and stratigraphically occupies the position of the maximum cold around 18,000 BP (MUSISI 1991). The next higher one may then be correlated with the Younger Dryas drought, thus suggesting that this climatic cold fluctuation was a global phenomenon even affecting the Tropical Equatorial Belt rather than a particular event around the Northern Atlantic Ocean. The section of Sumbi reveals the presence of stonelines in places without any particular stratigraphic geo-soil sequence reflecting most probably the position of DP 1, DP 2, DP 3 and DRYAS (for Upper Dryas) in the other sections of the Geo-Soil Traverse. It should

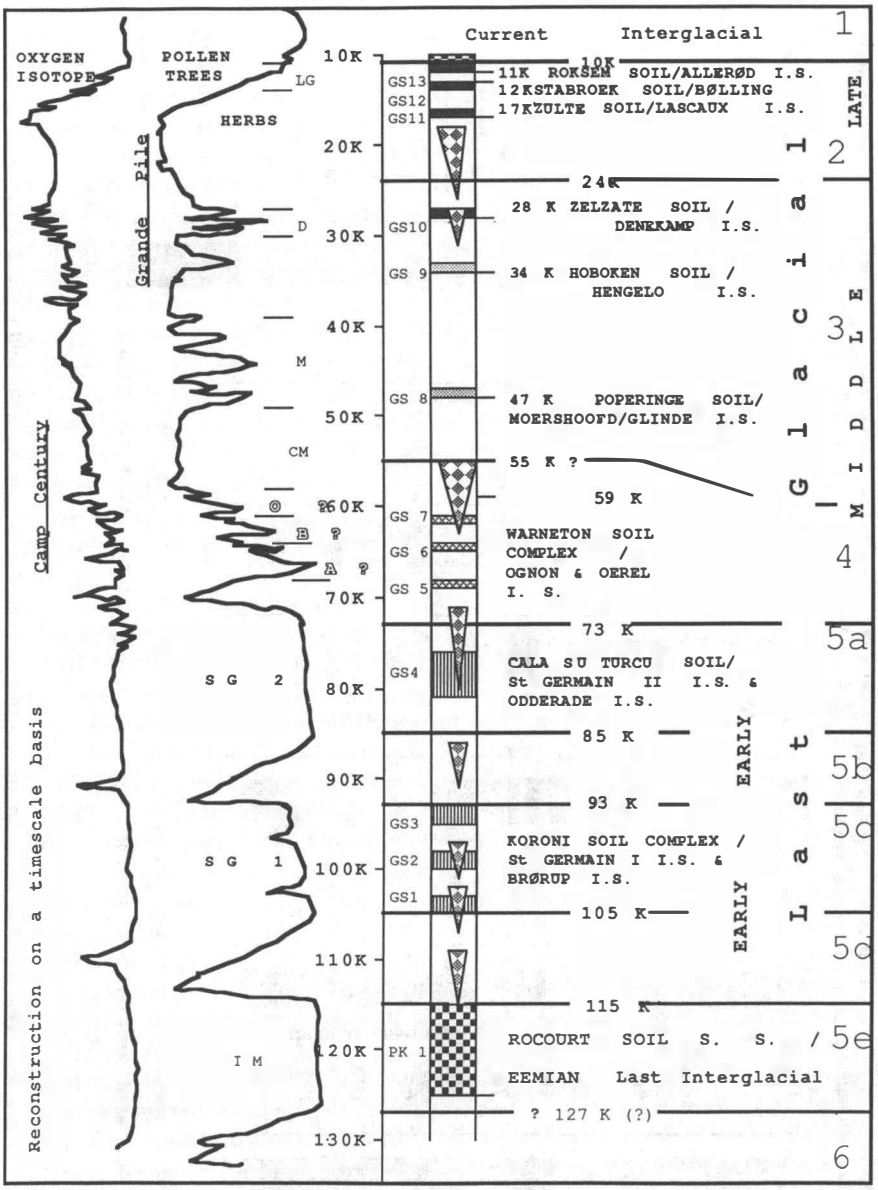


Fig. 3. — Correlation of deep-sea oxygen-isotope curve, pollen curer and palaeosoils and frostwedge levels (upside down triangles) of the Last Interglacial-Glacial Cycle.

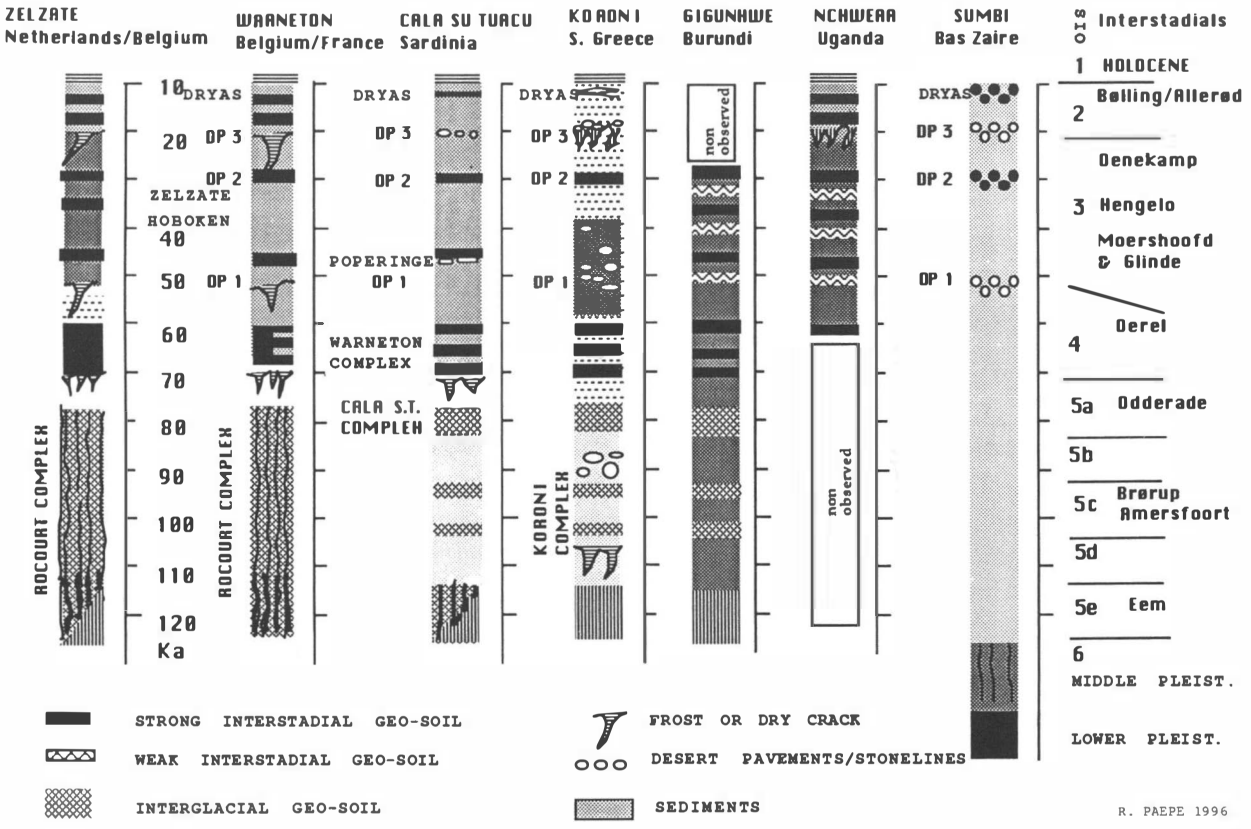


Fig. 4. — Geo-Soil Traverse from the North Sea to the Mediterranean Basin and Central Africa.

be reminded here that already in 1965 the presence of local erosion levels coinciding with that stratigraphical position had been reported from investigation in Belgium and Greece (PAEPE *et al.* 1990b).

2.2.2.3. Second intermediate conclusive remarks

Herewith a second series of conclusive remarks can be formulated specifically for the Last Interglacial/Last Glacial Land Cycle especially in the Central Equatorial belt of Africa.

1. The Middle Time Series being enclosed at its base by the Last Interglacial and at its top by the ultimate Current Interglacial or Holocene, the intermediate geo-soils dealing with are interstadial features. Correlation between the 13 interstadial geo-soils is optimal.

2. Of the three boreal cold/dry phases occurring about 70, 50 and 20 Ka the 20 Ka level is constantly present in the lowest latitudinal position in Southern Europe and in Equatorial Africa. The eolian sands found along with these dry cracks point at periods of desertification in the Equatorial Belt simultaneously with those of the Sahara and Polar desert conditions in Europe. The Upper Dryas drought is found on the equator as well.

3. Likewise the four groups of each three interstadial geo-soils occur continuously in the same stratigraphic position along the Geo-Soil Traverse from the North Sea to the Mediterranean and to Central Equatorial Africa. Above the Last Interglacial Geo-Soil (Rocourt Soil in Belgium) occurs everywhere along the Geo-Soil Traverse the threefold well-developed and clay-enriched geo-soil complex corresponding to OIS 5 and Interstadials Amersfoort, Brørup, Odderade named Harmegnies Complex in Belgium, Koroni Complex in Southern Greece and although well-developed, not yet named in Gigunhwe in Burundi. After the first extreme cold/dry peak of 73 Ka follows the Warneton Soil Complex of Taiga/Tundra fabric in the North and of Steppe as of Southern Europe or dry Savanna in the Equatorial Region ; it corresponds to OIS 4 and the Oerel Interstadial of the Early Glacial and survives without any interruption as well throughout the Geo-Soil Traverse leaving no doubt about its synchronism and by and large its magnitude as a general global signal. The next three Middle Glacial Interstadials Moershoofd, Hengelo and Denekamp corresponding with OIS 3, which occur after another severe cold peak at 50 Ka, are the generally weak Geo-Soils of Poperinge (46 Ka), Hoboken (37 Ka) and Zelzate (28 Ka) which are by far the most intensively developed as humid soils in NW Europe nearby the North Sea (Belgium and The

Netherlands) and in Equatorial Africa (Gigunhwe and Nchwera). In-between these extremes it was probably too dry and the signal too weak to have these interstadial geo-soils strongly developed so that most often only the last and youngest one at the Zelzate Geo-Soil level is present. Above the ultimate severe cold peak of about 20 Ka follow the interstadials of the Late Glacial upwarming corresponding with the Lascaux, Bolling and allerod interstadials or OIS 2 ; in terms of Geo-Soils they read as Zulte, Stabroek and Roksem Geo-Soils. Again as for Geo-soils of the Warneton Complex, they show better development in humid areas as around the North Sea and on the equator in Nchwera. Probably time for development was a limiting factor as well since they occur in-between a series of eolian sands pointing at the rapid change between humidity and strong aridity (DRYAS) in the short phase of warming-up between the maximum cold at 20 Ka and the Holocene at 10 Ka.

4. Finally there are the three Desert pavements (DP 1,2 and 3) attesting from North to Equator of synchronous desert development either warm or polar, but certainly bringing drought all over the Globe. As stated above, there were probably also weaker desertifications although of global impact as the one of the Upper Dryas drought and the one about 73 Ka between OIS 4 and 5.

5. The synchronism between the Boreal and Equatorial Regions for droughts and humid periods at the level of the interstadial climatic changes is hereby also attested.

2.2.3. Short-Term Geo-Soil Traverse and the Holocene (last 10 Ka) Time Series

The complete Geo-Soil Sequence of the Holocene, called the Short-Term Time Series, originated from the systematic study of archaeological sites in Attica, Greece (Paepe *et al.* 1986). It gave not only insight in the climato-environmental changes of the current interglacial extending over the last 10,000 years. One could possibly extend the lower limit of the current interglacial to 15,000 BP, hence including the warming-up of the Late Glacial. Thus the timespan of the current interglacial would be of the same time interval as the Last Interglacial. However, the last 10,000 years have been always considered as relatively monotonous as to changes in temperature. The flatness of the curve after the steep rising of the Late Glacial pleads for this. However, it is advocated here that numerous changes with impact on the environ-

ment occurred due to important changes in the hydrological situation rather than to temperature changes.

The first half of this interglacial dealt with the climato-environmental evolution during the cultural periods of the entire Mesolithic and Neolithic Periods ; the second half with the Bronze Age and the Historical Time. Like the other time series it remains very much the question if short-term changes occurring over a restricted period of 10,000 years may find their equivalent elsewhere and simultaneously. It would largely contribute to the concept of synchronism of climato-environmental changes on a global scale already mentioned for the long-term and middle time series.

2.2.3.1. The Standard Regional Short-Term Stratotype Sections of Greece

From the Standard Sections in Greece from Marathon and Kallikleios a subdivision of the Holocene was possible (Paepe *et al.* 1984, 1990). At least 20 holocene soils were found attesting a cyclicity of a 500 year-period. Another frequent cycle in the Geo-Soil Sequence was the one of 1,000 years whereas the 2,500 periodicity was found suitable by Blytt (1893) and Sernander (1910) for the subdivision of the Holocene. The 1,000 years' cycle is called the drought cycle because, since historical times, droughts with that interval of time have been reported in written documents. Recently it has been found that they perfectly tally with the astronomical drought cycle (Van Overloop *et al.* 1997, in press). Both the 1 000 and 500 years' cycle together are responsible for the rise and fall of the cultural periods (fig. 5). The 2,500 cycle, which is at the base of the geological subdivision into Boreal, Atlantic, Sub-Boreal and Sub-Atlantic, is indeed coinciding with the limits of the Mesolithic, Neolithic, Bronze Age, Hellenistic and Historical Periods. A better climatic determinism cannot be found. Each of these limits is materialized by a geo-soil which makes it evident that boundaries of cultural phases coincide with profound climato-environmental changes.

2.2.3.2. Geo-Soil Traverse of Short-Term Stratotype Sections in Tropical Regions of Africa

Starting from Greece it is possible to extend this subdivision to other parts such as the Delta of Bangladesh and the Loess Plateau in China where archaeo-geological studies are going on. In the light of the present work correlation will focus on the African equatorial region. In the

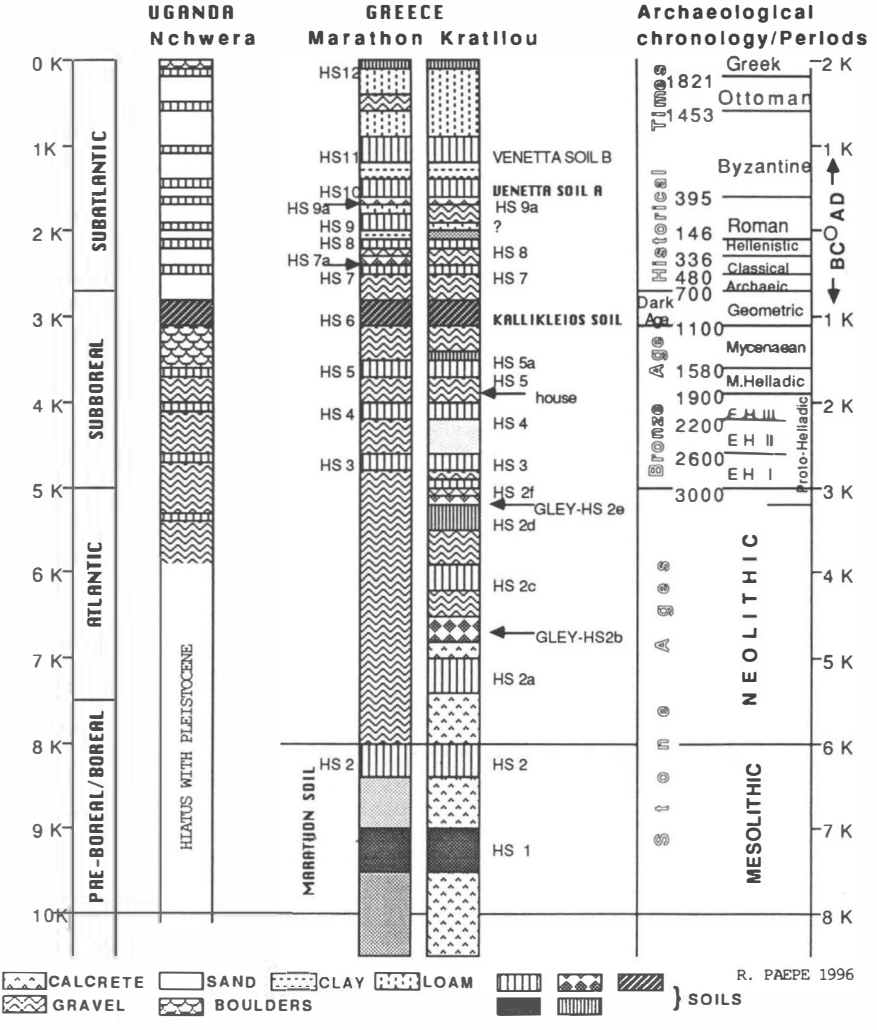


Fig. 5. — Litho-stratotypes of the Holocene Greece and Uganda.

Ruzizi Plain multiple Geo-Soil Sequences were detected by Ilunga and Paepe in 1983 but not yet studied ; however, in the same section of Nchwera in Uganda where the Younger Dryas was found 13 holocene soils were found. There was a sharp erosional unconformity between the Upper Pleistocene deposits and the Holocene so that it is possible that the lower part of the holocene soil sequence was either eroded or never deposited at that place. Notwithstanding this hiatus 13 holocene soils (HS) appeared with a marker horizon which showed a much deeper clay-enriched brown red soil horizon than all other horizons composed of peat. Unfortunately they could not be dated yet. However, lithostratigraphically the strongly developed soil occurring at the base of a sequence of eight soils covered by boulders and overlying a gravel bed separating the strong soil from another series of four similar soils as to the ones above, reminds the strong break at the limit between Sub-Boreal and Sub-Atlantic. In archaeological terms, this can be read as the boundary between the Bronze Age and the Historical Times. In Greece the Kallikleios Soil was found at this position. This soil sealed off the landscape as all former plains had been filled up to this level and sedimentation stopped in order to give pace for a period of standstill with soil development. Also at Nchwera the strong soils in the middle of all other weaker soils, seal off the deeper part of the valley which points to an equal flattening of the relief as the one which occurred in Greece and elsewhere in Europe about the transition of the Sub-Boreal to the Sub-Atlantic.

2.2.3.3. Third Intermediate Conclusive Remarks

The similarity of the soil and geomorphological evolution between regions so far apart infers that synchronism also existed even within shorter periodicities as those reflected in the Short Time Series of the Holocene of Southern Europe and Africa. Considering moreover the difference within short distances of the holocene soil development of the holostratotype of Marathon and that of the hypostratotype of Kratilou around Athens in Greece, it may be concluded that the geomorphological and tectonical position of the stratotype site is of great importance. It was concluded earlier by Paepe *et al.* (1986) that, in tectonically uplifted areas, the Geo-Soil Sequence consisted of a smaller number of holocene soils than in alluviating subsiding sites : rising Marathon has 12 dominant holocene soils and Kratilou in the sinking Kifissos Valley has 20 including the ultimate topsoil. The latter situation is also encountered in Nchwera (Uganda) in a valley position

where at least 13 holocene soils seem to occur in the last 6,000 years, *i.e.* above the Atlantic. Eight of these holocene soils occur in the Sub-Atlantic above the presumed equivalent of the Kallikleios Soil of Greece separating the Sub-Boreal from the Sub-Atlantic at about 2,750 BP. As some of the soils are grouped in pairs a periodicity of less than 300 years for cyclic changes of the climate must be envisaged. Below the Kallikleios equivalent 5 holocene soils occur in a similar position to the Marathon and Kratilou sites, *i.e.* more widely spaced all over the Sub-Boreal and into the very top of the Atlantic. It implies a greater periodicity, presumably of 500 years and longer, than those of the Sub-Atlantic. Considering the fact that the latter sub-stage is generally known as to be wetter than the previous one, climatic changes may occur more frequently during generally humid climatic periods than during the dryer ones as the Sub-Boreal. Anyhow, the equatorial climatic evolution during the Holocene shows a definite synchronism with the Sub-Tropical Belt of Southern Europe despite the Mediterranean Sea and the Sahara in-between.

3. The Global Synchronous Impact of Drought on Mankind and Civilization

It may be concluded from the three series of above-mentioned intermediate conclusive remarks that for all geo-soil time series concerned, periods of Drought of the Boreal Regions fully correspond with equally cooler periods of drought in the Tropical and Sub-Tropical Regions. Therefore a subdivision into tropical Pluvials and Interpluvials corresponding to Boreal Glacials and Interglacials is pure illusion and obsolete.

Since the Miocene, the global climatic, however complex, cyclic evolution in Tropical and Sub-Tropical Regions has occurred similarly as in any other point of the Earth's surface. As changes of drought (cooler or extremely cold) and moist (wetter or extremely wet) periods alternate synchronously with the same frequency and relative intensity all over the Earth they have become a serious challenge for Mankind. Especially the perfect synchronism of the major drought cycles corresponding to the seven Gravel Beds (A, B, C, D, E, F, F') of the Long-Term Time Series and the various Geo-Soil Sequences including smaller periods of drought in-between, should be emphasized. It was found that the geo-soils perfectly tally with the odd numbered warm stages of the OIS record of the Deep Sea. For a total of 51 odd OIS

stages a total of 67 geo-soils are recorded as some of the geo-soils are doubled in longer odd cycles. The latter together with the shorter drought phases in-between are controlled mainly by the 100,000 and 40,000 years periodicities. The six major gravel beds then reveal the 400,000 years megacycle also well-known from the deep sea. All recorded droughts were synchronous all over the World and produced warm deserts in the Tropics and Sub-Tropics and Polar Deserts with peak periglacial activities as of 28 N (Crete).

Besides the possible correlation between the Geo-Soil Sequences of Equatorial Africa and the Eastern Mediterranean, it was possible to extend this correlation to the Loess Plateau of China as well. Despite the smaller number of only 57 geo-soils in China against 67 in Sparta, they are equally separated by the aquiferous sand layers (L2, L6, L9, L15, L29, L35) occupying the same stratigraphical positions of the major Gravel Beds.

Considering the First Appearance Datum (FAD) and the Last Appearance Datum (LAD) of Man throughout the Long-Term and Middle-Term Time Series, coincidence with definite periods of Droughts is brought to light as is shown in the comparative list below :

Droughts and Mankind

Upper Pliocene

3.7 - 2.6 Ma : End Pliocene Drought (Gravel Bed F')
LAD of LUCY or *Australopithecus afarensis*

Lower Pleistocene

2.6 - 1.9 Ma : 3 long droughts (Gravels F', F and E)
16 small droughts
alternating with forest and savanna
FAD of *Australopithecus africanus*

1.9 - 1.4 Ma : 2 long droughts (Gravels E and D)
14 small droughts
Forest and savanna decays
LAD of : *Australopithecus robustus*
Australopithecus boisei
Homo habilis

1.4 - 0.7 Ma : 3 long droughts (Gravels D,C and B)
18 small droughts
Desertification of Africa generalized
Low sea level

First colonization by Early Man of all parts of the entire World
LAD of : *Pithecanthropus javaensis*
Sinanthropus pekinensis
Homo erectus (continuous after Gravel B)

Middle Pleistocene

0.7 - 0.4 Ma : 1 long drought (Gravel B)
3 small droughts
Desertification stronger
Homo erectus continues
FAD of *Homo sapiens*

Middle Pleistocene / Upper Pleistocene

0.4 - 0.05 Ma : 1 long drought (Gravel A)
7 small droughts
World-wide desertification
LAD of *Homo erectus*
FAD of *Homo sapiens neanderthalensis*
0.05 - present : 13 small droughts / maximum cold of Pleistocene
LAD of *Homo sapiens neanderthalensis*
FAD of *Homo sapiens sapiens*

Thus it became evident that Mankind could stand the test of 81 known severe drought phases which seem to have strongly conditioned his evolution. Assuming the fact that each of the former Glacial phases may potentially be subdivided into 13 stadial/interstadial cycles and each of the Interglacials into another 20 stadial/interstadial cycles equally to the evolution during respectively the Last Glacial cycle and the Holocene, the number of drought cycles that Man has faced over the last 2.6 Myr may eventually total up to $(81 \times 13) + (81 \times 20) = 2{,}673$. This is an average of one per each millennium. The Little Ice Age of the presently ending millennium is a good example of it. Throughout all these challenges, it was not only himself but also his rising civilization, *i.e.* the cultural environmental heritage of which he was the very creator himself that he had to maintain alive. Droughts rather than Pluvials in the Equatorial Belt of Africa provided Ancient Man with the necessary courage and force of the fittest to cope with this challenge in his daily struggle for life!

REFERENCES

BLYTT, A. 1893. Uber die phytogeographischen und phytopaläontologischen Gründe für die Annahme von Klimaänderungen während der Quartärzeit. — *Christiana Vid. Selsk. Forh.*, **5**.

BUEDEL, J. 1981. Klima Geomorphologie. — Gebrueder Borntraeger, Berlin Stuttgart, 304 pp.

CLARK, J. D. & COLE, S. 1957. Subdivision of the African Quaternary. — *In* : Proceedings of the Third Pan African Congress on Prehistory of Northern Rhodesia.

COLE, S. 1964. The Prehistory of East Africa. — Weidenfeld and Nicolson, London, 382 pp.

DANSGAARD,W., JOHNSEN, S. J., MOLLER ; J. & LANGWAY, C. C. 1969. One thousand centuries of climatic record from Camp Century on the Greenland ice sheet. — *Science*, **166** : 377-381.

DANSGAARD, W., JOHNSEN, S. J., CLAUSEN, H. B. & LANGWAY , C. C. 1971. Climatic record revealed by the Camp Century ice core. — *In* : TUREKIAN, K. K. (ed.), The Late Cenozoic glacial ages. Yale Univ. Press, New Haven, pp. 37-56.

GAUTIER, A. 1967. New Observations on the Later Tertiary and Early Quaternary in the Western Rift : The Stratigraphic and Palaeontological Evidence. — *In* : BISHOP, W. W. & CLARK, J. D. (eds.), Background to Evolution in Africa. Univ. Chicago Press, pp. 73-87.

ILUNGA, Lutumba K. P. 1984. Le Quaternaire de la Plaine de la Ruzizi, Zaïre. — Ph.D. Thesis, Vrije Universiteit Brussel, Brussel, 353 pp.

KAFUMU DALALY, P. 1995. The Palaeosoils in the lithosequences of the Olduvai Gorge Beds, Tanzania. — MS Thesis, Vrije Universiteit Brussel, Brussel, 82 pp.

KASEBA MBUY KABONGO, S. 1996. Formations bauxitiques latériques du Bas-Zaïre. — Ph.D. Thesis, Vrije Universiteit Brussel, Brussel, 298 pp.

LEAKEY, L. B. S. 1936. Stone Age Africa. — Oxford Univ. Press, 218 pp.

LEAKEY, L. B. S. 1959. A new fossil skull from Olduvai. — *Nature,* **184**, pp. 491-493.

LEAKEY, L. B. S. 1965. Olduvai Gorge 1951-61. — Cambridge Univ. Press, 118 pp.

LYELL, C. 1839. Principles of geology. — Murray, London, **3** : 398 pp.

MCCALL, G. J. H., BAKER, B. H. & WALSH, J. 1967. Late Tertiary and Quaternary Sediments of the Kenya Rift Valley. — *In* : BISHOP, W. W. & CLARK, J. D. (eds.), Background to Evolution in Africa. Univ. Chicago Press, pp. 191-220.

MILANKOVITCH, M. 1941. Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitproblem. — Acad. R. Serbe, Ed. spéc. **133** : 633 pp.

MORRISON, R. B. 1967. Principles of Quaternary soil stratigraphy in means of correlation of Quaternary successions. — *In*: MORRISON, M. B. & WRIGHT, M. E. (eds.), INQUA Proceedings VII - Congress, **9**: 1-69.

MUSISI, J. H. 1991. The Neogene-Quaternary Geology of the Lake George - Edward Basin, Uganda. — Ph.D. Thesis, Vrije Universiteit Brussel, Brussel, 298 pp.

NILLSON, E. 1931. Quaternary glaciations and pluvial lakes in British East Africa. — *Geogr. Ann.*, **13**: 249-348.

NILLSON, E. 1963. Pluvial lakes and glaciers in East Africa. — *Stockholm Contrib. in Geol.*, **11**: 21-57.

PAEPE, R. 1963. Bouw en Oorsprong van de Vlakte van de Leie. — Ph.D. Thesis, Rijksuniversiteit Gent, 225 pp.

PAEPE, R., HADZIOTIS, M. E. & VAN OVERLOOP, E. 1995. Twenty Cyclic Pulses of Drought and Humidity during the Holocene. — *In*: FINKL, C. W. Jnr. (ed.), Holocene Cycles. *Journal of Coastal Research*, Special Issue **17**: 55-61.

PAEPE, R., MARIOLAKOS, I., NASSOPOULOU, S., VAN OVERLOOP, E. & VOULOUMANOS, N. 1996. Quaternary Periodicities of Drought in Greece. — *In*: ANGELAKIS, A. N. & ISSAR, A. S. (eds.), Diachronic Climatic Impacts on Water Resources, NATO ASI Series I, **36**: 77-110.

PAEPE, R., MARIOLAKOS, I., VAN OVERLOOP, E. & KEPPENS, E. 1990b. Last Interglacial-Glacial Geo-Soil Traverse (from stratotypes in the North Sea Basin and in the Eastern Mediterranean). — *Quaternary International*, **5**: 57-70.

PAEPE, R. & VAN OVERLOOP, E. 1990a. River and Soil Cyclicities interfering with sea level changes. — *In*: PAEPE, R., FAIRBRIDGE, R. W. & JELGERSMA, S. (eds.), Greenhouse Effect, Sea Level and Drought, NATO ASI Series C, pp. 253-280.

PAEPE, R., VAN OVERLOOP, E., HATZIOTIS, M. E. & THOREZ, J. 1984. Desertification cycles in historical Greece. — *Progress in Biometeorology*, **3**: 55-64.

PAEPE, R. & ZAGWIJN, W. H. 1972. Possibilités de corrélation des dépôts weichséliens de la Belgique et des Pays-Bas. — *Bull. Association française pour l'étude du Quaternaire*, **1**: 59-69.

PENCK, A. & BRUECKNER, E. 1910. Die Alpen im Eiszeitalter. 1-3. — Tauchnitz, Leipzig, 1199 pp.

PETIT-MAIRE, N. 1990. Natural Aridification or Man-made desertification? — *In*: PAEPE, R., FAIRBRIDGE, R. W. & JELGERSMA, S. (eds.), Greenhouse Effect, Sea Level and Drought, NATO ASI Series C, pp. 281-285.

SERNANDER, R. 1910. Die Schwedischen Torfmoore als Zeugen Postglazialer Klimaschwankungen. — 11th IGC, Stockholm, pp. 197-246.

SHACKLETON, N. J. & OPDYKE, N. D. 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238 ; oxygen isotope temperatures and ice volume on a 10^5 year and 10^6 year scale. — *Quaternary Research,* **3** : 39-55.

SHACKLETON, N. J., BERGER, A. & PELTIER, W. 1990. An alternative astronomical calibration of the Lower Pleistocene time-scale based on ODP Site 677. — *In* : Transactions of the Roy. Soc. of Edinburgh, *Earth Sciences,* **81** : 251-261.

VAN OVERLOOP, E. & PAEPE, R. 1997. Global Correlation of Holocene Climatic Changes. — *In* : BROWN, N. & ISAR, A. (eds.), Water Environment and Society in Times of Climate Change. Kluwer Academic Publishers (in press).

WAYLAND, E. J. 1934. Rifts, rivers, rains and Early Man in Uganda. — *J. R. Anthrop. Inst.*, **64** : 333-352.

WAYLAND, E. J. 1952. The study of past climates in tropical Africa. — Pan-African Congress on Pre-History, 1947, Blackwell, Oxford.

WOILLARD, G. & MOOK, G. W. 1982. Carbon-14 dates at Grande Pile : correlation of land and sea chronologies. — *Science*, **215** : 159-161.

YAMBA TSHISUNGU KANTU, P. 1993. Etude lithostratigraphique des dépôts quaternaires de la Plaine de Rutshuru. — Ph.D. Thesis, Vrije Universiteit Brussel, Brussel, 174 pp.

ZAGWIJN, W. H. & PAEPE, R. 1968. Die Stratigraphie der Weichselzeitlichen Ablagerungen der Niederlande und Belgiens. — *Eiszeitalter und Gegenwart*, **19** : 126-146.

CLIMATOLOGY

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 179-190 (1998)

Etude des fluctuations de la température de l'air et des précipitations au Sénégal de 1854 à 1990

par

Cheikh MBAYE *

MOTS-CLES. — Précipitations ; Température de l'air ; Tendance.

RESUME. — L'étude porte, d'une part, sur l'analyse spatio-temporelle des précipitations et de leur dimunition et, d'autre part, sur les fluctuations de la température de l'air. Pour une telle étude, nous avons calculé pour la période 1951-1990 la moyenne de la saison sèche, de la saison des pluies et de l'année, de la température de l'air et des précipitations de quelques stations météorologiques du Sénégal. Et pour l'étude des tendances, nous avons utilisé l'analyse de régression. Les résultats ont permis de juger de la valeur approximative des variations des deux éléments météorologiques.

TREFWOORDEN. — Neerslag ; Luchttemperatuur ; Trend.

SAMENVATTING. — *Studie van de fluctuaties van de temperatuur van de lucht en van de neerslag in Senegal van 1854 tot 1990.* — Deze studie behandelt enerzijds de ruimtelijke-tijdsgebonden analyse van de neerslagen en de daling ervan, en anderzijds de fluctuaties van de luchttemperatuur. Voor een dergelijke studie hebben we het gemiddelde berekend voor de periode 1951-1990 van het droog seizoen, van het neerslagseizoen en van het jaar, van zowel de luchttemperatuur als de neerslagen en dit voor enkele meteorologische stations in Senegal. Voor de studie van de tendensen hebben we gebruik gemaakt van een regressieanalyse. De resultaten hebben een benaderende waardebeoordeling toegelaten van de variaties van deze twee meteorologische elementen.

KEYWORDS. — Precipitation ; Air Temperature ; Trend.

ABSTRACT. — *Study of the Fluctuations of the Air Temperature and of the Precipitation in Senegal from 1854 till 1990.* — The study deals, on the one hand, with the spatiotemporal analysis of the rainfall and its decrease and, on the other hand, with the fluctuations of the air temperature. For

* Etudiant en géographie et cartographie, Faculté des Sciences, Université Masaryk Kotlé, 611 37 Brno (République Tchèque) (décédé).

this purpose, we have computed for the reference period 1951-1990 the mean of the dry season, of the wet season and of the year, of the air temperature and the rainfall of some meteorological stations in Senegal. Regression analysis was used for the trend analysis. The results have allowed to judge the approximate value of the variations of the two meteorological elements.

1. Introduction

L'agriculture qui est à la base des économies africaines est menacée par la désertification qui se manifeste par une diminution importante des hauteurs pluviométriques entraînant toutes sortes de perturbations des activités humaines dans la zone sahélienne. Le Sénégal se trouve dans la partie ouest de cette zone. D'après ADEJUWON *et al.* (1990), la diminution des hauteurs pluviométriques en Afrique de l'Ouest est indiscutable. De nombreux auteurs ont tenté de décrire et de comprendre les mécanismes régissant les pluies dans cette partie du monde (VANNITSEM & DEMAREE 1991). Le but de ce travail n'est pas de chercher les causes des fluctuations de la température de l'air et des précipitations au Sénégal, mais d'évaluer leurs tendances spatio-temporelles.

2. Les données

Les données proviennent de l'Université d'East Anglia (Royaume-Uni) sans informations supplémentaires sur l'histoire des stations utilisées (tableau 1). La figure 1 montre leur répartition et le tableau 2 leurs caractéristiques géographiques. Certaines lacunes sont à déplorer, à savoir des données manquantes au sein de quelques séries. Nous supposerons par la suite que les séries peuvent contenir une hétérogénéité d'origine humaine (que nous essayerons d'éliminer), comme par exemple un changement de position de la station ou un changement d'instrument ou bien encore une modification de la méthode d'observation.

3. Test et méthodes utilisés

Sur la base des données mensuelles, nous avons étudié l'homogénéité relative des séries avec le test de MARONNA & YOHAI (1978) qui nous permet de détecter l'année de l'hétérogénéité, sa valeur et son importance statistique.

Tableau 1

Périodes d'observations des stations utilisées

Stations	Eléments météo	Périodes d'observations
Bakel (Bl) *	P T	1918-1973 —
Bambey (By)	P T	1921-1986 —
Dakar-yoff (Dk)	P T	1898-1993 1898-1990
Diourbel (Dl)	P T	1919-1990 1951-1990
Fatick (Fk)	P T	1918-1990 —
Kaolack (Kk)	P T	1933-1990 1931-1990
Kolda (Ka)	P T	1933-1990 1951-1990
Kédougou (Ku)	P T	1918-1990 —
Linguère (Lr)	P T	1933-1990 1951-1990
Matam (Mm)	P T	1918-1990 1951-1990
Podor (Pr)	P T	1918-1990 1951-1990
St-Louis (Ss)	P T	1854-1993 1892-1990
Sédhiou (Su)	P T	1905-1974 —
Tambacounda (Ta)	P T	1920-1990 1923-1990
Thiès (Ts)	P T	1918-1973 —
Ziguinchor (Zr)	P T	1918-1990 1923-1990

P = précipitations ; T = température de l'air.
* abréviations des stations.

Tableau 2

Caractères géographiques des stations utilisées

Stations	Latitude	Longitude	Altitude (m)
Bakel	14°9′	12°4′	25
Bambey	14°7′	16°4′	20
Dakar-yoff	14°7′	17°5′	24
Diourbel	14°8′	16°3′	7
Fatick	14°3′	16°4′	6
Kaolack	14°1′	16°1′	6
Kolda	12°5′	14°9′	22
Kédougou	12°6′	12°2′	165
Linguère	15°4′	15°5′	21
Matam	15°6′	13°3′	15
Podor	16°6′	14°9′	6
St-Louis	16°1′	16°5′	4
Sédhiou	12°7′	15°5′	15
Tambacounda	13°8′	13°7′	50
Thiès	14°4′	16°5′	76
Ziguinchor	12°6′	16°3′	19

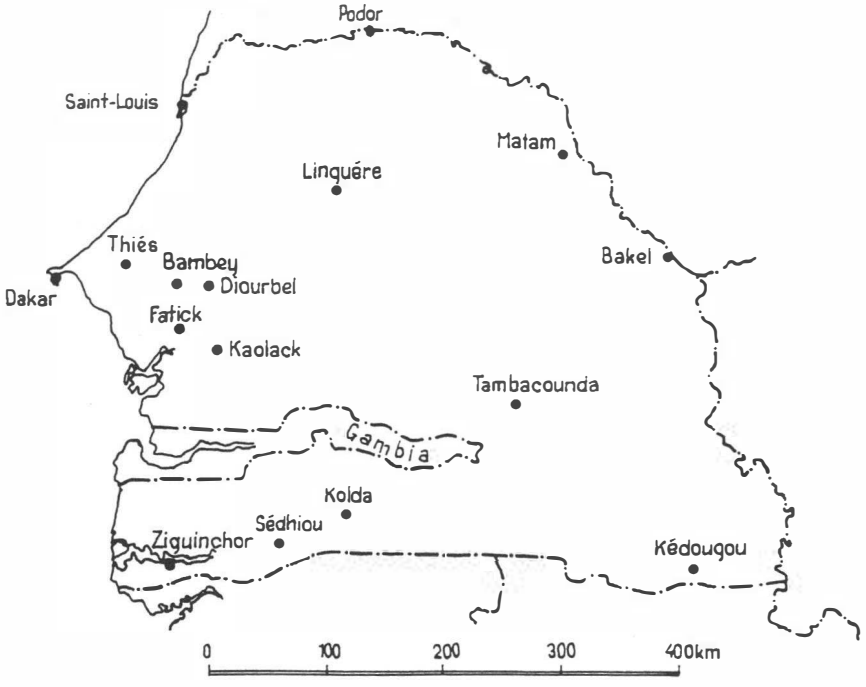


Fig. 1. — Répartition géographique des stations utilisées.

Les cas où la série choisie comparée avec les séries des stations voisines montrent un coefficient de corrélation supérieur ou égal à 0,70 sont considérés comme hétérogènes. Les coefficients de corrélation entre les stations étant très faibles (tableau 3), nous concluons que l'hétérogénéité des séries est négligeable.

Tableau 3

Valeurs significatives des coefficients de corrélation exprimées en (%) entre les stations

a) Précipitations

		By	Bl	Dk	Dl	Fk	Kk	Ka	Ku	Lr	Mm	Pr	Ss	Ta	Ts	Zr	Su
n – 1 autres	s.s.	33	0	26	26	26	0	0	0	0	0	0	6	0	26	0	0
	s.p.	33	0	20	26	33	20	6	0	0	0	0	0	0	13	0	0
	a.	33	0	20	26	22	26	13	0	0	6	0	0	0	6	0	0

s.s. = saison sèche ; s.p. = saison des pluies ; a. = année ; n = nombre de stations ; By : abréviation (voir tableau 1).

b) Température de l'air

		Dk	Dl	Ka	Kk	Lr	Mm	Pr	Ss	Ta	Zr
n - 1 autres	s.s.	0	0	0	0	10	0	10	0	10	10
	s.p.	0	0	0	0	0	0	0	0	0	10
	a.	0	0	0	0	0	20	30	0	0	0

s.s. = saison sèche ; s.p. = saison des pluies ; a. = année ; n = nombre de stations ; By : abréviation (voir tableau 1).

Avec la méthode des moyennes arithmétiques nous avons calculé la moyenne de la température de l'air (saison sèche, saison des pluies et l'année) et des précipitations (saison sèche, saison des pluies et l'année) pour toutes les stations, pour la période 1951-1990. La moyenne de la température de l'air et des précipitations du Sénégal a été calculée pour la même période en tenant compte du nombre très limité de stations. Cette moyenne a été prolongée par la méthode de l'analyse de régression jusqu'à 1918 pour les précipitations et 1923 pour la température de l'air.

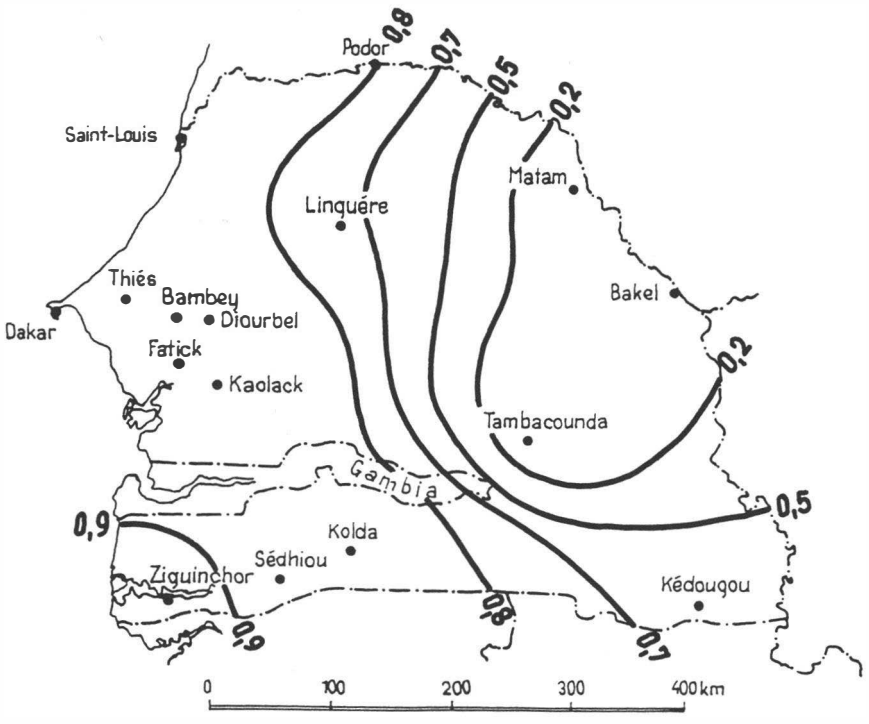


Fig. 2. — Répartition de l'indicateur local de l'homogénéité spatiale h calculée (à l'aide du coefficient de corrélation de rang Rs de Spearmann) entre la moyenne pluviométrique du Sénégal et la moyenne de chaque station pour la période 1933-1973.

Pour l'étude de l'homogénéité spatiale des précipitations annuelles, nous avons pris la période 1933-1973 commune à toutes les stations, puis nous avons calculé le coefficient de corrélation de Rang Rs de Spearman comme décrit dans le travail de BULTOT & GELLENS (1994) ; les résultats nous ont permis d'établir la carte des isoplèthes (fig. 2). La corrélation entre les stations et la moyenne du Sénégal nous a permis de tracer la carte des isolignes (fig. 3).

Pour l'étude des tendances nous avons utilisé l'analyse de régression de la forme $Y = a + bx$ décrite par ANYADIKE (1994), Y étant le temps et la pente b nous donnant la valeur de la diminution. Nous avons appliqué cette méthode à toutes les stations pour la période 1951-1990 (tableaux 4 et 5).

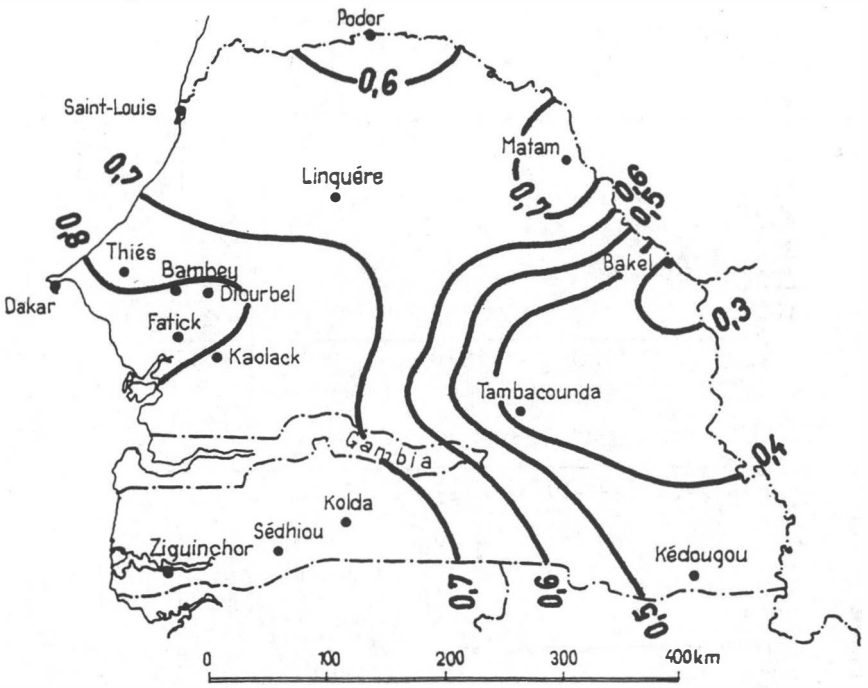


Fig. 3. — Carte des isolignes des coefficients de corrélation entre la moyenne pluviométrique du Sénégal et la moyenne de chaque station pour la période 1933-1973.

Avec la moyenne du Sénégal et les stations ayant des séries assez longues (Dakar, St-Louis), nous avons étudié graphiquement les variations (saison sèche, saison des pluies et l'année), à l'aide des moyennes chevauchantes. Les résultats montrent les fluctuations de la température de l'air et des précipitations (figs 4 et 5).

4. Résultats

Le test de MARONNA & YOHAI appliqué aux séries de la température de l'air et à celles des précipitations du Sénégal montre, dans la plupart des cas, une hétérogénéité pour les années 1913, 1968, 1972. Si on exclut les erreurs humaines, nous pouvons penser que cette hétérogénéité est liée aux trois sécheresses sahéliennes décrites par VANNITSEM & DEMAREE (1991).

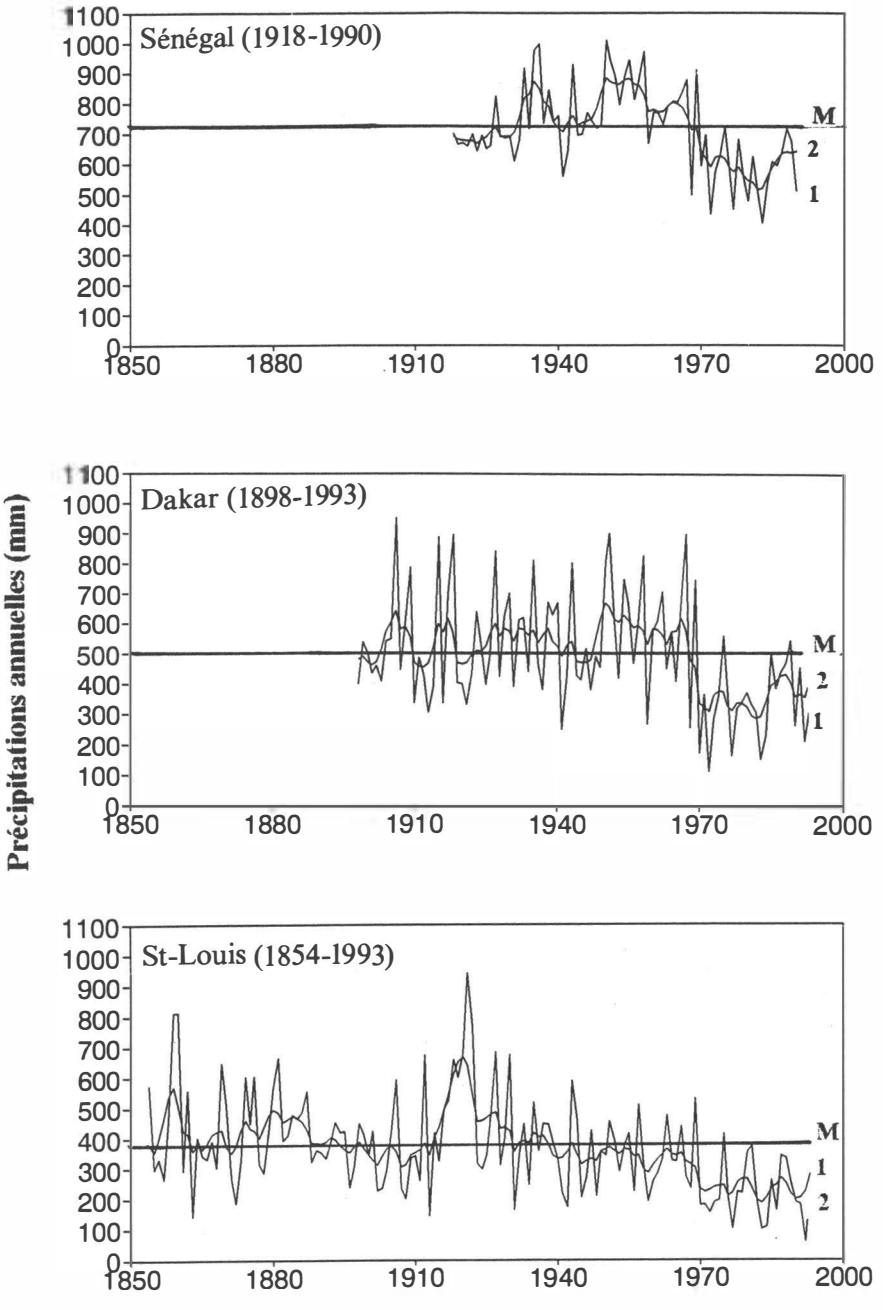


Fig. 4. — Tendance séculaire des précipitations annuelles (1. Précipitations annuelles, 2. Moyennes chevauchantes, M : moyenne de la série).

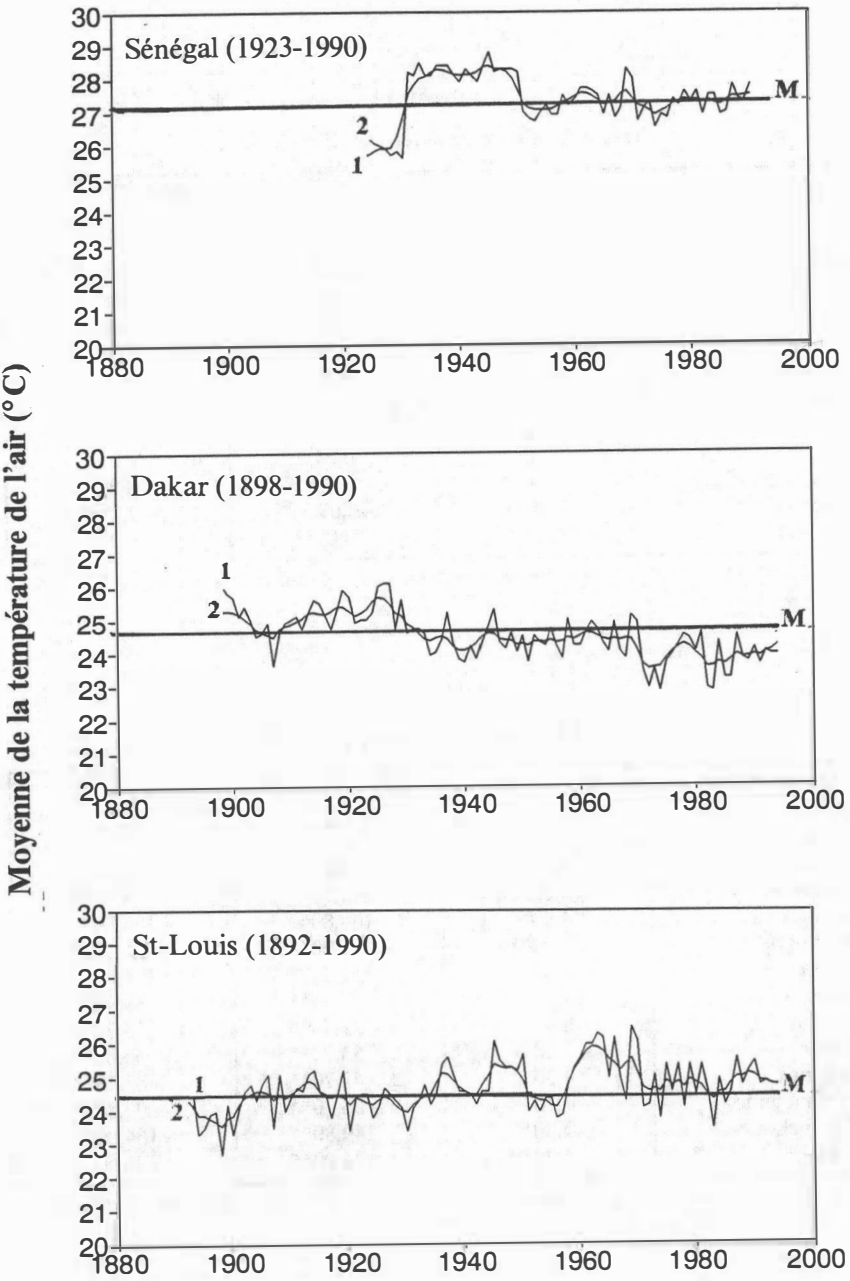


Fig. 5. — Tendance séculaire de la moyenne de la température de l'air (1. Température moyenne de l'air, 2. Moyennes chevauchantes, M : moyenne de la série).

Tableau 4

Test de tendance de la température de l'air

Stations	Tendance en °C/ 10 ans (1951-1990)		
	s.s.	s.p.	a.
Dakar	– 0,20*	0,07	0,20**
Diourbel	– 0,09	0,10	0,05
Kaolack	0,10	0,06	0,09
Kolda	– 0,30**	– 0,04	0,20**
Linguère	0,30**	0,22**	0,33**
Matam	0,50**	0,51**	0,60**
Podor	0,11	0,20**	0,10**
St-Louis	0,10	0,04	0,04
Tambacounda	0,30**	0,10**	0,20**
Ziguinchor	– 0,20**	– 0,09	– 0,20**
Sénégal	0,08	0,09*	0,07

s.s. = saison sèche ; s.p. = saison des pluies ; a. = année ; seuil de signification : * = 90 %, ** = 95 %.

Tableau 5

Test de tendance des précipitations

Stations	Tendance en mm/ 10 ans (1951-1990)		
	s.s.	s.p.	a.
Dakar	– 3,33*	– 88,60**	– 92,80**
Diourbel	– 4,80*	– 113,70**	– 118,40**
Kaolack	– 4,90	– 100,80*	– 105,80**
Kédougou	– 7,20**	– 111,90**	– 119 ;30**
Kolda	– 0,30	– 152,20**	– 154,00**
Lingère	– 2,70	– 37,20**	– 39,90**
Matam	– 2,00	– 71,70**	– 73,70**
Podor	– 2,20	– 53,70**	– 55,80**
St-Louis	– 1,30	– 42,20**	– 43,10**
Tambacounda	– 1,10	– 06,70**	– 97,80**
Ziguinchor	– 4,30**	– 149,80**	– 154,00**
Sénégal	– 3,20**	– 134,00**	– 96,50

s.s. = saison sèche ; s.p. = saison des pluies ; a. = année ; seuil de signification : * = 90 %, ** = 95 %.

L'étude de la carte des isoplèthes montre que l'homogénéité spatiale est plus marquante à l'ouest du territoire qu'à l'est, la carte des isolignes confirme une réelle homogénéité de la partie ouest. Ceci est peut-être dû à la forte concentration des stations dans cette zone.

Le test de tendance montre une diminution des hauteurs pluviométriques dans toutes les stations météorologiques que nous avons étudiées. Cependant, les valeurs de la diminution diffèrent selon les régions. Ainsi la diminution est de l'ordre de 100 à 150 mm/10 ans au sud tandis qu'au nord, elle est de 50 à 80 mm/10 ans.

La même méthode appliquée aux températures de l'air montre une tendance au refroidissement (– 0,20°C/10 ans) pour les régions de Dakar, Diourbel, Kolda, Ziguinchor et une tendance au réchauffement (0,05 à 0,6°C/10 ans) pour les régions de Kaolack, Linguère, Matam, Podor, St-Louis, Tambacounda.

5. Conclusions

La diminution des hauteurs pluviométriques observée au Sahel depuis les années 1968 est une réalité. L'étude spatio-temporelle des précipitations annuelles de quelques stations météorologiques du Sénégal confirme une réelle diminution des précipitations avec des valeurs approximatives de 80 à 150 mm/10 ans. Quant à la température de l'air, nous distinguons deux types de variations, l'une caractérisée par une tendance au refroidissement (Dakar, Diourbel, Kolda, Ziguinchor), l'autre par une tendance au réchauffement (Linguère, Matam, Podor, St-Louis et Tambacounda).

Pour mieux comprendre les variations des deux éléments météorologiques, il serait bon de vérifier l'homogénéité des séries et tenir compte des facteurs locaux (déforestation) et globaux (influence de l'océan Atlantique, circulation atmosphérique, ENSO, ...) qui pourraient agir sur les variations des deux éléments météorologiques.

REMERCIEMENTS

Je remercie sincèrement le professeur R. Brázdil pour ses remarques et suggestions.

BIBLIOGRAPHIE

ADEJUWON, J. O., BALOGUN, E. E. & ADEJUWON, S. A. 1990. On the annual and seasonal patterns of rainfall fluctuations in Sub-Saharan West Africa. — *Int. J. Climatol.*, **10** : 839-840.

ANYADIKE, R. N. C. 1994. Rainfalll over Lagos, Nigeria, 1898-1987. Part 1. Monthly and annual variations. — *Weather*, **49** (5) : 163-168.

ANYADIKE, R. N. C. 1994. Rainfall over Lagos, Nigeria, 1898- 1987. Part 2. Variations in the character of the seasons. — *Weather*, **49** (7) : 239-243.

BULTOT, F. & GELLENS, D. 1994. Sur le caractère stationnaire et cyclique des précipitations au Rwanda. — Mém. Acad. R. Sci. Outre-Mer, Bruxelles, 53 pp.

MARONNA, R. & YOHAI, V. J. 1978. A bivariate test for the detection of a systematic change in mean. — *J. Amer. Stat. Assoc.*, **73** : 640-645.

VANNITSEM, S. & DEMAREE, G. 1991. Détection et modélisation des sécheresses au Sahel : proposition d'une nouvelle méthodologie. — *La Revue d'Hydrologie Continentale*, **6** (2) : 155-171.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 191-199 (1998)

The Variability of Rainfall in Tanzania

by

Ari VENÄLÄINEN * & M. MHITA **

KEYWORDS. — Variability ; Rainfall ; Tanzania.

ABSTRACT. — In Tanzania agriculture is mainly rainfall-limited. In some areas agriculture is limited by the length of the rainy season while in others it is limited by the amount of rain. In this paper the length of the rainy seasons, the probability of a long harmful dry spell during the growing season and the variability of rainfall within and between seasons were studied. The long-term time series were also briefly examined.

MOTS-CLES. — Variabilité ; Précipitations ; Tanzanie.

RESUME. — *La variabilité des précipitations en Tanzanie.* — En Tanzanie, l'agriculture est principalement conditionnée par les précipitations. Dans certaines régions, l'agriculture est limitée par la longueur de la saison des pluies, tandis que dans d'autres régions elle est limitée par les quantités précipitées. Dans cet article, la longueur des saisons de pluie, la probabilité d'une longue période sèche nuisible pendant la saison de croissance et la variabilité des précipitations dans et entre les saisons sont étudiées. Les séries temporelles longues sont examinées brièvement.

TREFWOORDEN. — Variabiliteit ; Neerslag ; Tanzania.

SAMENVATTING. — *De variabiliteit van de neerslag in Tanzania.* — In Tanzania wordt de landbouw gelimiteerd door de neerslag ; in sommige gebieden wordt de landbouw gelimiteerd door de duur van het regenseizoen, terwijl in andere gebieden hij gelimiteerd wordt door de neerslaghoeveelheid. In dit artikel werden de lengte van het neerslagseizoen, de waarschijnlijkheid van een lange en schadelijke droge periode gedurende het groeiseizoen en de variabiliteit van de neerslag tussen de seizoenen bestudeerd. De langetermijn-tijdreeksen werden eveneens kort onderzocht.

* Finnish Meteorological Institute, P.O. Box 503, SF-00101 Helsinki (Finland).
** Directorate of Meteorology, P.O. Box 3056, Dar es Salaam (Tanzania).

Introduction

In Tanzania, as in most of the seasonally-arid tropics, agriculture is mainly rainfall-limited. Rainfall events such as the onset, end and length of the rainy seasons and the amount of rainfall, as well as the occurrence of long dry spells during the growing season are therefore important. The onset and cessation of the rains define the length of the growing season. In some areas agriculture is limited by the length of the rainy season while in others it is amount-limited (MHITA 1984). The effects of long dry spells on growing crops range from a reduction in growth and/or crop development rate to total crop failure (DOORENBOS & KASSAM 1979, STEGMAN 1982). For a dry spell of a given length the effect is more severe if it occurs at flowering than correspondingly at maturity or during vegetative growth.

In this paper we look at the reliability and variability of rainfall in the different regions of Tanzania. Firstly, we discuss the start and end of the rains and secondly, we look at the occurrence of long dry spells ; thirdly, we investigate the probability of ten-day rainfall sums. As a result of an intensified greenhouse effect, the discussion about climate change is becoming more and more important (e.g. NICHOLSON 1989 and HULME 1992) ; in this paper long-term time series for a few stations' annual rainfall sums have also been plotted.

Data and Methods

A study was made of ten-day rainfall data for 13 stations with records ranging from 30 to 65 years (fig. 1, Bagamoyo being used only for the long-term time series studies). The stations represent the three main rainfall regimes in Tanzania, namely the bimodal, unimodal and transitional patterns (MHITA & NASSIB 1987). In bimodal areas there are two rainy seasons, while in the unimodal regions only a single rainfall peak exists. Between these two lie regions, the transitional areas, which have essentially two peaks but with no discernible dry season between the short and long rains. The type of rainfall regime for each station is also indicated in figure 1.

The analyses commenced on January 1. The 20, 50 and 80 % values for ten-day rainfall were determined for six stations, Moshi, Mwanza, Songea, Dodoma, Dar es Salaam and Tabora. These were smoothed using a three-year running mean and then plotted. The probability of long dry spells exceeding 15 days was also determined for two

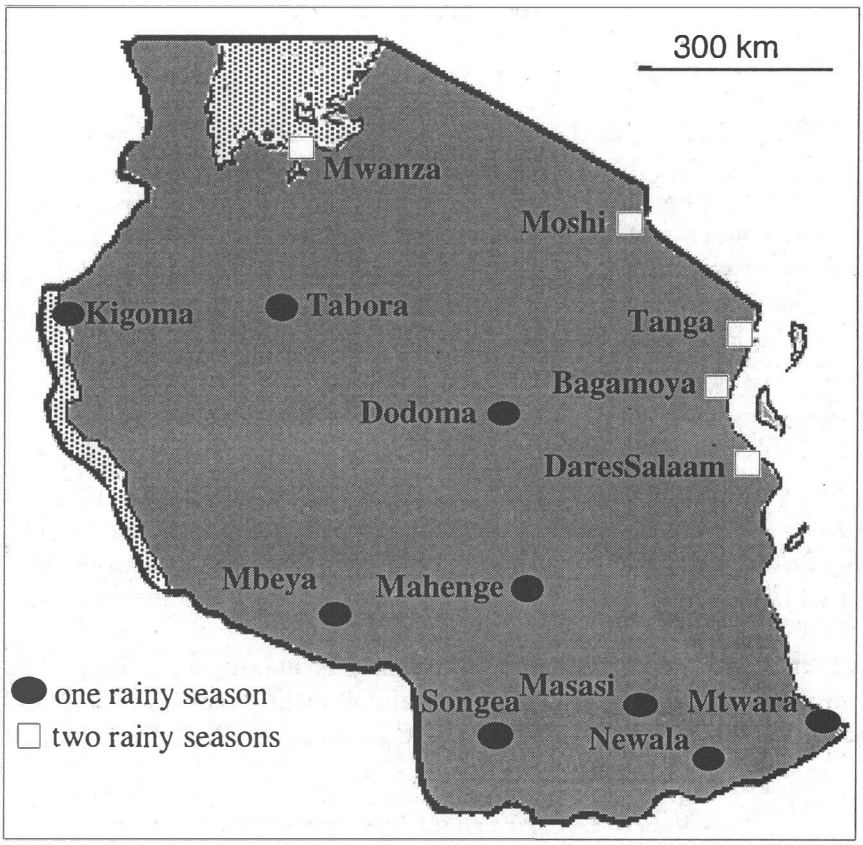


Fig. 1. — Map of Tanzania with the stations used in this study.

stations, Moshi and Dodoma. A dry day was defined as one with less than 1.0 mm of rainfall. For the onset and end of the rains the method of MHITA & NASSIB (1987) was used. The rains were considered to have started if the ten-day rainfall exceeded 20 mm with no dry spell of more than 20 days in the following 30 days. Similarly, the rains were said to have ended when the ten-day rainfall fell below 15 mm with no rainfall above this amount in the following 30 days.

Monthly data for the long-term time series analyses were selected from three stations, Moshi, Tabora and Bagamoyo, having data going back about one hundred years. All stations lack observations for the years 1913-1920 due to the First World War.

Results

The Onset and End of Rains

Tables 1 and 2 give the onset and end of rains for selected stations over Tanzania.

It can be seen that in single-peak areas the main onset is between mid-November and early December. The mean end of the seasonal rains is between mid-April and mid-May (table 2). In double-peak areas the short „vuli" rains begin by 25 October and end by mid-January while the long „masika" rains start by mid-March and end by early June in 75 % of the years.

Occurrence of Long Dry Spells

In this study it was considered that dry spells of 15 days or more during the growing season will affect growing crops. It can be seen (fig. 2) that at Moshi the probability of long dry spells decreases from about 70 % in mid-February to zero in mid-April before increasing in late May and early June.

During the short rains the probability is about 50 %. This is an indication of the high variability of rainfall during the short rains and hence its unsuitability for dependable agriculture. Dodoma is one of

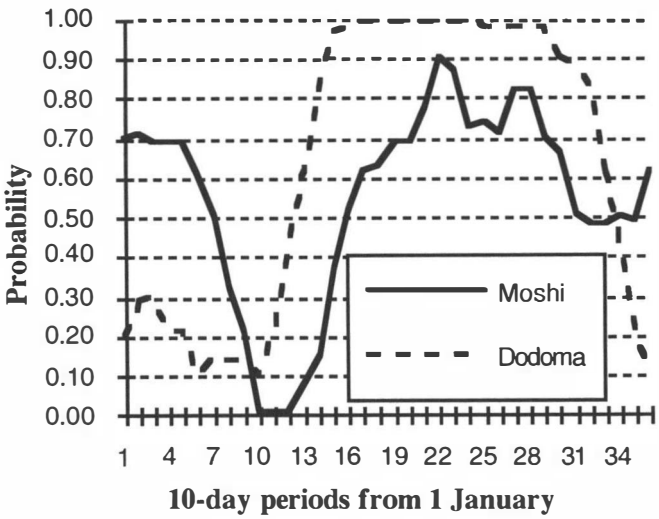


Fig. 2. — The probability of dry spells of 15 days or more at Moshi and at Dodoma.

Table 1

Mean week and percentile points of the onset of rains assuming a normal distribution. Nov-2 means the 2nd week of November, etc.

	Short rains			Seasonal rains			Long rains		
Stations	25 %	50 %	75 %	25 %	50 %	75 %	25 %	50 %	75 %
Mwanza	Oct-1	Oct-2	Oct-3	—	—	—	Feb-2	Feb-3	Feb-4
Moshi	Oct-2	Oct-3	Oct-4	—	—	—	Feb-3	Mar-1	Mar-3
Tanga	Oct-1	Oct-3	Oct-3	—	—	—	Feb-3	Feb-4	Mar-2
Dar es Salaam	Oct-1	Oct-3	Oct-4	—	—	—	Feb-2	Feb-4	Mar-2
Tabora	—	—	—	Nov-1	Nov-2	Nov-3	—	—	—
Kigoma	—	—	—	Oct-4	Nov-1	Nov-2	—	—	—
Dodoma	—	—	—	Nov-4	Dec-1	Dec-2	—	—	—
Mahenge	—	—	—	Nov-2	Nov-4	Dec-1	—	—	—
Mbeya	—	—	—	Nov-1	Nov-2	Nov-3	—	—	—
Songea	—	—	—	Nov-2	Nov-4	Dec-1	—	—	—
Masasi	—	—	—	Nov-2	Nov-4	Dec-1	—	—	—
Newala	—	—	—	Nov-2	Nov-4	Dec-1	—	—	—
Mtwara	—	—	—	Nov-2	Nov-4	Dec-1	—	—	—

Table 2

Mean week and percentile points of the end of rains assuming a normal distribution. Nov-2 means the 2nd week of November, etc.

	Short rains			Seasonal rains			Long rains		
Stations	25 %	50 %	75 %	25 %	50 %	75 %	25 %	50 %	75 %
Mwanza	Jan-1	Jan-2	Jan-3	—	—	—	May-2	May-4	Jun-1
Moshi	Dec-3	Dec-4	Jan-1	—	—	—	May-4	Jun-1	Jun-2
Tanga	Dec-4	Jan-1	Jan-2	—	—	—	May-3	Jun-1	Jun-2
Dar es Salaam	Dec-4	Jan-1	Jan-2	—	—	—	May-4	Jun-2	Jun-3
Tabora	—	—	—	Apr-3	Apr-4	May-2	—	—	—
Kigoma	—	—	—	May-1	May-2	May-4	—	—	—
Dodoma	—	—	—	Apr-1	Apr-2	Apr-4	—	—	—
Mahenge	—	—	—	Apr-4	May-1	May-2	—	—	—
Mbeya	—	—	—	Apr-3	Apr-4	May-2	—	—	—
Songea	—	—	—	Apr-3	Apr-4	May-1	—	—	—
Masasi	—	—	—	Apr-3	May-1	May-2	—	—	—
Newala	—	—	—	Apr-3	May-1	May-3	—	—	—
Mtwara	—	—	—	May-1	May-2	May-3	—	—	—

the driest stations in Tanzania, and even during the seasonal rains there is about a 10 % probability of a long dry spell there.

Variability within and between Seasons

The 20, 50 and 80 % values of ten-day rainfall were calculated for six stations (fig. 3). At Dodoma rainfall is not reliable. In 20 % of the years ten-day rainfall amounts do not exceed 15 mm. In half of

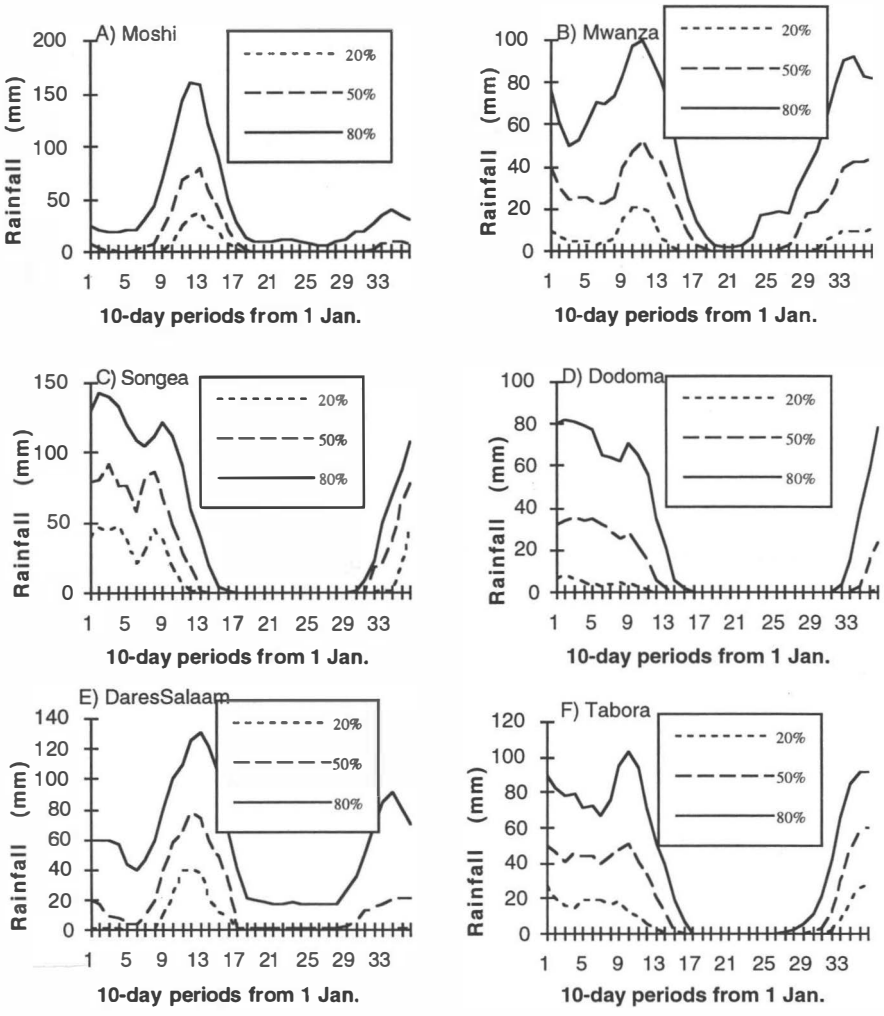


Fig. 3. — The 20, 50 and 80 percentiles of ten-day rainfall at six stations in Tanzania.

the years the amounts exceed the above threshold from about 1 December to 9 March. Tabora exhibits approximately the same unreliability of rainfall as Dodoma. In 80 % of the years the amounts of ten-day rainfall reach 15 mm only from early December to mid-March, and in half of the years from early November to early April.

The rains show more reliability at Songea than at Dodoma and Tabora. In four out of five years at Songea ten-day rainfall amounts exceed 15 mm between 8 December and 28 March and on the average rainfall exceeds the above-mentioned value from mid-November to early April.

In areas along the coast and in north-eastern areas with two rainy seasons, the short rains are less reliable than the long rains. During the short rains at Dar es Salaam, ten-day rainfalls are generally below 10 mm in about 20 % of years. The 50 % curve exceeds 15 mm between late November and mid-January. During the long rains at Dar es Salaam the ten-day rainfall exceeds 20 mm in 80 % of cases.

Time Series Analyses

In Tanzania several meteorological stations have been operational since 1890-1900. Unfortunately there is a gap in the time series during 1912-1920 because of the First World War. In this study the long-term time series were plotted for three Tanzanian stations (fig. 4). According to Hulme (1992), the annual rainfall sums were found to have increased in East Africa when the normal periods 1931-1960 and 1961-1990 were compared, and this similar pattern can be found at these stations as well. When time series of these three stations are compared with those of East Africa published by Hulme (1992) and also by Nicholson (1989), there are features which are common to all of these three studies : high anomalies between 1900-1910, low anomalies around 1920, low anomalies in 1945-1950, and low anomalies again in 1970-1975. The highest precipitation in Hulme's and Nicholson's studies was found in 1961 ; at Bagamoyo and Tabora the highest precipitation values were also observed in 1961. At Moshi the 1961 value is the third highest value ; in 1979 and in 1912 even higher values were measured.

Unfortunately we have no so-called station metadata. We do not know how the surroundings around the stations have changed, or whether the location of a station has changed during the one hundred years period. Measuring equipment must also surely have changed

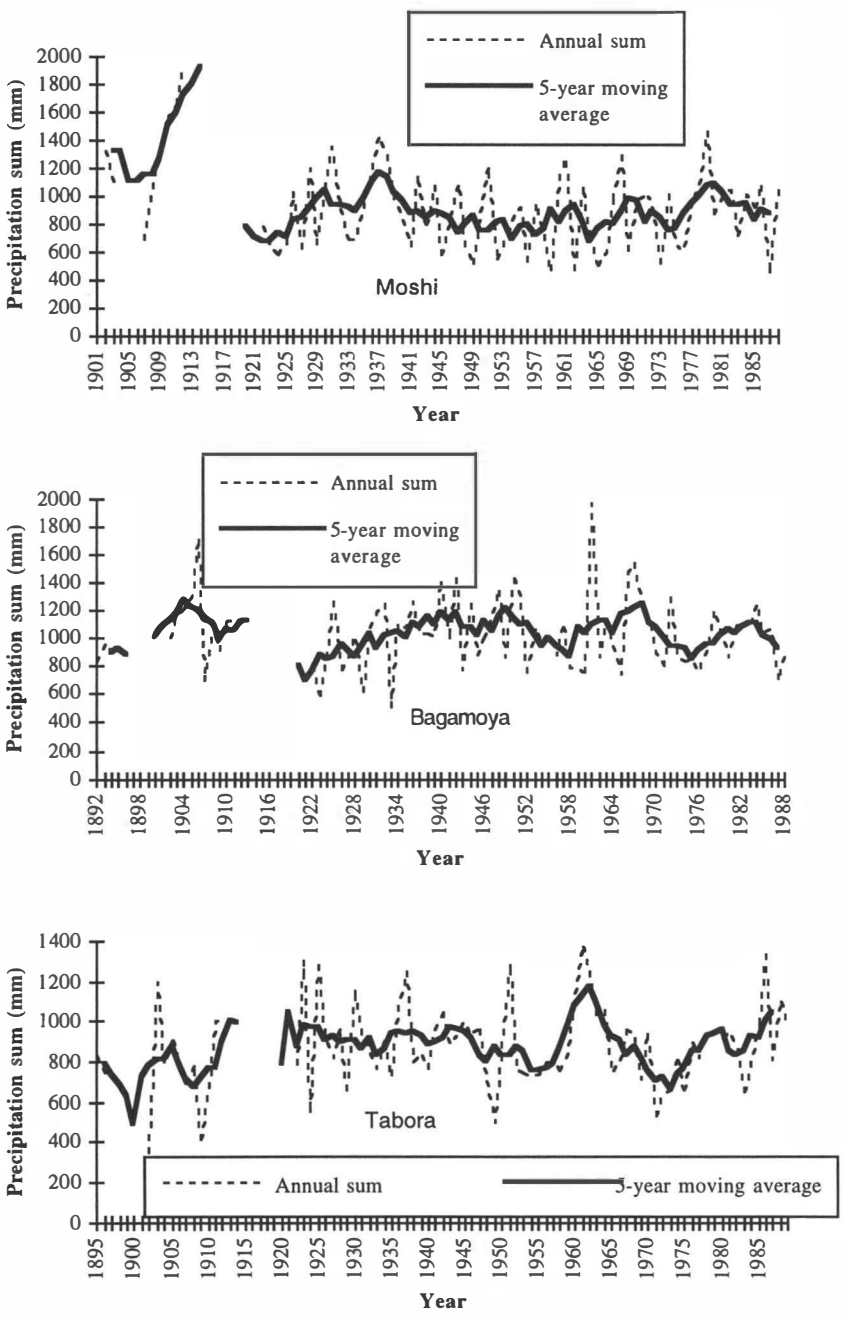


Fig. 4. — The annual rainfall sums at Moshi, Bagamoyo and Tabora in Tanzania.

during this long period. As precipitation measurements are very sensitive to the measuring site's conditions, one should regard the oldest records with caution unless the laborious work of homogenization of the time series has been done (HEINO 1994).

ACKNOWLEDGEMENTS

This article was prepared through FINNIDA/SATCC/WMO-meteorology project for the SADCC countries with the financial contribution of the Finnish International Development Agency (FINNIDA) and within the framework of Finnish development co-operation.

REFERENCES

DOORENBOS, J. & KASSAM, A. H. 1979. Yield response to water. — *FAO Irrigation and Drainage Paper*, **33** : 45-51.

HEINO, R. 1994. Climate in Finland during the period of meteorological observations. Contributions, 12. Finnish Meteorological Institute, Helsinki, 209 pp.

HULME, M. 1992. Rainfall changes in Africa : 1931-1960 to 1961-1990. — *International Journal of Climatology*, **12** : 685-699.

MHITA, M. S. 1984. The use of water balance models in the optimation of cereal yields in seasonally-arid tropical regions. — Diss. University of Reading, Reading, 211 pp.

MHITA, M. S. & NASSIB, I. R. 1987. The onset and end of rains in Tanzania. — *In* : Proceedings of the 1st Technical Conference on Meteorological Research in Eastern and Southern Africa (Nairobi 1987), pp. 101-115.

NICHOLSON, S. E. 1989. Long-term changes in African rainfall. — *Weather*, **44** : 47-56.

STEGMAN, E. C. 1982. Corn yield as influence by timing of evapotranspiration deficits. — *Irrigation Science*, **3** : 75-87.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 200-211 (1998)

Début de la sécheresse en Afrique de l'Ouest

par

Robert MOREL *

MOTS-CLES. — Afrique de l'Ouest ; Sahel ; Sécheresse ; Pluies.

RESUME. — L'étude des changements de tendance met en évidence l'intérêt d'analyser la structure des séries chronologiques des pluies. Le présent document présente une application aux pluies annuelles de l'Afrique de l'Ouest pour préciser le début de la dernière sécheresse. Plusieurs tests sont utilisés conjointement pour l'analyse des pluies sur la période 1950-1990. Une fois déterminée l'année de rupture on emploie un tableur pour étudier les différents aspects de la sécheresse. L'échantillon employé représente plus d'un millier de postes pluviométriques. On vérifie la diminution des pluies par comparaison entre les deux populations situées de part et d'autre de l'année de rupture.

TREFWOORDEN. — West-Afrika ; Sahel ; Droogte ; Neerslagen.

SAMENVATTING. — *Begin van de droogte in West-Afrika.* — De studie van trendveranderingen toont de noodzaak aan van de analyse van de structuur van tijdreeksen van de neerslag. Deze bijdrage vertegenwoordigt een toepassing op de jaarlijkse neerslaghoeveelheden in West-Afrika om het begin van de laatste droogteperiode aan te tonen. Meerdere tests worden terzelfder tijd gebruikt voor de analyse van de neerslag gedurende de periode 1950-1990. Eens het breekjaar gekend is, wordt een tabel gebruikt voor de studie van de verschillende aspecten van de droogte. Het gebruikte monster bevat meer dan duizend pluviometrische meetpunten. De vermindering van de neerslag wordt geverifieerd door vergelijking van de twee populaties aan beide zijden van het breekpunt.

KEYWORDS. — West Africa ; Sahel ; Drought ; Rains.

ABSTRACT. — *Start of the Drought in West Africa.* — The study of changes in the trend brings to the fore the interest of analysing the structure of rainfall time-series. This paper presents an application on annual rainfall data in West Africa in order to assess the start of the latest drought. Several tests are jointly

* Ingénieur général honoraire d'Agronomie.

used for the analysis of rainfall in the time period 1950-1990. The year of the change is determined for each time-series. The sample represents more than a thousand stations. The decrease in the rainfall is analysed by comparison of the two populations situated on both sides of the change point.

*
* *

Sur la durée bornée par les années 1950 et 1990, la sécheresse fait très souvent parler d'elle notamment en Afrique de l'Ouest et plus particulièrement au Sahel. Afin d'estimer les effets de la diminution des pluies, on compare la période qui a enregistré des déficits pluviométriques à celle plus humide qui l'a précédée. La date de séparation de ces deux groupes d'années pose un problème car, selon les lieux et les auteurs, il n'y a pas concordance sur les dates d'apparition des pluies déficitaires. Pour appréhender le problème sur l'ensemble de la région, il était indispensable d'étudier le phénomène du changement de tendance dans les pluies sur le plus grand nombre possible de postes pluviométriques répartis dans le domaine géographique concerné.

1. Les termes du problème

L'analyse a été faite sur l'ensemble de l'Afrique de l'Ouest et plus d'un millier de séries pluviométriques ont été traitées du Sénégal au Soudan et du Sahel au Cameroun. La distribution fantasque des pluies tropicales, généralement d'origine convective, fait que deux postes voisins peuvent présenter une rupture de tendance avec plus de dix années d'écart. Les facteurs locaux peuvent certainement expliquer cela car ils canalisent, plus ou moins, les noyaux nuageux. L'irrégularité des précipitations fait que les types d'années humides ou sèches sont rarement regroupés de façon continue ; elles alternent souvent sans règle définie. Nous sommes donc dans le cas de séries chronologiques fluctuantes et leur analyse montrera s'il y a permanence ou changement et à quelle date. Pour des raisons statistiques, on a souvent comparé des groupes d'années égaux, mais on peut envisager de prendre des périodes de durées différentes. Pour avoir une idée des changements climatiques régionaux, on compare des périodes limitées par des dates précises. Ainsi on peut cartographier les normales trentenaires 1931-60 et 1961-90, les médianes 1950-67 et 1968-90, mais aussi leurs différences. Cette étude montre qu'il n'est ni convenable, ni nécessaire de fixer une unique date de rupture de tendance.

2. La détermination de la rupture de tendance

Si on observe les variations interannuelles des pluies par leurs écarts à la moyenne, on voit bien l'irrégularité de la distribution avec, toutefois, un groupe d'années humides à partir de 1950 alors qu'en fin de série les années sont déficitaires. Le problème est de déterminer la date de rupture entre la période humide et la période sèche. Nous avons utilisé un certain nombre de tests pour obtenir le résultat le plus concordant. D'abord, d'après VANDIEPENBEECK (1995), ceux basés sur la statistique de corrélation de rang t (test de Mann) : le test de Kendall ascendant et rétrograde, la méthode de Pettitt. L'analyse des écarts à la moyenne permet de faire des cumuls et des histogrammes. Enfin, on recherche la plus grande différence des médianes ou des moyennes de part et d'autre d'une année glissante. La figure 1 donne quelques exemples de tests, on y voit à Saraféré que la tendance déficitaire commence en 1966 comme le confirme le maximum des écarts, alors qu'à Nioro du Rip l'année du début de sécheresse est 1968.

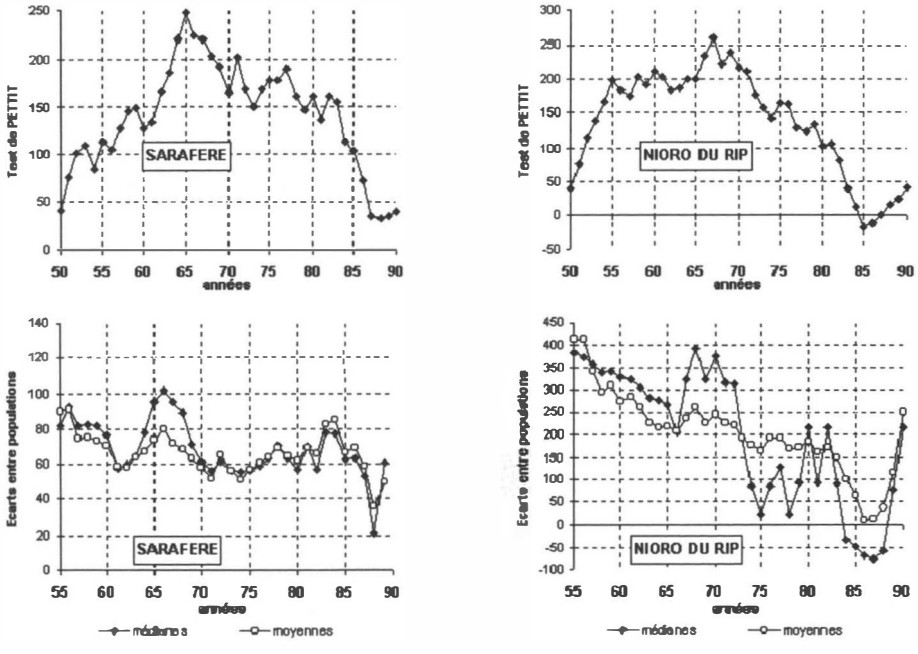


Fig. 1. — Exemples de détermination de la rupture climatique.

Les calculs ont été assez longs pour déterminer les 1 154 dates d'apparition de la sécheresse. Elles sont assez dispersées et varient de 1961 à 1986 pour les valeurs extrêmes. L'histogramme de la distribution fréquentielle des années montre, sur la figure 2, un mode de 16 % pour l'année 1968. Cela explique pourquoi cette année a souvent été prise comme date de début de la sécheresse mais l'approximation n'est pas bonne. La figure 3 est le pointage de quelques dates sur une carte du domaine étudié, elle indique la variabilité du phénomène. Un décalage géographique est perceptible selon la longitude et la latitude. Le changement est plus précoce à l'ouest, commençant en 1967 au Sénégal. La rupture de tendance devient plus tardive à la fois vers l'est et le sud, elle commence en moyenne en 1974 au Soudan. Les semis de points correspondant à chaque année montrent une certaine imbrication. Pour schématiser le phénomène, il suffit de tracer les enveloppes de chaque nuage annuel de points. Le déplacement des limites de ces enveloppes, sur la figure 4, donne une idée de la progression, au plus tôt, de la sécheresse. Mais on voit le biais d'une telle représentation car la progression est floue ; il faudrait aussi réaliser le même schéma avec les limites occidentales des nuages de points, pour avoir une idée de la progression au plus tard.

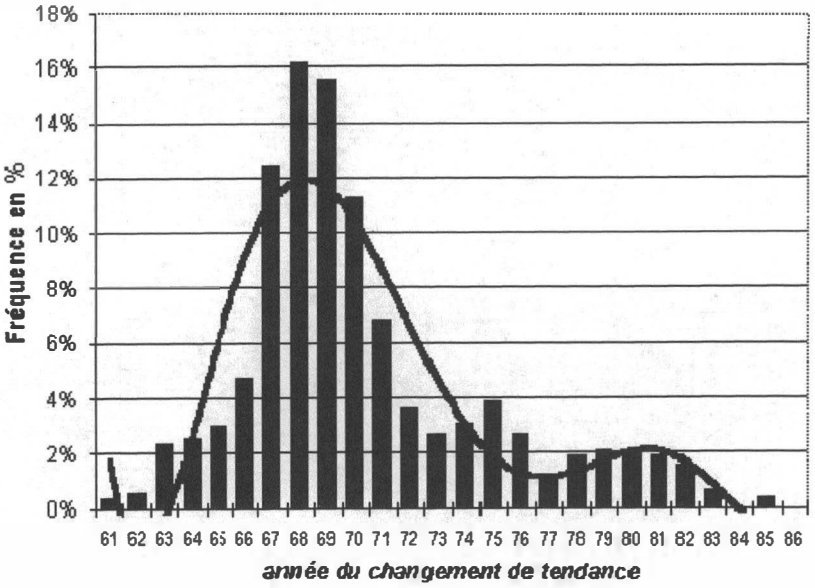


Fig. 2. — Variabilité du début de sécheresse.

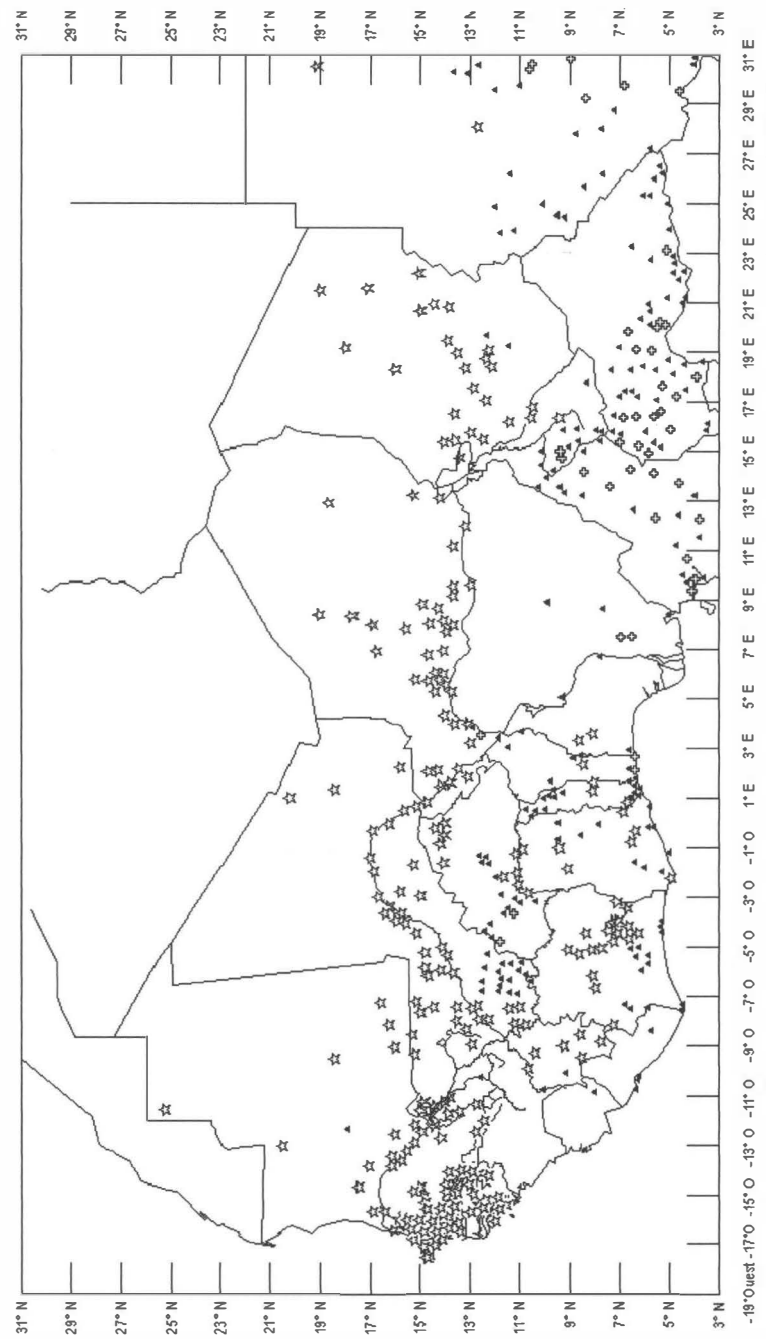


Fig. 3. — Trois classes de changement et les postes correspondants.

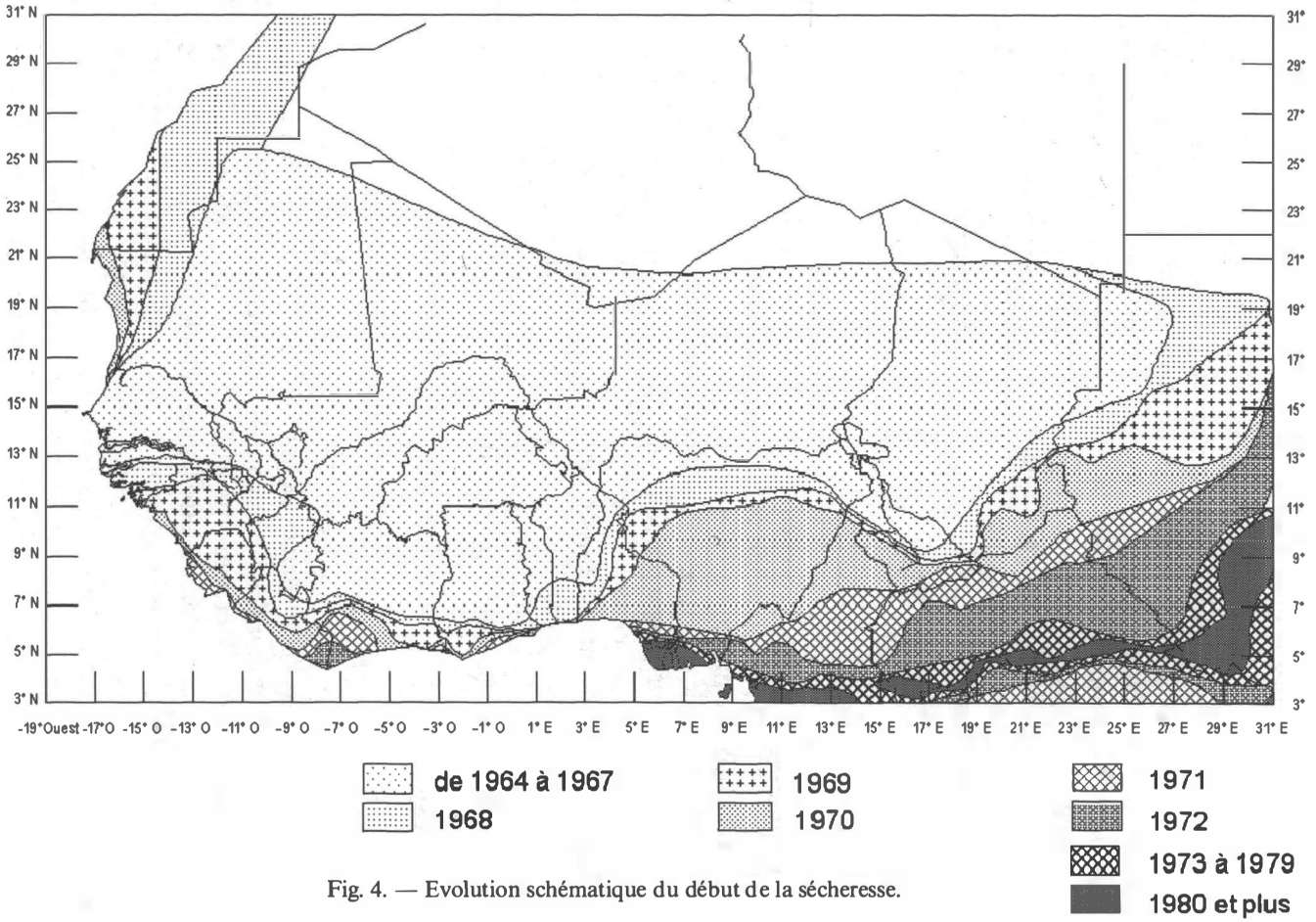


Fig. 4. — Evolution schématique du début de la sécheresse.

3. Les caractères de la sécheresse

Pour chaque station, si on découpe la série 1950-90 de part et d'autre de la date de début de la sécheresse, on obtient deux populations qui sont généralement indépendantes au point de vue statistique, avec des variances et des moyennes significativement différentes. Ainsi, la rupture de tendance permet de diviser la série en deux avec un échantillon pluvieux et un autre plus sec. L'écart entre ces échantillons est retenu pour quantifier la diminution de pluviométrie. Cette méthode permet de cartographier les effets maximaux de la sécheresse, estimés par moyennes ou médianes, et le schéma devient indépendant de la date de changement.

3.1. L'evolution spatio-temporelle

Nous avons vu que la sécheresse est un phénomène flou, les années successives sont plus ou moins pluvieuses. Il paraît judicieux d'employer un tableur pour mettre en évidence les fluctuations spatio-temporelles de la pluviométrie. Les dates calculées peuvent être présentées en nuages de points soit par longitude, soit par latitude, comme sur la figure 5. L'ajustement de la tendance avec une courbe polynomiale montre le changement d'une manière lissée alors que le semis de points transcrit la variabilité. La bordure nord est touchée la première ainsi que la bordure ouest. En simplifiant, on voit que la sécheresse progresse du nord-ouest vers le sud-est passant de 20°N et 18°O en 1968 à 5°N et 30°E en 1974.

3.2. La quantification de la secheresse

Pour mettre en évidence les modifications, on peut comparer poste à poste les valeurs des médianes sèches avec celles de la période humide. Cette approche utilise deux populations de longueurs différentes dont on calcule les écarts et leurs pourcentages par rapport aux valeurs humides. Le résultat donne deux sortes de valeurs : la diminution de la pluviométrie en valeur absolue ou en pourcentages. Si on les reporte sur un graphique, on met en évidence les variations suivant leur localisation géographique. La dégradation de la pluviosité sur l'Afrique de l'Ouest n'est pas homogène dans l'espace. L'ensemble des graphiques montre, par la variation des nuages de points, l'hétérogénéité de l'implantation des postes pluviométriques, notamment en longitude.

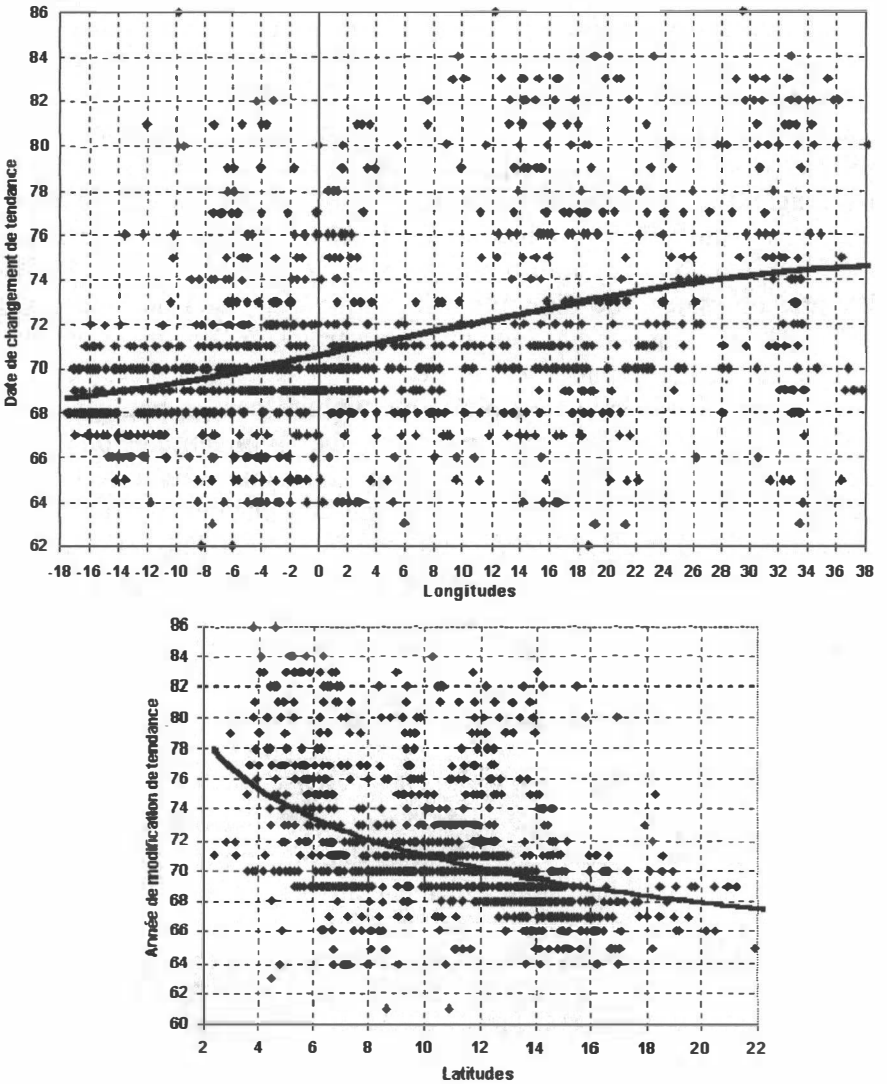


Fig. 5. — Début de la sécheresse en Afrique de l'Ouest entre 1950 et 1990.

L'intensité de la sécheresse, exprimée en millimètres par an, montre une variabilité nord-sud et une autre structure d'évolution d'ouest en est (fig. 6). En latitude, on aperçoit deux bandes de forte diminution des pluies. La première, vers la côte entre 5 et 7°, correspond aux régions les plus pluvieuses voisines du golfe de Guinée. La seconde est une zone qui oscille entre 10 et 14° de latitude nord. Cette région soudano-sahélienne subit les battements du Front intertropical qui, souvent trop au sud, provoquent les déficits pluviométriques. Suivant les longitudes, on observe l'accentuation de la baisse, vers la côte atlantique, qui est bien mise en évidence à l'ouest du quatrième méridien. On voit que, pour des longitudes comprises entre 0 et 24°E, il existe un plateau de diminution identique des pluies de l'ordre de 150 à 200 mm par an. Le Soudan, qui se trouve à l'est du 23e degré, semble moins affecté par la sécheresse.

La diminution relative des pluies est traduite par les pourcentages de baisse des hauteurs annuelles médianes (fig. 7). En latitude, on passe de 2 à 55 % en allant vers le nord. La zone côtière évoquée précédemment présente une accentuation du phénomène qui peut atteindre 30 %. Les plus fortes diminutions s'observent dans les latitudes élevées correspondant aux zones pré-sahariennes et sahéliennes. D'ouest en est, en passant de 18 à 4°O, la baisse est maximale et évolue entre 40 et 20 %. Le plateau homogène s'ajuste autour de 20 % de diminution.

4. Conclusions et perspectives d'étude

Il était important d'aborder l'étude de la sécheresse en tenant compte de la variabilité de la date de rupture dans les séries pluviométriques. Les effets de la sécheresse sont calculés indépendamment de cette date. Il faut les cartographier non seulement au pas de temps annuel du présent document, mais descendre au niveau du mois pour analyser la distribution intermensuelle de la sécheresse. Eventuellement, on pourra aller à la décade pour les mois les plus touchés. La variation géographique de la sécheresse est très nette et devrait être détaillée par transects (*cf.* Ozer 1995) nord-sud ou par isohyètes.

La méthode exposée ci-dessus doit être appliquée complètement aux pluies en recherchant le début des années humides, celui de la sécheresse des années 40. En prenant la date calculée pour la période humide, au lieu de la borne 1950 des fichiers, l'appréciation de la sécheresse sera meilleure surtout pour les régions orientales qui subissent les fluctuations climatiques avec un certain retard. Il faudra également

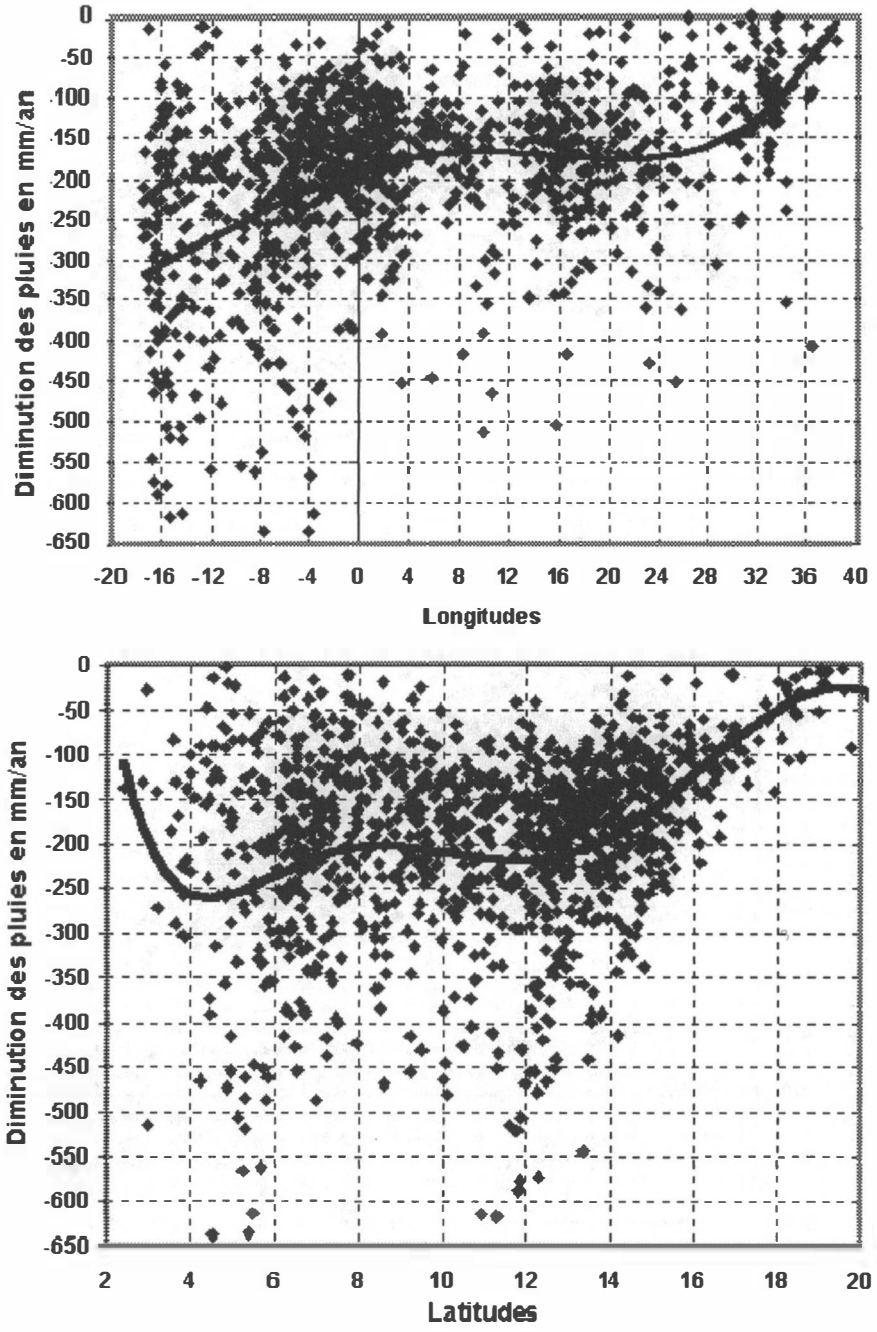


Fig. 6. — Effet de la sécheresse en Afrique de l'Ouest entre 1950 et 1990.

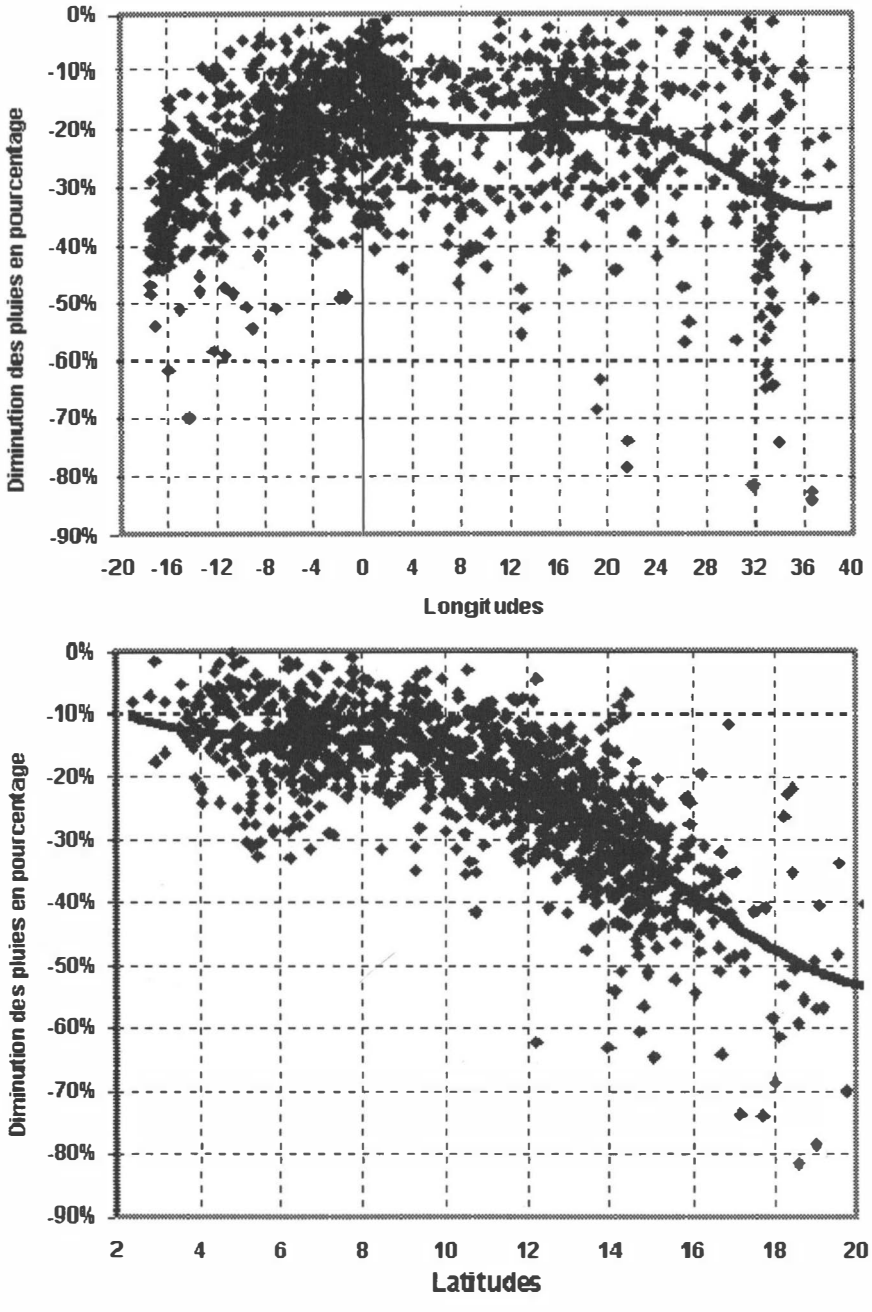


Fig. 7. — Effet de la sécheresse en Afrique de l'Ouest entre 1950 et 1990.

surveiller la fin de la présente sécheresse car, pour l'instant, l'année terminale est 1990 dans toutes les séries. Enfin, les autres paramètres climatiques peuvent subir les mêmes traitements. Le nombre de postes climatiques étant bien inférieur à celui des pluviomètres, on peut penser que les calculs seraient moins longs à effectuer.

BIBLIOGRAPHIE

JANICOT, S. 1990. Variabilité des précipitations en Afrique de l'Ouest et circulation quasi stationnaire durant une phase de transition climatique. — Thèse de Doct., Paris VI, Synthèse, 180 pp. + annexes.

LEROUX, M. 1983. Le climat de l'Afrique tropicale. — Ed. H. Champion/ M. Slatkine, Paris/Genève, Tome I, 636 pp., 349 figs. ; Tome 2 : notice et atlas de 250 cartes.

MOREL, R. 1992. Atlas agroclimatologique des pays de la zone du CILSS. — Centre AGRHYMET (B.P. 11011 Niamey), 11 vol. dont 3 de cartes.

MOREL, R. 1995. La sécheresse en Afrique de l'Ouest. — *Revue de Géographie de Lyon*, **70** (3-4) : 215-222, 11 figs.

MOREL, R. 1995. Pluviométrie 1961-1990 en Afrique de l'Ouest — In : *Publications de l'Ass. Intern. de Climatologie*, vol. 8, 361-368.

OZER, P. 1995. Application des transects pluviométriques spatio-temporels annuels au territoire sahélien — In : *Publications de l'Ass. Intern. de Climatologie*, vol. 8, 369-377.

VANDIEPENBEECK, M. 1995. Détection pratique de changement de climat dans le cas d'une alternative au caractère aléatoire — In : *Publications de l'Ass. Intern. de Climatologie*, vol. 8, 116-124.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 212-227 (1998)

Lithometeors and Wind Velocity in Relation with Desertification during the Dry Season from 1951 to 1994 in Niger

by

Pierre OZER *

KEYWORDS. — Desertification ; Lithometeor ; Dry Season ; Niger.

ABSTRACT. — The evolution of the lithometeor frequency and the wind velocity recorded during the dry season in eight meteorological stations of Niger is analysed from 1951 to 1994. The rise of airborne dust is constantly augmenting from the desert (Bilma) to the southern Sahelian stations (Niamey) where it has increased by a factor five. It has also been showed that the area of Bilma did not provide the Sahelian zone with airborne dust during the 80s as was suggested by several authors. All stations have recorded a general increase of wind velocity. In Niamey, the rise is of 70 % during the 44-year period passing from 4.3 m s^{-1} to 7.1 m s^{-1}. The increase of lithometeors frequency as well as the wind velocity during the drought period is not explained by the aridification. But their direct relation is significant in Bilma and Niamey.

MOTS-CLES. — Désertification ; Lithométéore ; Saison sèche ; Niger.

RESUME. — *Lithométéores et vitesse du vent en relation avec la désertification pendant la saison sèche de 1951 jusque 1994 au Niger.* — L'évolution de la fréquence des lithométéores et de la vitesse du vent enregistrée pendant la saison sèche dans huit stations synoptiques du Niger est étudiée de 1951 à 1994. L'accroissement du nombre de jours affectés par les lithométéores augmente depuis les régions désertiques (Bilma) vers le sud sahélien (Niamey) où une augmentation de facteur cinq y est enregistrée. Il est montré également que la région de Bilma n'a pas été une zone source significative durant les années 80 comme cela est suggéré par plusieurs auteurs. Toutes les stations ont enregistré un accroissement général de la vitesse du vent. Elle est de l'ordre

* Dipartimento di Scienze della Terra, Università degli Studi di Genova, Corso Europa 26, I-16132 Genova (Italy).

de 70 % durant les 44 ans à Niamey où la vitesse est passée de 4,3 m/s à 7,1 m/s. L'augmentation de la fréquence des lithométéores et de la vitesse du vent durant la sécheresse n'est pas corrélée à l'aridification. Par contre, leur relation directe est significative à Bilma et Niamey.

TREFWOORDEN. — Desertificatie ; Lithometeor ; Droog seizoen ; Niger.

SAMENVATTING. — *Lithometeoren en windsnelheid in relatie met de desertificatie gedurende het droge seizoen van 1951 tot 1994 in Niger.* — De evolutie van de frequentie van de lithometeoren en de windsnelheid, gemeten tijdens het droog seizoen in acht meteorologische stations van Niger, werd bestudeerd gedurende de periode 1951-1994. De verhoging van het aantal dagen beïnvloed door lithometeoren stijgt gestadig van de woestijnzone (Bilma) naar de zuidelijke Sahelstations (Niamey) waar een verhoging met factor 5 wordt geregistreerd. Tevens wordt aangetoond dat de regio Bilma geen belangrijke voedingszone is geweest gedurende de jaren 80 zoals verschillende auteurs beweren. Alle stations vertonen daarenboven een algemene stijging van de windsnelheid. Deze is in de grootteorde van 70 % in Niamey gedurende een 44-jarige periode en is gestegen van 4,3 m/s tot 7,1 m/s. De verhoging van de frequentie van lithometeoren en van de windsnelheid gedurende het droog seizoen wordt niet verklaard door de aridificatie. Hun directe relatie echter is wel belangrijk in Bilma en Niamey.

1. Introduction

The severe drought which is affecting the whole Sahelian area has been fully studied and followed from the rainfall data by many authors since the early 70s (e.g. LAMB 1982, NICHOLSON 1989, HULME 1992, MOREL 1995, OZER 1995a).

This aridification has been suggested to be responsible for an increasing quantity of airborne dust in West Africa. Moreover, after having established that Saharan dust is moving across the Atlantic Ocean and reaching the Barbados or Miami (e.g. DELANY *et al.* 1967, CARLSON & PROSPERO 1972, PROSPERO & CARLSON 1972, SAVOIE & PROSPERO 1977) ; PROSPERO & NEES (1977), on a 11-year period, recorded an increase by a factor of three during the 1972-1974 period of the concentration of aerosol in the lower troposphere of the western equatorial North Atlantic Ocean. They related it to the drought in the Sahelian zone. Later on, the same authors (PROSPERO & NEES 1986) analysed the concentrations of African mineral dust from 1965 to 1984 at Barbados and found an unprecedented high value in 1983 and 1984 which exceeded the pre-drought means by a factor of four.

They also underlined a spectacular increase of the winter dust concentrations which were in 1982-1983 ten times greater than the previous drought values. According to these authors, these modifications appear to be related to large-scale circulation changes associated with El Niño rather than the drought. At the same time, MIDDLETON (1985) presented a dramatic increase of dust-storm activity of a factor six in Mauritania and up to a factor five in Sudan during the drought years.

Although our understanding of wind erosion processes has increased significantly for the past decades (e.g. MORALES 1979, PEWE 1981, COUDE-GAUSSEN 1990), few detailed studies of dust production have been carried out in the studied area (Niger).

In the Sahara and the Sahel, the Harmattan, dry north-easterly surface wind, dominates the surface flow pattern over continental West Africa during the dry season. It carries very large quantities of dust from Niger westwards towards Mali and Burkina Faso (MAINGUET *et al.* 1983, OZER 1993, FODE *et al.* 1994) or from northern Niger and Chad (Bilma - Faya-Largeau) to Nigeria (HAMILTON & ARCHBOLD 1945, KALU 1979, MCTAINSH & WALKER 1982, ADEDOKUN *et al.* 1989). Visibility at Kano is very often reduced by the lithometeors which leads frequently to the closing-down of the airport (ADEFOLALU 1984). MCTAINSH & WALKER (1982) measured there dust deposition rates up to 181 t km^{-2} yr^{-1}.

The aim of this work is to document the lithometeor evolution recorded in eight meteorological stations of Niger together with the wind velocity from 1951 to 1994. Data were collected from the handwritten observations contained in the *Tableaux Climatologiques Mensuels* available at the "Direction de la Météorologie Nationale du Niger". We assume that all recorded data are reliable as the stations used are part of the ASECNA network.

2. Analysis of Rainfall Fluctuations

The eight meteorological stations represent the different bioclimatic zones of Niger (fig. 1). Bilma is a typical Saharan station with the mean annual rainfall (1951-1994 average) of 10 mm. The stations of Agadez and N'Guigmi are located in the pastoral Sahel (100-300 mm) as defined by QUEZEL (1965) and LE HOUEROU (1990) with respectively 136 and 213 mm y^{-1}. The dry culture Sahel (300-500 mm) (VERHEYE 1990) is represented here by the stations of Mainé-Soroa (308 mm),

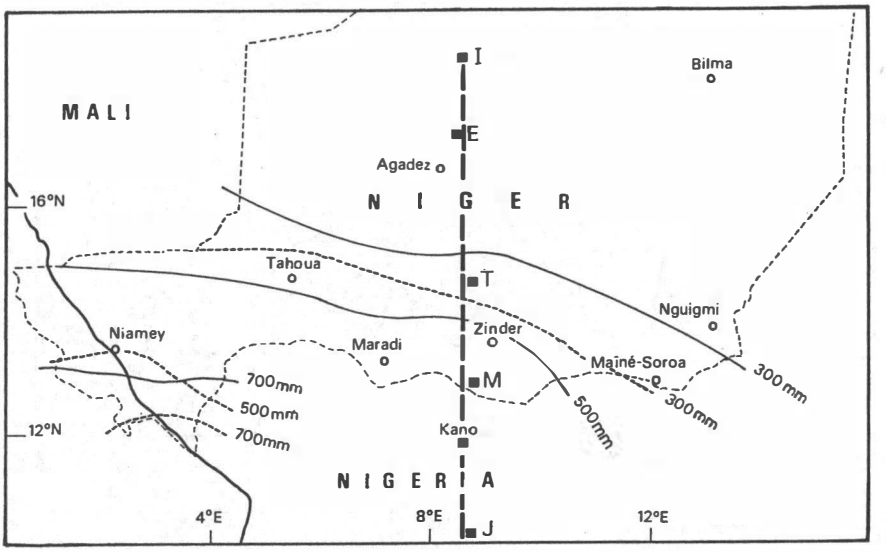


Fig. 1. — Location of the stations. Mapped isohyets are calculated for the 1951-1967 humid period (—) and for the 1968-1987 dry one (- - -). The dashed line shows the direction of the profile linking Jos with Iferouane presented in figure 2.

Tahoua (389 mm) and Zinder (444 mm). Finally, Maradi and Niamey are located in the rainy culture Sahel (500-700 mm) with a mean annual rainfall of respectively 524 and 562 mm.

Niger, like the whole Sahelian zone, has recorded very important modifications in rainfall since 1951 (Ozer & Erpicum 1995). As a matter of fact, the wettest period of the century occurred during the 1953-1965 period almost directly followed by the longest drought since 1968 with dramatic rainfall deficit in the early 70s and 80s.

The annual rainfall fluctuations from 1940 to 1988 are presented on figure 2 by a south-north annual spatiotemporal rainfall profile linking Jos in Sudanese climate (10°N - km 0 - Nigeria) with Iferouane in desert climate (19°N - km 1020 - Niger). It is based on rainfall data recorded in eight stations (for methodology, see Ozer 1995a or Ozer & Erpicum 1995) which are, from south to north, Jos, Kano, Magaria, Zinder, Tanout, Agadez, Elmeki and Iferouane (location on fig. 1).

The analysis of this profile underlines the climatic pejoration of the last 25 years and highlights the severe aridification progressing slowly from north to south. Since 1962, the drought has been spreading out in the northern part of the profile. The sliding of the 100 mm curve

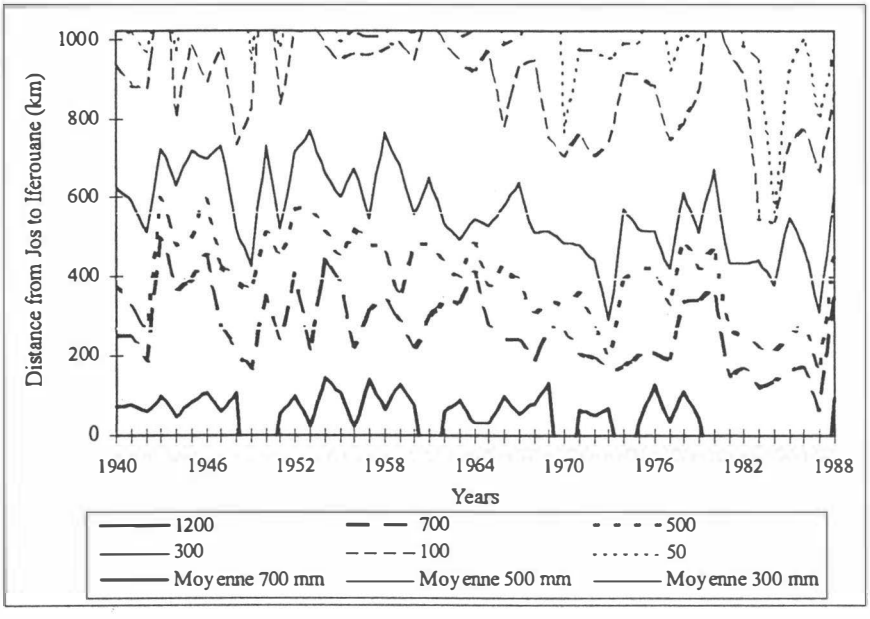


Fig. 2. — Annual spatiotemporal rainfall profile linking Jos with Iferouane from 1940 to 1988.

of 200 to 300 km southwards is impressive and persisted until 1988. In the same period, the 300 mm curve moved south of its mean position. The aridification started affecting the 500 and 700 mm curves in 1967. The drought was severe from 1968 to 1977 and then even more intense from 1981 to 1987 while all curves moved 150 to 200 km south of their respective mean position. In fact, during these 7 years, the 500 mm curve remained south of the 700 mm mean position and the 1 200 mm curve disappeared from the profile. In 1983 and 1984, the 50 and 100 mm curves reached km 550 on the profile which was almost the position of Zinder. Finally, 1988 showed a come-back of normal rainfall average.

3. Lithometeors Evolution

A lithometeor is defined by the W.M.O. (1966) as a "meteor consisting of an ensemble of particles in which most are solid and non-aqueous. The particles are more or less suspended in the air or lifted by the wind from the ground". This includes smoke (forest fires

or industrial smokes), dry hazes, dust whirls, sand whirls, dust storms and sandstorms. All days affected by these airborne particles, except smokes, are considered in this paper when reducing horizontal visibility by less than 5 km.

The evolution of the frequency of the days affected by lithometeors during the dry season (October to April) is presented in figure 3 with corresponding yearly rainfall data and their respective regression lines (all equations showed correspond to the lithometeors regression line).

Different trends emerge from these graphs. Bilma, Saharan station, had a spectacular and unique maximum during the early 70s with no other tendency during the 44-year period (70 % of the annual records are contained in the 50 $\pm$ 20 days of lithometeors range). The station of Agadez presents two specific periods : the first one with relatively low frequency of lithometeors ($<$ 40 per year) from 1951 to 1967 and the second one since 1968 where values of lithometeors are ranging between 30 and 80 without tendency. At N'Guigmi, a complete absence of trend is still noted except for the 1983-1987 period which recorded twice more lithometeors than the mean calculated on the whole period. The five other stations (Sahelian with annual mean rainfall $>$ 300 mm) have the same evolution : low frequency during the pre-drought period followed by a constant increase of lithometeors with a first high frequency during the early 70s and an other dramatic unprecedented maximum during the 1982-1987 period and specially the 1982, 1984 and 1987 extremely dry years.

The regression line of each graph shows that the rise of lithometeors is constantly augmenting from the desert to the southern Sahelian stations (except Zinder). The mean frequency of reduced visibility recorded in Niamey has increased by a factor five. This is probably one of the most significant changes in the actual climate of the Sahel. Moreover, this raising tendency does not seem to be perturbed by the several ultimate relatively humid years during which airborne dust concentration remained very high.

It appears that no significant relation exists between rainfalls and the number of days affected by the lithometeors. As a matter of fact, the closest relation is presented at the station of Maradi with a $r^2 = 0.50$ and the worst one, obviously, at Bilma where $r^2 = 0.00$ (fig. 4). All the determination coefficients are presented in table 1.

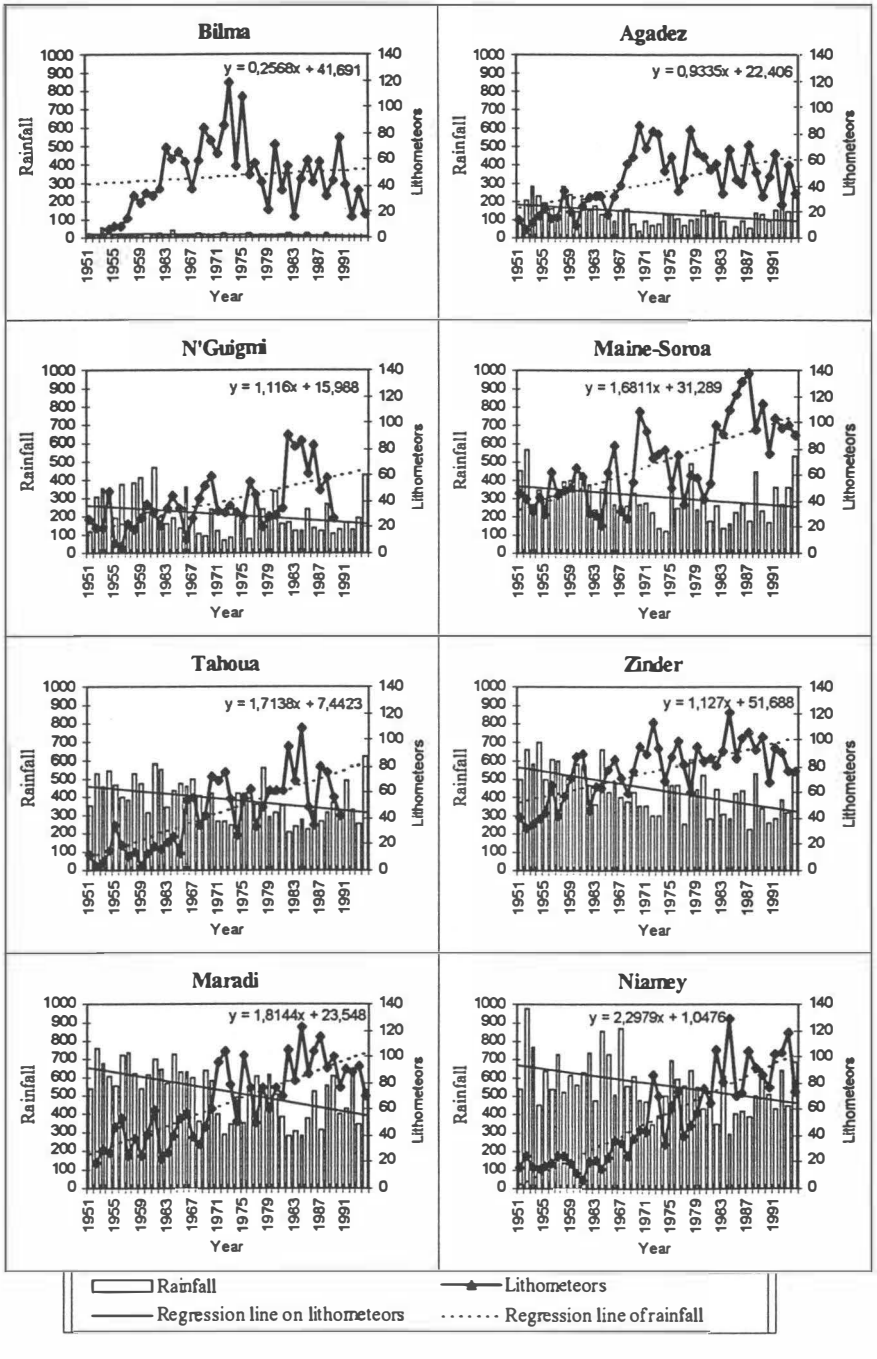


Fig. 3. — Evolution of yearly rainfall and lithometeors during the dry season from 1951 to 1994 in eight meteorological stations of Niger.

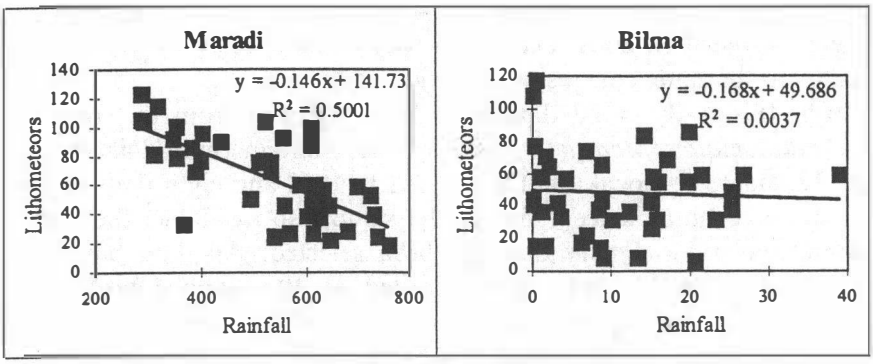


Fig. 4. — Relation between rainfalls and number of days affected by the lithometeors at the stations of Maradi and Bilma (period 1951-1994).

Table 1

Determination coefficients between rainfalls and number of days affected by the lithometeors at all the stations (period 1951-1994)

	Niamey	Maradi	Zinder	Tahoua	Mainé-Soroa	Nguigmi	Agadez	Bilma
r^2	0.29	0.50	0.37	0.38	0.09	0.13	0.36	0.00

4. Wind Speed Analysis

The increase of lithometeors frequency in the Sahel has often been linked to the continuous aridification (e.g. COUDE-GAUSSEN 1994), of course added to anthropogenic impacts as overgrazing, deforestation for cooking and timber wood necessary for everyday life and the poor land-use practices (OZER 1995b). Indeed, the drought seriously damages the vegetation cover and more the soil tends towards a bare surface, more it is sensitive to all erosion types in which dust mobilization (LUNDHOLM 1979). Moreover, in theory, a scattered or disappeared vegetation cover diminishes the roughness of the soil and so favours an increase of wind velocity which can then easily reach its threshold velocity and mobilize dust or transport it on longer distances. MCTAINSH (1980) showed a relation between wind velocity and dust concentration in Kano (northern Nigeria). Nevertheless, COUREL & CHAMARD (1988) did not remark any significant increase of wind velocity in Tombouctou

during the 1976-1986 period. A 44-year study (1951-1994) on four meteorological stations located on the Atlantic coast of West Africa led us to the same conclusions (OZER 1996).

For this study, wind data have been digitized from the *Tableaux Climatologiques Mensuels*. These reports contain three daily records (6, 12 and 18 h - local time) from 1951 to 1960 and eight daily records every three hours since 1961. In the sample so available, the highest wind velocity for every day has been selected. All data have been standardized as if they were recorded at 10 m above ground for diminishing the measure modifications generated from anemometer height changes in time. Finally, a research on wind characteristics in time cannot be led on records of a unique station because of the reliability of the measurement instruments which are very fragile in this environment (Morel, oral communication) ; a good example will be showed with wind data at Maradi.

For the analysed network, the highest mean wind velocity is found at Bilma with 7.7 m s^{-1}. This seems normal seeing that the ground presents very low roughness to wind and this for very long distances. On the other hand, N'Guigmi presents the lowest one : 4.8 m s^{-1}. All mean wind velocities are presented in table 2. We could have expected a decreasing velocity from desert to most humid stations, but it is not the case probably because of the location itself (topoclimatic effects) of the meteorological stations ; we will therefore focus on its variability.

Table 2

Mean wind velocity at all the stations (period 1951-1994)

	Niamey	Maradi	Zinder	Tahoua	Mainé-Soroa	Nguigmi	Agadez	Bilma
Wind velocity (m s^{-1})	5.7	5.2	5	6.2	5.2	5.8	7.3	7.7

The evolution of wind velocity in all stations in the 1951-1994 period is presented in figure 5 with corresponding yearly rainfall data and their respective regression lines (all equations showed correspond to the wind velocity regression line).

The station of Bilma presents a maximum of wind velocity relatively long in time : all averaged wind data (except 1966) are contained in a 10 $\pm$ 2 m s^{-1} range during the 1963-1980 period. Outside this period, wind velocities are always lower than 8 m s^{-1}. At Agadez, the velocity is increasing continuously with high values during the 1965-1967, 1982-

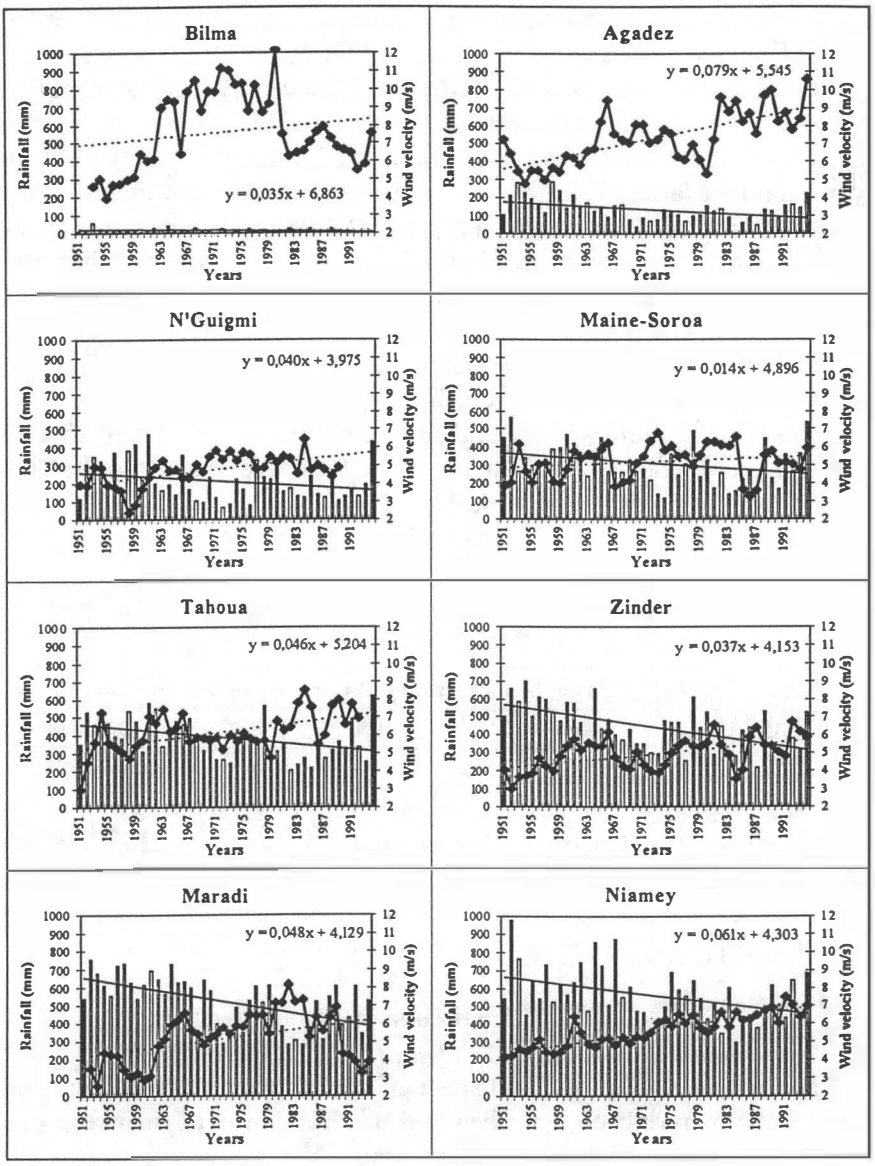


Fig. 5. — Evolution of yearly rainfall and wind velocity during the dry season from 1951 to 1994 in eight meteorological stations in Niger.

1984 and 1988-1989 periods and lower ones during the late 70s. Wind speed fluctuations present the same behaviour at Tahoua. All other stations present a maximum value during the early 70s (except Zinder) and the early 80s (mostly Maradi) directly followed by the lowest values ever recorded in Mainé-Soroa and clearly confirmed by the nearby station of Zinder and slightly by the others. Finally, our attention is focused on the latter evolution of wind velocity at Maradi which showed up a spectacular decrease during the last five years while the trend is increasing at all other stations. It seems, in this case, that the anemometer has been damaged as confirmed afterwards by Daouda ("Météorologie Nationale du Niger").

As for the lithometeors, it appears that no significant relation exists between rainfalls and wind velocity. Indeed, the relations are even poorer. Best relation is presented at N'Guigmi with a $r^2 = 0.25$ and the worst one still at Bilma where $r^2 = 0.01$. All the determination coefficients are presented in table 3.

Table 3

Determination coefficients between rainfalls and wind velocity at all the stations (period 1951-1994)

	Niamey	Maradi	Zinder	Tahoua	Mainé-Soroa	Nguigmi	Agadez	Bilma
r^2	0.15	0.20	0.06	0.20	0.06	0.25	0.15	0.01

The general trend as presented on figure 5 shows that the increase of wind velocity is common to all stations. As a matter of fact, the highest rise of wind speed is recorded at Niamey with 70 % during the 44-year period passing from 4,3 m s^{-1} to 7,1 m s^{-1}.

5. Discussion

The fluctuations in time and space of the lithometeor frequency and wind velocity have been described and the calculation of their response to rainfall has been proved insignificant. We present hereafter the relation between the visibility and wind factors. This relation too has no signification for all the stations (tab. 4) except for Bilma ($r^2 = 0.53$) and Niamey ($r^2 = 0.60$) (fig. 4).

At the station of Bilma, where anthropogenic effects on environment and vegetation cover modifications are non-existent, a good relation

Table 4

Determination coefficients between the number of days affected by the lithometeors and wind velocity at all the stations (period 1951-1994)

	Niamey	Maradi	Zinder	Tahoua	Mainé-Soroa	Nguigmi	Agadez	Bilma
r^2	0.60	0.42*	0.17	0.17	0.00	0.18	0.10	0.53

* wind value until 1989 in Maradi.

was expected between the two factors but, in fact, proved relatively low. The causes of the remaining 47 % that have to be understood are then of climatic order. But the decrease of air relative humidity and soil moisture in this region is too slight during the October-April period (MOREL 1992) for having any influence. It is therefore on the turbulence of the wind, as well as on its direction and on global circulation that further studies should be undertaken.

The best determination coefficient is presented in Niamey. At this station, very distant from dust sources (BEN MOHAMED *et al.* 1992), the relation is much more complex. Indeed, the drought and anthropogenic effects on dust production are supposed to be important but are not well quantified. Nevertheless, as wind is blowing stronger, the airborne dust mobilized in eastern Niger can then be carried on longer distances by the Harmattan as MCTAINSH (1982) showed for Kano in Nigeria. This relation with wind velocity could be partly completed by the decrease of relative humidity recorded in Sahel during the drought (MOREL 1992) but also with the wind direction fluctuation in time as the visibility in Niamey depends on foreign supplies.

The other stations have an insignificant determination coefficient with a r^2 ranging from 0.00 to 0.42. This expresses the extreme complexity of the phenomenon in the fragile fringes which have been the most damaged during the last 30 years.

6. Conclusion

The increase of lithometeor frequency as well as the wind velocity during the drought period is not explained by the aridification. But their direct relation is significant in Bilma and Niamey, respectively the driest and the wettest stations of our network.

It has also been showed that the area of Bilma did not provide the Sahelian zone with airborne dust during the 80s as suggested by several authors.

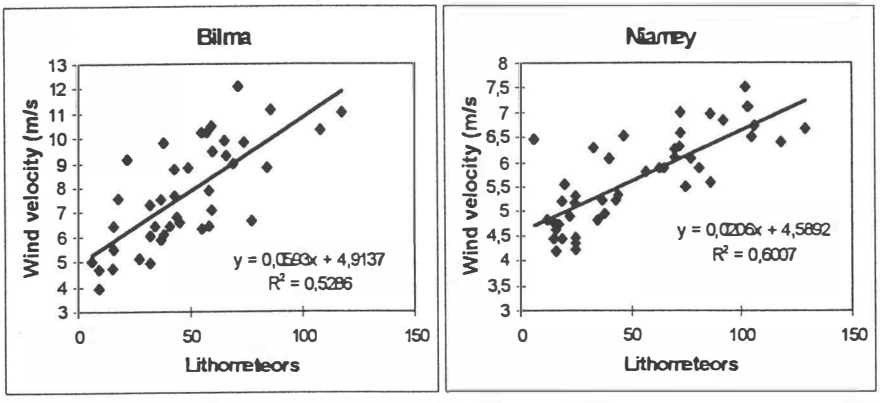


Fig. 6. — Relation between wind velocity and number of days affected by the lithometeors at the stations of Bilma and Niamey (period 1951-1994).

The causes of this phenomenon have to be searched in the effect of the drought on climate and environment. We have already discussed the diminishing vegetation cover which generates a lower protection of the soil enhanced by dramatic overgrazing and collection of wood, dead or not, which has been multiplied by three over the last 35 years in Niger (OZER 1995b). Moreover, the soil moisture is then reduced which engender a lesser coherence of the soil particles. This is even aggravated by the poor land-use practices : from 1975 to 1990, the surfaces of cultivated lands increased by 68 % while yields decreased by 19 % (OZER 1993).

The evolution of the number of days affected by the lithometeors could then be taken as a good indicator of global environmental degradation more than a direct response to rainfall deficit.

The diminishing air relative humidity recorded all over West Africa (MOREL 1992) is also to take into account because this permits the transport of airborne dust on longer distances. Finally, a close study of wind direction should be taken because lifting of sand and dust can easily occur when the dunes are approached by "contrary" winds in different direction of an equilibrium previously established (DUBIEF 1979). This would lead to the study of global circulation changes in the Sahel for a best understanding of these processes.

ACKNOWLEDGEMENTS

This research is funded by the Environment Program (Climatology) of the DG XII - European Commission (contract No. EV5V-CT-94-5244) and supervised by Dr. M. Erpicum, University of Liège, and Prof. G. C. Cortemiglia, University of Genoa. I would like to thank Prof. J. Alexandre for his useful comments of the University of Liège and Mr R. Morel for furnishing rainfall data. Thanks also to Mr J. L. Génicot for his help in computing wind data. The assistance of Dr. S. Karimoune from the „Ecole Normale Supérieure", Niamey, as well as Mr I. Also and Mr M. Daouda from the „Direction de la Météorologie Nationale du Niger", Niamey, are gratefully acknowledged for logistical support and constant attention. Special thanks are finally given to the Belgian Embassy for its kind help and support during the coup d'Etat in February 1996.

REFERENCES

ADEDOKUN, J. A., EMOFURIETA, W. O. & ADEDEJI, O. A. 1989. Physical, mineralogical and chemical properties of Harmattan dust at Ile-Ife, Nigeria. — *Theor. Appl. Climatol.*, **40** : 161-169.

ADEFOLALU, D. O. 1984. On bioclimatological aspects of Harmattan dust haze in Nigeria. — *Arch. Met. Geoph. Biocl.*, Ser. B, **33** : 387-404.

BEN MOHAMED, A., FRANGI, J. P., FONTAN, J. & DRUILHET, A. 1992. Spatial and temporal variations of atmospheric turbidity and related parameters in Niger. — *J. Appl. Meteor.*, **31** : 1286-1294.

CARLSON, T. N. & PROSPERO, J. M. 1972. The large-scale movement of Saharan air outbreaks over the northern Equatorial Atlantic. — *J. Appl. Met.*, **11** : 283-297.

COUDE-GAUSSEN, G. 1990. Les poussières sahariennes. Cycle sédimentaire et place dans les environnements et paléoenvironnements désertiques. — John Libbey Eurotext, Paris, 485 pp.

COUDE-GAUSSEN, G. 1994. Erosion éolienne au Sahel et sécheresse. — *Sécheresse*, **5** : 199-210.

COUREL, M. F. & CHAMARD, P. C. 1988. Apparition de nouvelles formes dunaires dans l'Azawad et le Gourma septentrional (Mali). — *In* : ERPICUM, M. (éd.), Actes des Journées de Climatologie, Presses Universitaires de Liège, pp. 7-28.

DELANY, A. C., PARKIN, D. W., GRIFFIN, J. J., GOLDBERG, E. D. & REIMANN, B. E. F. 1967. Airborne dust collected at Barbados. — *Geochimica et Cosmochimica Acta*, **31** : 885-909.

DUBIEF, J. 1979. Review of the North African climate with particular emphasis on the production of eolian dust in the Sahel zone and in the Sahara. — *In* : MORALES, D. (ed.), Saharan dust : Mobilization, transport, deposition. Wiley, New York, *Scope,* **14** : 27-48.

FODE, M., OUSMANE MANGA, A. & ARNAUD, Y. 1994. Detection of dust clouds over West Africa from METEOSAT IR data. — 10th Meteosat Scientific Users' Conference, pp. 383-389.

HAMILTON, R. A. & ARCHBOLD, J. W. 1945. Meteorology of Nigeria and adjacent territory. — *Quart. J. R. Met. Soc.,* **71** : 231-265.

HULME, M. 1992. Rainfall changes in Africa : 1931-1960 to 1961-1990. — *Int. J. Climatol.*, **12** : 685-699.

KALU, A. E. 1979. The African dust plume : its characteristics and propagation across West Africa in winter. — *In* : MORALES, D. (ed.), Saharan dust : Mobilization, transport, deposition. Wiley, New York, *Scope,* **14** : 95-118.

LAMB, P. J. 1982. Persistence of subsaharan drought. — *Nature*, **299** : 46-48.

LE HOUEROU, H. N. 1990. Définition et limites bioclimatiques du Sahara. — *Sécheresse*, **1** : 246-259.

LUNDHOLM, B. 1979. Ecology and dust transport. — *In* : MORALES, D. (ed.), Saharan dust : Mobilization, transport, deposition. Wiley, New York, *Scope,* **14** : 61-68.

MAINGUET, M., VIMEUX-RICHEUX, M. & CHEMIN, M. C. 1983. Autochtonie et allochtonie des sables de la zone saharo-sahélienne du Niger. — *Rev. Géol. Dyn. Géog. Phys.*, **24** : 167-175.

MCTAINSH, G. H. 1980. Harmattan dust deposition in northern Nigeria. — *Nature*, **286** : 587-588.

MCTAINSH, G. H. & WALKER, P. H. 1982. Nature and distribution of Harmattan dust. — *Z. Geomorph.*, N.F., **26** : 417-435.

MIDDLETON, N. J. 1985. Effect of drought on dust production in Sahel. — *Nature*, **316** : 431-434.

MORALES, D. 1979. Saharan dust : Mobilization, transport, deposition. — Wiley, New York, *Scope,* **14** : 289 pp.

MOREL, R. 1992. Humidité de l'air et pluviométrie en Afrique de l'Ouest. — *Publ. de l'Ass. Inter. Climatologie*, **5** : 169-178.

MOREL, R. 1995. Pluviométrie 1961-1990 en Afrique de l'Ouest. — *Publ. de l'Ass. Intern. Climatologie*, **8** : 361-368.

NICHOLSON, S. E. 1989. Long-term changes in African rainfall. — *Weather*, **44** (2) : 44-56.

OZER, P. 1993. Contribution à l'étude de la désertification en région sahélienne. Le cas du Niger. Problèmes posés par les précipitations et les lithométéores. — Mém. de licence, Fac. des Sci., Univ. de Liège, 177 pp.

OZER, P. 1995a. Application des transects pluviométriques spatio-temporels annuels au territoire sahélien. — *Publ. de l'Ass. Intern. Climatologie*, **8** : 369-377.

OZER, P. 1995b. Lithometeors in relation with desertification in the Sahelian area of Niger. — *In* : FANTECHI, R., PETER, D., BALABANIS, P. & RUBIO,

J. L. (eds.), Desertification in a European context : physical and socio-economic aspects, Report EUR 15415 EN, European Commission, Luxembourg, pp. 567-574.

OZER, P. 1996. Evolution des directions et des vitesses des vents de 1951 à 1994 sur la façade atlantique de l'Afrique de l'Ouest du sud du Sénégal au nord de la Mauritanie. — *Publ. de l'Ass. Intern. Climatologie,* **9** : 479-486.

OZER, P. & ERPICUM, M. 1995. Méthodologie pour une meilleure représentation spatio-temporelle des fluctuations pluviométriques observées au Niger depuis 1905. — *Sécheresse*, **6** : 103-108.

PEWE, T. L. 1981. Desert dust : origin, characteristics, and effect on man. — *Geol. Soc. Amer.*, **186** : 303 pp.

PROSPERO, J. M. & CARLSON, T. M. 1972. Vertical and areal surface distribution of Saharan dust over the western equatorial North Atlantic Ocean. — *J. Geophys. Res.*, **77** : 5255-5265.

PROSPERO, J. M. & NEES, R. T. 1977. Dust concentration in the atmosphere of the equatorial North Atlantic : possible relationship to the Sahelian drought. — *Science*, **196** : 1196-1198.

PROSPERO, J. M. & NEES, R. T. 1986. Impact of the North African drought and El Niño on mineral dust in the Barbados trade winds. — *Nature*, **320** : 735-738.

QUEZEL, P. 1965. La végétation du Sahara. Du Tchad à la Mauritanie. — Gustav Fisher Verlag, Stuttgart, 333 pp.

SAVOIE, D. L. & PROSPERO, J. M. 1977. Aerosol concentration statistics for the northern tropical Atlantic. — *J. Geophys. Res.*, **82** : 5954-5964.

VERHEYE, W. H. 1990. Une approche agropédologique de la désertification. — *Sécheresse*, **1** : 94-97.

W.M.O. (O.M.M.) 1966. Vocabulaire météorologique international. — No. 182, TP. 91, 296 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 228-250 (1998)

Lake Tanganyika : Recent Climate Changes and Teleconnections with ENSO

by

Pierre-Denis PLISNIER *

KEYWORDS. — Climate Changes ; East Africa ; El Niño ; Lake Tanganyika ; *Lates stappersii* ; Limnology ; Fisheries ; *Limnothrissa miodon* ; *Stolothrissa tanganicae* ; Teleconnections.

ABSTRACT. — Average air temperature is increasing in Lake Tanganyika area (0.7 to 0.9 °C from 1964 to 1990) while the speed of surface winds has decreased, particularly since the late 70s. South-east trade winds induce a tilting of the epilimnion and upwelling in the south from May to September. Currents linked to the re-establishment of the epilimnion toward an equilibrium state after the end of the monsoon winds re-activate internal waves. Depending on fluctuating climatic conditions, the lake could have different hydrodynamic intensities influencing dynamics and nutrition of fish populations. The long-term trend in the catches per unit of effort of the industrial fisheries shows a marked decrease of the clupeids at both ends of the lake and a segregation of *Lates stappersii* (Boulenger 1914) more abundant in the southern compared to the northern end. This might be tied with decreased upwelling intensity, increased stratification and change in thermocline depth. Meteorological series show oscillations correlated with ENSO (El Niño/Southern Oscillation) and fluctuating yearly catches of pelagic fishes. *Clupeid* catches per unit of effort are negatively correlated with air temperature and El Niño events. Teleconnections with ENSO offer interesting possibilities for pelagic fisheries forecasting of Lake Tanganyika and for studies of the interannual variation of the East African climate.

MOTS-CLES. — Changement climatique ; Afrique de l'Est ; El Niño ; Lac Tanganyika ; *Lates stappersii* ; Limnologie ; Pêcherie ; *Limnothrissa miodon* ; *Stolothrissa tanganicae* ; Téléconnection.

* Royal Museum for Central Africa. Department Geology and Mineralogy, Leuvensestw. 13, B-3080 Tervuren (Belgium).

RESUME. — *Le lac Tanganyika : changements climatiques récents et téléconnections avec ENSO.* — La température moyenne de l'air a augmenté dans la région du lac Tanganyika (0,7 °C à 0,9 °C de 1964 à 1990), tandis que la vitesse des vents de surface a diminué depuis la fin des années 70. Les vents du sud-est entraînent une inclinaison de l'épilimnion et un «upwelling» au sud de juin à septembre. Les courants liés au rétablissement de l'épilimnion vers sa position d'équilibre à la fin de la saison des vents du sud-est réactivent les vagues internes. En fonction des conditions climatiques, le lac semble présenter une intensité variable de phénomènes hydrodynamiques influençant la dynamique de population et l'alimentation des poissons. La tendance à long terme des captures par unité d'effort de pêche industrielle montre un net déclin des clupéides aux deux extrémités du lac et une ségrégation de *Lates stappersii* (Boulenger 1914) plus abondant au sud qu'au nord. Ceci pourrait être lié à une diminution d'intensité des «upwelling», une stratification plus marquée et des changements de la profondeur de la thermocline. Les séries météorologiques montrent des oscillations corrélées à ENSO (El Niño/Oscillation Australe) et aux fluctuations annuelles des captures de poissons pélagiques. Les captures par unité d'effort des clupéidés sont négativement corrélées à la température de l'air et aux événements El Niño. Les téléconnections avec ENSO offrent des perspectives intéressantes de prévision des pêches pour l'exploitation des poissons pélagiques du lac Tanganyika et l'étude de la variation interannuelle du climat en Afrique de l'Est.

TREFWOORDEN. — Klimaatverandering ; Oost-Afrika ; El Niño ; Tanganyika meer ; *Lates stappersii* ; Limnologie ; Visserij ; *Limnothrissa miodon* ; *Stolothrissa tanganicae* ; Teleconnecties.

SAMENVATTING. — *Het Tanganyika meer : recente klimaatveranderingen en teleconnecties met ENSO.* — In het gebied van het Tanganyikameer is de gemiddelde luchttemperatuur gestegen met 0,7-0,9 °C tussen 1964 en 1990 terwijl de snelheid van oppervlaktewinden afnam vooral sinds het einde van de jaren 70. Zuidoostelijke winden induceren een inclinatie van het epilimnion en *upwelling* van juni tot september. Stromingen, te wijten aan het zich herstellen van een evenwichtstoestand na het einde van de passaatwinden, reactiveren interne golven. Afhankelijk van de fluctuerende klimaatcondities kan het meer verschillende hydrodynamische intensiteiten vertonen die op hun beurt de dynamiek en voeding van vispopulaties beïnvloeden. De trend op lange termijn wat betreft de vangsten per visprestatie-eenheid van de industriële visserij vertoont een duidelijke daling van de clupeiden aan beide uiteinden van het meer en een segregatie van *Lates stappersii* (Boulenger 1914) die talrijker in het zuiden dan in het noorden van het meer voorkomt. Dit zou verband kunnen houden met een verminderde intensiteit van *upwelling*, met een verhoogde stratificatie en met een verandering in de diepte van de

thermocline. Meteorologische gegevensreeksen vertonen oscillaties die een correlatie vertonen met ENSO (El Niño/Southern Oscillation) en met jaarlijkse schommelingen in de vangsten van pelagische vissen. De vangsten per visprestatieëenheid van clupeiden tonen een negatieve correlatie met de luchttemperatuur en met de El Niño gebeurtenissen. De teleconnecties met ENSO bieden interessante mogelijkheden om voorspellingen te doen over de pelagische visserij in het Tanganyika meer en om de oorzaken van de interannuele variaties van het klimaat in Oost-Afrika te bestuderen.

Introduction

Lake Tanganyika occupies a deep and narrow trough of the western branch of the Rift Valley of East Africa between 3°30′ and 8°50′ S and 29°05′ and 31°15′ E (COULTER 1994) (fig. 1). It is the second-largest body of freshwater in the world after Lake Baïkal (HUTCHINSON 1957).

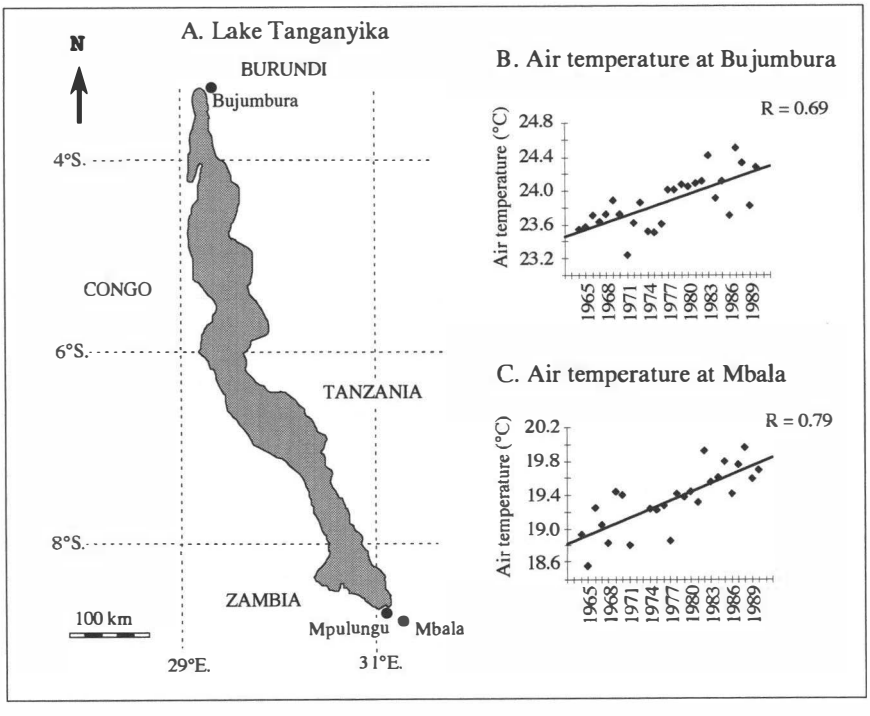


Fig. 1. — Map of Lake Tanganyika showing Bujumbura and Mbala meteorological stations (A). Linear regressions of yearly mean air temperature from 1964 to 1990 in (B) Bujumbura and (C) Mbala.

Stratification is permanent (meromixis) and most of the volume (18,880 km^3) is constituted by an anoxic hypolimnion below *ca.* 70 m at the north end and *ca.* 200 m at the South (COULTER 1994). Lake Tanganyika's limnology presents some challenging questions amongst which the basis of the biological production and the trophic status of the lake remain to be detailed. Qualitative observations have first led investigators to qualify the lake as oligotrophic because of high transparency of the water apparently caused by the high thermal stability and the paucity of nutrients in the epilimnion (BEAUCHAMP 1939, KUFFERATH 1952). VAN MEEL (1954) noted from observations of dense phytoplankton blooms and diurnal vertical movements of zooplankton and fish, that certain areas of the lake were productive. This led him to classify the lake as pseudoeutrophic, i.e. possessing both oligotrophic and eutrophic characteristics. A quantitative estimated overall annual rate of primary production (0.8 g/cm^2/day) was compared with that of other tropical lakes (4.5, 1.45 and 1.7 g/cm^2/day for Lakes George, Titicaca and Lanao respectively) and it was concluded that the rate of primary production in Lake Tanganyika is not high (HECKY & FEE 1981, HECKY *et al.* 1981). However HECKY *et al.* (1981) noted that the carbon transfer efficiency derived from the percentage proportion of clupeid production to primary production was extremely high (0.45 %). They suggested that the high efficiency of trophic structure in Lake Tanganyika could be due to (a) a relatively short food chain leading to harvestable fish and (b) the great age of the lake which has allowed for the selection of trophically efficient populations.

Lake Tanganyika is pointed by several authors to be very sensitive to climate forcing (DEGENS *et al.* 1971, HABERYAN & HECKY 1987). Climate changes in Lake Tanganyika area during the recent decades were investigated and some correlations with limnological observations are presented here.

Material and Methods

The location of the meteorological station at Bujumbura Airport is 3.32 °S, 29.32 °E, while the meteorological station at Mbala Airport is 8.85 °S, 31.33 °E. The stations are integrated in the network of the World Meteorological Organization (W.M.O.). Their identification numbers (WMOID) are 6439000 for Bujumbura and 6741300 for Mbala stations. The Southern Oscillation Index (SOI) is based on the

standardized sea level pressure difference between Tahiti (French Polynesia) and Darwin (Australia) (PHILANDER 1990). Some of the results presented here have been collected during the course of a FAO/FINNIDA project (GCP/RAF/271/FIN) "Research for the management of the fisheries on Lake Tanganyika". Limnological methods are detailed in PLISNIER *et al.* (1996). Conductivity is expressed in μS/cm. It was measured every two or three weeks by a Hach conductivity metre, model 44600 at 4 km from the shore at a depth of 120 m near Bujumbura. The instrument automatically compensates for temperature deviation from 25 °C. Data about fisheries statistics were collected by the Zambian Department of Fisheries (PEARCE 1992). The catches per unit of effort are defined as the catches made by one industrial boat (purse-seiner) fishing during one night.

Results

AIR TEMPERATURE

Since the 60s, an increase in air temperature has been noted in two stations at each end of Lake Tanganyika (fig. 1). At Bujumbura Airport, the average increase, based on the linear regression of annual mean temperature data between 1964 and 1990, is 0.7 °C ($r = 0.69$). At Mbala Airport, the average increase for the same period is 0.9 °C ($r = 0.79$). Several limnological observations seem to indicate a warming trend for the lake itself similar to the temperature increase of lake Victoria during the last three decades (HECKY *et al.* 1994, PLISNIER 1997). According to HASTENRATH & KRUSS (1992), there is evidence for a warming trend in East Africa since 1960. The most consistent warming noted by IPCC (1990) is found in subtropical and tropical regions, especially the Indian Ocean and regions nearby.

Beside the general trend of increase in the air temperature, oscillations can be noted around the mean (fig. 2). This variation can be linked to the ENSO phenomena. There is a significant correlation between the air temperature in Bujumbura and Mbala with the sea surface temperature (SST) of the Pacific Ocean such as Niño 4 area. The strongest correlation between air temperature and SST of Niño 4 was 0.67 at Bujumbura and 0.41 at Mbala ($P < 0.01$) with a 4-month lag between SST peak and the following air temperature peak at Bujumbura and Mbala. Air temperature was 0.6 °C higher on average during El Niño years than during La Niña years for the period from

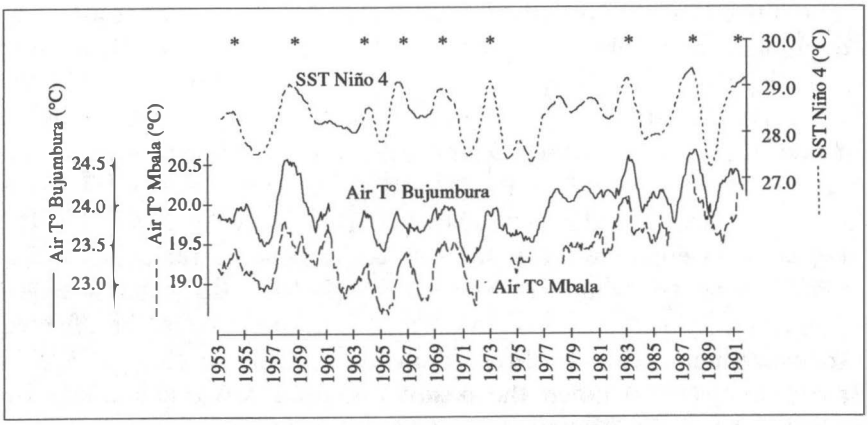


Fig. 2. — Monthly air temperature (°C) at Bujumbura and Mbala and sea surface temperature (SST in °C) in Niño 4 area of Pacific Ocean (150° W. to 160° E and 5° S to 5° N) from January 1953 to July 1991. Observed El Niño events are marked with asteriks. Running averages of 12 months are shown.

1953 to 1991 at both ends of the lake. A preliminary analysis from air temperature observations shows that recent El Niños were well observed at Lake Tanganyika in 1954, 1958, 1966, 1969, 1973, 1983, 1988 and 1991-94 (fig. 2). Increase in air temperature for years corresponding to El Niño events could reach 1.0 °C in Bujumbura and 0.83 °C in Mbala. This corresponds to 59 % and 24 % of the average amplitude of monthly air temperature during an annual cycle at Bujumbura (1.7° C) and at Mbala (3.5 °C) respectively. Through the fluctuations of air temperature, ENSO may thus be linked to the stability of the water column of Lake Tanganyika since the lake thermal stratification is observed within a small range (2.3° C on average) and is highly sensitive to variations of air temperature apparently small but proportionally important.

Winds

Lake Tanganyika position and geographical orientation make it particularly dependent upon regular unidirectional SE trade winds from May to September. Those winds affect also large parts of South and East Africa and seem correlated with ENSO. In the Indian Ocean, monsoon winds are weaker during El Niño years and stronger during La Niña years (Tourre & White 1994).

For fifteen years winds have decreased in Lake Tanganyika area. Preliminary available data show that winds in Bujumbura were fluctuating between 1.4 and 2.5 m/s on average from 1964 until the end of the 70s (PLISNIER 1997). Between 1986 and 1990, the wind fluctuations were between 0.5 and 1.5 m/s. In Mbala, wind speed decreased from the end of the 70s to a minimum in 1983. Then it increased but not to the previous levels (fig. 7). At both ends of the lake, winds were very weak in 1982-83, a year of major El Niño. Fishermen at the south of the lake reported also wind strength diminishing from the end of the 70s. Local winds could be affected also by changing climate. From daily data in the south of the lake, BEAUCHAMP (1939) noted the positive relation between temperature maxima and minima range and winds. A strong reduction in monthly temperature range in Mbala has been noted (PLISNIER 1997). This

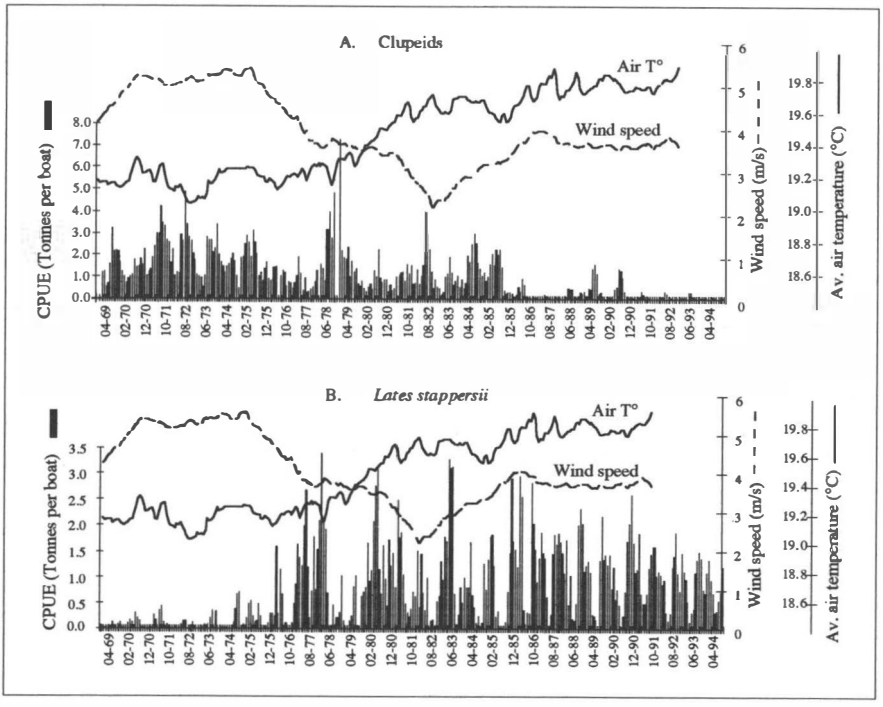


Fig. 3. — Catches per unit of effort (CPUE) for the clupeids and *Lates stappersii* (industrial fishing) in Mpulungu and average of air temperature (° C) and wind speed (m/s) from 1968-69 to 1994 (running average of 12 months for air t° and 48 months for wind speed).

reduction could be tied to a buffered differential heating (lake-land) inducing weaker local on and off-shore winds.

The effects of SE winds during the dry season from May to September on Lake Tanganyika's limnology are to accumulate warm epilimnion water toward the north of the lake. This induces a tilting of the epilimnion, deep return currents toward the south and upwelling. Interannual differences linked to the SE winds' intensity are suggested in the preliminary schematized extreme situations (fig. 4) :

— "Windy year" : during a year of strong winds, the SE wind piles up more epilimnion water in the northern part of the lake (fig. 4A). The thermocline depth is proportionally important near Bujumbura. The return currents in the deeper layers generate during this season from May to September a strong upwelling in the southern part of the lake. The monsoon shows its annual inversion of direction around September and SE winds stop. Movements of water to re-equilibrate the tilted layer of water are important. The intense hydrodynamic events (currents, oscillations of layers, internal waves, turbulence, ...) positively influence productivity of the epilimnion by allowing important mixing of nutrients in the euphotic zone. Productivity of phytoplankton and zooplankton is favoured. Internal waves induce a pulse production whose amplitude may be well observed in those years. Algae blooms and fish kills are likely to be well marked. Turbulence level may favourably influence pelagic fishes. For the oceans, it has been demonstrated theoretically that even a small increase in the turbulence level may greatly increase the contact frequency between fish larvae and food particles. The turbulence intensity may play a decisive part in the establishment of the magnitude of year classes for fish (FURNES 1992).

— "Calm year" : during a year of weaker winds, the dynamics of the whole ecosystem is reduced. There is less tilting of epilimnion by SE winds. Less potential energy being accumulated in the north of the lake, phenomena described above may have a decreased intensity. Higher air temperature during those years favours also the lake stability. However, the thermocline depth being closer from the surface in the north during the dry season may positively influence primary production since the nutricline is closer to the surface than during a "windy year". During this season and in this area, primary production may be favoured since mixing through turbulence or pulse production induced by internal waves, for

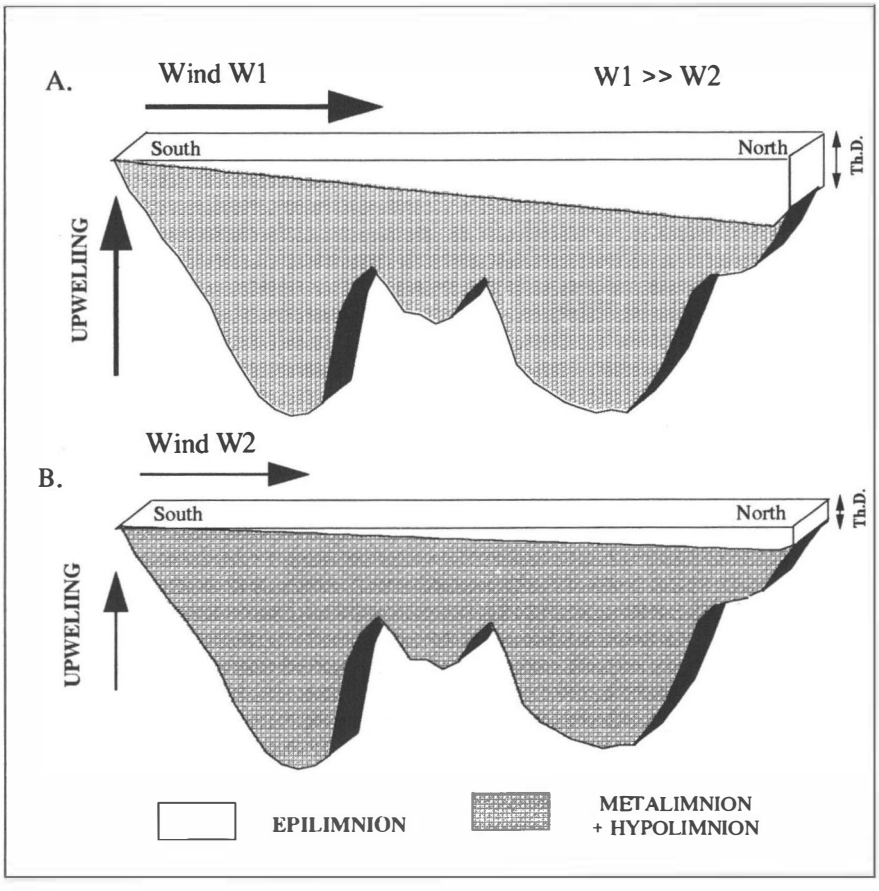


Fig. 4. — Schematic profile of Lake Tanganyika showing (A) an important tilting of epilimnion and a strong upwelling during a windy dry season and (B) a slight tilting and weak upwelling during a less windy dry season (situation such as in September, Th.D. for thermocline depth near Bujumbura, drawing not to scale).

example, has a higher probability to reach the euphotic zone (fig. 4B).

Thermocline depth in the north was around 70 m in 1993-94 and the southern upwelling was clearly measured through the use of eleven thermistors recording temperature every hour during one year from 0 to 300 m. At the end of the monsoon winds, currents rhythmically flow back and forth until the lake reaches a new equilibrium in accordance with MORTIMER's (1952) observations on lake hydrody-

namics. COULTER (1991) suggested that oscillations are accompanied by water movements that take the form of a large amplitude, progressive wave which gradually transforms into a standing wave. He suggested that such a surge could cause a "local severe mixing". In October 1994, I observed strong waves called "Chimbanfula" waves by local fishermen in the south. Chimbanfula means "digging for the rain" as local populations know that rains will come a few weeks after the observation of those waves. This may be easily understood since the end of the SE monsoon corresponds to the return of the ITCZ and the rains from the north. The surface waves near the shores of Mpulungu were extremely strong and noisy. Just before the occurrence of these waves, the fishermen pull their boats several metres outside the lake to avoid damages. In some places, crops bordering the shore may be damaged. Quantities of stones can be accumulated on the most exposed shores. The waves lasted for about two days in 1994. Fishermen near Mpulungu report that Chimbanfula waves occur every year along all the shores in the southern area that they know and come from the north. They are observed every year with different intensity around September-October and can be associated with fish kills and plankton blooms. A fish kill was observed in September 1993. Chimbanfula waves are noted once or twice a few weeks after their first occurrence. They may be related to travelling waves and oscillations of the metalimnion when there are no more forces from the SE winds to maintain the tilting of the epilimnion. There was no wind during Chimbanfula waves of 1994. This surge travelling along the whole lake probably reactivates internal waves. Those are observed all year round. A frequency of 26-33 days and an amplitude of *ca.* 20 m were noted in 1993-94. These waves allow nutrient-rich deep water to reach the biotic layer of the epilimnion. At the ends of the lake, dampened oscillations of the whole epilimnion have been well observed through the isopleth fluctuations of several parameters such as conductivity (fig. 5C) during a yearly cycle. Dampening could be observed also in the fluctuation of phytoplankton and protozoan biomass in 1975 (HECKY & KLING 1981) when a similar period of the year is compared (starting in September) (figs 5A, 5B). Important variation is noted between September and December. This time of the year has been traditionally the time when observations of phytoplankton blooms have been made in the north of the lake (SYMOENS 1955ab, DUBOIS 1958). This suggests that internal loading of nutrients results from hydrodynamic events whose amplitude could be dependent on the energy

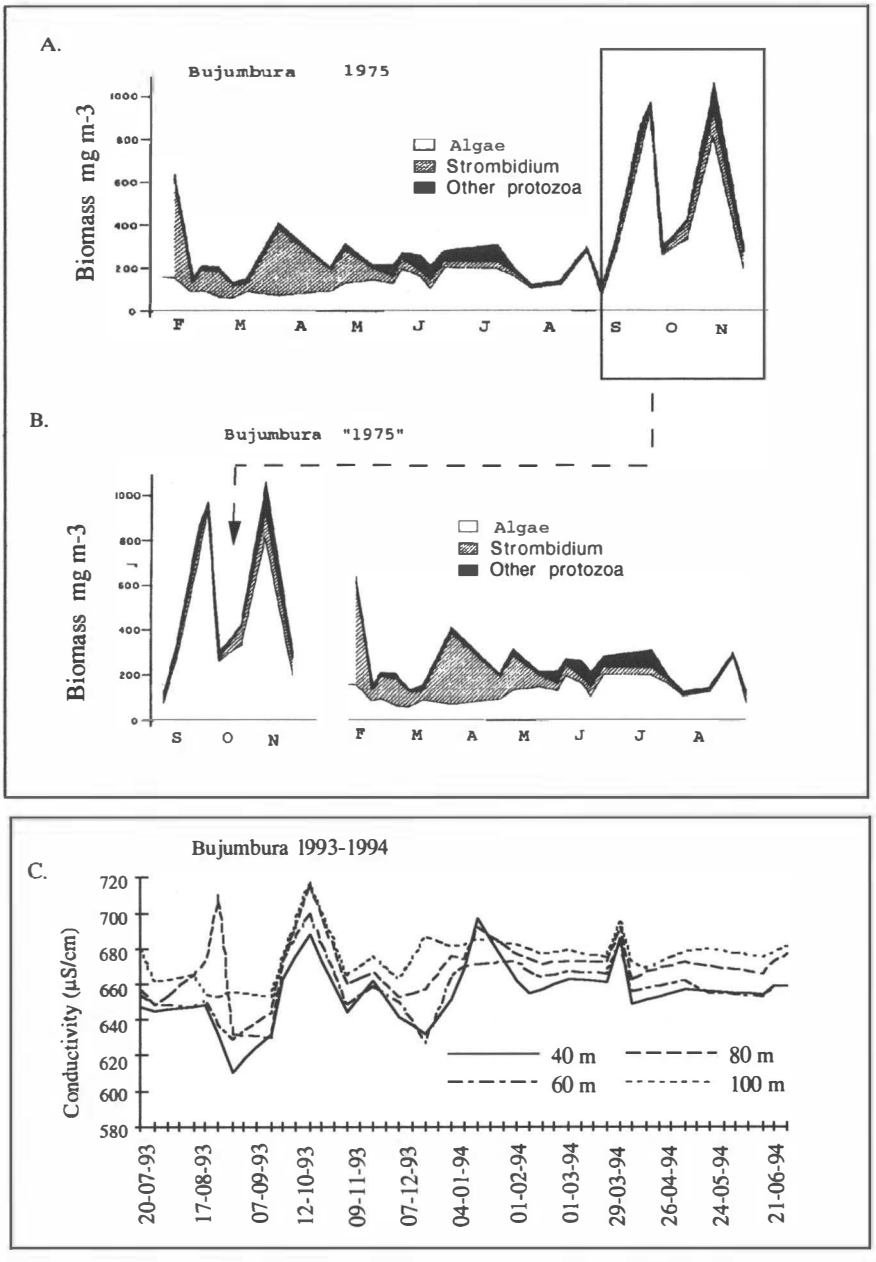


Fig. 5. — (A) Phytoplankton and protozoan abundance near Bujumbura in 1975 (HECKY & KLING 1981) ; (B) idem as (A) if sampling would have started in September (modified after HECKY & KLING 1981) ; (C) changes in conductivity (µS/cm) at 4 depths of Bujumbura in 1993-1994.

input by the winds and the stratification of the water column. Secondary upwellings have been suggested (PLISNIER & COENEN, in print). Interannual differences in amplitude of the water movements (such as fluctuations of thermocline depth) are most probably linked to interannual differences in meteorological environment, particularly SE winds, such as schematized in figures 4 and 6.

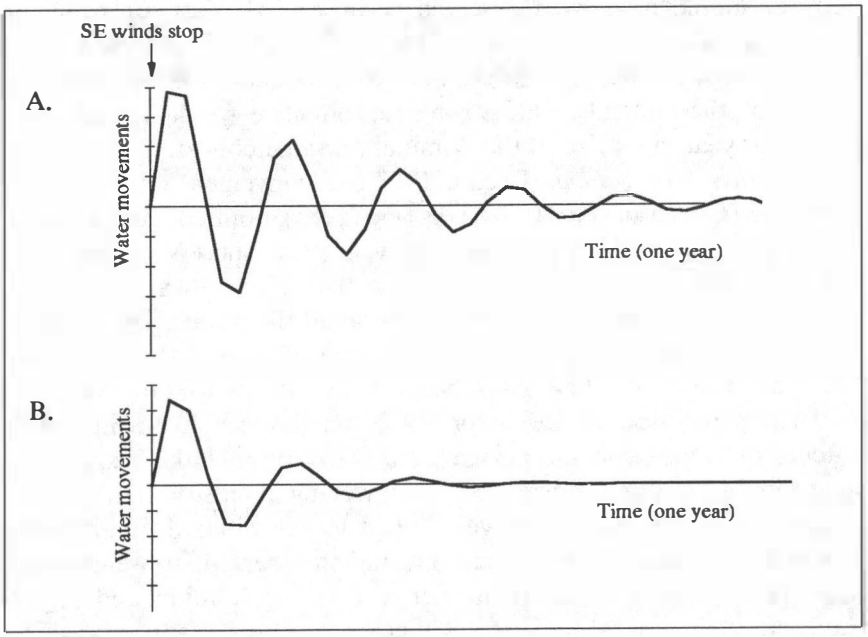


Fig. 6. — Dampened oscillation in a given station (Bujumbura for example) when SE wind season stops (around September) and the epilimnion oscillates during (A) a year with a marked windy season and (B) a year with a weak windy season (*cf.* fig. 4).

The decrease of the wind in the last fifteen years seems to correspond to a shift from the "windy year" situation (fig. 4A) to the "calm year" situation (fig. 4B). Comparison with data from DUBOIS (1958) and FAO/FINNIDA are coherent with a decrease of tilting of thermocline depth in the north of the lake linked to a decreased oxic layer and decrease of transparency there (PLISNIER 1997). Interannual oscillations between those extreme situations might be linked to the monsoon intensity fluctuations in the Indian Ocean and ENSO. The lake hydrodynamics are of course complex and a detailed study is under way (Huttula, personal communication).

Clupeids

Clupeids have strongly decreased in Lake Tanganyika since the early 80s. Example is provided for the south of the lake (fig. 3A). It could be argued that this has been caused mainly by the increased fishing effort in the 80s. However, in the north of the lake, catches of clupeids have also decreased but fishing effort has decreased there. A fast recovery should have been observed because of the fast turnover and high resilience of the clupeids. This has not been observed. It is suggested that the fishing effort is not the main cause for the decreased catches of the clupeids. One strong reproductive (or larval survival) peak each year gives rise to the dominant annual cohort. The life span of *Stolothrissa tanganicae* Regan, 1917 can conveniently be regarded as a year (Coulter 1991). As Lasker (1985) pointed out, with the clupeids, there may be an important year class success arising from small to virtually non-existent population. There may always be enough fertilized eggs produced, no matter how small the population (because of overfishing for example), to produce a good year if the conditions are right. There are close links between pelagic plankton cycles and the feeding regime and life history of *S. tanganicae* (Coulter 1991). Catches of clupeids in the pelagic area of southern Lake Tanganyika are probably strongly correlated to upwelling intensity. The clupeid catches in the south are positively linked to the winds during the dry season from May to September. During this period, upwellings are tied with increased inputs of nutrients in the epilimnion and phytoplankton peaks of abundance. Clupeids are more appreciated by consumers during this period as they contain more fat and taste better (Sililo, pers. comm.). *Limnothrissa miodon* (Boulenger 1906) invades the pelagic waters probably from the shores while *S. tanganicae* probably migrates from a more distant location (Pearce 1992). During an annual cycle, average *L. miodon* CPUE increase simultaneously with an increase of the wind ($r = 0.77$, $p < 0.01$) while *S. tanganicae* CPUE show the strongest correlation with the wind ($r = 0.87$, $p < 0.01$) with a time lag of two months (fig. 7A) (Plisnier 1997).

Air temperature fluctuations infuence the limnology of the lake and possibly contribute also to the fluctuation of the clupeids. The increase in air temperature was almost simultaneous with the decrease of the wind and the decrease of the clupeids CPUE in the recent decades (fig. 3A). From data between 1963 and 1991, an inverse relationship between clupeid catches and air temperature has been observed ($r =$

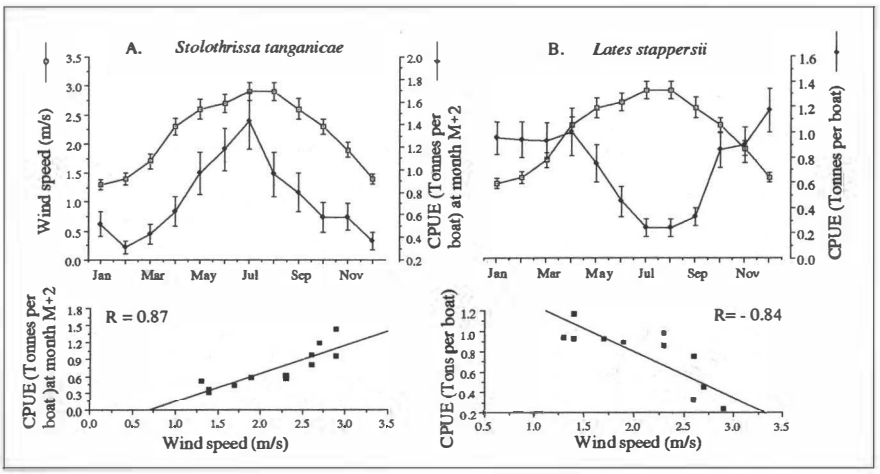


Fig. 7. — Relations between monthly average (from 1967 to 1994) wind speed (m/s) in Mbala and monthly average catches per unit of effort (CPUE) of *Stolothrissa tanganicae* and *Lates stappersii* for industrial fishery in Mpulungu (standard errors are indicated).

– 0.73) (fig. 8A). As there are ENSO teleconnections with air temperature (fig. 2) this suggests direct links between ENSO and CPUE of clupeids. Positive correlation with SOI of February-March and following catches of clupeids (from April to July) indicate teleconnections with ENSO ($r = 0.58$, $P < 0.01$) (fig. 8B). Similar relations have been found with CPUE of clupeids at the north of the Lake and with fluctuations of *Lates stappersii* CPUE (PLISNIER 1997). Fluctuations in monsoon of the Indian Ocean tied with ENSO (TOURRE & WHITE 1994) and interannual differences in climate could affect Lake Tanganyika's ecosystem and the abundance of pelagic fishes.

LATES STAPPERSII

Contrary to the clupeids, since the mid-70s, the catches per unit of *Lates stappersii* in the south have shown an important increase (fig. 3B). They represented 96 % of the total catches of the industrial fisheries in 1994 (PLISNIER 1995). While this is probably tied with the decrease of the other *Lates* species, environmental changes could also be involved. During an average year in the south of the lake (from data between 1967 and 1994), it can be observed that the catches per

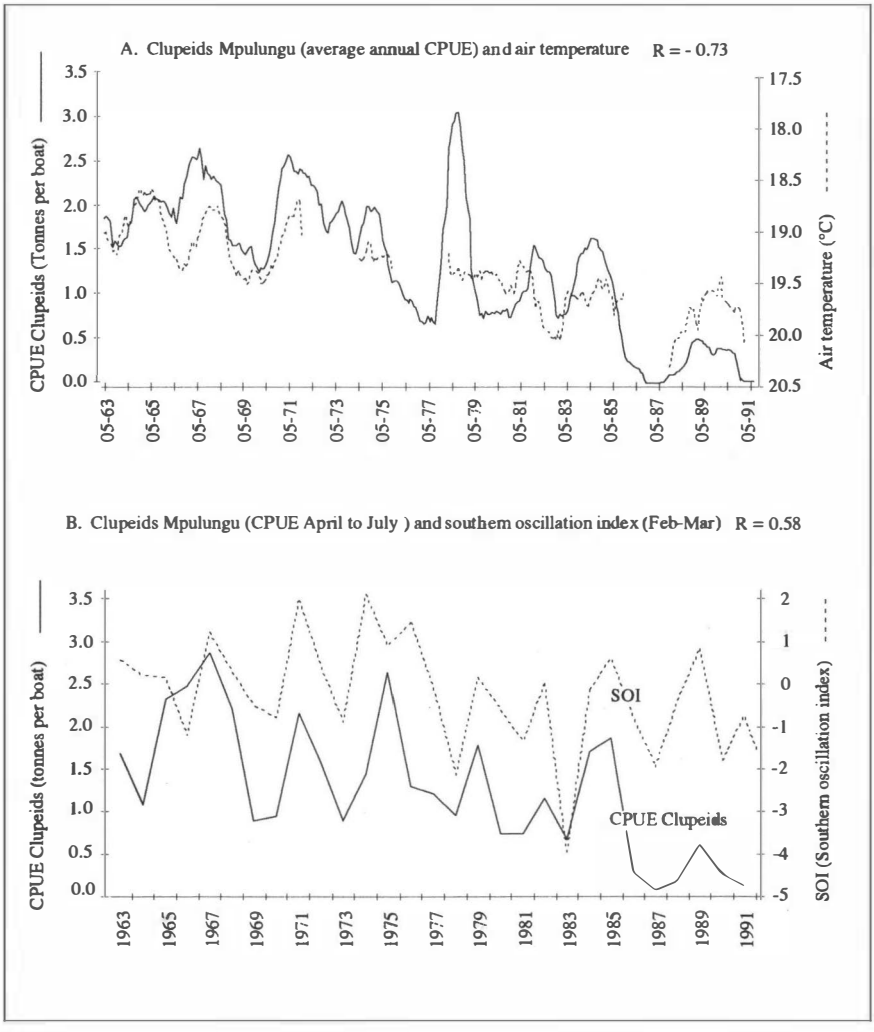


Fig. 8. — Catches per unit of effort (CPUE) of clupeids (Mpulungu) by industrial fisheries from 1963 to 1991, (A) annual CPUE and air temperature in Mbala (inverted scale for temperature), (B) averages of CPUE from April to July and southern oscillation index (SOI) from preceding February and March of each year.

unit of effort of *L. stappersii* are inversely related to the wind speed ($R = -0.84$, $p < 0.01$) (fig. 7B). Adults *L. stappersii* is seldom caught during the dry and windy season (from May to September) in the south (MANNINI *et al.* 1996). It seems that the decreased transparency during the upwelling is a main cause for this. *L. stappersii* is a visual predator, hence transparency could be one of the key factors to explain its distribution in the lake. The transparency was highly correlated with the Zambian monthly catches in 1993-1994 ($r = 0.75$, $p < 0.01$). *L. stappersii* is seldom caught in the north of the lake, an area that actually shows a reduced transparency (annual average of 9 m in 1993-94 instead of 13.6 m in 1995-57) (PLISNIER *et al.* 1996, DUBOIS 1958). *Lates stappersii* seems actually more abundant in the south compared to the northern end. The decrease of the winds in the mid-70s and temperature increase coincided with the increase of the catches of *L. stappersii* (fig. 3B). More stable conditions of the lake and possible increased transparency in the south could favour visual predation and increase catchability by light fishing. An increase of shrimps may also have favourably influenced *L. stappersii* in the south. PEARCE (1985) recorded during a three-year period that shrimps were the main food item of adult *L. stappersii* while *S. tanganicae* came second in importance. Recent observations have shown also that shrimps were a major food item for *L. s*tappersii (Milindi, pers. comm.). In the north, *L. stappersii* CPUE have much decreased. Industrial fishing effort may not explain this trend since it has decreased there. Those changes might be tied to climatic changes leading to changes in the ecosystem such as a reduced transparency in the north of the lake. The recent echo-soundings and trawling experiments in the lake by FAO/FINNIDA (Aro and Mannini, pers. comm.) might bring information to better understand the distribution of *L. stappersii* in the lake and the causing factors.

Discussion

It is generally agreed that world climate will warm significantly over the next half century (HEALEY 1990). None of the existing models give much regional precision. The observed apparent elevated increase in air temperature of Lake Tanganyika area (fig. 1) in the last *ca.* 30 years suggests that the increase might be relatively important in this area. Thermic stratification would increase and upwelling intensity might still decrease if the intensities of winds continue to weaken. Reduced

upwelling, lower turbulence level, decreased amplitude of internal waves, increased stratification caused by climatic changes might induce changes in the energy transfer and food webs of the lake. The overall productivity of the lake might be lower. It has been shown that vertical mixing induced by turbulence to a large degree controls the photosynthetic performance of algae in nature (LEWIS *et al.* 1984). In the oceans, it has been estimated that a 5 % reduction of primary production would lead to a 6 to 9 % reduction in fisheries (NIXON 1988). The northern end could however show an increased primary productivity because of the proximity of the nutrient-rich layers from the surface when tilting of the epilimnion is less marked and nutrients closer from the euphotic zone (fig. 4B). This situation seems not favourable for the pelagic fishes (decrease of clupeids and *Lates stappersii* in the north). A possible explanation is the simultaneous anoxic depth change beside the effect of fishing : the decreased thickness of the oxygenated layer in the north might be responsible for a poor recruitment of pelagic fishes since sinking eggs would reach faster the close anoxic layers, particularly when turbulence is low. In the oceans, it has been suggested that the degree of mixing in the upper layers influences the contact rate between fish larvae and its prey (MACKENZIE & LEGGET 1991). Such decrease in calm years would negatively influence some pelagic fishes in Lake Tanganyika.

The extreme situations suggested above and corresponding to "windy" and "little windy" years need to be investigated in more detail once sufficient limnological and meteorological observations will be available. Computation of the dynamics of the thermal regime of such a large lake depends on accurate estimations of wind-induced shear stresses over the lake and on correct identification of vertical turbulent diffusion which control the processes of vertical mixing (HUTTULA & PODSETCHINE 1994).

Beside the trend in the climate of the recent decades, oscillations in air temperature (and fisheries catches) have been observed. They can be partially linked to the El Niño phenomenon. These oscillations will certainly continue but their frequency might show a change because of increased El Niño phases compared to La Niña phases. In the mid-1970s, the frequency of El Niño accentuated (BAKUN 1993). Recently, for the first time on record, El Niño has returned for a fourth consecutive year since 1991. It is not known why and these aberrations may signal a worldwide change in climate (WUETHRICH 1995). There could be a link between the higher frequency of El Niño and the global

change in climate in the world but this is still hypothetical. It has been suggested that effects of climate change on fisheries will be region-specific with some regions benefiting and some not (KENNEDY 1994). It is probable that in Lake Tanganyika, this may also affect differently the species and give rise to a new food web equilibrium. In this way, such changes provide interesting fields of research concerning the biodiversity and the adaptation of the species to their environment.

Predator-prey relationships have been often quoted as a possible explanation for opposite fluctuations of catches between clupeids and *L. stappersii*. Doubts about this have been raised because of the highly variable duration of the "cycles" (BAYONA 1985). The catch curves appearing as "predator-prey" relationships may arise from correlation in opposed direction to climatic changes. A predator-prey relationship is probably present but might not be the main cause for the observed fluctuations. In the oceans, fluctuations in catches of sardines and anchovies are seemingly dominated by long-term environmental variations which cause large and prolonged changes in abundance and give rise to "regimes" of sardines or anchovies. These long-term fluctuations seem associated with persistent environmental changes on oceanic to global scale (LLUCH-BELDA *et al.* 1989). Periodicities and abundance of *S. tanganicae* in Lake Tanganyika seem main factors regulating the annual physiological cycles of all their major predators (COULTER 1991). *S. tanganicae* periodicities and abundance appear to be much dependent on climate fluctuations which ultimately seem to be the key factors for the pelagic fishes fluctuations. There is little question today that there are natural fluctuations of great magnitude in fish populations which are attributable to causes other than fishing (LASKER 1985).

Beside a change in abundance of clupeids, there might be another regime of distribution and an increased sedentarity of *S. tanganicae* population. There have been indications that *S. tanganicae* can make extensive movements in the lake, but other evidence suggested that individuals generally do not move far (COULTER 1991). Worldwide distribution patterns of clupeids such as sardines and anchovies (LLUCH-BELDA *et al.* 1989) show that when their abundance is low, sardines contract into a few relatively fixed locations, and migratory behaviour is greatly reduced. A similar geographic strategy might be observed for Lake Tanganyika sardines. This would explain why there are differing observations on *S. tanganicae* migrating behaviour. The survival of these pelagic fishes would be much dependent on their ability

to track the food. Abundant sedentary populations would rapidly deplete their resources. Migratory behaviour is then a major survival adaptation strategy as observed for other animal species in different ecosystems.

As for oceanic fisheries (BEAMISH 1993), it is to be expected that there will be periods when environmental conditions result in poor survival. Managers need to recognize when these conditions are occurring and make timely adjustments to fishing plants that recognize that the main changes in abundance are occurring for natural reasons. The forecast of fisheries of Lake Tanganyika (in quantity and quality) would allow a better exploitation of resources (type of nets, fishing zones, processing equipment, marketing) as well as giving useful signals for management of the resources by the Authorities of the riparian countries (preparation of stock sharing, adjustment of licensing, etc.). Longer-term planning could be useful for donors also in decision-making concerning fisheries development around the lake. It is probable that the productivity of the lake is climate-dependent. Meteorological and limnological monitoring are key points in developing fisheries forecasting models in the Lake Tanganyika area. The links between ENSO and the main pelagic fisheries of Lake Tanganyika could allow forecasting in fisheries yield and quality (type of catches) because of the lag. Indices of El Niño such as the sea-surface temperature of the equatorial Pacific can be predicted by statistical models several months in advance and by physical coupled ocean-atmosphere models at lead times exceeding one year. A recently improved model extended prediction for El Niño up to eighteen to twenty months ahead (CHEN *et al.* 1995).

Conclusions

Long-term changes in temperature and winds have been detected in the Lake Tanganyika area for the last thirty years. This trend seems to be linked to long-term changes in clupeids and *L. stappersii* abundance and catchability. Oscillations in climatic parameters and fisheries statistics are noted on a shorter-time scale (3-7 years). They can be partially linked to the El Niño-southern oscillation (ENSO) that represents one of the major mode of natural variability of the earth's climate system (DIAZ & PULWARTY 1994). It is known that ENSO is linked to precipitation in Africa (IPCC 1990). ENSO variability influences zonal atmospheric circulation and the Indian

Ocean monsoon. Variability in energy inputs by the winds and air temperature influences hydrodynamics of the lake and trophic conditions in surface waters.

A highly dynamic environment would favour the clupeids, particularly *S. tanganicae*, while stable conditions seem more favourable to *L. stappersii*. Improved understanding of the links between global and regional climate, the lake hydrodynamics and limnology and their influence on fish biology, give much hope for the establishment of reliable forecasting models in fisheries with predictions up to one or two years' time ahead and longer estimations concerning the trend. Sea surface temperature of the oceans could be useful in fisheries forecast as it is for Zimbabwean maize (CANE *et al.* 1994). To reach this objective, the fisheries and limnological regional monitoring along with the strengthening of national meteorological stations along the lake should be considered one of the priorities.

Lake Tanganyika is not oligotrophic as deep waters contain extremely large quantities of nutrients. However, it may not be called eutrophic either as surface water is often poor in nutrients. The uneven distribution of nutrients is largely the consequence of the existence of thermal stratification in the lake (PLISNIER *et al.* 1996). This stratification depends upon a small gradient of temperature. Fluctuations in the extent of stratification determine the degree of nutrient influx into the euphotic zone. The expression of the trophic character of the lake is probably highly dependent on the extent of hydrodynamic phenomena and climatic conditions. These influences seem sufficiently considerable as to be linked to pelagic fish fluctuations.

ACKNOWLEDGEMENTS

The Department of Meteorology in Burundi (I.G.E.B.U.) and Zambia (Z.M.D.) provided meteorological records. Data from the Pacific Ocean were provided by the Climate Prediction Centre in Washington. Limnological sampling was realized in 1993-1995 during the FAO/FINNIDA project "Research for the Management of the Fisheries on Lake Tanganyika" (L.T.R.-project). I thank all my colleagues of the LTR-project in the field as well as at FAO (Rome) and at the University of Kuopio and other research Institutions in Finland. Their support was much appreciated in this research. I particularly appreciated the help of E. Coenen in exchanging views and editing the manuscript. Part of this work was financed by the Prime Minister's Office - Federal Office for Scientific, Technical and Cultural Affairs, Belgium.

REFERENCES

BAKUN, A. 1993. Global climate variations and potential impacts on the Gulf of Guinea Sardinella fishery. — *In* : Proceedings of the Scientific Meeting on Dynamics and Uses of Sardinella resources from upwelling of Ghana and Côte-d'Ivoire (Accra, Ghana, Oct. 1993), 9 pp.

BAYONA, J. D. R. 1985. A review of the biological productivity and fish predation in Lake Tanganyika. — United Nations Food and Agriculture Organisation, CIFA Symposium SAWG/85/WPI : also in LEWIS, D. (ed.), 1988, CIFA *Occasional Papers,* **15** : 1-17.

BEAMISH, R. J. 1993. Climate and exceptional fish production off the West Coast of North America. — *Canadian Journal of Fisheries and Aquatic Sciences*, **50** (10) : 2270-2291.

BEAUCHAMP, R. S. A. 1939. Hydrology of Lake Tanganyika. — *Intern. Rev. der gesamten Hydr. und Hydrogr.*, **39** (34) : 316-353.

CANE, A. C., ESHEL, G. & BUCKLAND, R. W. 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. — *Nature*, **370** : 204-205.

CHEN, D., ZEBIACK, S. E., BUSALACCHI, S. E. & CANE, M. A. 1995. An improved procedure for El Niño forecasting : implication for predictability. — *Science*, **269** : 1699-1702.

COULTER, G. W. 1991. Lake Tanganyika and its Life. — Oxford University Press, London, 354 pp.

COULTER, G. W. 1994. Lake Tanganyika. — *In* : MARTENS, K, GODDERIS, B. & COULTER, G. (eds.), Speciation in Ancient Lakes. *Arch. Hydrobiol. Beith. Ergebn. Limnol.*, Stuttgart, **44** : 13-18.

DEGENS, E. T., VON HERZEN, R. P. & WONG, H.-K. 1971. Lake Tanganyika : water chemistry, sediments, geological structure. — *Naturwissenschaften*, **58** : 229-241.

DIAZ, H. F. & PULWARTY, R. S. 1994. An analysis of the time scales of variability in centuries-long ENSO-sensitive records in the last 1000 years. — *Climatic Changes*, **26** : 317-342.

DUBOIS, J. T. 1958. Evolution de la température, de l'oxygène dissous et de la transparence dans la baie nord du lac Tanganyika. — *Hydrobiologia*, **10** : 215-240.

FURNES, G. K. 1992. Climatic variations of oceanographic processes in the North European Seas. A Review of the 1970s and 1980s. — *Cont. Shelf Res.*, **12** : 2-3.

HABERYAN, K. & HECKY, R., 1987. The late Pleistocene and Holocene stratigraphy and paleolimnology of Lakes Kivu and Tanganyika. — *Palaeogeogr., Palaeoclim., Palaeoec.*, **61** : 169-197.

HASTENRATH, S. & KRUSS, R. 1992. Greenhouse indicators in Kenya. — *Nature*, **355** : 503-504.

HEALEY, M. C. 1990. Implications of climate change for fisheries management policy. — *Trans. Am. Fish. Soc.*, **119** (2) : 366-373.

HECKY, R. E., BUGENYI, F. W. B., OCHUMBA, P. , TALLING, J. F., MUGIDDE, R., GOPHEN, M. & KAUFMAN, L. 1994. Deoxygenation of the deepwater of Lake Victoria, East Africa. — *Limnol. and Oceanogr.*, **39** (6) : 1476-1481.

HECKY, R. E. & FEE, E. J. 1981. Primary production and rates of algal growth in Lake Tanganyika. — *Limnol. and Oceanogr.*, **26** : 532-547.

HECKY, R. E., FEE, E. J., KLING, H. J. & RUDD, J. W. 1981. Relationship between primary production and fish production in Lake Tanganyika. — *Trans. Am. Fish. Soc.*, **110** : 336-345.

HECKY, R. E. & KLING, H. J. 1981. The phytoplankton and protozooplankton of the euphotic zone of Lake Tanganyika : Species composition biomass chlorophyll content and spatio-temporal distribution. — *Limnol. and Oceanogr.*, **26** (3) : 548-564.

HUTCHINSON, G. E. 1957. A Treatise on Limnology. I. — Wiley, New York, 1015 pp.

HUTTULA, T. & PODSETCHINE, V. 1994. Hydrological modeling of Lake Tanganyika. — FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika, GCP/RAF/271/FIN-TD/20 (En) : 19 pp.

IPCC 1990. Climate Change. — *In* : HOUGHTON, J. T., JENKINS, G. J. & EPHRAUMS, J. J. (eds.), The IPCC Scientific Assessment. Intergovernmental Panel on Climate Change. Cambridge, 364 pp.

KENNEDY, V. S. 1994. Climate warming and estuarine and marine coastal ecosystems. — *In* : MATHAI, C. V. & STENSLAND, G. (eds.), Global Climate Change. Proceedings of the Air and Waste Management Association International Specialty Conf., Phoenix, pp. 538-547.

KUFFERATH, J. 1952. Le milieu biochimique. Résultats scientifiques de l'exploration hydrobiologique du Lac Tanganika (1946-1947). — Inst. R. Sci. Nat. Belg., **1** : 31-47.

LASKER, R. 1985. What Limits Clupeoid Production? — *Can. J. Fish. Aquat. Sci.*, **42** : 31-37.

LEWIS, M. R., HORNE, E. P. W., CULLEN, J. J., OAKEY, N. S. & PLATT, T. 1984. Turbulent motions may control phytoplankton photosynthesis in the upper ocean. — *Nature*, **311** : 49-50.

LLUCH-BELDA, D., CRAWFORD, R. J. M., KAWASAKI, T., MACCALL, A. D., PARRISH, R. H., SCHWARTZLOSE, R. A. & SMITH, P. E. 1989. World-wide fluctuations of Sardine and Anchovy Stocks - The regime problem. — *South Afr. J. of Mar. Sci. - Suid-Afrikaanse Tydskrif vir Seewetenskap*, **8** : 195-205.

MACKENZIE, B. R. & LEGGETT, W. C. 1991. Quantifying the contribution of small-scale turbulence to the encounter rates between larval fish and their zooplankton prey. Effects of wind and tide. — *Mar. Ecol. Progr. Ser.*, **73** : 2-3.

MANNINI, P., ARO, E., KATONDA, B., MANBONA, C., MILINDI, G., PAFFEN, P. & VERBURG, P. 1996. Pelagic Fish Stocks of Lake Tanganyika : Biology and Exploitation. — FAO/FINNIDA Research for the man-

agement of the fisheries of Lake Tanganyika. GCP/RAF/271/FIN/53 (En) : 85 pp.

MORTIMER, C. H. 1952. Water movements in lakes during summer stratification. Evidence from the distribution of temperature in Windermere. — Proc. Roy. Soc. London (ser.B), **236** : 355-404.

NIXON, S. W. 1988. Physical energy inputs and the comparative ecology of lakes and marine ecosystems. — *Limnol.Oceangr.*, **33** (4, 2) : 1005-1025.

PEARCE, M. J. 1985. A description and stock assessment of the pelagic fishery in the south-east arm of the Zambian waters of Lake Tanganyika. — Report of the Department of Fisheries, Zambia, 74 pp.

PEARCE, M. J. 1992. The development of the pelagic fisheries since 1980 and its effect on the pelagic fish stocks in the South of Lake Tanganyika. — Final Report, Department of Fisheries, Zambia, 129 pp.

PHILANDER, S. G. H. 1990. El Niño, La Niña, and the Southern Oscillation. — Academic Press, San Diego, 281 pp.

PLISNIER, P.-D. 1995. Catch assessment survey in Zambian waters of Lake Tanganyika in 1994. — FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika GCP/RAF/271/FIN-TD/41 (En) : 26 pp.

PLISNIER, P.-D. 1997. Climate, limnology and fisheries changes of Lake Tanganyika. — FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika GCP/RAF/271/FIN/72 (En) : 39 pp.

PLISNIER, P.-D., LANGENBERG, V., MWAPE, L., CHITAMWEMBWA, D., TSHIBANGU, K. & COENEN, E. 1996. Limnological sampling during an annual cycle at three stations of Lake Tanganyika (1993-94). — FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika GCP/RAF/271/FIN-TD/46 (En) : 136 pp.

PLISNIER, P.-D. & COENEN, E. J. Pulsed and dampened annual limnological fluctuations in Lake Tanganyika. — *In* : MUNAWAR, M. & HECKY, R. (eds.), "The Great Lakes of the World", Aquatic Ecosystem Health and Management Society, Burlington, Canada. In print.

SYMOENS, J. J. 1955a. Observation d'une fleur d'eau à cyanophycées au lac Tanganyika. — *Folia scientifica Africae centralis*, **1** (3) : 17.

SYMOENS, J. J. 1955b. Sur le maximum planctonique observé en fin de saison sèche dans le bassin nord du lac Tanganyika. — *Folia scientifica Africae centralis*, **1** (4) : 12.

TOURRE, Y. M. & WHITE, W. B. 1994. Indian Ocean may have El Niño of its own. — EOS (Dec. 13) : 3.

VAN MEEL, L. 1954. Le phytoplancton. Résultats scientifiques. — *In* : Exploration hydrobiologique du lac Tanganyika (1946-47), Inst. R. Sci. Nat. Belg., **4** : 681 pp.

WUETHRICH, B. 1995. El Niño goes Critical. — *New Scientist*, **4** (Feb. 1995) : 32-35.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 251-262 (1998)

Etude du lien relief-convection dans l'Ouest-Cameroun, analyse d'images Météosat

par

Armelle SANTIAGO-JEGADEN * & J. SUCHEL **

MOTS-CLES. — Altitude ; Convection ; Météosat ; Ouest-Cameroun ; Pluviométrie.

RESUME. — Une analyse des images d'occurrences de nuages à sommet froid (synthèses thermiques Météosat) en relation avec une image digitalisée du relief du Cameroun a été réalisée. Dans la région ouest, la présence de la dorsale camerounaise influence fortement la répartition géographique des phénomènes convectifs. L'altitude, les orientations des pentes et l'éloignement de l'océan sont autant de facteurs dont l'impact apparaît nettement sur les images Météosat. Une analyse statistique multivariée nous a permis de valider notre méthode de travail et les résultats obtenus.

TREFWOORDEN. — Hoogte ; Convectie ; Meteosat ; West-Kameroen ; Pluviometrie.

SAMENVATTING. — *Studie van de connectie reliëf-convectie in West-Kameroen, analyse van METEOSAT-beelden.* — Een analyse van beelden van het voorkomen van wolken met koude top (Meteosat thermische synthese) in relatie met een digitaal beeld van het reliëf van Kameroen werd uitgevoerd. In het westelijk gebied beïnvloedt het Kameroenese gebergte sterk de geografische verspreiding van convectiefenomenen. De hoogte, de oriëntaties van de hellingen en de afstand tot de oceaan zijn sommige van de factoren waarvan de impact op Meteosatbeelden duidelijk waarneembaar zijn. Een multivariabele statistische analyse heeft ons toegelaten onze werkmethode en de bekomen resultaten te valideren.

KEYWORDS. — Altitude ; Convection ; Meteosat ; West Cameroon ; Pluviometry.

ABSTRACT. — *Study of the Relief-convection Connection in West Cameroon, Meteosat Images Analysis.* — An analysis of cold cloud occurrence images

* Centre de Recherche en Climatologie, Univ. Bourgogne, F-21000 Dijon (France).
** Univ. Jean Monnet, F-42000 Saint-Etienne (France).

(Meteosat thermic synthesis) with a digital image of the relief of Cameroon was realized. In the west region, the presence of the Cameroonian ridge influences strongly the geographical distribution of convection phenomena. Altitude, orientations of the slopes and distance from the ocean are some of the factors of which the impact appears clearly on the Meteosat images. A multivariate statistical analysis has allowed us to validate our work method and the results obtained.

1. Introduction

Ouverte sur l'océan au sud-ouest, la région ouest du Cameroun se caractérise par une topographie très contrastée (fig. 1). Les plaines entourent la dorsale camerounaise qui relie les massifs les plus élevés du pays, dont le Mont Cameroun, isolé au sud (4 095 m). Les fichiers d'occurrences de nuages à sommet froid, réalisés et archivés au Centre de Météorologie Spatiale de Lannion, donnent de bonnes informations sur la répartition des nuages convectifs, supposés pluviogènes, à la surface terrestre.

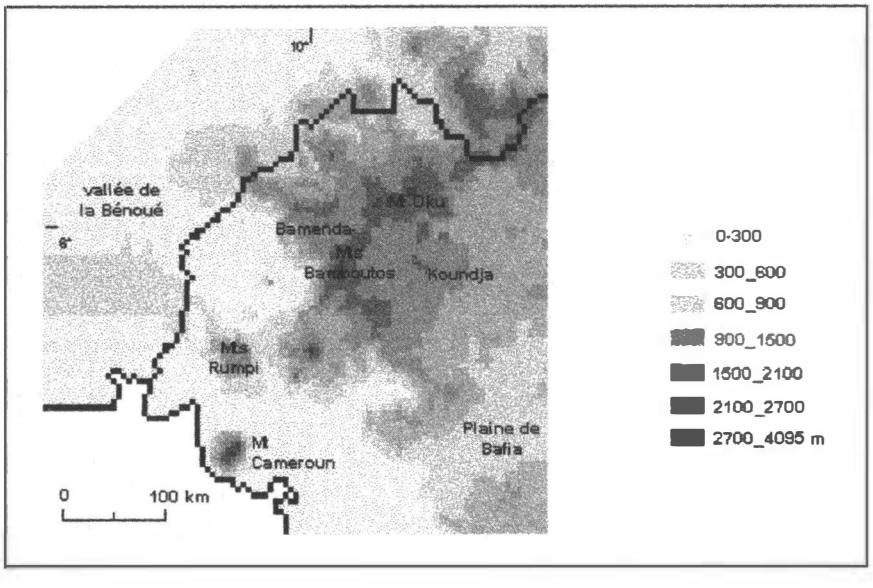


Fig. 1. — Topographie de l'Ouest-Cameroun. Image digitalisée du relief. L'altitude dominante a été retenue pour chaque pixel.

Nous avons testé une nouvelle méthode d'analyse sur la période 1990-93, dont les années sont assez spécifiques sur le plan pluviométrique. Les résultats ont été obtenus à l'aide du logiciel «Xvision», permettant une confrontation de données de natures différentes à l'échelle du pixel (SANTIAGO-JEGADEN *et al.* 1995).

2. L'opposition des versants nord-ouest et sud-est de la dorsale

Nous nous intéressons ici à la partie des fichiers d'occurrences de nuages à sommet froid qui concernent le Cameroun (222 lignes × 314 colonnes) et plus précisément la région ouest. Rappelons que pour chaque pixel (25 km^2), le nombre de fois où une température inférieure à moins quarante degrés celcius a été enregistrée est comptabilisée par décades et/ou pentades. Cette valeur est ensuite rapportée au nombre d'images utilisées dans la période et on obtient des données en pourcentages, comparables d'une période à une autre (GUILLOT 1988).

Nous avons, d'autre part, digitalisé une carte topographique du Cameroun, pour obtenir un fichier «relief» où les pixels ont la même échelle, la même situation géographique et la même déformation que ceux des fichiers Météosat. Ces deux bases de données sont alors comparables entre elles, pixel par pixel. Les images du relief et l'image d'occurrences de la deuxième décade d'avril 1991 dans l'ouest du pays sont présentées ici.

La concentration de noyaux de convection au niveau de la dorsale camerounaise attire l'attention, et on rencontre cette situation très fréquemment de mars à octobre. Lorsqu'on suit l'orientation SO-NE de la dorsale et sa situation dans l'Ouest-Cameroun, il semble que les amas convectifs ne se développent pas uniformément sur ce secteur, mais de préférence à l'ouest.

A l'aide du logiciel Xvision, nous avons superposé l'image des altitudes comprises entre 900 et 1 500 m, entourant les sommets de la dorsale, et l'image d'occurrence en ne conservant que les pixels communs aux deux, et la légende de la seconde (fig. 2). On observe très bien le contraste entre les versants NO et SE. Cette opération a été répétée pour tous les fichiers de notre échantillon de données et les classes d'altitude plus basses. Nous avons fait le même constat dans la majorité des cas. Les écarts de pourcentages d'un versant à l'autre sont élevés et dépassent parfois les 20 % comme en avril 1992 et en octobre 1993 (fig. 3).

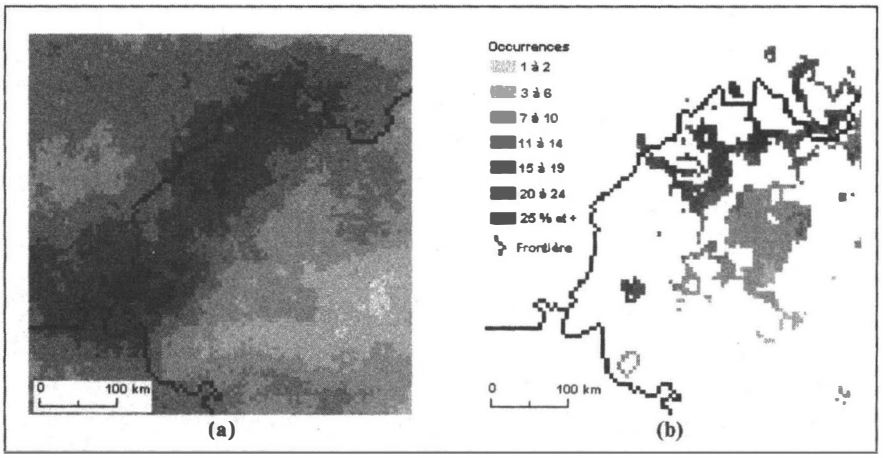


Fig. 2. — (a) Occurrences de nuages à sommet froid en deuxième décade d'avril ; (b) Même image pour les pixels ayant une altitude comprise entre 900 et 1 500 m.

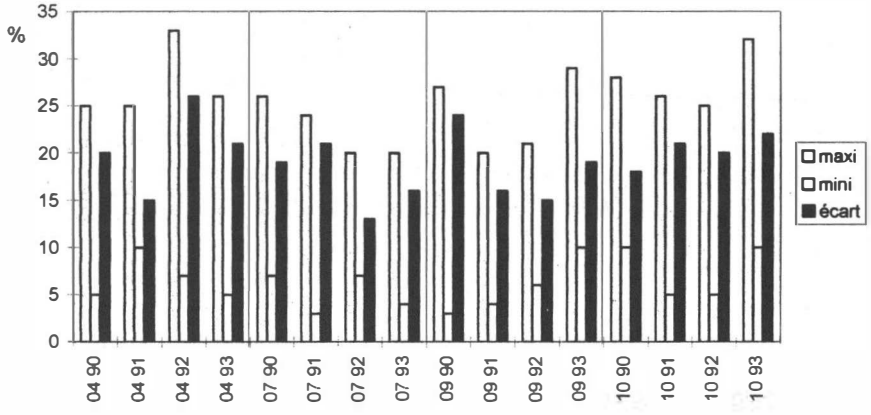


Fig. 3. — Maxima, minima et écarts d'occurrences (%) relevés sur les versants NO et SE de la dorsale camerounaise au pas de temps mensuel.

L'orientation des pentes est donc visiblement un facteur déterminant dans la répartition géographique de ces nuages d'origine convective. SUCHEL (1988) souligne l'importance climatique de l'exposition des stations météorologiques de cette région. Il présente notamment Bamenda-Météo comme représentative du climat régional du versant occidental de la dorsale, et la compare à plusieurs reprises à Koundja, située sur le versant oriental. Les données pluviométriques de ces deux stations pour 1990-93 nous permettent de préciser le lien pluie-convection. Au pas de temps mensuel (fig. 4), quinze mois sur quarante-huit sont favorables à Koundja, mais, à part en août et novembre 1992, l'écart avec la hauteur des précipitations tombées à Bamenda n'excède pas 60 mm. Les pluies sont donc plus abondantes sur le versant ouest au cours des trente-trois mois suivants, et de façon très marquée en septembre et octobre. Au pas de temps décadaire, 66 % des cas favorisent Bamenda.

Si on effectue les mêmes calculs pour les occurrences, la domination du versant occidental est écrasante mais les écarts atteignent au plus 14 %, qui plus est un mois où il n'y a pas eu de phénomènes convectifs à Koundja (occurrences à 0 %).

Dès le mois d'avril, et jusqu'en octobre, l'Ouest-Cameroun est sous l'influence permanente de la masse d'air équatoriale caractérisée par le développement de cumulonimbus (LEROUX 1970), recensés par les données satellitales utilisées ici. Mais, à partir du mois de juin, la masse d'air tropical de mousson recouvre également la région et favorise essentiellement la formation d'altostratus et d'altocumulus. La répartition des pluies dans l'Ouest-Cameroun peut donc être reliée à celle des nuages à sommet froid, mais en partie seulement, car le régime de mousson *stricto sensu* apporte la majorité des pluies sur le versant NO de la dorsale.

3. L'importance des altitudes moyennes

Nous venons de cerner l'importance des orientations des pentes sur la répartition des phénomènes convectifs dans cette région ; il reste à déterminer l'impact de l'altitude elle-même, car la dorsale camerounaise est avant tout un puissant obstacle orographique qui peut «forcer» l'ascendance de l'air humide d'origine océanique.

Sur notre exemple d'avril 1991, les fenêtres d'altitude entourant les sommets correspondent visiblement aux plus fortes occurrences de nuages à sommet froid. La méthode de superposition d'images nous

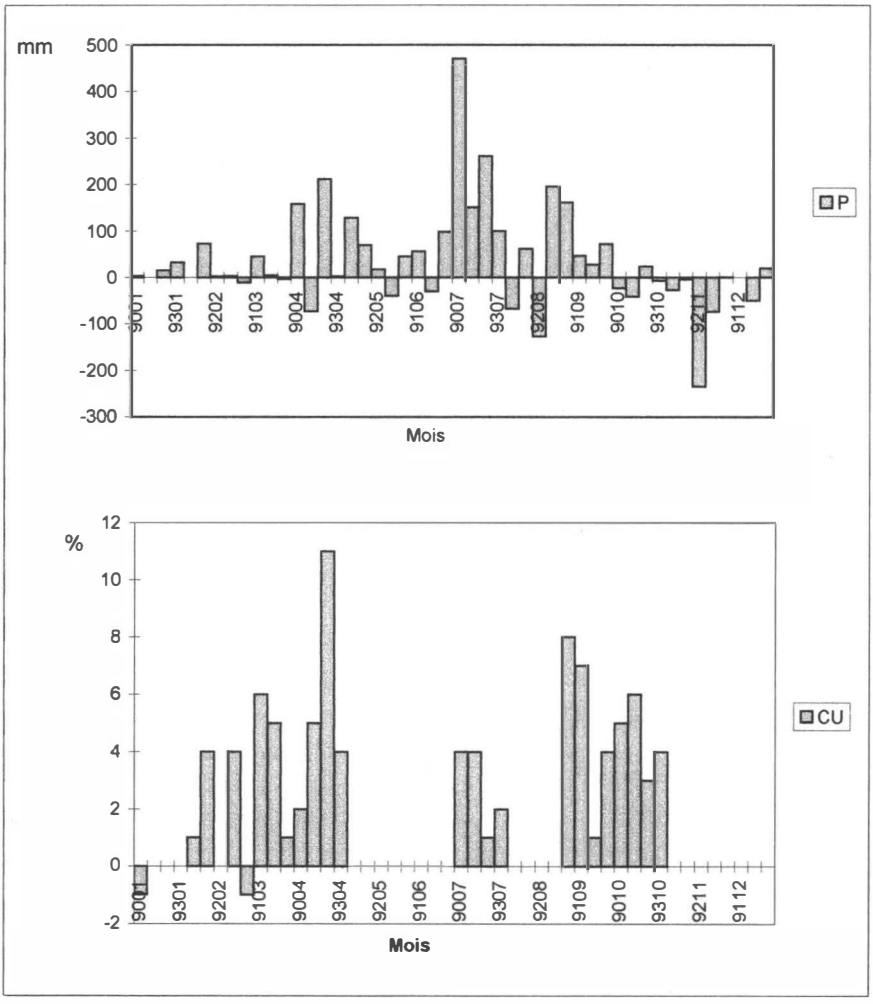


Fig. 4. — Comparaison des stations météorologiques de Bamenda et Koundja : écarts de pluviométrie (mm) et d'occurrences (%) au pas de temps mensuel.

a permis de vérifier cette hypothèse. Mais, comme les altitudes les plus élevées ne concernent que très peu de pixels, nous présentons ici des vues en coupe, plus nettes, réalisées suivant des axes NO-SE, comparant les valeurs d'occurrences aux altitudes.

L'analyse systématique de toutes les décades et pentades montre que les pourcentages les plus élevés se situent le plus souvent au niveau des altitudes moyennes, entre 600 et 2 100 m, suivant les cas (classes 3 à 5 du relief). De plus, la courbe fléchit presque toujours sur le versant NO du massif le plus élevé qu'elle traverse. A la hauteur du Mont Oku, ce phénomène est très fréquent et prend de l'ampleur en septembre et octobre, comme le montre l'exemple des troisièmes décades d'octobre pour les quatre années (fig. 5). En cette saison, le flux de mousson est très dévié et aborde l'Ouest-Cameroun par le NO. Sa température et son humidité lui confèrent une instabilité marquée et les premiers obstacles qu'il rencontre suffisent à déclencher l'ascendance de l'air et la formation de cumulonimbus. Les contrastes avec le versant opposé sont donc beaucoup plus nets.

Cela est par contre très rare en juillet, mois de prédilection du flux de mousson *stricto sensu* et plutôt favorable au versant SE, sous l'influence des ondes d'est. Le lien avec les altitudes moyennes est

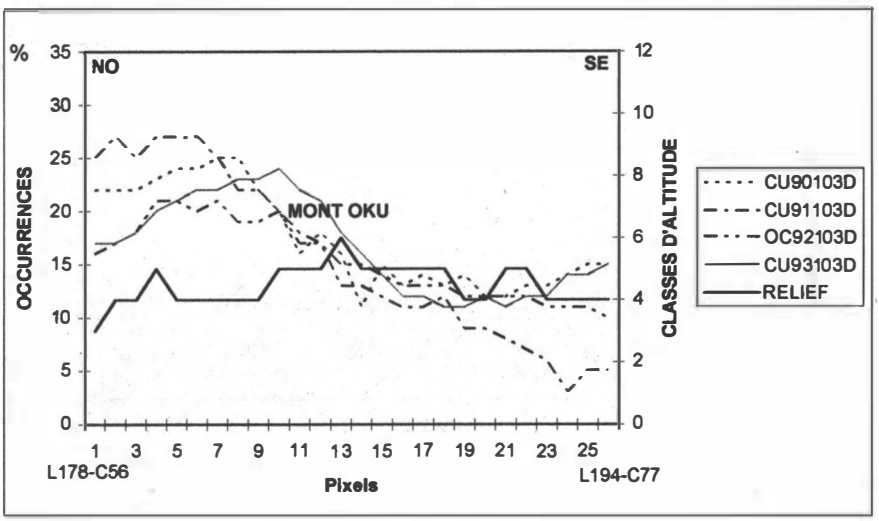


Fig. 5. — L'opposition des versants de la dorsale camerounaise : répartition des occurrences en fonction de l'altitude sur un axe NO-SE à la hauteur du Mont Oku.

également valable ici, de même qu'avec la pluviométrie. Bamenda est en effet située à 1 608 m.

Venant confirmer de façon assez inattendue ces résultats, l'évolution différente des occurrences sur le Mont Cameroun (4 095 m) et les Monts Rumpi (2 460 m) est spectaculaire. Les nuages convectifs se développent beaucoup plus fréquemment sur ces derniers. L'image de la figure 1 qui montre ce contraste n'est pas une exception, loin de là. Cinq décades de notre base de données présentent une situation inverse, mais elles ne sont pas consécutives et ne laissent aucune trace sur les situations mensuelles. Les écarts entre ces deux reliefs n'ont pas tous la même importance, mais la faiblesse des occurrences sur le Mont Cameroun est une réalité, quels que soient l'année, le mois (de février à novembre) et le pas de temps considérés. La même décade de septembre pour les quatre années illustre bien ce propos, et les écarts avec les Monts Rumpi peuvent atteindre 23 % pour les extrêmes (fig. 6).

L'efficacité pluviométrique d'un obstacle tel que le Mont Cameroun, émergeant de la plaine côtière, sur la trajectoire des principaux flux humides est connue. Au pied de ce relief volcanique, on relève en moyenne 10 m de précipitations annuelles à Debunscha, où un record

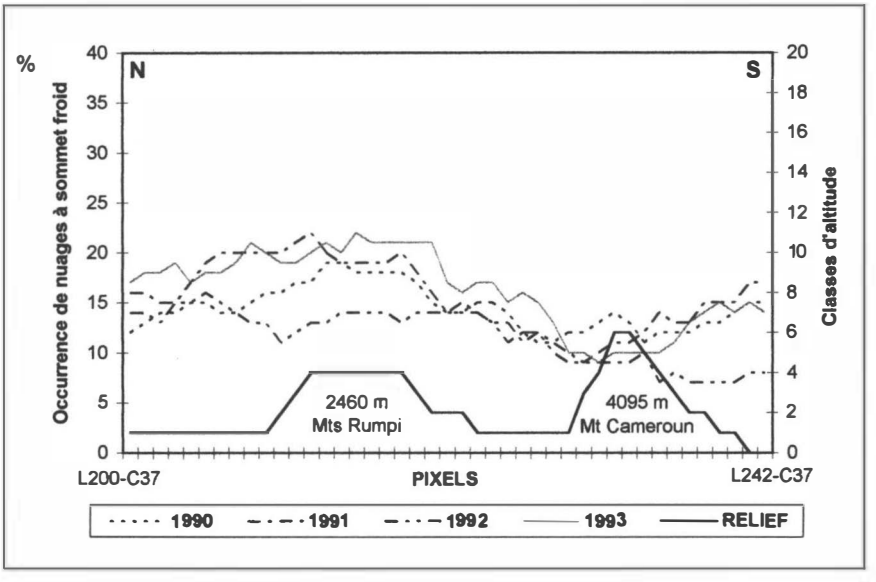


Fig. 6. — Comparaison des occurrences de nuages à sommet froid sur le Mont Cameroun et les Monts Rumpi en avril : coupe le long d'un axe nord-sud traversant ces deux reliefs.

de 14 m a été enregistré en 1919 (OLIVRY 1986). Les occurrences sont rarement nulles sur ses versants tournés vers le sud et le SO. L'ascendance forcée de l'air provoque donc bien la formation de cumulonimbus. Mais visiblement, ce mécanisme n'est pas le plus fréquent et ces nuages se développent beaucoup plus facilement à la hauteur des Monts Rumpi, moins élevés, et en retrait de la côte. L'action stabilisatrice océanique est donc prépondérante, même en présence d'un obstacle orographique aussi puissant, et la majeure partie des précipitations est issue de nuages stratiformes. Les travaux de SIGHOMNOU *et al.* (1993) vont d'ailleurs dans ce sens.

4. Vérification statistique des résultats

N'ayant que peu de données pluviométriques à notre disposition, nous avons effectué une analyse statistique multivariée des données pour valider notre méthodologie. Une Analyse Fréquentielle de Correspondance croise les données satellitales avec les bases de données digitalisées. Cette étude de l'impact du relief sur la convection s'intègre en effet dans un travail plus vaste, intégrant d'autres états de surface continentaux comme la végétation, l'hydrologie, les orientations des pentes, les intensités des commandements et l'implantation humaine. Cette démarche statistique vise à déterminer la part d'influence de chacun de ces caractères qualitatifs par rapport aux autres (LEBART 1982) sur la convection.

La préparation des données consiste à comptabiliser pour chaque fichier Météosat, et chaque classe d'occurrence, le nombre de pixels de l'ensemble du fichier communs avec la première classe d'altitude A du relief, puis la seconde, etc., puis de même avec les cinq autres bases cartographiques. Nous avons ensuite réduit cette matrice en regroupant les «comptages» par saison : S1 : janvier-février, S2 : mars-avril, S3 : juillet-septembre, S4 : octobre.

Un traitement préalable des valeurs obtenues nous a permis d'évaluer des seuils saisonniers significatifs dans la répartition des occurrences sur l'ensemble du Cameroun. Ce deuxième calcul porte sur un fichier relatif aux occurrences dépassant ce seuil (fig. 7). Nous voyons que la saison 1 est une information dominante sur le premier axe qui explique 93 % des variations. Les caractères A, B, C, F et G ont des indices assez importants sur ce même axe. Ces deux informations sont complémentaires et signifient que, sur ce premier axe, le caractère G (altitude comprise entre 2 700 et 4 095 m) est associé à la saison 1.

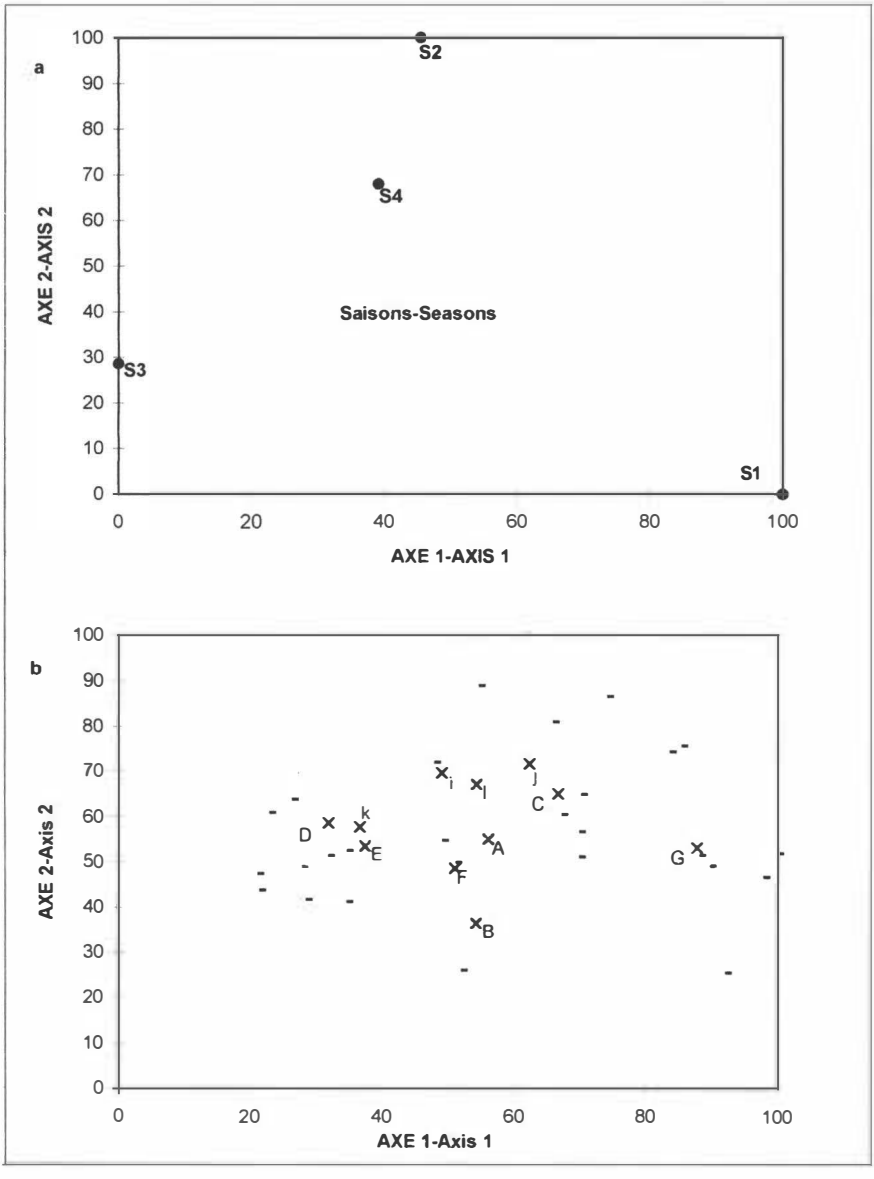


Fig. 7. — Représentation graphique des résultats d'une Analyse Fréquentielle de Correspondance des données (indices). Cette analyse porte sur les valeurs d'occurrences supérieures à un seuil déterminé par une analyse préliminaire. La disposition des caractères sur l'axe 1 et l'axe 2 (b) correspond au lien qu'ils ont avec l'existence d'occurrences de nuages à sommet froid supérieures au seuil, pour la saison qui a une position proche de la leur sur le graphique (a). — S1 : janvier-février, S2 : mars-avril, S3 : juillet-septembre, S4 : octobre.

Les caractères E (1 500-2 100 m) et F (2 100-2 700 m) sont associés à la saison 2 et dans une moindre mesure à la saison 4. On notera la situation des caractères i (orientation sud-ouest), j (ouest), k (nord-ouest), l (nord), centrée sur le graphique en lien avec mars-avril et septembre-octobre.

A première vue, ces résultats ne confirment que très peu les observations faites précédemment : les plus fortes altitudes sont liées aux mois de janvier et février et seule une partie des altitudes moyennes à mars-avril et octobre. Toutefois, il faut bien considérer que cette analyse statistique est faite sur l'ensemble du Cameroun alors que nos observations concernent uniquement l'ouest du pays. La topographie des autres régions n'a pas la même influence sur la convection. Ainsi, les orientations de secteur ouest et les altitudes moyennes ne favorisent pas partout la formation de nuages convectifs avec la même intensité, voire pas du tout. On peut évoquer les phénomènes de blocage du FIT sur le versant sud de l'Adamaoua de février à avril, l'importance des ondes d'est en juillet et la prépondérance des occurrences sur les reliefs les plus élevés à l'ouest de ce plateau, ...

Ce sont autant de facteurs climatiques qui viennent perturber les résultats statistiques. Mais pour certains états de surface, comme la végétation, nous avons pu valider totalement l'aboutissement de notre travail. Ainsi, les points entourant la classe G du relief sur le graphique de la figure 7 sont tous relatifs à des faciès forestiers. On voit très bien qu'ils sont tous associés à la saison 1 et dans une moindre mesure à la saison 2. Ceci va dans le sens de nos recherches qui montrent que le sud-forestier camerounais favorise la formation et le maintien de la convection par rapport aux secteurs de savanes en janvier-février et en mars. Dans ce cas précis, la présence d'avril vient en partie masquer l'influence du mois de mars.

5. Conclusion

L'influence de la topographie sur la convection et la pluviométrie dans l'Ouest-Cameroun est importante. Les orientations des pentes, l'altitude et la disposition générale du relief sont liées à la répartition saisonnière des nuages pluviogènes dans cette région.

Nous avons pu montrer que les pixels situés sur le versant NO de la dorsale camerounaise sont plus fréquemment traversés par des nuages convectifs que ceux orientés au SE. De même, les altitudes moyennes

et l'éloignement du bord de côte jouent visiblement un rôle prépondérant sur la dynamique convective.

Notre vérification statistique apporte des résultats moins nets que notre méthodologie, mais va sensiblement dans le même sens. La réaction des synthèses thermiques aux états de surface est très nette dans l'ouest du Cameroun mais existe également dans les autres régions et de façon différente.

Il est désormais envisageable d'étendre ce type d'étude à d'autres pays africains, pour répondre aux objectifs de l'Atlas de veille climatique (LAHUEC 1994) et du programme EPSAT (Estimation des Pluies par SATellites) d'une part, et pour tester notre méthode de travail sur d'autres milieux naturels, d'autre part.

BIBLIOGRAPHIE

GUILLOT, B. 1988. Description des synthèses thermiques effectuées au Centre de Météorologie Spatiale de Lannion. — Veille Climatique Satellitaire, Orstom-Météofrance, **25** : 48 pp.

LAHUEC, J. P. 1994. Satellite et surveillance du climat, atlas de veille climatique : 1986-94. — Ministère de la coopération, Orstom-Météo-france, 91 pp.

LEBART, L., MORINEAU, A. & FENELON, J. P. 1982. Traitement des données statistiques. Méthodes et programmes. — Dunod.

LEROUX, M. 1970. La dynamique des précipitations en Afrique occidentale. — ASECNA, Publ. D.E.M., Dakar, **23** : 281 pp.

OLIVRY, J. C. 1986. Fleuves et rivières du Cameroun. — Monog. Hydrol. Orstom, Mesres-Orstom, Paris, **9** : 733 pp.

SANTIAGO-JEGADEN, A., SANTIAGO, L. & SUCHEL, J. B. 1995. Exemple de l'impact du relief sur la dynamique pluvieuse au Cameroun. — *Publ. de l'Association Internationale de Climatologie*, **8** : 180-186.

SIGHOMNOU, D., NKANDJOU, S. & TANYILEKE, G. 1993. Les fortes pluies dans la région du Mont Cameroun. Le cas d'Idenau. — *La Météorologie*, 8e série, **2** : 41-47.

SUCHEL, J. B. 1988. Les climats du Cameroun. — Thèse de doctorat d'Etat (4 tomes), Bordeaux, pp. 955-1095.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 263-278 (1998)

Further Characteristics of Climate Change in the Sahel Region and West Africa

by

Bruno Van Gompel * & Hugo Decleir *

Keywords. — Climate Change ; Rainfall ; Sahel ; West Africa

Abstract. — The recent sub-Saharan drought in the Sahel has been clearly defined, both in time and geographically, on the basis of the study of rainfall totals. In this paper it is shown how this drought can further be characterized by the study of the change in the frequency distribution of the rainfall amounts and the number of rainy days. This approach also leads to the identification of the Soudano-Sahel zone as a homogeneously responding climatic entity reacting differently from the surrounding areas such as the Guinean zone to the south.

Mots-cles. — Changement climatique ; Précipitations ; Sahel ; Afrique de l'Ouest.

Resume. — *Autres caractéristiques d'un changement climatique dans la région sahélienne et en Afrique de l'Ouest.* — La sécheresse sub-saharienne dans le Sahel a été définie clairement, tant dans le temps que dans l'espace, sur base de l'étude des quantités précipitées. Dans cet article, il est démontré comment cette sécheresse peut être caractérisée par l'étude du changement dans la distribution fréquentielle des quantités précipitées et le nombre de jours de pluie. Cette approche mène aussi à l'identification de la région soudano-sahélienne comme une entité climatique réagissant d'une façon homogène qui se différencie des régions limitrophes comme la région guinéenne au sud.

Trefwoorden. — Klimaatverandering ; Neerslag ; Sahel ; West-Africa.

Samenvatting. — *Verdere karakteristieken van klimaatverandering in de Sahelzone en West-Afrika.* — De recente sub-Sahara droogte in de Sahel is duidelijk gedefinieerd, zowel in tijd als ruimte, en dit op basis van de studie van neerslagtotalen. In deze studie wordt aangetoond hoe deze droogte verder

* Geografisch Instituut, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

kan gekarakteriseerd worden door de studie van de verandering in de frequentieverdeling van de neerslaghoeveelheden en van het aantal regendagen. Deze benadering leidt ook tot de identificatie van de Soedano-Sahel zone als een homogeen beantwoordend klimatische entiteit die verschillend reageert ten opzichte van de omliggende gebieden zoals de Guineese zone in het zuiden.

1. Introduction

In contrast to the early dry periods (1913s and 1940s) of this century, the recent sub-Saharan drought (1960s) was clearly identified by a large number of papers during the last 10 to 15 years (DRUYAN 1989, JANICOT & FONTAINE 1993, NICHOLSON & PALAO 1993, LEROUX 1995, ROWELL *et al.* 1995). These authors were able — among other things — to differentiate the rainfall anomalies geographically and to document on the significant downward trend in the rainfall amount.

The latter was basically demonstrated by a time series analysis of the yearly or monthly rainfall totals. The present analysis goes a little further in stressing the importance of the change in the statistical rainfall distribution during the last 70 years of West African climatology.

The starting-point of our research is the recognition by a number of authors (DEMAREE & CHADILLY 1988, DEMAREE & NICOLIS 1990, MOREL 1995) of the existence of two statistically significant different and stable stationary rainfall regimes — a "wet" and a "dry" regime —, separated by a well-defined downward jump in the long-term mean in the second part of the 1960s. The identification of this downward jump was carried out in the present paper by the successive application of three non-parametric statistical tests on the historical series of the yearly rainfall data of a dozen stations in West Africa, located in an east-west band along 14 N and in a north-south band along 1 E (see fig. 1).

2. The Non-Parametric Analysis

Three non-parametric tests were applied to the historical series of the yearly rainfall totals and yearly number of rainy days for the twelve stations, as shown on figure 1.

The first test is that of Mann-Kendall-Sneyers (M.K.S.-test) to detect the significant overall trend inside the series. The second one is the Lombard test enabling to evaluate the number of changes of the mean

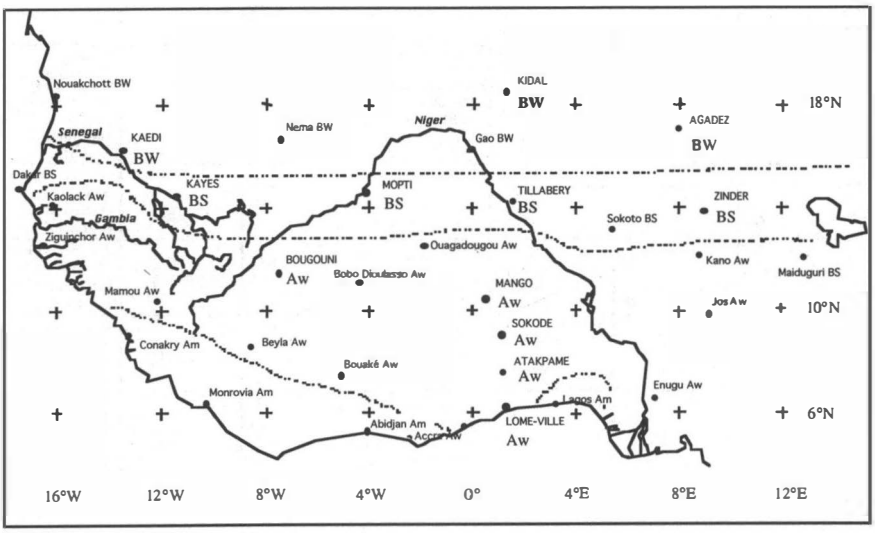


Fig. 1. — Map of West Africa, indicating the climatic types according to Köppen (—··—··—) : climatic boundaries ; Aw : tropical savanna ; Am : tropical monsoon ; BS : semi-arid ; BW : desert). The twelve stations used for the analysis are shown in capitals.

value within a given time series. Finally, with respect to the significant number of possible changes found by the previous analysis, the series was submitted to the Pettitt change-point test in order to locate the most significant abrupt change in time (VANNITSEM & DEMAREE 1991). If Lombard's test revealed more than one significant change, the original series was divided on the basis of the already found transition in two subseries and again submitted to the Pettitt change-point test.

For the description of the three tests, see for example PETTITT (1979), VANNITSEM & DEMAREE (1991), MORON (1992) and VANDIEPENBEECK (1995).

3. The Results for the Yearly Rainfall Totals

The results of the three tests applied to the twelve time series for the rainfall totals (table 1) clearly indicate the existence of two contrasting homogeneous groups :

1. Lomé-Ville, Atakpame, Sokode, Mango and Kidal show a stationary regime over the whole period with no significant downward or upward trend nor abrupt changes. Atakpame can be taken as a

Table 1

Results of the non-parametric analysis on the yearly rainfall totals

YearlyRain Totals	1921-92					
N° station	MKS (a=5%)	Lombard (a=5%)	Pettitt (a=5%)	Conclusion n° 1	Results n° 2	Final: Conclusion
1 Lomé-Ville	NoTrend	NoChanges	NoJump			No particular evolution-stationairy regime
2 Atakpamé	NoTrend	NoChanges	NoJump			No particular evolution-stationairy regime
3 Sokode	NoTrend	2Changes	NoJump			No particular evolution-stationairy regime
4 Mango	NoTrend	8Changes	NoJump			No particular evolution-stationairy regime
5 Bougouni	Trend : Down	1Change	64-65(1%) down			Downward Trend char.by 1 change-point: : 1964-65
6 Zinder	Trend(1%) : Down	1Change(1%)	64-65(1%) down			Downward Trend char.by 1 change-point: : 1964-65
7 Tillabery	Trend(1%) : Down	1Change(1%) 2Changes	67-68(1%) down	Splitting up into 2 subseries required :1921-67 and 1968-92	MKS (a=5%) : NoTrend Lombard (a=5%) : NoChanges Pettitt (a=5%): NoJump	Downward Trend char.by 1 change-point: : 1967-68
8 Agadez	Trend(1%) : Down	2Changes(1%) 1Change(1%)	68-69(1%) down 28-29(?%)up	Splitting up into 2 subseries required: 1921-68 and 1969-92	MKS (a=5%) : NoTrend Lombard (a=5%) : NoChanges Pettitt (a=5%): NoJump	Downward Trend char.by 1 change-point: : 1968-69
9 Kidal	NoTrend	NoChanges	NoJump			No particular evolution - stationairy regime
10 Mopti	Trend(1%) : Down	2Changes	71-72(1%) down 27-28(?%)up	Splitting up into 2 subseries required: 1921-71 and 1972-92	MKS (a=5%) : NoTrend Lombard (a=5%) : NoChanges Pettitt (a=5%): NoJump	Downward Trend char.by 1 change-point: : 1971-72
11 Kayes	Trend(5%) : Down	2Changes	66-67(1%) down 31-32(?%)up	Splitting up into 2 subseries required: 1921-66 and 1967-92	MKS (a=5%) : NoTrend Lombard (a=5%) : NoChanges Pettitt (a=5%):42-43(1%)up(*)	Downward Trend char.by 1 change-point: : 1966-67
12 Kaedi	Trend(1%) : Down	1Change(1%)	67-68(1%) down			Downward Trend char.by 1 change-point: : 1967-68

(*) : we do not accept the change-point on the base of significant results of the Pettitt's Change-point test only.

typical example for this group (fig. 2). It comprises stations lying both towards the south (more humid) and more to the north (more arid) of the Sahel area.

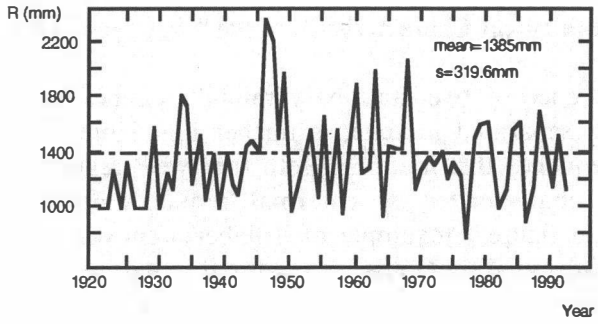


Fig. 2. — Time series (1921-92) of the yearly rainfall totals for Atakpame (s = standard deviation).

2. Bougouni, Zinder, Tillabery, Agadez, Mopti, Kayes and Kaedi (the Soudano-Sahel group), on the other hand, show a marked downward trend characterized by a very significant (1 % level) change-point situated in the time period from 1965 to 1971. Bougouni is shown here as an example for this group, with a jump in 1964-65 (fig. 3).

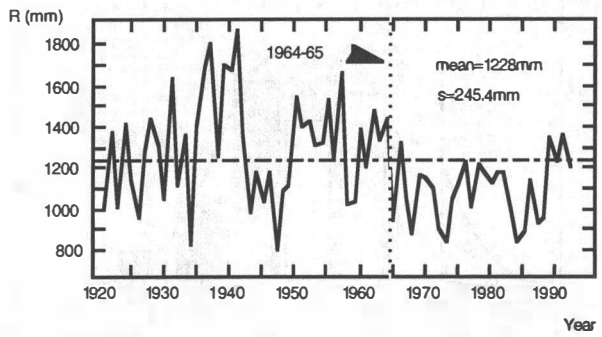


Fig. 3. — Time series (1921-92) of the yearly rainfall totals for Bougouni (s = standard deviation).

The spatial distribution of these two groups is shown in fig. 11, on which the time series characterization is symbolized by ▬ (stationary), and by ▬ (significant downward jump in the late sixties). It reveals that the occurrence of a former "wet" period and a more recent "dry"

period is typical of and restricted to the Soudano-Sahel area. Towards the north (the desert climate zone) and to the south (Guinean zone with a more humid climate), the time series are stationary.

4. The Statistical Characteristics of the "Wet" and "Dry" Periods

The existence of two stationary rainfall regimes in the Soudano-Sahel area, separated in time, is further highlighted by the analysis of their frequency distributions. Both the "wet" regime and the "dry" regime are characterized by a normal frequency distribution. This is visualized in figure 4 (example of Tillabery) showing the histograms and the corresponding Gauss curves for the two rainfall regimes. The change in rainfall regime is most significant for the drop in the mean value, as shown by the t-test in table 2. As can be seen from this table, the change in the yearly rainfall totals is spectacular and ranges from 16 % (Bougouni) to 44 % (Kaedi). This reduction in the rainfall amount is associated with a substantial decrease in the standard deviation, ranging from 10 % (Tillabery) to 42 % (Kaedi). The F-test, testing the homogeneity of the variances, shows however a significant difference only in 3 cases out of 7 (table 2). These conclusions are comparable to those found by HULME (1992).

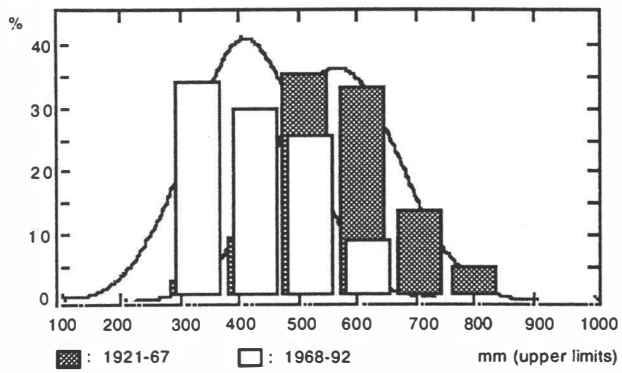


Fig. 4. — Histograms and associated Gauss curves for the "wet" (1921-67) and "dry" (1968-92) regimes (Tillabery).

Analysing this climatic change on a monthly scale, it is clear that the rainfall reduction in the Soudano-Sahel region is restricted to the summer season. Figure 5 shows the example of Tillabery.

Table 2

Descriptive statistics of the yearly rainfall totals for the "wet" and "dry" subperiods of the Soudano-Sahelian stations

	change-point	'wet'		'dry'		F-test	t-test
		mean	st.dev	mean	st.dev	(α=5%)	(α=5%)
Kayes	66-67	753.6	156.5	607.5	112.2	$s_1=s_2$	$x_1 \neq x_2$
Kaedi	67-68	415.1	127.2	234.3	74.3	$s_1 \neq s_2$	$x_1 \neq x_2$
Mopti	71-72	548.2	123.4	421.0	76.1	$s_1 \neq s_2$	$x_1 \neq x_2$
Agadez	68-69	167.4	54.3	95.7	37.1	$s_1=s_2$	$x_1 \neq x_2$
Tillabery	67-68	506.2	102.1	361.1	91.9	$s_1=s_2$	$x_1 \neq x_2$
Zinder	64-65	534.1	112.1	393.5	98.4	$s_1=s_2$	$x_1 \neq x_2$
Bougouni	64-65	1307.2	258.0	1094.8	153.1	$s_1 \neq s_2$	$x_1 \neq x_2$

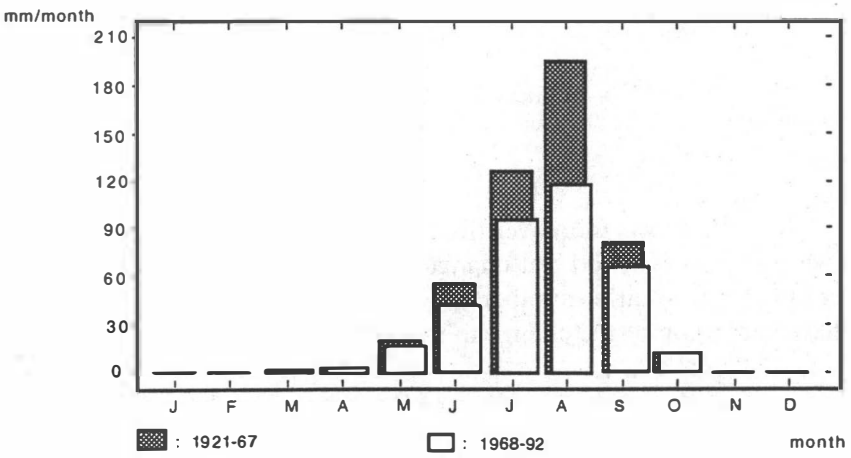


Fig. 5. — Comparison of the monthly rainfall distribution between the "wet" (1921-67) and the "dry" (1968-92) period for Tillabery.

During this season, the Soudano-Sahel zone experiences a northward advance of the West African summer monsoon, providing the area with most of the yearly rainfall sum (the months of May to September account for 88 to 98 % of the yearly rainfall totals for the seven Soudano-Sahelian stations of table 2). Going south the rainy season becomes longer, while it also shows a tendency towards a double rainfall maximum.

Looking now more closely at the daily rainfall distribution (fig. 6, case of Tillabery) reveals that the major contribution to the decrease should be attributed to the higher classes of rainfall amounts (20.1 mm/day and more) while at the same time, one notices an increase in the frequency of small rainfall amounts (class from 0.1 to 5.0 mm/day).

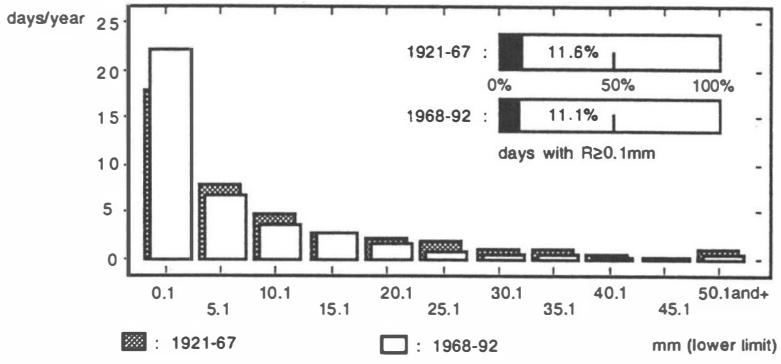


Fig. 6 — Comparison of the daily rainfall distribution between the "wet" (1921-67) and the "dry' (1968-92) period for Tillabery.

The insert shows moreover that the total number of rainy days (days with $R \geq 0.1$ mm) did not change. This led us to investigate the time series of the yearly number of rainy days as a possible further characterization of the change in rainfall regime.

5. The Non-Parametric Analysis of the Yearly Number of Rainy Days

The three non-parametric tests (see section 2) were again applied to the time series of the number of rainy days and the results are summarized in table 3a and 3b.

Although the distribution of the frequency of rainy days, both in space and in time, is more complicated than for the distribution of rainfall totals, the core area of the Soudano-Sahelian belt, comprising the stations of Kayes, Bougouni, Mopti, Tillabery, Agadez, Zinder and Mango, is again responding homogeneously (see for their geographical distribution, fig. 11) : the time series of all these stations show a positive change in the 40s, or early 50s, followed by an abrupt decrease in the second half of the 1960s. The latter downward trend is felt later

Table 3a

Results of the non-parametric analysis on the yearly number of rainy days

Yearly # RainyDays	1921-92					
N° station	MKS (a=5%)	Lombard (a=5%)	Pettitt (a=5%)	Conclusion n° 1	Results n° 2	Final: Conclusion
1 Lomé-Ville	Trend(1%) : Down	2Changes(1%)	63-64(1%) down 30-31(?%)up	Splitting up into 2 subseries required: 1921-63 and 1964-92	MKS(a=5%): Trend(1%):Up Lombard (a=5%): NoChanges Pettitt (a=5%): 39-40 up (*)	Upward Trend followed by downward Trend char.by 1 change-point: :1963-64
2 Atakpamé	Trend(1%) : Up	1Change 2Changes (10%) 3Changes (10%)	54-55(1%)up ?80-81(?%) down?			Upward Trend char.by 1 change-point: : 1954-55
3 Sokode	Trend(1%) : Up	1Change(1%) 2Changes	46-47(1%)up 80-81(?%) down	Splitting up into 2 subseries required1921-46 and 1947-92	MKS (a=5%) : NoTrend Lombard (a=5%) : NoChanges Pettitt (a=5%): NoJump	Upward Trend char.by 1 change-point:: 1946-47
4 Mango	Trend : Up	2Changes(1%) 1Change	46-47(1%)up 82-83(?%) down	Splitting up into 2 subseries required: 1921-46 and 1947-92	MKS (a=5%) : Trend : Down Lombard (a=5%): 2Changes Pettitt(a=5%): 82-83 (1%) down 56-57 (?%) up	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: 1946-47 and 1982-83
5 Bougouni	Trend(1%) : Up	2Changes(1%) 1Change(1%)	48-49(1%)up 90-91(?%) down	Splitting up into 2 subseries required: 1921-48 and 1949-92	MKS (a=5%) : Trend(1%) : Down Lombard (a=5%): 1Change(1%) Pettitt (a=5%): 67-68(1%) down	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: :1948-49 and1967-68
6 Zinder	NoTrend	2Changes(1%)	44-45 up 68-69(?%) down	Splitting up into 2 subseries required: 1921-44 and 1945-92	MKS (a=5%) :Trend (1%) : Down Lombard (a=5%) : 1Change Pettitt(a=5%): 68-69 (1%) down	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: :1944-45 and 1968-69
7 Tillabery	Trend : Up	2Changes(1%)	42-43(1%) up/(or 49-50)up 79-80(?%)down	Splitting up into 2 subseries required: 1921-42 and 1943-92 / (or 21-49 and 50-92)	MKS (a=5%): Trend(1%) down/(Trend (1%)down) Lombard (a=5%):1 change/ (1Change (1%)) Pettitt (a=5%):69-70(1%)down/ (67-68(1%)down)	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: :1942-43 and 1969-70 / or 1949-50 and 1967-68

(*) : we do not accept the change-point on the base of significant results of the Pettitt's Change-point test only.

Table 3b

Results of the non-parametric analysis on the yearly number of rainy days

Yearly # RainyDays	1921-92					
N° station	MKS (a=5%)	Lombard (a=5%)	Pettitt (a=5%)	Conclusion n° 1	Results n° 2	Final: Conclusion
8 Agadez	NoTrend	2Changes(1%)	49-50 up 68-69(?%) down	Splitting up into 2 subseries required: 1921-49 and 1950-92	MKS (a=5%): Trend (1%) : Down Lombard (a=5%) : 1Change (1%) Pettitt (a=5%): 68-69 (1%) down	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: 1949-50 and 1968-69
9 Kidal	NoTrend	NoChanges	52-53(1%)up 81-82(?%) down			No particular evolution-stationairy regime(*)
10 Mopti	NoTrend	2Changes(1%) 3Changes(1%)	78-79(1%) down 49-50(?%)up	Splitting up into 2 subseries required: 1921-78 and 1979-92	MKS (a=5%) : Trend(1%) : Up Lombard (a=5%) : 1Change(1%) Pettitt(a=5%): 51-52(1%)Up	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: :1951-52 and 1978-79
11 Kayes	NoTrend	2Changes(1%)	67-68 down 34-35(?%)up	Splitting up into 2 subseries required: 1921-67 and 1968-92	MKS (a=5%):Trend (1%) : Up Lombard (a=5%): 1Change(1%) Pettitt(a=5%): 49-50 (1%) up	Upward Trend char.by 1 change-point followed by downward Trend char.by a 2nd change-point: :1949-50 and 1967-68
12 Kaedi	Trend(1%) : Down	1Change(1%)	65-66(1%) down			Downward Trend char.by 1 change-point: : 1965-66
(*) : we do not accept the change-point on the base of significant results of the Pettitt's Change-point test only.						

in time for Mopti (1978-79) and Mango (1982-83). The simplified temporal evolution of the rainy days of the Soudano-Sahel zone can be schematized as |-¬|. Figure 7 shows for example the results for Zinder, where we recognize two significant jumps, an upward in 1944-45 and a downward jump in 1968-69.

Towards the south (Guinean zone : Atakpame and Sokode), there is only one jump, a significant abrupt increase around the 1950s (schematized as |-¬| in fig. 11). Figure 8 shows this for Sokode.

Towards the north, the only real desert station (Kidal) shows a stationary regime over the whole period just as in the case for the rainfall totals (schematized as ⌴ in fig. 11).

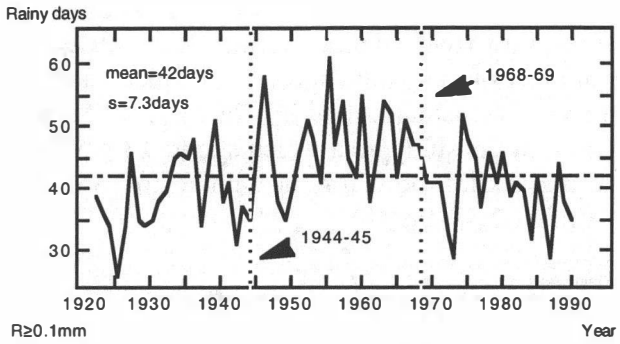


Fig. 7. — Time series of the yearly number of rainy days for Zinder (s = standard deviation).

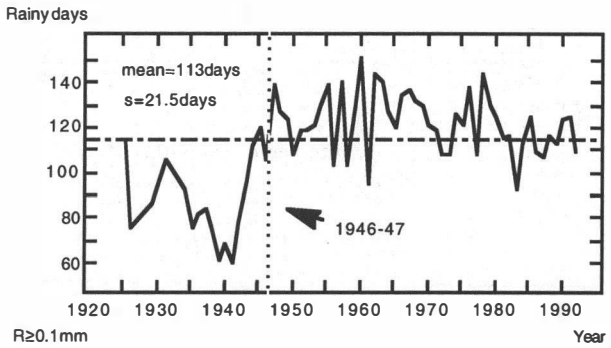


Fig. 8. — Time series of the yearly number of rainy days for Sokode (s = standard deviation).

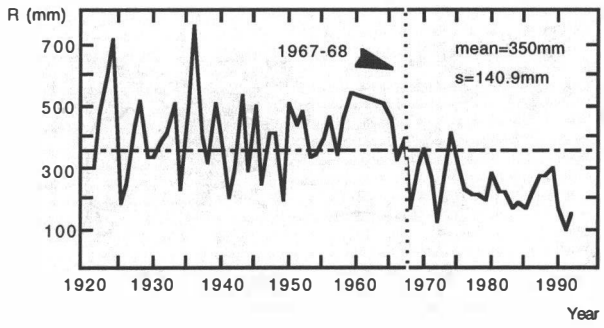


Fig. 9. — Time series of the yearly rainfall totals for Kaedi (s = standard deviation).

Approaching the coast, both to the south (the Guinean Gulf : Lomé-Ville) as to the west (the Atlantic Ocean : Kaedi), the distribution in time of the number of rainy days shows a conspicuous downward jump in the mid-sixties (schematized as |-| in fig. 11). As such, Kaedi is the only station in the study area which shows a significant downward jump in the mid-sixties, both for the rainfall totals (fig. 9) as for the frequency of rainy days (fig. 10).

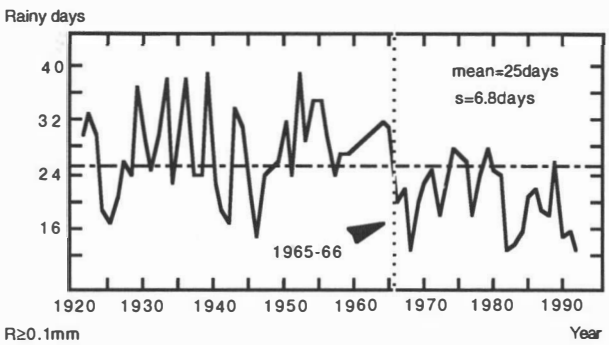


Fig. 10. — Time series of the yearly number of rainy days for Kaedi (s = standard deviation).

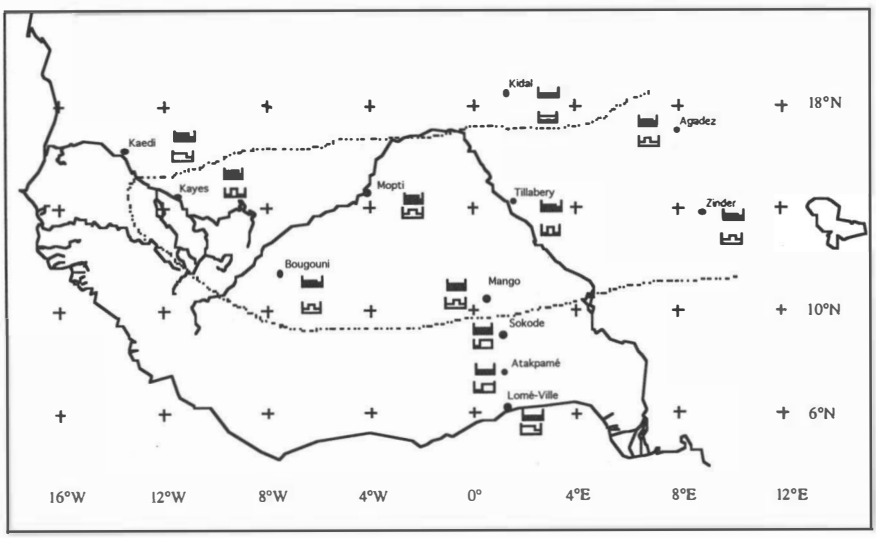


Fig. 11. — Map representing the symbolized results of the non-parametric analysis. For the symbol explanation, see text.

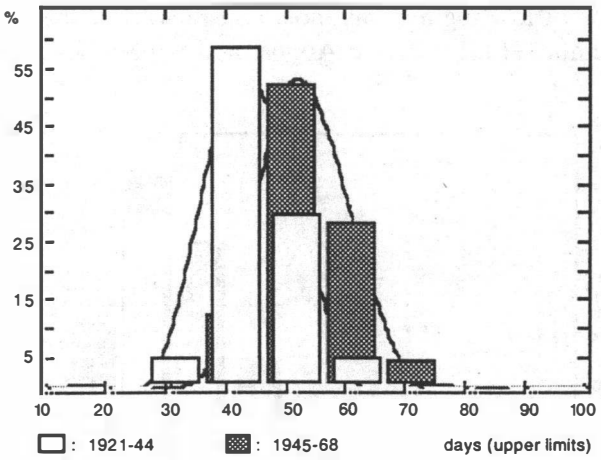


Fig. 12a. — Histograms and associated Gauss curves for the "low" (1921-44) and "high" (1945-68) regimes with respect to the number of rainy days (Zinder).

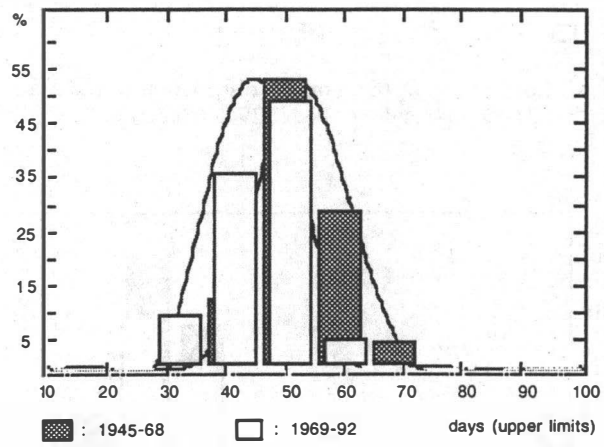


Fig. 12b. — Histograms and associated Gauss curves for the "low" (1969-92) and "high" (1945-68) regimes with respect to the number of rainy days (Zinder).

Figures 12a,b and 13a,b further illustrate the shift in rainfall frequency, characteristic for the central Soudano-Sahel area (case of Zider). Most remarkably is the near-absence (less than 5 %) of years with a total of 60 rainy days and more during the periods 1921-44 and 1969-92, while they occur in more than 30 % of the cases during the high regime from 1945-68. The decrease in rainfall frequency during

the periods of low regime was most conspicious in the months of July and September (1921-44), and August and September (1969-92).

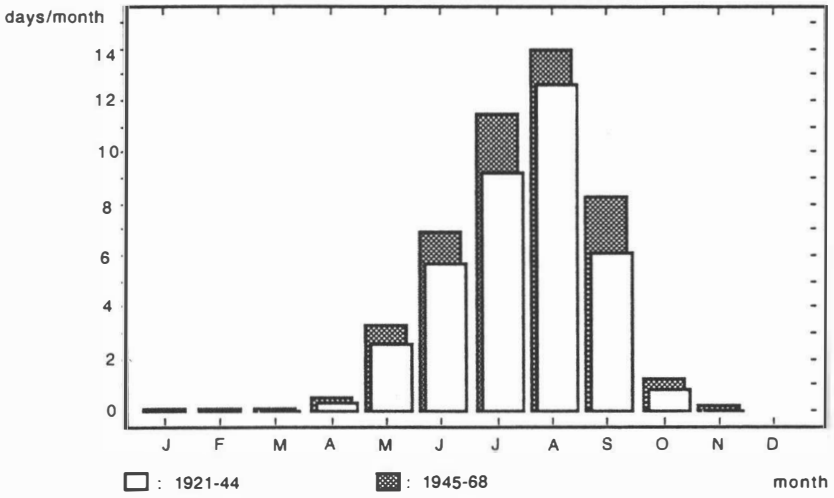


Fig. 13a. — Comparison of the monthly distribution of the number of rainy days between the "low" (1921-44) and the "high" (1945-68) period for Zinder.

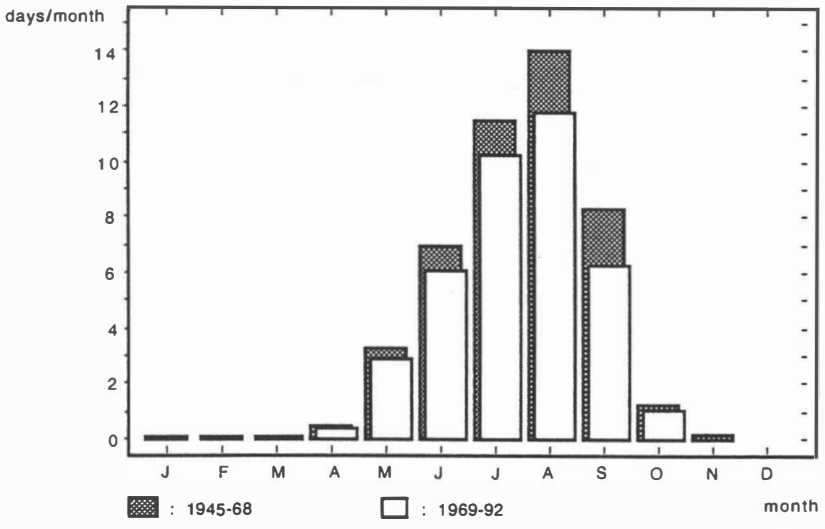


Fig. 13b. — Comparison of the monthly distribution of the number of rainy days between the "low" (1969-92) and the "high" (1945-68) period for Zinder.

6. Conclusions

1. It is possible to characterize the Soudano-Sahel zone in West Africa, not only by its downward change in the rainfall totals, but also by the whole frequency distribution, including the frequency of rainy days.

2. The analysis of the time series of both the rainfall totals and the number of rainy days adds weight to the existence of a well-defined region which responds homogeneously within the complex pattern of global changes. This zone encloses a vast area situated between 10 ° and 18 °N and extends from 12 °W to the east (see fig. 11). It corresponds to the Central Sahel (zonal divisions 14 and 15) and Southern Sahel (zonal divisions 19 and 20) of Nicholson (NICHOLSON & PALAO 1993). Unfortunately we do not know the eastern boundary.

3. The remarkably different response of the Guinean Gulf zone as compared to the core area of the Soudano-Sahel area suggests a modification of the climatic conditions over West Africa during periods of dry spells which is more complicated than a simple shift of the climatic zonation. This is at present under investigation for a north-south transect along the Greenwich Meridian.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Schietecat and his staff of the DARE I-program, Brussels, for their contribution in producing the data. They also wish to thank Dr. G. Demarée for his help. Bruno Van Gompel is indebted to the F.W.O.-Vlaanderen for the financial support.

REFERENCES

DEMAREE, G. R. & CHADILLY, M. S. 1988. The Sahelian drought(s) as seen from the rainfall data of a Mauritanian station. — *In* : OUAZAR, D., BREBBIA, C. A. & DE KOSINSKY; V. (eds.), Computer Methods and Water Resources, 1st International Conference, Morocco, Vol. 3, Computational Hydrology, Computational Mechanics Publications, Springer-Verlag, Berlin, pp. 15-23.

DEMAREE, G. R. & NICOLIS, C. 1990. Onset of Sahelian drought viewed as a fluctuation-induced transition. — *Quaternaly Journal of the Royal Meteorological Society*, **116** : 221-238.

DRUYAN, L. M. 1989. Review article : Advances in the study of sub-Saharan drought. — *International Journal of Climatology*, **9** :77-90.

HULME, M. 1992. Rainfall changes in Africa : 1931-1960 to 1961-1990. — *International Journal of Climatology*, **12** : 685-699.

JANICOT, S. & FONTAINE, B. 1993. L'évolution des idées sur la variabilité interannuelle récente des précipitations en Afrique de l'Ouest. — *La Météorologie*, **8** (1) : 28-53.

LEROUX, M. 1995. La dynamique de la Grande Sécheresse sahélienne. — *Revue de Géographie de Lyon*, **70** (3-4) : 223-232.

MOREL, R. 1995. La sécheresse en Afrique de l'Ouest. — *Revue de Géographie de Lyon*, **70** (3-4) : 215-222.

MORON, V. 1992. Variabilité spatio-temporelle des précipitations en Afrique sahélienne et guinéenne (1933-1990). — *La Météorologie*, **7** (43-44) : 24-30.

NICHOLSON, S. E. & PALAO, I. M. 1993. A re-evaluation of rainfall variability in the Sahel. Part I. Characteristics of rainfall fluctuations. — *International Journal of Climatology*, **13** (4) : 371-389.

PETTITT, A. N. 1979. A non-parametric approach to the change-point problem. — *Applied Statistics*, **28** (2) : 126-135.

ROWELL, D. P., FOLLAND, C. K., MASKELL, K. & WARD, M. N. 1995. Variability of summer rainfall over tropical North Africa (1906-92) : Observations and modelling. — *Quaternaly Journal of the Royal Meteorological Society*, **121** : 669-704.

VANDIEPENBEECK, M. 1995. Practice of climate change detection in the case of a special alternative to randomness. — Abstract Volume Oral and Poster Presentations of the 6th I.M.S.C., Galway, Ireland.

VANNITSEM, S. & DEMAREE, G. R. 1991. Détection et modélisation des sécheresses au Sahel : Proposition d'une nouvelle méthodologie. — *La Revue d'Hydrologie Continentale*, Orstom, **6** (2) :155-171.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 279-287 (1998)

Bioclimatic Regions of Nigeria

by

Krzysztof OLSZEWSKI *

KEYWORDS. — Bioclimatology ; Climatic Zones ; Nigeria.

ABSTRACT. — The influence of climate on human well-being and health has been well known since ancient times. The main climatic variables determining human physical comfort are solar radiation, air temperature, air humidity and wind speed. Physical comfort can be described by many indices. A widely-used measure of comfort is known as the effective temperature (TE). It can be derived from the Missenard's formula. Effective temperature for thirty-nine meteorological stations in Nigeria and neighbouring countries has been calculated using above index (fig. 2). The distribution of effective temperature over Nigeria has been drawn for selected months (fig. 3), as well as the duration of periods with the different types of thermal conditions : comfortable, warm, hot (fig. 4). Based on above maps the bioclimatic map of Nigeria has been prepared (fig. 5). The result shows warm conditions in the SW part of Nigeria during at least three months. In the NE part the thermal conditions indicate the "comfortable" during three months. The effect of relief is reflected over highland areas like the Adamawa massif and Jos Plateau.

MOTS-CLES. — Bioclimatologie ; Zones climatologiques ; Nigeria.

RESUME. — *Les régions bioclimatiques du Nigeria.* — L'influence du climat sur la santé et les dispositions psychophysiques de l'homme dépend essentiellement de facteurs tels que le rayonnement solaire, la température et l'humidité de l'air ainsi que la vitesse du vent. La sensation de chaleur peut être déterminée à l'aide de nombreux indices. Le plus souvent, c'est la température effective (TE) qui peut être déterminée à l'aide de la formule Missenard. On a recouru à cette dépendance afin de calculer la température effective (fig. 2) pour trente-neuf stations météorologiques situées aussi bien au Nigeria que dans les pays voisins. On a établi la distribution de la

* Faculty of Geography and Regional Studies, University of Warsaw, Krakowskie Przedmiescie 30, PL-00-927 Warsaw (Poland).

température effective (fig. 3) et la distribution du nombre de mois avec les sensations définies de chaleur (fig. 4) pour les mois choisis. Partant de ces données, on a dressé la carte des zones bioclimatiques du Nigeria (fig. 5). Il résulte de cette carte que les conditions bioclimatiques les plus favorables (une sensation de confort durant au moins six mois) se trouvent dans le sud-est du Nigeria et sur le Plateau Jos. Les conditions climatiques les moins favorables (l'absence de la sensation de confort, la sensation de chaleur pendant au moins trois mois) sont attestées au sud-ouest de la rivière Bénoué.

TREFWOORDEN. — Bioklimatologie ; Klimaatzones ; Nigeria.

SAMENVATTING. — *Bioklimatologische streken van Nigeria.* — De invloed van het klimaat op het algemeen welzijn en de gezondheid van de mens is van oudsher bekend. De belangrijkste klimatologische variabelen die het menselijke fysische comfort bepalen zijn de zonnestraling, de luchttemperatuur, de luchtvochtigheid en de windsnelheid. Het fysische comfort kan beschreven worden door vele indices. Een veel gebruikte waardemeter voor het comfort is gekend als de effectieve temperatuur (TE). Deze kan met de formule van Missenard afgeleid worden. De effectieve temperatuur voor negenendertig meteorologische stations in Nigeria en omliggende landen werd berekend door gebruik te maken van de bovengenoemde index (fig. 2). De verdeling van de effectieve temperatuur binnen Nigeria werd opgesteld voor geselecteerde maanden (fig. 3), zowel als de duur van de periode van de verschillende thermische condities : comfortabel, warm, heet (fig. 4). Gebaseerd op de genoemde kaarten werd een bioklimatologische kaart van Nigeria ontworpen (fig. 5). Het resultaat toont warme condities in het zuidwestelijke deel van Nigeria aan gedurende ten minste drie maanden. In het noordoostelijke deel worden de thermische condities gedurende drie maanden als comfortabel beschouwd. Het reliëfeffect wordt het meest gevoeld over de hooglanden, zoals het Adamawa-massief en het Jos-plateau.

Introduction

The influence of climate on human well-being and health has been well known since ancient times. The main climatic variables determining human physical comfort are solar radiation, air temperature, air humidity and wind speed. The summaric influence of air temperature and humidity can be determined by many indices. A widely-used measure of comfort is known as the effective temperature (ET). It indicates the intensity of warmth exchange between the environment and the human organism. The conditions in which the human body loses as much warmth as is provided by the metabolism are named the conditions of comfort, as they are accompanied by a pleasant feeling

of warmth. Thermal discomfort appears when the body must defend itself against the excess or shortage of warmth. In the intertropical zone, in particular in countries of large meridional extent, air temperature and humidity changes within the day and within the year may vary significantly; consequently, effective temperature changes are also extensive. Nigeria, located in this area, is characteristic of such regional diversification of climatic conditions (fig. 1). Its southern part is situated in the zone of humid equatorial forests and mangroves, the central belt in the savanna zone, while the northern east belongs to the Sahel. The climatic mosaic is completed by the Adamawa mountains in the south-eastern part and the Jos Plateau in the centre of the country.

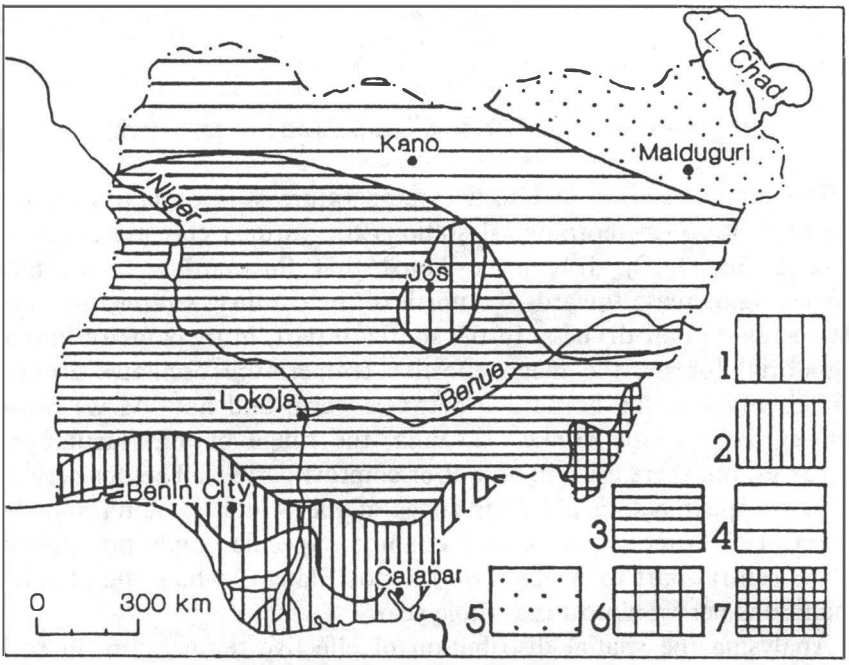


Fig. 1. — Climatic-vegetation zones of Nigeria: 1. mangrove; 2. rain forest; 3. Guinea savanna; 4. Sudan savanna; 5. Sahel; 6. plateau grasslands; 7. mountains.

Method

In this paper climatological data from eighteen Nigerian meteorological stations and from twenty-one from adjoining countries were

used. The mean monthly values are coming generally from the 30-year period 1930-1960. On this basis, applying Missenard's formula, the effective temperature (TE) was calculated :

$$TE = t - 0.4 \cdot (t - 10) \cdot (1 - 0.01 \cdot RH)$$

where : t = air temperature in °C,
RH = relative humidity in %.

The boundaries of comfort zones on the basis of TE were assumed after TERJUNG (1966) :

< 18 °C = cool; 18-22 °C = comfortable; 22-26 °C = warm;
26-30 °C = hot.

Diversification of Effective Temperature over Nigeria

The annual course of effective temperature was observed on the example of six meteorological stations for various climatic zones of Nigeria (figs. 1, 2). It can be noted that fluctuations in warmth perceiving increase towards the north of the country, so together with the increase in air dryness. In the southern part, in the zone of humid equatorial forests, the mean effective temperature oscillates around 26 °C, which is the borderline between warm and hot. As we move further towards the Guinea savanna, the range of TE fluctuations increases, but there are still no hot or comfort periods. The hot periods do not appear before the drier zones of the Sudan savanna and the Sahel at the time of the spring equinox. Specific conditions prevail in the central part of Nigeria, on the Jos Plateau, where the comfort conditions persist almost the whole year.

Analysing the spatial distribution of effective temperature in four months (fig. 3), it can be noted that during the warmest period of the year (March-October) TE increases from the south-east towards the north-west. This is the time of deep penetration of this part of the continent by the Intertropical Convergence Zone (I.T.C.Z.). It is followed by warm and humid air from the equator. In the cool part of the year (November-February) the effective temperature increases from the north-east towards south-west. This is so because at that time the cool, dry and dusty harmattan blows from the Sahara.

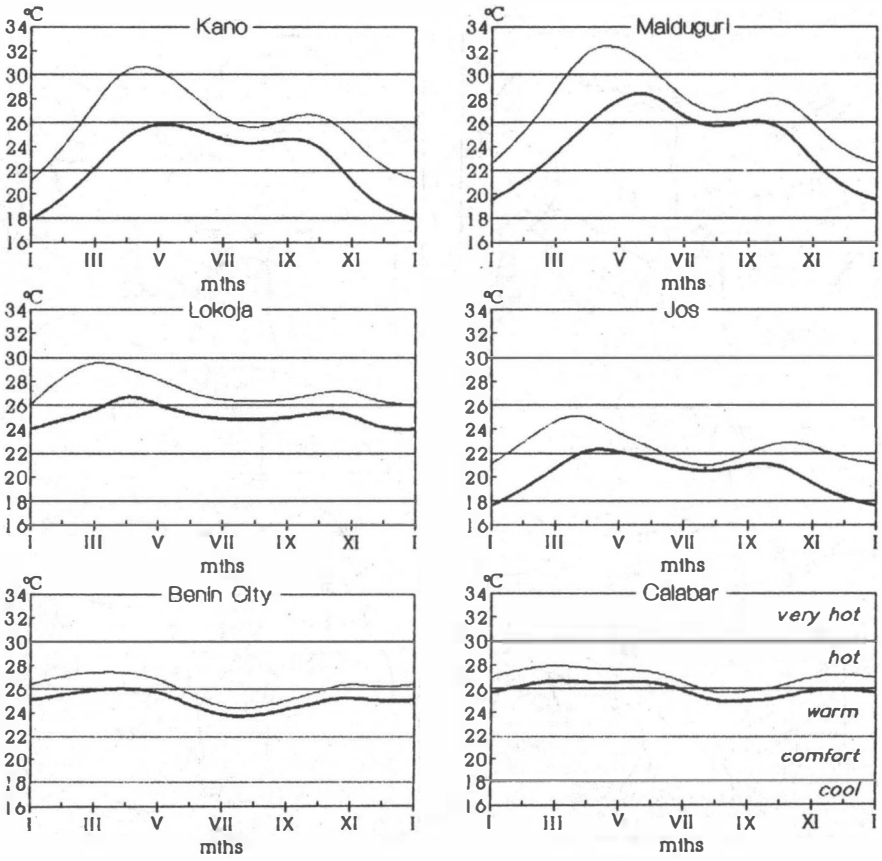


Fig. 2. — Annual changes in the air temperature (thin line) and the effective temperature (thick line).

Bioclimatic Regions of Nigeria

Under the extreme thermal conditions not only the distribution of the effective temperature is important but also the distribution of persistence of particular zones of warmth perceiving, which has been presented on the maps (fig. 4). The maps have been used for separation of bioclimatic regions. A network of squares with the side equal to 100 km was drawn upon which the isolines of the number of months with the specified conditions of warmth perceiving (comfort, warm, hot) were successively superimposed, thus defining the period of

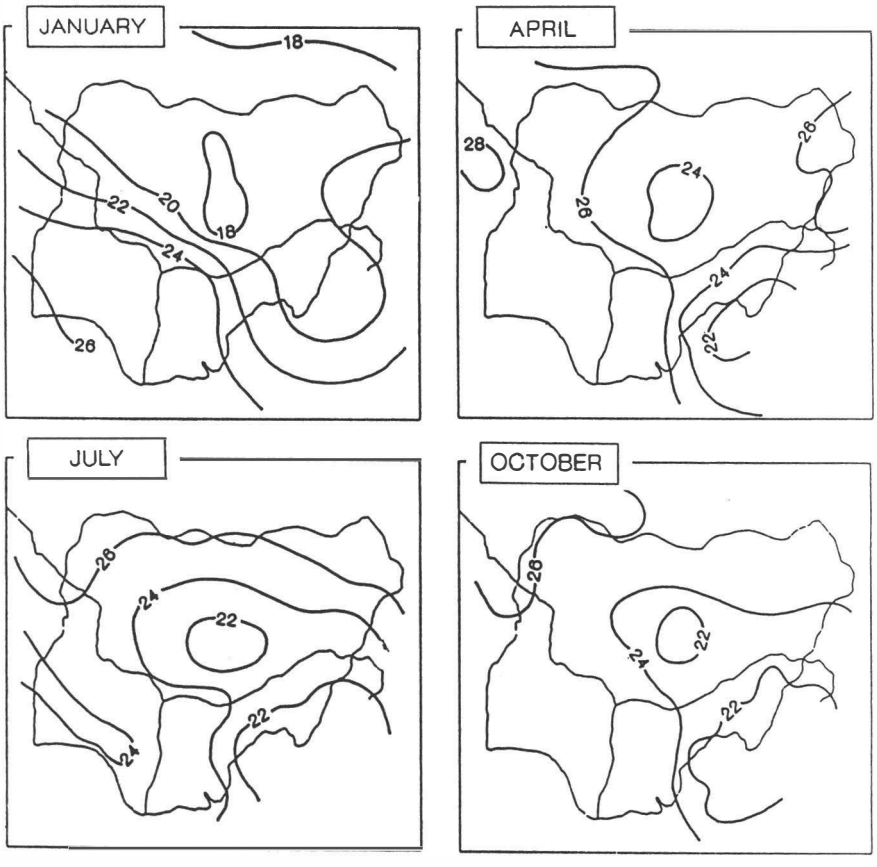


Fig. 3. — Distribution of the effective temperature (°C) in selected months.

persistence of such conditions in the given square. The result of such procedure is a map of bioclimatic regions of Nigeria (fig. 5).

The most favourable conditions prevail in the south-eastern part of Nigeria (the Adamawa massif). The conditions of comfort persist here on average all the year through and in the higher parts of these mountains even the feeling of coolness may appear during one month. On the borders of Adamawa massif and on the Jos Plateau the condition of comfort persists for at least half a year (the dry season). The other part of the year, not longer than six months, is warm. The whole part of Nigeria, situated north from the Niger and Benue rivers, is characteristic of worse thermal sensations. The period of comfort does not exceed three months, the warm season lasts at least three

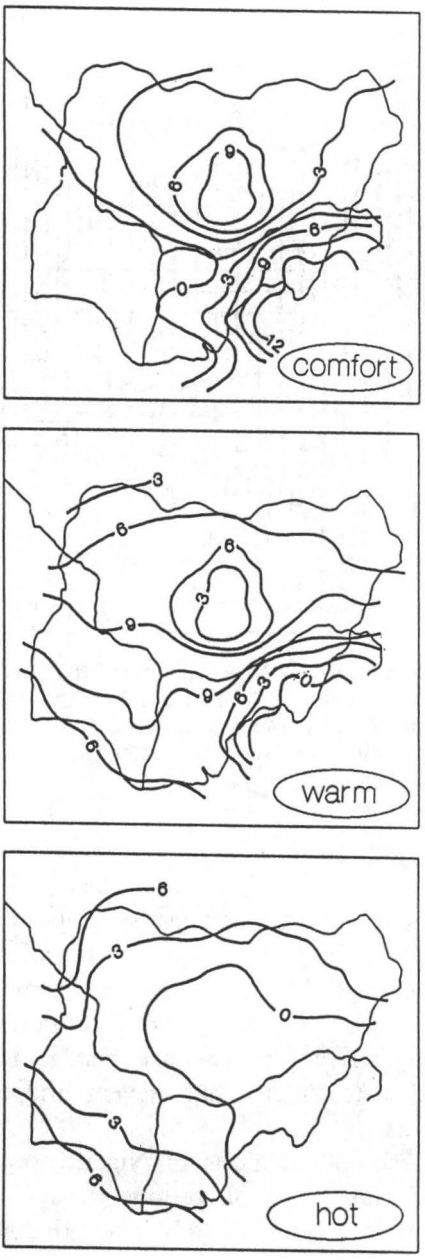


Fig. 4. — Number of months with different thermal sensations.

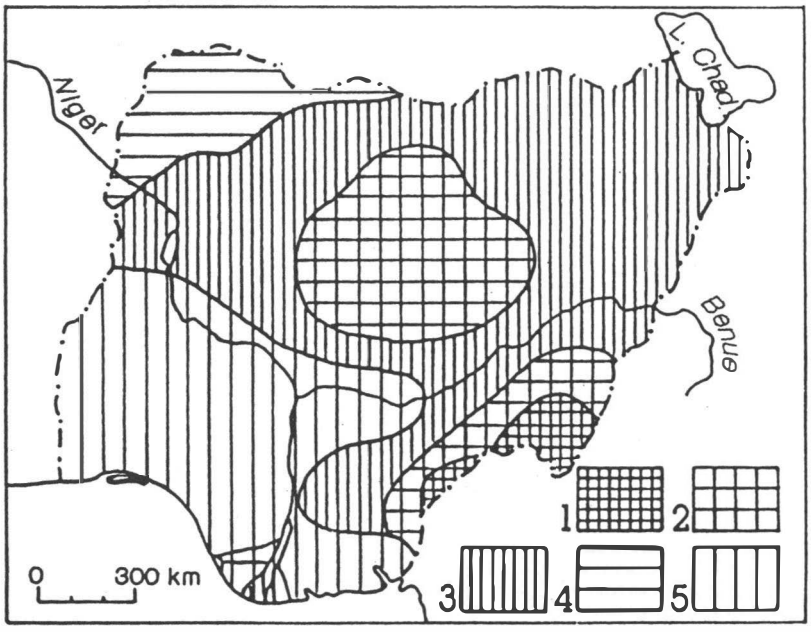


Fig. 5. — Bioclimatic zones of Nigeria: 1. comfort all the year round; 2. comfort over 6 to 12 months, warm over 1 to 6 months; 3. comfort over 1 to 3 months, warm over 3 to 9 months, hot over 1 to 3 months; 4. comfort over 1 to 3 months, warm over 1 to 3 months, hot over 3 to 6 months; 5. warm over 6 to 9 months, hot over 3 to 6 months.

months and in one up to three months the hot period has been observed. The north-western small part is characteristic of conditions similar to the preceding region, only the hot period extends to six months, at the cost of warm period. The least favourable conditions prevail south-west from the Niger river. In this part there is no period of comfort, the warm period lasts at least half a year and the hot period from three to six months.

Comparing bioclimatic regions of Nigeria, separated on the basis of the period of persistence of various thermal sensations with the climatic and vegetation zones, it can be noted that by a complex analysis of climatic elements their belt configuration disappears. It is the altitude above sea level, which is decisive here and which causes that in the intertropical zones of Nigeria the thermal comfort is perceived relatively often.

REFERENCES

KOWAL, J. & KNABE, D. 1972. An agroclimatological atlas of the Northern States of Nigeria. — ABU Press, Zaria, 16 maps, 111 pp.

OJO, O. 1977. The climates of West Africa. — Heinemann, London-Ibadan-Nairobi-Lusaka, 219 pp.

TERJUNG, W. H. 1966. Physiologic climates of conterminous United State: a bioclimatic classification based on man. — *Ann. Ass. Amer. Geogr.*, **56** (1): 141-179.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 288-291 (1998)

Rainfall and Sunshine in Irian Jaya (New Guinea)*

by

Taeke RIDDER **

KEYWORDS. — Irian Jaya ; New Guinea ; Rainfall ; Sunshine ; Solar Radiation ; Sea Salt.

ABSTRACT. — Measurements of rainfall and the distribution of rainfall per season and during day and night are described. Heavy rains at Hollandia (New Guinea) are compared with heavy rains at De Bilt (The Netherlands). Sunshine and rainfall data are investigated as factors in the production of sea salt by evaporation.

MOTS-CLES. — Irian Jaya ; Nouvelle-Guinée ; Précipitation ; Ensoleillement ; Radiation solaire ; Sel marin.

RESUME. — *Précipitations et ensoleillement en Irian Jaya (Nouvelle-Guinée).* — Les mesures de précipitation et de distribution de la précipitation par saison et pendant le jour et la nuit sont présentées. Les averses à Hollandia (Nouvelle-Guinée) sont comparées aux averses à De Bilt (Pays-Bas). L'influence de l'ensoleillement et de la précipitation sur la production de sel marin par évaporation est étudiée.

TREFWOORDEN. — Irian Jaya ; Nieuw-Guinea ; Neerslag ; Zonneschijn ; Zonnestraling ; Zeezout.

SAMENVATTING. — *Neerslag en zonneschijn in Irian Jaya (Nieuw-Guinea).* — Beschreven worden de regenval en de verdeling van de regenval per seizoen en gedurende dag en nacht. Een vergelijking wordt gemaakt tussen zware regens te Hollandia (Nieuw-Guinea) en zware regens te De Bilt (Nederland). De invloed van zonneschijn en regenval op de productie van zeezout door verdamping wordt nagegaan.

* * *

* Poster presentation.

** Former Head of the Climatological Service in New Guinea ; former employee at the Royal Netherlands Meteorological Institute († 28 November, 1997).

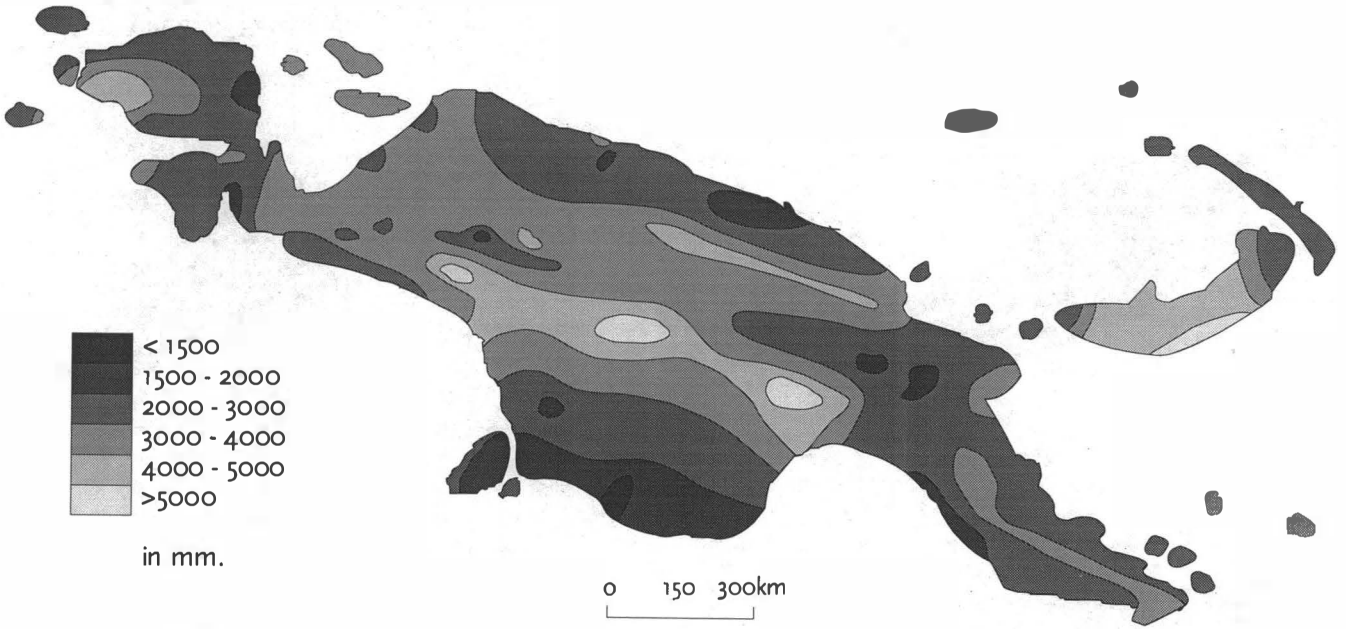


Fig. 1. — Mean annual amount of rainfall. This map shows the integrated picture of the annual rainfall over the entire island of New Guinea, as derived from long-term observations of successive Governments. The isolines agree well on both sides of the border. However, in regions in the inland (with hardly any rainfall stations) the reliability of the isolines is poor. (Data derived from McAlpine, J. R. & Keig, Gael with Falls, R., Climate of Papua New Guinea.)

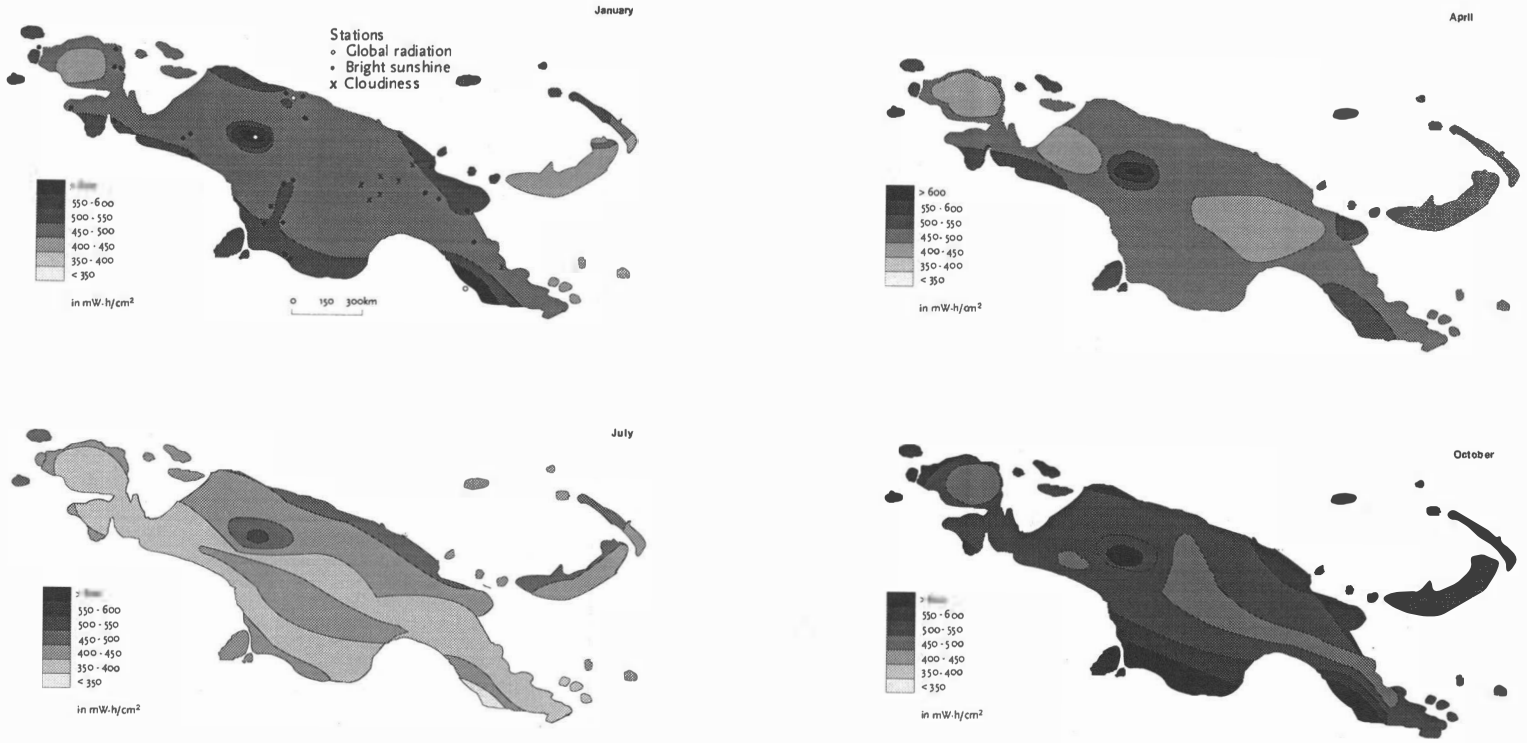


Fig. 2. — Global solar radiation. Maps with the global radiation for the entire island of New Guinea have been published by Kalma, J.D. (CSIRO, Australia). He used data of sunshine and cloudiness to estimate the amount of radiation for stations lacking radiation measuring instruments. Radiation data of the station Baliem (Wamena) in Irian Jaya have been added to his maps. (KALMA, J. D. 1972. Solar radiation over New Guinea and adjacent islands. — *Austr. Meteor. Mag.*, **20** : 116-127.)

As the most eastern part of Indonesia Irian Jaya lies in the tropics just south of the equator. The size of Irian Jaya is about thirteen times Belgium. Climatological data of Irian Jaya are investigated and compared with data from Papua New Guinea.

Rainfall

The yearly amount of rainfall in Irian Jaya varies from less than 1,500 mm in the south to more than 5,000 mm in the inland (fig. 1). Maps show that the seasons vary considerably. From place to place there is much difference in the distribution of the rainfall over day and night.

Sunshine and Solar Radiation

Measurements of sunshine and solar radiation show that the distribution of the total annual global radiation varies from nearly 200 Wh/cm^2 per year at the coast to 160 Wh/cm^2 in the inland (see fig. 2).

Production of Sea Salt

Production of sea salt out of sea water depends on evaporation and rainfall. In the dry season the amounts of rainfall vary much more than the values of evaporation.

To estimate the possibility of the production of sea salt definite limits for the amount of rainfall are assumed. Using the long series of rainfall data of Merauke (in the South of Irian Jaya), it has been concluded with the necessary restrictions that the production of sea salt at Merauke — on average — will be successful every other year.

REFERENCE

RIDDER, T. B. 1995. Rainfall in New Guinea (Irian Jaya). — KNMI publication, No. 183-1.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 292-296 (1998)

Rainfall in the Northern Part of Surinam (South America)*

by

Kees VAN SCHERPENZEEL **

KEYWORDS . — Surinam ; Rainfall ; Season ; Intertropical Convergence Zone.

ABSTRACT. — A description is given of the annual and monthly rainfall pattern and the areal distribution. Normally Surinam has two wet and two dry seasons. The periods in which they occur are closely related with the position of the Intertropical Convergence Zone (I.T.C.Z.). The hourly distribution differs from season to season.

MOTS-CLES. — Surinam ; Pluie ; Saison ; Zone de convergence intertropicale.

RESUME. — *Les précipitations dans la partie nord du Surinam (Amérique du Sud).* — Une description est donnée de la distribution annuelle et mensuelle de la précipitation, et de la distribution spatiale. En général, le Surinam a deux saisons humides et deux saisons sèches, qui sont associées avec la position du Front Intertropical de Convergence. La distribution de la pluie pendant un jour dépend de la saison.

TREFWOORDEN. — Suriname ; Neerslag ; Seizoen ; Intertropische Convergentiezone.

SAMENVATTING. — *Neerslag in het noordelijke gedeelte van Suriname (Zuid-Amerika).* — Een beschrijving wordt gegeven van de jaarlijkse en maandelijkse patronen van de regenval en de ruimtelijke verdeling. Meestal heeft Suriname twee natte en twee droge seizoenen. De perioden waarin deze optreden zijn nauw verbonden met de positie van de Intertropische Convergentie Zone (I.T.C.Z.). De verdeling van de neerslag over de dag verschilt van seizoen tot seizoen.

*
* *

* Poster presentation.

** Royal Netherlands Meteorological Institute, P.O. Box 201, NL-3730 AE De Bilt (The Netherlands).

Surinam is situated on the northern coast of South America between 2° and 6° northern latitude and 54° and 58° western longitude. It has a sunny, warm and humid climate. The mean monthly temperature varies between 25° and 29 °C. The mean yearly rainfall increases from 1,500 mm near the coast up to nearly 3,000 mm in higher parts in the central and south-east of the country (fig. 1).

The difference between a wet year and a dry year is especially due to the rainfall in the first five months. For example, in Paramaribo, April in a wet year has an average rainfall of 343 mm, the 70-year average is 218 mm and the average in a dry year is 69 mm.

According to the climate classification of Köppen, Surinam has a tropical rain climate. Three climate types can be distinguished : Af (mean amount of rainfall for every month more than 60 mm), Am (one or more months less than 60 mm, but a high yearly total) and Aw (wet and dry, the month(s) with less than 60 mm are not compensated by a high yearly total). In the northern part the two types Aw and Am are only present in a small zone along the coast.

Annual Cycle

The climate or more specifically the rainfall is dominated by the N ⇔ S movement of the Intertropical Convergence Zone (I.T.C.Z.).

The position of the I.T.C.Z. marks the convective activity and hence the rainfall and the main wind direction. In the course of the year the I.T.C.Z. is roughly situated south of Surinam in February and March ; over Surinam from April till August ; north of Surinam in September, October and November ; and again over Surinam in December and January.

The position of the I.T.C.Z. is well reflected in the rainfall amounts of the diagrams of monthly rainfall. In the first months of the year the I.T.C.Z. is situated over the Amazon Basin. Manaus has the maximum rainfall in March. In most parts of Surinam the highest rainfall occurs in May. Along the coast it is June. More to the north, Barbados, the maximum shifts to November.

Moving northwards over Surinam the abundant rainfall creates the "Long Rainy Season". During the southwards movement the "Short Rainy Season" reigns. In-between are the "Long" and "Short Dry Season". However, the Short Seasons are not always well pronounced.

During the Dry Seasons rainfall is related with disturbances from the northern or southern hemisphere, depending on the position of

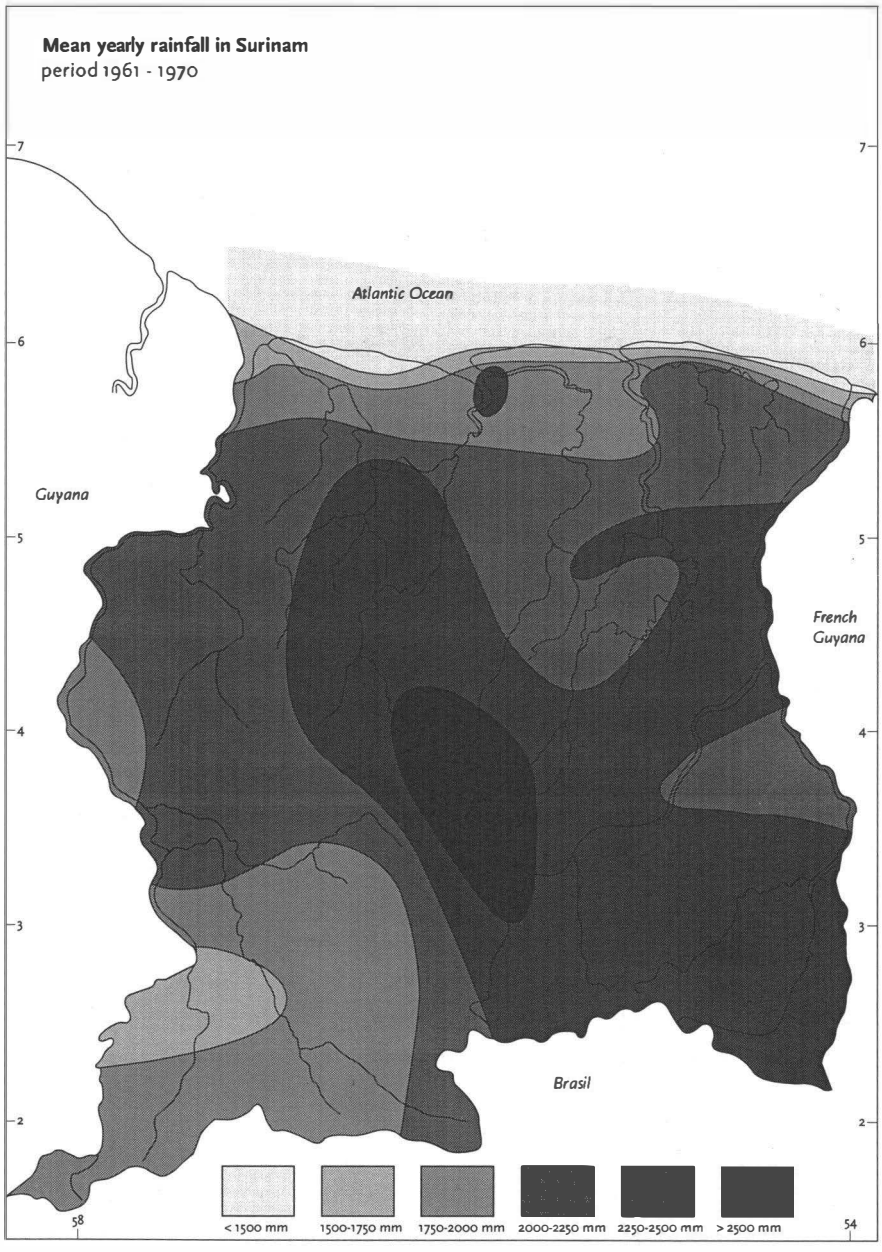


Fig. 1. — Mean yearly rainfall in Surinam, period 1961-1970.

the I.T.C.Z. For each season the probability is calculated of a rainy day with rainfall in the range of 0-3 mm, 3-10 mm, 10-25 mm, 25-50 mm and ≧ 50 mm (see fig. 2).

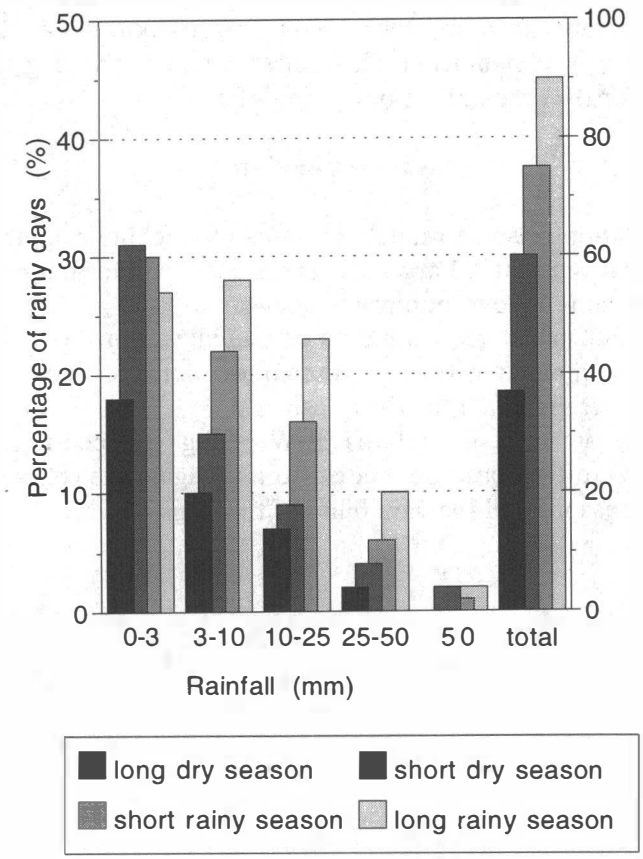


Fig. 2. — Rainy days for the four seasons, time period : 1901-1970.

This shows that even the "dry" seasons have still a great number of rainy days. The chance of very light rainfall, 0-3 mm, is for the seasons (long rainy season, short rainy season and short dry season) around 30 % and therefore not characteristic for a season. Very heavy rainfall, ≥ 50 mm, may occur in these three seasons with equal chance.

Daily Pattern

Nearly all the precipitation falls in showers with high intensities. The time of occurrence of the showers has a typical daily variation. In some months two maxima occur during day time and two during the night. In the course of the year the time of maxima moves and may coincide or disappear completely. In the first 100 km from the coast the sea breeze is a significant phenomenon and is for a great deal responsible for the time and amount of rainfall.

Areal Distribution

The correlation between rainfall amounts of neighbouring observing stations is relatively small. Large differences occur and local topography influences the amount and number of showers.

Areal rainfall, calculated from data of rainfall stations with Thiessen polygons, is compared with river discharges. Satellite data are more promising in deriving data for river basins.

Differences in rainfall patterns E-W along the coast and N-S perpendicular to the coast are studied to investigate the characteristics of the rainy seasons and the variability of the rains.

METEOROLOGY

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 299-312 (1998)

Importance of the Convective Adjustment Scheme in the Simulation of the Diurnal Cycle of Convective Activity in Africa

by

Olivier BRASSEUR *, Christian TRICOT **, Vincent NTEZIMANA *,
Hubert GALLÉE * & Guy SCHAYES *

KEYWORDS. — Convection ; Mesoscale ; Meteorology ; Modelling.

ABSTRACT. — The purpose of this study is to examine the processes responsible for the diurnal cycle in the Lake Victoria area (Central East Africa), a region characterized by intense convective activity. Among the different factors governing the climate of Central East Africa, the Lake Victoria is certainly one of the most important, since it is responsible for a well-marked diurnal cycle of thermal breezes and for an important supply of moisture in the atmosphere. According to earlier studies, local convection induced by thermal breezes generates a regular cycle of nocturnal precipitation above the lake. A mesoscale model developed at the "Université Catholique de Louvain", the MAR ("Modèle Atmosphérique Régional") was used to simulate the convective activity in this area. The MAR (GALLÉE & SCHAYES 1994) is a three-dimensional mesoscale hydrostatic primitive equations model. It contains a cloud microphysical scheme (NTEZIMANA 1993) and a convective adjustment scheme (FRITSCH & CHAPPELL 1980). The aim of this work is also to assess the impact of the convective adjustment scheme on the simulated convective activity related to the mesoscale forcing.

MOTS-CLES. — Convection ; Méso-échelle ; Météorologie ; Modélisation.

RESUME. — *Importance du schéma d'ajustement convectif pour la simulation du cycle diurne de l'activité convective en Afrique.* — Le but de cette étude consiste à examiner les principaux processus physiques responsables du cycle

* Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, chemin du Cyclotron, B-1348 Louvain-la-Neuve (Belgium).

** Royal Meteorological Institute of Belgium, Department of Climatology, av. Circulaire 3, B-1180 Brussels (Belgium).

diurne convectif dans la région du lac Victoria (Afrique centrale). Parmi les différents facteurs influençant le climat de l'Afrique centrale, le lac Victoria joue certainement un rôle prépondérant puisqu'il est responsable d'un cycle diurne marqué de brises thermiques et représente un important réservoir d'humidité pour l'atmosphère. En accord avec de récentes études, la convection locale induite par les brises thermiques génère un cycle régulier de précipitations nocturnes au-dessus du lac. Un modèle méso-échelle développé à l'Université Catholique de Louvain — en l'occurrence, le MAR (Modèle Atmosphérique Régional) — est utilisé pour simuler l'activité convective dans cette région. Le MAR (GALLÉE & SCHAYES 1994) est un modèle hydrostatique et tridimensionnel, écrit en équations primitives. Il contient un schéma de représentation de la microphysique nuageuse (NTEZIMANA 1993) ainsi qu'un schéma d'ajustement convectif (FRITSCH & CHAPPELL 1980). Ce travail vise par ailleurs à montrer l'importance de l'ajustement convectif dans la représentation de l'activité convective et des précipitations.

TREFWOORDEN. — Convectie ; Mesoschaal ; Meteorologie ; Modellering.

SAMENVATTING. — *Belang van het convectieschema in de simulatie van de convectieve dagcyclus in Afrika.* — Het doel van deze studie is het onderzoeken van de processen die verantwoordelijk zijn voor de dagcyclus in de regio van het Victoriameer, een streek die gekenmerkt wordt door intense convectie. Van de factoren die het klimaat van Centraal Oost-Afrika bepalen is het Victoriameer een van de belangrijkste, vermits het meer verantwoordelijk is voor een duidelijk aanwezige dagcyclus van thermische briezen, alsmede voor een belangrijke vochttoevoer naar de atmosfeer. Uit eerdere studies blijkt dat de lokale convectie, teweeggebracht door thermische briezen, een regelmatige cyclus van nachtelijke regenval boven het meer genereert. Het mesoschaalmodel MAR („Modèle Atmosphérique Régional") ontwikkeld aan de „Université Catholique de Louvain", werd gebruikt voor het simuleren van de convectie in dit gebied. Het model MAR (GALLÉE & SCHAYES 1994) is een driedimensionaal mesoschaal hydrostatisch model, gebaseerd op de primitieve vergelijkingen. Het bevat een microfysicaschema voor de wolken en een convectieschema (FRITSCH & CHAPPELL 1980). Deze studie heeft eveneens als doel de bepaling van de invloed van het convectieschema op de gesimuleerde convectie in verband met de mesoschaal*forcing*.

1. Introduction

The Lake Victoria area is situated in Central East Africa. This region is characterized by intense convective activity. Up to now, only a few investigations have been conducted about the climate variability of Central East Africa. This situation is mainly due to the lack of climatological data in these regions. On the other hand, agricultural

activities are the most important economic resources of these developing countries. Indeed they occupy more than 90 % of the population. The supply of food is vulnerable to climatic change and climatic variability. For those reasons, a good assessment of climatic variations and an investigation of their causes is needed.

2. Geographic Location

Lake Victoria lies in the tropical region of East Africa. It is one of the largest lake in the world and the largest lake in Central Africa with an area of about 68,000 km^2. From a geographic point of view, the lake lies approximately between latitudes 0.5 °N and 2.5 °S, and between longitudes 32 °E and 34 °E. The elevation of water lake level is about 1,135 m above mean sea level. The elevation of the surrounding mountains close to the lake reaches about 2,350 m. The north and the south of the lake are covered by large plateaus whereas its western and eastern coasts are surrounded by mountains whose elevation somewhere reaches levels higher than 3,000 m.

The Lake Victoria region is close to the equator, consequently the insolation is strong throughout the year. The lake lies in a valley between two mountain ranges running in nearly north-south direction. It is also influenced by the large-scale atmospheric circulation (MUKABANA & PIELKE 1996).

3. Clouds and Precipitation Observations

As reported in FRAEDRICH (1972), an annual amount of precipitation up to 1,585 mm is recorded near the lake centre, whereas only 1,000 mm are recorded in its vicinity. This difference is related to the nocturnal land breeze effect.

As described in ASNANI (1993), the monthly average rainfall over Lake Victoria shows two important periods. June to September is the season of minimum rainfall. Another minimum occurs during December-February. There are two seasons of maximum rainfall. The major maximum occurs in April. During this month, the I.T.C.Z. (InterTropical Convergence Zone) crosses the lake in its northward journey from the Southern Hemisphere to the Northern Hemisphere. March to May is the season of "long rains" in Kenya and Uganda. The minor maximum of rainfall occurs around November, when the I.T.C.Z.

crosses Lake Victoria during its southward journey. October and November represent the season of "short rains".

A recent study associated to the Eastern Africa climate was carried out by DESBOIS *et al.* (1989). The purpose of their study was to characterize convective clouds in the tropical African area covered by Meteosat. DESBOIS *et al.* (1989) underlined the existence of a diurnal cycle which affects the evolution of the cloud coverage in the Lake Victoria area. They especially pointed out an intensification of the cloud coverage above the lake during the second half of the night or in the early morning between 1 h 30 and 8 h 30 LT (local time). The maximum cloud occurrence takes place at the end of the afternoon in the surrounding mountainous areas. These conclusions obtained from satellite data analysis are in agreement with those based on *in situ* observed data (FRAEDRICH 1972).

4. Impact of the Large-scale Circulation on the Precipitation

The large-scale flow over the Lake Victoria area and neighbourhood during the year is generally easterly, with a northerly component or a southerly component depending on the season : northerly component is found in the lower troposphere during southern winter. The orientation of the mountain ranges is such that easterly wind flows down the slopes of the eastern mountain range, reaches the Lake. Then it propagates over the Lake and ascends the slopes of the mountain range lying to the west of the Lake. These ascending and descending motions give relatively more rain to the west of the Lake (ASNANI 1993).

Besides, during late night and in the early morning, the land breeze generates upward motion over the Lake. This ascent is intensified in the western part of the Lake by the large-scale easterly flow which increases the convergence by the encounter with the mesoscale westerly land breeze. The interactions between the large-scale easterly trades and the intense mesoscale circulations produce various patterns of diurnal precipitation.

5. Data Sets

The existence of data sets is a determining factor which might be considered for an investigation of climate variations. Such a study must be carried out over large areas and consequently needs an efficient

network of meteorological stations. However, it is still difficult to gather local data from the region of interest for many reasons. Among those, the most important are : 1. some difficulties resulting from inadequate communication routes ; 2. the lack of specialists for maintaining meteorological stations. The lack of observations *in situ* might be substituted by satellite data. However, in spite of the homogeneous distribution of parameters provided by satellite data, they are not easily converted into usual atmospheric parameters. They must be interpreted by a comparison with conventional data (DESBOIS *et al.* 1989).

6. Model Formulation

The formulation of the present version of MAR is detailed in GALLÉE & SCHAYES (1994) and GALLÉE (1995). The MAR is a hydrostatic primitive equation model in which the vertical coordinate is the normalized pressure $\sigma = (p - p_t) / (p_s - p_t)$ where p, p_s a dn p_t are the actual pressure, the top pressure and the surface pressure respectively. The use of σ vertical coordinate allows the representation of the surface topography which strongly varies in the Lake Victoria region. The full continuity equation is taken into account. The vertical subgrid scale fluxes are treated according to DUYNKERKE & VAN DEN BROEKE (1994) in the surface layer and using the E-ε turbulence closure (DUYNKERKE 1988) above. The solar radiation scheme is that of TRICOT & BERGER (1988) modified by GALLÉE *et al.* (1991). The long-wave radiation scheme follows a wide-band formulation of the radiative transfer equation (MORCRETTE 1984). The surface heat exchanges are treated using the DEARDORFF (1978) soil model. The hydrological cycle is fully described in NTEZIMANA (1993).

For our simulations, the convective adjustment scheme of FRITSCH & CHAPPELL (1980) has also been included. This scheme is especially designed for mesoscale models having a resolution of about 25 km. All stages of the convection are specified in a grid column. Briefly, the formulation is based on the hypothesis that the buoyant energy available to the parcel can be used, in combination with a prescribed period of time for the convection to remove that energy, to regulate the amount of convection in a grid element of the mesoscale model. The trigger function depends on air convergence in the lower layers and positive buoyancy. Individual clouds are represented as entraining moist updraft and downdraft plumes. Since updraft and downdraft areas are sometimes a substantial fraction of mesoscale model grid-

element areas, grid-point adjusted temperatures are an area-weighted mean of updraft, downdraft and environmental temperatures. An important advantage of this formulation lies in the fact that convection responds not only to the rate at which the large scale is generating buoyant energy, but also to the buoyant energy generated and stored prior to the onset of deep convection.

7. Characteristics of the Simulation Domain

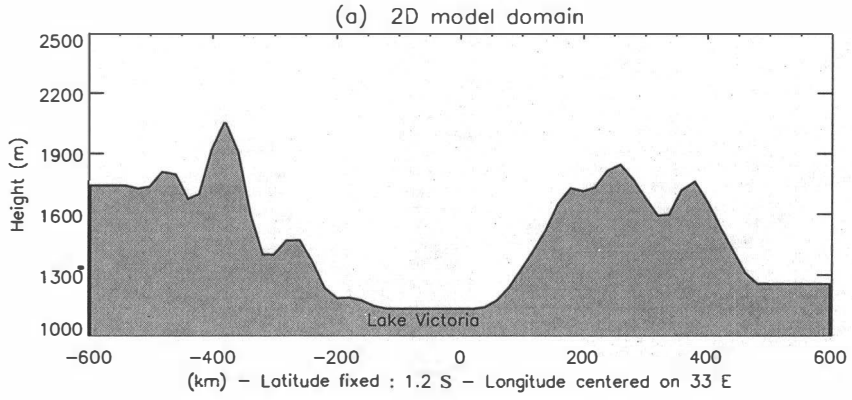
For our simulations, the large-scale effects are not taken into account. We focus rather on the mesoscale processes in this study.

Two model domains are considered (fig. 1). The first (fig. 1a) is a two-dimensional domain extending from 27.6 °E to 38.4 °E in longitude, the latitude being fixed to 1.2 °S. Such choice turns the relative north-south symmetry of topography into advantage. The second (fig. 1b) is a three-dimensional domain extending from 27.6 °E to 38.4 °E in longitude, from 4.8 °S to 2.4 °N in latitude. The topography is given by the Etopo Data (*Etopo 5 Global Ocean Depth and Land Elevation, 5 minutes* — Sloss, National Ocean and Atmospheric Administration, National Geophysical Data Center).

The horizontal resolution is 20 km, with 60*1 grid points in the two-dimensional case and 60*40 grid points in the three-dimensional case. There are thirty levels in the vertical, with a finer resolution in the boundary layer. The initial level heights above the lake have been fixed to 5, 10, 20, 39, 76, 145, 269, 477, 792, 1,212, 1,705, 2,221, 2,729, 3,220, 3,704, 4,196, 4,711, 5,263, 5,863, 6,521, 7,246, 8,048, 8,936, 9,921, 11,014, 12,226, 13,571, 15,064, 16,722 and 18,561 m. The time step is 80 s. This is required to satisfy the stability criterions of the numerical schemes. The initial vertical sounding is interpolated from climatological data (DHONNEUR 1980) and is used to initialize the whole domain. A zero gradient is assumed at the boundaries (open boundaries).

8. Mesoscale Circulations : Two-dimensional Simulations

Figure 2 represents the flow fields obtained during the two-dimensional simulation including the convective adjustment scheme. The results are plotted for 5 h 00 a.m. (fig. 2a) and 3 h 00 p.m. (fig. 2b). The isolines represent the potential temperature. The grey-filled areas indicate the cumulus clouds.



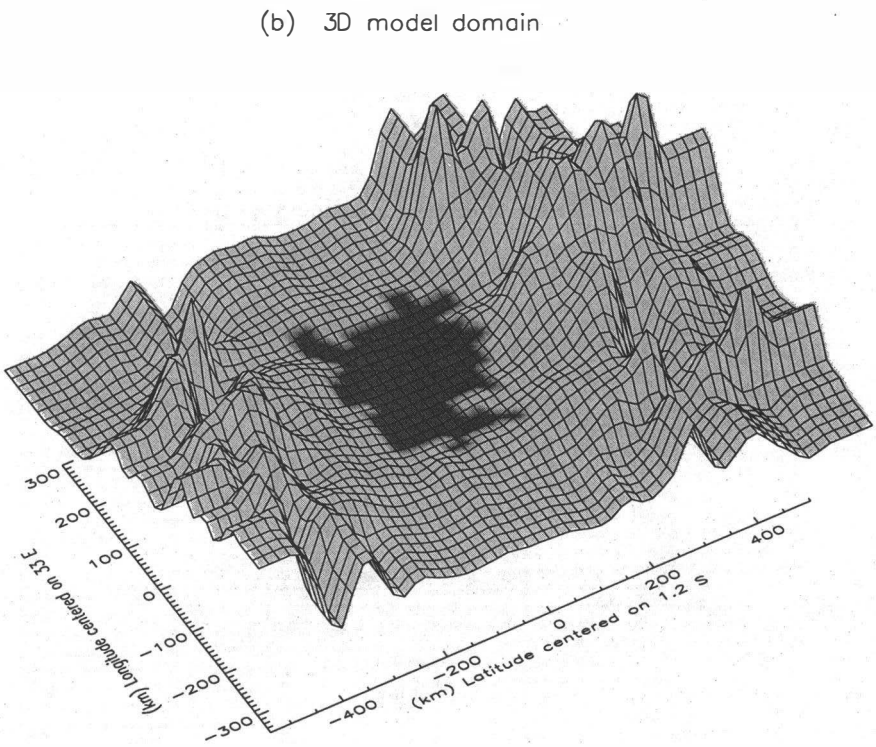


Fig. 1. — Model domains used for (a) the two-dimensional simulation and (b) the three-dimensional simulation.

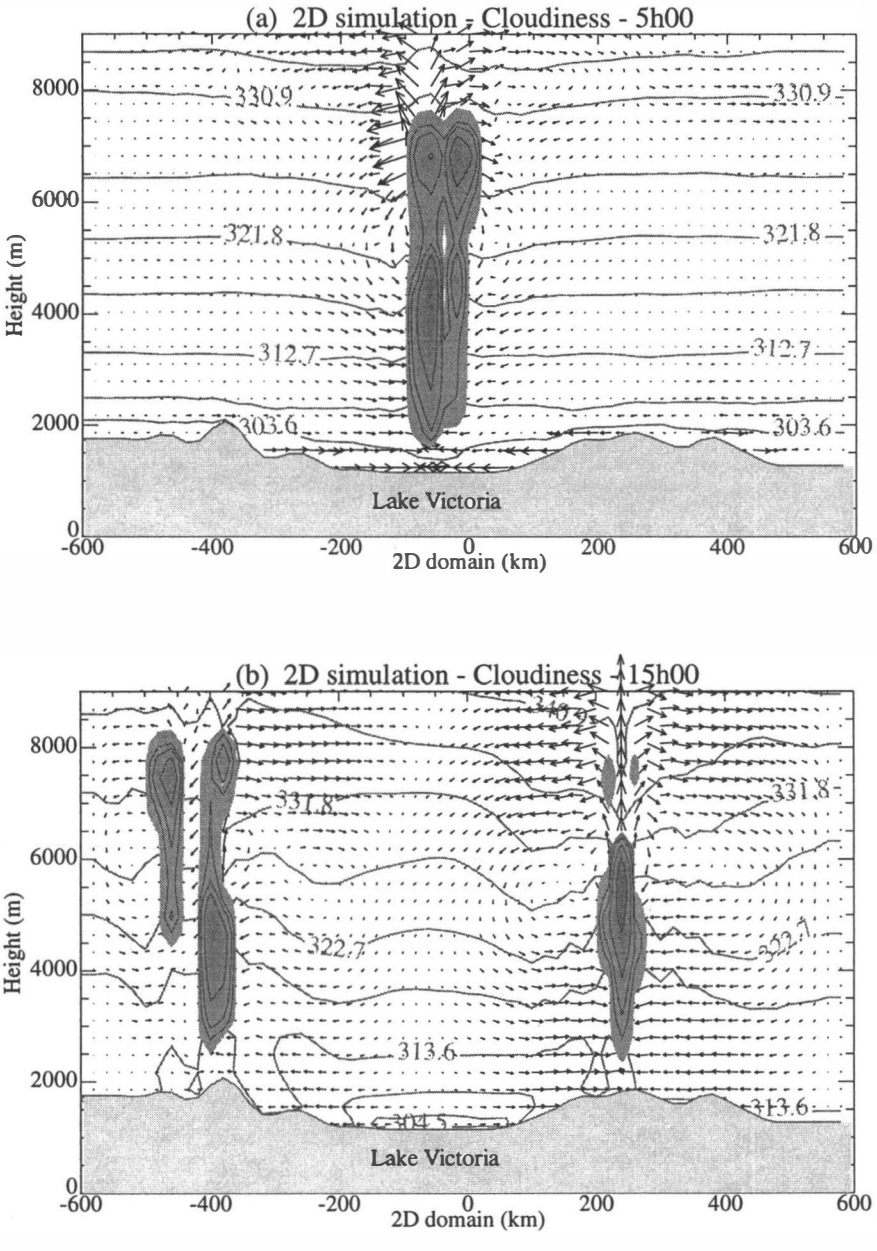


Fig. 2. — Flow fields obtained with the two-dimensional simulation at (a) 5 h 00 a.m. ; (b) 3 h 00 p.m. The X-axis is the horizontal extent of the domain ; the Y-axis is the altitude. The isolines represent the potential temperature. The grey filled areas indicate the cumulus clouds.

The particular orographic characteristics and the intense equatorial insolation generate a strong mesoscale circulation influencing the cloudiness and the convective precipitation. Two important processes have to be considered : the land-lake breezes resulting from the temperature difference between the lake and the mountains, and the anabatic-katabatic winds generated by the topography variations. We describe now the mesoscale circulations with more details. The lake surface temperature variation is less important than that of land. During the day, the lake is colder than the surrounding mountains and a lake breeze is generated. The breeze and the anabatic wind contribute to the rising motion. When a given parcel reaches the lifting condensation level, latent heat is released and the upward motion intensifies. All these processes contribute to produce cumulus clouds and precipitation above the mountains. During the night, the atmosphere stabilizes above the mountains. Furthermore, the lake is warmer than the mountains and a land breeze is produced. The vertical upward motion taking place above the lake is a consequence of the interaction between the land breeze and the katabatic downslope wind. Consequently, clouds and rain are produced. Therefore, the cycle of breezes generates a diurnal cycle for the cloud coverage and the precipitation.

The importance of the convective adjustment scheme is examined comparing the simulations obtained with and without the FRITSCH & CHAPPELL (1980) scheme. Figure 3 shows the precipitation rate for the two-dimensional experiments in function of time. The precipitation rate is given in millimetres per hour. Besides, two simulations are examined. The first is obtained without the convective adjustment scheme (fig. 3a). In this case, a diurnal cycle of precipitation is simulated above the mountains in good agreement with the observations between 12 h 00 a.m. and 10 h 00 p.m. The decrease in the convective intensity above the mountains is related to the decrease of the insolation. The second simulation is performed with the convective adjustment scheme (fig. 3b). Again strong convective activity is simulated above the mountains between 12 h 00 a.m. and 10 h 00 p.m. Between 11 h 00 p.m. and 3 h 00 a.m., no significant convective activity occurs. Precipitation is simulated over the lake between 4 h 00 a.m. and 11 h 00 a.m. The difference between both simulations underlines the importance of the convective parameterization at 20 km resolution. This lies mainly in the fact that the nocturnal mesoscale circulation is not strong enough to generate the cumulus cloud. With the convective adjustment scheme, the cumulus clouds' representation is dependent on the trigger function

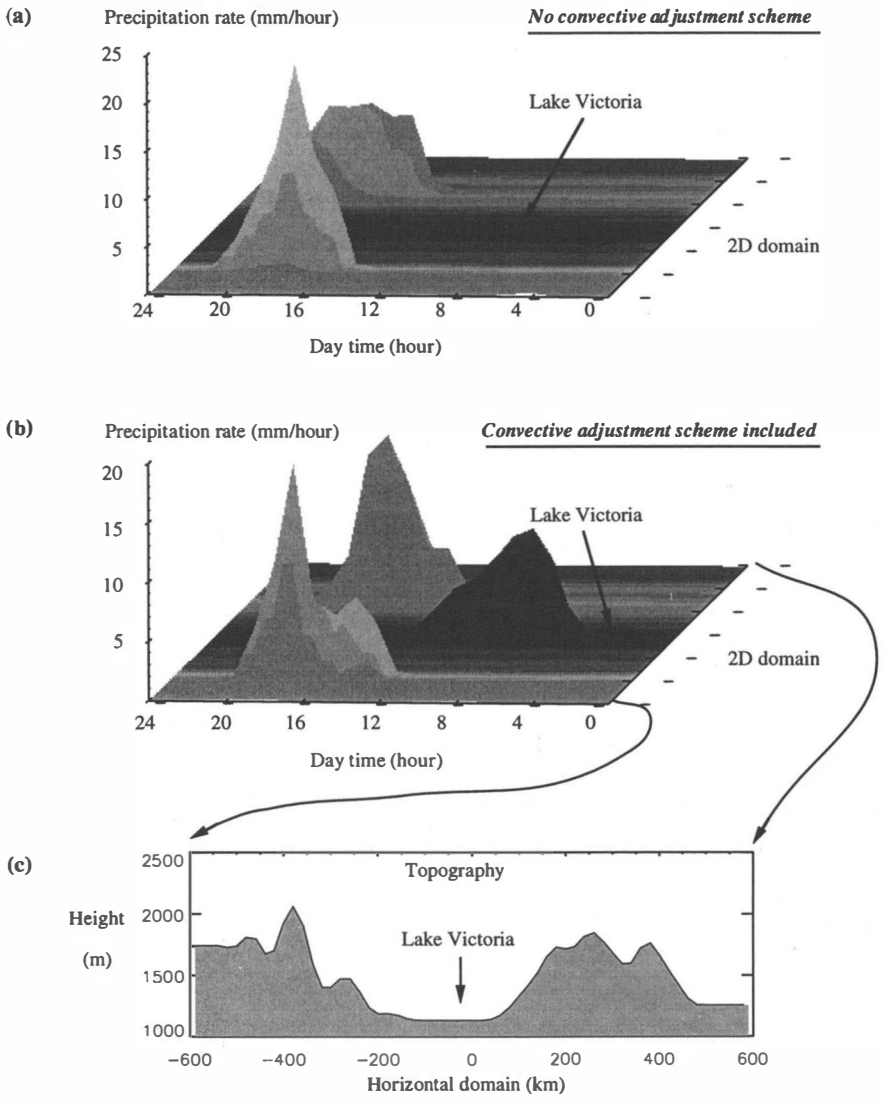


Fig. 3. — Precipitation rate given in millimetres per hour during a diurnal cycle and above the two-dimensional domain (a) without convective adjustment scheme; (b) with the convective adjustment scheme of FRITSCH & CHAPPELL (1980); (c) is the representation of the two-dimensional domain.

decision of the convective parameterization. They could be produced when the atmosphere is sufficiently unstable, even if the resolved motion is unable to produce the convection. The convective activity reaches a minimum at about 1 h 00 a.m. After this time, the mountains are colder than the lake. Consequently, katabatic winds and a land breeze are generated. The latter is less strong than the lake breeze during the day, but it is sufficient to produce cumulus clouds above the lake in the second half of the night and in the early morning, in a qualitative agreement with the observations.

9. Mesoscale Circulations : Three-dimensional Simulations

Figure 4 shows the diurnal cycle obtained with the three-dimensional version of MAR. The plotted variable is the columnar equivalent total water content and indicates the cloud coverage above the three-dimensional domain. Similarly to the two-dimensional case, clouds are generated over the lake during the late night and in the early morning, in particular between 4 h 00 a.m. and 11 h 00 a.m. The convective activity is stronger than in the two-dimensional case probably because of a stronger convergence of air mass (in addition to north-south convergence in the three-dimensional case). At 5 h 00 a.m. (fig. 4a), the clouds are simulated just above the lake, but no cloud is found above the mountains. In the afternoon, the convective activity is particularly intense above the surrounding mountains. At 3 h 00 p.m. (fig. 4b), there is no cloud above the lake. The diurnal cycle obtained is in good agreement with the observations.

10. Conclusions

From a qualitative point of view, a good agreement is found between the simulated and the observed diurnal cycle of clouds and precipitation above the Lake Victoria area. Three periods of convective activity may be distinguished. Between 4 h 00 and 12 h 00, precipitation occurs above the lake, with a maximum around 7 h 00 a.m. Between 12 h 00 a.m. and 10 h 00 p.m., an intense cloud activity is simulated above the surrounding mountains. Between 11 h 00 p.m. and 3 h 00 a.m., no significant convection occurs. These results are obtained with the two- and three-dimensional simulations.

The main processes responsible for the diurnal cycle of clouds and precipitation are : 1. land-lake breezes generated by the temperature

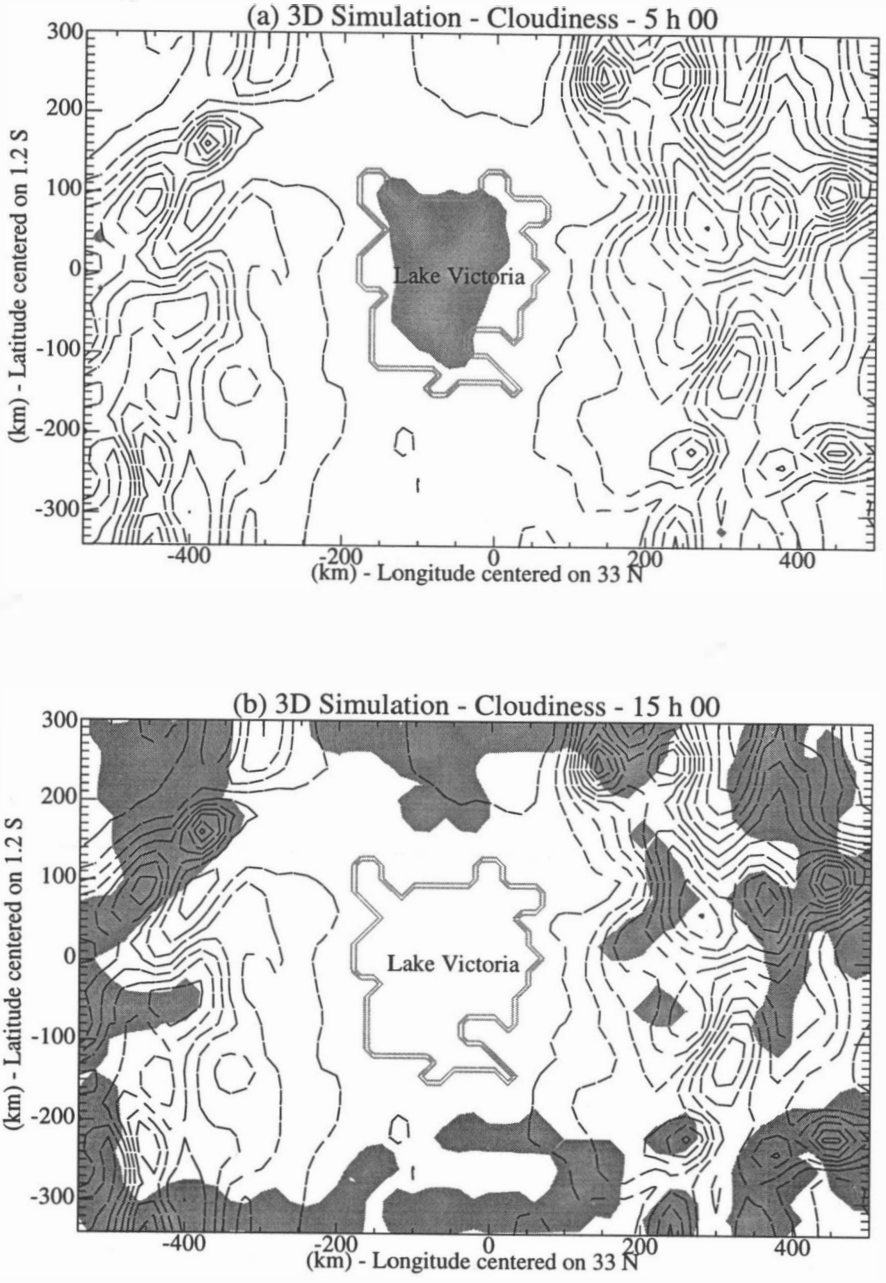


Fig. 4. — Columnar equivalent water content obtained with the three-dimensional version of MAR at (a) 5 h 00 a.m. ; (b) 3 h 00 p.m.

difference between the lake and the surrounding mountains ; 2. anabatic-katabatic winds arising from the particular orographic characteristics. These are also influenced by the marked diurnal cycle of the equatorial insolation. Although they are not taken into account for this study, the large-scale effects supply the moisture in the atmosphere and increase convergence when the I.T.C.Z. crosses the lake.

These simulations have shown the importance of the convective adjustment scheme at 20 km horizontal resolution for reproducing the precipitation above the lake. Further research will include simulations at 10 km resolution. In this case, the FRITSCH & CHAPPELL (1980) scheme should be modified in order to allow an horizontal communication of the convective activity between adjacent grid cells and to avoid the double "counting" between the parameterization and the explicit representation.

ACKNOWLEDGEMENTS

This work is part of a collaborative project between the "Université Catholique de Louvain" (U.C.L.) and the Royal Meteorological Institute of Belgium (R.M.I.B.) on regional climate modelling. We are grateful to the Director of R.M.I.B. for allowing access to the CRAY J908 and to the staff of R.M.I.B. Computer Center for computing assistance. The first author thanks the FRIA ("Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture") for the financial support of this research.

REFERENCES

ASNANI, G. C. 1993. Tropical Meteorology. — Indian Institute of Tropical Meteorology, Ph. D. thesis, vols. I and II.

DEARDORFF, J. W. 1978. Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. — *J. Geophys. Res.*, **83** : 1889-1903.

DESBOIS, M., KAYIRANGA, T. & GNAMIEN, B. 1989. Diurnal cycle of convective cloudiness over Tropical Africa observed from Meteosat : Geographic characterization and interannual variations. — *Annales Geophysicae*, **4** : 395-404.

DHONNEUR, G. 1980. Traité de météorologie tropicale : application au cas particulier de l'Afrique occidentale et centrale. — Météo nationale, France, 151 pp.

DUYNKERKE, P. G. 1988. Application of the E-ε turbulence closure model to the neutral and stable atmospheric boundary layer. — *J. Atmos. Sci.*, **45** : 865-880.

DUYNKERKE, P. G. & VAN DEN BROEKE, M. R. 1994. Surface energy balance and katabatic flow over glacier and tundra during GIMEX-91. — *Global and Planetary Change*, **9** : 17-28.

FRAEDRICH, K. 1972. A simple climatological model of the dynamics and energetics of the nocturnal circulation at Lake Victoria. — *Quart. J. Roy. Meteor. Soc.*, **98** : 322-335.

FRITSCH, J. M. & CHAPPELL, C. F. 1980. Numerical prediction of convectively driven mesoscale pressure systems, part I : Convective parameterization. — *J. Atmos. Sci.*, **44** : 3787-3799.

GALLÉE, H. 1995. Simulation of the Mesocyclonic Activity in the Ross Sea, Antarctica. — *Monthly Weather Rev.*, **123** : 2051-2069.

GALLÉE, H. & SCHAYES, G. 1994. Development of a Three-Dimensional Meso-Gamma Primitive Equations Model, Katabatic Winds Simulation in the Area of Terra Nova Bay, Antarctica. — *Monthly Weather Rev.*, **122** : 671-685.

GALLÉE, H., VAN YPERSELE, J. P., FICHEFET, T., TRICOT, C. & BERGER, A. 1991. Simulation of the Last Glacial Cycle by a Coupled 2-D Climate-Ice Sheet Model, 1, The Climate Model. — *J. Geophys. Res.*, **96** : 13139-13161.

MORCRETTE, J.-J. 1984. Sur la paramétrisation du rayonnement dans les modèles de la circulation générale atmosphérique. — Université de Lille, France, unpublished thesis.

MUKABANA, J. R. & PIELKE, R. A. 1996. Investigating the influence of synoptic-scale monsoonal winds and mesoscale circulations on diurnal weather patterns over Kenya using a mesoscale numerical model. — *Monthly Weather Rev.*, **124** : 224-243.

NTEZIMANA, V. 1993. Simulation d'un front côtier avec un modèle atmosphérique régional comprenant une représentation explicite de la microphysique des nuages. — UCL, Institut d'Astronomie et de Géophysique G. Lemaître, unpublished thesis.

TRICOT, C. & BERGER, A. 1988. Sensitivity of present-day climate to astronomical forcing, in long and short-term variablility of climate. — *In* : WANNER, H. & SIEGENTHALER, U. (eds.), Lect. Notes Earth Sci., **16** : 132-152.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 313-327 (1998)

Predictions of Precipitation from Two Global Circulation Models and an Empirical Technique

by

Andrew COLMAN *

KEYWORDS. — Forecast ; Rainfall ; Global Circulation Model.

ABSTRACT. — Two sets of ensemble simulations have been run using different climate versions of the UK Meteorological Office (UKMO) Atmosphere Global Circulation Model (AGCM) over the common period 1979-1990. Both ensemble sets are forced with simultaneous observed Sea Surface Temperature (SST). One ensemble set consists of short (4-month) runs using atmospheric initial conditions observed near the start of the season to be simulated, while the other set is taken from long-term (1949-93) AGCM runs with no real atmosphere input. Precipitation predictions by the AGCMs have been assessed by comparison with observations and compared with a set of statistical linear regression forecasts using two SST predictors related to El Niño / Southern Oscillation events (ENSO). The two sets of simulations and the regression predictions have significant skill. The AGCM simulations using beginning of season initial atmospheric conditions have the highest skill, particularly in the first month of the season. There is considerable overlap in predictability between the AGCM ensembles but not much overlap between the AGCM simulations and the ENSO-based regression predictions.

MOTS-CLES. — Prévision ; Précipitations ; Modèle atmosphérique global.

RESUME. — *Prévisions des précipitations de deux modèles de circulation globale et une technique empirique.* — Deux jeux de données de simulations d'ensemble ont été obtenus en utilisant des versions différentes du Modèle de Circulation Atmosphérique Globale du «UK Meteorological Office» (UKMO) sur la période de référence commune 1979-1990. Les deux jeux de données d'ensemble ont été forcés par des températures de la surface de la mer (SST) simultanées. Un des ensembles consiste en une intégration

* Hadley Centre, Meteorological Office, Bracknell, Berkshire, RG 12 2SY (United Kingdom).

numérique courte (4 mois) utilisant des conditions atmosphériques initiales observées au début de la saison à simuler, tandis que l'autre provient d'intégrations numériques longues (1949-93) sans entrée d'atmosphère vraie. Des prévisions en provenance des intégrations numériques ont été déterminées en les comparant aux observations et ont été comparées avec un jeu de données de prévisions obtenues par des procédés de régression linéaire utilisant deux prédicteurs reliés à l'El Niño / Oscillation australe (ENSO). Les deux jeux de données de simulations et les prévisions de régression ont une performance significative. Les simulations par intégration numérique utilisant des conditions initiales atmosphériques de début de saison ont une performance supérieure, surtout pour le premier mois de la saison. On note un recouvrement considérable en prévisibilité entre les ensembles d'intégration numérique, mais un faible recouvrement entre les simulations par intégration numérique et les prévisions de régression basées sur ENSO.

TREFWOORDEN. — Voorspelling ; Neerslag ; Globaal circulatiemodel.

SAMENVATTING. — *Neerslagvoorspellingen van twee globale circulatiemodellen en een empirische techniek.* — Twee sets van *ensemble* simulaties werden gerund gebruik makende van verschillende versies van het U.K. Meteorological Office (UKMO) atmosferisch globale circulatiemodel (A.G.C.M.) over het gemeenschappelijke tijdvak 1979-1990. Beide *ensemble* sets werden gedwongen door de waargenomen zee-oppervlaktetemperaturen (S.S.T.). Een *ensemble* set bestaat uit korte (4 maanden) *runs* gebruik makende van atmosferische beginvoorwaarden waargenomen bij de start van het te simuleren seizoen terwijl de andere set genomen werd van de langdurige (1949-93) A.G.C.M.-*runs* met geen reële atmosferische *input*. Neerslagvoorspellingen door de A.G.C.M.s werden bepaald door vergelijking met de waarnemingen en vergeleken met een set van statistische lineaire regressievoorspellingen met twee S.S.T.-predictoren die verband houden met El Niño / Southern Oscillation gebeurtenissen (ENSO).

1. Introduction

The UK Meteorological Office has been issuing experimental real-time forecasts for seasonal rainfall for selected regions in the tropics since 1986, from preceding global-scale sea surface temperature (SST) patterns using empirical techniques (FOLLAND *et al.* 1991, WARD & FOLLAND 1991). Since 1994, information from an AGCM has been included in the real-time forecasts. In this paper the potential predictability from such AGCMs is assessed globally by comparing modelled and observed rainfall for two seasons, December-January-February (DJF) and March-April-May (MAM).

2. The C20C (Climate of 20th Century) Simulations

ROWELL (1996) found useful potential predictability of tropical rainfall from an ensemble of six 45-year runs of the UKMO AGCM version HADAM 1 forced with observed SST from the Meteorological Office Global Ice and Sea Surface Temperature (GISST 1.1) dataset (PARKER *et al.* 1995). The ensemble runs are distinguished from each other only by the use of different initial conditions at the beginning of the 45-year period. The initial conditions used were not the real ones for the start date of the run but were randomly selected from a series of analyses for the appropriate time of year. The only observed data input to these runs were the sea temperatures and ice coverage; no observed atmospheric or land surface data were used. These runs were made as part of the Climate of the 20th Century project and will be referred to henceforth as the C20C runs.

3. The IC (Initial Condition) Simulations

More recently a set of AGCM runs have been carried out at UKMO as part of the PROVOST project (**PR**ediction **O**f climate **V**ariability **O**n **S**easonal and interannual **T**imescales), a joint project supported by the European Commission involving several European climate modelling centres (EVANS & EVANS 1996). These runs differ from the C20C runs in that the model starts each season with the correct atmospheric conditions as well as being forced with simultaneous SST. Since these runs use atmospheric initial conditions, they are here referred to as the IC runs. These runs use the more recent HADAM 2B version of the UKMO model. Compared with HADAM 1, a number of small changes have been made (HALL *et al.* 1995). The most significant effects of these changes on the rainfall climatology are generally higher (more accurate) and smoother rainfall patterns over land, with reductions in rainfall in mountain areas due to reduced diffusion. Overall though, the rainfall climatologies of HADAM 1 and HADAM 2B are both similar to the observed globally complete LEGATES & WILLMOT (1990) climatology (HALL *et al.* 1995, fig. 19).

The IC runs were made for boreal winters (December-February) and springs (March-May) over the period December 1979 - May 1990. The winter runs used atmospheric initial conditions from the end of November and the spring runs used initial conditions for the end of February. An ensemble of nine runs were made for each season, the

ensemble members being distinguished from each other through slightly different start times. The first winter run was started with initial conditions for 00Z 22nd November, the second run was started with initial conditions for 00Z 23rd November, the third used 00Z 24th November, etc. The spring runs were likewise initialized at 24 hourly intervals near the end of February.

The SST data used by the IC runs is slightly different to those used by the C20C runs over the period 1982-1990. Over this period, the IC runs used an SST dataset created by REYNOLDS & SMITH (1994) using Optimum Interpolation (OI). Data coverage over 1982-1990 is good so that the two globally complete OI and GISST datasets are quite similar. GISST was made using smaller-scale interpolation and is generally less smooth than the OI data. The largest differences occur south of 40S, well away from the main areas being considered in this study.

4. Linear Regression Predictions using ENSO-related SST Patterns

The El-Niño Southern Oscillation cycle is widely documented as the most important source of interannual rainfall variability in the tropics. ROPELEWSKI & HALPERT (1987, 1989, 1996) identified tropical or sub-tropical regions all around the globe whose climate is affected by the ENSO cycle. ENSO predictors contribute to the forecasts of North African and NE Brazil seasonal rainfall issued by UKMO (FOLLAND *et al.* 1991, WARD & FOLLAND 1991). For comparison with the AGCM results, linear regression precipitation forecasts were made for gridpoints worldwide over the same period as the AGCM runs using two ENSO-related SST predictors. This was done to determine if the AGCMs could perform a simple empirical forecast and to find out whether there is any link between AGCM predictability and predictability from ENSO. The predictors used were the time series of 2 global SST Empirical Orthogonal Functions (EOFs) representing phases of ENSO. The first predictor was the time series of the first EOF of High Frequency (HF) SST anomalies over 1901-90 (fig. 1a). Prior to calculating the EOFs, HF data was created by filtering out interdecadal variability on timescales greater than 8 years so that patterns clearly representing ENSO could be calculated without distortion due to low frequency variability and climate change. Unfiltered data was used to calculate the EOF time series (the series of dot products between the EOF pattern and the SST anomaly patterns). The positive/negative

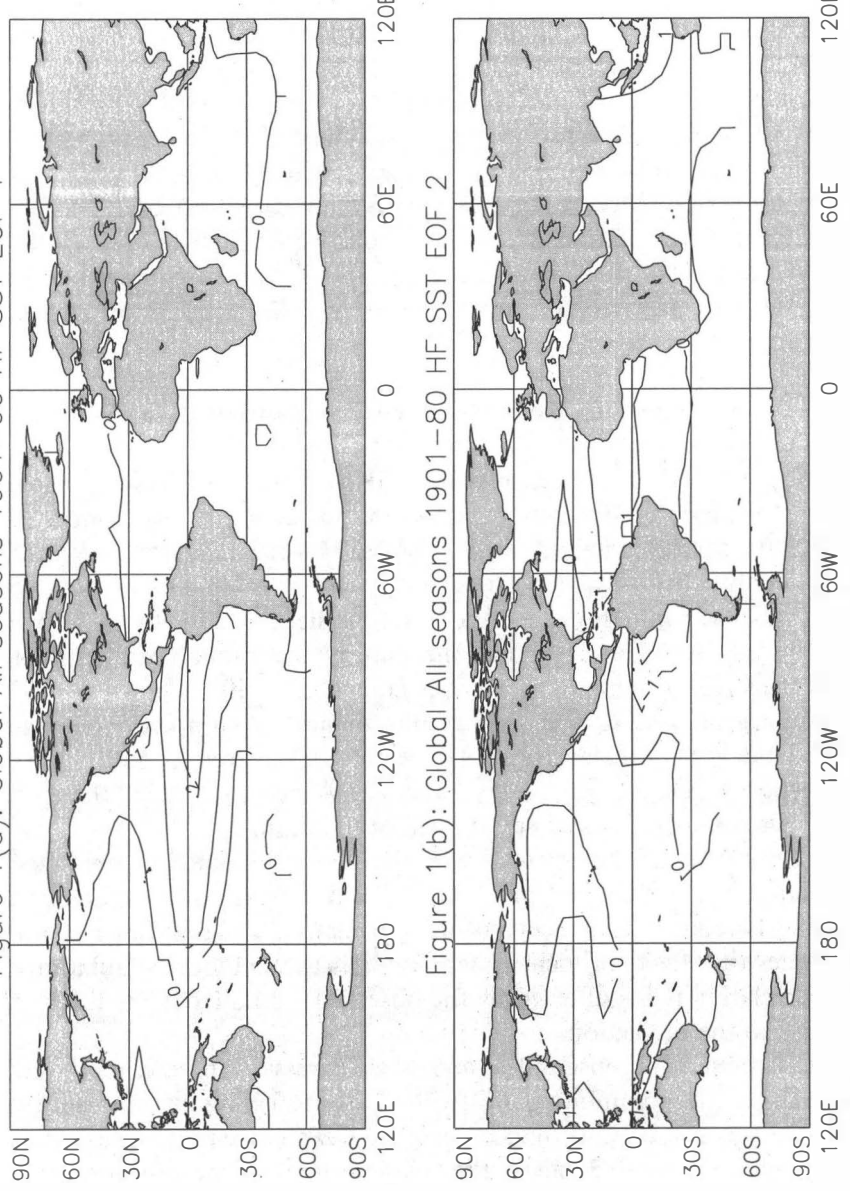


Fig. 1. — (a) Global All seasons 1901-90 HF SST EOF 1; (b) Global All seasons 1901-80 HF SST EOF 2.

phases of this EOF represent El Niño/La Niña events. The second predictor (fig. 1b) is the second EOF of high frequency SST anomalies. The positive/negative phases of this EOF represent SST early in a La Niña/El Niño event. The first and second EOFs are associated with 13 and 4 % of the total SST variance respectively.

These predictions differ importantly from the AGCM simulations as they are genuine forecasts assessed on independent data. September-November SST observations are used to predict December-February precipitation and December-February SST are used to predict March-May precipitation. The regression equations were calculated over 1901-78 and tested over 1979-90. Since these predictions are based on El Niño, they are henceforth referred to as El Niño Regression (ENR) predictions.

5. Verification using Observed Precipitation Data

HULME (1994) has made available to UKMO one of the best available datasets of observed monthly precipitation for land stations worldwide which have been gridded onto the same 2.5° latitude × 3.75° longitude grid used by the AGCMs. These data were used to assess the two sets of AGCM simulations and the ENR predictions. Due to the global scale of this study and to minimize noise, the rainfall simulations, predictions and observations were averaged to a 10° latitude × 15° longitude grid. Use of this grid results in almost complete coverage of all land areas outside the polar regions. However in data sparse areas such as centres of South America, Africa and Asia, the grid point values may only be based on just one station.

To measure skill, the correlation between the simulated or predicted precipitation and observed precipitation was calculated for every grid box and is referred to henceforth as "correlation". Using this measure eliminates the effects of local systematic bias in the model simulations. The correlation is not affected by the observed values having a different variance to the predictions.

The two sets of ensembles and the regression predictions were assessed over the common period 1979-90. For assessing the simulations, the nine member IC and the six member C20C ensemble means were used. Figures 2 and 3 show the spatial distribution of Significant Correlation (SC) of the C20C and IC ensemble means and of the ENR predictions. Boxes where the correlation from at least one method is significant at the 5 % level are shaded with a pattern dependent on

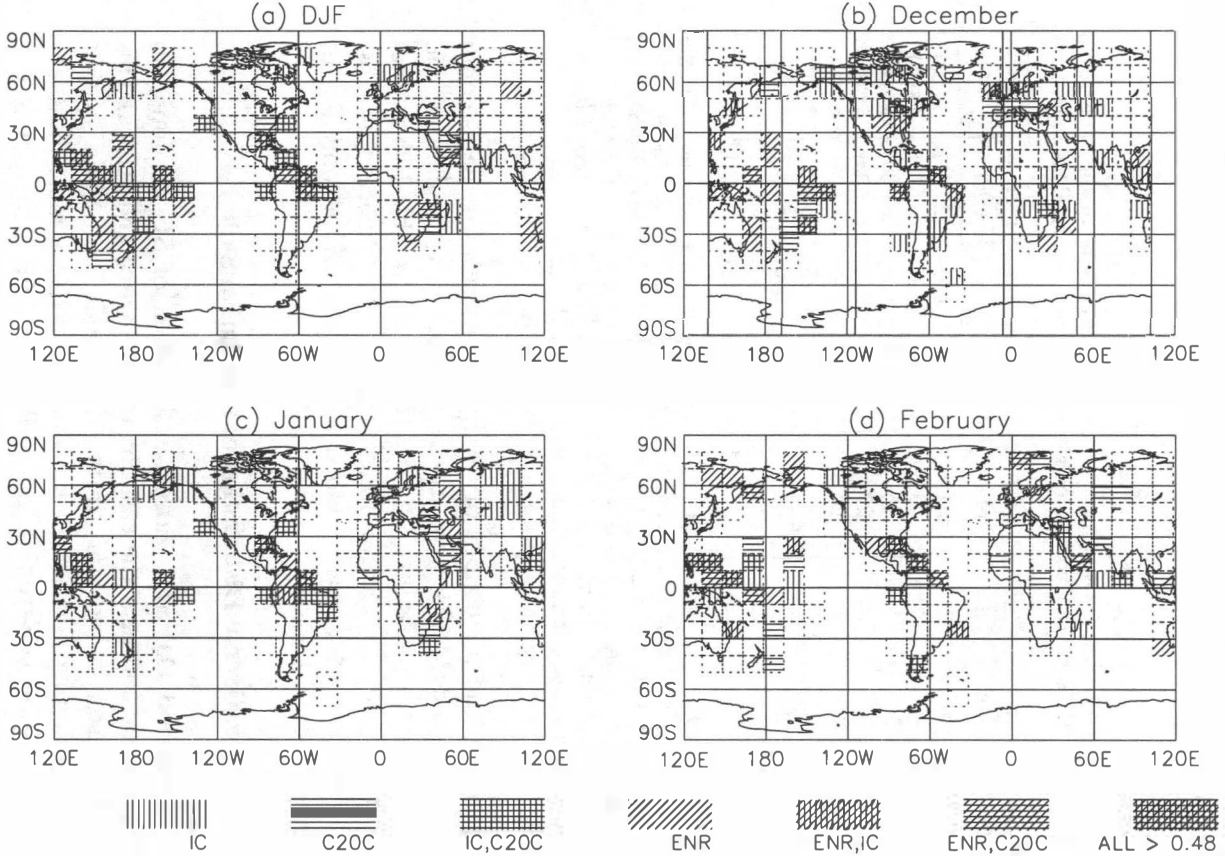


Fig. 2. — Comparison of three methods of predicting precipitation 1979/80-1989/90. Shaded boxes show where method(s) in key have 5 % significant correlation skill.

what combination of methods have SC. Boxes for which predictions are made but no method has SC are blank. Numbers of boxes with each type of shading are listed in Table 1.

Table 1

Number of 10 × 15 areas for which the following combinations of simulations and predictions have 5 % significant correlation globewide, poisson probabilities in brackets

Method Month	IC total	C20C total	ENR total	IC & C20C	ENR & IC	ENR & C20C	All
DJF*	29	28	31	15 (.04)	7 (.03)	12 (.01)	6 (.00)
Dec*	40	20	23	7 (.00)	9 (.01)	6 (.01)	4 (.00)
Jan*	31	25	16	14 (.00)	7 (.00)	6 (.00)	5 (.00)
Feb*	21	30	22	10 (.00)	8 (.21)	11 (.00)	5 (.00)
March*	27	26	24	15 (.00)	6 (.07)	5 (.08)	4 (.00)
MAM	50	43	42	25 (.01)	16 (.45)	15 (.08)	9 (.01)
March	76	26	24	18 (.00)	9 (.06)	5 (.01)	4 (.00)
April	23	27	17	11 (.02)	4 (.05)	6 (.14)	3 (.00)
May	22	25	36	7 (.00)	7 (.05)	7 (.02)	5 (.00)

IC runs for periods annotated with * use atmospheric initial conditions for the last nine days in November, the remainder use initial conditions for the last nine days in February (Dec = December, Jan = January, Feb = February). Probabilities shown are the probabilities of the observed totals from the two or more methods given the observed totals from the individual methods listed in the three left-hand columns. Probabilities are calculated using the Poisson equation.

Simulations and predictions of precipitation totals for the 3-month seasons DJF and MAM were assessed along with simulations and predictions for the individual months. The results in table 1 show that SC is much more extensive than expected by chance for most predictions (by chance, each method would have SC in only 5% of the boxes - about 10 boxes).

6. Overall Distribution of Correlation Skill

For the period DJF (fig. 2a), extensive areas of SC are found in the West Pacific and near the east coasts of America and Africa. This is the dry season in most of North Africa and South Asia so that the lack of extensive SC here is less important. SC is most prevalent in the tropics and sub-tropics, especially in coastal areas but is not prevalent in southern South America, West Australia and South West Africa however. The individual month assessments for December (fig. 2b), January (fig. 2c) and February (fig. 2d) show a similar

distribution of SC, the most notable exception being the IC predictions for December which have extensive SC in the northern extra-tropics.

In MAM the ITCZ moves north near the equator. The SC in March-May is less concentrated in particular areas but is generally more extensive than in DJF, particularly in Asia (fig. 3a). Average correlation is generally higher for the MAM predictions than for the DJF predictions (table 2). Only precipitation over land is assessed however and most of the ITCZ in DJF is over sea. Using analysis of variance, ROWELL (1996) found that for the C20C runs, there is usually better agreement between the ensemble members in predicting rainfall over tropical ocean areas than in predicting rainfall over land. Similar results have been found for the IC runs. The individual month assessments for MAM show SC to be quite scattered but correlation is generally higher than for the DJF individual months. For both DJF and MAM and for all three methods, 3-month simulations or predictions are generally more skilful than single-month simulations or predictions respectively.

Table 2

Average correlation from the simulations and predictions

	GLOBE			TROPICS (30 N - 30 S)		
	IC	C20C	ENR	IC	C20C	ENR
DJF*	.18	.16	.10	.22	.19	.14
Dec*	.29	.06	.08	.20	.06	.12
Jan*	.13	.11	.07	.18	.15	.09
Feb*	.08	.12	.13	.13	.17	.16
March*	.07	.11	.09	.14	.17	.14
MAM	.19	.17	.13	.28	.24	.19
March	.34	.11	.09	.36	.16	.14
April	.08	.15	.05	.13	.19	.09
May	.08	.10	.13	.14	.12	.16

IC runs for periods annotated with * use atmospheric initial conditions for the last nine days in November, the remainder use initial conditions for the last nine days in February.

7. The El-Niño Regression Predictions

ENR SC is confined mainly to the West Pacific and Caribbean regions with some scattered SC elsewhere. ENR correlation is generally lower than AGCM correlation which is expected because the ENR predictions are based on SST observed in advance of the rainfall season,

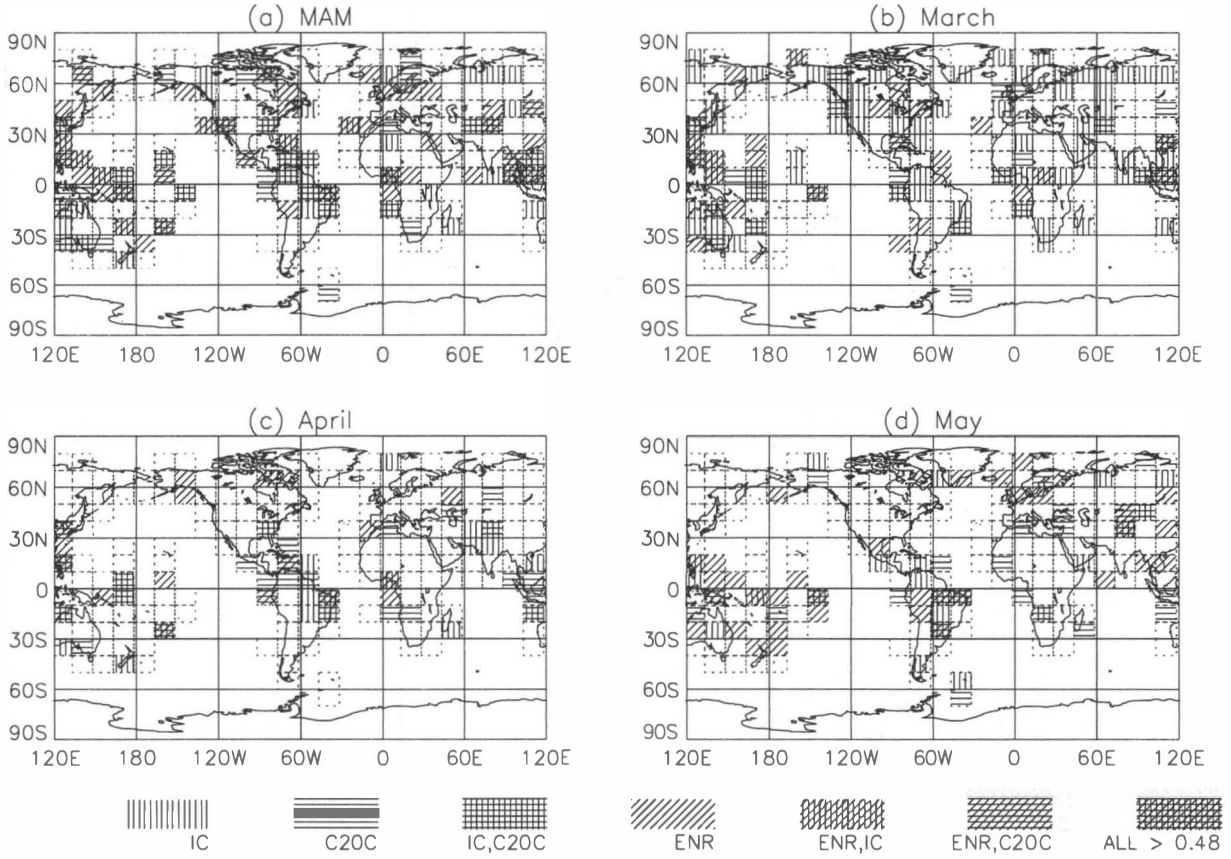


Fig. 3. — Comparison of three methods of predicting precipitation 1980-1990. Shaded boxes show where method(s) in key have 5 % significant correlation skill.

while the AGCM simulations are based on simultaneous SST and because ENR is based on just 2 predictor indices while the AGCMs use SST from all over the world. The locations of the significant ENR predictions correspond well with the results of ROPELEWSKI & HALPERT (1987, 1989, 1996). For example, DJF rainfall in North Brazil, South USA, the SW Tropical Pacific and SE Africa was linked to ENSO by ROPELEWSKI & HALPERT and was predicted with SC by ENR.

The number of areas with SC from ENR and at least one AGCM simulation (table 1, 5th and 6th columns) was generally less than the number of areas with SC from both AGCM simulations (table 1, 4th column) and not significantly higher than expected by chance in several months given the total number of areas with SC from each method (table 1, 1st, 2nd and 3rd columns). The insignificant probabilities in the 5th and 6th columns of table 1 suggest that in these months, much of the AGCM predictability is independent of ENSO and *vice versa.*

An interesting exception to the generally low ENR skill relative to the AGCM skill is in May when the ENR prediction skill becomes much more extensive than in previous months, particularly around the NW Atlantic and in Asia. In May ENR has higher average skill than the AGCM simulations inside or outside the tropics.

8. Impact of Initial Conditions on Correlation Skill

The IC correlation is expected to be slightly better than the C20C correlation on average because of the use of correct atmospheric initial conditions. For December-February (fig. 2a) the IC simulations do have marginally better correlation (table 2, average $r = 0.18$) than the C20C simulations ($r = 0.16$) or the ENR predictions ($r = 0.10$). The correlation is higher when assessment is restricted to the tropics but the scores for the three methods are in the same order. The difference between IC and C20C correlation could be due to initial conditions or a superior model being used for the IC runs.

The assessment of December simulations (fig. 2b) provides a strong clue to explaining the difference between IC and C20C correlation. The most notable difference between the DJF and December result is a substantially greater number of areas with SC from the IC simulations. This increased correlation for December relative to DJF can be attributed to the impact of relatively recent initial atmospheric conditions for the following reasons : a. no similar correlation increase is observed in the C20C simulations or ENR predictions which are

entirely based on sea temperatures ; b. the correlation increase is concentrated in areas where the correlations from C20C simulations or ENR predictions are insignificant. In fact the number of areas where there is SC from IC and from one or more of the other methods is reduced (table 1). The IC correlation increase is concentrated outside the tropics ; in the tropics, average correlation falls from 0.22 to 0.20 (table 2).

In January (fig. 2c), November initial conditions have less impact on IC correlation. IC still has higher correlation than the IC simulations or ENR predictions however. In February (fig. 2d) the IC correlation is much less than in January or December. In contrast correlation from C20C in February is generally higher than correlation from IC in February or from C20C in December or January.

The simulations for March to May show a similar story. SC from IC is concentrated in March (fig. 3b), when the late February initial conditions have most impact but IC correlation falls off quickly in April and May (figs. 3c, 3d) while C20C shows a modest improvement in April and May relative to March. Also when March is simulated using atmospheric initial conditions for late November instead of for late February, correlation from the IC simulations is no longer higher than correlation from the C20C simulations (fig. 4).

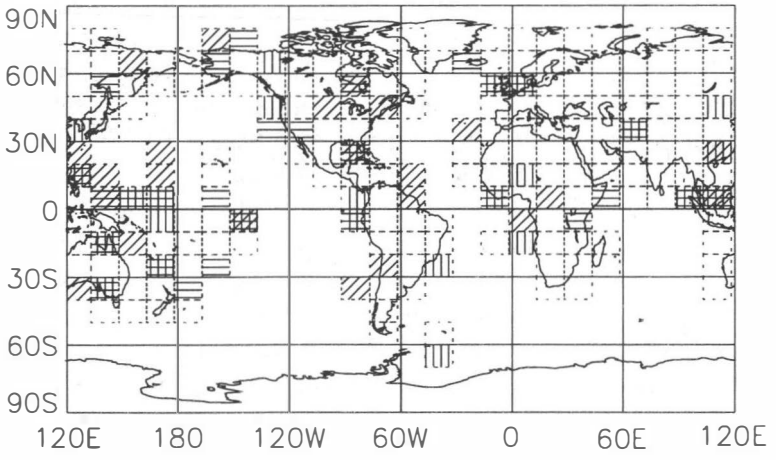


Fig. 4. — Same as fig. 3b, but IC simulations use November atmospheric initial conditions.

9. Conclusions

Precipitation simulations by 2 AGCMs were assessed alongside empirical precipitation predictions for eleven years. Conclusions from this study should be taken with caution as the period of assessment is shorter than ideal. The grid boxes used are large and it should not be assumed that if a grid box average is predictable then everywhere within the box is predictable. Precipitation observations for some of the boxes were sparse with the box means not always giving a very good indication of actual average precipitation within the box area. To check on how this problem may affect results, the study was repeated with 2.5° latitude × 3.75° longitude boxes. While there were many local differences, conclusions a to e below also applied to the smaller grid boxes suggesting that the conclusions are, to a certain extent, independent of box area size.

a. Both AGCM simulations and the ENR predictions have significant skill in predicting rainfall, especially in the tropics. AGCM skill is generally a little higher than ENR skill.
b. There is some overlap in the distribution of prediction skill particularly in the tropical West Pacific. However most AGCM predictability is independent of the ENSO-based regression predictions and *vice versa*, demonstrating (not surprisingly) that other SST patterns are important besides ENSO.
c. The IC predictions have slightly higher skill than the C20C predictions when predicting rainfall totals for three months but this difference in skill is concentrated in the first month and is probably due to the use of correct atmospheric initial conditions by the IC runs. There is no evidence from these results that one model was better than the other.
d. Over land areas, March-May predictions are better than December-February.
e. May rainfall in the North Atlantic seems predictable from ENSO. Further research into this link is recommended.

This investigation may not have demonstrated all the precipitation predictability from the AGCM simulations or the ENR predictions. For example there may be significant skill in predicting a rainfall pattern over a wide area but insignificant skill in predicting rainfall for a region within this area.

ACKNOWLEDGEMENTS

Thanks to : David Rowell, Chris Folland, David Sexton, John Davies and Alison Renshaw, for producing and providing the results of the C20C experiments ; Mike Hulme for providing observed rainfall data ; Mike Harrison, David Richardson, Anthony Evans and Ruth Evans for producing and providing the results of the IC experiments ; also to Mike Davey for assisting me in the drafting of this paper. The UK Department of the Environment partially supported the C20C experiments under contract PECD7/12/37. The European Commission partially supported the C20C experiments under contract EV5V-CT92-0121 and IC experiments under contract ENV4-CT95-0109.

REFERENCES

EVANS, A. D. L. & GRAHAM, R. J. 1998. Seasonal predictability experiments with the UKMO model and joint model ensembles. — *In* : Research activities in oceanic and atmospheric modelling, awaiting publication by WMO.

FOLLAND, C. K., WARD, M. N., OWEN, J. A. & COLMAN, A. W. 1991. Prediction of seasonal rainfall in the Sahel region of Africa using empirical and dynamic techniques. — *J. Forecasting*, **10** : 21-56.

HALL, C. D., STRATTON, R. A. & GALLANI, M. L. 1995. Climate simulations with the unified model : AMIP runs. — UK Meteorological Office, Climate Research, Technical Note 61.

HULME, M. 1994. Validation of large-scale precipitation fields in general circulation models. — *In* : DEBOIS, M. & DESALMUND, F. (eds.), Global precipitation and climate change, NATO ASI Series, Vol. I (26), Springer-Verlag, Berlin, pp. 387-405.

LEGATES, D. R. & WILLMOTT, C. J. 1990. Mean seasonal and spatial variability in guage-corrected, global precipitation. — *Int. J. Clim.*, **10** : 111-127.

PARKER, D. E., FOLLAND, C. K., BEVAN, A., WARD, M. N., JACKSON, M. & MASKELL, K. 1995. Marine surface data for analysis of climatic fluctuations on interannual to century timescales. — *In* : MARTISON *et al.* (eds.), Natural Climate Variability on decade to century timescales. National Academy Press, Washington DC, pp. 241-250.

REYNOLDS, R. W. & SMITH, T. M. 1994. Improved global sea surface temperature analysis using optimum interpolation. — *J. Clim.*, **7** : 929-948.

RICHARDSON, D. S. & HARRISON, M. S. J. 1996. The use of ensemble forecasting techniques at the UK Meteorological Office now and in the future. — UK Meteorological Office, Forecasting Research, Technical Report 185.

ROPELEWSKI, C. F. & HALPERT, M. S. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. — *Monthly Weather Rev.*, **115** : 1606-1626.

ROPELEWSKI, C. F. & HALPERT, M. S. 1989. Precipitation patterns associated with the high index phase of the Southern Oscillation. — *J. Clim.*, **2** : 268-284.

ROPELEWSKI, C. F. & HALPERT, M. S. 1996. Quantifying Southern Oscillation - precipitation relationships. — *J. Clim.*, **9** : 1043-1059.

ROWELL, D. P. 1996. Using an Ensemble of multi-decadal GCM simulations to assess potential seasonal predictability. — UK Meteorological Office, Climate Research, Technical Note 69 (also in preparation for *J. Clim.*).

WARD, M. N. & FOLLAND, C. K. 1991. Prediction of seasonal rainfall in the north Nordeste of Brazil using eigenvectors of sea surface temperatures. — *Int. J. Clim.*, **11** : 711-743.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 328-340 (1998)

The Evolution of Atmosphere Circulation Anomalies during El Niño - Southern Oscillation

by

Daria GUSCHCHINA*, E. SEMENOV * & S. LAKEEV **

KEYWORDS. — Atmosphere Circulation Anomalies in Tropics ; El Niño - Southern Oscillation ; Tropical Meteorology.

ABSTRACT. — The empirical model of synoptic-scale circulation in tropics has been developed on the ground of generalization of all aerosynoptic information available for the last dramatic ENSO cases (1982-83, 1986-87, 1991). The evolution of circulation characteristics was studied on a basis of velocity potential, stream function and vertical velocity distribution analysis. It was shown the main circulation anomalies can be revealed even on the averaged fields that point to the stable evolution and common nature of ENSO phenomenon. The characteristics of ENSO atmosphere circulation anomalies in low and upper troposphere were emerged.

MOTS-CLES. — Anomalies de circulations atmosphériques tropicales ; El Niño - Oscillation Australe ; Météorologie tropicale.

RESUME. — *L'évolution des anomalies de la circulation atmosphérique lors des phénomènes El Niño - Oscillation Australe.* — Le modèle de circulation empirique d'échelle synoptique dans les tropiques a été développé sur base d'une généralisation de toute l'information aérosynoptique disponible pour les derniers cas dramatiques des phénomènes ENSO (1982-83, 1986-87, 1991). L'évolution des caractéristiques de circulation fut étudiée sur base du potentiel de vitesse, de la fonction de courant et de l'analyse de la distribution de la vitesse verticale. Il fut démontré que les anomalies principales de circulation peuvent même se révéler dans les champs moyennés, indiquant l'évolution stable et la nature commune des phénomènes ENSO. Les caractéristiques des anomalies de circulation atmosphérique d'ENSO dans la basse et la haute troposphère furent démontrées.

* Meteorological Department, Moscow State University, Leninskie gory, Moscow, 117899 (Russia).

** Karpov Institute of Physical Chemistry, 10 Vorontsovo pole st., Moscow, 103064 (Russia).

TREFWOORDEN. — Anomalieën in tropische atmosferische stromingen ; El Niño - Zuidelijke Oscillatie ; Tropische meteorologie.

SAMENVATTING. — *De evolutie van de atmosferische circulatie-anomalieën tijdens de El Niño - Southern Oscillation gebeurtenissen.* — Het empirische synoptische schaalmodel voor de circulatie in de tropen werd ontwikkeld op basis van de veralgemening van alle aërosynoptische informatie beschikbaar ten tijde van de laatste dramatische ENSO-gevallen (1982-83, 1986-87, 1991). De evolutie van de circulatiekarakteristieken werd bestudeerd op basis van het snelheidspotentiaal, stroomfunctie en verticale snelheidsverdelingsanalyse. Er werd aangetoond dat er belangrijke circulatie-anomalieën waargenomen worden zelfs op de gemiddelde velden die wijzen op de stabiele evolutie en algemene aard van ENSO-fenomenen. Het karakteristieke beeld van ENSO atmosferische circulatie-anomalieën in de lagere en hogere troposfeer werd duidelijker.

*
* *

El Niño - Southern Oscillation (ENSO) phenomenon is one of the prominent examples of interannual climate variability in the system ocean-atmosphere. The study of these events is one of the hottest problems because of their dramatic impact on the climate variability all around the world. El Niño - Southern Oscillation occurs quasi-periodically with an interval of three to ten years. It appears in the form of a warming of the tropical Pacific as well as a global reorganization of atmosphere circulation (CANE 1986). Through the teleconnections ENSO has pronounced effects on the climate variability in the mid latitudes (ENFIELD 1989).

The mechanism of ENSO is based on the interaction of tropical troposphere and the upper level of the ocean, particularly : the SST anomalies affect the atmosphere changing the direction of air currents, which in turn excite the paquet of various-scale waves : Kelvine waves and Rossby waves. At the beginning of the cycle these ocean waves contribute to the growth of anomalies in ocean and atmosphere through the mechanism of positive and negative feedback, and within some period these waves cause the inversion of the ENSO cycle (GRAHAM & WHITE 1988).

In the early 80s the generalized scenario of ENSO evolution was created which received the name of canonical El Niño (RASMUSSON & CARPENTER 1982). But since the late 70s the nature of the events has significantly changed (WANG 1995). In the light of these changes,

the creation of a new chart of ENSO evolution was of particular interest.

In this study we have tried to develop an empirical model of tropical atmosphere circulation under ENSO conditions on the ground of generalization of all aerosynoptic information available for the last three dramatic ENSO events (1982-83, 1986-87, 1991-92). Since this model is concerned with the evolution of circulation characteristics, the processes in the ocean are not taken into consideration.

In the framework of this model the composite fields of the principal circulation characteristics (vertical velocity, velocity potential and stream function) were plotted. The calculations are based on the mean monthly wind data received from NMC objective analysis. On the ground of calculation results the distribution maps of all characteristics on the main isobaric surfaces of tropical troposphere were plotted (850, 700, 500 and 200 hPa) as well as zonal and meridional cross-sections.

The meteorological characteristics mentioned above were chosen from the following reasons :

— The common analysis of velocity potential and stream function allows to receive the complete view above the tropical circulation in horizontal and vertical plane ;
— The velocity potential representing the divergent part of atmosphere circulation allows to investigate the structure, intensity and space localization of zonal and meridional circulation cells of tropical troposphere, which can be considered as principal structure elements of tropical circulation mechanism ;
— The stream function, representing the vortex part of the atmosphere circulation, is an integral parameter reflecting the atmosphere circulation in horizontal plane and allowing to localize the main atmosphere forcing centres in tropics and the directions of leading currents in the upper and low troposphere ;
— The vertical motions are the third important components of the circulation system in tropics because they reflect the processes taking place in the whole width of atmosphere and they influence the various meteorological events.

The velocity potential and the stream function were calculated on the ground of Poisson equation solution with peculiar set boundary conditions (KRISHNAMURTI 1973).

We were interested not only in spatial but in time distribution of circulation characteristics as well. In this connection, to analyse the

evolution of the event we subdivided the event into six phases characterizing the key moments of the ENSO cycle: the normal conditions (1st phase), two development phases (2nd and 3rd phase), the major phase (4th phase), the mature phase (5th phase) and post-El Niño conditions (6th phase). All circulation characteristics were averaged within each phase.

Since the empirical model proposed takes account of a pure circulation, only the phase-subdivision technique was based on the circulation criterion, particularly on the analysis of localization and intensity changes of the equatorial zone of westerly winds over the Pacific Ocean. We have chosen this specific criterion since the most dramatic changes in atmosphere circulation, related to the anomalies of the whole system ocean-atmosphere and maintaining the ENSO development, occur in the region of the equatorial westerlies. In the phase-subdivision model we have also taken into consideration the evolution of anomalies in the Pacific, in particular the evolution of SST anomaly. The principal distinction of the proposed phase-subdivision method is its independence on the specific months of the year which allows to use the advanced model for any event whenever it onsets.

Let us analyse the empirical model components beginning from the velocity potential.

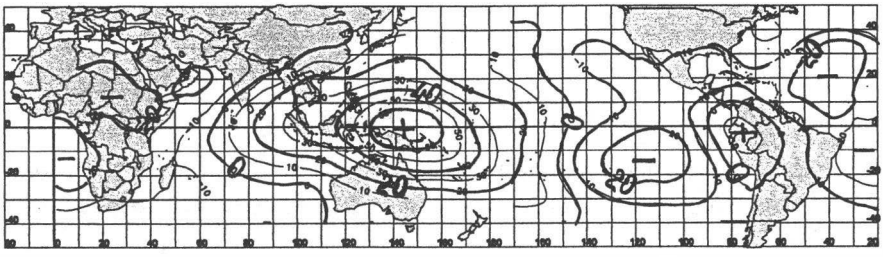
The Analysis of the Velocity Potential during ENSO

The analysis of velocity potential distribution allowed to study the intensity and localization of zonal and meridional vertical circulation cells in tropics and primarily to follow the evolution of Walker cell which may be considered as one of the most important units of the tropical circulation mechanism.

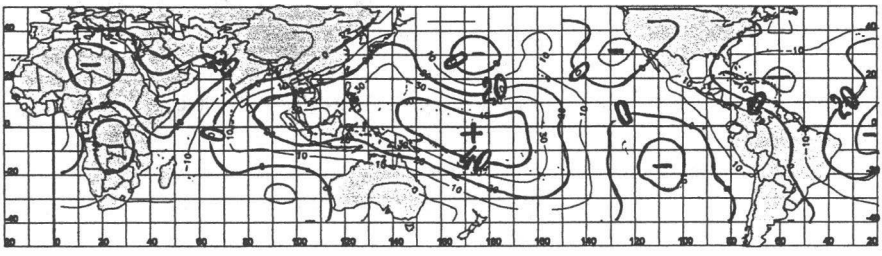
Analysing the velocity potential distribution it is necessary to take into account the fact that the ascending branch of the vertical cell coincides with the zone of a negative potential in the low troposphere and of a positive one in the upper troposphere, the descending branch corresponds to the inverse distribution (fig. 1).

The principal anomaly of zonal circulation in vertical plane which can be revealed on the maps of potential distribution is the consequent shift of Walker circulation cell over the Pacific to the East and then its return to the West during the period of the ENSO cycle leading to the large-scale reorganization of air currents in the low and upper

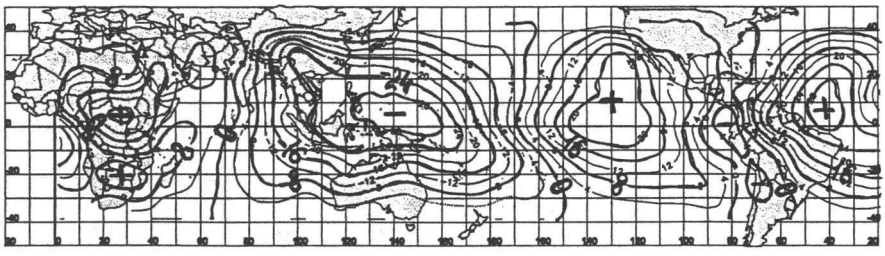
200 hPa 1 phase a)



200 hPa 4 phase b)



850 hPa 1 phase c)



850 hPa 4 phase d)

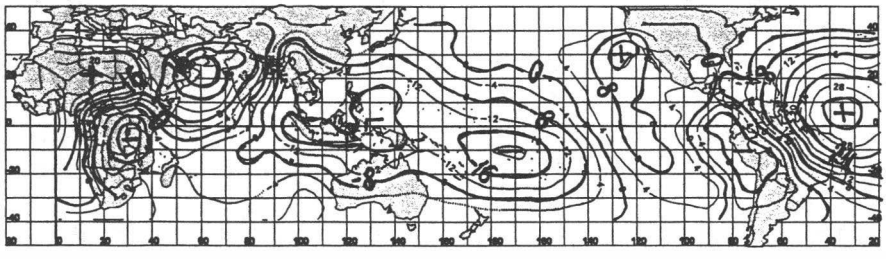


Fig. 1. — The velocity potential distribution (unit 10^5 m^2 s^{-1}). Averaged over three ENSO events (1982-83, 1986-87, 1991).

troposphere over the Pacific Ocean. One can see that during the period from the first phase (figs. 1a, 1c) to the major phase (figs. 1b, 1d) the centre of convergence in the low troposphere and the centre of divergence in the upper troposphere move from the region of maritime subcontinent Indonesia to the central Pacific, while the ascending branch intensifies. On the other hand, the intensity of the descending branch decreases and it moves too to the East in the direction of South American coasts. As a result of the Walker cell shift, the zone of equatorial westerlies, one of the most important elements of tropical circulation characteristics of the Indian Ocean monsoon regions, moves to the central Pacific replacing the typical trade winds transport.

In addition, it should be noted that during the major phase the intensity of the ascending branch over South America increases significantly being a possible cause for the extreme precipitation observed under ENSO conditions over this continent (figs. 1b, 1d). Over the African continent we observe the intensification of the descending branch which in turn can result in severe droughts typical of the El Niño period (figs. 1b, 1d).

The second important feature characterizing the anomalous circulation conditions during ENSO is the shift tendency of negative potential maxima in the low troposphere, positive potential maxima in the upper troposphere and Walker circulation cell linked with them, from the continent to the oceans as compared to normal circulation conditions. This fact emphasizes the process of heating centres' redistribution within the tropical zone. The principal heating centre during the period of ENSO culmination in contrast to normal circulation conditions is localized not over the Eurasian but over the Pacific Ocean, which can lead to serious climatic consequences.

The 5th phase of ENSO evolution corresponds to the process of normal circulation condition restoration; during this phase the consequent shift to the West of the Pacific Walker circulation cell is observed. The picture of vertical zonal circulation cell localization during the 6th phase of the ENSO cycle is practically opposite the picture during the first phase.

The Analysis of the Stream Function during ENSO

The analysis of stream function distribution allowed to reveal the causes for anomalous atmosphere circulation patterns observed during ENSO, particularly to localize the basic atmosphere centres, determine

their shifts and to analyse the direction of principal air currents in the upper (200 hPa) and low (850 hPa) troposphere.

The characteristic feature of the stream function field evolution during the ENSO event is the formation and shift to the central Pacific of the near-equatorial cyclonic vortex in the system of SHCZ in the low troposphere and two anticyclonic vortexes over the equator in the upper troposphere resulting in the large-scale redistribution of horizontal currents in the whole depth of the atmosphere.

During the period of ENSO development in the upper troposphere we can observe the shift to the East of the equatorial upper troposphere easterly wind zone, normally localized over Indonesia and Indian ocean (figs. 2a, 2b). This shift is due to the formation of two upper troposphere anticyclones in the equatorial regions over the Pacific, the easterly currents zone appearing in their equatorial periphery. At the same time in the low troposphere in the near-equatorial regions the centre of cyclonic vorticity shifts to the East (figs. 2c, 2d). The formation of this centre results in propagation of the equatorial westerly zone to the central regions of the Pacific.

An important feature of the stream function field evolution is the earlier development of an anomalous circulation system in the upper troposphere as compared to the low troposphere processes (figs. 2b, 2d). This fact is in a good agreement with the results of our correlation analysis (GUSHCHINA *et al.* 1995) and it may be of prediction significance because the reorganization of atmosphere circulation in the upper troposphere can be considered as a precursor of El Niño culmination.

The evolution of basic atmosphere centres is in excellent accordance with the evolution of vertical circulation cells that allow to suggest that it is the formation of new cyclonic and anticyclonic vortexes and the changes in their localization under ENSO conditions that define the reorganization of the vertical cell system.

The Analysis of Vertical Motions during ENSO

For more detailed investigation of the structure, intensity and space heterogeneity of the vertical motion field during El Niño the composite fields of vertical velocity analogue were plotted.

The analysis of vertical motion fields allowed to reveal not only the anomalies of vertical circulation cells but to plot the complete picture of anomalous circulation in vertical plane in tropical and

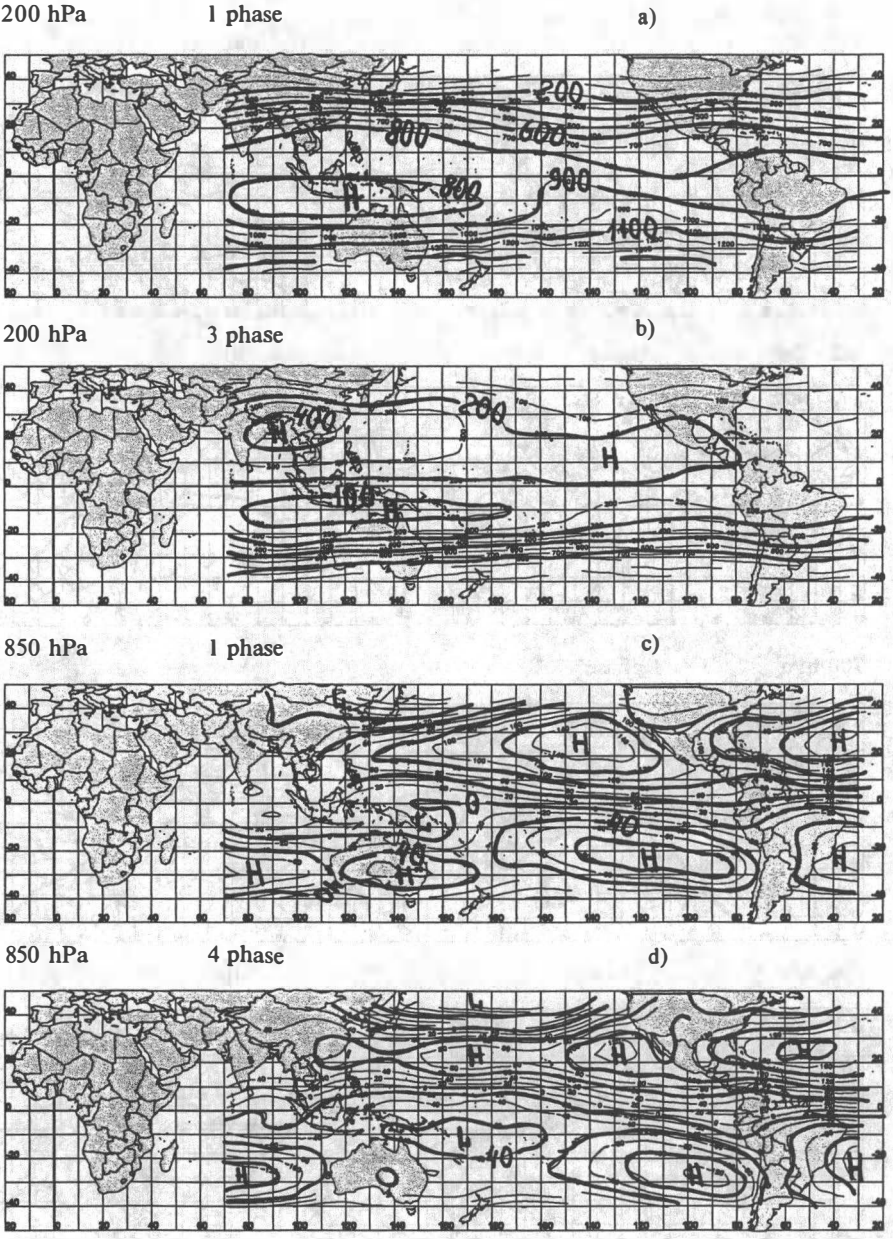


Fig. 2. — The stream function distribution (unit 10^5 m^2 s^{-1}). Averaged over three ENSO events (1982-83, 1986-87, 1991).

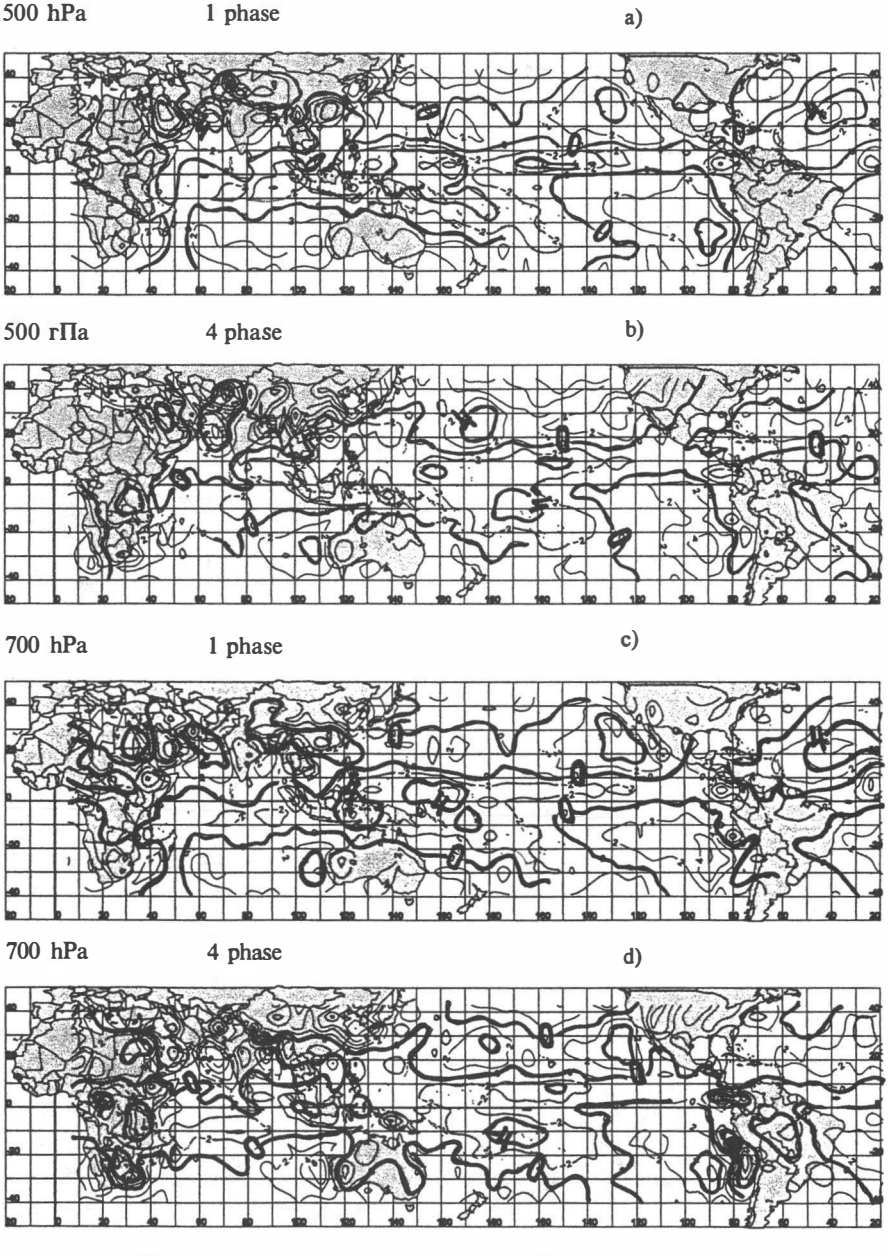


Fig. 3. — The vertical velocity distribution (unit 10^4 hPa s^{-1}). Averaged over three ENSO events (1982-83, 1986-87, 1991).

subtropical latitudes and to follow its evolution during the ENSO cycle. The analysis of vertical motion fields shows that a significant transformation of the vertical circulation occurs during the ENSO event.

The picture of vertical motions observed under normal circulation conditions is characterized by a narrow band of ascending currents localized near the equator over the central and eastern regions of the Pacific, which is typical of the trade-wind type of ITCZ (figs. 3a, 3c). The maximum of vertical velocity is situated over the western Pacific and Indonesia. During the culmination period the picture of vertical motions over the Pacific looks more like the vertical circulation system observed over the Indian Ocean during the period of the Indian summer monsoon. Namely a strong and intensive zone of ascending motions appears over the Pacific and spreads over the whole tropical Pacific regions, the maximum of vertical velocities shifts to the central Pacific to the Cook islands (figs. 3b, 3d). By its structure, intensity, meridional extent and vertical scale this zone is similar to the system of vertical currents observed in the monsoon type of ITCZ.

During the period of ENSO culmination the second maximum of ascending vertical motions appears over South America in the region of Bolivia and Chile (figs. 3b, 3d). The formation of the intensive centre of air rising indubitably is the cause for catastrophic precipitation occurring over the Pacific coasts of South America under the ENSO conditions.

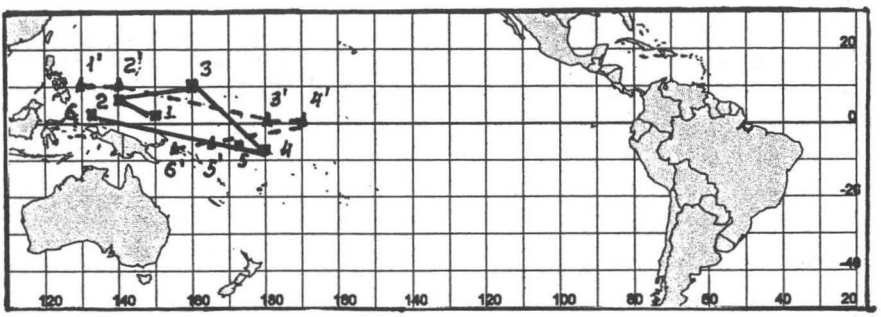
As a result of the vertical velocities' distribution analysis we can suggest that the characteristic feature of vertical circulation evolution during El Niño is the formation and latter disappearance of developed ITCZ of monsoon type over the tropical Pacific Ocean with inherent intensive vertical motions spreading over the whole troposphere.

The fact that the principal ENSO-associated anomalies were revealed even in the mean fields points to the common nature and stable evolution of the event. However, each case was characterized by its specific features of atmosphere and ocean anomalies, resulting from specific intensity, localization and onset time of the event.

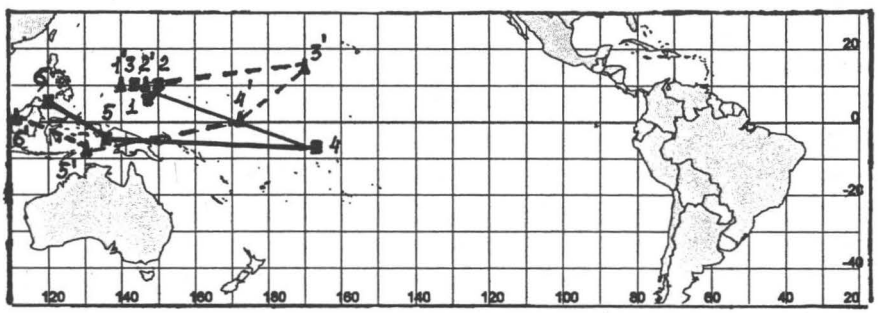
For example, the ENSO of 1982-83 was unprecedented for the space scale, duration and intensity of anomalies in the atmosphere and Pacific Ocean. This fact is well represented in the evolution of all circulation parameters. The empirical model was checked on the basis of independent data from El Niño of 1994-95.

The comparison of velocity potential and stream function fields for the specific phase showed that during the ENSO of 1994-95 similar

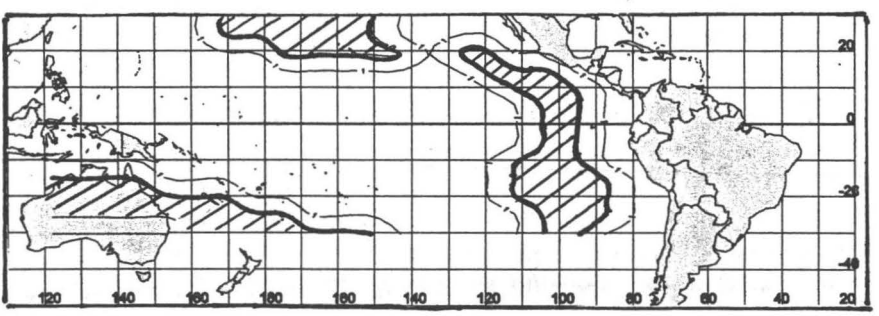
a)


1'
2'
3
2
1
3'
4'
4
6'
5'
5
120
140
160
180
160
140
120
100
80
60
40
20
0
-20
-40

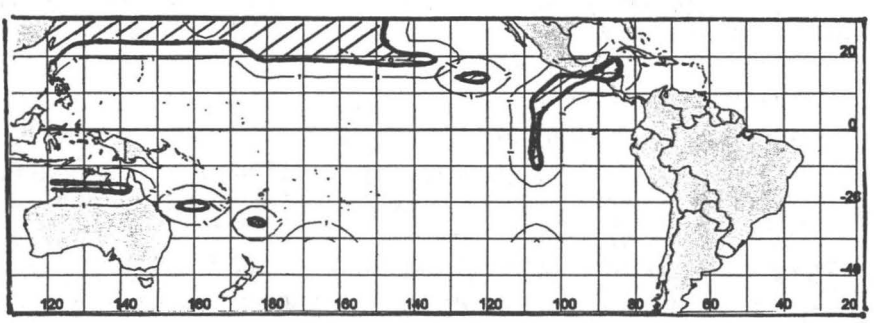
b)


1
3
2'
2
3'
4
5
1
4
5'
120
140
160
180
160
140
120
100
80
60
40
20
0
-20
-40

c)


120
140
160
180
160
140
120
100
80
60
40
20
0
-20
-40

d)


120
140
160
180
160
140
120
100
80
60
40
20
0
-20
-40

anomalies of the circulation parameters were observed, with a good agreement between the shifting trajectories being observed (figs. 4a, 4b). The coefficients of field accordance were calculated and the maps of accordance between the circulation fields for 1994-95 and the model results were plotted. Their analysis suggests that in the regions where the maximum ENSO-associated anomalies are observed (shaded regions on fig. 4c) a good agreement between two fields exists (white areas on fig. 4d).

Eventually, the results of this checking showed that an independent event can be described in the frame of the evolution scenario suggested in this empirical model. The best agreement is characteristic of the onset and culmination phases.

Conclusion

The new generalized scenario of ENSO evolution was created on the basis of the analysis of principal circulation parameters. This scenario can be considered as a new scheme of the event in terms of the change in ENSO characteristics since the early 80s.

REFERENCES

CANE, M. A. 1986. El Niño. — *Ann. Rev. Earth Planet Sci.*, **14** : 43-70.

ENFIELD, D. B. 1989. El Niño, past and present. — *Rev. Geophys.*, **27** : 159-187.

GRAHAM, N. E. & WHITE, W. B. 1988. The El Niño cycle : Pacific Ocean-atmosphere system. — *Science*, **240** : 1293-1302.

GUSHCHINA, D. Y., LAKEEV, S. G. & SEMENOV, E. K. 1995. The anomalies of vertical circulation in the tropical troposphere during El Niño Southern Oscillation. — *In* : Proceedings of the International Scientific Conference for TOGA (Melbourne, Australia, 2-7 April 1995), WMO/TD - No. 717 (1) : 241-245.

KRISHNAMURTI, T. N. 1973. Workbook on numerical weather prediction for the tropics for the training of class 1 and class 2 meteorological personnel. — WMO No. 669, Geneva, 355 pp.

←

Fig. 4. — Trajectories of velocity potential maximum during ENSO for : a) 200 hPa ; b) 850 hPa - the field accordance for velocity potential at the surface 200 hPa ; c) accordance between the first and the fourth phases (on the empirical model data) ; d) accordance between the 1994-95 and model data during the fourth phase. —— averaged (empirical model) data ; – – – 1994-95 data.

RASMUSSON, M. E. & CARPENTER, T. N. 1982. Variations in the tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/ El Niño. — *Monthly Weather Rev.*, **110** : 354-384.

WANG, B. 1995. Interdecadal changes in El Niño onset in the last four decades. — *In* : Proceedings of the International Scientific Conference for TOGA (Melbourne, Australia, 2-7 April 1995), WMO/TD - No. 717 (1) : 88-92.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 341-354 (1998)

Statistical Method of Forecasting the Probability of Tropical Cyclone Recurvature in the Philippines

by

Esperanza CAYANAN * & Carina LAO *

KEYWORDS. — Forecast ; Tropical Cyclone ; Recurvature ; Philippines.

ABSTRACT. — A statistical method to predict the probability of recurvature of tropical cyclones affecting the Philippines was developed using surface and upper-air observations from Japan, Korea and China stations. The predictors include surface pressure, geopotential heights and upper-level winds and temperature. In the generation of forecast equations, stepwise regression analysis was applied to the selected predictor data set. Six pairs of recurving and non-recurving tropical cyclones chosen from a nineteen-year (1972-1990) tropical cyclone archive was utilized as developmental data set. Forecast verification was conducted using twelve (12) independent cases randomly selected from the 1991-1994 data set. The equations with predictors observed at Shanghai and Beijing (Equation 3) and Chichijima and Ryukyu (Equation 2) can predict recurvature better than the equation with predictors observed at Hachijojima and Pohang (Equation 1). However, in their total performance including the prediction of non-recurvature, Equation 1 and Equation 3 obtained a higher percentage of correct forecast.

MOTS-CLES. — Prédiction ; Cyclone tropical ; Recourbure ; Philippines.

RESUME. — *Méthode statistique de prévision de la probabilité de recourbure des cyclones tropicaux aux Philippines.* — Une méthode statistique de prévision de la probabilité de recourbure des cyclones tropicaux affectant les Philippines a été développée au moyen d'observations à la surface et en altitude en provenance de stations japonaises, coréennes et chinoises. Les variables d'entrée sont la pression atmosphérique à la surface, les hauteurs géopotentielles, les vents en altitude et la température. Dans la génération des équations de prévision, une régression progressive a été appliquée au jeu de données de prédiction sélectionné. Six paires de cyclones présentant des aspects de

* Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Quezon City (1104) (Philippines).

recourbure et de non-recourbure ont été extraites des archives de cyclones tropicaux (1972-1990) comme jeu de données de développement. La vérification de la prévision a été assurée en utilisant douze cas indépendants choisis dans la période 1991-1994. Les équations des prédicteurs observés à Shangai et Beijing (équation 3) et Chichijima et Ryukyu (équation 2) peuvent mieux prévoir la recourbure que l'équation des prédicteurs à Hachijojima et Pohang (équation 1). Néanmoins, dans leur performance totale incluant la prévision de non-recourbure, les équations 1 et 3 obtenaient un pourcentage plus élevé de prévision correcte.

TREFWOORDEN. — Voorspelling ; Tropische cycloon ; Afbuiging ; Filippijnen.

SAMENVATTING. — *Statistische methode voor het voorspellen van de waarschijnlijkheid van afbuiging van tropische cyclonen in de Filippijnen.* — Een statistische methode om de waarschijnlijkheid van de afbuiging van tropische cyclonen die de Filippijnen treffen te voorspellen werd ontwikkeld, daarbij gebruik makend van Japanse, Koreaanse en Chinese oppervlaktewaarnemingen en waarnemingen van de hogere luchtlagen. De predictoren omvatten de atmosferische druk aan de oppervlakte, de geopotentiële hoogte, en de wind en de temperatuur in de bovenste luchtlagen. In de ontwikkeling van de voorspellingsvergelijkingen werd een stapsgewijze regressieanalyse toegepast op de geselecteerde predictorendataset. Zes paren van afgebogen en niet-afgebogen tropische cyclonen werden geselecteerd uit een archief van waarnemingen van tropische cyclonen uit de negentienjarige periode 1972-1990 die gebruikt werden als basisdataset. De verificatie van de voorspelling werd uitgevoerd op twaalf (12) onafhankelijke en op toevallige wijze geselecteerde gebeurtenissen uit de 1991-1994 dataset. De vergelijkingen die gebruik maken van de waargenomen parameters te Shanghai en Beijing (vergelijking 3) en Chichijima en Ryukyu (vergelijking 2) kunnen de afbuiging beter voorspellen dan de vergelijking die gebruik maakt van de geobserveerde predictoren te Hachijojima en Pohang (vergelijking 1). Nochtans, als geheel, met inbegrip van de voorspelling van de niet-afbuiging, bereiken vergelijkingen 1 en 3 een hoger percentage van correctheid wat de voorspelling betreft.

1. Introduction

Like in any tropical country, tropical cyclone is considered to be the most important weather phenomenon in the Philippines. An average of nineteen tropical cyclones enter the Philippine Area of Responsibility (PAR), nine of which cross and affect the country each year. In most cases, these cause tremendous damage and loss of life. More accurate forecasts of the tracks of these cyclones can allow more

timely preparations and therefore can reduce damage if not totally avoid it.

One aspect which is considered in tropical cyclone track forecasting is recurvature. According to the Joint Typhoon Warning Center (JWTC 1988) in Guam, tropical cyclone recurvature is the turning of a tropical cyclone from an initial path west and poleward to east and poleward. The same definition was adopted in this study. Most of the tropical cyclones that affect the Philippines originate in the Pacific Ocean moving on a west and poleward direction. Generally, recurvature occurs, hence the Philippines is spared from the rage of tropical cyclones. If recurvature is predicted before the tropical cyclone reaches the land but it did not recurve, unprepared residents in the country will be greatly affected which consequently results to greater damage. However, if the cyclone is predicted to move in a more or less west and poleward direction but it recurved, the country is spared from the damage. In either case, incorrect forecasts cause the public to have less confidence in forecast warnings the next time a cyclone threatens the area. In other words, credibility is lost.

Many studies have been made worldwide on tropical cyclone motion, like the studies of CHAN (1984), HOLLAND (1984), PIKE (1985), ELSEBERRY *et al.* (1988, 1992, 1993) and others. In the Philippines, only a few have been published with respect to statistical tropical cyclone track forecasting.

For its main objective, this study aims to derive statistical forecast equations to predict the probability of recurvature of tropical cyclones originating in the Western North Pacific that may affect the Philippines.

2. Methodology

A statistical method to predict the probability of recurvature of tropical cyclones affecting the Philippines was developed using ten weather parameters observed at three stations in Japan, two in China and one in Korea. The stations were chosen based on the availability of continuous data sets. The weather parameters which are used as predictors include surface pressure, pressure heights at 700 and 500 hPa, levels temperature at 700 hPa and zonal and meridional wind components at 700, 500 and 200 hPa levels. The upper level winds and pressure heights are selected based on the study of GEORGE & GRAY (1976). According to them, significant differences are observed between the 700 hPa wind fields of recurving and non-recurving cyclones. They

noted that westerlies are located approximately 16-20 degrees to the north of non-recurving cyclones while in the recurving ones, westerlies are slightly stronger and are found at only 10 degrees to the north of the cyclone centre. Significant wind field differences between the 200 hPa wind fields of recurving and non-recurving cyclones are likewise noted. Similar results were noted by CAYANAN *et al.* (1992) in their subjective analysis of the wind and pressure height fields of six pairs of tropical cyclones that entered the PAR. Another significant difference is the presence of a trough from the surface to 500 hPa level at about 20 degrees to the north-east of a recurving cyclone while a blocking high pressure cell is noted for non-recurving ones on this position.

The choice of stations used in this project is also based on the above-mentioned studies. However, due to limited stations with upper-air data over the Pacific region, only six stations were considered. The three Japanese and one Korean stations selected are approximately located 20 degrees north of Yap, an island in the Pacific Ocean where the cyclones usually originate. These stations are Chichijima (47971), Hachijojima (47678), Ryukyu (47909) and Pohang (47138). And for the Chinese stations which are located north-east of the Philippines, Beijing (58993) and Shanghai (58367) are used. Figure 1 shows the distribution of stations used.

The data used in the study were extracted from the Japan Meteorological Agency (JMA) Weather Maps. Six pairs of recurving and non-recurving tropical cyclones chosen from a nineteen-year (1972-1990) tropical cyclone archive were utilized as the developmental data set in deriving the forecast equations. The tracks of these cyclones are shown in figure 2.

Stepwise regression analysis was applied to screen the predictors selected. In this type of analysis, the correlation of every predictor with the predictand was computed. Each predictor was then entered for regression starting with the most highly correlated. A variable entered at an early stage may, at a later stage, be superfluous because of its relationship with the other variables already in the regression. The partial F-criterion for each variable in the regression at any stage of calculation was evaluated and compared with a pre-selected percentage point of the appropriate F-distribution. This provided a judgment on the contribution made by each variable as though it had been the most recent variable entered, irrespective of its actual point of entry in the regression analysis. Any variable which provided an insignificant

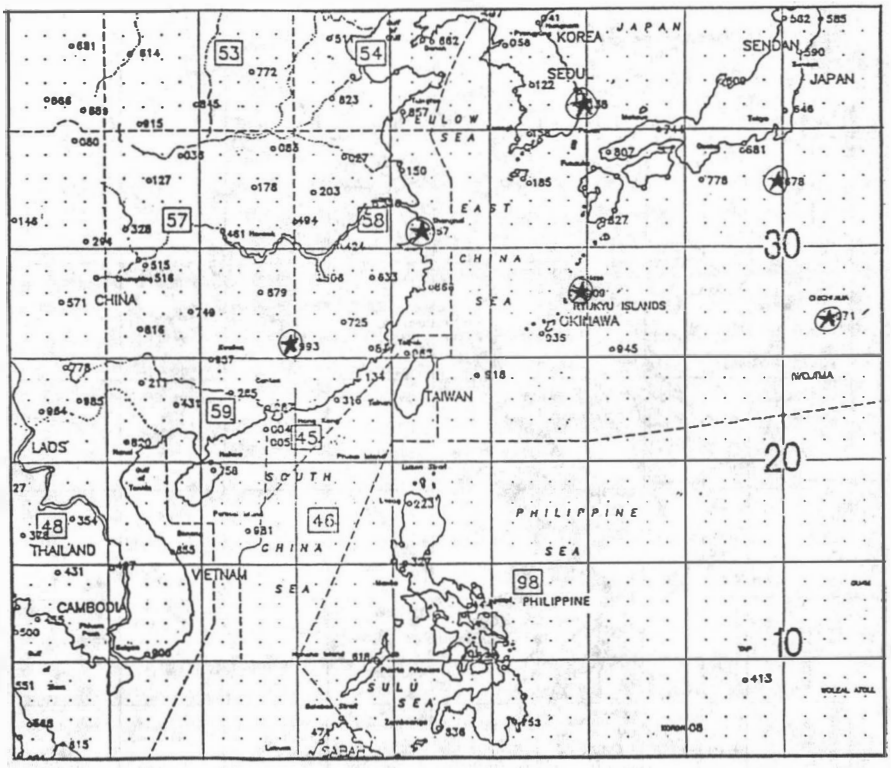


Fig. 1. — Location of stations (marked *) used in the study.

contribution was removed from the set of predictors. This process was continued until no more variable was admitted in or rejected from the equation. The equation developed is in the form :

$$P = K + a_1x_1 + a_2x_2 + \ldots + a_nx_n$$

where : P = Probability of recurvature
K = constant
$a_1, a_2, \ldots a_n$ = regression coefficients
$x_1, x_2, \ldots x_n$ = predictors
n = number of predictors.

Three forecast equations were formulated to predict the probability of recurvature within the next seventy-two hours of tropical cyclones that originated in the Pacific Ocean. The first forecast equation involves predictors observed at Hachijojima (47678) and Pohang (47138), the

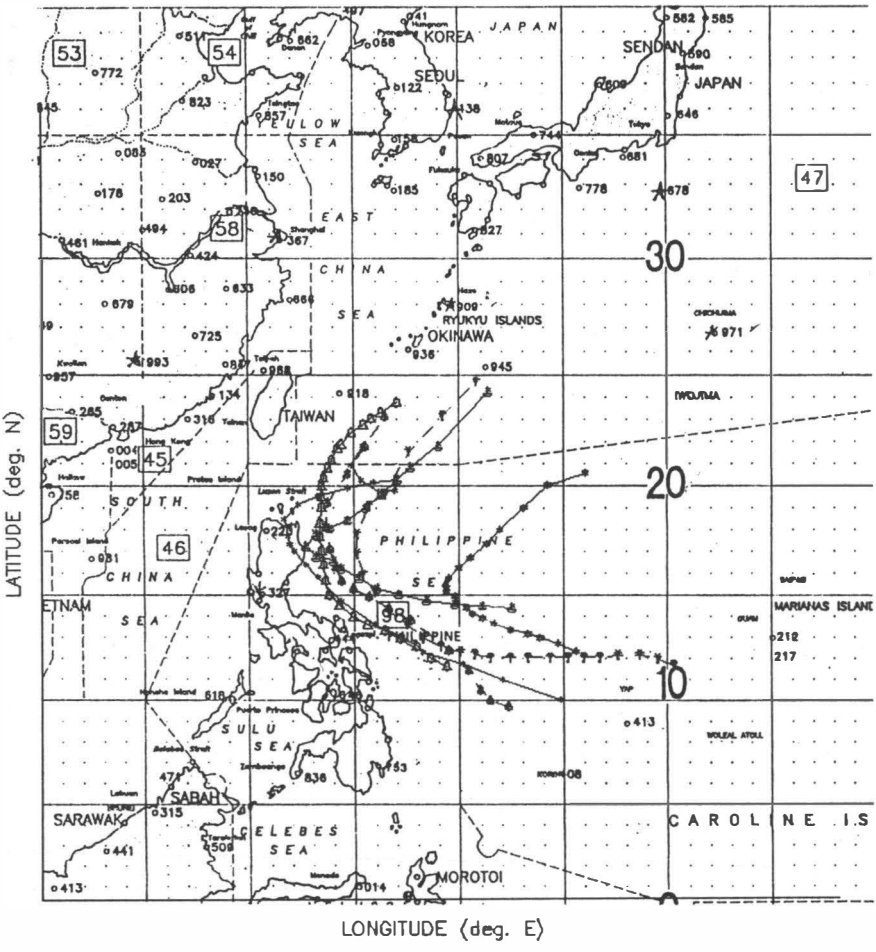


Fig. 2. — Tracks of recurving tropical cyclones used as developmental/dependent data set.

second predictors from Ryukyu (47909) and Chichijima (47971) and the last involves predictors from Shanghai (58367) and Beijing (58993).

The performance of the three equations was tested using the same developmental data set and an independent data set which involves twelve tropical cyclones randomly selected from 1991-1994. Probabilities of recurvature were computed and plotted against time.

3. Results

Three forecast equations were derived to predict the probability of recurvature of tropical cyclones in north-western Pacific within the next seventy-two hours. Equation 1 involves predictors observed at Hachijojima and Pohang, stations situated beyond 20 degrees north of Yap. Yap is one of the small islands over the Pacific, situated at about 90 °N, 138 °E, where most tropical cyclones originate. Out of twenty weather parameters (ten from each station), only six were selected as good predictors. In Equation 2, which utilizes predictors observed at Ryukyu and Chichijima (stations located 15-20° north of Yap), eight predictors were accepted. Finally, Equation 3, which involves Beijing and Shanghai, included four predictors. Most of the predictors selected include zonal and meridional wind components at 700 and 200 hPa levels and pressure heights at 500 hPa. The multiple regression coefficients of the three equations are above 70 %. This means that good correlation exists between the predictors and predictand. Moreover, the standard errors of estimates are low.

3.1. Tests and Forecast Verifications

The performance of the forecast equations was tested using dependent data sets. A threshold value equal to 0.5 was established to serve as the limit of forecast. If the computed probability was equal to or greater than the threshold value, it was predicted that the cyclone will recurve. On the other hand, if the computed probability was less, the opposite was predicted. The results indicate that high percentage of events were correctly predicted by the three equations. Equation 1 correctly predicted (100 % correct) the non-recurvature of six cyclones but only predicted 85 % for recurvature. Equation 2 performed best at 92.05 % in predicting both recurving (6) and non-recurving (6) cyclones, while Equation 3 only rated 89.66 % for both types of cyclones.

Based on the analyses using dependent data sets, it was observed that the performance of the equations is good. But using independent data of recurving cyclones, only Equations 2 and 3 predicted higher probability of recurvature. The parameters observed at Ryukyu and Chichijima (Japan stations 15-20° north of Yap) and at Beijing and Shanghai (China stations north-east of the Philippines) can be regarded as good predictors.

Other tests were carried out using independent data of randomly selected tropical cyclones. Figure 3 shows the tracks of recurving

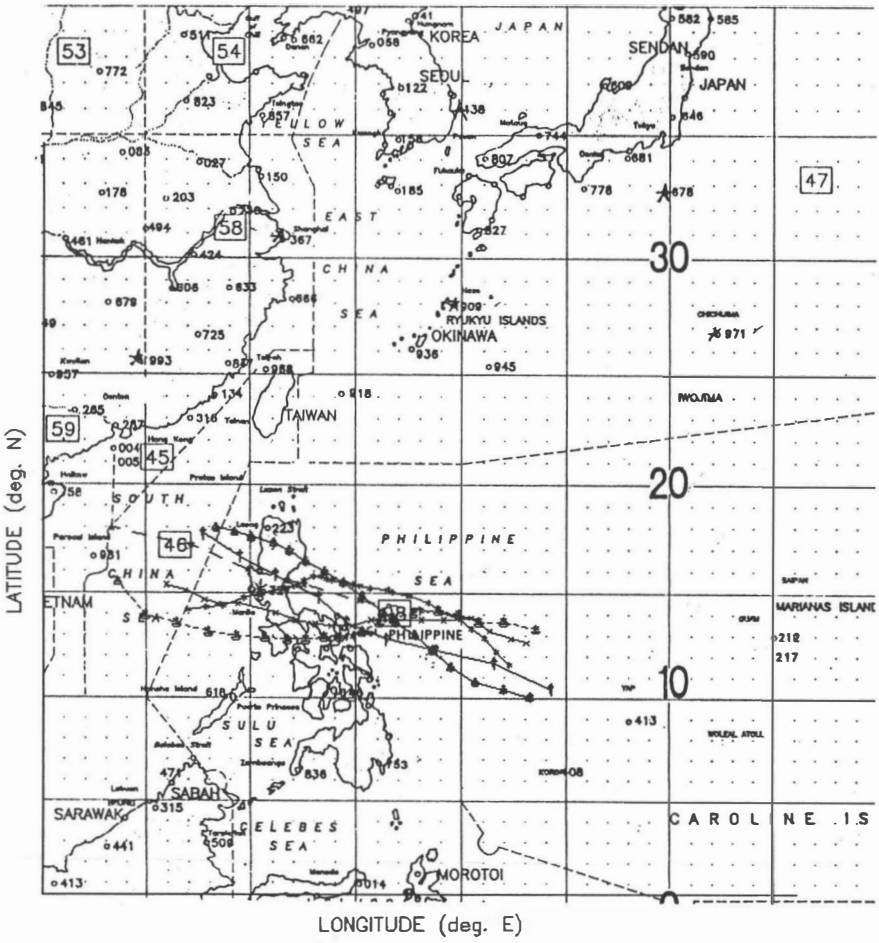


Fig. 3. — Tracks of non-recurving tropical cyclones used as developmental/ dependent data set.

tropical cyclones employed as independent data. By applying Equation 1, probabilities of recurvature of recurving cyclones were computed and plotted against time (number of hours before recurvature) as shown in figure 4.1. It can be noted in the graph that the probabilities of all the tropical cyclones are above 0.5 at the time of recurvature. But twelve hours before, only two cyclones obtained a degree of probability greater than 0.75. In figure 4.2, high percentage of recurvature can be seen for three recurving cyclones using Equation 2 except for TY Yvette. Looking at the cyclone tracks in figure 3, it was noted that TY Yvette had a variable direction which is different from the rest

of the tracks. Unlike the tracks of the recurving tropical cyclones used as developmental data found in figure 2.1, it started on a north-westerly track, then shifted to south-westerly, became stationary for about twenty-four hours before making a sharp turn to north-easterly direction.

From this observation, it can be stated that the equations developed cannot predict the recurvature of tropical cyclones with irregular tracks or variable directions. On the other hand, Equation 3 produced probabilities greater than 0.70 for the three cyclones even as early as fourty-eight hours prior to recurvature, then it continued to increase to about 1.0 at recurving point. This is clearly seen in figure 4.3. Only three cyclones were used to test Equation 3 because some of the data in the fourth cyclone (TY 9104) were missing. Nevertheless, among the three, Equations 2 and 3 performed well for they produced high probabilities of recurvature for the three recurving cyclones at the earliest time possible (fourty-eight hours before recurvature) up to recurving point. Using independent test data, Equation 3 correctly predicted recurvature by 90.47 % while Equation 2 with 74.07 %. But excluding TY Yvette in the test, Equation 2 rates 95 % correct.

Independent data sets of eight non-recurving cyclones were also used to test the forecast equations developed. A scattered plot of computed

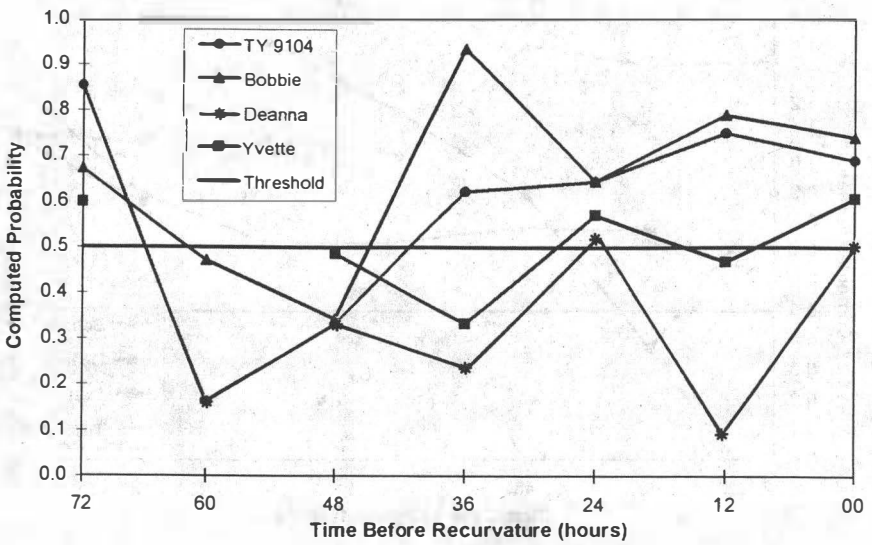


Fig. 4.1. — Computed probability of recurvature against the number of hours before recurvature using independent test data of recurving cyclones for Equation 1. The recurving point is at 00.

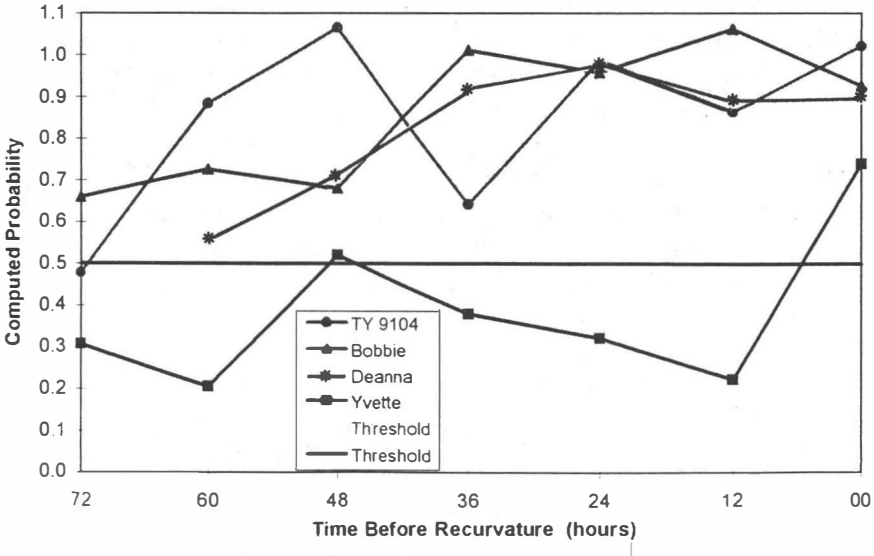


Fig. 4.2. — Computed probability of recurvature against the number of hours before recurvature using independent test data of recurving cyclones for Equation 2. The recurving point is at 00.

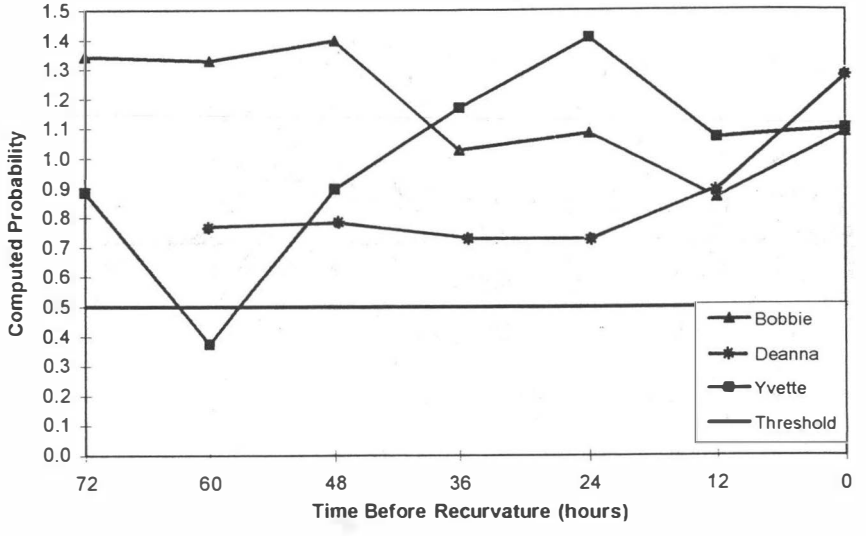


Fig. 4.3. — Computed probability of recurvature against the number of hours before recurvature using independent test data of recurving cyclones for Equation 3. The recurving point is at 00.

probabilities are shown in figures 5.1-5.3 while the tracks of the cyclones are illustrated in figures 6.1-6.2. In figure 5.1, it is evident that most of the probabilities of recurvature of five cyclones (TY Eli, Brendan, Koryn, 9307 & Marian) predicted by Equation 1 are low. It predicted non-recurvature by 67.2 %. Meanwhile, figure 5.2 shows only three cyclones with low probabilities of recurvature for Equation 2, so its prediction of non-recurvature rated only 47.36 %. Lastly, Equation 3 predicted low probabilities for four non-recurving cyclones and it rated 54.17 % correct in predicting non-recurvature.

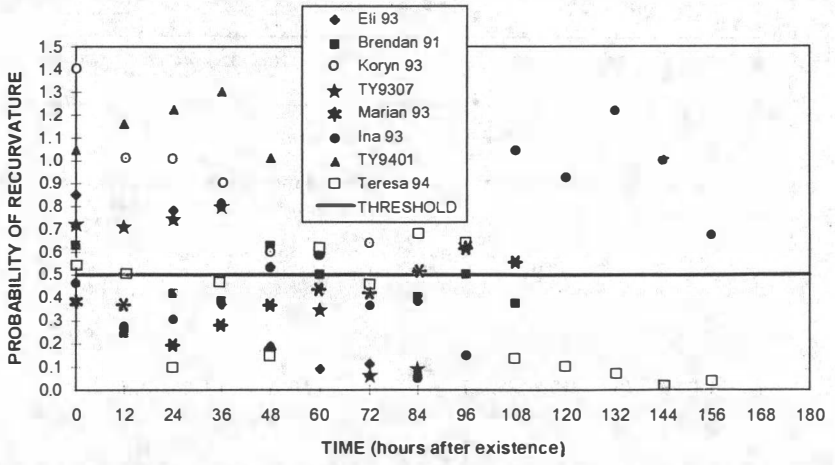


Fig. 5.1. — Computed probability of recurvature of independent set of non-recurving cyclones using Equation 1.

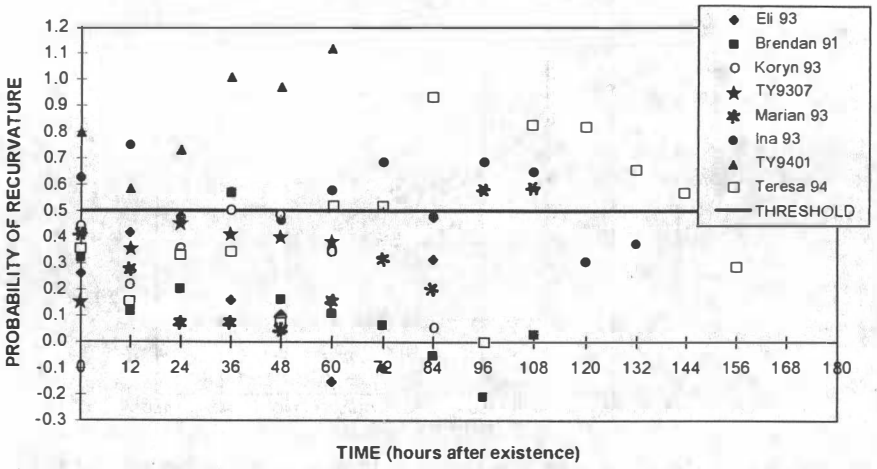


Fig. 5.2. — Computed probability of recurvature of independent set of non-recurving cyclones using Equation 2.

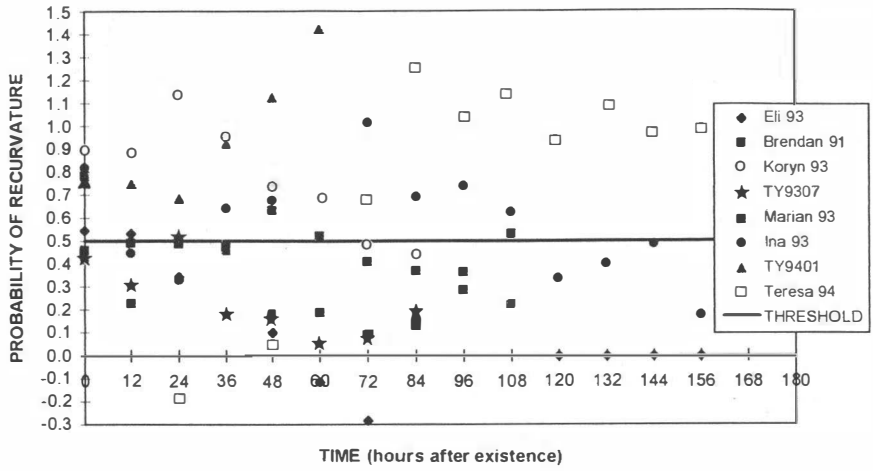


Fig. 5.3. — Computed probability of recurvature of independent set of non-recurving cyclones using Equation 3.

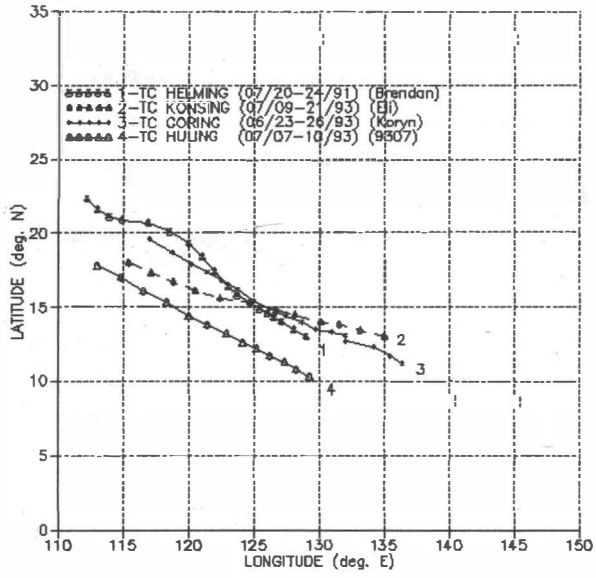


Fig. 6.1. — Tracks of four non-recurving tropical cyclones used as independent test data.

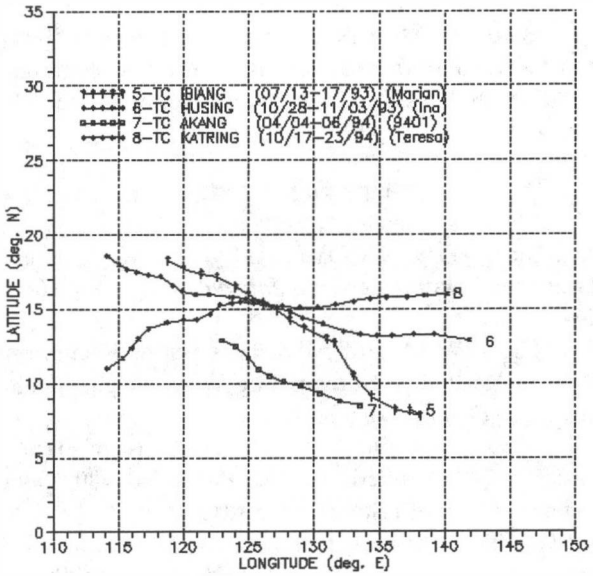


Fig. 6.2. — Tracks of another four non-recurving tropical cyclones used as independent test data.

4. Summary and Recommendations

The study undertaken showed promising results in predicting the probability of recurvature of recurving tropical cyclones. Upper-level winds from Chichijima and Ryukyu (Equation 2) and from Shanghai and Beijing (Equation 3) performed better in predicting the probability of recurving cyclones. However, the equations developed also predicted high probabilities for some of the non-recurving cyclones, which is off-target. It is therefore recommended that a further study be made to improve this forecasting technique. Other parameters, like latitude and longitude of the origin of the cyclone and Julian date or month of occurrence, should be considered as predictors. A bigger set of dependent data should be employed to come up with better results.

ACKNOWLEDGEMENTS

This research project was supported by the PAGASA which is under the Department of Science and Technology (DOST). The authors are grateful to Dr. Leoncio A. Amadore, the PAGASA Director, Dr. Bernardo M. Soriano

Jr. and Mr. Claro S. Doctor for their support and guidance. Likewise, gratitude also goes to Dr. Mariano A. Estoque who contributed important ideas for the improvement of the study. This project was accomplished through the effort of the research staff of the Atmospheric Science Research Unit (ASRU).

REFERENCES

GEORGE, J. E. & GRAY, W. E. 1976. Tropical Cyclone Motion and Surrounding Flow Parameter Relationships. — *Journal of Applied Meteorology*, **15** : 1252-1264.

GEORGE, J. E. & GRAY, W. M. 1977. Tropical Cyclone Recurvature and Non-recurvature as Related to Surrounding Wind-Height Fields. — *Journal of Applied Meteorology*, **16** : 34-42.

HODANISH, S. J. 1991. An Observational Analysis of Tropical Cyclone Recurvature. — Atmospheric Science Paper No. 480, Dept. of Atmospheric Science, Colorado State University.

LEFTWICH, P. W. 1979. Regression Estimation of the Probability of Tropical Cyclone Recurvature. — Sixth Conference on Probability and Statistics in Atmospheric Science, American Meteorological Society, pp. 63-99.

PANOFSKY, H. A. & BRIER, G. W. 1968. Some Applications of Statistics to Meteorology. — University Park, Pennsylvania, pp. 198-206.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 355-362 (1998)

Spectral and Wavelet Analysis of Circulation Processes during the ENSO

by

S. Lakeev *, Daria Guschchina** & N. Astafyeva***

Keywords. — ENSO Circulation Mechanism ; Spectral Analysis ; Wavelet Analysis.

Abstract. — The origin of main circulation system anomalies in tropics was considered on the ENSO 1986-87 example. The contribution of various time-scale processes in the reorganization of basic circulation cells of low latitudes during the ENSO episode was objectively estimated. On the ground of wavelet analysis of wind time series the mechanism of anomalies initiation and disappearance was examined in terms of activity of various time-scale processes.

Mots-cles. — Mécanisme de circulation ENSO ; Analyse spectrale ; Analyse d'ondelettes.

Resume. — *Analyse spectrale et en ondelettes des processus de circulation atmosphérique pendant les phénomènes ENSO.* — L'origine des principales anomalies du système de circulation dans les tropiques fut considérée pour l'exemple ENSO 1986-87. La contribution de plusieurs processus temporels dans la réorganisation des cellules de base à basse latitude pendant l'épisode ENSO fut estimée d'une manière objective. Sur base de l'analyse d'ondelettes des séries temporelles de vent, le mécanisme d'apparition et de disparition des anomalies fut examiné à travers l'activité de plusieurs processus temporels.

Trefwoorden. — ENSO-omloopmechanisme ; Spectrale analyse ; *Wavelet*-analyse.

Samenvatting. — *Spectrale en golvenanalyse van de atmosferische circulatieprocessen tijdens de ENSO-gebeurtenissen.* — De oorsprong van de

* Karpov Institute of Physical Chemistry, 10 Vorontsovo pole st., Moscow, 103064 (Russia).

** Meteorological Department, Moscow State University, Leninskie gory, Moscow, 177899 (Russia).

*** Space Research Institute, 88/32 Profsoyuznaya st., Moscow, 117810 (Russia).

belangrijkste afwijkingen in circulatiesystemen in de tropen werd behandeld in functie van het ENSO 1986-87 voorbeeld. De bijdrage van verschillende tijdsprocessen in de reorganisatie van de basiscirculatiecellen op lage breedte gedurende de ENSO-episode werd objectief geschat. Op basis van de *wavelet*-analyse van tijdreeks van windmetingen werd het mechanisme van de initiatie en verdwijning van anomalieën onderzocht in functie van verschillende tijdsgebonden processen.

Goals and Method of Investigation

After the investigation of anomalous processes in the atmosphere in the frame of the ENSO evolution empirical model, the study of the origin of main circulation system anomalies in tropics was of particular interest. Specifically it was interesting to objectively estimate the contribution of various time-scale processes in the reorganization of basic circulation cells at low latitudes during the ENSO episode. To reach this goal the spectral analysis of various meteorological characteristics (zonal and meridional surface wind, sea level pressure, latent surface and sensible heat fluxes, air temperature, surface temperature and surface net shortwave radiation) was carried out on the grid 2.5 × 2.5°.

The data of objective analysis of ECMWF from TOGA CDs were used. For calculation we used the time series covering the major phase of ENSO of 1986-87 (October 1986 - February 1987). In an effort to correlate the results obtained for the ENSO period with the normal circulation conditions in tropics, the spectral density of all meteorological characteristics was calculated for the same months of 1985-1986.

It is known that the major part of dispersion of meteorological values in tropics falls on the oscillation periods 14-21 days (global-scale processes) and 3-5 days (synoptic-scale processes) (Monin 1969). As a value characterizing the intensity of processes the integral spectral density fell within the frequency interval, corresponding to the synoptic and global scales, was chosen. On the maps you can see the anomalies of integral spectral density which represent the difference between ENSO and normal conditions.

Results

The global-scale oscillations over the Pacific are connected with the fluctuations of the whole system of tropical circulation and above all

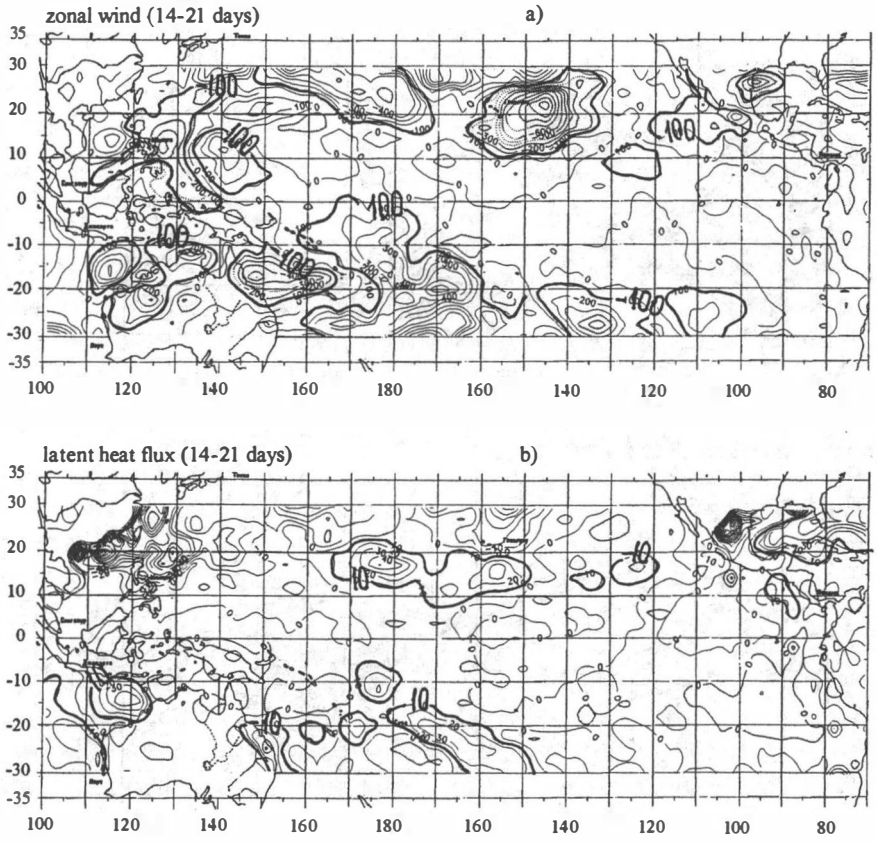


Fig. 1. — Anomalies of integral spectral density for global-scale oscillations with period 14-21 days for a) zonal component of surface wind (unit $m^2\ day^2/s^2$) ; b) surface latent heat flux (unit $10^{-4}\ W^2\ day^2/m^4$).

with the oscillations of ITCZ, SHCZ and subtropical maxima. The analysis of integral spectral density distribution revealed the following anomalies of global-scale circulation observed during ENSO 1986-87.

The main peculiarities of integral spectral density distribution for global-scale processes are the wide areas of positive anomalies localized near the Fiji and Cook islands and the wide areas of negative anomalies near the Australian coasts. We can follow this feature on the maps for zonal wind (fig. 1a), latent heat flux (fig. 1b) and net shortwave radiation (fig. 2a). This suggests that the reorganization of the circulation system within the SHCZ, namely its intensification over the western

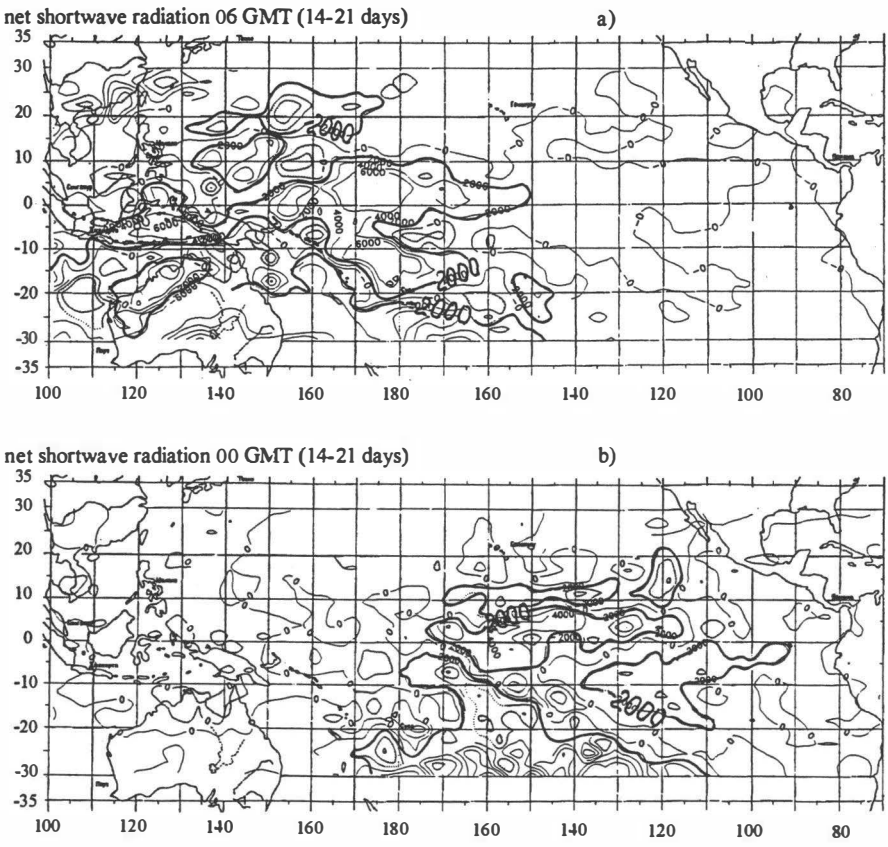


Fig. 2. — Anomalies of integral spectral density for global-scale oscillations with period 14-21 days for a) surface net shortwave radiation 06 GMT (unit W^2 day^2/m^4) ; b) surface net shortwave radiation 00 GMT (unit W^2 day^2/m^4).

and central Pacific and its disappearance in the region of Australian monsoon, is substantially linked with the processes of global scale (14-21 days).

The anomalous ENSO-associated processes in the Eastern Pacific manifest in the distribution of integral spectral density for global-scale processes as well. We can see on the map of net shortwave radiation the large zone of positive anomalies in the central and Eastern Pacific, which reflects the processes of large-scale cloudiness massive formation, connected by origin with the intensification of ITCZ in this region under the ENSO conditions (fig. 2b). The synoptic-scale processes in

tropics (period 3 to 5 days) are characteristic of tropical depressions within the ITCZ system as well as out of it.

On the grounds of results obtained we can emerge the following anomalies of synoptic-scale circulation characteristics of El Niño.

The analysis of spectral density distribution of synoptic-scale processes showed that the maximum positive anomalies are observed in the near-equatorial zone. Here we present the results for meridional components of surface wind (fig. 3a). It is significant that the areas of positive anomalies (shaded) essentially coincide with the areas of the equatorial westerly zone propagation during the period of ENSO culmination. This fact allows to make the important conclusion that the western wind anomalies, which is the key element of the ENSO cycle, are primarily connected with synoptic then global-scale patterns.

The process of ITCZ intensification in the Eastern Pacific is reflected in the distribution of integral spectral density for synoptic-scale processes as well. This fact can be seen on the map for net shortwave radiation (fig. 3b).

Summarizing the results of spectral analysis showed the different genesis of atmosphere anomalies during ENSO :

— The anomaly of Southern Pacific SHCZ is due to global-scale atmospheric processes ;
— Contrary to common opinion, the westerly wind anomaly in the western and central equatorial Pacific is linked with synoptic scale processes.

To elucidate the origin of ENSO-associated circulation system anomalies we made the attempt to examine the process of anomalies initiation and disappearance in terms of activity of various time-scale processes.

This has been carried out using the wavelet analysis of wind time series *f(t)*. Wavelet technique is a new method of long-time series handling allowing to analyse the non-regular signal properties in time-frequency space : physical (time) and spectral space simultaneously. The wavelet transformation consists in signal expansion of basic set, $\Psi (t - b)/a)$, constructed from soliton-like function ("mother wavelet") through the translations *(b)* and dilations *(a)* (KAISER 1994) :

$$W(a, b) = a^{-1/2} \int \Psi \left(\frac{t - b}{a} \right) f(t)\, dt.$$

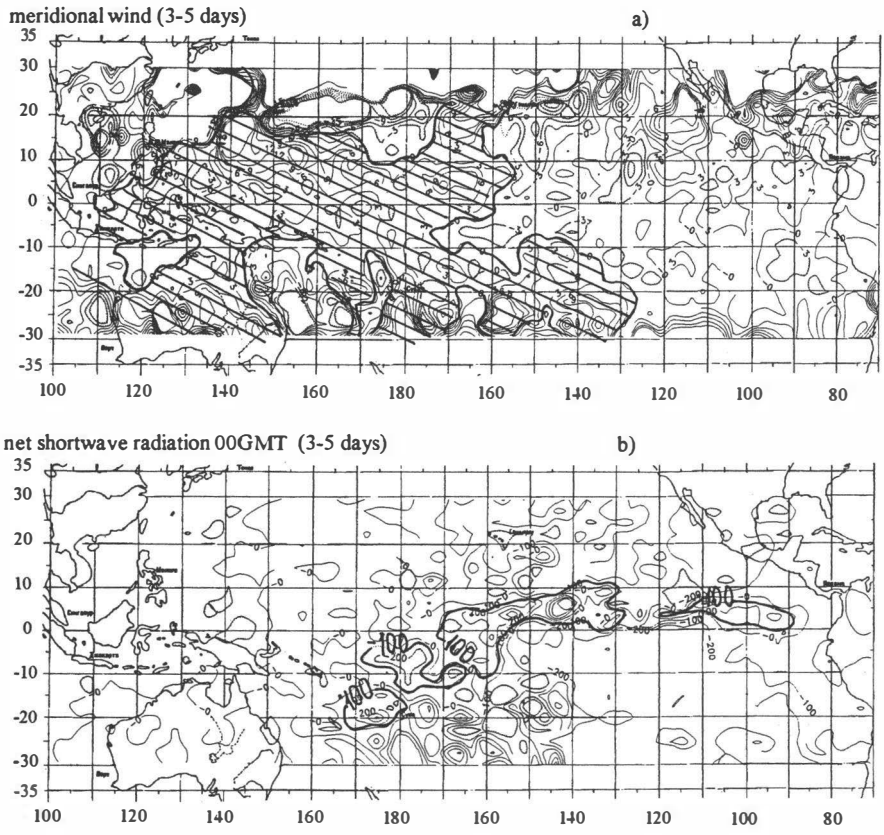


Fig. 3. — Anomalies of integral spectral density for synoptic-scale oscillations with period 3-5 days for a) meridional component of surface wind (unit $m^2\ day^2/s^{29}$) ; b) surface net shortwave radiation 00 GMT (unit $W^2\ day^2/m^4$).

Each function from this basic set characterizes the specific frequency as well as localization in physical (time) space.

The calculations were carried out for time series of zonal and meridional wind in two points where the maximum of spectral density anomalies was observed for point 1 — the maximum for synoptic-scale processes, and point 2 — the maximum for global-scale processes.

On figures 4 and 5 one can see the projection of W^2 (a, b) coefficients on the plane *(a, t)*, where abscissa is a time coordinate, ordinata is a coordinate analogous to the period in spectral analysis. The white band coincides with maximum coefficients, black bands with minimum ones. The scale of interest for us is marked by a solid line. The activity

of particular scale processes can be judged from the frequency of the white bands' length reaching the solid line. It can be seen that in point 1 the maximum activity falls to the synoptic-scale processes (fig. 4), in point 2 to the global-scale processes (fig. 5). In such a manner the results of wavelet analysis validate the hypothesis of different genesis of ENSO-associated circulation anomalies.

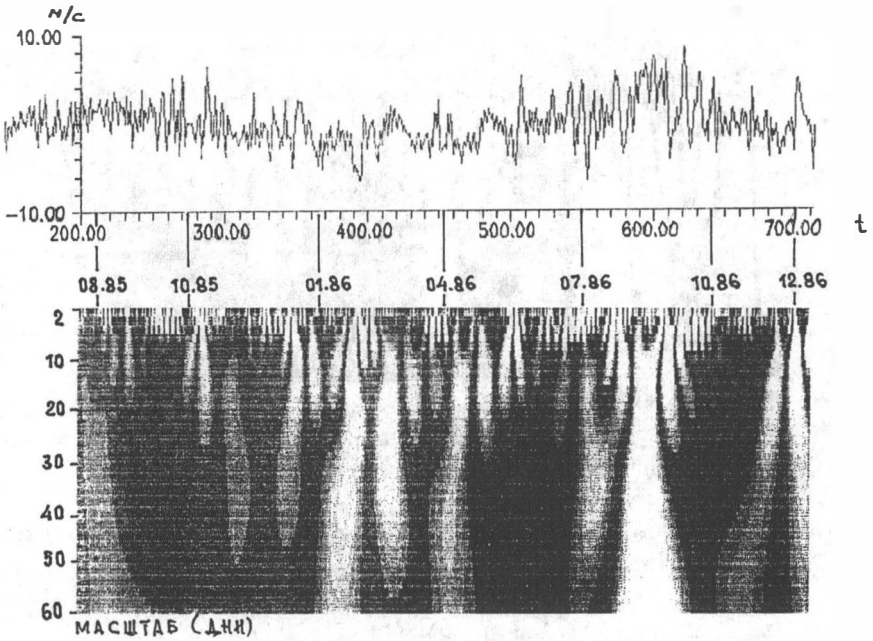


Fig. 4. — Time series of meridional wind (top) and wavelet coefficients of this series (bottom) for point 1 (147.5 °E, 7 °N).

The other intriguing result of wavelet analysis is the fact that in the near-equatorial region, known as a region of ENSO initiation, during the period of ENSO onset (from July to October 1986), the activity of synoptic-scale processes (3-5 days) increases substantially, then it diminishes (fig. 4). Thus it is the synoptic-scale processes that can play an important role in the mechanism of ENSO initiation, particularly in the origin of westerly wind anomalies in the Pacific. These results consist with the hypotheses of westerly wind bursts which suggest that the synoptic-scale systems occurred in the western equatorial Pacific can serve as ENSO trigger (Chou *et al.* 1995, Harten 1995, Fasullo 1995).

Summarizing we can say that the results of wavelet analysis confirm

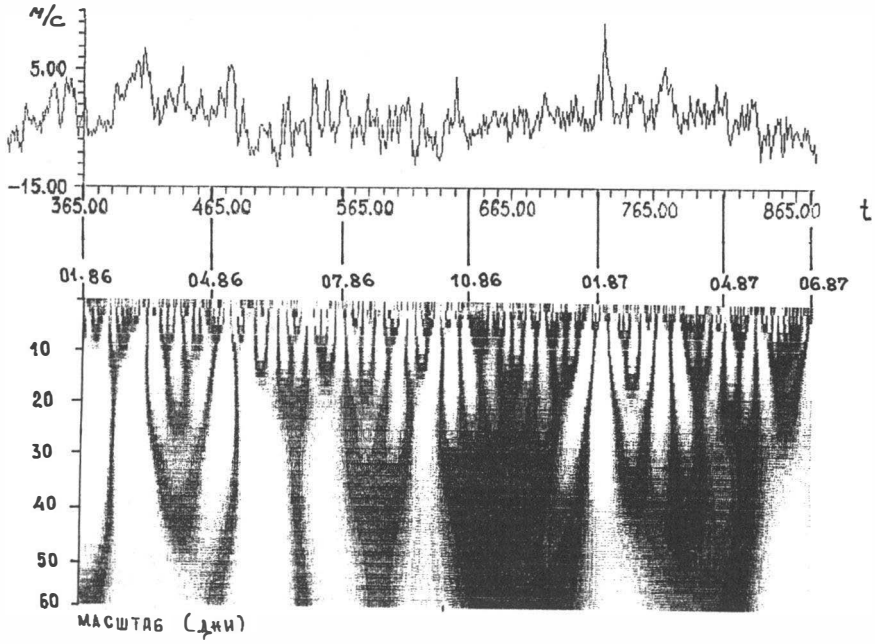


Fig. 5. — Time series of meridional wind (top) and wavelet coefficients of this series (bottom) for point 2 (180 °E, 15 °S).

that the synoptic-scale processes can play an important role during the period of ENSO onset.

REFERENCES

CHOU, S.-H., SHIE, C.-L., ATLAS, R. M. *et al.* 1995. The December 1992 westerly wind burst and its impact on evaporation determined from SSMI data. — *In* : Proceedings of the International Scientific Conference for TOGA (Melbourne, Australia, 2-7 April 1995), WMO/TD, No. 717 (1) : 489-493.

FASULLO, J. & WEBSTER, P. Aspects of ocean/atmosphere interaction during westerly wind bursts. — *In* : Proceedings of the International Scientific Conference for TOGA (Melbourne, Australia, 2-7 April 1995), WMO/TD, No. 717 (1) : 39-43.

HARTEN, L. M. The climatological and synoptic setting of westerly wind bursts. — *In* : Proceedings of the International Scientific Conference for TOGA (Melbourne, Australia, 2-7 April 1995), WMO/TD, No 717 (1) : 484-488.

KAISER, G. 1994. A friendly guide to wavelets. — Birkhauser, Boston.

MONIN, A. S. 1969. Forecast as a physics task. — Nauka, Moscow, 178 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 363-370 (1998)

The Empirical Model of Global-Scale Circulation in Tropical Atmosphere

by

E. SEMENOV *

KEYWORDS. — Empirical Model ; Global-Scale Circulation ; Low Altitudes ; Westerly Wind Zone.

ABSTRACT. — An empirical model of global-scale circulation in the tropics (in the range of radio sounding) was developed on the ground of all aerosynoptic information available. The model created intends to reflect quantitatively the main peculiarities of the mean wind regime in the free tropical atmosphere (the characteristics of the mean state and variability) with the maximum detalization and reliability available under up-to-date level of aerological observations in the tropics. On the grounds of this model the regularities of time-space distribution of the most important kinematic climate parameters, presented as global fields in the tropical troposphere and low stratosphere, was found.

MOTS-CLES. — Modèle empirique ; Circulation à échelle globale ; Latitudes basses ; Zone du vent d'ouest.

RESUME. — *Le modèle empirique à l'échelle globale de la circulation atmosphérique tropicale.* — Un modèle empirique de circulation atmosphérique globale dans les tropiques fut développé sur base de toute l'information aérosynoptique disponible. Le modèle créé tente de refléter quantitativement les principales particularités du régime du vent dans l'atmosphère tropicale libre (les caractéristiques de l'état moyen et la variabilité) avec le maximum de détails et de confiance possible dans les conditions actuelles des observations aérologiques dans les tropiques. Sur base de ce modèle, furent établies les lois de distribution spatio-temporelles des paramètres climatiques cinématiques les plus importants, présentés comme des champs globaux de la troposphère tropicale et de l'atmosphère basse.

* Meteorological Department, Geographical Faculty, Moscow State University, Leninskie gory, Moscow, 117899 (Russia).

TREFWOORDEN. — Empirisch model ; Globale-schaalcirculatie ; Lage breedtegraden ; Westelijke windzone.

SAMENVATTING. — *Het empirische model van globale circulatie in de tropische atmosfeer.* — Een empirisch model voor globale-schaalstromingen in de tropen (in het gebied van radiosondering) werd ontwikkeld op basis van alle beschikbare aërosynoptische informatie. Het uitgedachte model heeft als doel op kwalitatieve wijze de belangrijkste eigenaardigheden van het gemiddelde windregime in de vrije tropische atmosfeer (de karakteristieken van de gemiddelde toestand en de variabiliteit) met de maximum „detalizatie" en beschikbare betrouwbaarheid van *up-to-date* niveau aërologische waarnemingen in de tropen, aan te tonen. Op basis van dit model werden regelmatigheden gevonden van tijd-ruimte-verdelingen van de belangrijkste kinematische klimatologische parameters, en voorgesteld als globale velden in de tropische troposfeer en lage stratosfeer.

Principal Goal

The principal aim of the study was theoretical generalization and creation of an empirical model of global-scale circulation in the tropics (in the range of radio sounding) and establishment, on the grounds of this model, of the regularities of time-space distribution of the most important kinematic climate parameters presented as global fields in the tropical troposphere and low stratosphere. Based on all aerological and satellite information available, the model created intends to reflect quantitatively the main peculiarities of the mean wind regime in the free tropical atmosphere (the characteristics of the mean state and variability) with the maximum detalization and reliability available under up-to-date level of aerological observations in the tropics.

Data

This study is based on the data of statistical wind characteristics from 426 aerological stations situated in the latitude belt between 45 n.l. and 45 s.l. (fig. 1a). Over the major stations the averaging period constituted 10-15 years. To elucidate the wind regime over oceanic regions the results of radio sounding from 32 Soviet maritime expeditions in the Atlantic and 43 expeditions in the Indian Ocean were used. For the aquatory of the Pacific the materials of the complex observation system of the First Global Experiment PIGAP were attracted. For the isobaric surfaces 200 and 850 hPa the data of the fourth dimension objective analysis of wind fields from ECMWF were

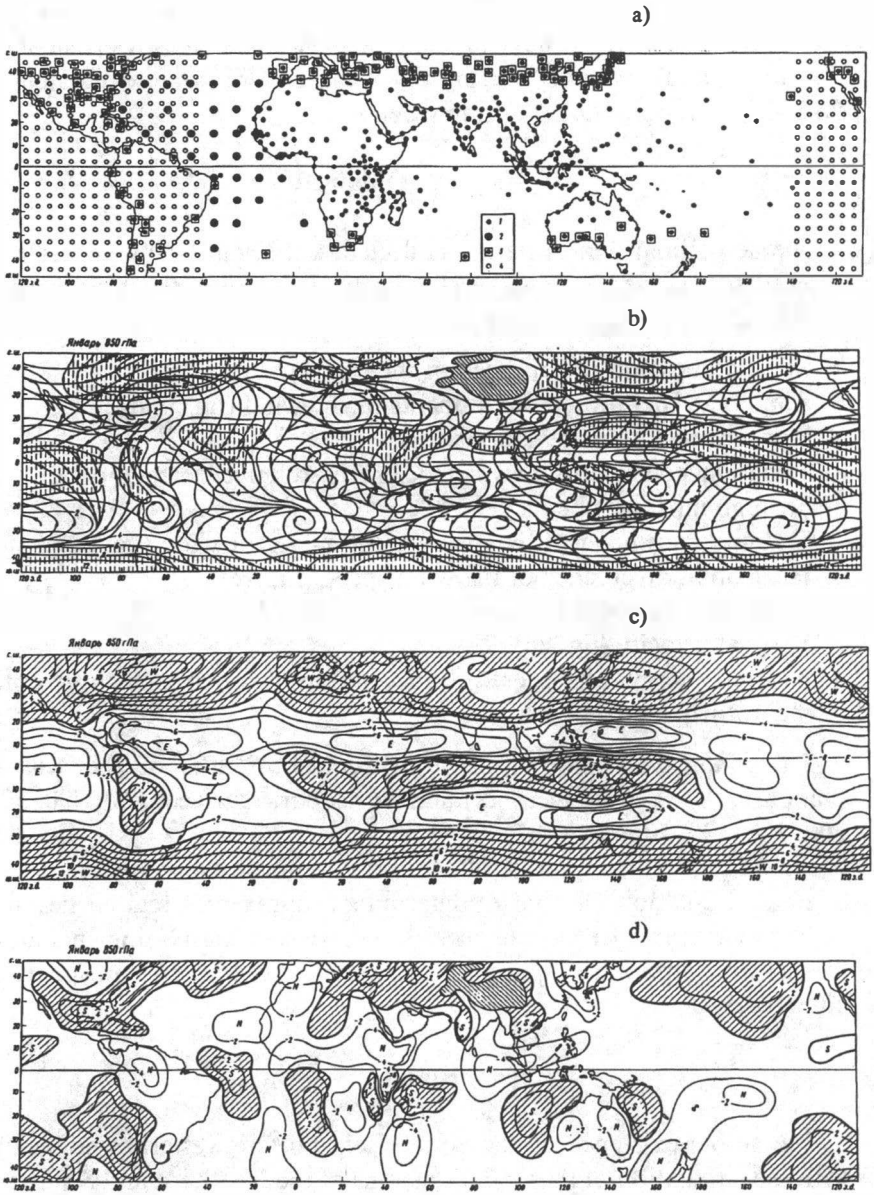


Fig. 1. — January, surface 850 hP : a) the net of stations ; b) streamlines and wind speed ; c) zonal component of the wind ; d) meridional component of the wind.

used. The analysis of the global cloudiness field in the tropics was carried out on the grounds of materials obtained in Soviet satellites "Kosmos" and "Meteor" during ten years and in American satellites *ESSA*, *ITOS* and *NOAA* during seven years.

Materials Obtained

The aeroclimatic information collected and scientifically generalized allowed to receive the reliable climate fields all over the tropical belt of the following circulation characteristics :

— Stream lines and mean speed of the real wind (fig. 1b) ;
— Zonal and meridional components of the wind (fig. 1c.d) ;
— Root mean square deviations ;
— Variation coefficients and coefficient of relative correlation of two orthogonal components ;
— Stability parameter of the mean resulting vector wind (fig. 2a) ;
— Horizontal divergence of the wind speed (fig. 2c) ;
— Vertical component of relative vorticity (fig. 2b) ;
— Vertical velocity (fig. 2d) ;
— Kinetic energy of ordered horizontal movement and horizontal macroturbulence.

The maps were plotted for four central months of the seasons (January, April, July, October) and for isobaric surfaces 850, 700, 500, 300, 200, 100, 50 and 30 hPa.

The plotted climate fields of the most important parameters of the tropical circulation allowed to determine a number of regularities and details of tropical free-atmosphere structure and circulation including the season variability, space inhomogeneity and inter-hemispherical differences.

Results

The stable existence of the equatorial zone of westerlies congenial with the circulation of tropical monsoons of the Northern and Southern Hemispheres was discovered in the low troposphere over the equator. This zone was proved to be an equally important component of general atmosphere circulation. It was detected that this zone migrates within the equatorial region during the year. It is extended in the form of a large continuous belt from the Guinea Gulf through Africa, the Indian

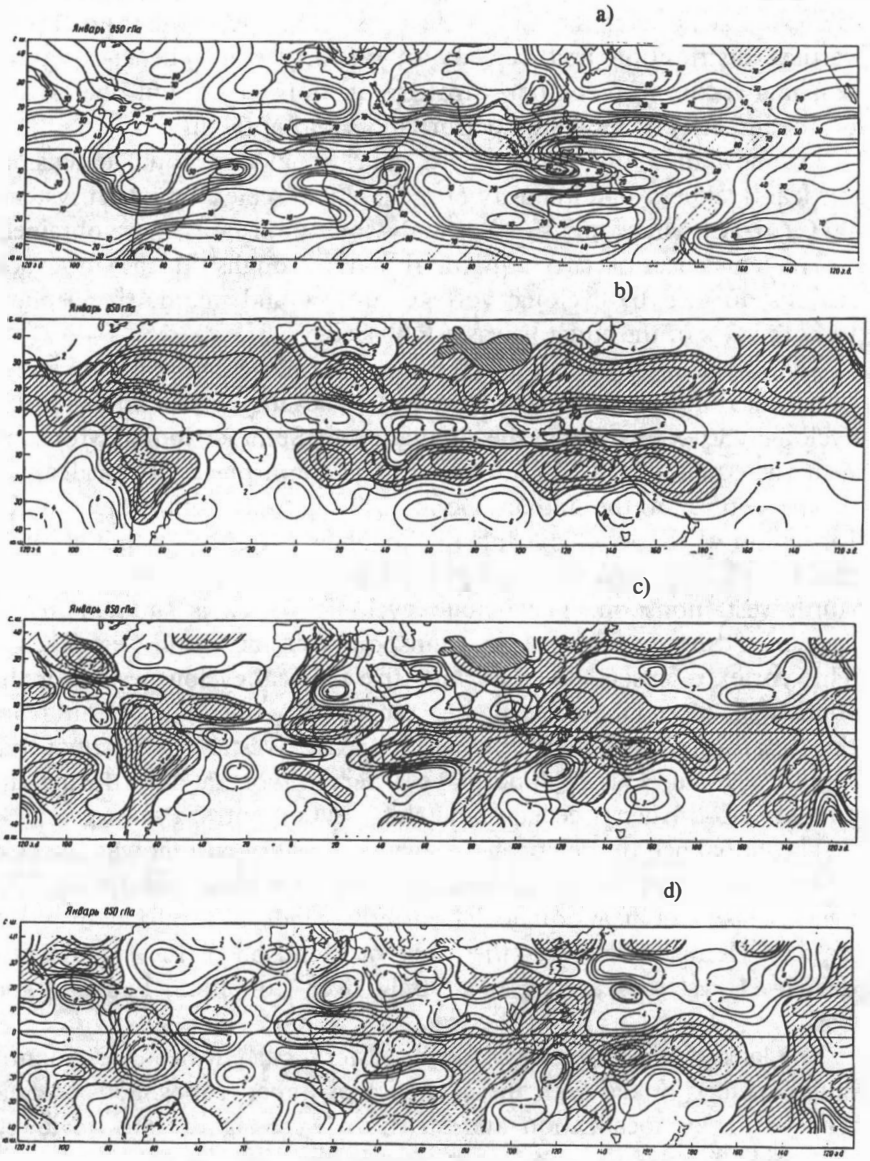


Fig. 2. — January, surface 850 hPa : a) stability parameter ; b) relative vorticity ; c) horizontal divergence ; d) vertical velocity (unit 10^{-4} hPa s^{-1}).

Ocean, Indonesia and Northern Australia to the Western Pacific (to 170 e.l). The zone of westerlies of secondary importance exists in the Eastern Pacific near the Colombia coast. The meridional dimension, vertical distribution and velocity of westerly winds depend on the seasonal localization of baric troughs in both the Hemispheres and on the intensity of separated perturbances within them.

The new data on the structure, meridional and zonal extension, vertical thickness, and intensity of main global-scale circulation systems (ITCZ, trade winds, and summer and winter monsoons) were obtained.

The existence of two equatorial baric troughs in the monsoon regions, formed by cyclonic vortexes in low and middle troposphere to both sides of the equator was established.

The localization of before-unknown seasonal climatic baric centres of tropical atmosphere was revealed. The first is the quasi-stable cyclonic vortex forming in the circulation of Summer Indian Monsoon near the equator in the Southern (winter) Hemisphere. Its localization in the centre of the Indian Ocean (70 e.l, 5 s.l) contributes to the formation of the low-troposphere Findleiter current. The initiation of this vortex may serve as an important predictor of intensifying of the south-west monsoon. The second cyclonic vortex is situated in the system of Summer Australian monsoon over the south-west Pacific. This vortex represents the very intensive tropical cyclogenesis over the south-west Oceania furthering the escape of wet equatorial air from the "maritime" continent Indonesia to the Western near-equatorial Pacific regions. This cyclone plays a very important role during the ENSO period when it deepens and shifts to the central Pacific.

The global belt of the upper-troposphere eastern current was detected to be intermittent during the winter of the Northern Hemisphere. The principal site of near-equatorial easterly winds is localized over the Eastern Hemisphere. Over the Western Hemisphere the significantly decreased easterlies are observed only over Colombia, Ecuador and Peru.

The lack of the upper-troposphere easterly current over the Atlantic and Pacific is linked with the existence of upper-troposphere oceanic troughs. Their localization and structure were significantly reviewed and studied in details in the course of this investigation.

It was determined that the regions of the low-troposphere westerlies nearly coincide with the regions of easterly winds in the upper troposphere over the tropical monsoon regions.

The regional empirical models of zonal and meridional circulation for eight tropical regions contrasting in their land-ocean distribution and separately for Western and Eastern Hemisphere were calculated. They allowed to characterize the vertical structure of wind fields in various physical-geographical conditions.

On the grounds of the data available, the three-dimensional chart of air currents in the equatorial atmosphere was plotted. The presence of vertical circulation cells, similar in their localization to the Walker cells, in the zonal circulation along the equator was detected. Over the Indian Ocean this cell manifests to be the most dramatic. In this region the strong upward currents from the sea level to the 200 hPa are observed. In the upper troposphere the ascending motions acquire the eastern component and form the near-equatorial easterly winds reaching the speed of a jet current. The downward branch of this cell is located near the eastern coast of Africa ; eventually, this cell is closed in low troposphere by the equatorial zone of westerly winds. The location of the zones of air ascending in the system of Walker circulation was detected to be in the regions where the ITCZ is close to the equator and has a significant activity. In the regions where ITCZ is poorly developed and is remoted from the equator one can observe the air descending. The calculations showed the air rise to dominate in the equatorial plane. The compensation occurs at the expense of inter-latitude exchange rather than within interior vertical equatorial circulation.

It was shown that there is no integral circulation mechanism in the meridional plane in tropics. The cells, similar in their localization and scale to the Hadley circulation cells, can be detected in the regions of active trade-wind circulation over the Pacific and Atlantic. Over the continental regions with the circulation of tropical monsoon, the upward motions in the whole width of tropical troposphere are observed, the vertical circulation in meridional plane having nothing in common with Hadley circulation cells both in spatial scales and in the order of magnitude of vertical and meridional components of the wind.

The correlation of an empirical model of tropical circulation with the global-scale reorganization of wind fields in the free tropical atmosphere, observed during ENSO 1982-83, showed the global character of this event and its relation to the whole mechanism of planet circulation. The relationships of anomalies in low and upper

troposphere were revealed. While the zone of westerlies in the low troposphere has been shifted to the east to the centre of the Pacific the anomalous upper-troposphere eastern current has been formed over the same region. Thus, the picture of air currents in the tropical belt of the Pacific during ENSO was close in its structure to the monsoon-region atmosphere circulation of the Indian Ocean.

Conclusion

All results which compose the empirical model of global-scale circulation in tropics are presented in the published „Atlas of circulation characteristics in the troposphere and low stratosphere of tropical zone" (SEMENOV & KORNUSHIN 1988).

REFERENCE

SEMENOV, E. K. & KORNUSHIN, O. G. 1988. Atlas of circulation characteristics in the troposphere and low stratosphere of tropical zone. — Hydrometeoizdat, Moscow, 156 pp.

REMOTE SENSING

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 373-389 (1998)

Sub-Pixel Scene Identification in ScaRaB Broad-Band Data of the Tropical Hurricane Kelvina by Collocation with High-Resolution Meteosat Data for the Study of Angular Dependency Models of Radiation Fields

by

Piet BOEKAERTS *, Dominique CROMMELYNCK ** & Jan CORNELIS *

KEYWORDS. — Earth Radiation Budget; Meteosat; ScaRaB; Scene Identification.

ABSTRACT. — The derivation of top of the atmosphere energy fluxes from measured satellite broad-band radiances requires the identification of local radiation fields, *i.e.* Earth surface and cloud types, and assumptions about the anisotropy of these fields, *i.e.* the development of angular dependence models. The present study shows that the scene identification results in ScaRaB data obtained with the ERBE-like scene identification algorithm can be enhanced by collocation of (low-resolution broad-band) ScaRaB and (high-resolution narrow-band) Meteosat data. Conventional scene identification algorithms, *e.g.* Maximum Likelihood Estimation (MLE), applied to broad-band measurements deal with a scene separability problem because different broad-band radiations (*i.e.* grey values in the image) are shared by different scene types. Cloud and Earth surface fields can be identified more accurately in the segment space of high-resolution composite images of Meteosat narrow-band radiation data, *i.e.* by identifying local tri-spectral value distributions. The collocation procedure of ScaRaB and Meteosat measurements is illustrated for a Meteosat window of Madagascar showing the hurricane Kelvina of March 1994. The obtained sub-pixel scene identification of ScaRaB broad-band data is compared with the ScaRaB secondary data processing products (A2 data).

* Department of Electronics (ETRO), Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

** Department of Aerology, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

MOTS-CLES. — Radiation ; Météosat ; ScaRab ; Identification de scènes.

RESUME. — *L'identification sub-pixel de scènes dans des données ScaRaB de l'ouragan tropical Kelvina au moyen de collocation avec des données Meteosat de haute résolution pour l'étude des modèles angulaires des champs de radiation.* — La détermination de flux énergétiques au sommet de l'atmosphère à partir de données de radiation mesurées par satellite, nécessite l'identification de champs de radiation locaux, à savoir des types de surface terrestre et de nuages, et des suppositions concernant l'anisotropie de ces champs, c'est-à-dire des modèles angulaires de radiation. La présente étude démontre que les résultats d'identification de données ScaRaB obtenus par l'algorithme ERBE peuvent être améliorés par la collocation des données ScaRaB et Météosat. L'application d'algorithmes conventionnels d'identification de scènes, p.e. *Maximum Likelihood Estimation* (MLE), sur des mesurages de radiation provoque des problèmes de séparation de scènes puisqu'un même mesurage de radiation (c'est-à-dire un niveau de gris dans l'image) peut appartenir à différentes scènes. Les différents types de nuages et de surface terrestre peuvent être identifiés avec plus de précision dans l'espace de segments d'une image composite des données multi-spectrales Météosat, notamment par l'identification de distributions locales de données tri-spectrales. La procédure de collocation de données ScaRaB et Météosat est illustrée pour une fenêtre Météosat de Madagascar montrant l'ouragan Kelvina de mars 1994. L'identification sub-pixel des données de radiation ScaRaB obtenue est comparée aux données A2 correspondantes.

TREFWOORDEN. — Straling ; Meteosat ; ScaRaB ; Scène-identificatie.

SAMENVATTING. — *Sub-pixel scène-identificatie in ScaRaB breedbandgegevens van de tropische orkaan Kelvina door collocatie met hoge resolutie Meteosatgegevens voor de studie van hoekafhankelijkheidsmodellen van stralingsvelden.* — De bepaling van energiefluxen aan de top van de atmosfeer aan de hand van breedbandsatellietgegevens vereist de identificatie van lokale stralingsvelden, namelijk aardoppervlakte- en wolkentypes, en veronderstellingen omtrent de anisotropie van deze stralingsvelden, namelijk de ontwikkeling van hoekafhankelijkheidsmodellen. De huidige studie toont aan dat de scène-identificatieresultaten in ScaRaB-gegevens bekomen met het ERBE-algoritme kunnen verbeterd worden door de collocatie van ScaRaB- en Meteosatgegevens. De toepassing van conventionele scène-identificatiealgoritmen, bijvoorbeeld *Maximum Likelihood Estimation* (MLE), op breedbandmetingen geven aanleiding tot een scheidbaarheidsprobleem van de scènes omdat eenzelfde breedbandmeting (namelijk een grijswaarde in het beeld) kan behoren tot verschillende scènes. Wolken- en aardoppervlaktetypes kunnen nauwkeuriger worden geïdentificeerd in de segmentruimte van composietbeelden van Meteosatsmalbandgegevens, namelijk door de identificatie van lokale tri-spectrale gegevensdistributies. De collocatieprocedure van ScaRaB- en

Meteosatgegevens wordt geïllustreerd voor een Meteosatvenster van Madagascar met de orkaan Kelvina van maart 1994. De bekomen sub-pixel scèneidentificatie van de ScaRaB breedbandgegevens wordt vergeleken met de corresponderende A2 gegevens.

1. Introduction

The global energy balance of the Earth (the Earth Radiation Budget) is not only influenced by the total incoming solar energy, but also by the appearance of clouds in the atmosphere and the physical composition of the Earth surface. The Earth Radiation Budget, expressed in terms of total energy fluxes at the top of the atmosphere, is defined as the difference between the total incoming solar energy flux and the total outgoing energy flux. The total outgoing energy flux at the top of the atmosphere contains two components : the shortwave fluxes, representing the total reflected solar energy, and the longwave fluxes, representing the total emitted thermal energy (fig. 1).

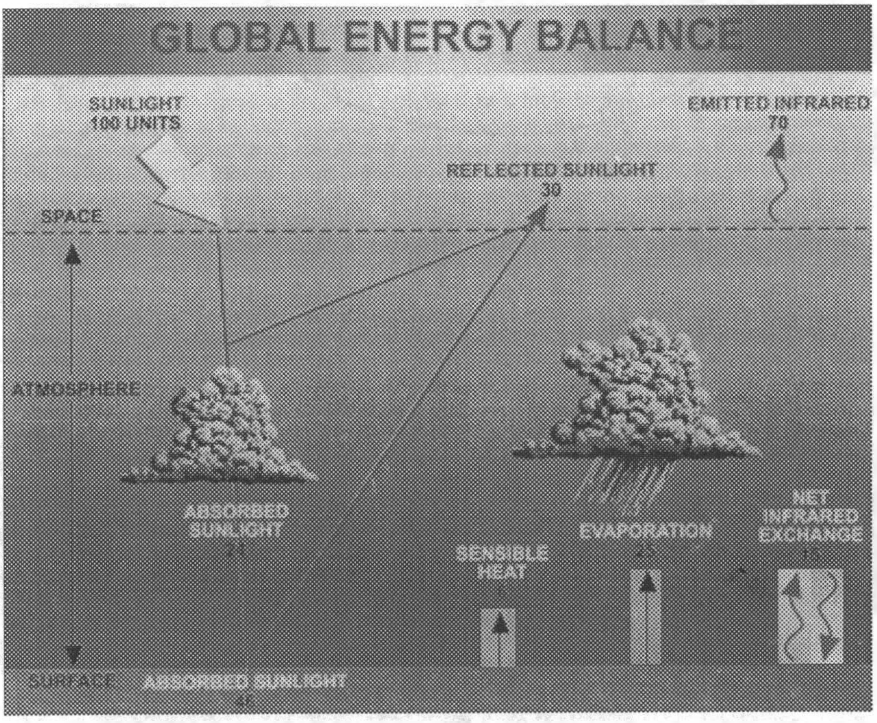


Fig. 1. — Global Energy Balance (WIELICKI *et al.* 1995).

Broad-band radiometers (scanners) on board of (polar) satellites can only measure long-wave and short-wave radiances at the top of the atmosphere. The (short-wave and long-wave) radiation observed at the top of the atmosphere is not only different for typical cloud and Earth surface types, but depends also strongly both on the viewing geometry of the observation (expressed with two angular parameters : the viewing zenith angle, Θ, and the relative azimuth, Φ_R, see fig. 2) and the relative position of the sun to the observation spot (the solar zenith angle, Θ_0, see fig. 2).

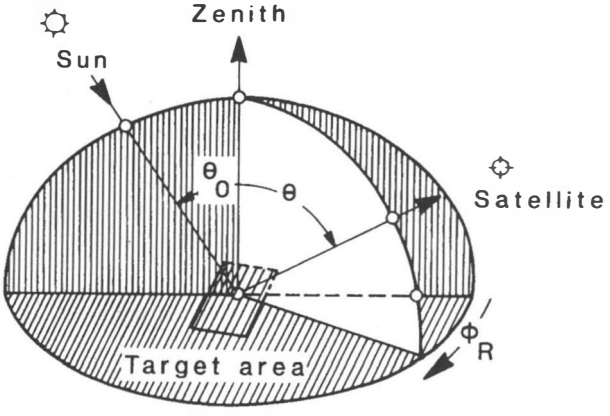


Fig. 2. — The solar zenith angle (Θ_0), viewing zenith angle (Θ) and the relative azimuth (Θ_R) (SMITH *et al.* 1988).

The study of the Earth Radiation Budget requires the conversion of broad-band radiances measured at the top of the atmosphere into energy fluxes. The radiance to flux conversion for the short-wave radiation (L) reflected by a given scene at the top of the atmosphere is given by (SMITH *et al.* 1988) :

$$M_{(\theta_0)} = \int_{\Phi=0}^{2\pi} d\Phi \int_{\theta=0}^{\pi/2} d\theta L(\theta_0, \theta, \Phi) \cos\theta \sin\theta \qquad (1)$$

The angular dependency of the (short-wave) radiation of the scene is given by an anisotropic function $\mathbf{R}_{(\theta_0, \theta, \Phi)}$:

$$\mathbf{R}_{(\theta_0, \theta, \Phi)} = \frac{\pi L_{(\theta_0, \theta, \Phi)}}{M_{(\theta_0)}} \qquad (2)$$

which implies the following normalization condition (1, 2) :

$$\pi^{-1} \int_{\Phi=0}^{2\pi} d\Phi \int_{\theta=0}^{\pi/2} d\theta \mathbf{R}_{(\theta_0, \theta, \Phi)} \cos\theta \sin\theta = 1 \qquad (3)$$

The anisotropic function (called the anisotropic factor in the discrete case) is an angular dependency model that reflects the intrinsic anisotropic (short-wave) radiation properties of radiation fields and can therefore be used for the derivation of energy fluxes from short-wave radiances measured during different missions.

The angular dependency models currently used for the derivation of energy fluxes from broad-band radiances were originally derived by NASA from the Nimbus 7 broad-band data set as part of the Earth Radiation Experiment (ERBE). The scenes (or radiation fields) considered in the ERBE-like radiance-to-flux conversion scheme include (SMITH *et al.* 1988) :

— Clear ocean, land, snow/ice, desert, mixed land-ocean (0-5 % cloud coverage) ;
— **Partly cloudy** over ocean, land or desert, mixed land-ocean (5-50 % coverage) ;
— **Mostly cloudy** over ocean, land or desert, mixed land-ocean (50-95 %) ;
— **Overcast** (95-100 % cloud coverage) ;
— Unknown scenes.

Typical examples of the anisotropic factors derived during ERBE are given in figure 3 for clear land, in figure 4 for clear ocean and in figure 5 for overcast scenes (SMITH *et al.* 1988).

2. Motivation of the Current Study

The derivation of energy fluxes from broad-band radiances with the current ERBE-like radiance-to-flux conversion scheme has two important shortcomings.

The first shortcoming relates to the scene identification scheme used for the recognition of radiation fields. It is known that the ERBE scene identification scheme (based on Maximum Likelihood Estimation) underestimates the cloudiness at high cloud amounts and that the errors of the obtained (short-wave) fluxes can reach more than 13 % due to scene misidentification (DIECKMAN & SMITH 1989).

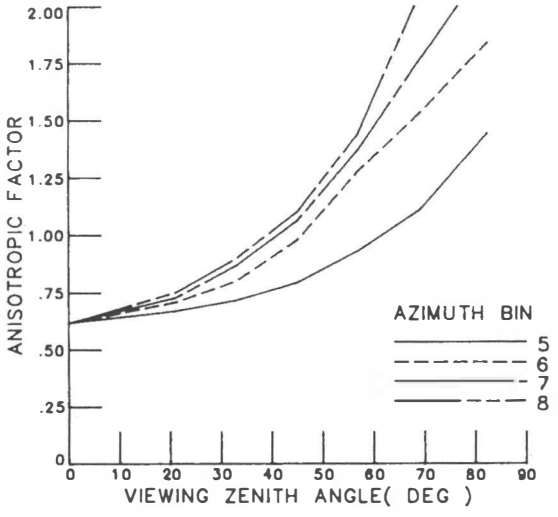


Fig. 3. — Examples of the anisotropic factors derived during ERBE for clear land (mean values for the solar-zenith-angle range of 72.54 to 78.46 degrees).

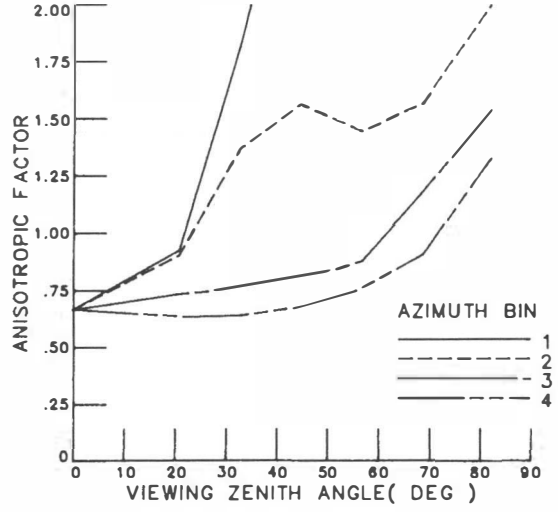


Fig. 4. — Examples of the anisotropic factors derived during ERBE for clear ocean (mean values for the solar-zenith-angle range of 45.57 to 53.13 degrees).

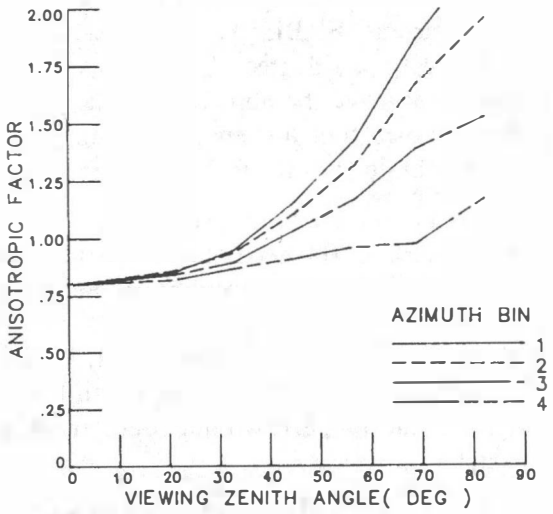


Fig. 5. — Examples of the anisotropic factors derived during ERBE for overcast scenes (mean values for the solar-zenith-angle range of 60.00 to 66.42 degrees).

The second important shortcoming results from the fact that Earth surface and cloud types are derived directly from broad-band measurements. Broad-band measurements have typically a very low spatial resolution (60×60 km^2). This implies that the set of scenes (and the corresponding angular dependency models) currently considered for the derivation of Earth Radiation Budget terms from broad-band radiances is very limited (see above) and that the considered scenes are not always physically consistent with the actual occurrence of clouds in the atmosphere and the nature of the Earth surface. The restricted number and the type of scenes considered in the current ERBE-like radiance-to-flux conversion scheme has important consequences for the validity of the assumptions about the anisotropy of the corresponding radiation fields, and thus for the validity of the angular dependency models used for the derivation of Earth Radiation Budget terms from broad-band measurements. The angular dependency models derived from Nimbus 7 data for the above scene classes implicitly include erroneous assumptions about the statistical averages of the anisotropy of very large radiation fields. It is known that the anisotropic properties of a given radiation field in the atmosphere are not only a function of the degree of cloud coverage, but are also, and more importantly,

a function of the type of clouds. The angular dependency models of cloud fields in the current ERBE-like radiance-to-flux conversion scheme are only related to the degree of cloud coverage and are not related to the physical nature of the observed clouds.

The present study shows that an enhanced scene identification of radiation fields can be obtained in the following way :

a) by the introduction of novel adaptive scene identification algorithms that are unsupervised (without the need of *ad hoc* statistical parameters of the scenes) and solve the scene separability problem of conventional scene identification models ;

b) by the simultaneous use of multi-sensor data, *i.e.* the collocation of low-resolution broad-band data from polar Earth Radiation Budget missions with high-resolution narrow-band data from geostationary (meteorological) satellites.

The proposed methodology is illustrated for scene analysis in ScaRaB (Scanner for Radiation Budget) data using a Meteosat window of Madagascar showing the hurricane Kelvina of March 1994. The obtained sub-pixel scene identification of ScaRaB broad-band data is compared with the ScaRaB secondary data processing products (A2 data). It is argued that the proposed methodology allows to derive new, enhanced angular dependency models of an extended set of physically relevant scenes which will be needed for the correct derivation of energy fluxes from broad-band measurements obtained during future Earth Radiation Budget missions.

3. Data Description

3.1. ScaRaB Broad-Band Measurements

The broad-band measurements used in this study were obtained with the ScaRaB instrument on board of the polar meteorological satellite Meteor 3 (Russia) during March 1994. The technical specifications (the spectral range and the resolution at nadir) of the long-wave (LW) and short-wave (SW) measurements of the ScaRaB radiometer are given in table 1. The (calibrated) data, together with the secondary data products (A2), including the scene identification labels (obtained with the ERBE scene identification scheme) were delivered by CNES (France).

Table 1

ScaRaB instrument data

	Spectral channel	Spectral range	Nadir resolution
narrow band	Visible (VIS)	0.5-0.7 μm	0.7 × 1.4 km²
	Infrared (IR)	10.5-12.5 μm	3 × 3 km²
broad band	Solar (SW)	0.2-4 μm	60 × 60 km²
	Total	0.2-50 μm	60 × 60 km²
	LW = total - solar	4-50 μm	60 × 60 km²

Table 2

Meteosat narrow-band data

Spectral channel	Spectral range	Nadir resolution
Visible (VIS)	0.4-1.1 μm	2.5 × 2.5 km²
Infrared (IR)	10.5-12.5 μm	5 × 5 km²
Water vapour (WV)	5.7-7.1 μm	5 × 5 km²

3.2. Meteosat Narrow-Band Measurements

The European geostationary Meteosat satellites observe the Earth with an imaging radiometer in three spectral (narrow-band) channels (called a slot): the Visible (VIS), Infrared (IR) and Water Vapour channel (see table 2 for the spectral range and the resolution at nadir of each channel). The VIS channel measures reflected solar radiation from clouds and the Earth's surface (*e.g.* land, sea), the IR channel measures thermal radiation in an atmospheric window region emitted from clouds and Earth surface and the WV channel observes the Earth's atmosphere in a strong absorption band and is sensitive to the atmospheric column water vapour in the upper troposphere above 600 hPa.

The raw Meteosat images used in this study were geometrically rectified at Eumetsat (Darmstadt, Germany) and were made available by the Royal Meteorological Institute of Belgium (RMIB, Brussels). We applied a bit-wise inversion to the IR and WV channels to obtain a consistent scene appearance in the three channels and reduced the resolution of the VIS channel by a factor two (giving the same resolution as the IR and WV channel and referred to as VIS2) in order to be able to represent tri-spectral Meteosat measurements as RGB composite images. The resulting VIS2, IR and WV measurements

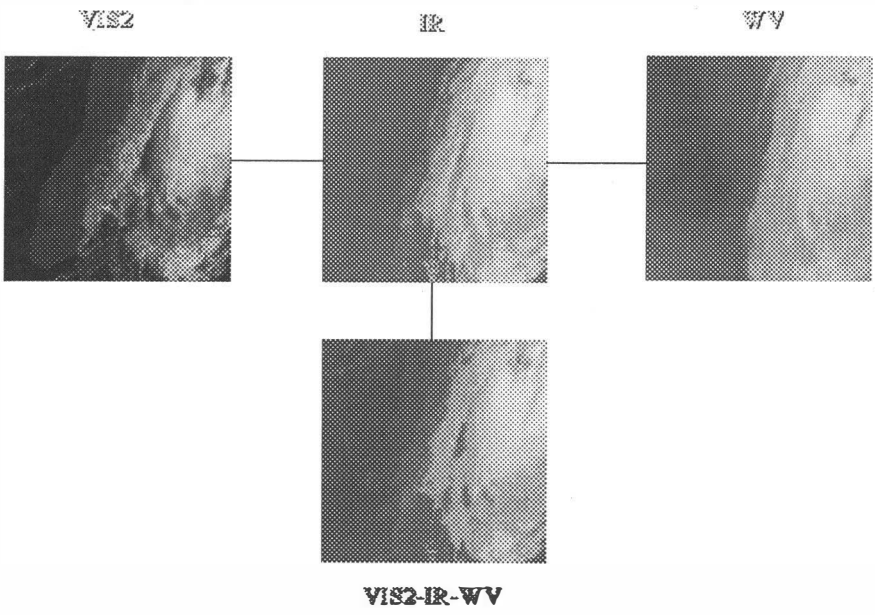


Fig. 6. — Meteosat VIS2 (half resolution, left), IR (inverted, middle), WV (inverted, right) channels and the corresponding RGB composite image (grey value representation, bottom) of the Tropical Hurricane Kelvina above Madagascar (07-03-94, slot 17).

and a grey value representation of the corresponding RGB composite image of a Meteosat window of Madagascar showing the hurricane Kelvina of March, 7 1994 (slot 17) is given in figure 6.

4. Autoadaptive Tri-spectral Scene Identification in Meteosat Data

It is known that tri-spectral Meteosat measurements (combined Visible, Infrared and Water Vapour measurements) reveal important information about the height of clouds in the atmosphere. The application of multi-spectral scene identification algorithms for the identification of radiation fields in high-resolution Meteosat composite images allows us to extend the cloud radiation fields considered in the current ERBE scene identification scheme (*i.e.* partly cloudy, mostly cloudy and overcast) by introducing an important cloud parameter : cloud height. The height of clouds is related to the atmospheric pressure and the internal temperature of clouds and is for this reason related to the internal structure of clouds. It is known that the structure of clouds contributes to the anisotropic properties of the reflected and emitted radiation.

The result of autoadaptive tri-spectral scene identification in the segment space (BOEKAERTS 1995, BOEKAERTS *et al.* 1996) of a Meteosat composite image is illustrated in figure 7. The left image represents the original composite image, the right image represents the scene identification results obtained with 40 code segments and a segment size of 3 × 3 pixels (both images are grey value representations of the original RGB images). Figure 7 illustrates that at least three types of cloud fields can be detected : low-level clouds (slightly brighter regions than the dark regions of the image representing clear ocean), medium-level clouds (grey regions) and high clouds (bright regions).

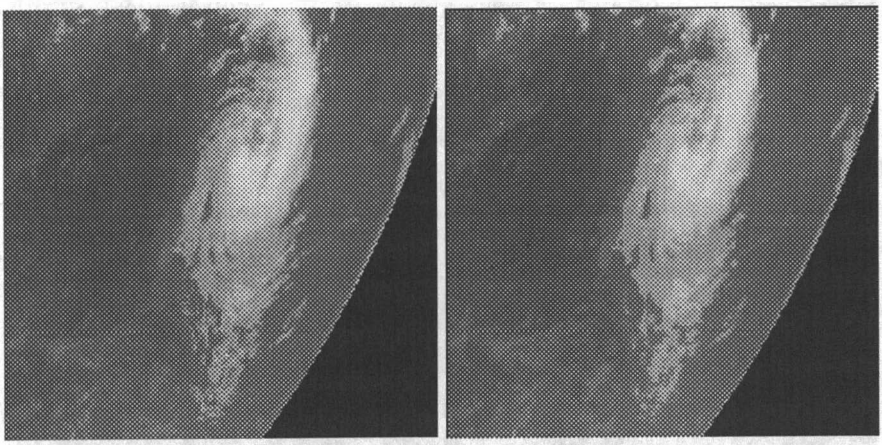


Fig. 7. — Tri-spectral scene identification result (39 classes, right) of a Meteosat composite window above Madagascar (left).

5. Collocation of ScaRaB and Meteosat Measurements

The collocation of low-resolution polar broad-band measurements (ScaRaB) with high-resolution geostationary Meteosat data (composite images) covers the determination of the footprint (or the geolocalization) of each broad-band measurement on Meteosat resolution. The collocation procedure requires the orbit specifications (position and time) of the polar satellite (Meteor 3) carrying the ScaRaB radiometer, the position of the geostationary Meteosat satellite (0 degrees latitude, 0 degrees longitude) and the technical specifications (the dynamic Point Spread Function or PSF) of the sensors of the ScaRaB instrument. The footprint of a given ScaRaB measurement can be derived by considering the set of Meteosat pixels within one percent of the

maximum of the ScaRaB PSF for the corresponding ScaRaB position. The position of Meteor 3 and the (universal) time are known for each ScaRaB measurement (and delivered with the A2 secondary data products). The dynamic point spread functions of the ScaRaB radiometer on METEOR 3 were not (yet) available during this study and a uniform block function was considered.

The collocation of ScaRaB long-wave measurements with Meteosat tri-spectral data is illustrated in figure 8. The right image in figure 8 represents a Meteosat composite image of the complete Earth disk (grey value representation). The left image was obtained by assigning each ScaRaB long-wave measurement to the central pixel of the corresponding footprint on Meteosat resolution (2.5 km $\times$ 2.5 km at nadir, see table 2). The footprints of the different ScaRaB long-wave measurements are overlapping, which is the reason why only the central pixel of the footprints is shown in the left image of figure 8.

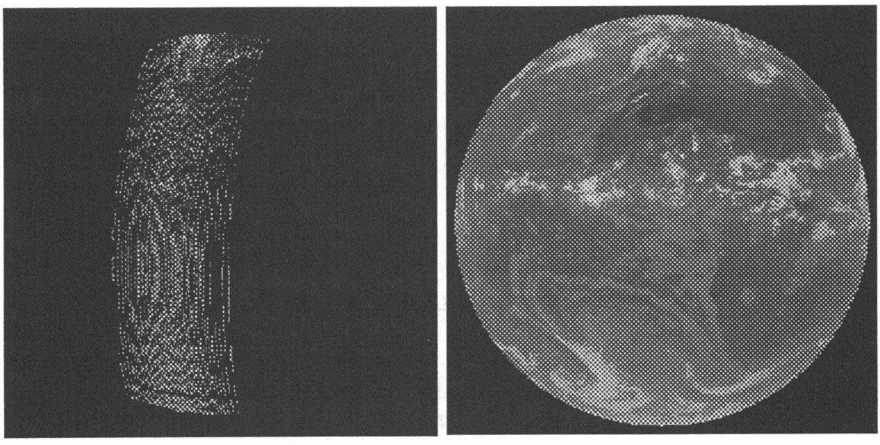


Fig. 8. — Collocation of ScaRaB long-wave measurements (left) with Meteosat tri-spectral data (right).

The right image in figure 9 illustrates the region in the Meteosat window of figure 7 (reproduced in the left image of figure 9) for which ScaRaB broad-band measurements were „simultaneously" available. Meteosat satellites deliver data every 30 minutes. ScaRaB broad-band measurements are considered to be captured simultaneously when they are detected within $\pm$ 15 minutes of the Meteosat slot. This time interpolation (see bottom of figure 9) introduces only small errors in the collocation of both data sets due to the low resolution of ScaRaB

data (table 1). The right image in figure 9 was obtained after selecting those pixels of the Meteosat window (left image) that occur at least once in the footprints of the corresponding long-wave measurements of ScaRaB (after time interpolation).

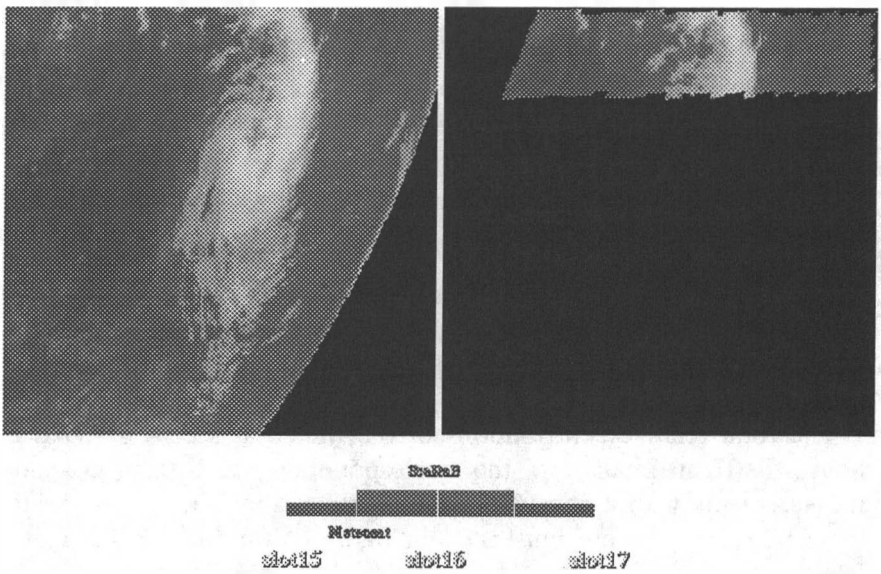


Fig. 9. — Region in the Meteosat window of figure 7 (left) for which ScaRaB broad-band measurements were available (right). Illustration of time interpolation during collocation of both data sets (bottom).

6. Sub-Pixel Scene Identification of ScaRaB Data

After having collocated a given (low-resolution) broad-band measurement with the (higher-resolution) tri-spectral narrow-band measurements of Meteosat, one can derive the (sub-pixel) scene composition of the broad-band measurement. For each broad-band measurement, the relative contribution of each scene as defined (and observed) in tri-spectral narrow-band measurements can be obtained.

The amount and the type of clouds (among the extended set of cloud types, including cloud height) that contribute to a given broad-band radiance observed at the top of the atmosphere is obtained from the scene identification results of the corresponding Meteosat data.

Once we know the footprint on Meteosat resolution for a given ScaRaB broad-band measurement and the corresponding PSF of the ScaRaB sensor (see section 5), then the total relative contribution of a Meteosat scene a to the broad-band measurement is given by the total sum of weighted pixels c_{ij}^a within the footprint of the ScaRaB broad-band measurement that were identified as belonging to that scene divided by the sum of the values of the PSF of the ScaRaB broad-band sensor for these pixels (PSF_{ij}, which defines also the weight factor for each pixel c_{ij}^a), *i.e.* :

$$C^a = \frac{\Sigma PSF_{ij} \times c_{ij}^a}{\Sigma PSF_{IJ}} \tag{4}$$

The de-convolution of Meteosat pixels with the PSF of the Meteosat sensors is not needed before applying the PSF of ScaRaB on the footprint of the classified Meteosat data because the high-resolution Meteosat pixels can be considered as points on the resolution of the ScaRaB measurements.

The total relative contributions of the Meteosat scenes detected in figure 7 (right image) to the corresponding ScaRaB broad-band measurements with a constant scene identification label (derived with the ERBE-scheme) are illustrated in figure 10 for the ERBE-label 1 (clear ocean) and in figure 11 for the ERBE-label 12 (overcast). The first line in the right image of figures 10 and 11 represents the Meteosat scenes of figure 7 (right image) ; the other lines of the same images represent the relative contribution of these Meteosat scenes to ScaRaB broad-band measurements with the above-mentioned constant ERBE scene identification labels. The left images of figures 10 and 11 represent the scene identification results of figure 7 (right) but the scene identification labels of those scenes that contribute to a large extent (at least 70 %) to the ScaRaB measurements (bright contributions in the right images) are given a pseudo-grey value label to highlight the sub-pixel scene contribution.

From these experiments we can conclude that the ERBE-like scene identification in ScaRaB data does not fit completely the physical reality of the scenes. From figure 10, we can derive that low-level clouds contribute to a large extent to the ERBE scenes that are identified as clear ocean. From figure 11, we can conclude that low-level clouds and even clear land contribute to a large extent to the ERBE scenes that are identified as overcast. The latter is not compatible with the observations of DIECKMAN & SMITH 1989.

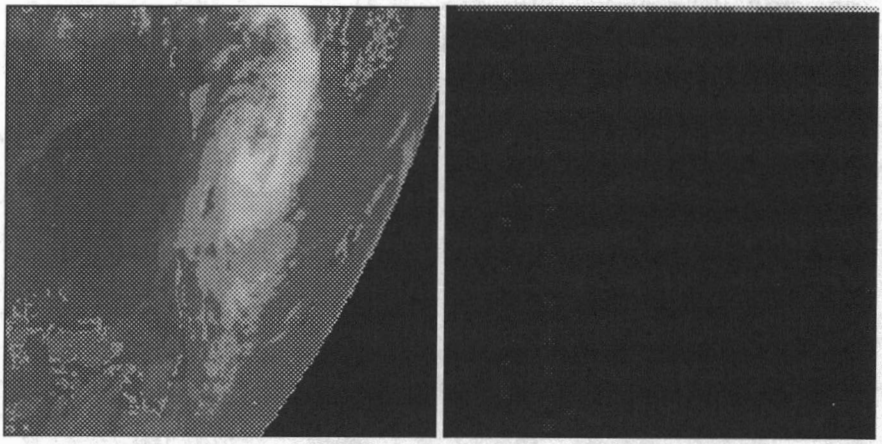


Fig. 10. — Total relative contributions of the Meteosat scenes of figure 7 (right) to the corresponding ScaRaB broad-band measurements with a constant ERBE scene identification label (label 1 : clear ocean).

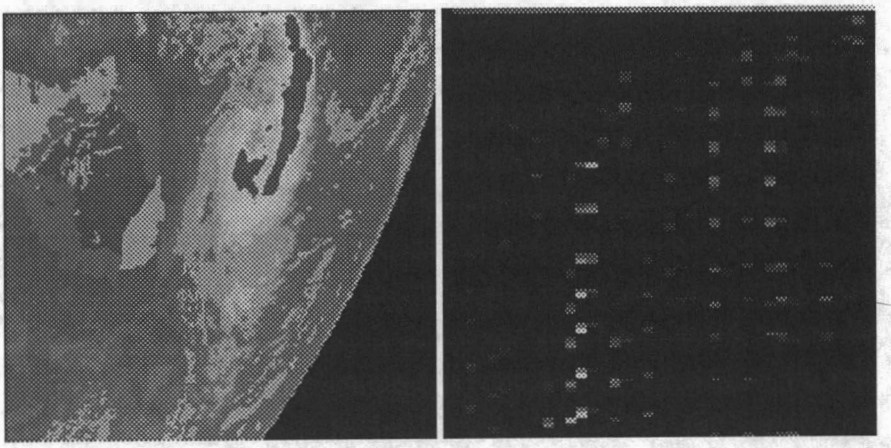


Fig. 11. — Total relative contributions of the Meteosat scenes of figure 7 (right) to the corresponding ScaRaB broad-band measurements with a constant ERBE scene identification label (label 12 : overcast).

Remark that the proposed methodology of sub-pixel scene identification of ScaRaB broad-band measurements allows to compose a set of equations (for the long-wave and short-wave measurement separately) in which the total observed long-wave and short-wave radiances are expressed, for a given angular geometry, in terms of unknown relative radiative contributions (with the same angular

geometry) of known (extended) scenes observed in Meteosat narrow-band data. The solutions of this set of equations allow in turn to derive an extended set of enhanced angular dependency models for the correct derivation of energy fluxes from broad-band measurements.

7. Conclusion

The present study showed that enhanced scene identification of cloud radiation fields for the purpose of Earth radiation Budget studies can be obtained by the application of autoadaptive scene identification algorithms in multi-spectral (geostationary) narrow-band measurements (*e.g.* Meteosat tri-spectral composite images) and the collocation of the resulting scene identification data with the (polar) broad-band measurements (*e.g.* ScaRaB data). The obtained sub-pixel scene identification of ScaRaB broad-band data allowed us to detect erroneous assumptions of the currently used ERBE-like scene identification scheme about the physical reality of scenes contributing to ScaRaB broad-band measurements (*e.g.* "clear land" and "overcast"). The proposed methodology opens interesting perspectives for the derivation of an extended set of enhanced angular dependency models needed for the correct derivation of energy fluxes from broad-band measurements observed at the top of the atmosphere.

8. International Partners and Funding

This research was performed as member of the International ScaRaB Science Working Group (ISSWG) under the direction of CNES/DARA/RosHydroMet and was funded by the Science Policy Office of Belgium, the Federal Office for Scientific, Technical and Cultural Affairs (DWTC/SSTC) as part of Telsat III (Program Teledetection, contract reference T3/03/41).

REFERENCES

BOEKAERTS, P. 1995. Autoadaptive cloud identification in Meteosat images. — ESA SP-1183, 58 pp.

BOEKAERTS, P., NYSSEN, E. & CORNELIS, J. 1995. Autoadaptive monospectral cloud identification in Meteosat satellite images. — *In* : Proceedings of the European Symposium on Satellite Remote Sensing, Conference on Image and Signal Processing for Remote Sensing II (Paris, 25-27 September), EOS/SPIE, Vol. 2579, pp. 259-271.

BOEKAERTS, P., STEENPUT, E., ACHEROY, M., VAN HAM, P. & CORNELIS, J. 1995. Cloud detection in Multi-Spectral NOAA-AVHRR data using Multi-Layer Perceptions : a pilot study. — *In* : Space Scientific Research in Belgium, Earth Observation, Vol. III, Part 1. Federal Office for Scientific, Technical and Cultural Affairs, pp.173-179.

BOEKAERTS, P., NYSSEN, E. & CORNELIS, J. 1996. Autoadaptive Scene Identification in Multi-Spectral Satellite Data. — *In* : Proceedings of the 5th Symposium on Remote Sensing : a Valuable Source of Information (Toulouse, 22-26 April 1996), Sensor and Propagation Panel NATO AGARD (accepted for publication).

DIECKMAN, F. J. & SMITH, G. L. 1989. Investigation of Scene Identification Algorithms for Radiation Budget Measurements. — *J. Geoph. Res.*, **94** (D3) : 3395-3412.

SMITH, G. I., SUTTLES, J. T., GREEN, R. N., MINNIS, P., STAYLOR, W. F., WIELICKI, B. A., WALKER, I. J., YOUNG, D. F., TOYLOR, V. R. & STOWE, L. L. 1988. Angular Radiation Models for Earth-Atmosphere System. — NASA 1184, Vol. I : Shortwave Radiation, 144 pp.

WIELICKI, B. A., CESS, R. D., KING, M. D., RANDALL, D. A. & HARRISON, E. F. 1995. Mission to Planet Earth : Role of Clouds and Radiation in Climate. — *Bull. Am. Met. Soc.*, **76** : 2125-2153.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 390-413 (1998)

Determination of Tropical Radiation Budget at High Time and Space Resolution by Combination of Geostationary and Polar Satellite Measurements

by

Steven DEWITTE *, Natividad MANALO-SMITH **,
Dominique CROMMELYNCK * & Jan CORNELIS ***

KEYWORDS. — Radiation ; Solar Reflection ; Emission ; Satellite ; Meteosat ; ERBE ; Collocation.

ABSTRACT. — RB (Radiation Budget) data describe how the earth gains energy, due to absorbed solar radiation flux, or loses energy, due to emitted thermal radiation flux. Since the atmospheric energetics is described by differential equations with derivatives in time and in space, high-resolution temporal and spatial RB data should be available. RB data derived from satellite measurements exist [ERBE (Earth Radiation Budget Experiment) described by BARKSTROM *et al.* (1989), ScaRaB (Scanning radiometer for Radiation Budget measurements) described by MONGE *et al.* (1991), planned : CERES (Cloud and the Earth's Radiant Energy System)] but the time/space resolution of these data is insufficient to use them directly as input to atmospheric models. The purpose of this work is to combine these data with the high time/space resolution images of geostationary meteorological satellites (such as Meteosat or the future MSG (Meteosat Second Generation) carrying SEVIRI (Spinning Enhanced Visible and Infrared Imager) and GERB (Geostationary Earth Radiation Budget)), in order to obtain RB data with much higher spatial and temporal resolution. As a test case, we derive this data from November 1986 Meteosat images and we compare the results with those of the ERBE instruments on the polar satellites NOAA 9 and NOAA

* Department of Aerology, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
** Analytical Services and Materials, Hampton, VA 23666 (United States).
*** Department of Electronics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

10. We obtain differences close to the minimum ones obtainable according to theoretical simulations.

MOTS-CLES. — Radiation ; Rayonnement solaire ; Emission ; Satellite ; Météosat ; ERBE ; Collocation.

RESUME. — *Détermination du bilan de radiation tropical à haute résolution temporelle et spatiale en combinant des observations en provenance de satellites géostationnaires et polaires.* — Les données du bilan radiatif terrestre décrivent la façon dont la terre gagne de l'énergie grâce au flux solaire radiatif absorbé, ou perd de l'énergie à cause du flux radiatif thermique émis. Depuis que les phénomènes énergétiques atmosphériques sont décrits par des équations différentielles avec dérivées spatio-temporelles, les données du bilan radiatif terrestre de haute résolution spatiale et temporelle doivent être connues. Ces données obtenues depuis des mesures de satellites existent déjà [ERBE, «Earth Radiation Budget Experiment», décrit par BARKSTROM *et al.* (1989), ScaRaB, «Scanning radiometer for Radiation Budget measurements», décrit par MONGE *et al.* (1991), ou sont planifiées : CERES, «Cloud and Earth's Radiant Energy System»]. Cependant, la résolution spatio-temporelle de ces données est insuffisante et ne permet pas de les utiliser directement dans des modèles atmosphériques. Le but de ce travail consiste à combiner ces données avec des images de résolution espace/temps obtenues grâce à des satellites météorologiques géostationnaires [Meteosat ou MSG («Meteosat Second Generation») à bord desquels se trouvent SEVIRI («Spinning Enhanced Visible and Infrared Imager») et GERB («Geostationary Earth Radiation Budget»)] afin d'obtenir des données du bilan radiatif terrestre avec une meilleure résolution spatio-temporelle. Comme exemple, nous reprenons les données prises par Météosat en novembre 1986 et les comparons à celles des instruments ERBE sur les satellites polaires NOAA 9 et NOAA 10. Nous obtenons des différences proches de celles déterminées au moyen de simulations théoriques.

TREFWOORDEN. — Straling ; Zonnestraling ; Emissie ; Satelliet ; Meteosat ; ERBE ; Collocatie.

SAMENVATTING. — *Bepaling van de tropische stralingsbalans met hoge resolutie in tijd en ruimte door samenbrengen van waarnemingen van geostationaire en polaire satellieten.* — De stralingsbalans van de aarde beschrijft hoe de aarde energie wint, door absorptie van de invallende straling, of verliest, door thermische emissie. Aangezien de atmosferische energetica beschreven wordt door differentiële vergelijkingen met afgeleiden in tijd en ruimte, is het nodig over stralingsbalansgegevens te beschikken met hoge ruimtelijke en tijdsresolutie. Stralingsbalansgegevens afgeleid uit satellietmetingen bestaan [ERBE, „Earth Radiation Budget Experiment", beschreven door BARKSTROM *et al.* (1989), ScaRaB, „Scanning radiometer for Radiation Budget measurements", beschreven door MONGE *et al.* (1991), gepland :

CERES], maar de tijds/ruimteresolutie van deze gegevens is onvoldoende om direct als input te dienen voor atmosferische modellen. Het doel van het hier gepresenteerde werk is het combineren van deze gegevens met de beelden (met hoge tijds/ruimteresolutie) van geostationaire weersatellieten (zoals de huidige Meteosat of de geplande SEVIRI en GERB aan boord van MSG). Voor de proefperiode november 1986 leiden we deze gegevens af van Meteosatbeelden en we vergelijken de resultaten met deze van de ERBE-instrumenten aan boord van de polaire satellieten. De verschillen die we bekomen benaderen de minimum mogelijke volgens theoretische simulaties.

Introduction

Weather prediction is based on a combination of the (partial) knowledge of processes that occur within the earth's atmosphere and on its surface, and of the (partial) measurement of the state of the earth's atmosphere and surface. In Numerical Weather Prediction (NWP) these two are combined in a Kalman filter-like way as described by BENGSTON (1985) and KALNAY *et al.* (1995). The knowledge is present as the internal equations of a numerical model of the atmosphere. The measurements are various kinds of meteorological observations, mainly ground-based and satellite-based, which are assimilated in the internal variables of the numerical model, *i.e.* the internal variables are updated to correspond better to the measurements. The assimilation of the measurements brings the internal variables in correspondence with reality, if the number of available independent measurements is sufficiently high, if they are accurate enough, and if they are sufficiently correlated with the internal variables. A large amount of measurements with uniform quality and high information content can be obtained using satellite data according to RAO *et al.* (1990). Currently mainly cloud motion winds and IR soundings are used as satellite data for NWP. A third possible candidate would be radiation budget data at high space/time resolution (at least synoptic), whose great potential interest was shown by VAN MIEGHEM (1958, 1962). Radiation budget data at the top of the atmosphere derived from polar satellite measurements exist [ERBE (Earth Radiation Budget Experiment), ScaRaB (Scanning radiometer for Radiation Budget measurements), planned : CERES (Cloud and the Earth's Radiant Energy System)] but the time resolution of these data is insufficient [1] * to obtain a synoptic time sampling. A much better

* The number in brackets refers to the note p. 411.

time resolution can be obtained with geostationary satellites [thirty minutes for the current Meteosat instruments, fifteen minutes for the planned MSG (Meteosat Second Generation) SEVIRI (Spinning Enhanced Visible and InfraRed Imager) instrument, five minutes for the planned MSG GERB (Geostationary Earth Radiation Budget) instrument)]. The possibility to derive the radiation budget terms from geostationary satellite instruments was demonstrated by SCHMETZ & LIU (1988) and SCHMETZ *et al.* (1990) (Meteosat-ERB longwave term), VESPERINI & FOUQUART (1994) (Meteosat-ERB shortwave term), MINNIS & HARRISON (1984) (GOES-ERB shortwave and longwave terms), MINNIS *et al.* (1991) (GOES-ERB longwave term) and DOELLING *et al.* (1990) (GOES-ERB shortwave term). In this paper we extend this work to Meteosat-ERB derived radiation budget term estimates at the highest possible time/space resolution (time resolution 30 minutes, spatial resolution : longwave : 5 km at nadir ; shortwave : 2.5 km at nadir) and we measure an experimental upper bound of the accuracy obtained at ERBE pixel level (size $\approx 50 \times 50$ km at nadir) by intercomparison of the ERBE and Meteosat-ERB estimates of the radiation budget terms over the ERBE pixel footprint. In section II we define the terms of the radiation budget of the earth, and of the satellite radiance's that are used to estimate them. In section III we describe the estimation of the radiation budget terms from full resolution Meteosat data. In section IV we compare the Meteosat-ERB estimates with the ERBE estimates over ERBE footprints. We formulate our conclusions in section V.

Definitions

The radiation from the sun is the prime energy source for the processes that occur within the earth's atmosphere and on its surface. Observed from earth, the sun can be considered in good approximation as a point source. The solar constant S_{SOLAR} is defined as the solar flux at the mean distance earth-sun (= 1 astronomical unit) for overhead sun. The value of S_{SOLAR} is varying with a recurrent eleven-year cycle between 1,363W/m^2 and 1,369W/m^2 as described by CROMMELYNCK & DEWITTE (1996). In good approximation it can be considered as a constant with value 1,366W/m^2. At a given point on earth we have a solar flux at the top of the atmosphere F_{SOLAR} :

$$F_{SOLAR} = S_{SOLAR} (r_{earth\text{-}sun}/1 \text{ a.u.})^2 (\theta_{sun}) \quad (1)$$

where $r_{earth\text{-}sun}$ is the earth-sun distance and θ_{sun} is the solar-zenith angle (angle between the direction of the sun and the vertical, depending on position on the earth, on date of the year and on time of the day). Part of the solar flux F_{SOLAR} is reflected back to space as the reflected shortwave flux at the top of the atmosphere F_{SW} :

$$\begin{aligned} F_{SW} &= \int_0^{\infty} d\lambda \int_0^{1\pi} d\varphi \int_0^{\pi/2} d\theta \, L_\lambda^{solar}(\theta, \varphi) \sin(\theta) \cos(\theta) \\ &\approx \int_0^{5\mu n} d\lambda \int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta \, L_\lambda^{solar}(\theta, \varphi) \sin(\theta) \cos(\theta) \end{aligned} \tag{2}$$

where φ and θ are the angular coordinates of a spherical coordinate system with z-axis corresponding to the local vertical direction. L_λ^{solar} is the spectral radiance from solar origin reflected at the top of the earth's atmosphere. As a result we have a net shortwave flux entering the top of the atmosphere $F_{SW,IN}$:

$$F_{SW,IN} = F_{SOLAR} - F_{SW} \tag{3}$$

If this flux were the only non-zero one at the top of the atmosphere, the mean temperature of the earth would be rising constantly. This is not the case, because all the components of the earth and its atmosphere have a certain temperature, and therefore emit some thermal radiation which results in an emitted longwave flux at the top of the atmosphere F_{LW} :

$$\begin{aligned} F_{LW} &= \int_0^{\infty} d\lambda \int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta \, L_\lambda^{earth}(\theta, \varphi) \sin(\theta) \cos(\theta) \\ &\approx \int_{5\mu n}^{50\mu n} d\lambda \int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta \, L_\lambda^{earth}(\theta, \varphi) \sin(\theta) \cos(\theta) \end{aligned} \tag{4}$$

where L_λ^{earth} is the spectral radiance from earthern origin at the top of the earth's atmosphere. L_λ^{solar} finds its origin in the radiation emitted by the sun, approximated roughly by black-body radiation with $T \approx 5{,}000$ K, L_λ^{earth} finds its origin in the radiation emitted by the earth, approximated roughly by black-body radiation with $T \approx 300$ K. Fortunately for remote sensing purposes, these temperatures are

sufficiently different to have a good spectral separation between L_λ^{solar} (spectral range $\approx$ [0-5 μm]) and L_λ^{earth} (spectral range $\approx$ [5-50 μm]). The combination of $F_{SW,IN}$ and F_{LW} gives the local instantaneous radiation budget at the top of the atmosphere RB :

$$RB = F_{SW,IN} - F_{LW} \tag{5}$$

which can be positive (local instantaneous heating) or negative (local instantaneous cooling). The long-term global annual mean of RB has to be zero to have a climate equilibrium. Its components are shown in figure 1, according to http : //asd-www.larc.nasa.gov/erbe/AS-Derbe.html.

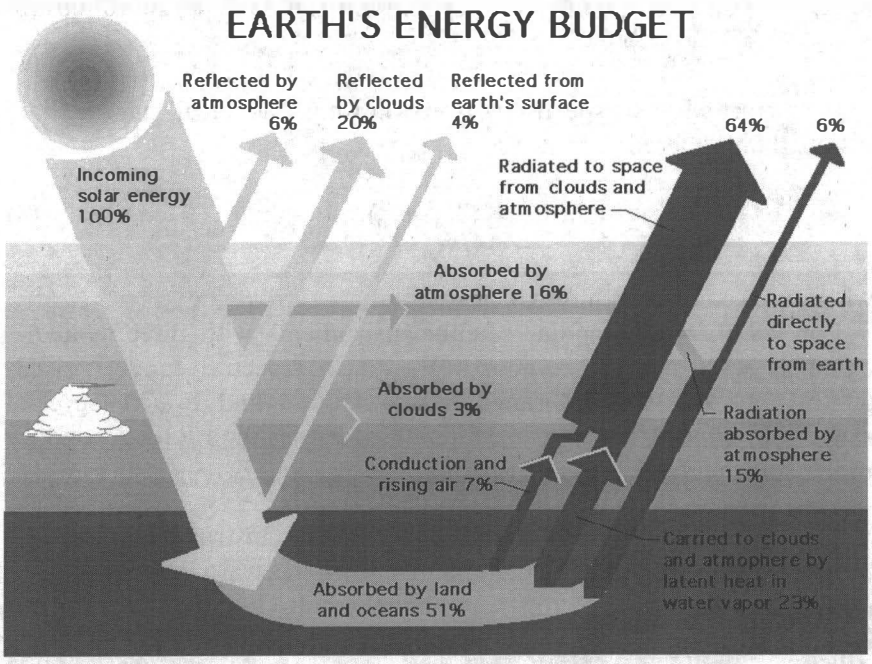


Fig. 1. — The components of the Earth's Radiation Budget, obtained from http : //asd-www.larc.nasa.gov / erbe / ASDerbe.html.

If we want to estimate the terms of RB from satellite instrument measurements, all we have available in general are a number of filtered radiance's $L_{sat,channel}$:

$$L_{sat,channel} = \int_0^\infty d\lambda\ \Phi_{channel}(\lambda)\ (L_\lambda^{solar} + L_\lambda^{earth})\ (\theta_{sat}, \varphi_{sat}) \qquad (6)$$

where θ_{sat} and φ_{sat} are the angular coordinates with which the satellite is seen from earth and where $\Phi_{channel}(\lambda)$ is the spectral response of the satellite instrument channel under consideration. To estimate F_{SW} or F_{LW} from filtered radiance's two conversions are necessary, an angular one and a spectral one. We can either start with the angular conversion, or we can start with the spectral conversion. If we start with the angular conversion we get as (ideal) intermediate results the filtered fluxes $F_{channel}$:

$$F_{channel} = \int_0^\infty d\lambda \int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta\ \Phi_{channel}(\lambda)\ (L_\lambda^{solar} + L_\lambda^{earth})\ (\theta, \varphi) \sin(\theta) \cos(\theta) \qquad (7)$$

If we start with the spectral conversion we get as (ideal) intermediate results the unfiltered radiance's $L_{sat,type}$:

$$L_{sat,type} = \int_0^\infty d\lambda\ L_\lambda^{type}\ (\theta_{sat}, \varphi_{sat}) \qquad (8)$$

where type equals earth or solar.

For ERBE we had polar satellite instruments with three available channels with spectral responses $F_{TOTAL}(\lambda)$ (spectral range $\approx$ [0.3-50 μm]), $F_{SW}(\lambda)$ (spectral range $\approx$ [0.3-5 μm]) and $F_{LW}(\lambda)$ (spectral range $\approx$ [5-50 μm]). From these filtered radiance's the ERBE secondary processing derives $F_{LW,ERBE}$ as estimate of F_{LW} and $F_{SW,ERBE}$ as estimate of F_{SW}.

For Meteosat we have a geostationary satellite instrument with three available channels : the visible channel with spectral response $F_{VIS}(\lambda)$ (spectral range $\approx$ [0.4-1.1 μm]) and digital count C_{VIS}, the water vapour channel with spectral response $F_{WV}(\lambda)$ (spectral range $\approx$ [5.7-7.1 μm]) and digital count C_{WV}, and the infrared window channel with spectral response $F_{IR}(\lambda)$ (spectral range $\approx$ [10.5-12.5 μm]) and digital count C_{IR}.

Estimation of Radiation Budget Terms from Meteosat Measurements

Longwave Flux

For the estimation of F_{LW} from Meteosat data we use the method of Schmetz & Liu (1988) and Schmetz *et al.* (1990) and apply it

to full resolution IR and WV data. We repeat the different steps here briefly.

The digital counts C_{IR}, C_{WV} are converted to calibrated filtered radiance's L_{IR}, L_{WV} using the linear calibration relations :

$$L_{IR} = k_{IR} (C_{IR}-C_{IR,0}) \tag{9}$$

$$L_{WV} = k_{WV} (C_{WV}-C_{WV,0}) \tag{10}$$

where the calibration coefficients k_{IR}, $C_{IR,0}$, k_{WV} and $C_{WV,0}$ are given in the radiometer calibration reports.

From the filtered radiance's L_{IR}, L_{WV} the filtered fluxes F_{IR}, F_{WV} are estimated as :

$$F_{IR} = a (\theta_{sat}) L_{IR} (\theta_{sat}) + b (\theta_{sat}) \tag{11}$$

$$F_{WV} = c (\theta_{sat}) L_{WV} (\theta_{sat}) + d (\theta_{sat}) \tag{12}$$

$$a (\theta_{sat}) = k_1 + k_2 (\sec(\theta_{sat})-1) + k_3 (\sec(\theta_{sat})-1)^2 \tag{13}$$

$$b (\theta_{sat}) = k_4 + k_5 (\sec(\theta_{sat})-1) + k_6 (\sec(\theta_{sat})-1)^2 \tag{14}$$

$$c (\theta_{sat}) = l_1 + l_2 (\sec(\theta_{sat})-1) + l_3 (\sec(\theta_{sat})-1)^2 \tag{15}$$

$$d (\theta_{sat}) = l_4 + l_5 (\sec(\theta_{sat})-1) + l_6 (\sec(\theta_{sat})-1)^2 \tag{16}$$

where the coefficients k_i, l_i, $i = 1, ..., 6$ are obtained as best fit coefficients from radiative transfer simulations by SCHMETZ & LIU (1988) and SCHMETZ *et al.* (1990).

From the filtered fluxes F_{IR}, F_{WV} the emitted longwave flux F_{LW} is estimated as :

$$F_{LW} = \xi_0 + \Sigma_{i=1}^{3} \xi_i F_{IR}^i + \Sigma_{i=1}^{3} \zeta_i F_{WV}^i \tag{17}$$

where the coefficients ξ_i, $i = 0, ..., 3$ ζ_i, $i = 1, ..., 3$ are also obtained as best fit coefficients from radiative transfer simulations by SCHMETZ & LIU (1988) and SCHMETZ *et al.* (1990).

Figure 2 shows the result of this procedure applied to the Meteosat IR and WV data of 08/11/1986 (dd/mm/yyyy) time slot 18 (nominally 08 :30-08 :55 GMT).

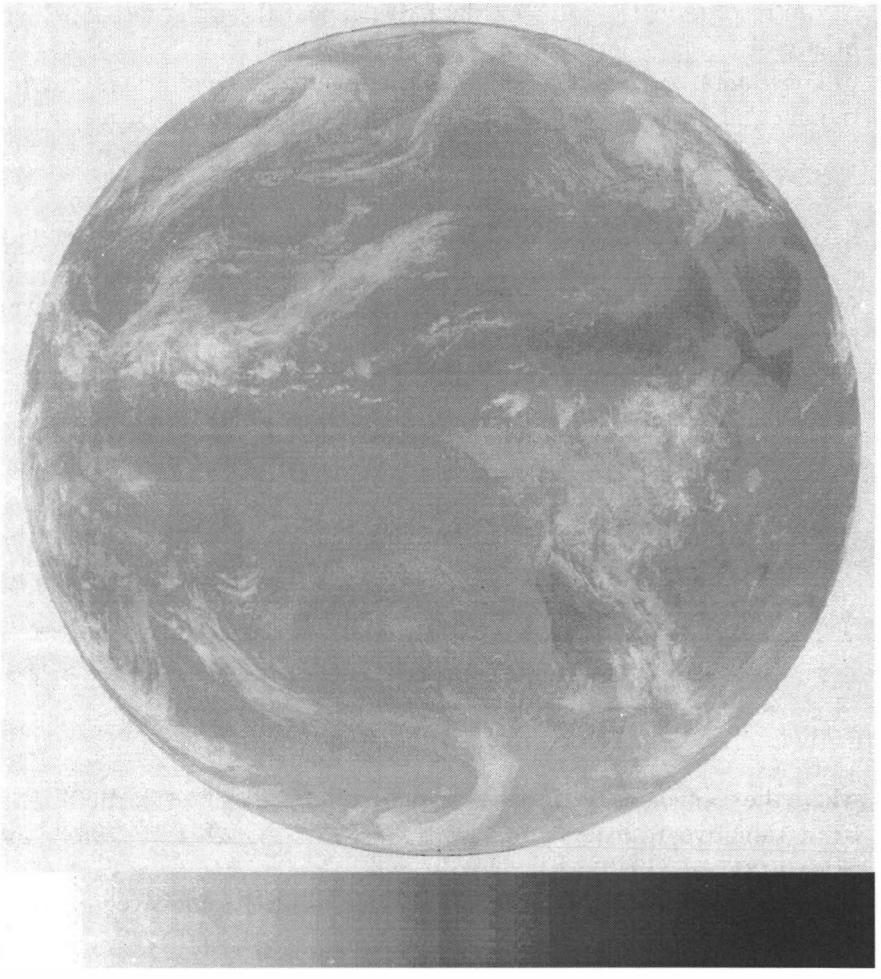


Fig. 2. — Longwave flux estimated from Meteosat IR and WV data, for 08/11/1986 time slot 18 (nominally 08 :30-08 :55 GMT).

Reflected Shortwave Flux

Calibration of Meteosat 2 Visible Channel

The digital counts C_{VIS} are converted to calibrated filtered radiance's L_{VIS} using the linear calibration relation :

$$L_{VIS} = k_{VIS} (C_{VIS}-C_{VIS,0}) \quad (18)$$

where $C_{VIS,0}$ = lowest count during night = 2 and where k_{VIS} is based on the factors :

$$k_{VIS,ISCCP}\,(\text{date}) = k_{VIS}^{\text{nominal}}\, k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}\,(\text{date}) \quad (19)$$

reported by Rossow *et al.* (1992). The factors $k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}$ (date) are measured every three months by comparison with Meteosat 2 visible channel measurements and NOAA 9 AVHHR channel 1 (spectral range $\approx$ [0.55-0.7 μm]) measurements with coinciding viewing geometry and time of acquisition. The factors $k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}$ (date) from 04/1985 to 04/1987, calculated from Rossow *et al.* (1992) are given in table 1.

Table 1

Factors $k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}$ (date) from 04/1985 to 04/1987 with time step of three months

04/ 1985	07/ 1985	10/ 1985	01/ 1986	04/ 1986	07/ 1986	10/ 1986	01/ 1987	04/ 1987
1.1886	1.1842	1.1702	1.1275	1.1731	1.1897	1.2397	1.1728	1.1946

We notice that the factors $k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}$ (date) are almost constant over this two-year period, with a downward exception for 01/1986 and an upward exception for 10/1986.

Using the four months (09/1986-12/1986) of Meteosat ISCCP B2 data we have available, we are able to identify a Meteosat timing problem which coincides with the exceptionally high $k_{VIS,ISCCP}^{\text{nominal} \rightarrow \text{absolute}}$ (10/1986) and explains it.

For selected days we estimated the true time of acquisition of the Meteosat images from the location of the day/night separation in the visible images and compared this to the nominal time of acquisition. The differences are given in table 2.

Table 2

Difference in estimated true acquisition time and nominal acquisition time of Meteosat images for selected days

02/09/1986	01/10/1986	08/11/1986	03/12/1986
0'	10'	15'	10'

We get an exceptionally high difference of 15' for 08/11/1986. If this is not taken into account in the measurement of $k_{VIS,ISCCP}^{nominal \rightarrow absolute}$ (10/1986), NOAA 9 measurements taken around 14.30 local time (this is the equator crossing time of the sun synchronous NOAA 9) are believed to be corresponding to Meteosat 2 measurements taken around 14.45 local time. Because of the lower illumination at 14.45 compared to 14.30, the obtained Meteosat calibration factor is too high with a factor approximately equal to :

$$\cos(2\pi 2.5/24)\cos(2\pi 2.75/24) = 0.79/0.75 = 1.055 \qquad (20)$$

If we correct $k_{VIS,ISCCP}^{nominal \rightarrow absolute}$ (10/1986) by this factor we find :

$$(k_{VIS,ISCCP}^{nominal \rightarrow absolute}\ (10/1986))\ \text{corrected} = 1.2397/1.055 = 1.1750 \qquad (21)$$

which is in the normal range of table 1. This leads us to the assumption that k_{VIS} is a constant in time (*i.e.* the Meteosat 2 visible channel does not seem to degrade in time). As best estimate we take the mean of the ISCCP measurements over the two-year period.

$$k_{VIS} = \sum_{date=04/85}^{04/87} k_{VIS,ISCCP}\ (date)\ /\ 9 = k_{VIS}\ nominal_{1.1807} \qquad (22)$$

Default Spectral Conversion

The highest contribution to F_{SW} is coming from the clouds in the atmosphere (albedo up to 80 % compared to albedo up to 30 % for clear-sky surfaces), and clouds can be modelled in good approximation as gray absorbers, i.e. they do not modify the spectral distribution of the incoming solar radiation according to CROMMELYNCK & JOUKOFF (1993).

This justifies the conversion of L_{VIS} to L_{SW} as a simple linear conversion with a constant conversion factor equal to the one for the reference solar spectrum $L^{solar,reference}(\lambda)$:

$$L_{SW} = \left(\int_0^\infty d\lambda\ L^{solar,reference}(\lambda) \Big/ \int_0^\infty d\lambda\ L^{solar,reference}(\lambda)\varphi_{VIS}(\lambda) \right) L_{VIS} \qquad (23)$$

where $f_{VIS}(\lambda)$ is the Meteosat VIS channel spectral sensitivity. We use the values calculated by Rossow *et al.* (1992).

Angular Conversion

Scene Separation

To estimate F_{SW} from L_{SW} it is necessary to know the angular distribution of L_{SW}, which depends strongly on the scene type and the cloud cover as decribed by WIELICKI *et al.* (1996). This knowledge is present for discrete cloud cover classes in the analytical reflection functions of MANALO-SMITH *et al.* (1994). It is necessary to do a scene identification/separation in order to use the correct reflection function to estimate F_{SW} from L_{SW}.

We decompose LSW as :

$$L_{SW} = (1\text{-}f)*L_{SW,\,scene\text{-}lower} + f*L_{SW,\,scene\text{-}upper} \tag{24}$$

where $L_{SW,scene\text{-}lower}$ and $L_{SW,scene\text{-}upper}$ are radiance's for the MANALO-SMITH *et al.* (1994) discrete cloud cover scenes and where f is a scene fraction with $0 < f < 1$. For this scene separation the previously obtained clear-sky/cloud separation results of DEWITTE *et al.* (1995) and DEWITTE *et al.* (1996) are used.

Single Scene Angular Conversion

For the discrete cloud cover scenes the fluxes are related to the radiance's by :

$$F_{SW,scene} = \pi L_{SW,scene} \,/\, BDRF_{scene}\,(\theta_{sun}, \theta_{sat}, \varphi) \tag{25}$$

where $BDRF_{scene}$ is the analytical bi-directional reflection function for the particular scene obtained by MANALO-SMITH *et al.* (1994). The analytic expression for BDRF was formulated by applying a fit to the ERBE operational bi-directional reflectance model tabulations from SUTTLES *et al.* (1988) by use of parameters in the expression. For every scene, there exists a set of model coefficients applicable to any combination of viewing conditions. The forms of these expressions are based on theoretical considerations. The models are smooth in terms of directional angles and satisfy reciprocity, *i.e.*, they are invariant with respect to the interchange of the incoming and outgoing directions.

Scene Recomposition

The flux F_{SW} is recomposed from the discrete cloud cover fluxes using :

$$F_{SW} = (1\text{-}f)*F_{SW,scene\text{-}lower} + f*F_{SW,scene\text{-}upper} \quad (26)$$

where f, scene-lower and scene-upper are the same as obtained in the radiance decomposition of equation 18.

Net Shortwave Flux entering the Top of the Atmosphere

For every Meteosat pixel F_{SOLAR} is calculated from equation 1. $F_{SW,IN}$ is calculated by equation 3 from F_{SOLAR} and F_{SW}. Figure 3 shows the result for 08/11/1986 time slot 18.

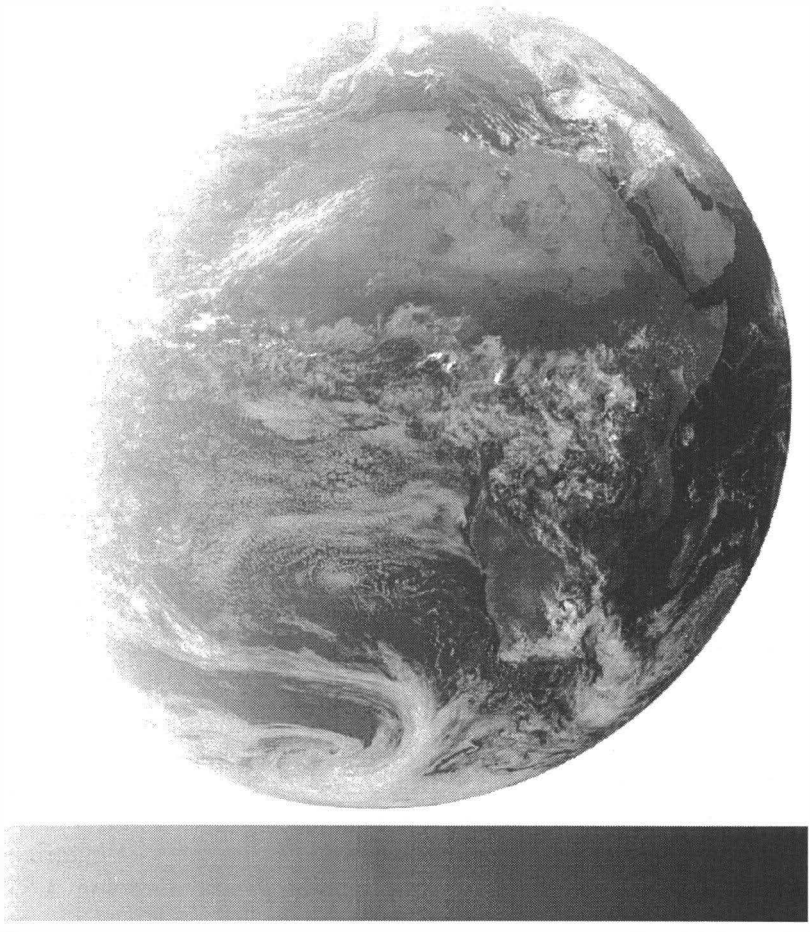


Fig. 3. — Shortwave flux estimated from Meteosat VIS data, for 08/11/1986 time slot 18 (nominally 08 :30-08 :55 GMT).

Radiation Budget at the Top of the Atmosphere

For every Meteosat pixel RB is calculated by equation 5 from $F_{SW,IN}$ and F_{LW}. Figure 4 shows the result for 08/11/1986 time slot 18.

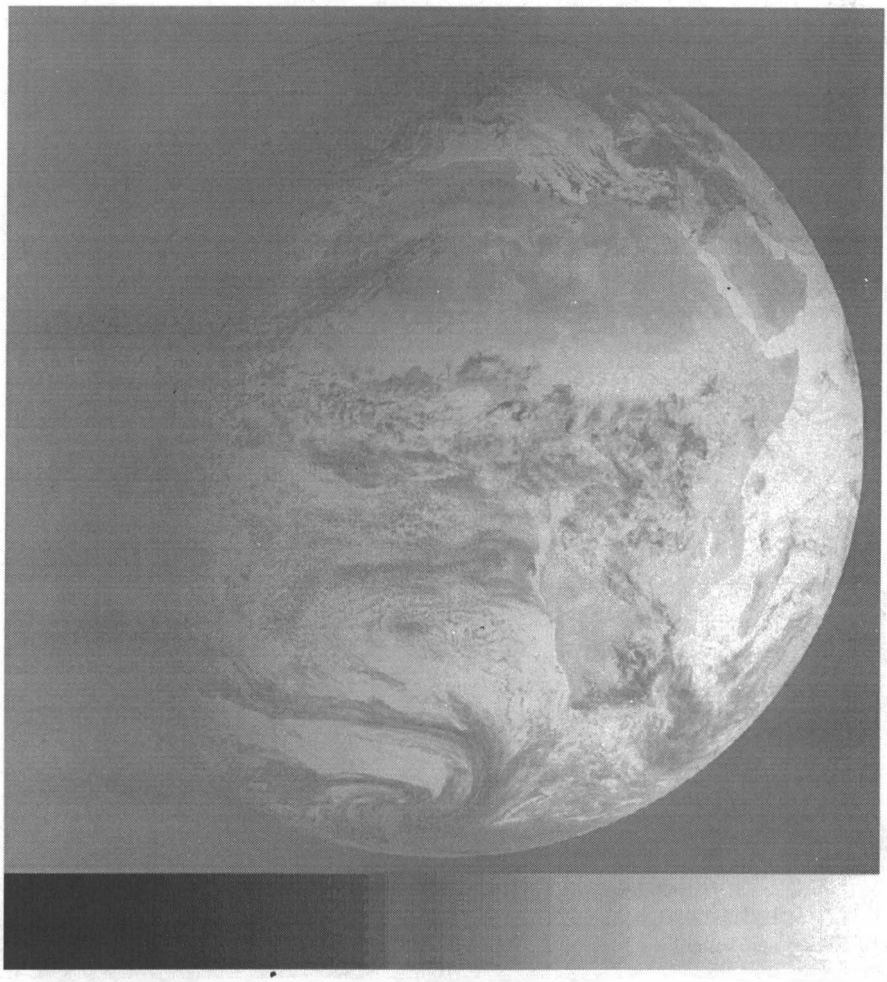


Fig. 4. — Radiation budget estimated from Meteosat IR, WV and VIS data, for 08/11/1986 time slot 18 (nominally 08 :30-08 :55 GMT).

Comparison of Meteosat-ERB and ERBE Estimations of Radiation Budget Terms

In this section we compare the obtained Meteosat-ERB fluxes with those obtained by ERBE. The comparison is made at ERBE pixel level.

We make the comparison of Meteosat-ERB with the ERBE instrument on board, the AM satellite NOAA 10, and with the ERBE instrument on board, the PM satellite NOAA 9. Figure 5 shows the Meteosat visible image at time slot 18 (nominally 08 :30-08 :55 GMT) and the corresponding NOAA 10 shortwave flux estimations. Figure 6 shows the Meteosat visible image at time slot 35 (nominally 17 :00-17 :25 GMT) and the corresponding NOAA 9 shortwave flux estimations. The Meteosat time slots 18 and 35 are those with the best time correspondence with the NOAA 10 and NOAA 9 measurements respectively.

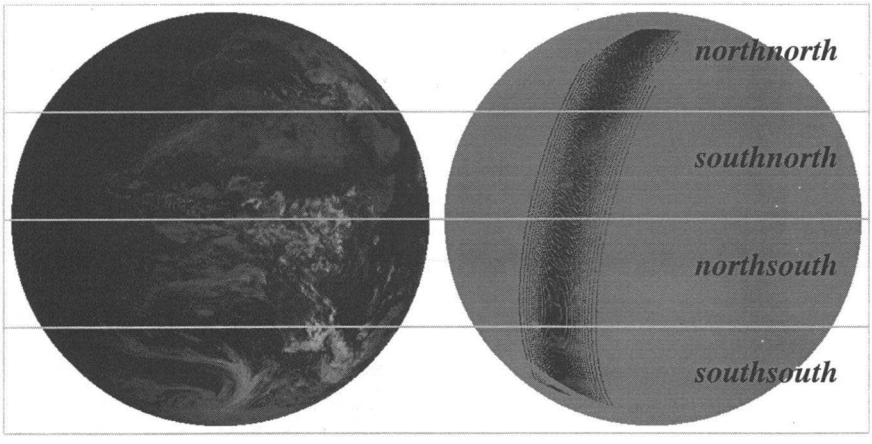


Fig. 5. — Left: Meteosat visible image for time slot 18 (nominally 08 :30-08 :55 GMT) of 08/11/1986, right: corresponding shortwave flux estimations from NOAA 10 ERBE instrument.

Convolution of Meteosat-ERB Estimation with ERBE Point Spread Function

To obtain Meteosat-ERB flux estimates at ERBE pixel level $F_{ERBE\ (Meteosat\text{-}ERB)}$ from the full resolution Meteosat-ERB fluxes $F_{Meteosat\text{-}ERB}$

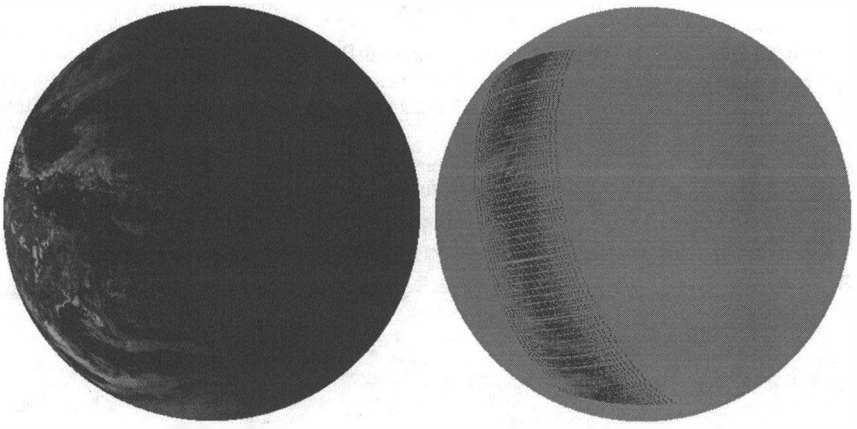


Fig. 6. — Left : Meteosat visible image for time slot 35 (nominally 17 :00-17 :25 GMT) of 08/11/1986, right : corresponding shortwave flux estimations from NOAA 9 ERBE instrument.

(F_{LW} or F_{SW} obtained in the previous section), a convolution is made with the ERBE point spread function PSF (α, β) :

$$F_{ERBE(Meteosat\text{-}ERB)} = PSF\ (\alpha, \beta)\ F_{Meteosat\text{-}ERB}\ d\alpha d\beta \qquad (27)$$

where α is the ERBE cross-track scan angle and β is the ERBE along-track scan angle.

Comparison of Longwave Flux Estimations

Figure 7 shows the Meteosat-ERB estimation versus the ERBE estimation of the emitted longwave flux over the ERBE footprints in the north-south region of figure 5. In the case of perfect agreement between the estimated fluxes this figure would show a perfect $y = x$ relation. In order to quantify the deviation from this perfect agreement case a linear fit $y = ax$ is performed. The best fitting line is shown in figure 7.

Table 3 shows the slopes "a" and the RMS differences "$\sqrt{\overline{(y\text{-}ax)^2}}$" obtained for the four regions north-north, south-north, north-south and south-south (see fig. 5) for the comparison of Meteosat time slot 18 (nominally 08 :30-08 :55 GMT) compared to NOAA 10 measurements (see fig. 5).

Table 4 shows the slopes a and the RMS differences "$\sqrt{\overline{(y\text{-}ax)^2}}$" obtained for the four regions north-north, south-north, north-south

Table 3

Slope of best linear fit through origin and residual RMS difference between Meteosat-ERB and NOAA 10 ERBE emitted longwave flux estimations. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

	north-north	south-north	north-south	south-south
Slope	0.98	0.95	0.98	0.95
RMS	8.1 W/m²	5.7 W/m²	6.7 W/m²	8.8 W/m²
% RMS	3.3 %	2.0 %	2.7 %	3.4 %

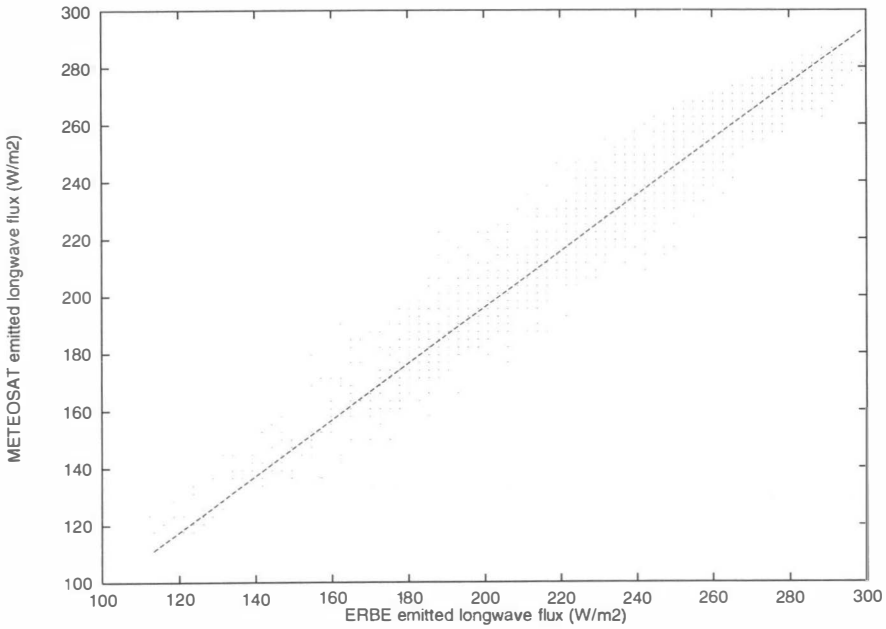


Fig. 7. — Comparison of ERBE (NOAA 10) and Meteosat-ERB estimations of longwave flux(W/m2) over ERBE footprints, for Meteosat north-south region, for 08/11/1986 Meteosat time slot 18 (nominally 08 :30-08 :55 GMT).

and south-south (see fig. 5) for the comparison of Meteosat time slot 34 (nominally 16 :30-16 :55 GMT) compared to NOAA 9 measurements (see fig. 6). Meteosat time slot 34 is used instead of time slot 35 (which corresponds better in time with the NOAA 9 measurements) because the Meteosat IR image is not available for time slot 35.

Table 4

Slope of best linear fit through origin and residual RMS difference between Meteosat-ERB and NOAA 9 ERBE emitted longwave flux estimations. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

	north-north	south-north	north-south	south-south
Slope	0.96	1.00	1.00	1.00
RMS	8.7 W/m²	9.9 W/m²	13.4 W/m²	12.0 W/m²
% RMS	3.7 %	3.7 %	5.8 %	5.1 %

Comparison of Shortwave Flux Estimations

Figure 8 shows the Meteosat-ERB estimation versus the ERBE estimation of the reflected shortwave flux over the ERBE footprints in the north-south region of figure 5. As for the longwave case in the case of perfect agreement between the estimated fluxes this figure would show a perfect $y = x$ relation. In order to quantify the deviation from this perfect agreement case a linear fit $y = ax$ is performed. The best fitting line is shown in figure 8.

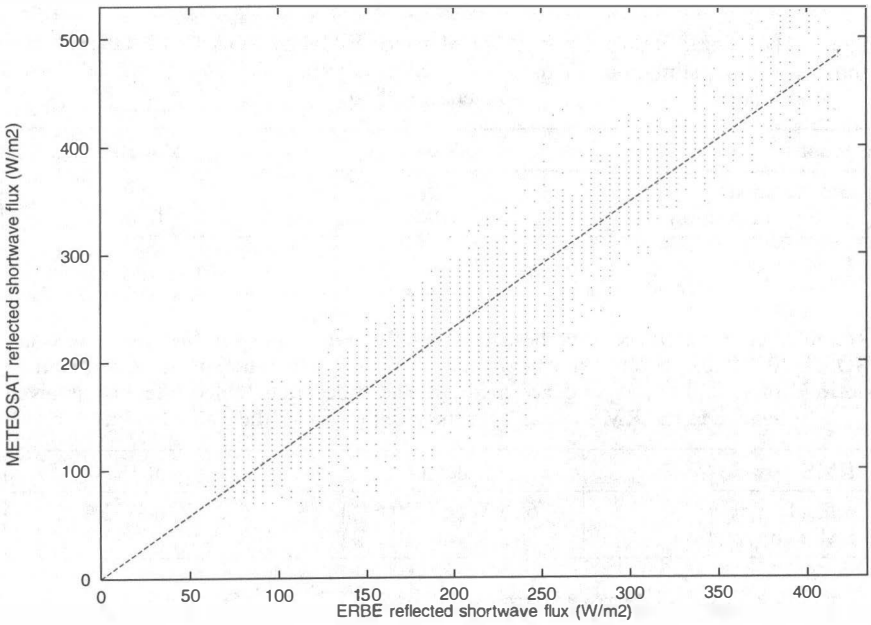


Fig. 8. — Comparison of ERBE (NOAA 10) and Meteosat-ERB estimations of shortwave flux (W/m²) over ERBE footprints, for Meteosat north-south region, for 08/11/1986 Meteosat time slot 18 (nominally 08 :30-08 :55 GMT).

For the comparison of different reflected shortwave flux estimates we expect a high sensitivity to time and space correspondence of these estimates, due to the high spatial (broken clouds) and temporal (solar-zenith angle) variation of these fluxes.

To investigate quantitatively the importance of an accurate spatial correspondence we make the comparison of figure 8 with and without convolution of the Meteosat-ERB fluxes with the point spread function associated to the ERBE pixel. In the case without convolution with the ERBE PSF, the Meteosat-ERB pixel lying in the centre of the ERBE footprint is taken as Meteosat-ERB estimate for the whole footprint.

To investigate quantitatively the importance of an accurate time correspondence we make the comparison of figure 8 at two times, once at the Meteosat time slot nearest to the ERBE acquisition and once at one Meteosat time slot earlier (half an hour earlier).

Table 5 shows the slopes "a" obtained in function of the time correspondence (best correspondence for slot 18) and of the spatial correspondence method (PSF convolution or central pixel selection).

Table 5

Slope of best linear fit through origin for Meteosat-ERB and NOAA 10 ERBE reflected shortwave flux estimations in function of Meteosat time slot and of spatial correspondence method

Slope	slot 17	slot 18
central : pixel	0.96	1.17
PSF : convolution	0.96	1.16

Table 6

Residual RMS difference after best linear fit through origin for Meteosat-ERB and NOAA 10 ERBE reflected shortwave flux estimations in function of Meteosat time slot and of spatial correspondence method. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

RMS	slot 17	slot 18
central : pixel	62.1 W/m^2 (30.6 %)	63.8 W/m^2 (31.4 %)
PSF : convolution	38.3 W/m^2 (18.7 %)	31.5 W/m^2 (15.4 %)

Table 6 shows the RMS differences "$\sqrt{\overline{(y-ax)^2}}$" obtained in function of the time correspondence (best correspondence for slot 18) and of the spatial correspondence method (PSF convolution or central pixel selection).

Table 7 shows the RMS differences "$\sqrt{\overline{(y-ax)^2}}$" relative to "a", *i.e.* "$\sqrt{\overline{((y/a)-x)^2}}$".

Table 7

Relative residual RMS difference after best linear fit through origin for Meteosat-ERB and NOAA 10 ERBE reflected shortwave flux estimations in function of Meteosat time slot and of spatial correspondence method. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

RMS/Slope	slot 17	slot 18
central : pixel	64.7 W/m² (30.6 %)	58.4 W/m² (31.4 %)
PSF : convolution	39.9 W/m² (18.7 %)	27.2 W/m² (15.4 %)

Table 8 shows the slopes "a" and the RMS differences "$\sqrt{\overline{(y-ax)^2}}$" obtained for the four regions north-north, south-north, north-south and south-south (see fig. 5) for the comparison of Meteosat time slot 18 (nominally 08 :30-08 :55 GMT) compared to NOAA 10 measurements (see fig. 6).

Table 8

Slope of best linear fit through origin and residual RMS difference between Meteosat-ERB and NOAA 10 ERBE reflected shortwave flux estimations. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

	north-north	south-north	north-south	south-south
Slope	1.40	0.99	1.16	0.93
RMS	34.5 W/m²	25.3 W/m²	31.5 W/m²	25.3 W/m²
% RMS	27.9 %	14.5 %	15.4 %	11.5 %

Table 9

Slope of best linear fit through origin and residual RMS difference between Meteosat-ERB and NOAA 9 ERBE reflected shortwave flux estimations. The procentual RMS difference is given relative to the RMS values over the given region of the estimated flux

	north-north	south-north	north-south	south-south
Slope	1.17	1.02	1.14	1.09
RMS	35.5 W/m²	42.0 W/m²	36.1 W/m²	43.3 W/m²
% RMS	15.9 %	20.9 %	13.3 %	15.5 %

Table 9 shows the slopes "a" and the RMS differences "$\sqrt{\overline{(y-ax)^2}}$" obtained for the four regions north-north, south-north, north-south

and south-south (see fig. 5) for the comparison of Meteosat time slot 35 (nominally 17 :00-17 :25 GMT) compared to NOAA 9 measurements (see fig. 6).

Conclusions

In the study presented in this paper we derived the radiation budget term estimates at the highest possible time/space resolution from Meteosat images and compared the results (more specifically the emitted longwave flux and the reflected shortwave flux), at the best possible temporal and spatial correspondence, with their ERBE estimates.

We made the comparison for four separate regions and for two ERBE instruments (more specifically the one carried by NOAA 10 and the one carried by NOAA 9). For both radiation budget terms (the emitted longwave flux and the reflected shortwave flux), for both ERBE instruments and for each region, we measured the systematic disagreement (slope of best linear fit different from one) and the stochastic disagreement (RMS difference around best linear fit) of Meteosat-ERB compared to ERBE.

For the longwave case we find slopes very close to one for all regions, and RMS differences in the range 5-9 W/m^2 for the NOAA 10 case, and in the range 8-14 W/m^2 for the NOAA 9 case. The worst results for NOAA 9 compared to NOAA 10 are most likely explained by the worst time correspondence Meteosat-ERB/ERBE.

For the shortwave case we find slopes rather close to one (neglectable compared to the RMS difference) for the south-north and the south-south region and substantially higher (not neglectable compared to the RMS difference) for the north-north and the north-south region. These last regions correspond exactly to the regions where the BDRF's to be applied to the Meteosat-ERB radiance's (see equation) are the largest, namely the sunglint region (north-south region in figs 5 and 6) and the region close to the day/night separation (north-north region in figs 5 and 6). Very likely this indicates that the applied BDRF's are not accurate enough or that they are not applied accurately enough to remove the largest anisotropy's completely.

If we believe the ERBE shortwave flux estimates to be regionally unbiased, we can correct the Meteosat-ERB shortwave flux estimates by dividing them by the fitted slopes. After this correction we find RMS differences Meteosat-ERB/ERBE in the range 24-28 W/m^2 for

the NOAA 10 case, and in the range 30-42 W/m^2 for the NOAA 9 case. The worst results for NOAA 9 might be explained by the Meteosat viewing-zenith angle, which is on average higher for figure 5 than for figure 6.

We can compare our results with the theoretical uncertainties on the radiation budget parameters found by DIEKMANN (1988), STANDFUSS *et al.* (1993) and WIELICKI *et al.* (1996). If we believe STANDFUSS *et al.* (1993) and WIELICKI *et al.* (1996) that the angular uncertainty is the dominant source of uncertainty in a single satellite estimation of a radiation budget term (F_{LW} or F_{SW}), the uncertainties on ERBE and Meteosat-ERB estimates should be essentially the same. If moreover we assume that the errors on these two estimates are stochastically independent, then the RMS differences we find between Meteosat-ERB and ERBE estimates on F_{LW} or F_{SW} at ERBE footprint level should be $\sqrt{2}$ higher than the single satellite estimation uncertainties found by DIEKMANN (1988). This leads us to estimated single satellite uncertainties of 4-7 W/m^2 on F_{LW} and of 17-20 W/m^2 on F_{SW} (for sufficiently low viewing-zenith and solar-zenith angles). The uncertainties found by DIEKMANN (1988) are 3.8 W/m^2 on F_{LW}, and ranging from 5-11 W/m^2 for clear-sky ocean scenes to 16-26 W/m^2 for overcast scenes on F_{SW}. We are rather close to this, which seems to indicate that the uncertainties on our Meteosat-ERB derived radiation budget term estimates are coming close to the minimum uncertainties possible using the currently known anisotropy models.

ACKNOWLEDGEMENTS

We would like to thank G. Duchossois, J. de Waard and J. Le Ber for supplying us with the full resolution Meteosat data we used in this study, W. B. Rossow for the ISCCP calibration results for the Meteosat visible channel, M. Vesperini for the software implementation of the longwave flux estimation from Meteosat data, and G. L. Smith for the data necessary to calculate the ERBE PSF.

NOTE

[1] Basically a polar satellite flies only two times a day over a given point on earth.

REFERENCES

BARKSTROM, B. R. *et al.* 1989. Earth Radiation Budget Experiment (ERBE) archival and April 1985 results. — *Bull. Am. Met. Soc.*, **70** : 1254-1262.

BENGSTON, L. 1985. Medium-Range Forecasting -The experience of ECMWF. — *Bull. Am. Met. Soc.*, **66** (9) : 1133-1146.

CROMMELYNCK, D. & DEWITTE, S. 1996. Solar constant temporal and frequency characteristics. — Accepted for publication in *Sol. Phys.*

CROMMELYNCK, D. & JOUKOFF, A. 1993. Estimation of the spectral distribution using a simple algorithm. — *In* : Proceedings of IRS' 92 : Current Problems in Atmospheric Radiation (Tallinn, August 1992), Deepak Publishing ISBN0-937194-28-X.

DEWITTE, S., CORNELIS, J. & CROMMELYNCK, D. 1996. A generic image processing tool : topdown Bayesian image analysis. — *In* : Proceedings of NATO AGARD conference "Remote Sensing : A valuable source of information" (Toulouse, April 1996).

DEWITTE, S., NYSSEN, E., CROMMELYNCK, D. & CORNELIS, J. 1995. Multi-stage analysis of Meteosat images. — *In* : Proceedings of European Symposium on Satellite Remote Sensing II (Paris, 25-28 September 1995), SPIE 2579, pp. 170-181.

DIEKMANN, F. J. 1988. Fehler in der Szeneidentifikation aus Satelliten Daten - Auswirkungen auf die Bestimmung von Strahlungshaushaltsparameters. — *Mitt. Inst. Geoph. Met. Univ. Köln*, **59**.

DOELLING, D. *et al.* 1990. On the role of satellite-measured narrowband radiances for computing the earths's radiation balance. — *In* : Proceedings of the Seventh Conference on Atmospheric Radiation (San Francisco, July 23-27), pp. 155-160.

KALNAY, E. 1995. The NCEP/NCAR Reanalysis Project. — *Bull. Am. Met. Soc.*, **77** : 437-471.

MANALO-SMITH, N., STAYLOR, W. F. & SMITH, G. L. 1994. Analytic forms of bi-directional reflectance functions. — *In* : Proceedings of the Seventh Conference on Satellite Meteorology and Oceanography (Monterey, June 6-10, 1994), pp. 542-545.

MINNIS, P. & HARRISON, E. F. 1984. Diurnal Variability of Regional Cloud and Clear-Sky Radiative Parameters Derived from GOES Data. Part III : November 1978 Radiative Parameters. — *J. Clim. Appl. Met.*, **23** (7) : 1032-1051.

MINNIS, P., YOUNG, D. F. & HARRISON, E. F. 1991. Examination of the Relationship between Outgoing Infrared Window and Total Longwave Fluxes using Satellite Data. — *J. Clim.*, **4** (11) : 1114-1133.

MONGE, J. L., KANDEL, R. S., PAKHOMOV, L. A. & ADASKO, V. I. 1991. ScaRaB Earth radiation budget scanning radiometer. — *In* : Proceedings

of New Developments and Applications in Optical Radiometry III (Davos, 1991), *Metrologia*, **28** : 261-264.

RAO, P. K. *et al.* 1990. Weather Satellites : Systems, Data and Environmental Applications. — Am. Met. Soc., Boston, 503 pp.

ROSSOW, W. B., DESORMEAUX, Y., BREST, C. L. & WALKER, A. 1992. International Satellite Cloud Climatology Project (ISCCP) Radiance Calibration Report. — World Meteorological Organization, WMO/TD, No. 520, WCRP-77, 104 pp.

SCHMETZ, J. & LIU, Q. 1988. Outgoing longwave radiation and its diurnal variation at regional scales derived from Meteosat. — *J. Geoph. Res.*, **93** (D9) : 11192-11204.

SCHMETZ, J., MHITA, M. & VANDEBERG, L. 1990. Meteosat observations of longwave cloud-radiative forcing for April 1985. — *J. Clim.*, **3** : 784-791.

SMITH, G. L. 1994. Effects of time response on point spread function of a scanning radiometer. — *Appl. Opt.*, **33** : 7031-7037.

STANDFUSS, C., HOLLWEG, H.-D. & GRASSL, H. 1993. The impact of a radiation budget scanner aboard meteosat second generation on the accuracy of regional radiation budget parameters. — ESA final report, ESTEC purchase order no. 125144.

SUTTLES, J. T. *et al.* 1988. Angular Radiation Models for Earth-Atmosphere System : Volume 1 - Shortwave Radiation. — NASA Reference Paper, Ref. 1184, Vol. 1, 144 pp.

VAN MIEGHEM, J. 1958. Radiation data needed in dynamical meteorology. — *Arch. Met. Geoph. Biokl.*, **10** (4) : 285-290.

VAN MIEGHEM, J. 1962. Pour une exploration synoptique du champ du rayonnement dans l'atmosphère. — *Arch. Met. Geoph. Biokl.*, **13** (2) : 129-143.

VESPERINI, M. & FOUQUART, Y. 1994. Determination of Broad-Band Shortwave Fluxes from the Meteosat Visible Channel by Comparison to ERBE. — *Beitr. Phys. Atmosph.*, **67** (2) : 121-132.

WIELICKI, B., CESS, R. D., KING, M. D., RANDALL, D. A. & HARRISON, E. F. 1996, Mission to Planet Earth : Role of Clouds and Radiation in Climate. — *Bull. Am. Meteor. Soc.*, **76** (11) : 2125-2153.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 414-421 (1998)

Satellite Rainfall Estimation and its Applications in Ethiopia

by

Tufa DINKU *

KEYWORDS. — Rainfall Estimation ; METEOSAT ; Ethiopia.

ABSTRACT. — We have been receiving half-hourly digital data from the European Meteorological Satellite (Meteosat) since 1990. The data is being used, among other things, for estimating ten-day total rainfall using the TAMSAT methodology developed at the university of Reading, UK. Though suitable for operational use, the methodology has got some limitations when applied to Ethiopia. During the last three years we have been trying to adapt this methodology to the Ethiopian weather/topographic conditions and come up with better rainfall estimates. The results obtained so far, though far from being perfect, are encouraging. The estimate has been found to be a good supplement to the very sparse surface rain gauge network. There are already some operational applications, the main one being drought early warning. The research is still in progress and there is still room for further improvement.

MOTS-CLES. — Estimation des précipitations ; METEOSAT ; Ethiopie.

RESUME. — *Estimation satellitaire des précipitations et ses applications en Ethiopie.* — Depuis 1990, on dispose de données digitales deux fois par heure en provenance du satellite météorologique européen (METEOSAT). Les données sont utilisées, entre autres, pour l'estimation des totaux des précipitations sur dix jours en utilisant la méthodologie TAMSAT développée à l'Université de Reading au Royaume-Uni. Bien que la méthode soit appropriée à des utilisations opérationelles, la méthodologie présente quelques limitations quant à son application en Ethiopie. Pendant les trois dernières années, nous avons tenté d'adapter cette méthodologie aux conditions éthiopiennes de temps et de conditions topographiques et de produire de meilleures estimations des précipitations. Les résultats obtenus jusqu'ici, loin d'être parfaits, sont encourageants. L'estimation s'est trouvée être un supplément utile au réseau des pluviomètres très limité. Il existe déjà quelques applications opérationnelles ;

* National Meteorological Services Agency, P.O. Box 1090, Addis Ababa (Ethiopia).

la principale est l'avertissement précoce de sécheresse. La recherche est en plein développement et des possibilités d'amélioration existent.

TREFWOORDEN. — Neerslagschatting ; METEOSAT ; Ethiopië.

SAMENVATTING. — *Satellietschatting van de neerslag en zijn toepassingen in Ethiopië.* — Sedert 1990 beschikt men over halfuurlijkse digitale Meteosat-gegevens. Deze gegevens worden onder andere gebruikt voor het schatten van de tiendagelijkse neerslaghoeveelheden, gebruik makend van de TAMSAT-methodologie, ontwikkeld door de universiteit van Reading, UK. Nochtans geschikt voor operationeel gebruik, heeft deze methodologie toch zekere beperkingen wanneer toegepast op Ethiopië. Gedurende de laatste drie jaar hebben we getracht deze methodologie aan te passen aan de Ethiopische weers- en topografische condities om betere neerslagsprognoses te bekomen. De resultaten die we tot nu toe hebben bekomen zijn niet perfect maar bemoedigend. De voorspelling wordt beschouwd als zijnde een goede aanvulling op het schaarse meetnet. Er zijn reeds een aantal operationele toepassingen in werking ; de belangrijkste is de „vroege droogtewaarschuwing". Het onderzoek is nog volop bezig en er is nog steeds ruimte voor verbetering.

1. Introduction

In Ethiopia the distribution of rainfall stations is very sparse. Besides, most of the stations are located along the main roads. Thus, it is difficult to get rainfall information away from these roads which are not many. What is worse, only about 8 % of these stations are equipped with radios and thus report on regular basis. It takes months to collect data from the other stations. As a result their utility for operational purposes such as drought monitoring, pest control, flood forecasting, etc., is very limited.

To alleviate this problem the National Meteorological Services Agency (NMSA) decided to supplement the sparse station network with rainfall estimated from Meteosat imagery. Accordingly, NMSA obtained a Primary Data Users Station (PDUS) in 1990 with the cooperation of the UK government. The PDUS system includes an automatic rainfall estimation module which is used to estimate decadal rainfall.

The coming sections of the paper will briefly present the methodology used, the calibration process, validation, some applications, problems and future plans.

2. Methodology

We employ a methodology developed by the TAMSAT (Tropical Application of Meteorology using SATellite and other data) group at the university of Reading, UK. The TAMSAT methodology, MILFORD & DUGDALE (1989), is based on the assumption that in tropical areas most of the rain comes from convective clouds. It also assumes simple linear relationship between rainfall and Cold Cloud Duration (CCD); CCD being the duration of a cloud, with top temperature below a predetermined threshold, over a given area. The relation between CCD and rainfall (RR) is given as :

$$RR = a * CCD + b \text{ if } CCD > 0$$
$$RR = 0 \text{ if } CCD = 0$$

Instead of relating rainfall to CCD, the regression is performed between mid-points of CCD classes and the median of the rainfall in the CCD class in order to overcome the skewness of the rainfall frequency distribution.

We have been using the calibration parameters determined for Ethiopia by TAMSAT. Since 1993 we have started our own calibration. Our calibration, which uses smaller calibration zones, has shown better performance over TAMSAT calibration. The calibration process involves the following steps.

2.1. Delineation of Zones of Homogeneous Rainfall Characteristics

Over Ethiopia the spatial variation of rainfall is very high. As a result the rainfall characteristics are different for different parts of the country. A temperature threshold selected for one region might not serve for another one. We have been trying to use smaller calibration zones instead of the larger ones proposed by TAMSAT. Topography has been found to play an important role in the delineation of these homogeneous zones. These homogeneous zones could have any shape and size. Yet, the current rainfall estimation software accepts only a limited number of rectangular regions. This problem was solved by preparing the regions using another software and putting it into the system indirectly (DINKU 1994). Now, zones of any size and shape could be used.

2.2. Selection of a Best Temperature Threshold which Reasonably Discriminates between Rain Giving and Inactive Clouds

Archived CCD is available with the TAMSAT at temperature thresholds of – 40, – 50 and – 60 °C. This data is used along with ground rainfall measurements in our archive to select the best temperature threshold. Because the available temperature thresholds are limited to – 40, – 50 and – 60, warmer thresholds have not been tested. Yet, it is not unusual to get rainfall from clouds much warmer than – 40 °C over Ethiopia. Cirrus cloud is an other source of error over some parts of the country. Among the available temperature thresholds, – 40 °C has been found to be the best for most parts of the country.

2.3. Parameter Determination

The parameters of the above equation are determined for each selected region and chosen temperature threshold using historical CCD and ground rainfall data. CCD data is available since 1990.

3. Validation

Let us first see how the estimate discriminates just between dry and wet conditions. In table 1 three arbitrary rainfall amounts (0, 10 and 20 mm) are taken as thresholds for "dry" and "wet" conditions. The percentage of accurate discrimination is given for 1994.

Table 1

Dry/wet discriminating accuracy (%) at different rainfall thresholds, for 1994. N is the number of data pairs compared

Month	N	at 0 mm	at 10 mm	at 20 mm
June	911	87.81	85.18	78.35
July	1 027	97.17	95.42	94.35
August	1 044	96.16	95.68	91.85
September	948	93.45	88.50	80.28

This accuracy could be good enough as a general indicator of crop and pasture conditions. Other applications might require better accuracy. However, there is a problem in comparing the estimated rainfall (which is an area average) with actual rainfall (a point data). These values

could significantly be different (FLITCROFT *et al.* 1988). Let us keep these facts in mind while judging the accuracy presented in the following figures.

Figure 1 compares the average of actual rainfall (Avg. 1), average of estimated rainfall (Avg. 2) and the standard deviation (SD) between the ground measurements and corresponding satellite estimates for stations over two different parts of the country during June to September 1994.

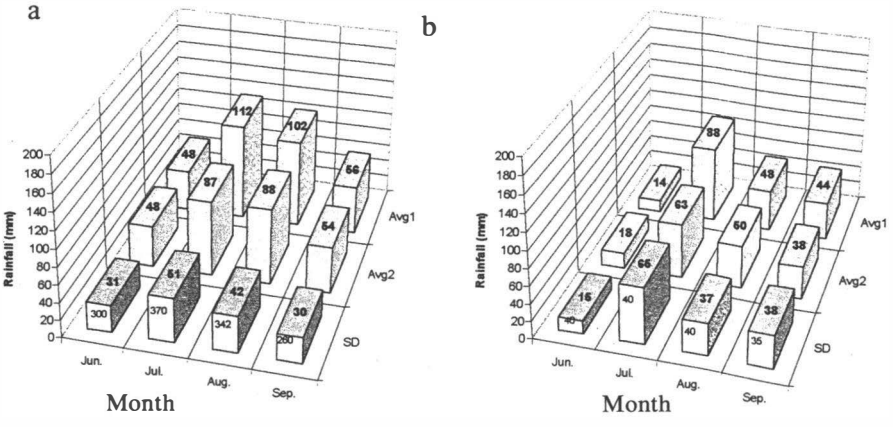


Fig. 1. — Comparison of measured ten-day total and corresponding estimated rainfall for stations over western (a) and north-eastern (b) Ethiopia in 1994 (see fig. 2 for details).

Figure 1a is for western Ethiopia where estimation is relatively better while figure 1b is for the north-eastern part of the country where accuracy is usually not good. SD is always less than the estimate for western Ethiopia while it is close to the estimate for the north-eastern part. One could notice that the data used for comparison are very few over the north-eastern part of the country ; the data used for calibration were also not sufficient. August is the month of relatively better estimation for both regions.

The accuracy is different for different rainfall ranges. Figure 2 presents the accuracy for different rainfall ranges during July 1995 for stations over the whole country. There is a relatively better accuracy for rainfall ranges of 21 to 50 and 51 to 100 mm ; SD is relatively low for these ranges. There is an overestimation for rainfall values below 20 mm and an underestimation for values above 150 mm. The

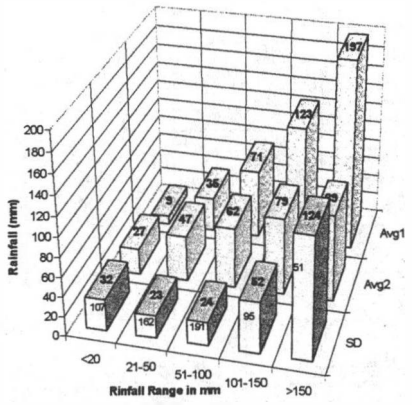


Fig. 2. — Comparison of actual and estimated rainfall for different rainfall ranges during July 1995 for the whole country. Avg. 1 is average of all rain gauge stations and Avg. 2 the corresponding estimated rainfall. SD is the Standard Deviation between the measured and estimated rainfall. The labels are the corresponding values while the numbers on the first bars are the numbers of data pairs compared.

below 20 mm and above 150 mm ranges are only about 26 % of the total data.

As mentioned earlier satellite rainfall estimation has been going on since 1991. Now we have five years' decadal average. Figure 3 presents the validation of these data for western (a) and north-western (b) parts of the country from March to October. As in the previous case accuracy is better over the western part of the country. There is significant improvement in accuracy from individual year's estimate to the five-year average. We have started re-calibration to improve the quality of the historical data, and it has shown significant improvement in the accuracy.

4. Applications

The main use of the data has so far been for drought monitoring. As the data is available on near-real time basis covering the entire country, it has been found to be very useful for crop early warning purposes (Dinku 1995). Besides drought monitoring mainly requires to know whether the rainfall amount is ample or not ; and the level of accuracy achieved is acceptable for this purpose. We produce a ten-daily bulletin which includes the map of the estimated rainfall and its comparison with expected mean values. Our users are mostly

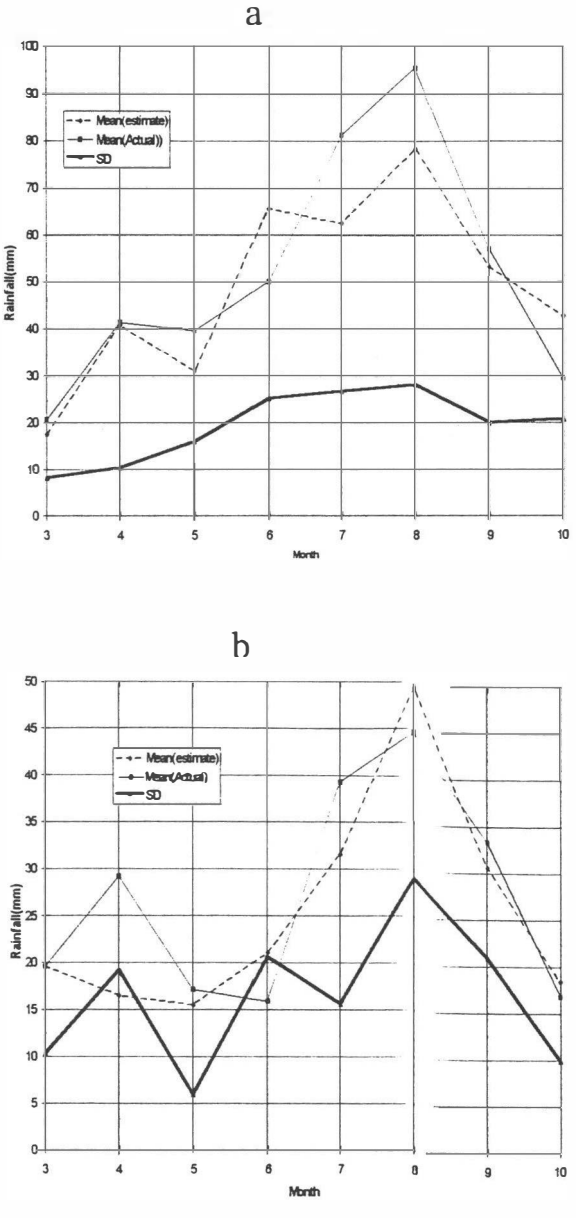


Fig. 3. — Comparison of actual and estimated 5-year average rainfall for western (a) and north-eastern (b) parts of Ethiopia from March to October.

governmental and non-governmental organizations involved in food-early-warning activities.

The data is also used for desert locust control. It is the only source of rainfall data over desert and inaccessible areas. Assessment of the water resource of some river basins has also been an other application. The data has been used in two big hydrological projects. It has also been used to justify water and electricity problems associated with rainfall shortage around the respective dams.

5. Conclusion

We have been estimating rainfall from Meteosat infrared images since 1991 using the TAMSAT methodology. Though suitable for automatic rainfall estimation, this methodology has some problems when applied to Ethiopia. Effect of topography, rainfall from warm clouds and the influence of Cirrus clouds have been some of the problems. An attempt has been made to reduce the effect of topography by using smaller calibration zones. This has shown some good results, but there is still some work to be done. The problem of warm clouds and Cirrus still persists and future plans are to find ways to solve it. Yet, the level of accuracy achieved so far is encouraging and has already been found useful in many applications, the main one being the monitoring of crop and range land conditions.

REFERENCES

BARETT, E. C & MARTIN, D. W. 1981. The use of satellite data in rainfall monitoring. — Academic Press, London.

DINKU, T. 1994. The use of smaller calibration zones for better rainfall estimation over Ethiopia. — Paper presented at a workshop on Evaluation of Precipitation by Satellite, 1-7 December 1994, Niamey, Niger.

DINKU, T. 1995. The use of satellite data for drought monitoring over Ethiopia. — *In* : ICTP Conference on African Drought, 31 July-4 Aug. 1995, Trieste, Italy.

FLITCROFT, I. D., MILFORD, J. R. & DUGDALE, G. 1988. Relating point to area rainfall in semi-arid West Africa and the implication for rainfall estimates. — *J. Appl. Met.*, **28** : 252-266.

MILFORD, J. R. & DUGDALE, G. 1989. Estimation of rainfall using geostationary satellite data. — *In* : Application of Remote Sensing in Agriculture. Proc. 48th Easter School in Agric. Sci., Univ. Nottingham, April 1989. Butterworth, London.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 422-440 (1998)

Eco-Geographic Classifications Based on Time Series of HRPT NDVI Images

by

Silvio GRIGUOLO * & Paolo SANTACROCE *

KEYWORDS. — Classification ; HRPT ; NDVI ; NOAA ; Remote Sensing.

SUMMARY. — NDVI GAC images from the AVHRR sensor are quite a common input to monitor vegetation in vast areas in Africa. Both monthly and dekadal [1] ** images are regularly produced and distributed, and the evolution of phenomena of interest can be analysed from a time series of such images. An analytical method, the core of which is a Principal Component Analysis followed by a non-hierarchical Clustering procedure, has recently been proposed and implemented on Personal Computer. The software, named ADDAPIX, is distributed by FAO. Pixels are grouped according to the similarity of their time patterns, thus creating a convenient number of classes. The time profile of any pixel can then be displayed in order to investigate local peculiarities. This paper deals briefly with problems and advantages related to the use of the same method for eco-geographic classifications on high-resolution (HRTP) data, which are getting more and more easily available. The results of an analysis carried out in Kenya and based on high-resolution NDVI images are reported in some detail.

MOTS-CLES. — Classification ; HRPT ; NDVI ; NOAA ; Télédétection.

RESUME. — *Classifications éco-géographiques à partir des séries des images HRPT NDVI.* — En Afrique, les images GAC-AVHRR du NDVI sont souvent utilisées pour le monitorage de la végétation de zones très vastes. Elles sont régulièrement produites et disponibles tous les mois ou tous les dix jours. Il est donc possible de suivre l'évolution d'un phénomène à travers l'analyse d'une série de ces images. Récemment, il a été proposé et établi sur micro-ordinateur une procédure séquentielle d'analyse dont l'Analyse en Composantes Principales suivie par une procédure de «classification automatique» sont les éléments fondamentaux. Le logiciel, appelé ADDAPIX, est

* DAEST, Ca' Tron, S. Croce 1957, 30135 Venezia (Italy).
** The numbers in brackets [ ] refer to the notes pp. 437-438.

à présent distribué par la FAO. Les pixels sont agrégés à partir de leur similarité dans le temps, définissant ainsi un certain nombre de groupes divers. Le profil de chaque pixel peut être analysé de près pour faire émerger les particularités locales. Grâce au soutien de nombreux projets internationaux, les images à haute résolution (HRPT) deviennent de plus en plus disponibles. Ce travail a donc comme but de considérer, bien que brièvement, les éléments pour ou contre l'utilisation des séries historiques des images à haute résolution (HRPT) pour les classifications éco-géographiques. Les résultats d'un exercice mené pour le Kenya, basé sur une série d'images du NDVI à haute résolution, sont expliqués en détail.

TREFWOORDEN. — Classificatie ; HRPT ; NDVI ; NOAA ; Afstandswaarneming.

SAMENVATTING. — *Eco-geografische classificatie gebaseerd op tijdreeksen van HRPT NDVI-afbeeldingen.* — NDVI GAC-beelden van de AVHRR-sensor zijn een veel gebruikt hulpmiddel voor het monitoren van vegetatie over grote delen van Afrika. Zowel maandelijkse als tiendaagse beelden worden routinematig geproduceerd en verspreid en de evolutie van bepaalde verschijnselen kan bestudeerd worden middels een tijdreeks van zulke beelden. Een analytische methode, gebaseerd op een Principale Component Analyse gevolgd door een niet-hiërarchische *Clustering*procedure, is recentlijk voorgesteld en ontwikkeld op pc's. Het programma, ADDAPIX genaamd, wordt verdeeld door de FAO. Beeldelementen worden gegroepeerd op basis van de gelijkenis van hun tijdprofiel. Hierdoor worden een aantal klassen gevormd. Het tijdprofiel van elk individueel beeldelement kan zichtbaar worden gemaakt om de lokale karakteristieken te onderzoeken. Dankzij een aantal internationale projecten zijn hogere resolutie (HRPT)beelden nu meer en meer beschikbaar. Dit artikel behandelt kort de problemen en de voordelen die verbonden zijn aan het gebruik van dezelfde methodologie voor ecologisch-geografische classificatie van HRPT-beelden. De resultaten van een analyse gedaan in Kenia, middels hogere resolutie NDVI-beelden, worden in enig detail gepresenteerd.

1. Introduction

AVHRR Global Area Coverage (GAC) NDVI images are commonly used for large-area vegetation monitoring in Africa. This is usually done by calculating some appropriate *uni-dimensional indicators* (cumulated NDVI, difference between two consecutive images, etc.). As images representing the intensity and distribution of various phenomena (Vegetation development cycle, Cold Cloud Duration, Number of Rainfall days, etc.) are regularly produced from NOAA-

AVHRR or MeteoSat channels and made available on a dekadal or monthly basis, it is convenient to follow the evolution of a phenomenon of interest *by processing simultaneously a time series of images.* Individual pixels can be clustered according to the similarity of their time patterns (profiles), whose detailed inspection enables a fine exploration of peculiar local features.

Several examples of multidimensional processing can be found in the literature (TOWNSHEND & JUSTICE 1986, DERRIEN *et al.* 1992). Most of them are aimed at recognizing the vegetation cover type on the basis of the annual cycle, trying to cope with problems caused by the ever-present mix of vegetal species (QUARMBY *et al.* 1992). However, these studies do not establish an operationally simple method that can be applied regularly and repeatedly, deriving from remotely-sensed imagery some synthetic and easily transmittable information, to be compared with the one derived from other sources.

An analytical path has been recently proposed and implemented on PCs, whose core is a multidimensional unsupervised clustering procedure, preceded by a Principal Component Analysis. The package, named ADDAPIX [2], is distributed by FAO for climatological and Early Warning applications (GRIGUOLO 1996). All the exercises carried out so far have assumed as input a time series of *low-resolution* (GAC) NDVI images from the AVHRR sensor, producing some eco-geographic maps of Mauritania, Ethiopia and the Africa's Horn (GRIGUOLO & SANTACROCE 1993). These latter maps were used in the preparation of a "Crop Production System Zones of the IGADD Subregions" Atlas (VAN VELTHUIZEN *et al.* 1995). A method that used ADDAPIX for vegetation monitoring, aimed at singling out areas where the current cropping season presents a risk of failure, is proposed in GRIGUOLO (1994).

Paragraph 2 discusses briefly pros and contras of the use of high-resolution [3] data for a multitemporal classification. Paragraphs 3 and 4 comment in detail a pixel-by-pixel eco-geographic zoning exercise for Kenya, based on an annual series of high-resolution dekadal NDVI images, resampled to 2 km. Paragraph 5 sketches some brief conclusions.

2. Availability of HRPT Images, and Related Problems

There is a large consensus on the utility of NOAA-AVHRR images for large-area analyses. GAC (Global Area Coverage) data are commonly used for crop monitoring in Africa, and international organi-

zations like FAO and FEWS (Famine Early Warning System of the USAID) distribute NDVI composite images for that continent with a ten-day cadence. Only rarely have these images been used for fully multitemporal analyses, and their use has been mostly limited to the creation of cumulate images over the season, or to inter-image comparison aimed at appreciating pixel-by-pixel the NDVI change over a decade. Examples of multichannel analyses, based upon the simultaneous utilization of all the AVHRR channels at one or several dates, though found in the literature, belong more to the research world than to field operational practice.

As recourse to highly specialized and expensive commercial packages is far from appearing feasible in the daily Early Warning practice, FAO-ARTEMIS [4] has recently supported the development of the package ADDAPIX, with the purpose of making it possible to carry out on a PC, in a friendly and standardized way, multitemporal analyses of image time series for zoning agro-climatic areas or for monitoring the cropping season.

ADDAPIX enables the user to follow an easy sequence of analytical steps aimed at clustering multitemporal or multispectral patterns : pixels are assigned to a limited number of groups (the classes), according to the global similarity of their patterns. In principle, this could be done in a supervised or an unsupervised way, or by means of a Neural Network. The *unsupervised cluster analysis* carried out by ADDAPIX can be considered as a first exploratory step, useful to investigate the features of the groups that emerge spontaneously, so as to reach a suitable definition of the classes from which, in case, a successive supervised clustering can be performed.

Though exercises carried out so far have mostly assumed as input a time series of *dekadal* NDVI images, it is worth noting that according to some researchers *monthly* composites appear more convenient in some particularly humid regions of Africa (Fuller & Prince 1996). A monthly cadence certainly limits the advantage of multitemporality, and a time difference of up to one month can exist between different parts of the image ; yet, it is sometimes necessary in order to improve the image quality through a more accurate elimination of undesired effects like atmospheric distortion, presence of clouds and large viewing angles.

Results obtained from GAC data are satisfactory, but GAC images are very coarse. The pixel size (7.6 km) avoids significant registration problems, yet the mixture of different ground characters within a pixel

can be confusing and mislead interpretation. In fact, a pixel's reflectance on a channel is the weighted sum of the reflectances of all the various parts of which it consists. Only in particular cases it is possible, for example, to single out a river or a small oasis in a classified image at the GAC level of resolution.

In order to increase spatial details the use of high-resolution AVHRR images appeared advantageous. Analyses concerning single countries are still perfectly feasible, as the size of the database involved is manageable. We will now briefly discuss the availability and reliability of AVHRR-HRPT images.

During the last years a number of stations able to receive daily the HRPT 1 km images transmitted by the satellite have been established all over the world — including Africa — by international organizations, academic and research institutions, etc. In a more or less accurate way, almost all of them go through the complete cycle of image pre-processing, from calibration to atmospheric and geometric correction.

The main advantage of NOAA images is their high temporal resolution (two images per day). HRPT pixels have a size of 1.1 km at the nadir of the sensor, but in order to achieve a daily quasi-global scanning the swath width is 2,700 km, corresponding to a maximum scan angle of 55.4° on either side of the nadir. Owing to this large angle, off-nadir pixels are considerably larger, with a consequent imperfect correspondence among images in which the same pixel is observed under significantly different angles. The current opinion is that only a track of no more than 700 pixels on both sides of nadir can be used safely. This limits somehow the multitemporality, as the daily coverage, so restricted, is no longer global.

The pre-processing phase to which captured images are submitted consists essentially of the following steps :

— **Radiometric calibration** : the actual reflectance on the ground is computed from the digital radiances via a correction model that keeps into account date, time and local latitude.

— **Atmospheric correction** : diffusion, reflection and absorption, not homogeneously distributed over the spectrum, depend on the depth and composition of the atmospheric layer crossed by the signal before reaching the sensor. The atmospheric contents of water vapour, aerosols and ozone are specially important. The reflectance measured by the sensor is different from the true reflectance on the ground and must be corrected. Various models have been and still are being proposed.

— **Geometric correction** : different images are generally not exactly geometrically coincident (superimposable). Casual alterations are mainly due to irregularities in the movement of the satellite and the scanner. As a multitemporal analysis processes a set of images forming a time series, their geometric registration is critical : the risk is to compare pixels that do not represent the same ground point. Images must therefore be resampled using some suitable geometric transformations in order to make them perfectly superimposable. This is done by taking advantage of the existence of points well-recognizable in both the image to be corrected and a reference map, and whose geographic co-ordinates are known exactly. Transition points between land and water, along the sea coast or internal lakes, are used for this purpose. Their co-ordinates are derived from the Digital Chart of the World or the World Vector Shoreline.

While radiometric correction is based on sound models, on which a consensus exists, the latter two correction steps are less well defined and different receiving stations carry out the correction in not at all equivalent ways. The resulting archives are therefore inconsistent, and cannot be thought to make up a global database.

In particular, there is no universally accepted method to correct the effect of water vapour and aerosol absorption, whose impact on NDVI can be as high as 0.04-0.08 and 0.04-0.2 respectively (Townshend *et al.* 1994). These are considerably high errors : according to some authors, the fluctuations due to the atmospheric distortion are often greater than the difference between the present NDVI time patterns. In particular, it is worth remarking that channel 2 of the AVHRR sensor includes a water absorption band : following the NDVI definition, this can cause a significant reduction of computed NDVI values in areas characterized by a high atmospheric contents of water vapour.

Another problem is cloud screening. While methods exist to isolate and mask pixels that are totally clouded, it is difficult to recognize pixels only partially affected by clouds, whose NDVI value is reduced by an unknown amount.

Anyway, the actual situation is not so tragic as it might appear from the notes above. There are many facts that suggest the possibility of an easy and convenient future utilization of HRPT images.

— The growing awareness that more resources should be allocated for data distribution, in order not to frustrate the effort spent in

data collecting and processing, has led to an increasing availability of this type of images. Some large international agencies have started joint projects to build and regularly maintain large 1 km AVHRR databases, in some cases making them available to the land research community. We mention the MARS and the MERCATOR [5] archives of the EC Joint Research Centre at Ispra, but above all the International Biosphere and Geosphere Project (BELWARD 1996), whose purpose is the construction of a *global* 1 km Land Cover database, to be used as one of the inputs for environmental models. A brief survey of environmental applications on the global or continental scale that will benefit from the 1 km Land Cover database (general circulation models affected by factors like surface roughness or albedo, models of carbon or nitrogen cycles, water-energy-vegetation studies, climatic studies, etc.) can be found in TOWNSHEND *et al.* 1994. The Project has collected, stored and processed 4.4 Terabytes of data from 23 stations. A large set of daily images, globally covering the planet, have already been archived. Global dekadal composite images for the period ranging from April 1992 to September 1993 can be visually browsed on the Internet, and selected parts thereof downloaded via Netscape. The production should continue at least until 1998 [6]. The Land Cover classification is complete for North and South America and Africa. The product is being submitted to a group of experts who should trace gross errors, then it will be validated by comparison with high-resolution imagery from LANDSAT, SPOT, RESURS-01. The validation process is expected to be completed by 1998.

— As the IGBP is a *de facto* reference for all people dealing with HRPT images, a standard way of processing the images might gain a hold. The correction accuracy achieved so far with the best orbital models is ± 2 pixels, enhanced to 0.7 pixel through accurate use of Ground Control Points in registration. This appears sufficient for a multitemporal treatment.

— Computing tools and storing devices are getting cheaper and more and more powerful ; storing and clustering large images on Personal Computers is now possible.

— The future is promising. A new generation of sensors is being designed, building upon the experience gained from the preceding ones. In particular, for large-scale Earth Observation the MODIS (MODerate resolution Images Spectrometer) sensor, expected to be fully operational very shortly, will offer a great improvement

when compared with the AVHRR : MODIS has a higher number of channels, and this will improve the atmospheric correction (TOWNSHEND *et al.* 1991). New sensors are being designed also for other Earth observation satellites, like LANDSAT and SPOT. Of course, this stresses the need to maintain long data series, collected by different sensors, without losing consistence. In particular, MODIS' near-infrared channel will exclude the water absorption band present in the Channel 2 of the AVHRR. This will decrease NDVI errors, but will also result in NDVI values non-equivalent to those computed from the AVHRR, creating the need of some suitable conversion algorithms.

3. Presentation of the Analysis in Kenya

This analysis tries to identify/classify the different seasonal vegetation patterns present in the study area, using a time series of zero or low-cost images. Without having recourse to expensive LANDSAT or SPOT images, we intended to investigate if time series of HRPT images from the AVHRR sensor, processed through ADDAPIX, could provide a quick and reliable screening for large and not easily accessible areas.

A series of thirty-six dekadal images, kindly provided by the Kenya Meteorological Department (Agro-meteorological Section) [7], were assumed as the input for the clustering sequence. Figure 1 shows the study area : it is a window surrounding Lake Turkana and limited by the delta of the Omo River (north), Lake Baringo (south), Kitale (west) and Marsabit (east). The reason for this choice is that this part of the Kenyan territory is characterized by a variety of particularly challenging geological and climatological conditions.

The south-west corner of the window, affected by a persisting presence of clouds during the study period (August 1993 through July 1994), was excluded from the classification.

The lack of a longer time series hindered us from computing long-term average images, and we had to restrict our analysis to a particular year. This certainly limits the generality of the results we obtained, but the emerging classes represent well the ground truth and their validity goes probably beyond the particular year's seasonal fluctuations.

The selected area falls within the eastern part of the so-called Eastern African System and is characterized by very scanty vegetation. The

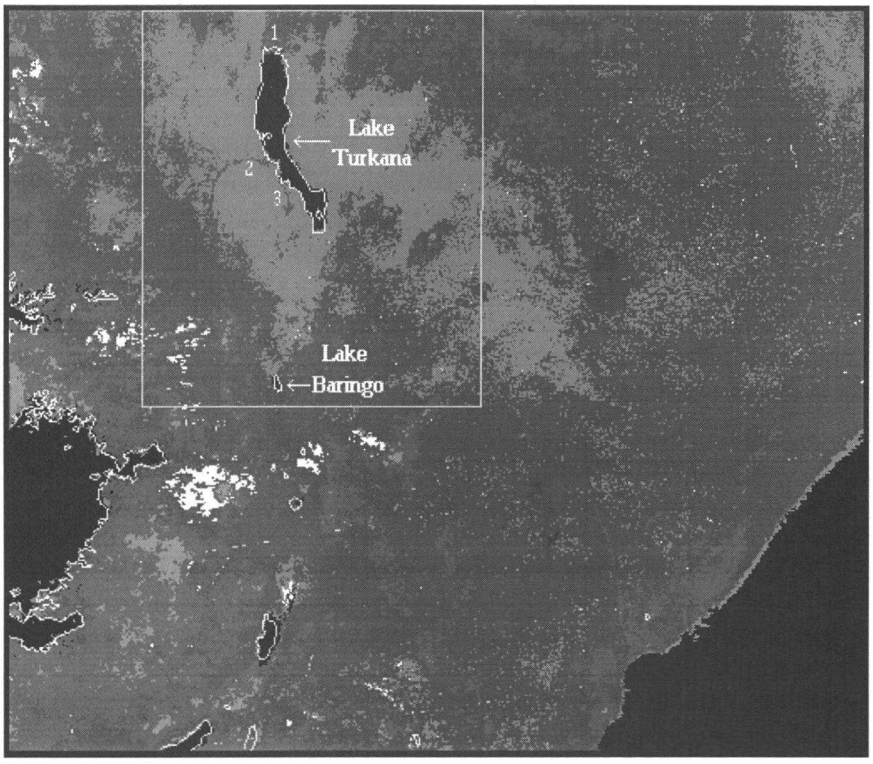


Fig. 1. — The Kenya window selected for the analysis.

dry environment of the central part of the basin presents two major rock formation : volcanic and colluvial-alluvial sediments. While most of the water input comes from the Omo River, marked with 1 in figure 1, which enters the lake from the north, the Turkana watershed includes two more major rivers, the Torkwel (2) and the Kerio (3), flowing into the lake from the west. Both are characterized by a high seasonality, due to the rainfall regime of the area.

The western side of the basin is delimited by some south-north alignments : the Cheragani Hills (in the clouded south-western part of the image), followed by the Parila-Karasuk-Lorosuk Hills alignment. The eastern border is delimited by the sequence of the Samburu Hill-Emurua Akirim Plateau, followed by Mount Kulal, the Bura Galadi Hills lava desert, and the Huri-Tatesa Hills.

On the west of the lake the plain is broken by several morphological episodes : the Loima Hills and the Pelekech Range, that delimits the watershed between Lake Turkana and the internal Lotikipi plain seasonal marshes, followed by the Murua Riih Hills and Lapurr Range. Four extremely barren lava plateau-hills are also apparent : the Kalimapsu and Nagpoi Hills, north of the Torkwel ; the Puch Prasir Plateau on the west, the Kangithigia Hills and Nachorugwai Desert on the east of the Torkwel River.

Between the south-eastern side of the Lake Turkana and the Mount Marsabit lie the Chalbi, Karoli and Kaisut Deserts, separated by the Headed Basin.

4. Analysis of Vegetation Cycles in Kenya : Some Results

The geo-morphological variety of the area was at least partially identified by the vegetation cycle classification procedure.

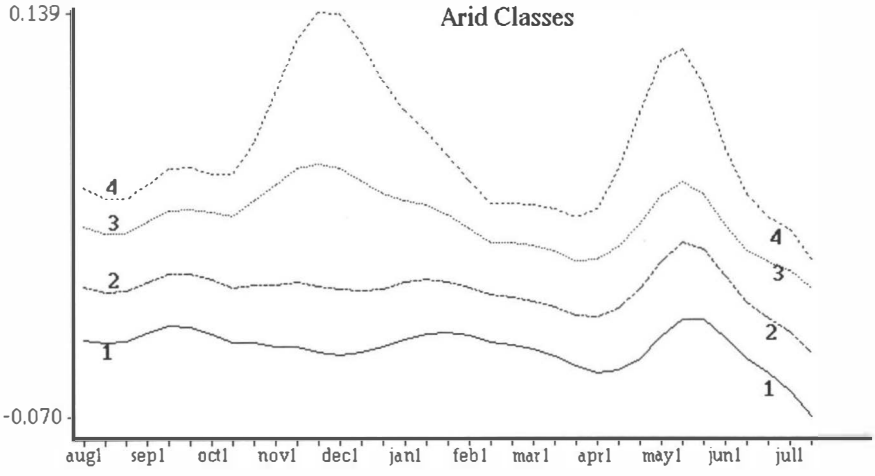
In the resulting classified image three groups of vegetation cycle patterns can be clearly distinguished :

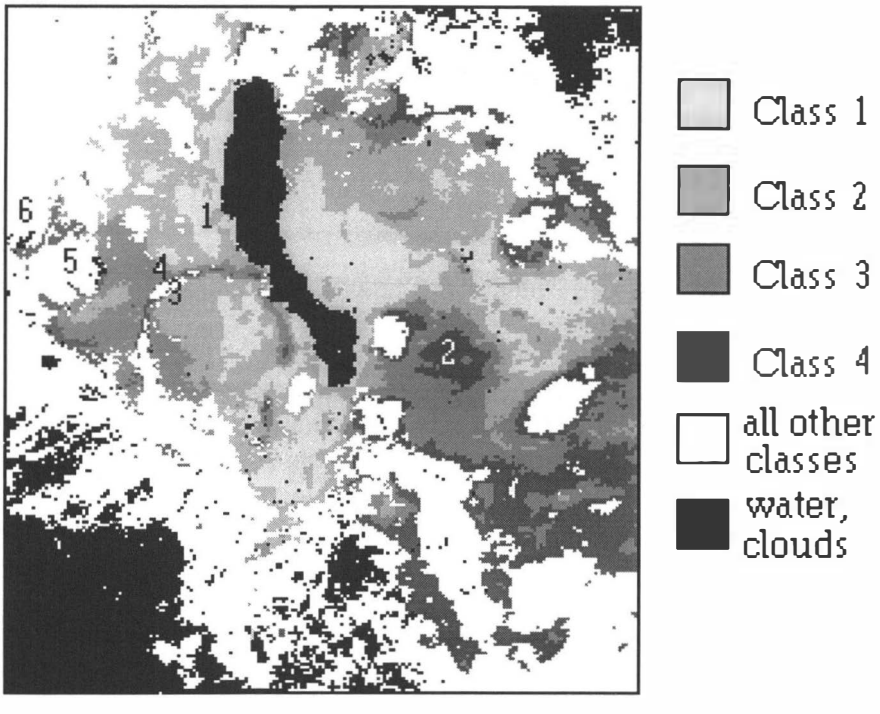
— Very arid areas, prevailing in the central part of the window ;
— Areas presenting a unimodal cycle, mainly located in the western part ;
— Areas with a bimodal cycle, prevailing in the eastern upper and lower parts of the image.

4.1. Identification of Different Behaviours in Very Arid Areas (figs. 2 and 3)

It is worth stressing to which classes the volcanic and alluvial soils, characterizing the central part of the image, are assigned (figs. 2 and 3). The rocky lava desert around Lake Turkana (class 1) presents a completely flat NDVI profile along the whole year. The cycle is only minimally affected by the spring season. The black Kalimapus Hills, marked with 1 in figure 3, on the road from Lodwar to Ferguson's Golf, belong to this class.

Arid colluvial and alluvial sedimentary areas are assigned to classes 2 and 3. While areas included in class 2 have a minimal vegetation activity during the spring season, areas in class 3 are also sensitive to a second season in autumn. A road journey from Pokot to Lodwar through Lokichar offers a good glance of these typologies.





Figs. 2 and 3. — Profiles (above) and distribution (below) of the arid classes.

Also class 4 is affected by a second dry season. The plain near the Karoli desert (2) (frequently defined in the cartography as "liable to flood"), on the east side of Lake Turkana, is singled out and assigned to this class.

In particular, areas in class 3 are interested in cattle transhumance : during the two short-peak wet periods animals are moved into these areas, and moved away as soon as drier conditions are re-established and water is no longer sufficient. On the west of the Turkana animals migrate from the plains along the Turkwel (3) and Kauwalathe (4) rivers to the upper grounds of Loima (5) and the Ngimoruitai Hills (6). Similar movements characterize the pastoral system in the upper-left corner of the images. From the Lotikipi plain herders move to the west towards the Songot Mountains (out of the image).

4.2. The Unimodal Front on the West of the Turkana Lake (figs. 4 and 5)

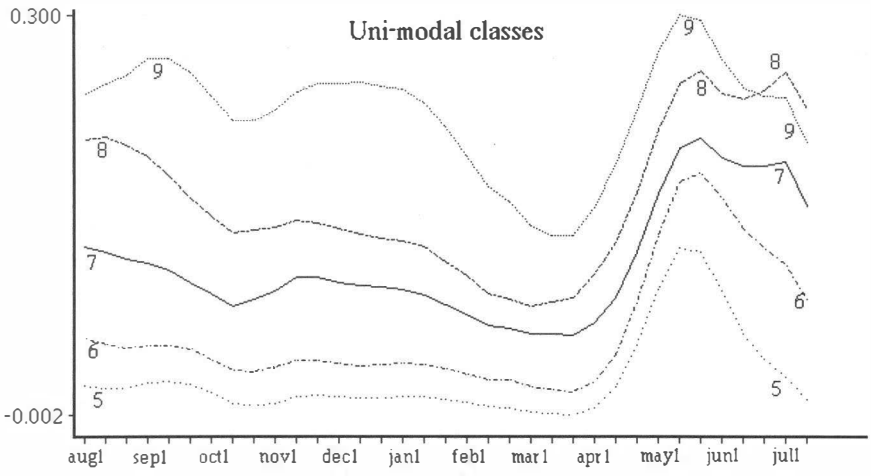
The escarpments on the west of the basin are generally affected only by one spring season ; classes 5 to 9, shown in figures 4 and 5, present similar NDVI patterns ranged in ascending order according to their level.

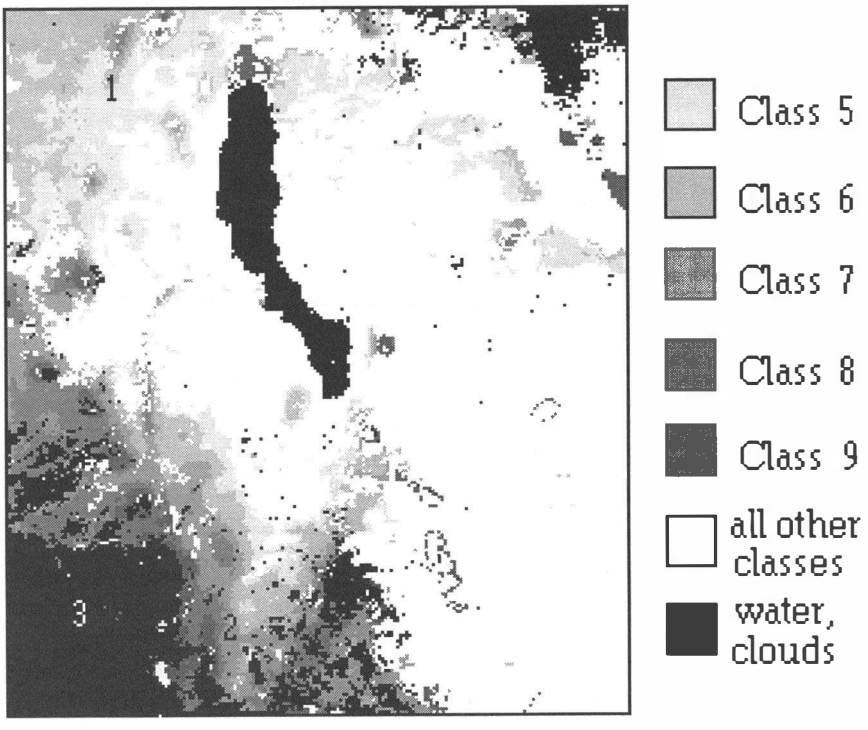
Areas assigned to classes 5 and 6 are characterized by a very short vegetative period, while classes 7 and 8 present a longer grazing period. Finally, class 9 identifies areas with a permanent vegetation activity, with a stress period just before the starting of the spring season.

The Lokitipi plain (marked with 1 in fig. 5) along the Tarach River, as well as the Kito Pass (2) landscape crossed when driving from Tot-Koloa to Ngynyang-Lake Baringo, belong to class 5. Vegetation is scattered and affected by a very high seasonality. As already remarked, the Lokitipi plain represents the "winter" component of the local pastoral system.

Areas included in class 6 offer better grazing conditions, but the season is very short and these areas appear to be part of a pastoral system based on seasonal migration.

Conditions are better in areas assigned to class 7, and still better in class 8. The really dry period is short and drought-resistant crops could be cultivated. Grazing conditions allow a more sedentary activity.





Figs. 4 and 5. — Average profiles and geographic distribution of the unimodal classes.

Finally, the pattern of areas in class 9 is quite different from the rest of this group, as the unimodal regime is very long and sometimes extended with respect to the rains, due to the availability of water resources emerging to the surface from the western border of the Rift Valley. It is not by chance that pixels assigned to this class lie often near pixels unclassified owing to a persistent presence of clouds. Some well-known and densely populated areas near the Cheragani Hills (3), like Tot or Tambach, belong to this class.

4.3. BiModal Areas (figs. 6 and 7)

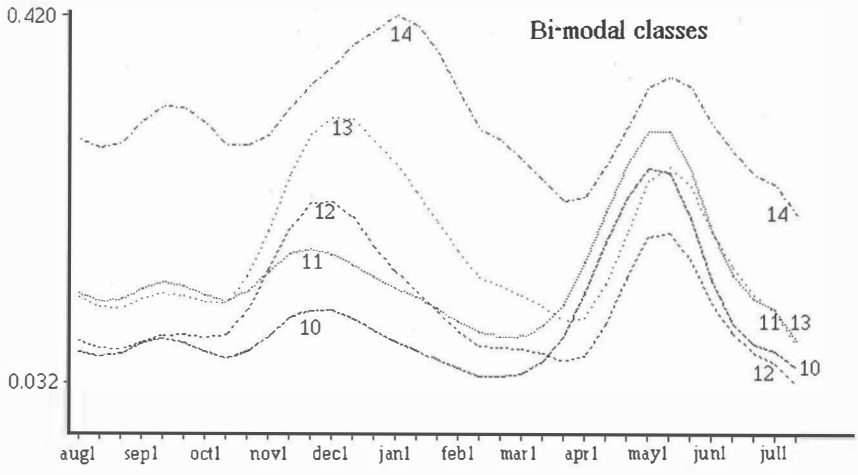
Most of the areas characterized by a bimodal vegetation cycle lie in the south and north-eastern corner of the window.

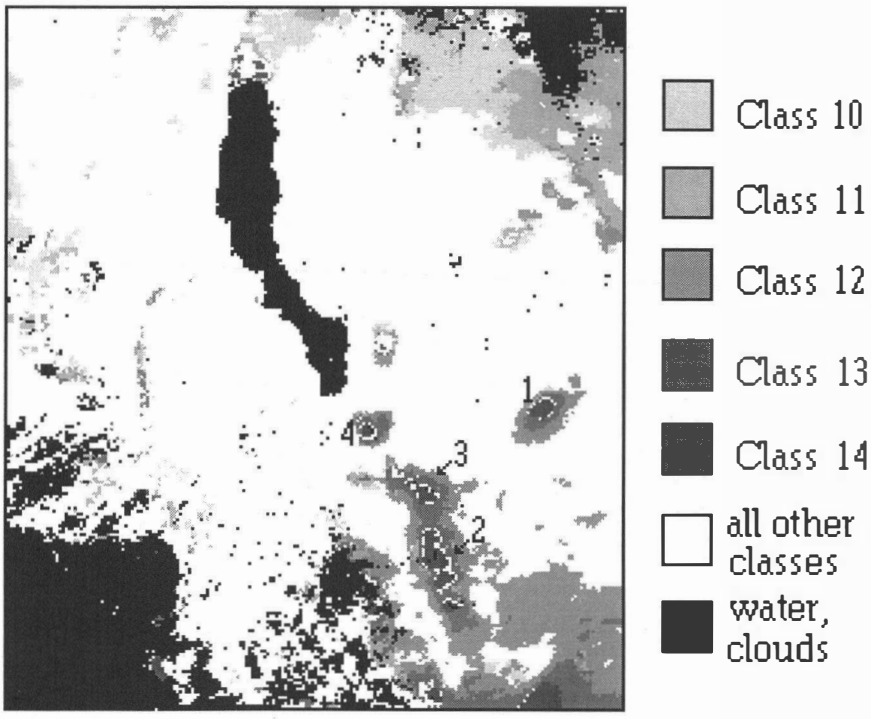
An intense bimodal vegetation cycle identifies the principal mountains. The volcanic mass of Mount Marsabit (1 in fig. 7), a classic continental island, emerges from the plain and offers a perfect example of altitude-related climatic and vegetation belts. The top is covered by an upland evergreen vegetation identified by a high NDVI bimodal cycle (class 14). At lower altitudes the level of the NDVI decreases progressively, still remaining characterized by a bimodal pattern (classes 13 and 12). The large basement of the volcano is assigned to class 4, already described, a bimodal dry one.

It is worth noting that the same sequence of altitude-dependent vegetation patterns characterizes the long south-north alignment from Oldoinyo Lemkiyio (Mathews Peak and Mathews Forest, 2 in fig. 7) to the Mdoto Mountains (3) and up to the northern Oldoinyo Nyiro (Mtanyiru Forest, 4). The lower parts of these mountains belong to class 12, followed by areas in class 4. These patterns are found in the entire south-east corner of the image.

On the contrary, areas in the north-east corner (forming classes 11 and 10 and lying beyond the Ethiopian border) present quite different vegetation patterns. While the prevalence of a bimodal cycle is still evident, the main season is here the second one (meher).

At least for once political boundaries seem to be supported by some agro-climatological rationale...





Figs. 6 and 7. — Average profiles and geographic distribution of the bimodal classes.

5. Conclusions

The identification/classification of eco-phytologic systems is still an urgent need in developing countries. As it appears likely that less and less resources will be available in the future for this type of studies, it is important to identify suitable information sources and analysis techniques liable to provide quick and low-cost results.

The Turkana basin case study intends to demonstrate that analyses based on an increasingly available remote sensing source, like the AVHRR-HRPT images, and utilizing public domain software, like the multivariate package ADDAPIX, can offer a significant contribution in this direction.

Through the classification of different seasonal vegetation patterns it was possible to provide a significant screening of the above basin. In particular, it was possible to identify geographical boundaries amongst :

— Different grazing system areas ;
— The grazing areas and areas more suitable for cropping.

As an additional result, the analysis was able to distinguish between volcanic and colluvial-alluvial sedimentary areas, thus providing a demonstration that this approach is quite promising, particularly when applied to large and not easily accessible areas.

We can expect that a further improvement in the image quality, achieved through a more accurate and refined correction and registration methodology, combined with an appropriate use of multivariate techniques, can offer an adequate answer, in terms of easy repetition and low cost, to the needs of producing and updating eco-geographic classification for large and not easily accessible areas.

We have limited ourselves to a series of NDVI images, but it is worth remarking that the potentiality of a multivariate approach operating on other appropriate channels or channel ratios is still open to investigation.

NOTES

[1] The word "dekadal" cannot yet be found in the dictionnary. It has come in use in remote sensing to indicate ten days.

[2] ADDAPIX stands for "**A**nalisi **D**ei **D**ati su **Pix**el" (Pixel-based Data Analysis). The package, conceived by S. Griguolo and written with M. Mazzanti, is distributed by FAO for agro-climatic applications, in particular for crop monitoring, but was designed to process up to 52 single-band 8-bit images of *any type*. The package

can be downloaded via ftp from the server of the University of Venice, Italy (Institute of Architecture) :

ftp :	cidoc.iuav.unive.it	(IP : 157.138.209.4)
login :	addapix	
passwd :	addapix	

or from the server of the Food and Agriculture Organisation of the UN :

ftp	ftp.fao.org	(IP : 193.43.36.7)
login	anonymous	
passwd	(your e-mail address)	
cd	SDRN/ADDAPIX	

Remember to retrieve text files in ascii mode, and files with extension "zip" or "exe" in binary mode.

[3] HRPT (High-Resolution Picture Transmission) AVHRR images are made up by sets of lines transmitted while they are scanned and received in digital format by the ground stations existing in the area. The "natural" resolution is 1.1 km, but images are often resampled for particular uses. The images we used for Kenya were received from KMD and were already resampled to 2 km. Instead, LAC (Local Area Coverage) images are stored on board and transmitted only to a few particular ground stations.

[4] **A**frica **R**eal **T**ime **E**nvironmental **M**onitoring **I**nformation **S**ystem.

[5] The MARS (Monitoring Agriculture by Remote Sensing) archive's images are being currently used for project PELCOM, funded by the European Commission, whose objective is the construction of a 1 km Land Cover classified database for the European continent; the MERCATOR archive is mostly aimed at monitoring tropical fires and forest destruction.

[6] The size of each image of the entire globe is approximately 634 MB/band for an 8-bit image. Each composite global image consists of ten bands, five of which are the AVHRR channels, suitably pre-processed.

[7] We particularly thank for his collaboration the Head of the KMD Agrometeorological Section, Mr John Mwikya, without whose determination in providing the images the analysis presented in this paper would not have been possible.

REFERENCES

BELWARD, A. S. 1996. The IGBP-DIS Global 1 km land cover data set "DISCover" - Proposal and implementation plan. IGBP-DIS Working Paper, IGBP-DIS Office, Toulouse.

DERRIEN, M. *et al.* 1992. Vegetation cover mapping over France using NOAA-11/AVHRR. — *Int. J. Remote Sensing*, **13** (9) : 1787-1795.

DIDAY, E. 1971. Une nouvelle méthode en classification automatique et reconnaissance des formes. — *Revue de statistique appliquée*, **13** (2).

FULLER, D O. & PRINCE, S. D. 1996. Rainfall and foliar dynamics in tropical southern Africa : potential impacts of global climatic change on savannah vegetation. — *Climatic Change*, **33** : 69-96.

GRIGUOLO, S. 1994. Pixel-by-pixel clustering for vegetation monitoring. — Proceedings of the International Conference on Early Warning and Environmental Monitoring (Niamey, November 1994). In press.

GRIGUOLO, S. 1996. ADDAPIX : a programme for Pixel-by-Pixel Classification for Zoning and Monitoring. — Technical Report SD :GCP/INT/578/NET, FAO, Rome, 78 pp.

GRIGUOLO, S. & SANTACROCE, P. 1993. Analysing, classifying and displaying time series of images pixel-by-pixel : the package ADDAPIX. — *In* : GOMMES, R. (ed.), Co-ordination and Harmonisation of databases and software for agroclimatic applications. Agrometeorology Series, Working Paper no. 13, FAO, Rome, pp. 243-257.

JUSTICE, C. O. & TOWNSHEND, J. R. 1994. Data sets for global remote sensing : lesson learnt. — *Int. J. Remote Sensing,* **15** (17) : 3621-3639.

QUARMBY, N. A., TOWNSHEND, J. R. G., SETTLE, J. J. & WHITE, K. H. 1992. Linear mixture modelling applied to AVHRR data for crop area estimation. — *Int. J. Remote Sensing*, pp. 415-424.

TOWNSHEND, J. R. & JUSTICE, C. O. 1986. Analysis of the dynamics of African vegetation using the normalised difference vegetation index. — *Int. J. Remote Sensing*, **7** (11) : 1435-1445.

TOWNSHEND, J. R., JUSTICE, C. O., SKOLE, D., MALINGREAU, J.-P., CHILAR, J., TEILLET, P., SADOWSKI, F. & RUTTEMBERG, S. 1994. The 1 km resolution global data set : needs of the International Geosphere Biosphere Programme. — *Int. J. Remote Sensing*, **15** (17) : 3417-3441.

TOWNSHEND, J. R., JUSTICE, C., WEI, L., GURNEY, C. & MCMANUS, J. 1991. Global land cover classification by remote sensing : present capabilities and future possibilities. — *Remote Sensing of Environment*, **35** : 243-255.

VAN VELTHUIZEN, H., VERELST, L. & SANTACROCE, P. 1995. Crop Production System Zones of the IGADD Sub-Region. — Agrometeorology Working Paper Series, no. 10, FAO, Rome.

APPENDIX
The package ADDAPIX : a brief description

Given a set of p images of the same area, each pixel x is described by an *ordered set* of *p* values $\{x_1 \ldots x_p\}$ drawn from the images taken in their order. When the *p* images are merged into the *merged pixel database* a multidimensional descriptive table is formed, whose rows refer to pixels and columns to variables (images). Whatever the nature of the images, the problem can be tackled according to the analytical path described below.

The main difficulty arises from the number of the units to be clustered. *The storing and computation requirements can be heavy also for a fast PC*, but a reasonable clustering time was achieved through a number of technical attentions.

Pixels are clustered via a sequence of menu-controlled procedures, whose core consists of a *Principal Component Analysis* followed by a *non-hierarchical Clustering*. Other procedures allow to merge the input images, to bound the pixels to be clustered, to inspect graphically the detailed behaviour of each pixel (DISPLAY), etc.

Firstly, the input images are merged to form a *merged pixel database*, where each pixel is represented by the series of its values drawn from the images. Pixels not fulfilling a user's specified condition are marked *excluded*.

The analysis is controlled by a *Work Image* that carries the information on which pixels are *active* or *excluded*. The first Work Image, written when merging, can undergo further changes : the *active* status of some pixels can be switched to *excluded* because they are of no interest, or are external to a set of user-chosen areas, etc.

The Principal Component Analysis procedure reads in the *merged pixel database* and reduces the dimensionality of the description limiting it to the most relevant factors. This has the double advantage of speeding up the subsequent classification and *of reducing the effect of errors in data*, as values unexpected on the basis of the existing correlations are loaded onto the last and less relevant (noise) components. The user decides *interactively* how many components to save for clustering.

The component with the highest variance is mapped onto the interval (- 32767, + 32767) ; the others are mapped onto intervals whose widths are proportional to the associate component's standard deviation (*i.e.*, to the square root of the corresponding eigenvalue). The relative importance of each component is thus maintained in the clustering procedure. Values are passed on as 16-bit signed integers, saving both core memory and computing time when clustering. On user's request the most relevant explanatory components are saved as displayable bit-mapped images.

The saved Principal Components are automatically loaded by the non-hierarchical Clustering programme, that computes a user-requested number of partitions. Even forty or fifty classes can be constructed, for a detailed exploration, when a SVGA is present and up to 256 colours are available to display and query the classified image.

Several partitions can be produced, each from a different set of initial centres. The clustering program is based on *Diday's dynamic clouds method* (DIDAY 1971), belonging to the family of the k-means algorithms : each partition is constructed around a set of initial aggregation centres and is iteratively improved until a local optimum is reached. The initial centres can be chosen randomly or provided by the user, who can thus try to give the clustering process a convenient initial "push" according to his specific expertise.

The package includes a program to examine the classified image : the user can choose graphically the pixels whose profile he/she wants to display. When the mouse's left button is clicked on a pixel, its time profile pops up in a window ; the right button commands the zooming of an area surrounding the selected pixel, thus easing the selection. The profile is continuously updated when the mouse is dragged holding down the left button, and the user can browse through the database getting an immediate graphic answer.

The displaying program is geo-referenced and can load images much larger than the part fitting in the screen. The switching between various parts of the image is very fast ; the image can be zoomed and the class/colour match, or the palette, can be changed very easily. Up to 15 vectorial files can be superimposed onto the raster image on the screen.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 441-453 (1998)

Contribution des satellites à la lutte contre la trypanosomose animale africaine

par

Guy HENDRICKX *, Ayitou NAPALA*,
David ROGERS ** & Jan SLINGENBERGH ***

MOTS-CLES. — Télédétection ; Analyse discriminatoire ; Glossines ; Limites géographiques ; Densités ; Trypanosomose ; Prévalence.

RESUME. — Un modèle basé sur l'analyse discriminatoire a récemment été appliqué au Togo en vue de prédire les limites géographiques et les densités des glossines, vecteurs de la trypanosomose africaine, et la prévalence de la maladie. Le modèle utilise des densités et prévalences mesurées sur le terrain et comme variables indépendantes une série de variables éco-climatiques mesurées au sol et par télédétection (NDVI : «Normalized Difference Vegetation Index» ; CCD : «Cold Cloud Duration» ; Therm : «Thermal Channel 4»). Les résultats obtenus sont illustrés par trois exemples : les limites géographiques et les densités de *Glossina tachinoides* et la prévalence combinée de *Trypanosoma congolense* et *T. vivax*. Les résultats obtenus sont commentés dans le cadre de leur potentiel en vue de réduire les coûts d'enquêtes de terrain.

TREFWOORDEN. — Afstandswaarneming ; Discriminantanalyse ; Glossina ; Geografische limieten ; Densiteiten ; Trypanosomose ; Prevalentie.

SAMENVATTING. — *Bijdrage van satellieten tot de controle van Afrikaanse trypanosomose bij dieren.* — Een model gebaseerd op discriminantanalyse werd onlangs toegepast in Togo om de limieten en densiteiten van glossina, de vectors van Afrikaanse trypanosomose, en de prevalentie van de ziekte te voorspellen. Het model gebruikt op het veld gemeten densiteiten en prevalenties en als onafhankelijke variabelen een reeks eco-klimatologische variabelen gemeten door grondstations en teledetectie (NDVI : „Normalized Difference Vegetation Index" ; CCD : „Cold Cloud Duration" ; Therm : „Thermal Channel 4"). Resultaten worden geïllustreerd door drie voorbeelden :

* GCP/TOG/013/BEL, B.P. 114, Sokodé (Togo) (Correspondance).
** Department of Zoology, South Parks Road, Oxford OX1 3PS (United Kingdom).
*** FAO, Via delle Terme di Caracalla, 00100 I-Rome 1 (Italy).

limieten en densiteiten van *Glossina tachinoides* en gecombineerde prevalentie van *Trypanosoma congolense* en *T. vivax*. Bekomen resultaten worden besproken in het kader van hun potentieel kostenbesparend te werken op veldstudies.

KEYWORDS. — Remote Sensing ; Discriminant Analysis ; Glossina ; Geographical Limits ; Abundance ; Trypanosomosis ; Prevalence.

ABSTRACT. — *Contribution of Satellites to the Control of African Animal Trypanosomosis.* — Recently a model based on discriminant analysis has been used in Togo to predict the limits and abundance of glossina, vectors of African trypanosomosis, and prevalence of the disease. The model is based on densities and prevalence measured in the field and uses as independent variables a set of eco-climatological variables measured on the ground and by remote sensing (NDVI : Normalized Difference Vegetation Index ; CCD : Cold Cloud Duration ; Therm : Thermal Channel 4). Results are illustrated by three examples : limits and densities of *Glossina tachinoides* and combined prevalence of *Trypanosoma congolense* and *T. vivax*. Results obtained are discussed according to their potential to reduce costs of field surveys.

1. Introduction

Les trypanosomoses animales africaines (TAA) sont des maladies protozoaires transmises par les mouches tsé-tsé. Elles sévissent dans la majeure partie de l'Afrique sub-saharienne dont le Togo. La TAA y a constitué un frein important pour l'élevage et son intégration à l'agriculture, y compris le développement de la traction animale (TOURE & MORTELMANS 1991).

Le contrôle efficace de la TAA nécessite une connaissance détaillée de son épizootiologie (entre autres présence et densité des mouches tsé-tsé, prévalence de la maladie). Ces données ne sont souvent pas disponibles ou sont périmées (ROGERS & RANDOLPH 1988). Des enquêtes de terrain tel le piégeage du vecteur et l'examen parasitologique du bétail demandent beaucoup de temps et d'argent. Il est donc nécessaire non seulement de rationaliser les méthodes d'enquêtes, mais également d'utiliser au maximum l'information disponible en l'extrapolant vers des zones similaires non prospectées.

2. Objectifs de l'étude

Partant du principe que la présence du vecteur est fortement liée à la disponibilité d'un écoclimat qui lui est favorable, l'objectif de la

présente étude est de vérifier si des données géo-climatiques mesurées au sol ou par satellite seraient en mesure de prédire dans l'espace la présence et la densité du vecteur ainsi que la prévalence de la maladie.

Des résultats obtenus à ce jour sont illustrés par trois exemples :

— Prédiction des limites de *Glossina tachinoides*, vecteur principal de la maladie ;
— Prédiction des densités de *G. tachinoides* ;
— Prédiction de la prévalence de la maladie (*Trypanosoma congolense* et *T. vivax* combinés).

Cette étude, financée par le Gouvernement belge et exécutée par la FAO en collaboration avec le Ministère togolais de l'Agriculture, de l'Elevage et des Pêches, est conçue dans le cadre d'une phase préliminaire d'un projet régional de lutte contre la TAA dans l'ouest africain.

3. Matériel et méthodes

a. Création d'une banque de données géoréférencée. Afin de pouvoir standardiser la méthodologie d'enquêtes et d'inventorier le problème (Hendrickx *et al.* 1995a), le territoire du Togo a été divisé suivant un canevas régulier de 0,125 degré (311 carrés pour tout le pays). Pour chaque carré les données suivantes sont rassemblées :

— Données récoltées par des équipes mobiles de terrain (enquêtes effectuées en 1990-1993 et 1994-1995) : présence / absence et densité (Log(x+1)) des vecteurs (captures par piège biconique, Challier & Laveissiere 1973) ; présence (densités) et type (taurin - zébu) de bétail ; composition des troupeaux ; prévalence de la maladie (détection du parasite dans le sang exprimé en %, hématocrite).
— Données géoclimatiques mesurées au sol : températures (C) mensuelles moyennes - minimales - maximales ; écart annuel des températures ; pluviosité annuelle (mm) ; nombre de mois secs (< 30 mm) et mois humides (> 100 mm) ; Index de Siccité de Martonne ; % des terres dans le cycle agricole ; altitude moyenne (m) ; densités de populations humaines.
— Données satellites corrélées à : la végétation (NDVI, «Normalized Difference Vegetation Index») (Bartholome 1988) ; la pluviosité (CCD, «Cold Cloud Duration») (Snijders 1991) et la température au sol (Therm, «Soil Surface Brightness Temperature») (James &

KALLURI 1994). En plus des moyennes, minima, maxima et écarts annuels, sont également reprises les amplitudes (Amp) et phases (Ph) des cycles annuels, bisannuels et trisannuels obtenus après analyse de Fourier. Ce type de données et d'autres à disposition ont récemment été revues par HAY *et al.* (1996). Les données mensuelles suivantes à une résolution de 7 km sont utilisées dans cette analyse ; NDVI de 1989 à 1990, CCD de 1988 à 1992 et Therm de 1984 à 1990.

b. Etude de la relation entre ces variables et leur incorporation dans un Système d'Information Géographique (SIG) permettant de mieux comprendre le problème au niveau national et de proposer des solutions adaptées aux différentes situations de terrain et applicables par les différents opérateurs (ex. : zones où un contrôle régulier du bétail et son traitement éventuel aux trypanocides suffisent, zones où une lutte contre le vecteur est à préconiser, zones où l'élevage du bétail trypanotolérant devrait être favorisé, etc.) (HENDRICKX *et al.* 1995b)

c. Finalement, ces variables sont intégrées dans un modèle de prédiction dans l'espace utilisant l'analyse discriminatoire non linéaire (méthode décrite en détail par ROGERS *et al.* 1996) afin de pouvoir explorer les possibilités de prédiction de variables biologiques (vecteur, maladie) en utilisant comme variables indépendantes les données géo-climatiques disponibles mesurées au sol ou par satellite. Dans le cas des limites géographiques de *G. tachinoides*, les prédictions ont été effectuées successivement sur la totalité du Togo, sur la moitié sud et sur la partie littorale. Pour les densités de *G. tachinoides*, le modèle est appliqué à l'intérieur des limites géographiques connues de la mouche et pour la prévalence de la trypanosomose uniquement au niveau des carrés ayant du bétail sédentaire. Les résultats obtenus sont présentés sous forme de tableaux et de cartes :

— Les tableaux reprennent les dix meilleures variables par ordre d'importance, leur valeur moyenne par classe (présence / absence, classe de densité ou de prévalence) et le pourcentage de prédictions correctes par classe.
— Les cartes reprennent les résultats observés et les résultats prédits. Dans le cas des densités et prévalences, les carrés où l'erreur est de plus d'une classe sont également indiqués, ce type d'erreur pouvant induire une prise de décision erronée dans le cas d'actions de lutte.

4. Résultats

4.1. Limites geographiques de *G. tachinoides*

Les trois types de variables satellites (NDVI, CCD, Therm) sont représentés en proportion similaire (tableau 1). Les données mesurées au sol n'interviennent que très peu. Les différentes prédictions ont 4 (T-S) et 3 (S-L) variables en commun. La sélection d'un set de variables adapté à chaque situation permet l'amélioration des résultats obtenus. Dans le premier cas (T), l'introduction successive des différentes variables permet une amélioration régulière de la spécificité (prédiction correcte de l'absence). Ceci se fait néanmoins au détriment de la sensitivité (prédiction correcte de la présence) et est le plus marqué en introduisant les 4 dernières variables. Cette perte de précision est due à l'introduction d'une série de fausses prédictions d'absence dans la moitié nord du pays, bien à l'intérieur des limites de la mouche (fig. 1). En éliminant du modèle la partie nord du pays, cette interférence n'intervient plus. Les prédictions dans la moitié sud (S) permettent une excellente description de la limite sud-ouest de la mouche. Les erreurs restantes à sa limite sud sont corrigées en se limitant à la zone littorale (L).

4.2. Densites de *G. tachinoides*

Les résultats montrent une précision moyenne de 62 % (tableau 2) en utilisant les dix meilleures variables. C'est au niveau des classes intermédiaires que le modèle fait le plus grand nombre d'erreurs : en moyenne 48 % de réponses correctes pour les classes 2, 3 et 4 contre 83 % pour les autres. Ceci semble lié au fait que dans la majorité des cas les moyennes des variables pour les classes extrêmes soient différentes de manière significative alors que ce n'est pas le cas pour les classes intermédiaires. En acceptant les erreurs d'une classe, les moyennes sont nettement relevées et la disparité diminue (respectivement 83 et 90 %). Les variables sélectionnées montrent une présence marquée de données mesurées au sol (4/10) alors qu'elles ne représentent que 28 % des variables disponibles. Des données satellites, les CCD, liées à la pluviosité, dominent (4/6) ; aucun NDVI n'est sélectionné. La mouche se rencontre en densités plus importantes dans les zones moins humides. Les cartes (fig. 2) montrent une perte de contraste des prédictions par rapport aux observations. La prédominance des faibles densités au sud du pays et des fortes densités au nord y est accentuée.

Tableau 1

Prédiction des limites géographiques de *Glossina tachinoides*

Totalité du Togo (T)							
		Valeurs moyennes des variables			Réponses correctes (%)		
Ordre	Variables	Absent (n=51)	Présent (n=260)	Total (n=311)	Absent	Présent	Total
1	NDVI Amplitude 1	0.092	0.154	0.144	66.7	96.9	92
2	CCD Phase 1	4.6	5.6	5.4	68.6	95.4	91
3	CCD Amplitude 3	12.9	16.7	16.1	80.4	94.6	92.3
4	CCD Phase 2	3.6	3.1	3.2	76.5	95	92
5	Therm Amplitude 1	5.3	8.7	8.1	78.4	93.1	90.7
6	Ecart température	3.7	4.6	4.5	86.3	91.2	90.3
7	Pluviosité	1249	1219	1224	88.2	89.2	89.1
8	Therm Phase 2	2.2	2.5	2.5	94.1	82.3	84.2
9	NDVI Phase 2	3.7	3.1	3.2	94.1	78.8	81.3
10	NDVI Phase 1	6.9	6.9	6.9	90.2	79.6	81.3
Zone éco-géographique Sud (S)							
		Valeurs moyennes des variables			Réponses correctes (%)		
Ordre	Variables	Absent (n=51)	Présent (n=145)	Total (n=196)	Absent	Présent	Total
1	NDVI Amplitude 1	0.091	0.142	0.128	66.7	94.5	87.2
2	NDVI Phase 1	6.9	6.6	6.7	56.9	93.8	84.2
3	CCD Amplitude 2	42.9	31.0	34.1	64.7	93.8	86.2
4	NDVI Phase 2	3.8	3.4	3.5	70.6	94.5	88.3
5	% Agriculture	40.8	34.4	36.1	66.7	95.2	87.8
6	CCD Maximal	51.4	47.9	48.8	78.4	93.8	89.8
7	CCD Phase 1	4.5	5.0	4.9	78.4	95.2	90.8
8	Therm Moyen	26.4	28.6	28.0	82.4	93.8	90.8
9	Therm Amplitude 2	0.737	0.791	0.777	88.2	95.2	93.4
10	NDVI Amplitude 2	0.075	0.07	0.071	88.2	95.2	93.4
Zone éco-géographique prélittorale et littorale (L)							
		Valeurs moyennes des variables			Réponses correctes (%)		
Ordre	Variables	Absent (n=25)	Présent (n=30)	Total (n=55)	Absent	Présent	Total
1	CCD Phase 2	3.9	3.7	3.8	72	90	81.8
2	CCD Amplitude 3	6.7	8.4	7.6	80	90	85.4
3	NDVI Phase 2	3.9	3.6	3.8	84	93.3	89.1
4	CCD Moyen	24.8	28.3	26.7	96	93.3	94.5
5	Therm Amplitude 3	0.467	0.538	0.505	88	96.7	92.7
6	Therm Phase 2	2.5	1.7	2.1	88	96.7	92.7
7	Therm Moyen	26.0	26.6	26.3	80	100	90.9
8	NDVI 89/90 Moy	0.359	0.393	0.378	92	96.7	94.5
9	CCD Maximal	49.0	50.1	49.6	96	96.7	96.4
10	NDVI Minimal	0.184	0.171	0.177	96	96.7	96.4

Légende : Dix meilleures variables sélectionnées par zone de prédiction. Les amplitudes et phases se réfèrent aux termes de l'analyse de Fourier, appliquée sur les données satellites (NDVI, CCD, Therm), pour les cycles annuels (1), bisannuels (2) et trisannuels (3). Ecart de température = différence entre la température moyenne mensuelle maximale et minimale mesurée au sol (normales sur 20 ans). Pluviosité = mm de précipitation par an. % Agriculture = pourcentage des terres recensées dans le cycle agricole.

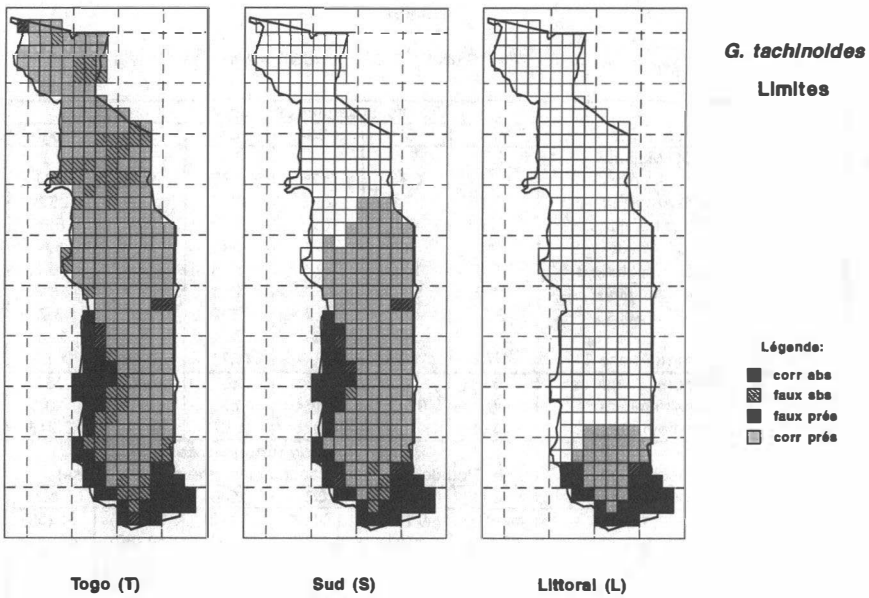


Fig. 1. — Cartes des prédictions des limites géographiques de *Glossina tachinoides* successivement sur la totalité du Togo (T), sur la moitié sud (S) et sur la zone prélittorale et littorale en utilisant les variables mentionnées au tableau 1.

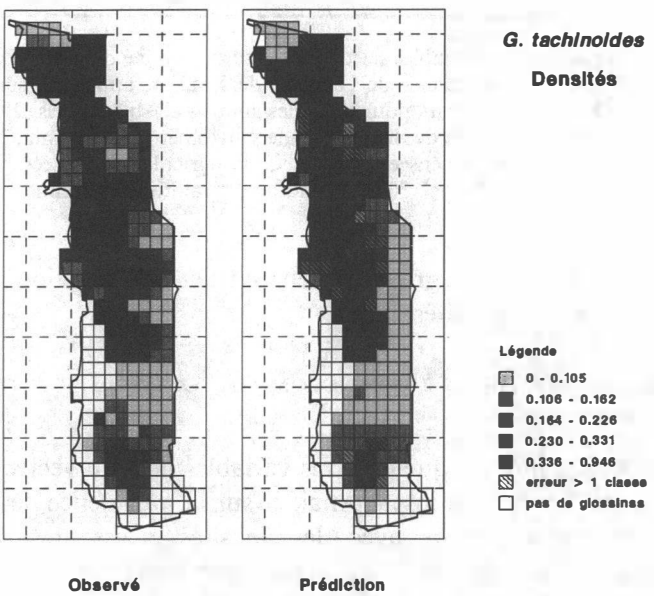


Fig. 2. — Carte des densités observées et prédites de *Glossina tachinoides* au Togo en utilisant les variables mentionnées au tableau 2.

Tableau 2

Prédiction des densités de *Glossina tachinoides*

Ordre	Variables	Valeurs moyennes des variables par classe					
		C1	C2	C3	C4	C5	Togo
1	CCD Minimum	3.7	2.6	2.1	1.9	0.7	2.2
2	Therm Amplitude 2	1.03	0.88	0.76	0.85	1.51	1.01
3	CCD Amplitude 2	27.0	27.9	26.8	28.2	17.0	25.3
4	Mois humides	6.3	6.1	6.1	6.1	5.4	6.0
5	CCD Phase 1	5.0	5.4	5.6	5.6	6.1	5.6
6	CCD Amplitude 3	13.8	15.2	17.8	18.5	18.1	16.7
7	% Agriculture	41.9	38.6	38.3	40.1	25.7	36.8
8	Mois secs	3.5	3.3	3.7	3.8	4.4	3.7
9	Altitude	271	290	307	304	251	284
10	Therm Phase 3	1.73	1.88	1.93	1.71	2.18	1.89
	Nombre de carrés	51	53	51	52	55	262
	Densité minimale	0	0.106	0.164	0.23	0.336	0
	Densité maximale	0.105	0.162	0.226	0.331	0.946	0.946

Variables utilisées	**Pourcentage de réponses correctes** (Pourcentages en acceptant les erreurs d'une classe)					
	C1	C2	C3	C4	C5	Total
1	62 (62)	0 (44)	12 (12)	0 (75)	98 (98)	35 (59)
2	46 (48)	4 (91)	63 (65)	8 (81)	80 (80)	40 (73)
3	42 (52)	17 (87)	53 (65)	10 (73)	91 (93)	43 (74)
4	48 (60)	15 (83)	57 (75)	12 (75)	89 (93)	44 (77)
5	70 (74)	20 (82)	47 (69)	27 (75)	89 (95)	51 (79)
6	76 (80)	26 (85)	47 (71)	29 (79)	89 (96)	54 (82)
7	80 (82)	35 (87)	49 (71)	29 (79)	93 (95)	57 (82)
8	76 (84)	37 (87)	49 (73)	33 (81)	89 (95)	57 (84)
9	74 (82)	43 (89)	45 (78)	58 (89)	93 (98)	63 (87)
10	76 (84)	39 (91)	49 (78)	56 (79)	89 (96)	62 (86)

Légende : Dix meilleures variables sélectionnées sur la totalité du Togo. Les amplitudes et phases se réfèrent aux termes de l'analyse de Fourier, appliquée sur les données satellites (NDVI, CCD, Therm), pour les cycles annuels (1), bisannuels (2) et trisannuels (3). Mois humides = nombre de mois avec une pluviométrie > 100 mm. % Agriculture = pourcentage de terres recensées dans le cycle agricole. Mois secs = nombre de mois avec une pluviométrie < 30 mm. Altitude = altitude moyenne (m) par carré.

La majorité des erreurs graves se rencontrent à la jonction entre zones de fortes et faibles densités.

4.3. Prevalence de la trypanosomose bovine (*T. congolense* et *T. vivax*)

Le tableau 3 montre que d'autres variables liées au vecteur, au bétail et à l'agriculture ont un impact majeur sur la prévalence de la maladie. La prévalence augmente avec des densités croissantes du vecteur. Inversement, la proportion de veaux par génitrice décroît avec la maladie. Les plus faibles densités de bétail et d'agriculture au niveau de la première classe correspondent à la zone des plateaux montagneux

Tableau 3

Prédiction de la prévalence de *Trypanosoma congolense* et *T. vivax*

Ordre	Variable	Valeurs moyennes des variables par classe					
		C1	C2	C3	C4	C5	Total
1	*G. tachinoides*	0.036	0.197	0.184	0.210	0.343	0.195
2	Therm Phase 2	2.0	2.6	2.5	2.7	3.3	2.6
3	Therm Phase 3	1.3	2.0	1.8	2.0	2.2	1.9
4	NDVI Maximal	0.506	0.485	0.506	0.487	0.486	0.494
5	% Agriculture	33.6	44.7	42.8	48.6	45.5	43.1
6	Veaux / Génitrice	0.49	0.46	0.47	0.42	0.40	0.45
7	Dens. de Bétail / km²	3.6	5.8	4.1	4.6	4.3	4.5
8	Temp. moy. men. max.	28.0	29.1	28.9	29.1	29.9	29.0
9	CCD Maximal	49.9	44.8	46.3	45.1	42.2	45.6
10	NDVI Amplitude 1	0.112	0.147	0.149	0.149	0.161	0.144
	Nombre de carrés	42	43	43	43	44	215
	Prévalence minimale	0	4.15	7.69	10.21	12.51	0
	Prévalence maximale	4.07	7.62	10.1	12.37	21.37	21.37

Variables utilisées	**Pourcentage de réponses correctes** (Pourcentages en acceptant les erreurs d'une classe)					
	C1	C2	C3	C4	C5	Total
1	88 (88)	0 (47)	0 (49)	81 (88)	46 (83)	43 (71)
2	83 (83)	0 (44)	2 (54)	74 (84)	41 (83)	40 (70)
3	88 (88)	2 (49)	9 (58)	72 (88)	44 (83)	43 (73)
4	86 (88)	12 (58)	12 (56)	65 (86)	52 (83)	45 (74)
5	86 (91)	12 (56)	21 (58)	65 (91)	63 (87)	50 (76)
6	88 (93)	9 (56)	26 (70)	65 (95)	60 (86)	49 (76)
7	86 (93)	7 (49)	26 (70)	72 (98)	61 (86)	50 (80)
8	91 (95)	23 (67)	40 (74)	65 (98)	61 (84)	56 (84)
9	86 (91)	26 (67)	42 (72)	65 (95)	55 (73)	54 (80)
10	91 (95)	30 (67)	51 (74)	67 (98)	61 (80)	60 (83)

Légende : Dix meilleures variables sélectionnées sur la totalité du Togo. Les amplitudes et phases se réfèrent aux termes de l'analyse de Fourier, appliquée sur les données satellites (NDVI, CCD, Therm), pour les cycles annuels (1), bisannuels (2) et trisannuels (3). *G. tachinoides* = densités moyennes mesurées (Log(x+1)) de la mouche. % Agriculture = pourcentage recensé des terres dans le cycle agricole. Veaux / Génitrice = nombre de veaux et velles par femelle en cycle de reproduction dans les troupeaux sédentaires. Dens. de Bétail / km² = nombre de bovins par unité de surface. Temp. moy. mens. max. = Température moyenne mensuelle maximale mesurée au sol (normales sur 20 ans).

où les glossines sont absentes et l'agriculture difficile. Au niveau des variables géoclimatiques, la température semble dominer. Le degré de précision obtenu est du même ordre de grandeur que dans le cas des densités de *G. tachinoides*. Les cartes (fig. 3) montrent un bon résultat global. Le modèle permet de démarquer les différents niveaux de prévalence. Les erreurs de plus d'une classe se rencontrent surtout dans la moitié nord du pays (23 % des carrés contre 13 % au sud) où elles sont regroupées au centre de la zone. Tout comme pour la mouche, les faibles prévalences se trouvent renforcées au sud et les fortes au nord.

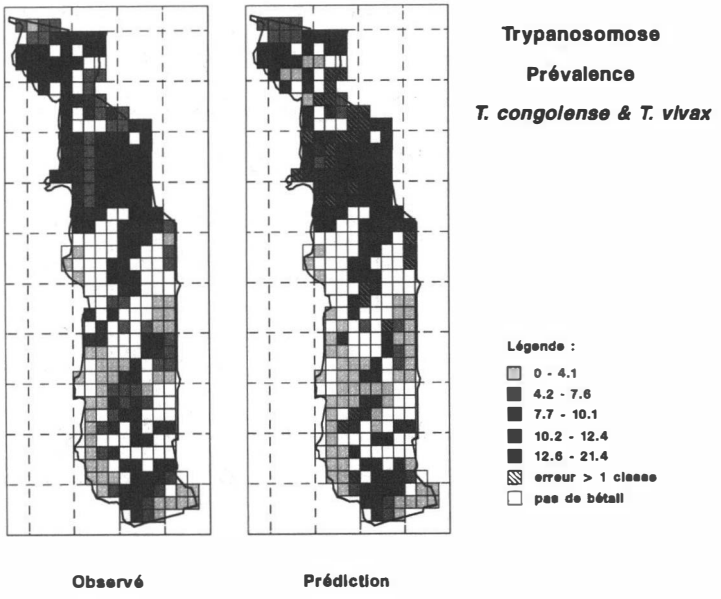


Fig. 3. — Carte de la prévalence combinée de *Trypanosoma congolense* et *T. vivax* observée et prédite au Togo en utilisant les variables mentionnées au tableau 3.

5. Discussion

Les résultats présentés confirment que l'utilisation de données récoltées par télédétection peut contribuer à prédire la distribution dans l'espace du vecteur, sa densité et la prévalence de la maladie qu'il transmet. Ils montrent une amélioration par rapport à des résultats antérieurs (ROGERS *et al.* 1994, HENDRICKX *et al.* 1995a). Les problèmes rencontrés pour décrire la limite sud de la mouche sont résolus de manière satisfaisante en éliminant du modèle la partie nord du pays. Cette approche permet de sélectionner un set de variables adaptées à la situation spécifique rencontrée à la limite sud de la mouche. Ces résultats suggèrent également qu'un set unique de variables ne permettra probablement pas de décrire avec précision les limites de vecteurs sur la totalité de leur aire de distribution. Des exercices de ce genre en Afrique de l'Est (ROGERS & RANDOLPH 1993) et en Afrique de l'Ouest (ROGERS *et al.* 1996) gagneront probablement en précision en sélectionnant au moins deux sets de variables séparées pour les limites sud

et nord. Une approche similaire permettra également d'améliorer les résultats des prédictions des densités (HENDRICKX *et al.*, en préparation) des vecteurs et des prévalences de la maladie.

Les variables satellites permettent à elles seules de décrire les limites géographiques du vecteur. Les CCD et NDVI prennent chacun un tiers à leur compte. Les termes de l'analyse de Fourier comptent pour deux tiers des variables sélectionnées, confirmant qu'ils contiennent des informations biologiques importantes en termes de saisonnalité (ROGERS & WILLIAMS 1994). Au fur et à mesure que l'analyse se concentre sur les limites proprement dites, celles-ci perdent d'importance (5/10) en faveur de dérivés classiques (moyenne, minimale, maximale). Dans le cas des densités, les variables mesurées au sol gardent toute leur importance, surtout en «fin» de prédiction où elles participent à l'amélioration de la précision au niveau des classes intermédiaires. La prédiction de la prévalence de la maladie dépend en grande partie d'autres variables biologiques. Des travaux futurs devront définir à quel point des variables géoclimatiques peuvent obtenir le même type de résultats.

Les exemples présentés font partie d'un travail qui n'est pas encore terminé. Actuellement, nous analysons la possibilité de combiner l'analyse multivariée et les enquêtes au sol en vue d'alléger de manière significative la densité de ces dernières et donc leur coût. Le remplacement des variables biologiques au niveau des prédictions de la maladie devrait avoir le même effet. La méthode devra également être validée hors du Togo dans les zones éco-climatiques similaires. Hors de ces zones, elle devra être adaptée aux conditions prévalant dans un environnement plus sec.

Entre autres avantages, le type de données satellites utilisé est disponible sur la totalité du continent, à des fréquences au moins journalières et actuellement à des résolutions de 1 km. Ceci indépendamment de frontières et de problèmes socio-politiques pouvant interférer avec la collecte de données au sol. La combinaison de prédictions et d'enquêtes de terrain devrait pouvoir fournir des données essentielles, à un coût moins élevé, pour la mise en œuvre de programmes de contrôle. Les données satellites ne remplaceront jamais le besoin en enquêtes de terrain mais elles devraient permettre à terme de les alléger. Là où des données au sol sont peu fiables, inexistantes ou difficiles à récolter, elles pourraient être le meilleur deuxième (seul) choix.

REMERCIEMENTS

Ce travail est effectué par le Projet de Lutte contre la Trypanosomose Animale au Togo, GCP-TOG-013-BEL, financé par le Gouvernement belge et exécuté par la FAO dans le cadre des activités du Ministère togolais de l'Agriculture, de l'Elevage et des Pêches. Les auteurs remercient J. Hielkema et F. Snijders du Projet ARTEMIS (FAO, Rome, Italie) pour avoir fourni les données satellites concernant les NDVI et CCD. Ils remercient également pour leurs commentaires constructifs et support permanent J. Mortelmans et R. De Deken (Institut de Médecine Tropicale d'Anvers, Belgique), B. Hursey et Ph. Marchot (FAO, Rome, Italie), J. Vercruysse (Parasitologie RUG, Gand, Belgique) et M. Denke et T. B. Kagnaya (Direction de l'Elevage et des pêches, Lomé, Togo).

BIBLIOGRAPHIE

BARTHOLOME, E. 1988. Radiometric measurement and crop yield forecasting : some observations over millet and sorghum experimental plots in Mali. — *Int. J. Remote Sensing*, **9** : 1539-1552.

CHALLIER, A. & LAVEISSIERE, C. 1973. Un nouveau piège pour la capture des glossines (*Glossina* : *Diptera, Muscidae*) : description et essais sur le terrain. — *Cah. Orstom, Sér. Entomol. méd. Parasitol.*, **11** : 251-262.

HAY, S. I., TUCKER, C. J., ROGERS, D. J. & PACKER, M. J. 1996. Remotely sensed surrogates of meteorological data for the study of the distribution and abundance of arthropod vectors of disease. — *Ann. Trop. Med. Parasitol.*, **90** (1) : 1-19.

HENDRICKX, G., NAPALA, A., ROGERS, D. J. & SLINGENBERGH, J. H. W. 1996. Systematic grid-based sampling of glossina. Part 2 : Contribution of remote sensing to ground-based surveys (en préparation).

HENDRICKX, G., NAPALA, A., SLINGENBERGH, J. H. W. & PALMER, H. B. 1995a. Facteurs affectant le contrôle de la trypanosomose au Togo. — *In* : Proceedings of 23rd Meeting of the ISCTRC, Banjul (Gambia), September 11-15, 1995 (sous presse).

HENDRICKX, G., ROGERS, D. J., NAPALA, A. & SLINGENBERGH, J. H. W. 1995b. Predicting the distribution of riverine tsetse and the prevalence of bovine trypanosomiasis in Togo using ground-based and satellite data. — *In* : Proceedings of the 22nd Meeting of the ISCTRC, Kampala (Uganda), October 25-29, 1993. O.A.U./S.T.R.C., **117** : 218-227.

JAMES, M. E. & KALLURI, S. N. V. 1994. The pathfinder AVHRR land data set - an improved course resolution data set for terrestrial monitoring. — *Int. J. Remote Sensing*, **15** : 3347-3363.

ROGERS, D. J., HAY, S. I. & PACKER, M. J. 1996. Predicting the distribution of tsetse flies in West Africa using temporal, Fourier-processed meteorological-satellite data. — *Ann. Trop. Med. Parasitol.*, **90** (3) (in press).

ROGERS, D. J., HENDRICKX, G. & SLINGENBERGH, J. H. W. 1994. Tsetse flies and their control. — *Rev. Sci. Tech. Off. Intern. Epizoot.*, **13** (4).

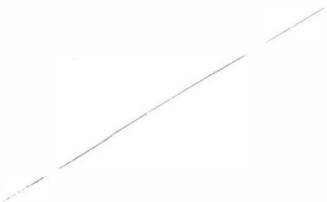
ROGERS, D. J. & RANDOLPH, S. 1988. The tsetse flies in Africa, bane or boon? — *Conserv. Biol.*, **2** : 57-65.

ROGERS, D. J. & RANDOLPH, S. 1993. Distribution of tsetse and ticks in Africa : past, present and future. — *Parasitol. Today*, **9** (7) : 266-271.

ROGERS, D. J. & WILLIAMS, B. G. 1994. Tsetse distribution in Africa : seeing the wood and the trees. — *In* : EDWARDS, P. J., MAY, R. & WEBB, N. R. (eds.), 35th Symposium of the British Ecological Society with the Society for Conservation Biology, University of Southampton, U.K., 14-16 April 1993. Blackwell Scientific Publications, Oxford, pp. 249-273.

SNIJDERS, F. L. 1991. Rainfall monitoring based on Meteosat data - a comparison of techniques applied to the Western Sahel. — *Int. J. Remote Sensing*, **12** (6) : 1331-1347.

TOURE, S. M. & MORTELMANS, J. 1991. Impact de la trypanosomose animale africaine (TAA). — *Bull. Séanc. Acad. R. Sci. Outre-Mer*, **36** (2) : 239-257.



HYDROLOGIE

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 457-469 (1998)

Cinquante ans d'études hydrologiques en Afrique de l'Ouest

par

Jacques SIRCOULON *

MOTS-CLES. — Recherche ; Hydrologie ; Afrique de l'Ouest.

RESUME. — L'auteur ébauche les étapes les plus importantes au cours de cinquante ans d'études hydrologiques en Afrique de l'Ouest. Il traite successivement la période des années quarante avec ses grands travaux d'infrastructure, l'avènement des nouvelles techniques de mesure dans les années septante et la décennie de grands projets et programmes internationaux en coopération dans les années quatre-vingt-dix.

TREFWOORDEN. — Onderzoek ; Hydrologie ; West-Afrika.

SAMENVATTING. — *Vijftig jaar hydrologische studies in West-Afrika.* — De auteur schetst de opvallendste stappen in het verloop van vijftig jaar hydrologische studies in West-Afrika. Hij behandelt achtereenvolgens de periode van de jaren veertig met de grote infrastructuurwerken, de opkomst van de nieuwe meettechnieken in de jaren zeventig en de internationale samenwerkingscampagnes in de jaren negentig.

KEYWORDS. — Research ; Hydrology ; West Africa.

SUMMARY. — *Fifty Years of Hydrologic Studies in West Africa.* — The author shows the most important steps in the development of fifty years of hydrologic research in West Africa. He successively deals with the period of the forties with large infrastructure works, the period of the seventies with the advent of new measuring technology and the period of the nineties characterized by international cooperation.

* Comité National Français des Sciences Hydrologiques, Orstom, 213 rue Lafayette, F-75480 Paris Cedex 10 (France).

*
* *

L'Afrique est un continent fortement contrasté en matière de ressources en eau : 60 % de sa surface sont arides et ne contribuent que pour 5 % à la ressource globale en eau.

Les régimes pluviométriques et donc hydrologiques y sont très diversifiés ; l'Afrique de l'Ouest présente ainsi sur un court axe nord-sud toute une gamme de climats depuis le régime le plus désertique jusqu'au régime équatorial humide.

L'Afrique est aussi un continent de paradoxes illustrés par deux exemples, seuls 5 % de sa ressource en eau totale annuelle (soit 140 milliards de m^3) sont utilisés et le Burkina Faso, pays souffrant pourtant de sécheresses répétées, dispose théoriquement par habitant d'autant d'eau que la France (3 500 m^3 /an).

Mais l'Afrique est principalement un continent de défis et d'incertitudes, car les chiffres précédents masquent des faits beaucoup plus dramatiques et tristement connus : difficulté de l'accès à l'eau, caractère souvent intermittent de l'écoulement, excès momentanés d'eau (crues) à caractère parfois destructeur, d'où en réalité un déséquilibre croissant entre une demande en hausse continue (démographie vigoureuse) et une ressource en eau renouvelable fluctuante et en baisse sur d'immenses régions (entre les normales pluviométriques 61-90 et 31-60 le déficit est parfois de 30 % au Sahel).

A l'aube d'un 3e millénaire où les «conflits d'eau à partager» prendront une part prépondérante, la connaissance actuelle des caractéristiques hydrologiques de ce continent est-elle suffisante pour améliorer une gestion appropriée des ressources en eau et relever ces défis majeurs?

L'exemple de l'Afrique de l'Ouest, à travers les études effectuées au cours de ces cinquante dernières années dans les pays francophones, permet de retracer les étapes marquantes de l'acquisition de cette «connaissance hydrologique» et d'apprécier les difficultés et les limites d'une telle entreprise.

1. La situation dans les années 45-50

Les besoins étaient alors immenses : constructions de ponts routiers et ferroviaires, énergie hydroélectrique, hydraulique agricole et fluviale, alimentation en eau et assainissement urbain, ... et l'information

existante rare, souvent peu accessible ou non exploitée et, de plus, très hétérogène.

1.1. Information pluviometrique

En 1945, il existait déjà plusieurs centaines de stations en activité sur l'ensemble de la zone grâce à la création en 1921/22 d'un service météorologique en Afrique occidentale, qui avait permis le lancement de véritables réseaux de base. Plusieurs dizaines d'entre elles fonctionnaient depuis le début du siècle, voire même avant au Sénégal. Toutefois, il n'existait pas pour l'utilisateur de fichiers cohérents et critiqués de ces données et leur consultation en était laborieuse.

1.2. Information hydrologique

La situation était beaucoup moins brillante : certes quarante stations existent alors sur les bassins des fleuves Sénégal et Niger (contre trois pour l'ensemble du Togo-Bénin), mais ce chiffre fait illusion, car installées pour les seuls besoins de la navigation fluviale, elles ne fournissent que de simples niveaux d'eau et sont de plus très rarement lues pendant la longue saison de basses eaux.

Autrement dit, à part leur comportement saisonnier global, on ne connaît rien à l'époque sur les véritables caractéristiques hydrologiques des grands fleuves tropicaux, c.-à.-d. leur régime, l'importance de l'écoulement, les débits en période de crue ou de basses eaux. Les conditions d'écoulement et l'importance des crues des cours d'eaux sahéliens étaient, quant à elles, totalement inconnues.

2. L'époque des pionniers : installation, acquisition et inventaire

2.1. Les reseaux hydrologiques

La constitution des données hydrologiques de base suit un schéma classique : établissement d'un réseau hydrométrique, acquisition de l'information brute, traitement des données puis constitution des fichiers et annuaires.

Mais ici installer un réseau et effectuer des mesures représentait un véritable défi car les structures en place à l'époque, comme la MAS (Mission d'Aménagement du fleuve Sénégal) ou la MEAN (Mission d'Aménagement du fleuve Niger), travaillaient dans une optique strictement de voies navigables.

Il fallait donc créer de véritables réseaux hydrologiques, c.-à.-d. installer des stations, faire des observations et étalonner les cours d'eau. Compte tenu de la grande diversité des zones géographiques à couvrir, cela impliquait la mise au point d'une méthodologie de mesures spéciale à chaque régime, trouver des techniques et des appareillages adaptés aux contraintes climatiques et d'environnement. Il fallait naturellement trouver des observateurs et les former et surtout constituer un corps d'hydrologues aguerris, capables de surmonter toutes les difficultés du terrain et sachant gérer des tournées de réseaux où parfois le simple fait d'accéder à une station était déjà un exploit.

Un homme doit être cité en tant que père de l'hydrologie tropicale africaine ; il s'agit du Dr Jean Rodier décédé en mai 1994 et qui entretenait d'étroites relations, tant scientifiques qu'amicales, avec le professeur Bultot. Un colloque tenu en mai 1995 à Paris a montré son rôle d'initiateur, de promoteur et de maître d'œuvre de l'hydrologie dans cette région du monde en tant que chef du service hydrologique de l'Orstom de 1949 à 1977.

Cet Institut de Recherche Scientifique pour le Développement en Coopération a joué un rôle essentiel dans le développement des réseaux hydrologiques sub-sahariens en ayant des modes d'intervention très variés suivant les pays, depuis la gestion directe sur budget propre jusqu'à un simple rôle de conseil de gestion et de conseil technique. En 1950 commence l'installation des réseaux, en collaboration avec EDF et les structures locales qui se mettent en place ; quinze cents stations seront ainsi implantées en zone intertropicale !

Bien entendu, à l'Indépendance, l'exploitation de ces réseaux sera prise en charge progressivement par des services nationaux, mais avec souvent le maintien d'une collaboration étroite et fructueuse.

2.2. Les bassins versants representatifs et experimentaux (BVRE)

En 1949 en Guinée, dès la saison des pluies, se pose l'évaluation de l'écoulement sur de petits bassins forestiers. L'année suivante, au Sahel cette fois, la destruction de franchissements routiers par de petits cours d'eau en crue renforce la conviction des premiers hydrologues que les réseaux qui s'installent ne pourront jamais répondre à tous les besoins de la connaissance hydrologique (alors uniquement opérationnelle). Ceci concerne particulièrement l'évaluation fine des relations pluies-débits sur des surfaces de quelques kilomètres carrés par exemple.

Les premiers bassins représentatifs seront installés en Afrique humide en 1951 et une campagne de dix bassins est montée en zone sahélienne en 1954 pour étudier le mécanisme de formation des crues. Dix ans plus tard, c'est l'apogée de l'exploitation des BVRE avec vingt-cinq bassins en activité à la fois, c.-à.-d. autant de bassins munis pendant 2 à 3 ans d'une forte densité d'appareils de mesure et d'une équipe, sur place au cours de la saison des pluies, intervenant dès le début des averses.

Deux cent cinquante ensembles de bassins en tout seront ainsi étudiés ; ils couvrent une gamme étendue de variation des facteurs conditionnels de l'écoulement et permettent une transposition géographique, en général satisfaisante, à des bassins non jaugés. De finalité appliquée au départ (pour fournir les normes hydrologiques nécessaires aux aménagistes), certains prendront une vocation de recherche, comme les bassins de Korhogo ou de Booro Borotou en Côte-d'Ivoire ou de la Mare d'Oursi au Burkina Faso.

3. Première valorisation

Les premiers annuaires, qui font leur apparition en 1949, étaient bien modestes, mais très vite ils vont s'étoffer chaque année de stations nouvelles ; les rapports de campagne sur petits bassins ou de mission itinérante de jaugeages et de contrôle (qui durent parfois trois mois) tissent également une précieuse trame d'information et les premiers fichiers de données de base se constituent rapidement, permettant la mise en chantier progressive des monographies hydrologiques des principaux fleuves et grands bassins (certaines seront remises à jour plusieurs fois, comme celle du bassin du lac Tchad, dont la première version date de 1959 et la dernière est sortie en 1996).

Au cours des années 60, les grands traits de l'hydrologie de cette région de l'Afrique étaient dessinés. On peut citer à ce sujet trois publications marquantes de l'époque :

— «Régimes hydrologiques de l'Afrique Noire à l'Ouest du Congo» (Rodier 1964) ;
— «Estimation des crues décennales pour les bassins de moins de 200 km² (Rodier & Auvray 1965) ;
— «Synthèse des observations réalisées de 51 à 69 sur BVRE» (Dubreuil *et al.* 1972).

On doit souligner le rôle important d'impulsion joué par le CIEH (Comité Interafricain d'Etudes Hydrauliques) fondé en 1960 à Ouagadougou (et disparu en 1994) dans le développement des études hydrologiques grâce à son rôle d'interface entre les institutions de recherche préoccupées par la connaissance et la compréhension du milieu physique et les Etats d'Afrique francophone désireux de se doter des équipements hydrauliques nécessaires.

4. Le tournant de la fin des années 60

La fin des années 60 allait être marquée par deux bouleversements majeurs : révolution informatique et catastrophe climatique durable (sécheresse) qui vont avoir des impacts considérables sur la façon d'appréhender l'hydrologie africaine.

4.1. L'impact de l'informatique

L'emploi progressif de l'informatique à partir de 1966-67 allait valoriser de nombreux domaines, comme l'accès à des données hydrologiques élaborées grâce à la mise sur fichiers des copieuses données numériques recueillies et l'écriture de programmes de traitement, la modélisation des relations pluies-débits enfin rendue praticable et une meilleure utilisation des indispensables lois statistiques.

4.1.1. Cas des banques de données

A la demande du CIEH, et avec l'appui de l'ASECNA (Association pour la Sécurité de la Navigation Aérienne) pour les données recueillies après 1965, l'Orstom allait constituer la banque de données pluviométriques journalières de tous les pays africains francophones (sauf la Guinée) de l'origine des stations jusqu'en 1980. Cette pluviométrie contrôlée et critiquée a été rassemblée à partir des documents originaux (en procédant dans chaque pays à un microfilmage systématique des archives, ce qui rejoignait l'opération de sauvetage des données météorologiques du programme DARE de l'OMM, financé par la Belgique).

En 1995, la Banque «Pluie» de l'Orstom contenait 57 000 années de précipitations journalières correspondant à 2 800 postes de mesure. La Banque «Hydro» contenait pour sa part 21 300 années de hauteurs d'eau provenant de 1 624 stations. Sous l'appellation «BADOIE», un ensemble de logiciels et de données a été remis en juin 1996 à Abidjan au projet Friend-AOC (cf. plus loin).

Les logiciels de traitement de ces deux banques, à savoir Hydrom et Pluviom, composantes de base du programme Shofm de l'OMM, sont diffusés gracieusement et largement utilisés dans une vingtaine de pays.

4.1.2. Cas de la modélisation

Pendant de nombreuses années, l'approche de la relation pluie-débit sur petit bassin-versant se faisait de façon globale, à l'aide de la théorie de l'hydrogramme unitaire, car la méthode des hydrogrammes synthétiques, introduisant un découpage du bassin en lignes isochrones de propagation de l'écoulement, était très difficile à exploiter à la main.

Les années 1966-67 marquent un tournant avec la mise au point des premiers modèles informatisés, mais il faudra encore attendre cinq ans pour voir la création décisive du modèle à discrétisation spatiale qui découpe les bassins en carreaux élémentaires sur chacun desquels les paramètres du cycle de l'eau sont calculés. Au début des années 70 se développent les modèles de simulation du fonctionnement des aménagements permettant, par exemple, d'optimiser les caractéristiques des barrages en construction (comme au Cameroun ou en Côte-d'Ivoire). Le début des années 80 coïncide avec l'avènement des modèles couplés associant les comportements des eaux de surface et des eaux souterraines ; c'est également l'essor des modèles de propagation de crues largement employés pour calculer l'évolution de la crue du fleuve Niger ou de la crue artificielle du fleuve Sénégal (à partir des lâchures de la retenue de Manantali).

Les années 90 voient enfin le développement de modèles simulant les impacts climatiques et/ou anthropiques sur le milieu naturel et la ressource en eau

4.2. L'IMPACT DE LA SECHERESSE

De nombreuses études, souvent réactualisées, ont fourni des données chiffrées sur la diminution durable des précipitations et donc des débits, en premier lieu sur la région sahélienne, puis, par la suite, également sur les régions tropicales humides et équatoriales.

On sait en effet que la sécheresse apparaît au Sahel vers 1968, atteint deux paroxysmes en 1972-73 et 1983-84 et n'a en fait jamais véritablement cessé depuis. Mais ces déficits gagnent également de façon durable l'Afrique humide au cours des années 80. Ainsi, pour cette décennie-là, les débits présentent globalement un déficit d'écoulement

de 27 % en zone sahélienne et de 16 % pour l'Afrique humide (bassin du fleuve Congo compris).

Cette situation catastrophique a provoqué l'émergence d'une active solidarité internationale et d'une collaboration des pays riverains des grands bassins fluviaux avec la mise en place de nouvelles structures comme celles du CILSS à Bamako (Comité inter-Etats de Lutte contre la Sécheresse au Sahel) en 1972-73 ou de l'AGRHYMET à Niamey en 1975 (Programme agro-hydro-météorologique). Ce programme privilégie la formation de spécialistes de terrain et la diffusion d'une information utile aux agriculteurs.

Mais l'Afrique a aussi joué un rôle précurseur dans les grandes interrogations sur la variabilité climatique et les effets anthropiques possibles. La communauté scientifique a ainsi pris conscience, devant la persistance du phénomène, et en concourant ainsi à la montée en puissance du concept de *Global Change*, de la non-stationnarité des ressources en eaux et de la fragilité de la notion de normale trentenaire, si chère aux climatologues, ou des normes hydrologiques en vigueur. A ce sujet, constatation a été faite que les grands aménagements africains réalisés dans les années 60, comme Akosombo sur la Volta (1965) ou Assouan sur le Nil (1966), ont été dimensionnés en s'appuyant à l'époque sur des normes hydrologiques surévaluées (?), la période humide 1950-65 conduisant à un optimisme trompeur. Une telle situation a montré la nécessité de mieux comprendre l'évolution du milieu et de son environnement sous les effets conjugués des actions climatiques et anthropiques, d'où l'obligation de renforcer la connaissance du «terrain» dans toutes ses composantes disciplinaires et avec des techniques d'acquisition améliorées.

Dans ce cadre d'idée, l'étroite collaboration sur le terrain des pédologues et des hydrologues qui s'instaure au milieu des années 70, afin de déterminer les états de surface des sols des BVRE et leur comportement hydrodynamique à l'aide du simulateur de pluie, a grandement amélioré la compréhension des conditions de ruissellement (ou d'infiltration) et l'ampleur des impacts subis par les bassins étudiés.

5. Evolution technologique du début des années 80

Les difficultés liées à la collecte des données, leur dépouillement et leur mise sur support informatique ont favorisé la mise au point de capteurs modernes avec enregistrement sur mémoire statique qui allaient préfigurer les plateformes d'acquisition en usage aujourd'hui

dans les projets internationaux. Toutefois, il faut reconnaître que les matériels anciens, robustes, peu coûteux et simples d'emploi, se rencontrent encore très fréquemment et fournissent toujours une information très précieuse.

Les satellites civils lançés à partir de 1977-78 allaient fournir une autre facilité, spectaculaire, dans la collecte et le contrôle des données. Une des premières utilisations du système Argos, testé par l'Orstom au Sénégal, concerne en effet la télétransmission des hauteurs d'eau par satellite. Les applications seront vite nombreuses et nous citerons deux exemples. Le premier lancé en 1980 est celui du Projet Hydroniger (coordination OMM/Agence de Bassin du Niger) doté de soixante-cinq stations couvrant huit pays pour rendre opérationnel un système de prévision hydrologique en temps réel relatif à l'ensemble du bassin du Niger. Le second est le Programme de Lutte contre l'Onchocercose (coopération Organisation Mondiale de la Santé/ Orstom) ; mis en place dès 1974, il permet, grâce à la connaissance en temps peu différé des débits, de combattre efficacement les larves de simulies par un dosage approprié d'insecticide dans les cours d'eau. Prévu au départ uniquement sur le bassin de la Volta, il s'étend aujourd'hui, vu son succès, sur plus d'un million de kilomètres carrés.

6. Années 90 et grands projets ou programmes internationaux

Le début de cette décennie voit le développement de grandes opérations qui concernent aussi bien l'hydrologie opérationnelle que l'hydrologie scientifique et qui correspondent à des préoccupations majeures :

1. L'acquisition des données demeure un problème crucial et malheureusement permanent ; il faut de longues séries pour apprécier l'évolution des ressources en eau, il faut des stations de référence stables pour établir les normes et les caractéristiques des régimes. Or les services nationaux (et ceci n'est pas l'apanage de l'Afrique) ont de plus en plus de mal à assurer une gestion satisfaisante des réseaux par manque de moyens matériels et de personnel. La situation en hydrologie comme en météorologie des services et réseaux nationaux a été expertisée par le «Programme d'évaluation des Ressources en eau en Afrique sub-Saharienne» financé par la Banque Mondiale pour le compte de l'OMM. Ce projet s'est déroulé de 1990 à 1992 et le rapport régional «Afrique de l'Ouest» qui en est issu souligne les difficultés rencontrées

par tous les services gestionnaires et l'insuffisance numérique des réseaux. Une réponse à ce dilemme est apportée par le programme WHYCOS de l'OMM («World Hydrological Cycle Observing System») qui vise à couvrir la planète d'un système de collecte et de dissémination d'informations hydrologiques portant sur les principaux fleuves. Parmi les programmes régionaux concernant ce continent, AOC-HYCOS, basé à Ouagadougou, se présente comme un observatoire hydrologique régional qui, depuis début 95, collecte les données acquises par d'autres institutions, les contrôle et les transfère dans une base de données accessible par un serveur Internet.

2. Une autre initiative majeure est la constitution, effective en 1994, du projet FRIEND-AOC («Flow Regimes from International Experimental and Network Data» — Afrique de l'Ouest et centrale). Le concept de base, sous l'égide de l'Unesco, est de promouvoir une recherche scientifique régionale s'appuyant sur la mise en commun des compétences hydrologiques nationales et, bien sûr, des données de base. Le premier projet a commencé pour l'Europe du Nord-Ouest il y a dix ans, et un projet en Afrique australe a vu le jour en 1992. FRIEND-AOC, basé à Abidjan, se veut un réseau de recherche en partenariat orienté vers les besoins du développement.

3. Au titre des grandes expériences internationales issues du Programme Mondial de Recherche sur le Climat (OMM) et du Programme International Géosphère-Biosphère, l'expérience Hapex-Sahel, qui s'est déroulée en 1992 sur une surface d'un degré carré près de Niamey (Niger) sur la thématique «Interactions surface continentale-atmosphère», a revêtu une signification particulière. C'était la première fois, en effet, qu'une opération scientifique internationale de cette envergure était entreprise en zone sahélienne. L'objectif principal de cette expérience était de mieux prendre en compte dans les modèles de circulation générale de l'atmosphère, comme dans les modèles d'hydrologie continentale, les caractéristiques hydriques et thermiques du sol et de la végétation.

7. Situation actuelle et perspectives

Par un long travail d'acquisition et d'interprétation des données, les grands traits de l'hydrologie de l'Afrique de l'Ouest et centrale ont été progressivement établis et la connaissance des caractéristiques propres à chaque zone climatique s'est affinée à travers une documentation considérable (monographies régionales réactualisées régulière-

ment, études sur BVRE conduisant à des études spécifiques de synthèse, banque de données élaborées, etc.).

Toutefois, un tel constat n'est pas aussi idyllique que cela pour des raisons évidentes :

— Il subsistera toujours des régions à l'hydrologie non ou mal connue ;
— Contraintes classiques et permanentes en hydrologie, telles que l'impossibilité à entretenir de façon satisfaisante des réseaux ou manque de personnel spécialisé, qui prennent ici un caractère d'autant plus aigu que le manque de moyens financiers est chronique ;
— Remise en question des normes hydrologiques usuelles du fait d'un déficit hydropluviométrique persistant et des impacts anthropiques sur l'environnement ;
— Isolement fréquent des scientifiques africains, trop souvent à l'écart des grandes manifestations internationales de leur discipline et ayant du mal à accéder aux indispensables données de base.

Face à une exigence de connaissance hydrologique sans cesse renouvelée et aux défis du troisième millénaire tout proche, plusieurs remarques, parfois en forme d'interrogations, se posent (formulation non exhaustive, ni classée par ordre d'importance) :

1. L'étude du milieu est indissociable du concept d'observatoire permanent ou de longue durée. Le projet WHYCOS, au travers de ces applications régionales africaines, semble apporter une réponse adaptée (observer moins mais mieux, aider les pays et diffuser l'information). Mais ceci ne dispensera pas les pays de garder leurs propres structures.

2. Comment mieux caractériser la ressource en eau et sa variabilité dans l'espace et dans le temps, comment mieux maitriser les risques hydrologiques (inondations ou pénuries)? La montée en puissance du projet AOC-FRIEND avec une mise en commun des données et du savoir est un élément de réponse, mais elle implique une collaboration étroite de tous les partenaires.

3. La connaissance du fonctionnement et des interactions sol-eau ou sol-eau-atmosphère est essentielle à la compréhension des mécanismes hydrologiques et donc à une modélisation. Une expérience du type Hapex-Sahel apporte des éléments de réponse pour les régions sèches mais elle a été très lourde et tous les résultats ne sont pas encore exploités. Une autre opération de ce genre, mais plus souple, est en préparation en zone humide (Bénin).

4. Quels sont les effets de l'anthropisation sur les systèmes hydrologiques et connaît-on bien les usages de l'eau et la façon de l'économiser? Le défi est crucial car il faut adapter une demande croissante à une ressource fixe ou en diminution. Afin d'apporter des réponses au moins partielles, de nombreux programmes pluridisciplinaires de recherche sont en cours sur la mise en valeur et la gestion des ressources en eau (citons des études portant sur des systèmes irrigués performants, les possibilités d'aménagement visant à parfaire les conditions d'exploitation agricole, l'exploitation des bas-fonds et celle des retenues collinaires, etc.).

Pour terminer ce rapide panorama des études entreprises au cours d'un demi-siècle dans cette région, une constatation essentielle et très encourageante peut être faite à partir de l'évolution constatée au cours de ces dernières années : la sortie de l'Afrique de l'Ouest de son isolement et de son cloisonnement. Au niveau des pays qui la composent, cela se concrétise par des collaborations et coopérations effectives rendues possibles par l'adhésion de chacun au projet FRIEND-AOC. Au niveau du continent, des liens prometteurs se tissent avec les autres projets régionaux : par exemple, des relations se nouent entre les différents projets FRIEND africains (avec ceux de l'Afrique australe et du Nil) ou prévus à brève échéance (par exemple l'Afrique de l'Est ou l'Afrique australe — HYCOS).

La récente création de l'AHA (Association des Hydrologues Africains), ayant son siège à Cotonou, est aussi très significative de cette volonté de regroupement des scientifiques.

L'Assemblée scientifique de l'AISH à Rabat en 1997 et la Conférence internationale sur la variabilité des ressources en eau au 20e siècle à Abidjan en 1998 seront des occasions privilégiées pour confirmer cette évolution.

BIBLIOGRAPHIE

AISH 1996. L'hydrologie tropicale : géoscience et outil pour le développement. — *In* : Chevallier, P. & Rodier, J. (éds), Mélanges à la mémoire de Jean Rodier, IAHS Publication n 238, 435 pp.

Casenave, A. & Valentin, Ch. 1990. Les états de surface de la zone sahélienne — Influence sur l'infiltration. — Orstom, Coll. Didactiques, 196 pl. coul., 229 pp.

Chevallier, P. *et al.* 1985. Pluies et crues au Sahel. Hydrologie de la Mare d'Oursi (Burkina Faso 1976-1981). — Orstom, Trav. et Doc., 251 pp.

DUBREUIL, P. *et al.* 1972. Recueil des données de base des bassins représentatifs et expérimentaux de l'Orstom (1951-1969). — Orstom, 916 pp.

IWRA, UNESCO 1989. The Sahel Forum on the state-of-the-art of hydrology and hydrogeology in the arid and semi-arid areas of Africa. — *In*: IWRA (ed.), Ouagadougou, nov. 88, 709 pp.

MOTT MACDONALD, BCEOM, SOGREAH, ORSTOM 1992. Evaluation hydrologique des pays de l'Afrique subsaharienne. Pays de l'Afrique de l'Ouest. Rapport régional. — Banque Mondiale, PNUD, BAD, Minecoop, 144 pp. + annexes.

OLIVRY, J-C. *et al.* 1996. Hydrologie du lac Tchad. — Orstom, Coll. Monographies Hydrologiques, n° 12, 266 pp.

OMM 1989. Statistics on regional networks of climatological stations, WMO Region. I- Africa. — WCDP-7, WMO-TD-n 305, 32 pp.

ORSTOM 1994. Sciences au Sud. Dictionnaire de 50 années de recherche pour le développement. — Orstom, 167 pp.

ORSTOM 1996. Interactions surface continentale/atmosphère. L'expérience Hapex-Sahel. — *In*: HOEPFFNER, M. *et al.* (éds), X^e Journées hydrologiques, sept. 94, Orstom, 758 pp.

OSS/UNESCO 1995. Les ressources en eau des pays de l'OSS : évaluation, utilisation et gestion. — 80 pp.

PEDRO, G. & DUBREUIL, P. 1987. Sols et eaux. — Orstom, Actes du séminaire tenu à la Banque Mondiale les 15 et 16 mai 1986, 183 pp.

ROCHE, M. 1983. L'apport de l'Orstom dans l'hydrologie de l'Afrique de l'Ouest. — *Cah. Orstom, sér. Hydrol.*, **20** (3-4) : 205-211.

RODIER, J. 1964. Régimes hydrologiques de l'Afrique noire à l'ouest du Congo. — Orstom, *Mém.*, n° 6, 137 pp.

RODIER, J. & AUVRAY, C. 1965. Estimation des débits de crues décennales pour les bassins de moins de 200 km² en Afrique occidentale — C.I.E.H./Orstom, 13 graph., 30 pp.

SIRCOULON, J. 1990. Impact possible des changements climatiques à venir sur les ressources en eau des régions arides et semi-arides. — WCAP-12,WMO/TD-n 380, 87 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 470-478 (1998)

Variability of African River Discharges and Lake Levels

by

Alfred GROVE *

KEYWORDS. — Lake Levels ; Radar Altimetry ; River Discharges ; Time Series ; Variability.

ABSTRACT. — The twentieth century has seen marked variations in African river discharges and lake levels which reflect regional variations in rainfall. The river and lake variations are of importance because of their economic consequences as well as their climatic significance. In recent years it has been difficult to collate the data. Now radar altimetry allows the levels of large lakes and very wide rivers to be measured, and time series to be updated rapidly.

MOTS-CLES. — Niveaux des lacs ; Altimétrie radar ; Débits ; Séries chronologiques ; Variabilité.

RESUME. — *Variabilité des débits et des niveaux des lacs africains.* — Le vingtième siècle a vu des variations prononcées dans les débits des rivières et des niveaux des lacs africains qui reflètent des variations régionales des précipitations. Les variations sont importantes vu leurs conséquences économiques ainsi que leur signification climatique. Ces dernières années, il a été difficile de rassembler les données. Aujourd'hui, des mesures altimétriques au radar permettent de mesurer les niveaux des grands lacs et des rivières très larges et de mettre à jour rapidement les séries chronologiques.

TREFWOORDEN. — Meerniveaus ; Radar altimetrie ; Rivierafvoeren ; Tijdreeks ; Variabiliteit.

SAMENVATTING. — *Variabiliteit van de Afrikaanse rivierafvoeren en de niveaus van de Afrikaanse meren.* — De twintigste eeuw heeft uitgesproken

* Department of Geography, University of Cambridge, UK CB2 3EN (United Kingdom).

variaties gezien in de afvoeren van de Afrikaanse rivieren en in de niveaus van de Afrikaanse meren die regionale variaties in de neerslag weerspiegelen. De variaties zijn belangrijk gezien hun economische gevolgen alsook hun klimaatbetekenis. In recente tijden was het moeilijk de gegevens te verzamelen. Heden ten dage laat de radaraltimetrie toe de niveaus van de grote meren en de zeer brede rivieren te meten en de tijdreeksen snel te actualiseren.

The Twentieth Century Record

At the beginning of the century a latitudinal zone equatorwards of the northern tropic was affected by strong negative departures of rainfall and run-off. KRAUS (1955) pointed to a widespread reduction around 1900 in the rainfall of intertropical semi-arid areas. HURST *et al.* (1965) noted that the mean discharge of the Nile at Aswan diminished from more than 100 km³ annually in the last decades of the 19th century to about 84 km³ in the first half of this 20th century. In the Sudan zone, the years around the beginning of the First World War were especially dry with the discharges of the Nile and Niger in 1913-1914 falling to levels lower than any they were to reach over the next 70 years (GROVE 1973).

In Central Africa, in the first half of the century, the annual discharge of the Congo/Zaire at Kinshasa fluctuated within 15 % of its mean value of 1,250 km³. The level of Lake Victoria oscillated between a metre above and a metre below its mean level with sufficient regularity for some observers to claim the influence of the sunspot "cycle". In East Africa, the most spectacular feature was the rise in the level of Lake Nyasa/Malawi and its overflow in the 1930s via Lake Malombe and the Shire River to the Zambezi. The flow of the Zambezi at the Victoria Falls, far upstream of the Shire confluence, varied from year to year by as much as 50 % above and below its mean value of 30 km³ a year.

The 1940s were dry in the Sudan-Sahel. Then, in the 1950s, both the northern and southern intertropical zones became wetter. The annual discharge of the Niger at Koulikoro increased by 50 % from 30 km³ annually in the mid-forties to 45 km³ in the 1950s and 1960s. The level of Lake Chad rose about 3 m, and its area increased to some 25,000 km². Between 1948 and 1980 the discharge of the Zambezi at the Victoria Falls was 45 km³ as compared with a mean of less than 30 km³ over the preceding forty years.

The post-war period was the great era of dam building in Africa, and the high discharges were not always welcomed. Not only had the dams been designed for lower discharges than those being experienced but construction work, for instance on Kariba in 1958 and Akosombo in 1963, was interrupted by floods higher than had ever been recorded.

The most remarkable hydrological phenomenon in the equatorial zone this century was the very high precipitation in the latter half of 1961 and the higher lake levels and river flows over the next decade or two. Lake Victoria rose by 2.5 m between the end of 1961 and the end of 1963. The lake's discharge to the White Nile, previously about 20 km^3 annually, more than doubled and remained about 40 km^3 for the next twenty years (SENE & PLINSTON 1994). Lake Tanganyika rose by 3 m between late 1961 and 1963. The discharge of the Congo/ Zaire, which earlier in the century had varied between 1,050 and 1,400 km^3 annually, increased to over 1,700 km^3 in 1962 and remained above the mean for the next ten years (BULTOT & DUPRIEZ 1987, p. 38). The other equatorial rivers of western Africa responded in a similar fashion. The onset of this wet episode appears to have been part of an event which extended from the west coast of Africa to Central India, through 70 of longitude and 20 of latitude. It affected not only Equatorial Africa but also much of the Indian sub-continent which experienced its highest monsoon rainfall this century (GROVE 1996).

In the course of the 1960s Lake Chad rose to its highest level this century and the discharges of the Nile and Niger were greater than they had been for about fifty years. A drying trend began in the Sudan zone in the late 1960s which was to continue to the present, with lower flows in the 1980s and especially in 1984 than at any other time this century. The northern lobe of Lake Chad dried up entirely and the southern pool, reduced to an area of little more than 2,000 km^2, retreated altogether from Nigeria.

Economic Effects of the Variability

In this century the effects of low floods were felt by trading companies with river steamers such as those employed on the Benue tributary of the Niger. If the floodwaters receded early in the season, shipping was stranded far up the river, towards Garoua, for the next nine months. The rise in level of the Great Lakes in the early 1960s flooded harbour works at a time when water transport was meeting increasing competition ; some shipping services have never been

resumed. Fisheries installations were flooded alongside Lake Chad and Lake Malawi. In the 1960s and 1970s the spillway on the Owens Fall Dam had to cope with larger flows of water than those for which it had been designed. In the late 1970s, holiday homes and fisheries installations near Lake Malawi were inundated. The area available to antelope and other game animals on the floor of the Rukwa rift was greatly reduced by the expansion of the lake. Levels of Lake Nasser, behind the High Dam at Aswan, became uncomfortably high in the late 1970s and then proceeded to fall to disturbingly low levels in the 1980s.

Drought in the western Sudan zone in the 1970s and 1980s so reduced the discharge of the Senegal and Gambia rivers that salt water penetrated far up-river. In April 1984, the Niger ceased to flow at Niamey which depended on the river for its water supplies. Low rainfall resulted in the discharge of the Volta river falling to unprecedentedly low levels with the result that power generation at Akosombo ceased and the plant converting alumina to aluminium at Tema had to close down for several months. The shrinking of Lake Chad removed the Nigerian lake edge so far east that it was impossible for pumps to extract water for the South Chad irrigation project in Borno. Farmers shifted eastwards to cultivate the lake floor as the water receded (KOLAWOLE 1987).

Causes of the Variability

There is evidently a connection between fluctuations in the Southern Oscillation Index (SOI), the El Niño, and rainfall in Africa (as well as in Australia and India). Low values of the Index were accompanied by reduced precipitation and river discharges in the Sudan zone in 1913-14, 1940-41, 1972-73, 1984-85 and 1992-95. High rainfall values are less readily explained in terms of the SOI, though both were high in 1916-17 and 1961.

More important than short-term fluctuations lasting a year or two are those variations that last for a matter of decades like those prominent in the lake and river flow time series records shown here and those that have been recognized from earlier centuries by OWEN *et al.* (1990) and NICHOLSON (1996).

In order to set twentieth century fluctuations in perspective more information is needed about lake level variations over the last few thousand years, especially about those lasting several decades. The



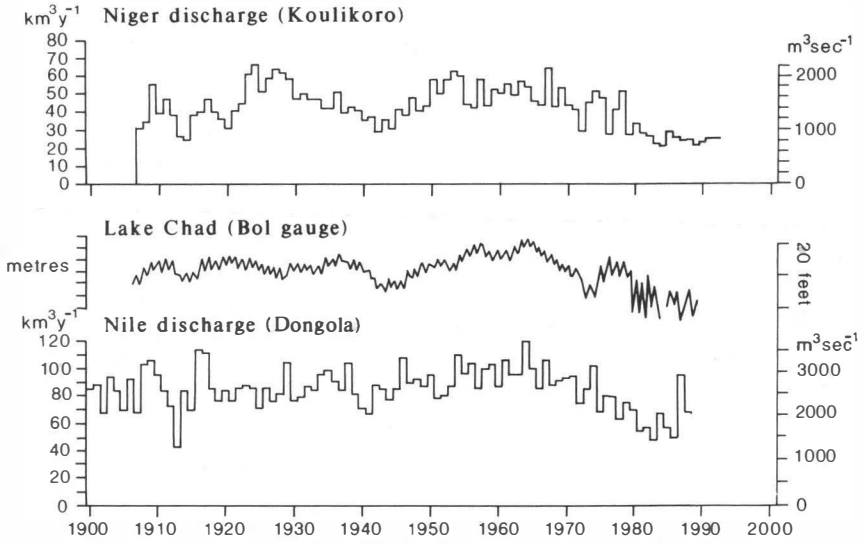
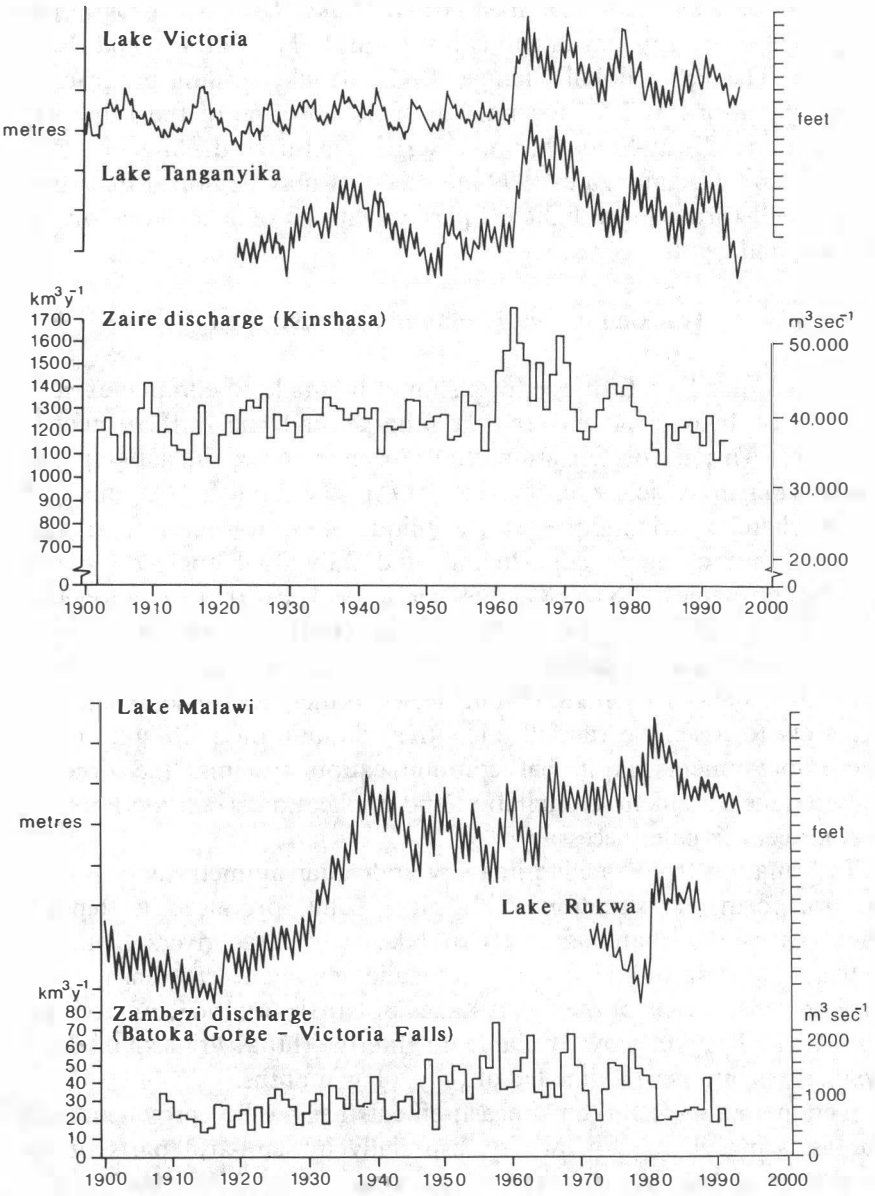


Fig. 1. — African river discharges and lake levels.

Sources : Niger at Koulikourou, Lake Chad at Bol and Zaire after 1982 at Brazzaville — ORSTOM ; Nile at Dongola — T. E. Evans in HOWELL & ALLAN 1996 ; Lake



Victoria 1960-89 at Entebbe Pier — Uganda Water Development Department ; Lake Tanganyika at Kigoma and Bujumbura, Lake Malawi-Department of Fisheries, Monkey Bay, Zaire before 1983 — BULTOT & DUPRIEZ 1987 ; Zambezi at Batoka Gorge, Victoria Falls — Zambezi River Authority.

International Decade for the East African Lakes (IDEAL) programme has been recovering sediment cores from Lake Victoria and Lake Malawi. The Past Global Change (PAGES) lake drilling programme plans operations in 1997 for Lake Edward and one of the Ethiopian lakes in the Ziway-Shala basin. PAGES envisages drilling in Lakes Malawi and Tanganyika in 1999 and 2000. It may be hoped that these efforts will throw more light on past variations of lake levels on the decadal and century time-scales.

Tracking the Variability : Radar Altimetry

In the immediate future, efforts should be made to compile existing records of lake level and river discharge and make them readily available. Various organizations have been involved in gauging and monitoring in Africa, notably ORSTOM (the French "Organisation de Recherche Scientifique et Technique d'Outre-Mer"), and also national hydrographic departments and individual engineering and mining companies. UNESCO (1969, 1971, 1974, 1979) brought together some of the figures in the 1970s but the effort was not maintained.

I have experienced considerable difficulty in collating the time series presented here. Comparable but lesser difficulties arise when one attempts to assemble rainfall and other climatic data. In spite of all the improvements in global communication systems, the time-lag between measurement, compilation and publication is considerable and would seem to be unnecessary.

Information from satellite imagery and radar altimetry is beginning to transform the situation, with plots being produced at ten-day intervals of the changing levels of lakes and large rivers (Birkett 1995a). The results, which have been validated against readings on the ground of the levels of the Great Lakes of North America, are accurate to 3-4 cm. They are now available on Internet (http : //msslsp.mssl.ucl.ac.uk/orgs/un) with a time lag of only a few months.

The main aim of Birkett's measurements has been to provide a basis for assessing changes in aridity, especially in semi-arid parts of the world by monitoring the heights and areas of lakes in closed basins (Birkett 1995a, Harris 1994, Mason *et al.* 1992, Mason *et al.* 1994). It has also been shown that it is possible to monitor the changing heights of rivers such as the Congo/Zaire at Pool Malebu (formerly known as Stanley Pool) and the changing heights and areas of swamps such as the Okavango and the Sudd (Birkett 1995b, fig. 3).

At present, the size of the radar "footprint" restricts height measurements to water surfaces with areas equal to or greater than 100 km^2 (BIRKETT 1994), so that measurement of river stage by altimetry is possible only where the water surface is unusually broad. On the other hand, measurement of water surface width on SPOT or Landsat imagery might conceivably provide a means of deriving river height above datum at a gauging site and thereby estimating river discharge.

The immediate need is to obtain simultaneous ground and radar measurements of water surfaces, so that the values calculated from satellite radar can be calibrated against the same zeros as the ground observations. So far this seems to have been done in Africa only for Lake Victoria, Lake Tanganyika and for the Congo/Zaire at Brazzaville on Pool Malebo. With quite a modest expenditure of time, effort and money, it would seem that the data relating to the levels of large lakes and reservoirs could be made available to everyone who wants them, without charge and without restriction, and with a time-lag, currently, of about three months.

ACKNOWLEDGEMENTS

My thanks to Dr Charon Birkett, Dr Fred Bugenyi, Terry Evans, Orton Kachinjika, Graeme Patterson, Dr P.-D. Plisnier, Dr Jacques Sircoulon and Dr Jayne Stack for assistance in contributing data, and to my colleague Michael Young for drawing the updated time series diagram.

REFERENCES

BIRKETT, C. M. 1994. Radar altimetry : a new concept in monitoring lake level changes. — *Eos, Trans. Geophysi. Union*, **75** : 273-275.

BIRKETT, C. M. 1995a. The global remote sensing of lakes, wetlands and rivers for hydrological and climate research. — *In* : Proceedings of the IGARSS conference on Quantitative Remote Sensing for Science and Applications (Firenze, Italy, July 1995), pp. 1979-1981.

BIRKETT, C. M. 1995b. The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. — *J. Geophys. Res.*, **100** (C12) : 25, 179-25, 204.

BULTOT, F. & DUPRIEZ, G. L. 1987. Niveaux et débits du fleuve Zaïre à Kinshasa. — *Bull. Séanc. Acad. R. Sci. Outre-Mer*, **VI** (2) : 49 pp..

EVANS, T. E. 1994. History of Nile Flows. — *In* : HOWELL, P. P. & ALLAN, J. A. (eds.), The Nile : sharing a scarce resource. Cambridge University Press, pp. 26-63.

GROVE, A. T. 1973. A note on the remarkably low rainfall of the Sudan zone in 1913. — *Savanna* (Zaria, Nigeria), **2** : 133-145.

GROVE, A. T. 1996. African River Discharges and Lake Levels in the Twentieth century. — *In* : JOHNSON, T. C. & ODADA, E. O. (eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes. Gordon and Breach, Newark, New Jersey, pp. 95-100.

HARRIS, A. R. 1994. Time series remote sensing of a climatically sensitive lake. — *Remote Sens. Environ.*, **50** : 83-94

HURST, H. E., BLACK, R. P. & SIMAIKA, Y. M. 1965. Long Term Storage. — London, Constable, 145 pp.

KOLAWOLE, A. 1987. Environmental change and the South Chad Irrigation Project (Nigeria). — *Jour. Arid Environments*, **13** : 169-176.

KRAUS, E. B. 1955. Secular changes in tropical rainfall regimes. — *Q. Jour. R. Met. Soc.*, **81** :198-210.

MASON, I. M., GUZKOWSKA, M. A. J., RAPLEY, C. G. & STREET-PERROTT, F. A. 1994. The response of lake levels and areas to climatic change. — *Climatic Change,* **27** : 161-197.

MASON, I. M., HARRIS, A. R., MOODY, J. N., BIRKETT, C. M., CUDLIP, W. & VLACHOGIANNIS, D. 1992. Monitoring wetland hydrology by remote sensing : a case study of the Sudd using infra-red imagery and radar altimetry — *In* : Proceedings of the Central Symposium of the International Space Year (Munich), European Space Agency SP-341, pp. 79-84.

NICHOLSON, S. E. 1996. Environmental change within the historical period. — *In* : ADAMS, W. M., GOUDIE, A. S. & ORME, A. R. E. (eds.), The Physical Geography of Africa. Oxford University Press, pp. 60-87.

OWEN, R. B., CROSSLEY, R., JOHNSON, T. C., TWEDDLE, D., KORNFIELD, R., DAVISON, S., ECCLES, D. H. & ENGSTROM, D. E. 1990. Major low levels of Lake Malawi and their implications for speciation rates in cichlid fishes. — *Proc. Roy. Soc. London* B, **240** : 519-553.

SENE, K. J. & PLINSTON, D. T. 1994. A review and update of the hydrology of Lake Victoria in East Africa. — *Hydrol. Sci. Jour.*, **39** : 47-63.

UNESCO 1969, 1971, 1974, 1979. Discharge of selected rivers of the World, Vols I, II, III, Paris.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 479-491 (1998)

Influence of Small Dams on the Water Table Level in Northern Togo

by

Hendrik VERMEULEN *, Patrick VAN DAMME *,
François DE TROCH * & Peter TROCH *

KEYWORDS. — Dynamic Simulation ; Penman ; Microclimatic Changes ; Small Dam Constructions ; Togo ; Water Table.

ABSTRACT. — Small dams (hand-constructed, max. 5 m high) are a popular means of providing water for livestock and human consumption in northern Togo. Through groundwater modelling, the influence of these dams on groundwater table was assessed. Modelling was based on hydrologic data gathered over the February 1994 - March 1995 period. The model showed that the influence of small dams is very limited both in time and related to surface. The rise in groundwater level does not seem to be sufficient to cause a change in vegetation but can be useful for agricultural and horticultural purposes during the dry season.

MOTS-CLES. — Simulation dynamique ; Penman ; Changements microclimatiques ; Construction de petits barrages ; Togo ; Niveau piézométrique.

RESUME. — *L'influence de petits réservoirs sur le niveau piézométrique de la nappe libre.* — Des petits réservoirs (construits à la main et avec une hauteur maximale de 5 m) sont des moyens populaires de fournir de l'eau pour le bétail et pour la consommation humaine dans le nord du Togo. L'influence de ces réservoirs sur le niveau piézométrique de la nappe libre fut examinée en modélisant les mouvements de l'eau souterraine. La modélisation fut réalisée en utilisant les données hydrologiques de la période de février 1994 à mars 1995. Le modèle montre que l'influence des petits réservoirs est très limitée tant dans le domaine temporel qu'au niveau de la surface. La montée du niveau de l'eau souterraine ne paraît pas être suffisante pour provoquer un changement dans la végétation mais peut être utilisée pour faire de l'agriculture et de l'horticulture pendant la saison sèche.

* Faculty of Agricultural and Applied Biological Sciences, Coupure Links 653, B-9000 Gent (Belgium).

TREFWOORDEN. — Dynamische simulatie ; Penman ; Microklimatische veranderingen ; Constructie van kleine waterreservoirs ; Togo ; Watertafel.

SAMENVATTING. — *De invloed van kleine dammen op het niveau van de watertafel in Noord-Togo.* — Kleine waterreservoirs (opgericht met handenarbeid, max. 5 m hoog) zijn een populaire manier voor de watervoorziening van het vee en voor menselijke consumptie in Noord-Togo. Door grondwatermodellering werd de invloed van deze reservoirs op de grondwatertafel gevolgd. De modellering was gebaseerd op de hydrologische gegevens verzameld gedurende de periode februari 1994 - maart 1995. Het model toonde aan dat de invloed van deze kleine reservoirs zeer beperkt is zowel in tijd als met betrekking tot het oppervlak. De stijging van het grondwaterniveau lijkt niet toereikend te zijn om een verandering in de vegetatie te veroorzaken maar kan bruikbaar zijn voor landbouwkundige en tuinbouwdoeleinden gedurende het droge seizoen.

1. Introduction

In general, precipitation is sufficient in Togo. Even in the Savanna region, which is very close to the Sahel, precipitation reaches about 1,000 mm per year. The problem is the non-uniform distribution of rainfall over the year and even during one rainy season. During the dry season (about six months), people have to exploit the water reserves in the soil and in the lakes. Moreover, water problems are worse sometimes due to the strong interannual variation.

Traditionally, the farmers never invested in hydroagricultural constructions : until the sixties, no irrigation system existed and even natural lowlands were hardly exploited.

At the end of the fifties, the construction of small dams in the Savanna region took a start. The aim was to capture and store run-off water. In this way, walking distance for herds in order to find water is limited. At the same time, peasants can take water directly from the dam or infiltration water from wells near the dam to maintain a garden during the dry season.

2. Problem

One of the motivations which is frequently used in order to promote the construction of small dams is their positive effect on the water table and thus on the availability of water for plants.

This impact on the water table, however, is not evident and not very clear. In the lowlands where these constructions have been built, the water table is close to the surface level. Detailed hydrologic studies of the region are not available and it is therefore impossible to confirm whether this high piezometric level is caused by the presence of the dam or by other groundwater flow phenomena.

It would therefore be useful to determine in which way these dams influence the level of the water table. The study which is presented in this paper aims to determine the impact of a small dam on the level of the water table in a region in northern Togo. At the same time, the parameters which cause a significant change in this impact will be determined. This has been done through groundwater modelling of a small catchment, draining to such a small dam.

3. The Groundwater Model

For the establishment of the groundwater model, we have chosen to use MODFLOW. MODFLOW is a modular three-dimensional finite-difference groundwater flow model (McDonald & Harbaugh 1988). The model consists of a main programme which arranges the execution of different subroutines or packages :

— The Block Centered Flow package calculates groundwater flow between adjoining cells using the Darcy formula and a water balance.
— The Recharge package treats groundwater recharge coming from rainfall.
— The Evapotranspiration package calculates the real evapotranspiration from the groundwater body.
— The River package calculates the leakage from a river or a surface water body into the aquifer. Input data are the water level in the river and a riverbed conductance which represents the combined effect of hydraulic conductivity (K), thickness (M), length (L) and width (W) of the riverbed : $c = K \,.\, L \,.\, W \,/\, M \; (m^2/s)$.
— The Drain package calculates the effect of drains introduced in the aquifer system. The package calculates the amount of water which flows from the aquifer into the drain. In our application, the package is used in order to model the influence of small creeks which do not contain water during the dry season and thus have only a draining effect.

4. Determination of Hydrologic Parameters

The Savanna region in northern Togo has a precipitation of about 1,000 mm/year falling mainly in July, August and September. From October till April, rainfall is scarce or absent while during the same period potential evapotranspiration reaches up to about 6.5 mm/day.

Geologically, the northern part of the Savanna region consists of a granite rock with an erosion and sedimentation mantle of about 25 m (varying between 0 and 60 m) (BERNARD *et al.* 1985). It is in this northern part of the region that most of the dams are concentrated. The groundwater flow observed in the erosion and sedimentation mantle is the subject of this study.

The Tidonti dam, situated somewhat central in this part of the Savanna region, has been chosen for the study. The dam was constructed in 1989 by the French volunteer organization "Association française des Volontaires du Progrès" and financed by the Flemish Non-Governemental Organization "Vredeseilanden". The surface of the drainage basin is about 70 ha, the dam has a capacity of about 50,000 m^3 and the lake occupies about 4 ha. Monitoring of the hydrologic parameters took place between 1 June 1994 and 2 May 1995.

4.1. TOPOGRAPHY AND MODEL LIMITS (fig. 1)

The conceptual model is limited on the west side and on the north side by a creek which flows from south-west to north-east. Another creek forms the limit on the east side whereas the southern limit is formed by a hilltop. In figure 1, the main creek running from south to north and draining to the dam is presented together with a smaller creek running from the south-east to the north-west. Downstream from the dam an overflow has been constructed which raises the water level in this downstream part considerably. Apart from this creek, the other creeks only contain water during and immediately after a heavy shower. During the dry season, these creeks run dry. Their impact has been simulated with the Drainpackage by introducing the creek-bed level and a high conductance value.

Downstream from the dam, ten wells, represented in figure 1 by an asterisk, have been constructed by "Vredeseilanden". The other wells (pu) and installed piezometers (pi) in the model area are also presented by an asterisk and a number.

During piezometer installation, the depth of the impermeable granite layer has been determined. This depth varied between 5 and 15 m under field level around the dam.

The x and y coordinates in figure 1 are UTM coordinates and are represented in metres. The presented levels are levels with regard to mean sea level.

4.2. Recharge

The recharge mentioned here is equal to rainfall minus surface run-off. Evapotranspiration has not yet been taken into account but will be calculated in the Evapotranspiration package. Rainfall has been measured using a pluviometer installed downstream from the dam. This place has been chosen because it is protected against animals.

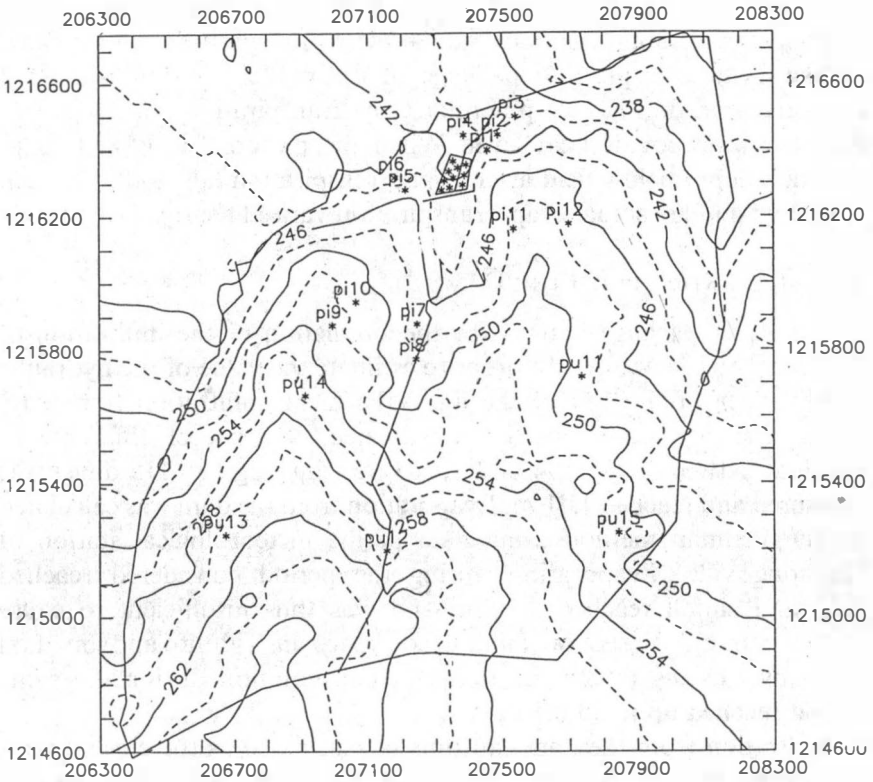


Fig. 1. — The catchment area of the Tidonti dam.

In order to have an idea on the amount of surface run-off during the rainy season of 1994, a limnigraph has been installed downstream of the dam, some metres upstream from the overflow. At the same time the water level in the dam has been measured weekly. It was thus possible to calculate a water balance (rainfall — surface run-off) of the catchment on a weekly basis. For the entire rainy season, a run-off coefficient of 0.29 has been calculated. Other studies (MONIOD *et al.* 1977, PNUD 1982, LAMAGAT 1970) on larger basins over larger periods gave much lower run-off coefficients (10-15 %), which is consistent with scaling effects in drainage basins. The difference between rainfall and run-off has been introduced in the Recharge package of the model.

4.3. EVAPOTRANSPIRATION

Daily meteorological data of the meteorological station of Dapaong ville were used to calculate an estimation of potential evapotranspiration through the Penman method. Actual evapotranspiration is calculated by the Evapotranspiration package of the model by supposing that evapotranspiration equals potential evapotranspiration when the piezometric level equals field level. When the piezometric level falls to a certain depth below field level, evapotranspiration falls to 0. Between these two depths, actual evapotranspiration varies linearly.

4.4. INFILTRATION FROM THE DAM

The River package is used for the simulation of the infiltration of the dam into the aquifer. In order to estimate the value of the hydraulic conductance of the bed of the dam, the mean infiltration (mm/day) during the dry season has been estimated. Water-level difference in the dam between 15/11/94 and 10/03/95 (time-lag t = 115 days) was measured and reached 1.41 m. Evaporation from the dam was calculated by the Penman method using data of the meteorological station of Dapaong ville. Evaporation during the period considered reached 1.03 m. Rainfall reached 0.2 mm and was thus insufficient to cause surface run-off. Based on animal countings in Tidonti and on data given by SERRES (1980), mean water consumption during the same period reached up to 39 m^3/day.

Infiltration from the dam can thus be calculated as the closure term of a water balance : $I = H + (P\text{-}E) - A_t/A_l$, with A_l = mean surface of the lake between 15/11/94 and 10/03/95 (25,900 m^2).

The estimated infiltration rate reached up to 2 mm/day. Based on this result and piezometric measures around the dam, a lake-bed conductance has been calculated. For a cell with a surface of 100 m^2, this conductance has been determined as 1×10^{-6} m^2/s.

The creek downstream from the dam, which contains water throughout the year, has been given a conductance value of 4×10^{-4} m^2/s for a surface of 100 m^2 based on calibration results.

4.5. Drainable Porosity

Near piezometers 8 and 12 and wells 11 and 14 (fig. 1), soil samples have been taken in order to perform granulometric analysis. This analysis pointed out that soil texture was predominantly of the sandy clay loam type (silt <30 %, sand >45 %, 20 % $<$ clay $<$ 35 %), a typical erosion product of granite (the underlying rock) in a tropical climate. For this soil type, Smedema & Rycroft (1983) gave a drainable porosity S_s of 4-8 %. In the model, 4 % has been applied.

4.6. Hydraulic Conductivity

For the determination of hydraulic conductivity, the principle of slug tests has been applied. During a slug test, a certain quantity of water is added to or removed instantly from a piezometer or a well. Afterwards, the evolution of the piezometric level in the piezometer or the well is monitored.

Depending on piezometer geometry, two different formulae are used for the treatment of the results of these tests : the formula of Ernst (1950) and the formula of Bouwer & Rice (1976). During calibration, it was noticed that conductivity values calculated in this way were too high. Moreover, only conductivity data for piezometers near the dam could be treated and no data were available for places further away from the dam. Therefore, a local modelling effort has been performed. The model searches, in an iterative way, the best fit between calculated and observed time series. The results of the data, treated with this local model, for $S_s = 4$ % are presented in table 1, together with the results of the same data treated with the Ernst and the Bouwer & Rice formulae resp.

Figure 2 presents the results of the slug test data treated by the model for well number 4 and figure 3 those for well number 8. In the case of well number 4, the standard deviation is quite high. Observation of the limnigrams of these wells showed that this is

probably due to the occurrence of local effects caused by the dam which is very close to the well. It is believed that hydrostatic pression of the dam caused the creation of preferential pathways through which water streams to wells number 4 and 7. The model does not take into account these local effects. Nevertheless, we notice that conductivity is in the same order of magnitude as in the case of the other wells where standard deviation is smaller. In the case of well number 8 (fig. 3), standard deviation is very small.

Figures 2 and 3 also show clearly that the variation of drainable porosity S_s between 3 and 9 % only causes a minor change in calculated hydraulic conductivity. We can thus accept the results of the model presented in table 1. Since the results of the calculations with the Ernst formula are significantly different from the results of the calculations with the model, we can conclude that the Ernst formula cannot be applied to the tests with the piezometers used here.

Calibration of the model also showed that the values of hydraulic conductivity as calculated by the model for piezometers 2, 3, 4 and

Table 1

K values calculated with the local model
and with the Ernst and Bouwer & Rice formulae

	K (Ernst) m/s	K (Bouwer & Rice) m/s	K (model) m/s	Standard deviation m	Number of measuring points
po 1			2.6 × 10-4	0.16	12
pu 3		02.4 × 10-3	0.04	9	
pu 4			3.9 × 10-4	0.32	12
pu 6			2.3 × 10-4	0.11	13
pu 8			1.3 × 10-4	0.03	11
pu 10			3.1 × 10-5	0.06	11
pu 12			2.7 × 10-5	0.07	13
pu 13			7.9 × 10-5	0.13	11
pi 2		1.0 × 10-7	5.7 × 10-7	0.13	10
pi 3		3.0 × 10-8	5.9 × 10-8	0.02	8
pi 4		1.0 × 10-7	3.9 × 10-7	0.06	10
pi 5		1.4 × 10-8	2.6 × 10-8	0.02	10
pi 7	2.0 × 10-8		1.4 × 10-5	0.001	3
pi 8	1.3 × 10-8		2.1 × 10-5	0.0004	3
pi 9	1.7 × 10-8		5.6 × 10-6	0.008	3
pi 10	1.0 × 10-8		6.2 × 10-6	0.006	3
pi 11	9.3 × 10-9		1.2 × 10-6	0.006	5
pi 12	1.9 × 10-8		4.5 × 10-6	0.008	8

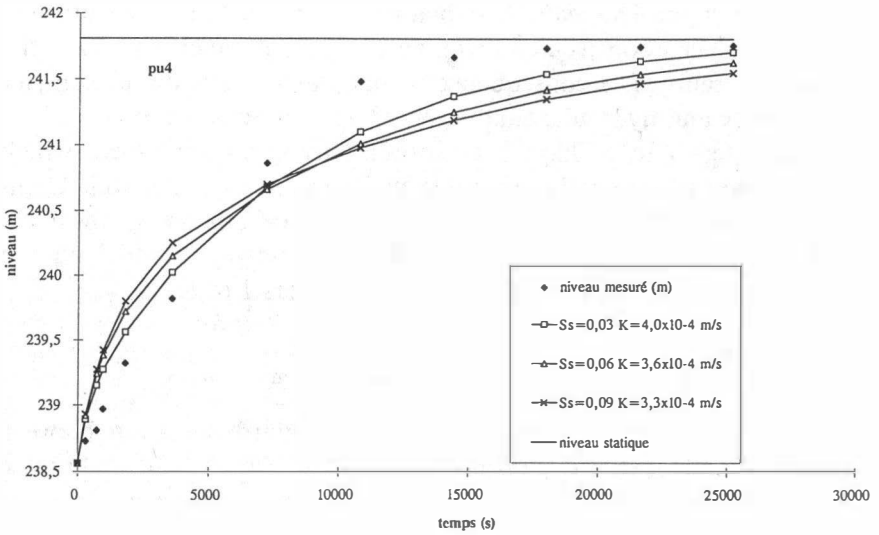


Fig. 2. — Results of the slug tests for well number 4 using a model with two dimensions.

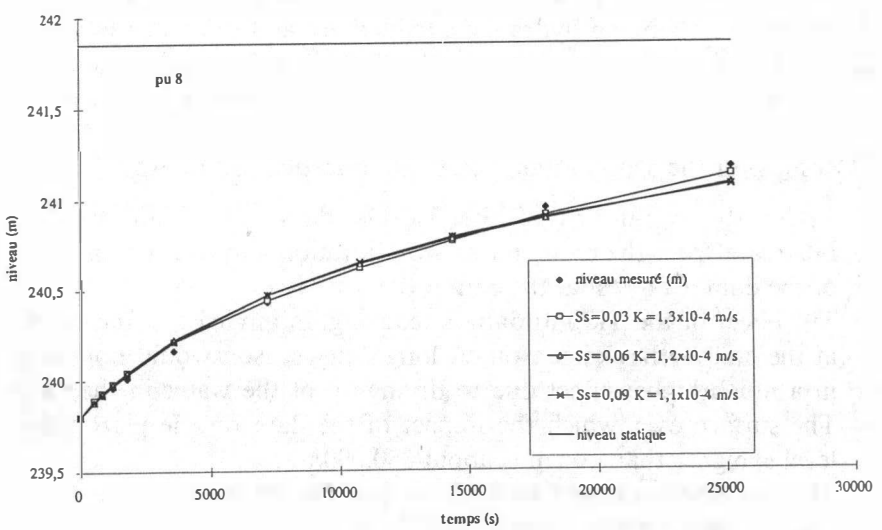


Fig. 3. — Results of the slug tests for well number 8 using a model with two dimensions.

5 were too high. This can be explained by the fact that piezometers 1 to 6 have been constructed using an instrument which compacts the soil considerably. The consequence is that water enters the piezometer more slowly and hydraulic conductivity therefore seems lower.

Piezometers 7 to 12 have been installed using an instrument which removes the soil from the borehole while penetrating the soil. Comparison of K-values for piezometers 7 to 12 calculated by the local model and those used in the calibrated groundwater model gave a much better result than in the case of piezometers 1 to 6.

4.7. Results of the Model and Sensitivity Analysis

Model calibration resulted in a mean standard deviation between calculated and observed piezometric levels of 0.29 m. This calibrated model has been executed with and without the presence of the dam. Piezometric levels obtained without dam have been subtracted from those obtained with dam. The spatial distribution of the difference in water table level is presented in figure 4.

In the following discussion, we use as an indicator for the impact of the dam the surface over which the influence of the dam on the piezometric level reaches 0.1 m or more.

Figure 5 presents the evolution of the influence of the dam and the impact of changing hydraulic conductivity and drainable porosity. Conductance of the dam and depth of the granite layer seemed to have a minor effect on the result so that their influence is not presented in figure 5.

Results for the Tidonti dam can be summarized as follows :

— Under the conditions of the Tidonti dam, where an overflow offstream from the dam causes an infiltration surplus, the influence of the dam is biggest at the end of the dry season.
— The effect of the Tidonti dam is reaching, in any case, a maximum at the end of the dry season. A longer dry season would not result in a much higher effect due to drying-up of the water in the dam.
— The surface over which the impact of the dam on the piezometric level is higher than 10 cm is about 380,000 m^a.
— The sensitivity analysis points out that this surface, in case of the Tidonti dam, cannot exceed 500,000 m^2 and cannot be lower than 250,000 m^2.

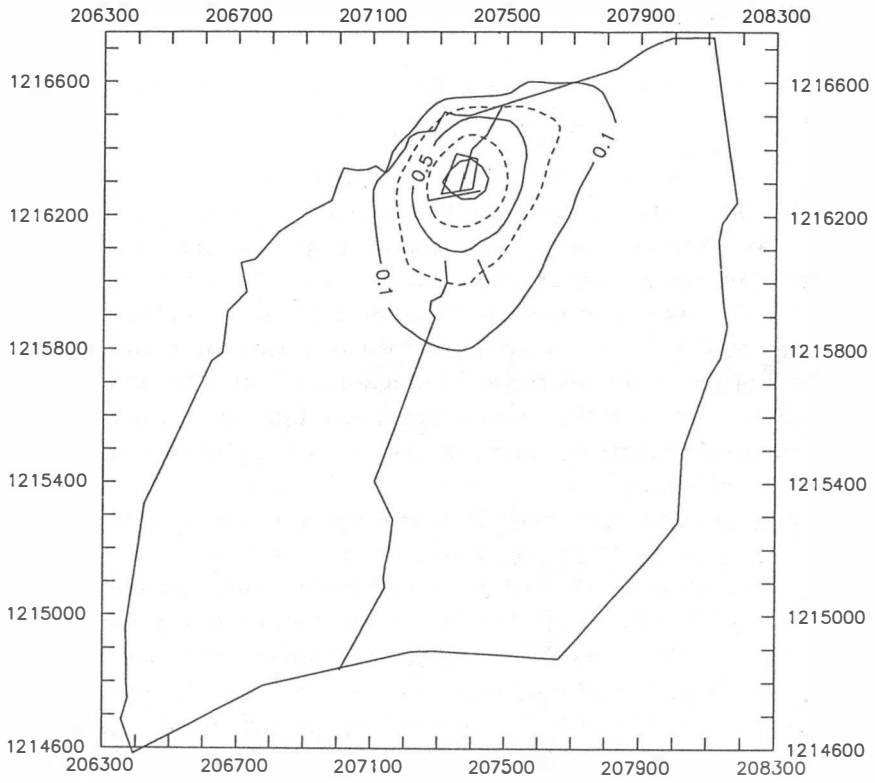


Fig. 4. — Spatial distribution of the difference in water table level.

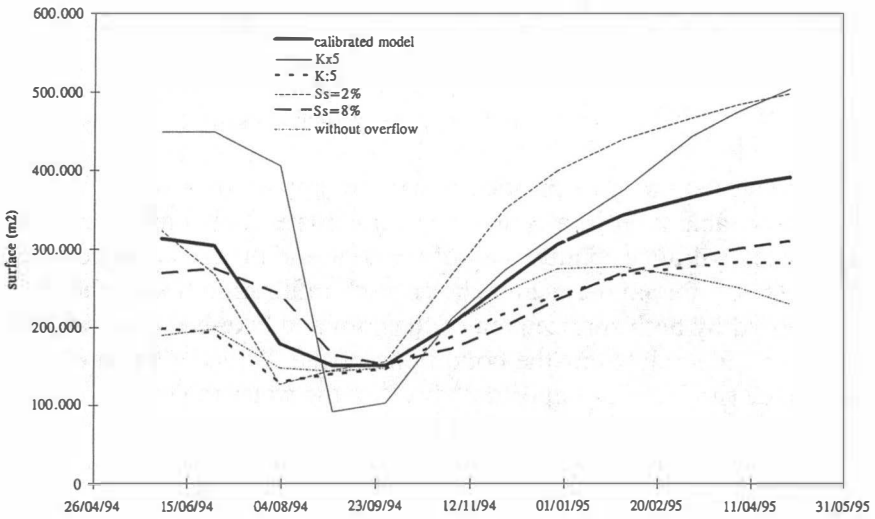


Fig. 5. — Evolution of the influence of the dam, impact of changing hydraulic conductivity and drainable porosity.

Extension of these results to other dams results into the following conclusions :

— When no overflow is present (as is the case with most constructions in the area) the influence of a dam like the dam of Tidonti on the soil water environment is biggest around January. Afterwards, probably because infiltration from the dam diminishes, the effect of the dam also decreases. In this case, infiltration only takes place from the dam and not from the river downstream from the dam. The impact of the hydraulic conductance of the dam will then be much higher. In the case of larger dams, the maximum effect can come later in time because the dam does not dry out at the end of the dry season.
— Higher conductivity, lower drainable porosity and a deeper impermeable layer cause a higher impact of the dam.
— Literature supports the hydraulic conductivity and drainable porosity values used in this study (granite zone). An infiltration study made in this granite zone showed that infiltration from dams varied between 0 and 8 mm/ day. When we consider these last two remarks, we can conclude that the Tidonti dam model as it has been developed here gives a good idea of the impact of small dams on the groundwater level in a granite zone of the Savanna region in northern Togo. In order to know the exact impact of a specific dam on the water table level around this dam, one should, however, make a model for the dam using data collected at the site itself and implementing them in the model as presented here.

4.8. Conclusions

Our calculations give an idea about the impact of a small dam on the water table level in a Soudan-Sahel climate. This impact depends mostly on hydraulic conductivity of the zone and on drainable porosity. If depth of the impermeable layer and infiltration from the dam (influenced by both surface area of the dam and lake-bed conductance) differ considerably from the conditions of the Tidonti dam presented here, they can have an important effect on the water table level.

REFERENCES

BERNARD, Ph., BONIN, H., CROCHET, Ph. & LE JONCOUR, M. 1985. Travaux d'hydraulique villageoise au Togo, 1re et 2e phases. Réalisation de 700 forages productifs dans les régions des Savanes et des Plateaux. — B.R.G.M., Orléans, 2 vol.

BOUWER, H. & RICE, R. C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. — *Water Resources Research*, **12** :423-28.

ERNST, L. F. 1950. A new formula for the calculation of the permeability factor with the auger-hole method. — T.N.O. Groningen, The Netherlands. Translated from the Dutch by H. Bouwer, Agr. Eng. Dept., Cornell Univ., Ithaca, N.Y.

LAMAGAT, J.-P. 1970. Etude hydrologique de la plaine de Mandouri (rapport des campagnes 1968-69-70). — Orstom, Lomé, 13 pp.

MCDONALD, M. G. & HARBAUGH, A. W. 1988. A modular three-dimensional finite-difference ground-water flow model, — Techniques of Water-Resources Investigations 06-A1, U.S.G.S., 576 pp.

MONIOD, F., POUYAUD, B. & SECHET, P. 1977. Le bassin du fleuve Volta. Monographies hydrologiques Orstom, Paris, n° 5, 513 pp.

PNUD 1982. Stratégie d'aménagement des eaux, ressources et besoins en eau. — Laboratoire central d'hydraulique de France, 11 planches.

SERRES, H. 1980. Politiques d'hydraulique pastorale (Techniques vivantes). — Agence de coopération culturelle et technique, Paris, 118 pp.

SMEDEMA, K. L. & RYCROFT, D. W. (1983). Land Drainage : Planning and Design of Agricultural Drainage Systems. — Batsford Academic and Educational Ltd, London, 376 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 492-496 (1998)

Pourra-t-on sauver les connaissances hydrologiques du bassin congolais/zaïrois?

par

Jean CHARLIER *

MOTS-CLES. — Bassin congolais-zaïrois ; Hydrologie ; Données.

RESUME. — L'intervention porte principalement sur la situation actuelle de dégradation du réseau des observations hydrologiques du fleuve Zaïre en se référant à la situation ancienne à travers les travaux scientifiques de Franz Bultot. L'auteur lance un appel à la reprise de la recherche scientifique dans le domaine précité.

TREFWOORDEN. — Congo-Zaïre bekken ; Hydrologie ; Data.

SAMENVATTING. — *Kan men de hydrologische kennis over het Congo/Zaïre bekken redden ?* — De interventie heeft hoofdzakelijk te maken met de huidige gedegradeerde toestand van de hydrologische waarnemingsnetten van de Zaïrestroom en vergelijkt deze met de vroegere situatie zoals ze spreekt uit het wetenschappelijk werk van Franz Bultot. De auteur breekt een lans voor de herneming van wetenschappelijk onderzoek in het geciteerde domein.

KEYWORDS. — Congo-Zaire Basin ; Hydrology ; Data.

SUMMARY. — *Can One Save the Hydrologic Knowledge on the Congo/Zaire Basin ?* — The paper deals mainly with the current deteriorating situation of the hydrological observational networks of the Zaire River referring to the previous situation through the scientific work of Franz Bultot. The author is making a call for taking up again scientific research in the above-mentioned field.

* Membre titulaire honoraire de la Classe des Sciences techniques de l'Académie Royale des Sciences d'Outre-Mer.

1. Introduction

Mon intervention ne sera pas une véritable contribution scientifique mais un appel afin que l'hydrologie congolaise, pour laquelle Monsieur Bultot a tant travaillé, soit remise à la place qui lui revient.

J'ai eu le privilège de connaître Monsieur Franz Bultot pendant plus de trente-cinq ans et de collaborer avec lui à l'édition de la série d'annuaires hydrologiques pour la Belgique au cours des années 60/70.

Mais, ayant personnellement été en charge pendant près de dix ans de la collecte des relevés d'hydrologie de surface dans l'ancien Congo belge (niveaux d'eau et débits sur l'ensemble du territoire congolais), j'ai tout spécialement apprécié les nombreuses contributions de Monsieur Bultot à l'analyse et à la diffusion des connaissances du bassin congolais/zaïrois.

Il avait souvent attiré mon attention sur la nécessité de disposer de relevés de base sans lesquels aucune étude sérieuse ne peut se faire ; certes, il est possible de développer de nombreux calculs et de formuler toute une série d'hypothèses pour lesquels des raisonnements comparatifs ou analogiques seront établis, mais peut-on leur conférer une valeur sûre s'ils ne sont pas étayés ou confirmés par des observations directes sur le terrain. N'est-ce pas d'ailleurs le grand hydrologue français Roche qui indiquait dans son ouvrage magistral «Hydrologie de surface» : «Une mauvaise mesure vaut mieux qu'un bon calcul».

Et c'est bien évidemment ici que la situation est critique et même parfois devenue irréversible.

Les travaux de Monsieur Bultot sur l'hydrologie de surface du bassin congolais ont pu se baser sur un réseau et une série d'observations remarquables par leur consistance et leur régularité.

Des observations quotidiennes des niveaux étaient relevées dans environ trois cent cinquante postes à la fin des années 50 ; leur valeur était assurée par de fréquents contrôles physiques sur le terrain. Le réseau avait été patiemment installé depuis plusieurs décennies ; nous en donnons pour preuve le fait que les étiages conventionnels auxquels se réfèreront toutes les cartes hydrographiques ultérieures (et encore aujourd'hui) ont été établis dès 1915 pour le fleuve Zaïre et dès 1919 pour son plus important affluent le Kasaï. La majeure partie de ces observations ont été consignées dans une série de publications éditées par notre Académie sous la signature de Monsieur Devroey jusqu'en 1959 exclusivement.

2. Description de la situation actuelle

On a assisté, dès le début des années 60, à une dégradation du réseau pour des raisons diverses encore présentes dans nos mémoires.

Ce qui nous paraît beaucoup plus préoccupant est que cette dégradation ne s'est jamais interrompue depuis lors quelles que soient les circonstances politiques ou économiques que le Zaïre a traversées au cours de cette période. Le résultat est qu'il ne subsiste plus aujourd'hui qu'une petite vingtaine de postes pour lesquels on dispose encore d'observations plus ou moins fiables.

Il faut encore ajouter que l'état dans lequel la plupart de ces postes se trouve est également très préoccupant ; j'ai eu l'occasion de vérifier celui de Kinshasa en septembre dernier et ne puis en être satisfait. Au cours d'un voyage le long du fleuve Kasaï, il y a quelques années, la plupart des installations étaient dans un état déplorable et les consignes de sécurité des installations et de régularité des relevés n'y étaient plus respectées ; je n'ai évidemment pas manqué de le faire observer par les responsables des services d'entretien mais apparemment sans aucun résultat.

On en est ainsi arrivé à une situation de réseau inférieure à ce qui existait avant la Première Guerre mondiale et il n'est donc pas surprenant que les contributions zaïroises aux colloques et organisations hydrologiques soient pratiquement inexistantes.

Ce que nous venons de décrire pour le réseau d'observations des niveaux est encore plus prononcé pour les observations de débit ; à l'exception du Bas-Zaïre (bief maritime), plus aucune observation régulière n'a été faite dans le bassin depuis environ trente ans.

Il n'est donc plus possible de trouver aujourd'hui les données de base indispensables à une connaissance récente, même sommaire, de l'hydrologie de surface zaïroise et toute contribution devrait se référer aux anciennes observations.

De telles contributions restent cependant possibles sans trop d'aléas vu la remarquable stabilité de régime du fleuve Zaïre, stabilité due elle-même à la répartition géographique du bassin pour les cours d'eau les plus importants, le Zaïre, le Kasaï, l'Oubangui, pour lesquels on peut toujours se baser sur les anciennes données ; il est évident que cela devient de plus en plus aléatoire dès que l'on étudie les affluents de moindre importance ou les biefs supérieurs des grands tributaires.

D'autre part, la récolte et l'archivage des anciennes observations ont également été très déficientes : il faut se rappeler que les crues maximales

du fleuve Zaïre en décembre 1961 et mai 1962 n'ont guère été répertoriées ; il en fut de même des niveaux maximaux atteints à partir de 1964 au lac Tanganyika et le long du fleuve Lualaba.

Ayant eu la possibilité d'attirer l'attention de multiples interlocuteurs sur l'importance de conserver de telles données (vraiment exceptionnelles) pour les générations et les projets futurs, je dois avouer n'avoir suscité qu'un intérêt ou une attention très éphémère.

A plusieurs reprises également, dans les années 70 et 80, je me suis rendu auprès du service conservant les archives antérieures, accompagné d'ingénieurs ou d'hydrographes zaïrois, pour les mettre en rapport avec les différents gardiens de cette documentation vraiment unique en espérant que cela susciterait une vocation ou une publication. En fait, les deux seules publications à ce sujet furent écrites par des étrangers : une hydrologue polonaise résidant momentanément à Kinshasa et un étudiant de l'U.C.L. qui y trouva matière à un travail de fin d'études.

Quant à l'état de conservation de ces archives, lors de ma dernière visite en 1987, cela défiait toute description et on comprendra dès lors le choix du titre de la présente communication.

3. Un appel et un espoir pour la relance?

Il est certainement surprenant que le bassin du fleuve Zaïre n'ait jamais fait l'objet d'études globales au cours des trente-cinq dernières années, à l'instar de la plupart des grands fleuves tropicaux pour lesquels les organisations internationales ont réuni des moyens financiers et matériels considérables ; citons le Parana et l'Orénoque en Amérique latine, le Sénégal et le Niger, le Nil en Afrique, le Bramapoutre, le Mékong en Asie du Sud et d'autres encore.

Je ne crains pas d'affirmer que les connaissances du bassin zaïrois étaient vers 1960 certainement comparables et souvent supérieures à celles de la plupart des autres bassins ; aujourd'hui, la situation est particulièrement déficiente à ce sujet et un effort global et urgent est nécessaire si l'on veut conserver d'abord et redévelopper ensuite notre connaissance hydrologique du bassin zaïrois.

Il me paraît évidemment utile de combler une lacune importante dans la nomenclature hydrologique internationale vu l'importance des débits du fleuve Zaïre, le second en importance mondiale pour les débits moyens.

Les moyens modernes permettent d'obtenir beaucoup de données valables plus rapidement que par le passé, l'intérêt de cette recherche

ne doit plus être démontré ; encore faut-il trouver la volonté d'y procéder et les outils pour la mettre en œuvre.

Nous avons le privilège aujourd'hui de voir rassemblés dans le présent symposium les représentants des organismes internationaux les plus prestigieux spécialement intéressés par ces questions ainsi que les hautes autorités scientifiques belges des sciences naturelles et de l'outre-mer. Je profite de cette circonstance exceptionnelle pour lancer un appel pressant afin qu'un effort coordonné soit entrepris rapidement pour éviter que les archives anciennes de l'hydrologie de surface zaïroise ne disparaissent à jamais et que les recherches en ce domaine ne soient remplacées par des pages blanches à l'instar de ce qui représentait le centre africain dans les atlas géographiques du siècle dernier.

Je ne doute pas qu'une telle action aurait été particulièrement appréciée par notre collègue Bultot en l'honneur duquel ce symposium a été tenu.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 497-506 (1998)

Conséquences de la sécheresse sur la longueur et l'amplitude de la saison des pluies au Niger

par

Mamadou DAOUDA *, Pierre OZER ** & Michel ERPICUM **

MOTS-CLES. — Sécheresse ; Saison des pluies ; Niger.

RESUME. — Le Niger est affecté par la sécheresse depuis 1968. Les conséquences de l'aridification sur la longueur et l'amplitude de la saison des pluies au Niger sont présentées. Il apparaît que la sécheresse a touché différemment le territoire nigérien suivant la latitude et la longitude. Ainsi, à partir du traitement des données pluviométriques quotidiennes des périodes 1950-1967 et 1968-1985, la station de Gaya, la plus méridienne du réseau, présente un déficit pluviométrique négligeable alors que, dans le nord, les stations enregistrent une diminution de plus de 35 % des précipitations et voient la disparition pure et simple de la saison des pluies.

TREFWOORDEN. — Droogte ; Regenseizoen ; Niger.

SAMENVATTING. — *Gevolgen van de droogte op de duur en de omvang van het regenseizoen in Niger.* — Niger wordt getroffen door een ernstige droogte sedert 1968. De gevolgen van de aridificatie op de duur en de omvang van het regenseizoen in Niger worden weergegeven. Het blijkt dat de droogte ongelijkmatig verdeeld is over het grondgebied van Niger zowel in breedte- als lengtegraad. Inderdaad, gebaseerd op de vergelijking van de neerslaggegevens gedurende de perioden 1950-1967 en 1968-1985 vertoont het meest zuidelijke station (Gaya) een verwaarloosbaar deficiet terwijl in het noordelijk gedeelte van Niger een dramatisch deficiet in de neerslag (> 35 %) wordt waargenomen en er kan gesproken worden over het verdwijnen van het regenseizoen.

* Service Agroclimatique et Recherche de la Direction de la Météorologie Nationale du Niger, Niamey (Niger).

** Laboratoire de Climatologie, Département de Géographie Physique, Université de Liège, allée du 6 Août 2, Bâtiment B11, B-4000 Liège (Belgique).

KEYWORDS. — Drought ; Rainy Season ; Niger.

ABSTRACT. — *Consequences of the Drought on the Length and Amplitude of the Rainy Season in Niger.* — Niger has been seriously affected by a severe drought since 1968. The consequences of the aridification on the length and the amplitude of the rainy season in several stations of Niger are presented. It appears that the drought has afflicted in a non-homogeneous way Niger and this in latitude and longitude. Indeed, based on the comparison of the 1950-1967 and the 1968-1985 rainfall data periods, the southern station (Gaya) has recorded a negligible pluviometric deficit while, in northern Niger, a dramatic decrease in the recorded rainfall (> 35 %) has led to the disappearance of the rainy season.

1. Introduction

Le Sahel a été largement affecté par d'importantes fluctuations pluviométriques au cours du 20e siècle et, notamment, par la «grande sécheresse» (LEROUX 1995) qui sévit sur toute cette région depuis la fin des années soixante. Cette dernière période de sécheresse a été particulièrement bien étudiée au Sahel (NICHOLSON 1989, HULME 1992, MOREL 1995, OZER 1995) et, plus en détail, au Niger (DAOUDA 1989, OZER & ERPICUM 1995).

Ainsi, le Niger a connu la période la plus humide du siècle de 1953 à 1965, suivie depuis 1968 par la plus longue et la plus sévère sécheresse connaissant des déficits pluviométriques particulièrement dramatiques au début des années septante et quatre-vingt (fig. 1). Dans un but

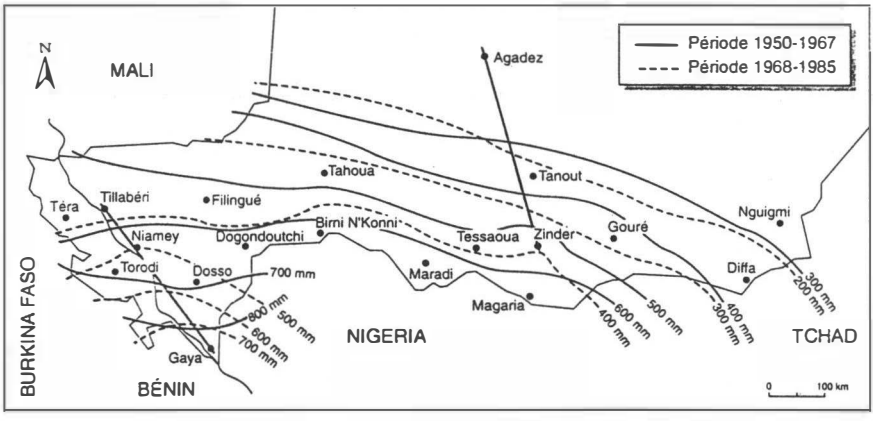


Fig. 1. — Carte pluviométrique du sud du Niger : les isohyètes sont calculées sur les périodes humide 1950-1967 et sèche 1968-1985. Localisation des stations utilisées.

d'efficacité de notre analyse, nous adopterons dans ce travail les deux périodes de même longueur respectivement humide (1950-1967) et sèche (1968-1985) déjà utilisées par TODOROV (1985) et OZER & ERPICUM (1995).

L'objectif de ce travail est de documenter les conséquences de la sécheresse sur la longueur de la saison des pluies au Niger avant et après 1967. Pour ce faire, nous appliquerons la méthode élaborée par ERPICUM *et al.* (1988) légèrement adaptée aux stations synoptiques les mieux représentatives des différentes zones climatiques du Niger. De plus, pour compléter l'analyse, nous introduirons également la notion d'amplitude de la saison des pluies.

L'analyse portera sur dix stations caractérisant le climat soudanien (Gaya), le Sahel à culture sous pluies (d'ouest en est : Niamey, Tillaberi, Tahoua, Maradi, Zinder, Goure et Maine Soroa) et la zone sahélienne pastorale (N'Guigmi et Agadez) (OZER 1993).

2. Méthodologie

Les jours de pluie (précipitations $>$ 1 mm), tout comme les jours secs, ont été comptés par périodes de cinq jours (pentades) du 1er avril au 31 octobre, selon la méthode élaborée par ERPICUM *et al.* (1988), afin de cerner au mieux les dates habituelles de début et de fin de la saison des pluies dans dix stations synoptiques du sud nigérien. La comparaison des valeurs moyennes de la longueur et des dates de début et de fin de la saison des pluies est ainsi menée sur les périodes humide (1950-1967) et sèche (1968-1985).

ERPICUM *et al.* (1988) ont montré que la saison des pluies commence au moment où la probabilité d'avoir un jour de pluie au cours d'une pentade déterminée est supérieure à celle d'avoir un jour sec appartenant à un épisode sec de plus de sept jours. Afin de gommer les périodes de transition peu évidentes entre la saison sèche et la saison des pluies, nous ne tiendrons compte que des écarts supérieurs à 5 % entre les deux courbes de probabilité.

La régularité interannuelle des précipitations au cours des pentades de la saison des pluies a été estimée en se fondant sur l'écart entre le pourcentage de jours pluvieux et celui de jours appartenant à un épisode sec dont la persistance est supérieure à 7 jours. Au moment où la saison des pluies est la plus régulière, ces écarts sont fortement positifs. La somme de ces écarts calculés de 5 en 5 jours constitue

donc un bon indicateur de la valeur agrométéorologique de la saison des pluies. Nous la nommerons «amplitude de la saison des pluies».

3. Résultats

De l'analyse du tableau 1 et de la figure 1, il apparaît une dégradation de la pluviosité selon un axe sud-nord dans la région du fleuve à l'ouest du pays, alors qu'une rotation de cet axe de dégradation dans le sens rétrograde est observée dans la partie orientale du pays.

Cette dégradation masque des conséquences différentes d'une région à l'autre sur la saison des pluies. En effet, la longueur de celle-ci accuse une réduction plus importante que la pluviosité moyenne à l'exception des stations de Niamey et Gaya dans le sud-ouest du pays (tableau 2).

En comparant les périodes avant et après 1967, on constate que la saison des pluies est meilleure à Gaya après 1967 (tableaux 2, 3). Par ailleurs, Niamey a connu un comportement singulier. On y constate une faible péjoration de la longueur de la saison des pluies (11 % de diminution) (tableau 2).

Par contre, de Tillaberi à Zinder, la diminution de la longueur de la saison des pluies oscille partout aux environs de 40 % (tableau 2). Pour ce qui est de l'amplitude de la saison des pluies, la réduction est de l'ordre de 55 % (tableau 3). La station de Tillaberi est toutefois particulièrement affectée au point de vue de l'amplitude de la saison des pluies (69 %) (tableau 3) ; ces valeurs sont confirmées par l'analyse de stations voisines (Ozer & Erpicum 1995).

Les trois stations les plus sèches du réseau analysé enregistrent un déficit pluviométrique de plus de 35 % (tableau 1). Elles subissent dès lors la disparition de leur saison des pluies (Agadez et N'Guigmi) et accusent un déficit de plus de 70 % (Goure) tant dans la longueur (tableau 2) que dans l'amplitude de la saison des pluies (tableau 3).

4. Discussion et conclusion

A la suite de la confrontation entre les variations de la longueur et de l'amplitude de la saison des pluies en période humide et en période sèche, et de la différence des épaisseurs des lames d'eau moyennes, une proposition de zonation des conséquences de la sécheresse peut être faite.

C'est ainsi que l'extrême sud du Niger (région de Gaya) a connu des saisons de pluies plus favorables (fig. 2), ce que la seule faible

Tableau 1

Pluviométrie Annuelle Moyenne en mm (P.A.M.) durant les périodes humide et sèche

Station	P.A.M. 1950-67	P.A.M. 1968-85	Différence (mm)	Différence (%)
Agadez	184	98	– 86	– 47
N'Guigmi	274	175	– 99	– 36
Goure	426	251	– 175	– 41
Maine-Soroa	445	316	– 129	– 29
Tahoua	462	332	– 130	– 28
Zinder	541	395	– 146	– 27
Tillaberi	547	365	– 182	– 33
Niamey	631	503	– 128	– 20
Maradi	654	438	– 216	– 33
Gaya	853	794	– 59	– 7

Tableau 2

Longueur moyenne (jours) de la Saison des Pluies (L.S.P.) durant les périodes humide et sèche

Station	L.S.P. 1950-67	L.S.P. 1968-85	Différence (jours)	Différence (%)
Agadez	15	0	– 15	– 100
N'Guigmi	15	0	– 15	– 100
Goure	52	15	– 37	– 71
Maine-Soroa	47	25	– 22	– 47
Tahoua	77	41	– 36	– 47
Zinder	82	52	– 30	– 37
Tillaberi	67	36	– 31	– 46
Niamey	87	77	– 10	– 11
Maradi	87	52	– 35	– 40
Gaya	72	102	+ 30	+ 42

Tableau 3

Amplitude de la Saison des Pluies (A.S.P.) durant les périodes humide et sèche

Station	A.S.P. 1950-67	A.S.P. 1968-85	Différence (mm)	Différence (%)
Agadez	70	0	– 70	– 100
N'Guigmi	61	0	– 61	– 100
Goure	210	62	– 148	– 70
Maine-Soroa	288	128	– 160	– 56
Tahoua	467	220	– 247	– 53
Zinder	342	196	– 146	– 43
Tillaberi	439	134	– 305	– 69
Niamey	574	323	– 251	– 44
Maradi	578	248	– 330	– 57
Gaya	549	664	+ 115	+ 21

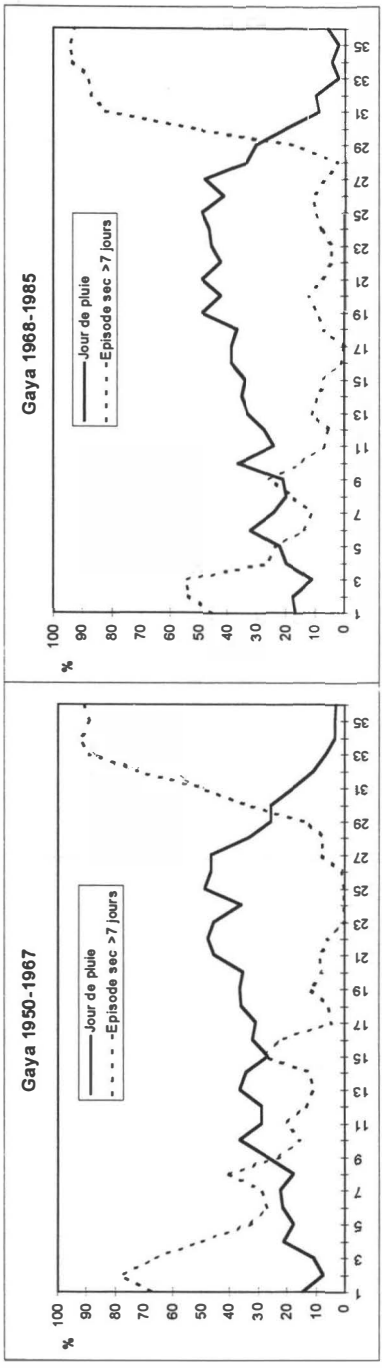

Gaya 1968-1985
Jour de pluie
Episode sec >7 jours
%
Gaya 1950-1967
Jour de pluie
Episode sec >7 jours
%

Fig. 2.

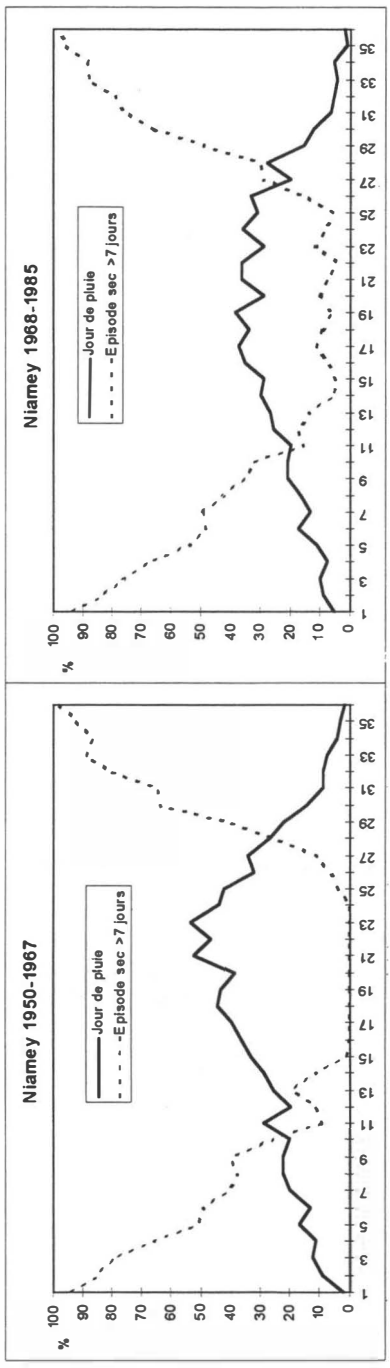

Niamey 1968-1985
Jour de pluie
Episode sec >7 jours
%
Niamey 1950-1967
Jour de pluie
Episode sec >7 jours
%

Fig. 3.

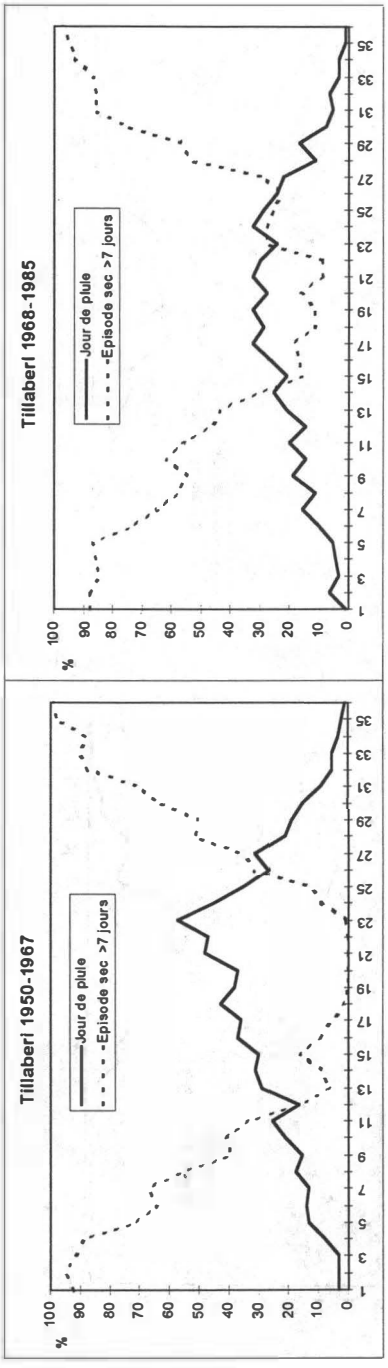

Tillaberi 1950-1967
Jour de pluie
-Episode sec >7 jours
%
Tillaberi 1968-1985
Jour de pluie
-Episode sec >7 jours
%

Fig. 4.

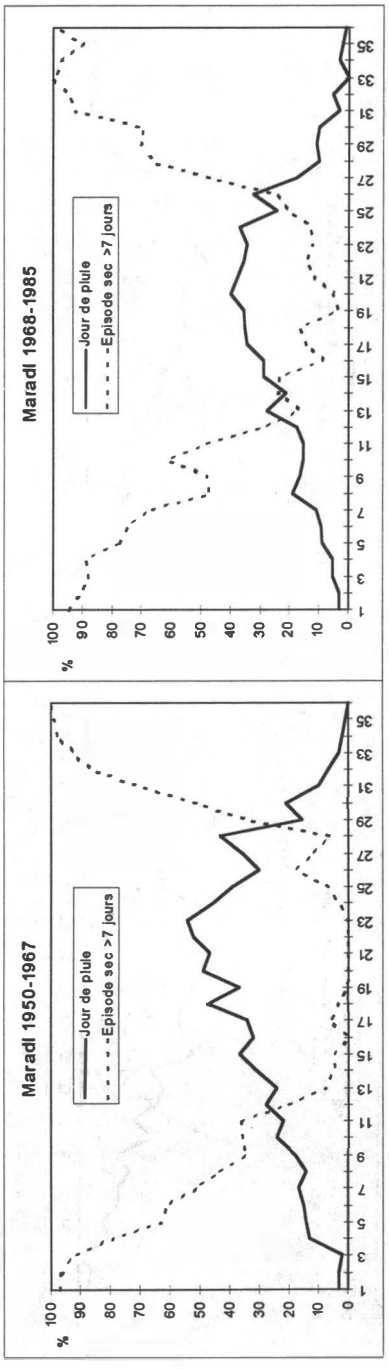

Maradi 1950-1967
Jour de pluie
-Episode sec >7 jours
%
Maradi 1968-1985
Jour de pluie
-Episode sec >7 jours
%

Fig. 5.

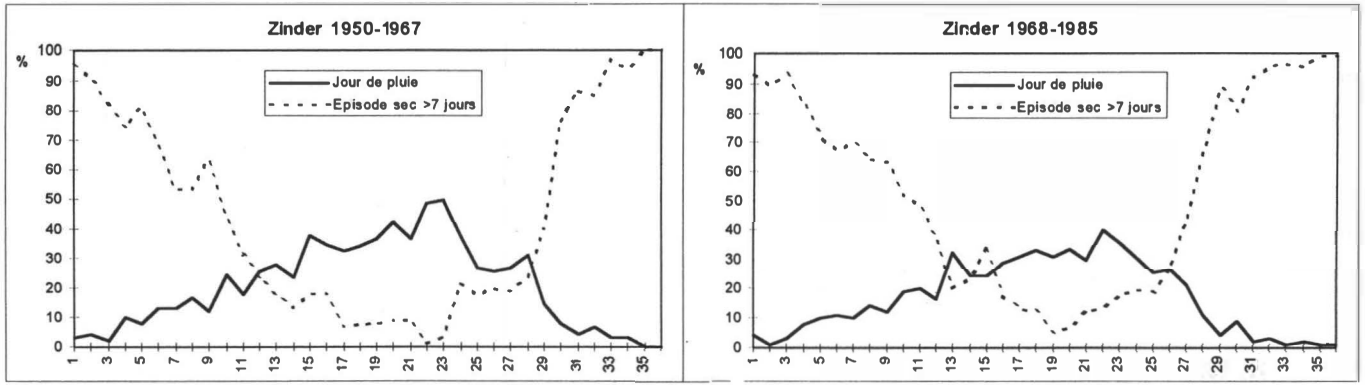


Fig. 6.

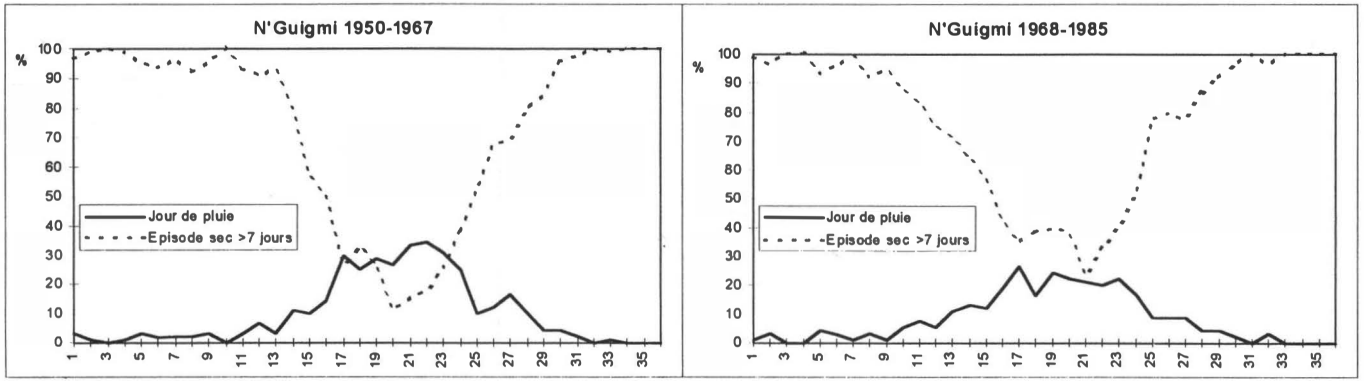


Fig. 7

Figs 2-7. — Longueur moyenne (jours) de la saison des pluies durant les périodes humide et sèche en six stations synoptiques du Niger.

diminution de la lame d'eau masquait. La région du fleuve située essentiellement aux alentours de Niamey (fig. 3) a connu une faible diminution de la longueur de la saison des pluies mais des séquences sèches plus fréquentes au sein de cette saison. Une longue zone ouest-est s'étendant depuis le nord de la région du fleuve (Tillaberi) (fig. 4) jusqu'au sud-est du Niger (Maine Soroa) et regroupant également les stations de Tahoua, Maradi (fig. 5) et Zinder (fig. 6) a été plus affectée par la sécheresse. La longueur de la saison des pluies y a fortement été raccourcie et son amplitude a partout diminué de plus de moitié. Quant à la région déjà très défavorisée au point de vue pluviométrique (Gouré, N'Guigmi — fig. 7 — et Agadez), on peut considérer que la saison des pluies y a disparu car la probabilité d'avoir un jour sec appartenant à un épisode de plus de sept jours secs durant la saison où il peut pleuvoir est devenue quasi systématiquement plus grande que celle d'avoir un jour de pluie.

D'autre part, tout le réseau des stations dites sahéliennes à l'exception de Goure enregistre une diminution plus importante de la longueur de la saison des pluies (– 38 %) et de son amplitude (– 54 %) que de la pluviosité annuelle moyenne (– 28 %). Cela signifie donc que non seulement les pluies se sont plus concentrées dans le temps mais également, et surtout, que l'intensité de celles-ci a augmenté de manière significative, ce qui concorde avec les observations de divers chercheurs dont Morel (1992) et Adefofalu (1986).

Finalement, il apparaît que la saison des pluies se raccourcit aussi bien à cause d'un début tardif que par une fin plus précoce. Ceci semble être un élément neuf dans l'étude du phénomène.

La prise en compte de la persistance des jours secs comme critère de variation de la saison des pluies a permis d'obtenir une meilleure compréhension des conséquences de la sécheresse d'une région à l'autre du sud du Niger. Les conséquences agrométéorologiques sur les pratiques agropastorales y ont été liées de près ou de loin.

REMERCIEMENTS

Nous tenons tout d'abord à remercier tout particulièrement les organisateurs de la Conférence Internationale réalisée en la mémoire de M. F. Bultot pour la bourse qui a été octroyée à M. M. Daouda. D'autre part, notre reconnaissance s'adresse aussi à M. le Prof. J. Alexandre (Laboratoire de Climatologie, Université de Liège) pour ses commentaires judicieux et à M. G. Mabille (Laboratoire de Climatologie, Université de Liège) pour son

assistance informatique. La contribution de M. P. Ozer a été financée par l'intermédiaire du Programme Environnement (Climatologie) de la DG XII — Commission Européenne (contrat n EV5V-CT-94-5244).

BIBLIOGRAPHIE

ADEFOLALU, D. O. 1986. Rainfall trends in Nigeria. *Theor. Appl. Climatol.*, **37** : 205-219.

DAOUDA, M. 1989. Les dates favorables des semis au Niger : exemple de la culture du mil. — Mémoire de Maîtrise en Sciences de l'Environnement, Agrométéorologie, FUL, Belgique, 93 pp.

ERPICUM, M., BINARD, M., PETERS, J. P. & ALEXANDRE, J. 1988. Une méthode d'analyse des caractéristiques de la saison des pluies en saison des pluies en région sahélienne (Exemples pris au Sénégal). — *In* : ERPICUM, M. (éd.), Actes des journées de Climatologie, 5-7 novembre 1987, Presses Universitaires de Liège, Liège, Belgique, pp. 43-56.

HULME, M. 1992. Rainfall changes in Africa : 1931-1960 to 1961-1990. — *Int. J. Climatol.*, **12**, 685-699.

LEROUX M. 1995. Editorial : La grande sécheresse. — *RGL*, **70** (3-4) : 179-180.

MOREL, R. 1992. Atlas agro-climatologique des pays de la zone du CILSS. — Centre AGRHYMET, Niamey, Niger, 11 vol.

MOREL, R. 1995. Pluviométrie 1961-1990 en Afrique de l'Ouest. — *Publications de l'Ass. Intern. de Climatologie*, **8** : 361-368.

NICHOLSON, S. E. 1989. Long-term changes in African rainfall. — *Weather*, **44** (2) : 44-56.

OZER, P. 1993. Contribution à l'étude de la désertification en région sahélienne. Le cas du Niger. Problèmes posés par les précipitations et les lithométéores. Mémoire de licence, Faculté des Sciences, Université de Liège, inédit, 177 pp.

OZER, P. 1995. Application des transects pluviométriques spatio-temporels annuels au territoire sahélien. — *Publications de l'Ass. Intern. de Climatologie*, **8** : 369-377.

OZER, P. & ERPICUM, M. 1995. Méthodologie pour une meilleure représentation spatio-temporelle des fluctuations pluviométriques observées au Niger depuis 1905. — *Sécheresse*, **6** : 103-108.

TORODOV, A. V. 1985. Sahel : The changing rainfall regime and the 'normals' used for its assessment. — *J. Climate. Appl. Meteor.*, **24** : 97-107.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 507-515 (1998)

Extreme Value Distributions of the Rainy Season Maximum Daily Precipitation Depths at Lubumbashi (Shaba), Zaire

by

Gaston DEMARÉE *, Slavica DERASSE * & Ali ASSANI **

KEYWORDS. — Extreme Value Distributions ; Rainfall ; Lubumbashi.

ABSTRACT. — Extreme value distributions of the GEV family are fitted to the rainy season maximum daily precipitation depths for the long-term series at the station of Lubumbashi, Gecamines (Shaba), Zaire. The data are covering seventy-three rainy seasons (October through April) from the reference period 1921/22-1995/96. The analysis yields valuable information for a region where recent data are scarce and where, in particular, long-term data are nearly non-existent. Reference is made to the pioneering work of Professor Franz Bultot in the field of the climatology of Central Africa and to an early application of extreme value distributions of tropical precipitation data.

MOTS-CLES. — Distributions des valeurs extrêmes ; Précipitations ; Lubumbashi.

RESUME. — *Les distributions extrêmes des sommes des précipitations maximales journalières durant la saison pluvieuse à Lubumbashi (Shaba), Zaïre.* — Des distributions extrêmes de la famille des GEV ont été ajustées aux données des précipitations journalières maximales durant la saison pluvieuse de la longue série d'observations à la station de Lubumbashi, Gécamines, (Shaba), Zaïre. Les données portent sur septante-trois saisons pluvieuses (octobre-avril), de la période de référence 1921/22 à 1995/96. L'analyse a produit une information précieuse pour une région où les données récentes se font très rares et, en particulier, où les données sur de longues périodes sont pratiquement inexistantes. Des références sont faites aux travaux

* Hydrology Section "Franz Bultot", Royal Meteorological Institute of Belgium, B-1080 Brussels (Belgium).
** Géographie Physique, Université de Liège, B-4000 Liège (Belgique).

scientifiques pionniers du professeur Franz Bultot dans le domaine de la climatologie de l'Afrique centrale et à une des premières applications des distributions extrêmes aux données de précipitations tropicales.

TREFWOORDEN. — Extreme waardenverdelingen ; Neerslag ; Lubumbashi.

SAMENVATTING — *Extreme waardenverdeling van de maximumdagsommen van de regenseizoenneerslag te Lubumbashi (Shaba), Zaïre.* — Extreme waardenverdelingen van de GEV-familie worden toegepast op de maximale dagelijkse neerslaghoeveelheden gedurende het neerslagseizoen van de langdurige tijdreeks van het station Lubumbashi, Gecamines (Shaba), Zaïre. De gegevens bestrijken een periode van drieënzeventig neerslagseizoenen (oktober tot april) voor het referentietijdvak 1921/22-1995/96. De analyse oogst waardevolle informatie voor een regio waarvoor recente data schaars zijn en waar, in het bijzonder, langdurige gegevens nagenoeg onbestaande zijn. Het pionierswerk van Franz Bultot met betrekking tot de klimatologie van Centraal-Afrika wordt aangehaald evenals een vroege toepassing van de extreme waardenverdelingen van tropische neerslaggegevens.

1. Station

Precipitation is observed at Lubumbashi at the following stations :

(a) Lubumbashi, Gecamines, at the headquarters of the mining company. This station was kept in former times by the "Union Minière du Haut Katanga" (U.M.H.K.). Its coordinates are 27°28 ′ E, 11°40 ′ S and is at an elevation of 1,200 m. The station has been active from 1916 onwards.

(b) Lubumbashi, town. This station was formerly called Elisabethville. Its coordinates are 27°28′ E, 11°39′ S. This station, which has probably been displaced several times, has been active from 1912 onwards.

BULTOT (1950) classified the climate of this region at an elevation of 1,000 m to 1,400 m, and already slightly away from the equator, as Cw in the climate classification of Köppen. The mean daily temperature in the dry winter months dips frequently below 18 °C. Based upon the reference period 1930-1952, BULTOT (1954) estimated for Lubumbashi (town), on the average, the length of the dry season as 186 days, 22nd October as starting date of the wet season and 19th April as starting date of the dry season.

2. Instrument and Data

The current instrument at Lubumbashi, Gecamines, is a rain-gauge produced by T. Cooke & Sons, Cape Town, and its opening has a diameter of 8″ (or 203.2 mm).

Daily precipitation depths at Lubumbashi, Gecamines, are available for the rainy season, which lasts generally from October through April next year for the reference period 1921/22-1995/96. Isolated small rainfall amounts during the beginning or ending month of the rainy season, or outside the rainy season, may be missing in the data set. Unfortunately, all data are missing for the two following subperiods : October 1933 through April 1934 (archives lost) and December 1961 through February 1962 (political disturbances). It should be noted that monthly totals have been available at Lubumbashi, Gecamines, since 1916/17 onwards ; however, for the starting period daily depths are lost.

Table 1

Frequency of occurrence of the rainy season maximum daily rainfall depths at Lubumbashi, Gecamines, within the different months

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
2	11	15	12	13	18	2

Monthly totals (in mm), with again missing values in the early 1960s, from Lubumbashi (town) are available in the CDIAC data bank under the name Lubumbashi for the reference period 1912-1973 (Vose *et al.* 1992).

Few metadata on the Lubumbashi station are known. Based on its full reference period, statistical tests showed that the series can be considered as stationary (Vannitsem & Demarée 1991).

3. The General Extreme Value (GEV) Distribution

An extreme value analysis of the daily maximum precipitation depths in the rainy season was carried out fitting a GEV distribution (Jenkinson 1969, Buishand 1989). The cumulative distribution function of the GEV variable is given by the following equation :

$$F(x) = \exp\left[-\left\{ 1 - k\left(\frac{x-u}{a} \right) \right\}^{\frac{1}{k}} \right], k \neq 0.$$

This function gives the probability that the value x will not be exceeded. The average return period T between two exceedances is given by :

$$T = \frac{1}{[1 - F(x)]}$$

The GEV distribution contains three unknown parameters : the location parameter u, the scale parameter α and the shape parameter k. The GEV is bounded by u + α/k from above if k > 0 and from below if k < 0 while the shape parameter k determines which extreme value distribution from the GEV family is taken. In the case of k = 0, the GEV distribution reduces to the Gumbel distribution, or the GEV 1 probability distribution. In this case the equation for F(x) is simplified to the expression :

$$F(x) = \exp\left[- e^{-\left(\frac{x-u}{a}\right)} \right] = \exp\left[-e^{-y}\right]$$

where

$$y = \left(\frac{x - u}{a} \right)$$

is called the standard Gumbel variate. The value for y is given by :

$$y = \ln\left[- \ln F(x)\right] = \ln\left[- \ln\left(1 - \frac{1}{T} \right) \right]$$

and the precipitation depth at a given return period T is given, in the case of a Gumbel distribution, by :

$$x = u + ay$$

and, in the case of the GEV distribution, by :

$$x = u + a\frac{1 - e^{-ky}}{k}, k \neq 0$$

A 3-parameter GEV and a 2-parameter Gumbel distribution were fitted to the data points ; their parameters were estimated with a Maximum Likelihood (ML) technique.

Table 2

Parameter values of the GEV and Gumbel probability distributions, ML estimates

	α	u	k
GEV	14.825	65.996	0.0406
Gumbel	14.767	65.500	—

The figures 1 and 2 represent the GEV and Gumbel distribution of the daily wet season maximum precipitation amounts at the station of Lubumbashi, Gecamines, for the reference period 1921/22-1995/96. The full lines represent the theoretical fitted distribution, the crosses the data points. The broken lines represent the 95 % confidence interval for the estimated values of the observed variable (to be read vertically), while the dotted lines deal with the reduced variate or the return period (to be read horizontally). In particular, the confidence interval is smaller in the case of the 2-parameter Gumbel than for the 3-parameter GEV distribution.

It is seen that the GEV does not differ much from a straight line in the selected bi-logarithmic scale (small value of shape parameter k). Does its value differ significantly from zero? The value of .221 for the one-sided A-test (OTTEN & VAN MONTFORT 1978) concludes to the acceptance of the null hypothesis $H_0: k = 0$ against the alternative hypothesis $H_1^+: k > 0$ at the 5 % confidence level. The Gumbel probability distribution is thus acceptable.

Quantiles corresponding to given return periods estimated by the fitted extreme value distributions are given in table 3.

Table 3

Estimated quantiles corresponding to given return periods for the estimated probability distribution functions

T	GEV	Gumbel
2	71.4	70.9
5	87.6	87.7
10	97.9	98.7
25	110.5	112.7
50	119.5	123.1
100	128.2	133.4
200	136.6	143.7

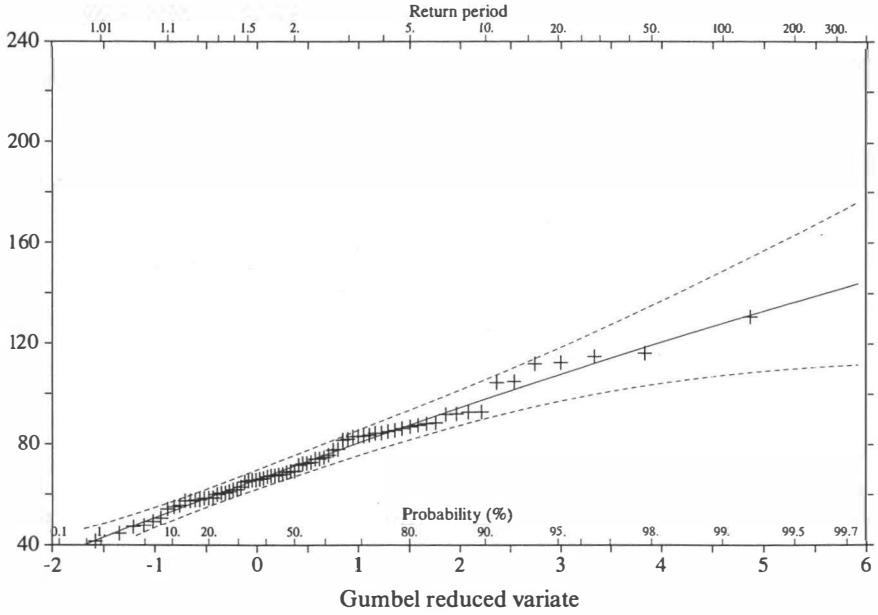


Fig. 1. — GEV probability distribution function of the daily wet season maximum precipitation depths at the Lubumbashi station, Gecamines, reference period 1921/22-1995/96.

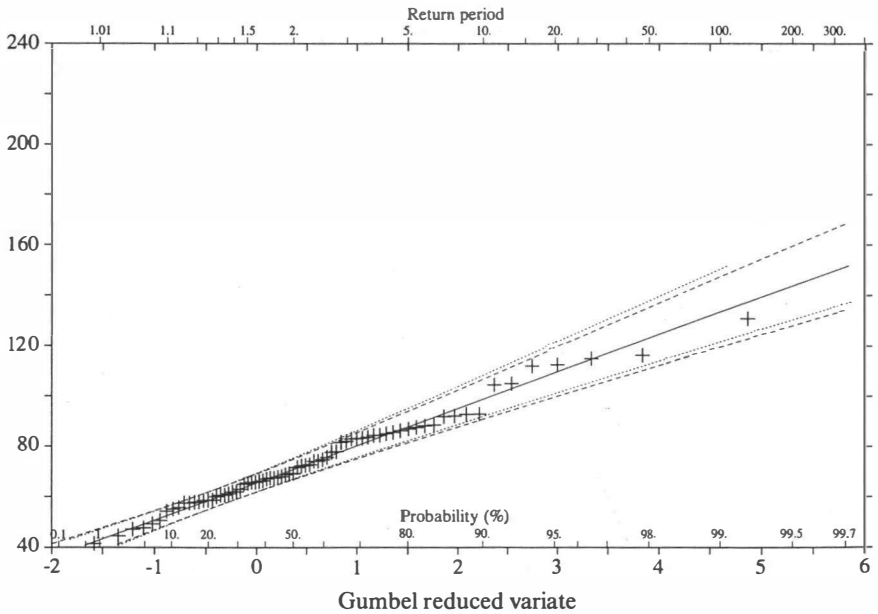


Fig. 2. — Gumbel probability distribution function of the daily wet-season maximum precipitation depths at the Lubumbashi station, Gecamines, reference period 1921/22-1995/96.

4. Jenkinson's Approach (1955) to the GEV Distribution

BULTOT (1956) did notice the Jenkinson (1955) paper on the GEV distribution at a very early stage. Later on, a FORTRAN code was produced at the Hydrology Section of the Royal Meteorological Institute of Belgium. The code was adapted to the current computer environment and fitted to the data set for special purpose at the TCMH-96 conference *in memoriam* of Franz Bultot.

The three parameters estimated according to JENKINSON (1955) are given in table 4 while figure 3 represents the fitted probability distribution function and the data points. It can be noticed that the fitted distribution is very similar to the GEV distribution of the section 3 of this paper.

Table 4

Estimated parameters of the Jenkinson's approach (1955) to the GEV distribution

	ξ_1	σ_1	k
JENKINSON (1955)	74.023	18.223	0.0562

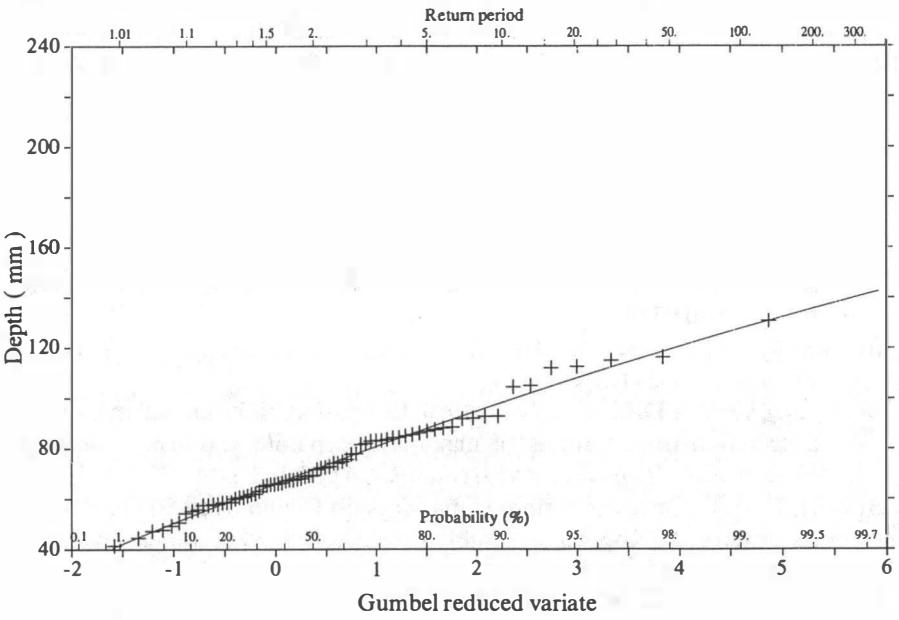


Fig. 3. — Jenkinson's GEV probability distribution function (1955) of the daily wet season maximum precipitation depths at the Lubumbashi station, Gecamines, reference period 1921/22-1995/96.

5. Conclusions

Extreme value distributions were fitted to the rainy season maximum daily precipitation depths observed at the Gecamines station, Lubumbashi, Zaire. This series constitutes without any doubt one of the longest time series from the Central African basin where recent data are known to be extremely scarce. Results are, for that reason, of utmost importance in African tropical climatology.

In a further stage of this research, an improvement of the results can be obtained using the multiplicative probability distribution function of the daily maximum values during the months of the rainy season following BUISHAND & DEMARÉE (1990).

The data points of the Lubumbashi rainy season maximum daily rainfall amounts are showing some organized structure (see the steps of data points in the figures) which is indicative of deterministic chaos (BALAKRISHNAN *et al.* 1995).

ACKNOWLEDGEMENTS

Ali Assani gratefully acknowledges the precious help from his colleagues at Gecamines to have made available the data set of this study. Thanks are also due to Cathy Nicolis and Stéphane Vannitsem for enlightening discussions on the chaotic aspect of the phenomenon studied.

REFERENCES

BALAKRISHNAN, V., NICOLIS, C. & NICOLIS, G. 1995. Extreme Value Distributions in Chaotic Dynamics. — *Journal of Statistical Physics*, **80** (1/2) : 307-336.

BUISHAND, T. A. 1989. Statistics of extremes in climatology. — *Statistica Neerlandica*, **43** (1), 30 pp.

BUISHAND, T. A. & DEMARÉE, G. R. 1990. Estimation of the annual maximum distribution from samples of maxima in separate seasons. — *Journal of Stochastic Hydrology and Hydraulics*, **4** : 89-103.

BULTOT, F. 1950. Carte des régions climatiques du Congo belge établie d'après les critères de Köppen. — Publ. INEAC, Bruxelles, Bureau climatologique, Comm. 2, 15 pp. + 1 pl.

BULTOT, F. 1954. Saisons et périodes sèches et pluvieuses au Congo Belge et au Ruanda-Urundi. — Publ. INEAC, Bruxelles, Bureau climatologique, Comm. 9, 70 pp.

BULTOT, F. 1956. Etude statistique des pluies intenses en un point et sur une

aire au Congo Belge et au Ruanda-Urundi. — Publ. INEAC, Bruxelles, Bureau climatologique, Comm. 11, 90 pp.

BULTOT, F. 1957. Risques d'années sèches et pluvieuses au Congo Belge et au Ruanda-Urundi. — Publ. INEAC, Bruxelles, Bureau climatologique, Comm. 13, 22 pp. + planches.

JENKINSON, A. F. 1955. The frequency distribution of the annual maximum (or minimum) values of meteorological elements. — *Quarterly Journal of the Royal Meteorological Society*, **81** : 158-171.

JENKINSON, A. F. 1969. Statistics of extremes. *In* : Estimation of Maximum Floods, Technical note 98, WMO — No. 233, Geneva, pp. 183-227.

OTTEN, A. & VAN MONTFORT, M. A. J. 1978. The power of two tests on the type of distributions of extremes. — *Journal of Hydrology*, **37** : 195-199.

VANNITSEM, S. & DEMARÉE, G. 1991. Détection et modélisation des sécheresses au Sahel. — *Hydrologie continentale*, **6** (2) : 155-171.

VOSE *et al.* 1992. The Global Historical Climatology Network : Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data. — Carbon Dioxide Information Center, Oak Ridge National Laboratory, ORNL/CDIAC-53, NDP-041.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 516-531 (1998)

Identifying the Major Cause of the Prevailing Summer Rainfall Deficit over the North-Central Ethiopian Highlands since the Mid-60s

by

Yilma SELESHI * & Gaston DEMARÉE **

KEYWORDS. — El Niño ; Ethiopia ; SOI ; SST ; Summer Rainfall Deficit ; Transfer Function Plus Noise Model ; Tropical East Pacific Ocean.

ABSTRACT. — The variability of the solar energy, which is partly measured by the sunspot numbers, is thought to have some effects on the world rainfall climate presumably by modulating variations of the global sea surface temperatures (SSTs) and the large-scale pressure systems such as the Southern Oscillation. It is known that, in general, ENSO events are associated with extreme weather across the world. For example, warm ENSO events are associated with drought in Ethiopia, Australia, southern Africa and to some extent in the Sahel. In this paper we show an application of transfer function stochastic modelling to identify the primary causes for the 8 % reduction in the June-September rainfall amounts over the north-central Ethiopian highlands in the period 1965-1990 as compared to the period 1939-1964. Possible causes considered are the April-June SST variations over the Tropical East Pacific (El-Niño effect), South Atlantic and South Indian Oceans (moisture factor), the Southern Oscillation Index (SOI) (atmospheric pressure factor) and the sunspot numbers (a solar variability factor). The results show that mainly April-June SST variations over the Tropical East Pacific Ocean induced this reduction in the summer rainfall over the north-central Ethiopian highlands. It is seen that the Tropical East Pacific Ocean SSTs were warmer on average by 26 % in the dry period 1965-1990 as compared to the wet period 1939-1964. Moreover, the autocorrelation structure on a yearly time basis of the Tropical East Pacific Ocean SSTs is markedly different in the dry and wet

* Department of Civil Engineering, Faculty of Technology, Addis Ababa University, P.O. Box 385, Addis Ababa (Ethiopia).

** Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

periods. Finally, we discuss physical links between SST variations over the Tropical East Pacific Ocean and the variation of the summer rains over the north-central Ethiopian highlands.

MOTS-CLES. — El Niño ; Ethiopie ; SOI ; SST ; Déficit des précipitations d'été ; Modèle de la fonction du transfer bruit ; Océan Est-Pacifique tropical.

RESUME. — *Identification de l'origine principale du déficit actuel des précipitations sur les régions montagneuses du centre nord de l'Ethiopie.* — La variabilité de l'énergie solaire, qui est mesurée partiellement par le nombre de taches solaires, est supposée avoir des effets sur le climat des précipitations au niveau mondial, probablement en modulant les variations de la température de la surface globale de la mer (SST) et les systèmes de pression à grande échelle tels que l'Oscillation Australe. Il est reconnu que, généralement, des événements ENSO sont associés à des conditions climatiques extrêmes dans le monde. Par exemple, des événements ENSO chauds sont associés aux sécheresses en Ethiopie, en Australie, en Afrique australe et jusqu'à un certain degré au Sahel. Dans cet article, nous montrons une application de la modélisation stochastique à fonction de transfert pour identifier les causes principales de la réduction de 8 % des précipitations de juin-septembre sur les régions montagneuses du centre nord de l'Ethiopie au cours de la période 1965-1990, comparées à celles de la période 1939-1964. Les causes possibles considérées sont les variations des SST en avril-juin sur le Pacifique est tropical (effet El Niño), sur l'Atlantique sud et l'océan Indien sud (source de vapeur d'eau), l'Oscillation Australe (SOI) (facteur de pression atmosphérique), et le nombre de taches solaires (un facteur de variabilité solaire). Les résultats montrent que principalement les variations avril-juin des SSTs sur le Pacifique est tropical ont induit cette réduction dans les précipitations sur la région montagneuse du centre nord de l'Ethiopie. Il est démontré que les SST de l'océan Pacifique est tropical étaient en moyenne 26 % plus chaud dans la période sèche 1965-1990 comparée à celle de la période pluvieuse 1939-1964. En plus, la structure d'autocorrélation à base annuelle des SST de l'océan Pacifique est tropical est significativement différente en période sèche ou pluvieuse. Finalement, les liens physiques entre les variations des SST de l'océan Pacifique est tropical et la variation des pluies d'été sur la région montagneuse centre nord de l'Ethiopie sont abordés.

TREFWOORDEN. — El Niño ; Ethiopië ; SOI ; SST ; Zomerneerslagdeficiet ; Transferfunctie en ruismodel ; Tropische Oost-Pacifische Oceaan.

SAMENVATTING. — *Identificatie van de belangrijkste oorzaak van het heersende neerslagtekort over de noord-centrale Ethiopische hooglanden sinds het midden van de jaren zestig.* — De variabiliteit van de zonne-energie, die gedeeltelijk gemeten wordt door het aantal zonnevlekken, wordt verondersteld bepaalde weerslagen te hebben op de neerslag in de wereld vermoedelijk door

modulerende variaties van de globale zeeoppervlaktetemperaturen (SSTs) en de grootschalige druksystemen zoals de Zuidelijke Oscillatie. Het is bekend dat, over het algemeen, ENSO-gebeurtenissen worden geassocieerd met extreme weersituaties over de wereld. Bijvoorbeeld, warme ENSO-gebeurtenissen gaan samen met droogtes in Ethiopië, Australië, zuidelijk Afrika en in zekere mate de Sahel. In dit artikel wordt een toepassing van een stochastisch transferfunctiemodel aangewend om de primaire oorzaken te identificeren van de 8 % verlaging van de juni-september neerslagsommen over de noordcentrale Ethiopische hooglanden in de periode 1965-1990 in vergelijking met de periode 1939-1964. Mogelijke oorzaken die worden beschouwd zijn de april-juni SST-variaties over de tropische Oost-Pacifische (El Niño effect), Zuid-Atlantische en Zuid-Indische Oceanen (vochtigheidsfactor), de Southern Oscillation Index (SOI) (atmosferische drukfactor) en het aantal zonnevlekken (zonnevariabiliteitsfactor). De resultaten tonen aan dat in hoofdzaak de april-juni SST-variaties over de tropische-Oost-Pacifische Oceaan deze verlaging van de zomerneerslag over de noordcentrale Ethiopische hooglanden teweegbrengt. Tevens blijken de tropische Oost-Pacifische Oceaan SSTs met een gemiddelde van 26 % warmer te zijn in de droge periode 1965-1990 in vergelijking met de natte periode 1939-1964. Bovendien is de autocorrelatiestructuur op jaarbasis in de tropische Oost-Pacifische SSTs merkelijk verschillend in de droge en vochtige periodes. Ten slotte worden fysische verbanden gelegd tussen SST-variaties over de tropische Oost-Pacifische Oceaan en de variaties van de zomerregens over de noordcentrale Ethiopische hooglanden.

1. Introduction

Water is life and indeed this statement is better understood in the semi-arid regions where water is scarce. It happens that where water is scarce it is also highly variable in space and time. Since water is the most important input into many water-related economic systems, its variability is affecting the output of these systems. Over the Ethiopian highlands, for example, the summer (June-September) rainfall amounts variabilities are strongly linked to the production of the rainfed agriculture. Moreover, these rainfall variations over the Ethiopian highlands are also inducing fluctuations of the Nile discharge, which is the major water resource for Egypt and Sudan. Thus understanding and then modelling of the causes for the summer rainfall variabilities over the Ethiopian highlands are of vital importance for water resource planning, designing and management purposes.

The basic question now is : what are the physical causes for the rainfall to vary from year to year over the Ethiopian highlands? Second

question : can we model the relationship between causal variables and the rainfall variability? To answer the first question, we need to identify causal variables. In this line some studies indicate teleconnections between ENSO and the Ethiopian rainfall. ININDA *et al.* (1987), HAILE (1990) and BABU (1991) concluded on a qualitative basis that warm ENSO events are generally characterized by drought in Ethiopia. SELESHI *et al.* (1993) also examined a qualitative relationship between the long-term Addis Ababa and Asmara rainfall with ENSO on the seasonal time-scale. The result shows a strong coexistence between the years of warm ENSO events and the years of below average rainfall particularly for the June-September rainfall. Moreover, BELTRANDO & CAMBERLIN (1993) suggested that especially at the beginning and the end of the main rainy season, heavy rains correspond to high SOI and to negative anomalies of SST and pressure over the north-western Indian Ocean. Recently, SELESHI & DEMARÉE (1995) presented teleconnections between the monthly SO index (SOI) and the monthly regional rainfall indices of the north-central Ethiopian highlands over the reference period 1900-1990. They found significant correlations between January sea level pressure at Darwin, Australia, and the beginning month of the summer rainy season (June), between July sea level pressure at Darwin and the last month of the summer rainy season (September) rainfall over the north-central Ethiopian highlands.

Non-terrestrial rainfall causal variable is also suggested. WOOD & LOVETT (1974) and SELESHI *et al.* (1994) showed a significant relationship between the annual sunspot numbers and the annual rainfall at Addis Ababa (9°02′ N, 38°45′ E, located at 2,450 m elevation in the central part of the Ethiopian highlands).

In this paper we attempt to answer the second question. More specifically, modelling the link between the causal variables and the rainfall variability. To do this we first identify the prime cause (among SST variations over Tropical East Pacific, South Atlantic and South Indian Oceans ; the SOI and sunspot numbers) for the summer rainfall deficit in the period 1965-1990 as compared to the period 1939-1964. The identification process is based on the transfer function plus noise model which stochastically links the causal variables with the rainfall variability over the north-central Ethiopian highlands.

The organization of this paper is as follows : section two presents Ethiopian precipitation regime and the data, then section three discusses the methodology used here. Section four presents the models, section five presents the result and a discussion on a possible physical

mechanism for the deficit of the summer rains over the north-central Ethiopian highlands. Finally conclusion is presented in section six.

2. Ethiopian Precipitation Regime and the Data

Precipitation regime

Ethiopia is situated in the north-east of Africa (fig. 1a). The north-east, the south-west and south-east monsoons bring moisture from the Atlantic and Indian Oceans respectively. In the northern hemisphere summer, moisture gradually penetrates into Ethiopia as the African sector of the Intertropical Convergence Zone (ITCZ) progresses northward (Griffiths 1972). The study region, north-central Ethiopian highlands (~ 9-14 N and ~ 35-40 E, on average 1,200 m above sea level), receives 73 % of the annual rainfall, 1,185 mm in the main rainy season from June to September (fig. 1b).

Data : rainfall, SST, the SOI and sunspot numbers

The data, monthly and annual rainfall totals from 1947 onwards, were provided by the Ethiopian Meteorological Services Agency ; data covering the previous period were extracted from Fantoli (1965). The basic sea surface temperature (SST) time series for this study consists of seasonal averages for (if there are sufficient data) January-March 1856, (...), October-December 1991 in sequence. The Meteorological Office Historical Sea Surface Temperature data version 5 (MOHSST5 data set) are used (for more detailed discussion, see Bottomley *et al.* 1990). Monthly mean values of the SOI and the Darwin sea level pressure were obtained from the National Centre for Atmospheric Research, Boulder, Colorado. The monthly mean relative Zürich sunspot numbers data were provided by the Sunspot Index Centre at the Royal Observatory of Belgium.

3. Methodology : a Brief Description of a Transfer Function Plus Noise Model

A transfer function plus noise model is applied to construct stochastic links between the causal variables (time variations of SST, SOI, and sunspot numbers) and the variable to be modelled in our case is the June-September rainfall totals over the north-central Ethiopian highlands. In addition to modelling the rainfall variability based on the

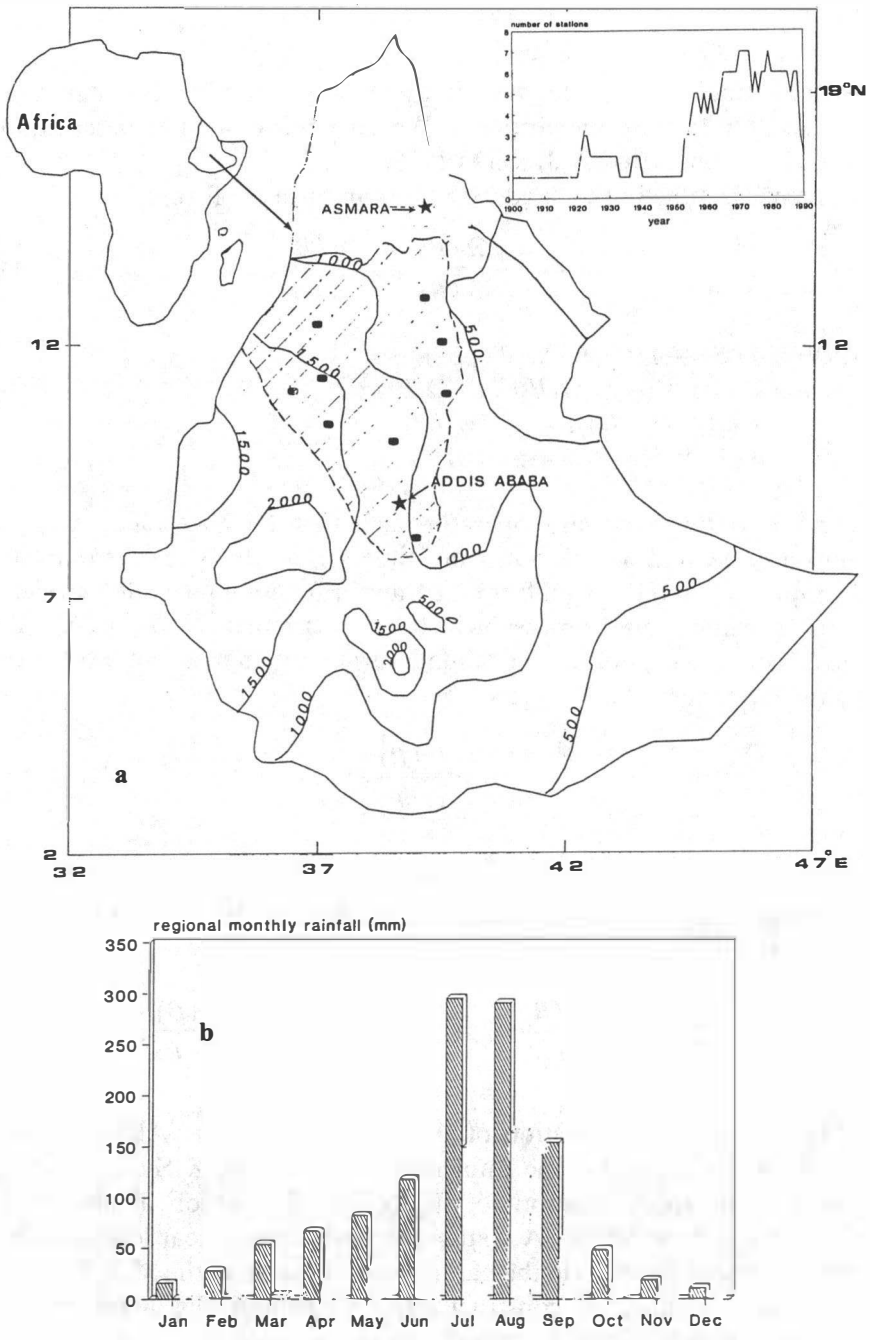


Fig. 1. — Locations of rainfall gauging stations used in this study in the north-central Ethiopian highlands (NCEH) represented by slant dotted lines ; (a) surface distribution of annual precipitation (mm), (b) regional monthly rainfall distributions. Time evolution of the number of stations used to estimate the regional rainfall index is shown at the top right corner.

causal variables, a transfer function plus noise model (TFN) can also be used for forecasting purposes. We give below a brief description of a TFN model (Box & Jenkins 1976).

A transfer function with added noise can have the form :

$$Y_t = C + \frac{\Omega(B)}{\delta(B)} X_t + \frac{\theta(B)}{\varphi(B)} e_t \qquad (1)$$

where : $\delta(B) = 1 - \delta_1 B - \ldots - \delta_\rho B^r)$
$\Omega(B) = (\Omega_0 + \Omega_1 B + \ldots + \Omega_s B^s)$
$\varphi(B) = (1 - \varphi_1 B - \ldots - \varphi_p B^p)$
$\theta(B) = (1 - \theta_1 B - \ldots - \theta_q B^q)$

where B is the backward operator such that $B^n X_t = X_{t-n}$. C is a constant ; X_t and Y_t are stationary time series which are respectively the input to and the output from the transfer function plus noise model ; e_t is a white noise process which is distributed N (o, σ_e^2). The disturbance, the part of the rainfall variability that is not explained by the input variable, N_t is given by

$$N_t = \frac{\theta(B)}{\varphi(B)} e_t \qquad (2)$$

The representation in Eq. (1) can be extended directly to the case of multiple-input transfer function plus noise model, for example for *m* inputs we have :

$$Y_t = C + \frac{\Omega^1(B)}{\delta_1(B)} X_{1t} + \ldots + \frac{\Omega^m(B)}{\delta_m(B)} X_{mt} + \frac{\Theta(B)}{\Phi(B)} e_t \qquad (3)$$

The method of estimation of the parameters in the ARIMA, and the TFN model is the one implemented by the SCA System (1992) which is an approximation to the likelihood function as shown in Hillmer & Tiao (1979). A Gauss-Marquardt non-linear least-squares method is used to perform the parameter estimation in the SCA System. In the next section, we construct transfer function plus noise models for the June-September rainfall amounts over the north-central Ethiopian highlands for two periods : the wet period 1939-1964 and the dry period 1965-1990.

4. Construction of a Transfer Function Plus Noise Model

The north-central Ethiopian highlands (9-14 N) receive low summer rainfall amounts over the period 1965-1990 compared to the period 1939-1964. Statistical characteristics of the summer rainfall amounts in the wet and the dry periods are given in table 1. We observe reductions in the mean by 8 % and the variability by 45 % of the areal rainfall from the period 1939-1964 to the period 1965-1990. Such a deficit of rainfall since about the late 60s is also reported for the Sahel region (11-18 N), e.g. : LAMB (1985), NICHOLSON (1989), DEMARÉE & NICOLIS (1990), and FOLLAND *et al.* (1991). In this paper, we are interested to investigate the prime causes (apart from local forcing factors such as the extent of vegetation covers and soil moisture condition) for this deficit of the summer rainfall amounts over the north-central Ethiopian highlands based on the transfer function plus noise model.

Table 1

Statistical characteristics of the June-September rains over the north-central Ethiopian highlands for the wet period 1939-1964 and the dry period 1965-1990

Period	1939-1964	1965-1990	1939-1990
Mean (mm)	860	794	827
Standard deviation (mm)	157	108	139
Autocorrelation coefficient at lag 1	+0.53	+0.11	+0.39

Recently, SELESHI (1996) has constructed a transfer function plus noise model that explains 70 % of the observed June-September rainfall totals variability over the north-central Ethiopian highlands covering the period 1900-1990. In this model, he showed that the parameters associated with the April-June SST over the Oceans of (1) Tropical East Pacific, (2) South Atlantic and (3) South Indian, (4) with the June Atmospheric pressure at Darwin, and (5) with the annual sunspot numbers have significant contribution in explaining the observed variance of the summer rain. This model describes the long-term (1900-1990) association between these causal variables and the summer rains. We apply the structure of this transfer function plus noise model to assess significant parameter value change from the wet period 1939-1964 to the dry period 1965-1990.

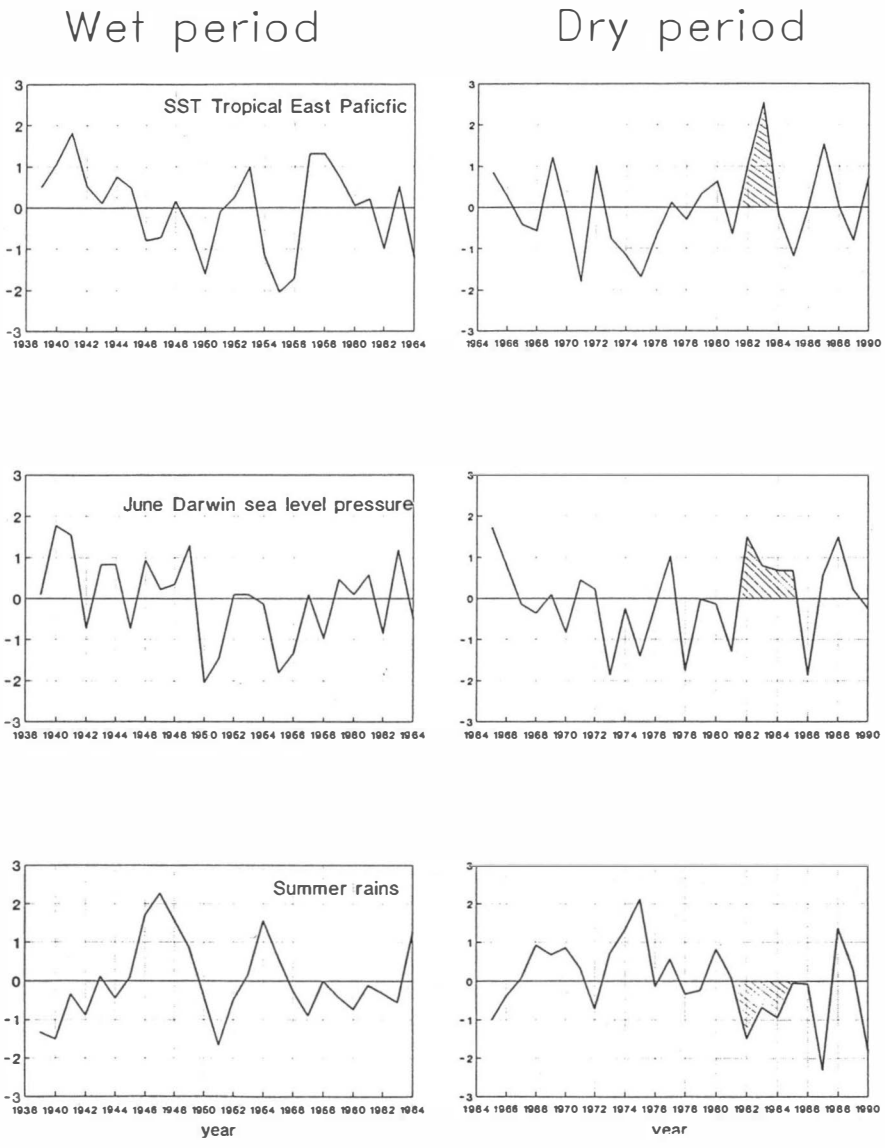


Fig. 2. — Standardized time series of inputs and outputs to the transfer function plus noise models right column for dry period 1939-1964 and left column for wet period 1965-1990. (Top) for April-June SST over Tropical East Pacific Ocean representing and non-El-Niño events, (middle) for June Darwin Sea level pressure representing SOI and (bottom) June-September rains over Ethiopian highlands. Each series is standardized by its corresponding mean and standard deviation obtained for the dry and the wet periods. Hatched areas represent ENSO conditions corresponding to 1982-1985 persistent droughts in the north-central Ethiopian highlands.

4.1. Modelling the Rains in the Wet and the Dry Periods

Standardized time series of the inputs into the TFN model and the rains for the wet and dry periods are displayed in figure 2. Qualitatively, from figure 2 we see that when SST over Tropical East Pacific Ocean is warm (hatched area), the summer rains over the north-central Ethiopian highlands are below average and the converse is also true. The prominent positive peak in figure 2 top right corresponds to the unusual warming of the Tropical East Pacific Ocean in 1982-1983. During 1965-1990, above average June Darwin sea level pressure corresponds to below average rains over the north-central Ethiopian highlands, but for the wet period this association appears to be weak.

The structure of the transfer function plus noise model constructed by Seleshi (1996) is fitted to the June-September rains for the wet and the dry periods respectively 1939-1964 and 1965-1990. Interesting results emerged from these models (table 2 and fig. 3). For both periods, only parameters associated with SST over the Tropical East Pacific Ocean which represent El-Niño effects are highly significant, and the transfer function plus noise models explain more than 80 % variance of the observed June-September rainfall amounts. R^2 is 0.85 for the wet period and R^2 is 0.81 for the dry period. Three-month-ahead forecasts for both wet and dry periods trace the observed rainfall very well (fig. 3).

5. Result and Discussion

When the transfer function plus noise models for the wet period and the dry period are compared, we see a difference in parameter values of $\in_0$, the coefficient that multiplies April-June SST over the Tropical East Pacific Ocean of year t. For the wet period $\in_0 = -25.5$ whereas for the dry period $\in_0 = -95.5$. This means that for the dry period 1965-1990 the El Niño effect $\in_0 = -95.5$ is felt strongly ($\sim$ 4 times of the wet period) on the rains in the same year. So warming of the SST (positive anomaly of the SST) of year t results in below average rains on year t over the north-central Ethiopian highlands, the converse is also true.

A close examination of the time series of the SST over the Tropical East Pacific Ocean in the periods 1939-1964 and 1965-1990 shows an average warming of the Tropical East Pacific Ocean SST by about 26 % in the period 1965-1990 as compared to the SST in the period

Table 2

Valid transfer function plus noise models for wet and dry periods for ln transformed June-September rains over the north-central Ethiopian highlands Y_t. The wet period here is 1939-1964 and the dry period is 1965-1990. Column 2 provides model input definition. Column 3 gives estimated parameter values and their standard errors, columns 4 and 5 give fraction of observed variances explained by the transfer function plus noise model R^2 and residuals standard error σ_e. All parameters are significant at 95 % confidence level

Period 1	Model inputs 2	Transfer function plus noise model 3	R^2 4	σ_e 5
Wet 1939-1964	April-June **Tropical East Pacific** sea surface E_t	$\pm .1930$ $Y_t = 5852 - 25.5233E_t + 65.6037\ E_{t-1} + \frac{(1 - .9873B^4)}{(1 - .6332B + 2.941B^3)} e_t$ $\pm 11.\ \ \pm 12.9475\ \ \pm 11.8289\ \ \ \pm .1603\ \ \ \pm .1476$	.812	67.168
Dry 1965-1990	April-June **Tropical East Pacific** sea surface E_t temperature and **June Darwin sea level pressures** D_t	$\pm .1837$ $Y_t = .5767. - 95.4777\ E_t - 81.098D_{t-2} + \frac{(1 - .9474\ B^4)}{(1 + .2183\ B^3)} e_t$ $\pm .4\ \ \ \pm 9.1740\ \ \ \pm 11.5452\ \ \ \pm .1565$	.851	47.350

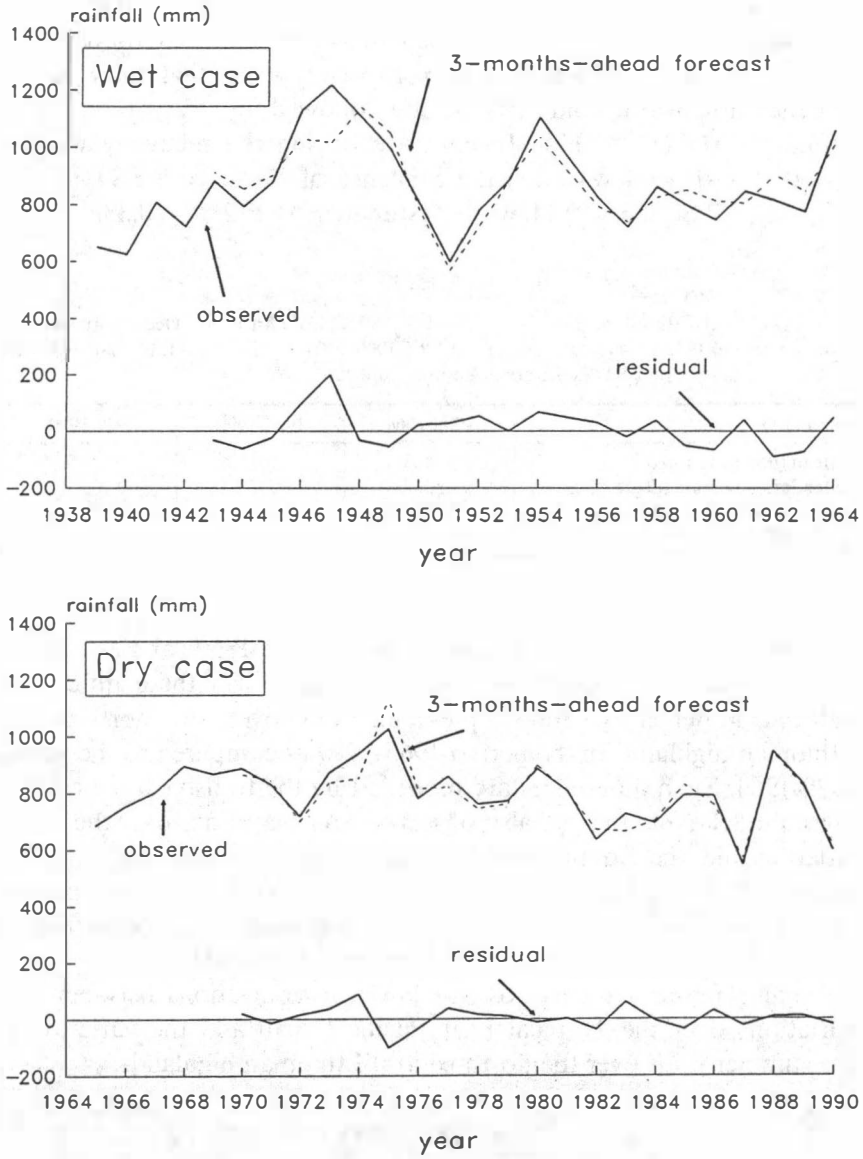


Fig. 3. — Observed series and three-month-ahead forecasts obtained by the transfer function plus noise models for wet and dry periods for the summer (June-September) rainfall amounts over the north-central Ethiopian highlands. The periods are defined as : wet period 1939-1964 with mean rainfall of 860 mm and dry period 1965-1990 with mean rainfall of 794 mm. The three-month-ahead forecasts begin from the year 1943 for the wet period and from the year 1970 for the dry period. Residuals from the transfer function plus noise models are also shown.

1939-1964 (table 3). At the same time the variability is reduced by 3.3 %. Persistent structure of the SST also markedly changed for the two periods. During the relatively cooler period 1939-1964 there was a tendency for warm/cold SST to be followed by warm/cold SST, estimated ACF(1) = 0.35. In contrast, during the relatively warmer period 1965-1990 it was seen the existence of warm/cold SST in year t if year $t - 2$ SST was cold/warm, estimated ACF(2) = – 0.33.

Table 3

Statistical characteristic of the April-June SST over the Tropical East Pacific Ocean corresponding to the wet period 1939-1964 and the dry period 1965-1990 in the north-central Ethiopian highlands. SST Values are deviations from 1951-1980 mean

Period	1939-1964	1965-1990	1939-1990
Mean (degree Celsius)	+ .465	+ 0.631	+ .548
Standard deviation (degree Celsius)	+ 3.860	+ 3.736	+ 3.800
Autocorrelation coefficient at lag 1 (lag 2)	+ 0.35 (.04)	+ 0.03 (– 0.33)	+ 0.19 (– 0.20)

Indeed, the mean and the persistency of the Tropical East Pacific Ocean SSTs are different for the two periods. So these differences induced a deficit in June-September rains over the north-central Ethiopian highlands in the period 1965-1990 as compared to the period 1939-1964. Such differences are modelled by the transfer function plus noise model. Note that we also observed SST warmings over the South Atlantic and the South Indian Oceans. But we found based on the transfer function plus noise model that over these two short periods they do not significantly contribute towards explaining the variability of the rains over the north-central Ethiopian highlands.

Finally, figure 4 shows possible physical associations between SST variations over the Tropical East Pacific Ocean and the variation of the summer rains over the north-central Ethiopian highlands.

6. Conclusion

Based on the transfer function plus noise model it is seen that mainly April-June SST variation over the Tropical East Pacific Ocean induced the reduction (by about 8 %) in the summer (June-September) rainfall amounts over the north-central Ethiopian highlands in the period 1965-1990 as compared to the period 1939-1964. This is so because :

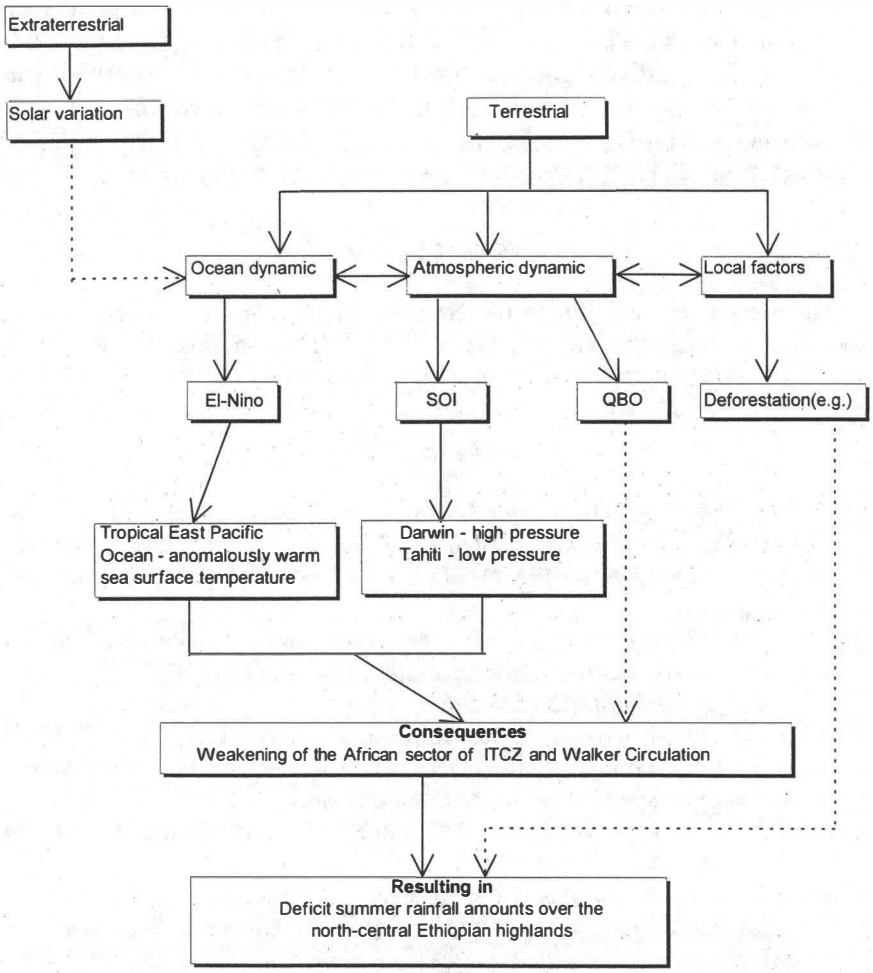


Fig. 4. — A flow chart outlining possible physical mechanisms for the causes of the summer rainfall amounts deficit over the north-central Ethiopian highlands. Dashed lines show relationships that are difficult to quantify as compared to the relationships shown by the solid lines.

— Tropical East Pacific Ocean SSTs were warmer on average by 26 % in the dry period 1965-1990 as compared to the wet period 1939-1964.

— The yearly autocorrelation (yearly persistency) of the Tropical East Pacific Ocean SSTs is markedly different in the dry and wet periods : during the relatively cooler period (wet period) 1939-1964 there was a tendency for warm/cold SST to be followed by warm/cold SST, estimated ACF(1) = 0.35. In contrast, during the warmer period 1965-1990 no such persistency was found (ACF(1) = 0.03).

ACKNOWLEDGEMENTS

The authors are grateful to the National Meteorological Services Agency in Addis Ababa, Ethiopia, for making the precipitation data available. I am grateful for the financial support of ABOS, Belgium.

REFERENCES

Babu, A. 1991. The influence of El Niño/Southern Oscillation (ENSO) on the Ethiopian seasonal rainfall. — Long-Range Forecasting Research Report Series No. 14, WMO/TD No. 395, Trieste, Italy, 8-12 April 1991, 13 pp.

Beltrando, G. & Camberlin, P. 1993. Interannual variability of rainfall in the eastern Horn of Africa and indicators of atmospheric circulation. — *Int. J. Climatol.*, **13** : 533-546.

Bottomley, M., Folland, C. K., Hsiung, J., Newell, R. E. & Parker, D. E. 1990. Global ocean surface temperature atlas. — Joint Meteorological Office/MIT project, HMSO, London.

Box, G. E. P. & Jenkins, J. M. 1976. Time series analysis and forecasting. — Holden-Day, 575 pp.

Demarée, G. R. & Nicolis, C. 1990. Onset of Sahelian drought viewed as a fluctuation- induced transition. — *Q. J. R. Meteorol. Soc.*, **116** : 221-238.

Fantoli, A. 1965. Contributo alla climatologia dell'Etiopia. — Riassunto dei Risultati e Tabelle Meteorologiche e Pluviometriche, Ministero degli Affari Esteri, Roma, 558 pp.

Folland, C., Owen, M., Ward, M. N. & Colman, A. 1991. Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. — *J. of Forecasting,* **10** : 21-56.

Griffiths, J. F. & Hemming, C. F. 1972. A rainfall map of Eastern Africa and Southern Arabia. — East African Meteorological Department, Memoirs, Vol. III, No. 10, 42 pp. + map.

HAILE, T. 1990. Drought in Ethiopia. — *In* : Extended abstracts of papers presented at the Third WMO Symposium on Meteorological Aspects of Tropical Droughts with Emphasis on Long- Range Forecasting (Niamey, Niger, 30 April — 4 May, 1990), WMO/TD — No. 353, pp. 273-278.

HILLMER, S. C. & TIAO, G. C. 1979. Likelihood Function of Stationary Multiple Autoregressive Moving Average Models. — *Journal of the American Statistical Association*, **74** : 652-660.

ININDA, J., DESALEGNE, B. & BEFEKADU, A. 1987. The characteristics of rainfall in Ethiopia and its relationship to El-Niño Southern Oscillation. — *In* : Proceedings of the First Technical Conference on Meteorological Research in Eastern and Southern Africa. Nairobi, Kenya, 6-9 January 1987, pp. 133-135.

LAMB, P. J. 1985. Rainfall in sub-Saharan West-Africa during 1941-83. — *Zeitschrift für Gletscherkunde und Glazialgeologie,* **21** : 131-139.

NICHOLSON, S. E. 1989. Long-term Changes in African Rainfall. — *Weather,* **44** (2) : 46-56.

SCA 1992. Forecasting and Time Series Analysis Using the SCA Statistical System. — Scientific Computing Associates, P.O. Box 625, DeKalb, Illinois 60115, U.S.A., Vol. 1.

SELESHI, Y. 1996. Stochastic prediction of summer rainfall amounts over the northeast African highlands and over India. — Ph.D. dissertation, Interuniversity Programme in Water Resources Engineering, Vrije Universiteit of Brussels, Belgium, V.U.B.-Hydrologie (**30**), 351 pp.

SELESHI, Y. & DEMARÉE, G. R. 1995. Rainfall variability in the Ethiopian and Eritrean highlands and its links with the Southern Oscillation index. — *J. of Biogeography*, **22** : 945-952.

SELESHI, Y., DELLEUR, J. W. & DEMARÉE, G. R. 1994. Sunspot numbers as a possible indicator of annual rainfall at Addis Ababa, Ethiopia. — *Int. J. Climatol.*, **14** : 911-923.

SELESHI, Y., DEMARÉE, G. R. & VANNITSEM, S. 1993. Statistical Analysis of Long-term Monthly and Annual Ethiopian Precipitation Series and their Relationship with ENSO Events. — *In* : Proceedings of the International Workshop on Climate Variabilities (IWCV), 13-17 July 1992, Beijing, China ; *China Meteorological Press Foreign Language Book*, **11** : 80-92.

WOOD, A. C. & LOVETT, R. R. 1974. Rainfall, drought and the solar cycle. — *Nature*, **251** : 594-596.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 532-555 (1998)

Application of Pure Run-off Models in Low Flow Analysis of Awash River Basin in Ethiopia

by

Fekadu MOREDA *, Georges VANDEWIELE **,
Gaston DEMARÉE *** & Willy BAUWENS *

KEYWORDS. — Periodic Autoregressive Models ; Thomas-Fiering Model ; Monte Carlo Simulation ; Low Flow Analysis.

ABSTRACT. — This paper reports on the application of three stochastic pure run-off models, Periodic Autoregressive (PAR), Thomas-Fiering (TF) and Simplified Thomas-Fiering (STF) models, to six monthly flows of subbasins located in the Awash River Basin in Ethiopia. The structures of the models are described and methods of parameter estimation and statistical tests are discussed. The model performances are tested by several statistical tests on residuals and on forecasting and simulation, and according to the test results, a model is selected for each subbasin for applications in low flow studies. The study showed that the TF model is good enough compared to the PAR model except for one river. The PAR and TF models are fairly good in forecasting at one month horizon, while the STF model is not a good model even compared to forecasting by seasonal means. The study on design of reservoir capacity by simulated flows using the models showed that the simulated flows by STF model result in greater capacities of reservoirs than PAR or TF models, especially for high demands and return periods. It has been observed also that for lower demands such as 50 % of long-term mean flow and return periods of ten to twenty years, the simulated flow of STF results in the same capacities as the other models.

* Laboratory of Hydrology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).
** Center for Statistic and Operational Research, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).
*** Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

MOTS-CLES. — Modèles autorégressifs périodiques ; Modèles Thomas-Fiering ; Simulation Monte-Carlo ; Etiages.

RESUME. — *Application des modèles d'écoulement stochastiques purs aux étiages de la rivière Awash en Ethiopie.* — Cette étude porte sur l'application de trois modèles d'écoulement stochastiques purs : le modèle autorégressif périodique (PAR), Thomas-Fiering (TF), et Thomas-Fiering simplifié (STF), aux écoulements semestriels des sous-bassins dans le bassin de la rivière Awash en Ethiopie. Les structures de ces modèles sont décrites et l'estimation des paramètres est discutée. La performance des modèles est analysée par plusieurs tests statistiques aux résidus, à la prévision et à la simulation, et suivant les résultats des tests, un modèle est choisi pour chaque sous-bassin pour des applications à l'étude des étiages. Cette étude montre que le modèle TF est suffisamment bon comparé au modèle PAR, excepté pour une seule rivière. Les modèles PAR et TF sont relativement bons en prévision à l'horizon d'un mois, où le modèle STF n'est pas bon, même appliqué aux prévisions saisonnières. L'étude de projet de la capacité du réservoir par simulation des écoulements en utilisant les modèles a montré que les écoulements simulés par le modèle STF résultent dans des capacités plus élevées des réservoirs que par les modèles PAR ou TF, particulièrement pour des demandes importantes et de longues périodes de retour. Il fut observé aussi que pour des demandes plus faibles, telles que 50 % de la moyenne de l'écoulement sur une longue période et des périodes de retour de dix à vingt années, les écoulements simulés par le modèle STF donnent lieu aux mêmes capacités que les autres modèles.

TREFWOORDEN. — Periodieke-autoregressiemodellen ; Thomas-Fiering model ; Monte-Carlo simulatie ; Lage waterstanden.

SAMENVATTING. — *Toepassing van zuivere afvoermodellen voor de analyse van lage waterstanden in het Awash Bekken in Ethiopië.* — Deze bijdrage behandelt de toepassing, via een stochastische analyse, van drie zuivere afvoermodellen, met name de Periodisch Autoregressieve (PAR), de Thomas-Fiering (TF) en de vereenvoudigde Thomas-Fiering (STF) modellen, van de zesmaandelijkse afvoeren van een aantal deelbekkens gesitueerd in het Awash-rivierbekken in Ethiopië. De structuren van deze modellen worden beschreven en de methodes voor de parameterschatting en statistische testen worden besproken. De prestaties van de modellen werden onderworpen aan verschillende statistische methodes die werden uitgevoerd op residus, voorspelling en simulatie. Afhangend van de testresultaten werd een model geselecteerd, voor ieder deelbekken, voor de toepassingen in tijden van lage afvoer. De studie heeft aangetoond dat het TF-model, met uitzondering van één rivier, goed is in vergelijking met het PAR-model. De PAR- en TF-modellen zijn redelijk goed voor voorspellingen die beperkt blijven tot één maand. Het STF-model daarentegen blijkt niet geschikt te zijn, zelfs indien vergeleken met seizoenale

voorspellingen. De studie van de ontwerpen voor het berekenen van de bekkencapaciteit, gebaseerd op gesimuleerde vloeden en gebruik makend van de modellen, heeft aangetoond dat de gesimuleerde vloeden met het STF-model grotere bekkencapaciteiten aangeven in vergelijking met de PAR- of TF-modellen, en zeker voor terugkeerperiodes en voor periodes wanneer de vraag hoog is. Verder werd waargenomen dat in periodes van lage vraag, zoals 50 % van de gemiddelde langetermijnvloed, en terugkeerperiodes van tien tot twintig jaar, de gesimuleerde vloed met het STF-model resulteert in dezelfde capaciteiten zoals deze berekend worden met de andere modellen.

1. Introduction

Low flow is defined on a seasonal basis and linked with the annual solar cycle and its regional or even local climatic factors (McMahon & Arenas 1982). A tropical regime has only one season during which there is only one period of low flow. An equatorial regime, on the other hand, is marked by two rainy seasons and two dry seasons usually of unequal length ; there is a corresponding absolute low flow and a secondary or relative low flow. Generally low flow of a river may be defined as the flow that exists during the period of no precipitation or small magnitude of precipitation.

Low flow studies are required whenever a water resource project aims to use run-of-the-river waters and when flow regulation is to be seasonal. Moreover as a result of man's activity, if the regime of the stream is to be substantially disturbed, it is of vital importance to have a sound understanding of the rivers' low flows and their characteristics. Water quality of waste water receiving rivers also depends on the availability of low flows.

Frequency analysis of historical records hardly gives the amount and duration of flows with given return period in a good precision especially when the record length is short. Therefore, there is a need to investigate the low flow amounts duration and return periods using a stochastic approach. The purpose of stochastic data generation modelling is to produce synthetic streamflow sequences with the same statistical parameters as the observed record. From a number of synthetic hydrological sequences, each of a given length, it is possible to examine the likely occurrences of low flows more systematically than is possible by conventional procedures, and hence to create a better basis for design.

There exist several models to generate synthetic streamflows, which can be grouped into two major categories depending on the structure and the data utilized.

The first category is the one which uses rainfall run-off models. First a rainfall run-off model is established. Several rainfall run-off models are available such as Simple Linear rainfall run-off models (KACHROO *et al.* 1991), Linear Perturbation Models (KOTHYARI *et al.* 1993), Monthly Water Balance Models (XU 1992) and many others. Then the rainfall series is generated using stochastic models such as ARIMA models (BOX & JENKINS 1976) or rainfall generators (MARIEN & VANDEWIELE 1986). The generated synthetic rainfall series is eventually transformed into the streamflow sequences by using the appropriate rainfall run-off models.

The second category is the so-called data generation by Monte Carlo simulation using pure run-off models such as AR, ARMA or ARIMA, Thomas-Fiering, the Non-Gaussian Multi-Component (NGM) (VANDEWIELE & DOM 1989, ZEBENE 1992). In this type of flow generation, first the time series of flow (daily, weekly, monthly or a longer-time base) is modelled using reasonable length of records. Then Monte Carlo simulation is possible by generating random numbers between 0 and 1, which can easily be transformed into random numbers of the required distribution which will be coupled with the model to give generated flows.

The second methodology is applied in this paper focusing on two objectives. The first one is to model the monthly stream-flow series of the Awash basin by pure run-off models available in literature. This consists of model selection, model estimation and verification with respect to the type of application. Secondly, from a set of models, a model is selected as the best model to use for applications in low flow studies.

2. Model Equations and Parameter Estimations

2.1. THE PERIODIC AUTOREGRESSIVE MODEL (PAR)

The present formulation of the PAR equation and parameter estimation follow the methodology developed by WANG & VANDEWIELE (1994). Let x_{ij} denote the seasonal streamflow (possibly transformed streamflow) during year i and season j, where $j = 1, 2, \ldots P$ and P is the number of seasons in the year. For example, $P = 12$ and

$P = 52$ for monthly and weekly flow series respectively. The seasonal mean is given as :

$$\overline{x_I} = \frac{1}{Y} \sum_{i=1}^{Y} x_{ij} \tag{1}$$

where Y is the length of the data in years. By subtracting the seasonal mean from the flow series a new series Z_{ij} is obtained :

$$Z_{ij} = x_{ij} - \overline{x_j} \tag{2}$$

The PAR model representing Zij may be written as :

$$Z_{ij} = a_{1j} Z_{ij-1} + a_{2j} Z_{ij-2} + \ldots a_{\omega jj} Z_{ij-\omega j} + e_{ij} \tag{3}$$

where a_{kj} are the periodic autoregressive coefficients and e_{ij} is an independent random variable with mean zero and standard deviation σ_j *and where* ω_j *is the order associated with season* j. It should be noted that in equation (3), when the second index of Z is non-positive, the complement with period P must be taken and the first index has to be diminished by a unit. This model is formulated on the concept that the departure from its long term mean flow of a month j is given as a function of the departures from their long-term mean flows of previous months $j-1$, $j-2$, etc. plus the random component which is not accounted for, such as measurement error and rainfall variations.

Equation (3) may be written in short form by using the backward shift operator B :

$$A_j(B)\, Z_{ij} = e_{ij} \tag{4}$$

The polynomial $A_j(B)$ has the following form :

$$A_j = 1 - a_{1j} B - a_{2j} B^2 - \ldots - a_{\overline{\omega} j} B^{\omega j} \tag{5}$$

Hence, the PAR model for period P has the parameter set of $\{a_{1j}, a_{2j}, \ldots a_{\omega j}, \sigma_j, j = 1, 2, \ldots \omega_j\}$ which are estimated from data.

For a non-periodic AR(1) model (*i.e.* when a_j *and* σ_j, $j = 1, 2, \ldots$, P are constant), the parameter space of $a_j = a$ is defined by the stationary condition $-1 < a < 1$ (Box & Jenkins 1976). Obeysekera & Salas (1986) showed that equivalent stationary condition for PAR(1) of period P is given as :

$$\left| \prod_{j=1}^{P} a_j \right| < 1 \tag{6}$$

For the general PAR model, the parameter spaces are too complicated to describe, and hence the generation of the data using the model for longer time could indicate whether the generated series is stationary.

2.2. Parameter Estimation

For the PAR model, since the likelihood function is factorized according to the seasons, order and parameters of a season can be separately identified and estimated. Actually parameters are estimated using the method of minimizing the sum of square of errors, *i.e.* the Least Square Method. For the purpose of easy representation of a season j the matrix form of equation (3) may be written as follows :

Let
$$Z_j^T = | \; z_{1j} \, z_{2j} \ldots z_{yj} \; |$$
$$X_j = \begin{vmatrix} Z_{1j-1} \, Z_{1j-2} \cdot Z_{1j-\omega_j} \\ Z_{2j-1} \, Z_{1j-2} \cdot Z_{1j-\omega_j} \\ Z_{Yj-1} \, Z_{1j-2} \cdot Z_{1j-\omega_j} \end{vmatrix}$$
$$A_j^T = | \; a_{1j} \, a_{2j} \ldots a_{\omega jj} \; |$$
$$E_j^Y = | \; e_{1j} \, E_{2j} \ldots e_{yj} \; |$$

where $[.]^T$ denotes the transpose of a matrix. Then the matrix form of PAR for season j is written as :

$$Z_j = X_j \, A_j + E_j \tag{7}$$

The sum of squares SSQ of residuals as a function of parameter vector A_j is given by :

$$SSQ\,(A_j) = (Z_j^T - A_j^T \, X_j^T)\,(Z_j - X_j \, A_j) \tag{8}$$

It can be shown that the maximum likelihood and least squares estimates of A_j are identical and equal to :

$$\hat{A}_j = (X_j^T \, X_j)^{-1} \, X_j^T \, Z_j \tag{9}$$

and the covariance of $\hat{A}_j$ is estimated by :

$$Cov\,(\hat{A}_j) = \sigma_j^2 \,(X_j^T \, X_j)^{-1} \tag{10}$$

where

$$\sigma_j^2 = \frac{SSQ\,(\hat{A}_j)}{Y - \overline{\omega}_j - 1} \tag{11}$$

The half width of the 95 % confidence interval (HWCI) of an estimate of parameter a_{kj} is :

$$HWCI(\hat{a}_{kj}) = 1.96\,\sigma_{kj} \tag{12}$$

where σ_{kj} is the square root of the *k-th* diagonal element of Cov $(\hat{A})$. Model identification is performed first by assuming a maximum order for the seasonal autoregressive coefficients. The feedback from the parameter estimates, *i.e.* the check of significance of the estimates, leads to further increase or decrease of the orders.

2.3. Thomas-Fiering Model (TF)

This model is apparently a special case of the PAR model, whereby the order of autoregression for all seasons is supposed to be one. This model has been commonly used to generate streamflows since it has been described by Thomas & Fiering (1962). The structure of the model is the same as in PAR model whereby $\omega_j = 1$ and hence equation (3) may be simplified as :

$$Z_{ij} = a_j Z_{ij-1} + e_{ij} \tag{13}$$

where all symbols are as defined in the previous section but the parameter set is now $\{a_j, \sigma_j, j = 1, 2, \ldots P\}$. The model parameters can easily be obtained from data. It can be shown that maximum likelihood estimates of the model parameters are given as :

$$\hat{\sigma}_j = s_j \sqrt{1 - r_j^2}, \qquad \hat{a}_j = r_j \frac{s_j}{s_{j-1}} \tag{14), (15}$$

where

$$s_j = \sqrt{\frac{1}{Y}\sum_{i=1}^{Y} Z_{ij}^2}, \qquad r_j = \frac{\frac{1}{Y}\sum_{i=1}^{Y} Z_{ij}^2}{s_j\, s_{j-1}} \tag{16}$$

The above equations depict that parameter estimation of the TF model requires, after reduction of the seasonal mean, computation of standard deviation of each season and autocorrelation of a season with a preceding season. Then the parameters are computed as shown in equation (14) and (15).

2.4. Simplified Thomas-Fiering Model (STF)

Further simplification of the TF model could be possible if the standard deviations and correlation do not exhibit large differences

for all seasons. If this model is successful in statistical tests it has an advantage over the previous models since it is parsimonious. The structure of the model is :

$$Z_{ij} = a\, Z_{ij-1} + e_{ij} \tag{17}$$

where all symbols are as defined in the previous section but the parameter set is now $\{a, \sigma\}$, which are common for all the seasons. It can be shown that maximum likelihood estimates of the model parameters are given as :

$$\hat{a} = \frac{1}{\hat{\sigma}^2 YP} \sum_{i=1}^{Y} \sum_{j=1}^{P} z_{ij}\, z_{ij-1}, \qquad \hat{\sigma} = \sqrt{\frac{1}{YP} \sum \sum z_{ij}^2} \tag{18}$$

The simplified Thomas-Fiering model is equivalent to AR(1) model after removal of seasonal mean. The same approach as for the AR(1) model could also be used for the stationary condition. In fact, the stationary condition is always fulfilled in this case since the parameter estimate of a is identical to the correlation coefficient between a season and the preceding season. The half width of confidence interval of the parameter is also inferred from the estimates of 95 % confidence of correlation coefficient as :

$$HWCI\,(\hat{a}) = \frac{1.96}{\sqrt{YP - 1}} \tag{19}$$

3. Data and Catchment Characteristics

This study is based on the streamflow data of the Awash Basin in Ethiopia (fig. 1). The total catchment area of the Awash basin is 112,697 km^2 which is characterized by its closed river system (no outlet to the sea) unlike most of the catchments where the rivers flow either to the neighbouring countries and hence to the sea. The estimated average annual areal rainfall ranges between 500 and 1,000 mm. The major rainy season is between June and mid September with a short monsoon rain from March to April. The annual minimum and maximum temperatures are 14 °C and 32 °C respectively. There are two major soil types in the catchment ; the deep red clay soil, Nitosol, and the dark clay soil, Vertisol (ALEM 1989). The Nitosols are found in the upland areas, whereas the Vertisols are found in lowland areas with slopes ranging from 2 to 8 %.

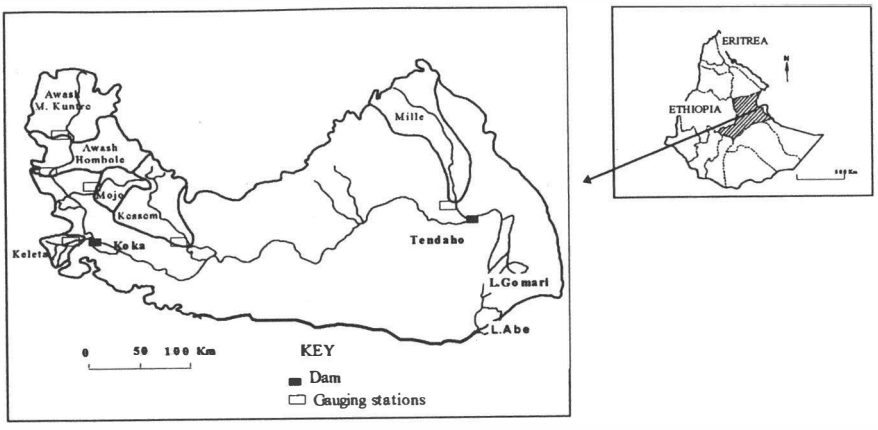


Fig. 1. — Location of the study subcatchments within the Awash River Basin (*Source* : Ethiopian Valleys Development Studies Authority).

The streamflow data are selected on the basis of two merits. First the streamflow should not be affected by major human activities such as regulation and diversion of the river since these effects cannot be accounted for by stochastic models. Secondly, the data should have reasonable length of record to draw rational conclusions from the analyses. Based on these two aspects six subbasins are considered which could reasonably represent the basin. Table 1 shows the major catchment characteristics.

Table 1

Catchment characteristics of the subbasins

River	Station	Reference period	Area (km^2)	Annual rainfall (mm)	Annual flow (mm)	Run-off coeff.
Awash	M. Kuntre	1966-1992	4,456	1,110	174	0.156
Awash	Hombole	1963-1992	7,656	997	191	0.191
Keleta	Sire	1967-1988	746	900	196	0.218
Mojo*	Mojo	1968-1992	1,205	890	119	0.133
Kessem	A. Melka	1969-1990	3,113	830	145	0.175
Mille	Mille	1965-1987	4,550	665	61	0.092

* missing data (1981-1982).

4. Results and Discussion

4.1. Selection of Flow Transformation

One of the conditions required to apply the models described in section two is that the seasonal flows have to be normally distributed. For this purpose the original data series were compared to the corresponding theoretical normal distribution for each month by Kolmogorov-Smirnov tests. The result obtained indicated that the monthly flow series are not normally distributed. Three transformations, namely square root, cube root and logarithmic, are proposed to transform the data, to obtain normally distributed series. Comparisons of original and transformed series with the theoretical normal distribution showed that all transformations have reduced the deviation from the theoretical distribution. The logarithmic transformation is found to be the best for the considered series. Therefore, all series are then transformed using the logarithmic transformation prior to model calibration.

4.2. Model Selection and Parameter Estimation

For the PAR model, selection of models was performed first by assuming a high order of regression and then parameters are estimated and compared to their HWCI. If an estimated parameter is smaller than its HWCI then the order is reduced for that month. If all estimated parameters for a month are greater than their HWCI then the order is increased. This trial and error procedure sometimes resulted in the reduction of the PAR model to the TF model. Also different orders of regression for different months are sometimes obtained.

The three models are calibrated for the selected six streamflow series. The discontinuous data of Mojo river has taken care of while modelling whereby the correlation of the month January for the year 1983 and the number of years for January is reduced by one for TF model and the number of data points are reduced by one for STF models.

Table 2 shows an example of parameter set. In this table the model parameter estimates of the PAR and TF models are given within one table for a given streamflow series, because for most of the months the values are identical. When different values are encountered, the two sets of model parameters are given for both. Table 3 shows an example of parameter estimates of the parsimonious model STF which has only two parameters for a streamflow series.

Table 2

PAR and TF model parameter estimates and 95 % confidence limits (HWCI) for Mojo river at Mojo station. The parameter estimates for both models are identical except for January through April

Month j		Parameters a_{1j}, a_{2j}, a_{3j}	HWCI (a_{1j}, a_{2j}, a_{3j})	Standard deviation σ_j
1	TF	0.787	0.269	0.792
	PAR	1.261,-0.524	0.389,0.350	0.667
2	TF	0.681	0.232	0.688
	PAR	0.998,0.-0.748,0.545	0.380,0.591,0.369	0.364
3	TF	0.898	0.252	0.657
	PAR	0.557,0.390	0.356,0.312	0.583
4	TF	0.835	0.204	0.576
	PAR	0.454,0.497	0.312,0.337	0.490
5		0.689	0.295	0.805
6		0.673	0.330	0.887
7		0.226	0.234	0.654
8		0.481	0.300	0.507
9		0.652	0.414	0.604
10		0.763	0.542	0.937
11		0.848	0.390	1.015
12		0.732	0.218	0.716

Table 3

STF model parameter estimates and 95 % confidence limits (HWCI) for Mojo river at Mojo station

Parameter a	HWCI (a)	Standard deviation σ
0.698	0.118	1.061

In general, for most of the subbasins the PAR model parameter estimates of higher order autoregression coefficients are statistically not different from zero and hence the PAR model is reduced to the TF model. The estimates are significant only in February for Keleta, January to April for Mojo (table 2) and August for Kessem. It is also noted that some parameter estimates are greater than one which would have violated the stationary condition of non-seasonal AR models. However in our case the absolute value of the product of all the parameter estimates should be smaller than one. This condition

is satisfied at least for TF and STF models. The stationary condition for the PAR models is tested indirectly by simulating synthetic flows, *i.e.* if long-term generation does not lead to diverging terms or resulting with very high values.

For PAR and TF models in some of the months the parameter estimates are less than the corresponding HWCI indicating that the flow of the present month is independent of the previous month (*e.g.* July and June flow for Mojo river). The model standard deviations σ_j are found to be smaller when higher orders are introduced, showing the model accuracy improvement. On the other hand, one can see that the model standard deviation s of STF which applies for all months is very high compared to the PAR and TF models.

4.3. Tests on Trend, Seasonality and Independence of Residuals

The standarized residual series obtained after fitting the models are tested on seasonality, trend and independence. Generally the residuals from PAR and TF models are non-seasonal for all the time series considered. From the time series plot of residuals (fig. 2), we observe that for Awash M. Kuntre the PAR and TF model resulted in random residuals. The STF model also resulted in a fairly equal number of positive and negative residuals. On the other hand, it can be seen from figure 3 that the TF and STF models resulted in residuals which are most of the time positive. To the contrary the residuals from the PAR model are non-seasonal and random. The premature conclusion could be drawn from this observation that the PAR model is best for the Mojo river. However, the model has yet to be tested for other analyses.

To check the independence of residuals the autocorrelation function of the residuals is computed versus time-lag. The autocorrelations of the residual series obtained from the three models and for all the rivers considered at lag ≥ 1 are all within the half width of critical interval.

4.4. Tests on Normality of Residuals

The Kolmogorov-Smirnov test is used to compare the distribution of the residual series with the theoretical normal distribution and the critical limits for the deviations are given at 5 % significance level. From table 4 one can see that the maximum deviations of the residuals from STF models exceeded the critical limits for Awash at M. Kuntre, Awash at Hombole and Mille. The tests for the PAR and TF models show the normality of the residuals.

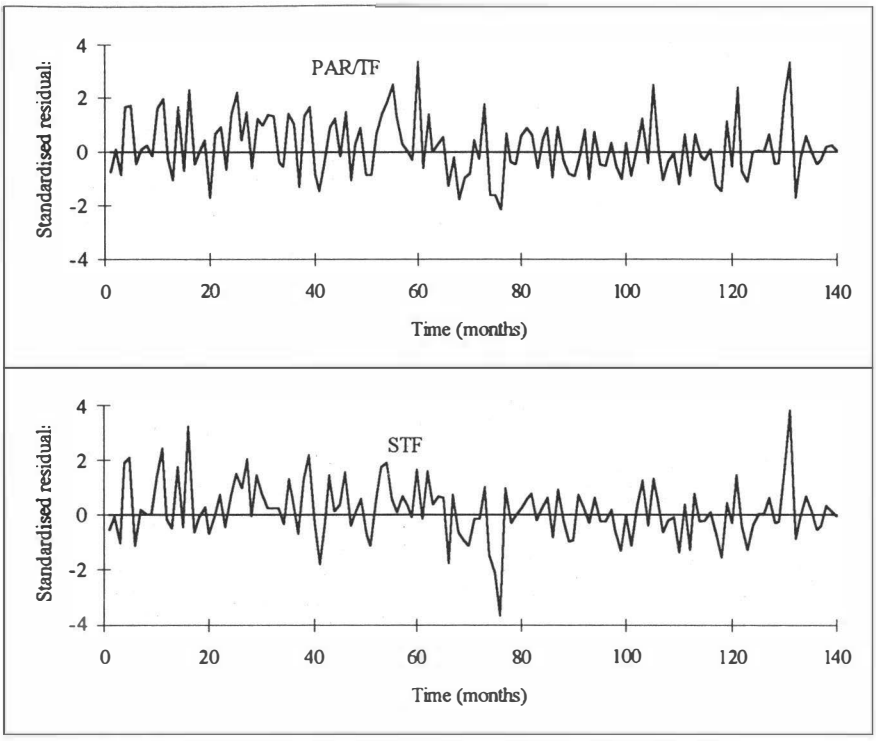


Fig. 2. — Time Series Plot of residuals from the three models for Awash River at Hombole.

Table 4

Kolmogorov-Smirnov normality test for the entire series of residuals for the three models at 5 % significance level

Catchment	Critical Deviation	Maximum observed deviation		
		PAR	TF	STF
Awash - M.Kuntre	0.076	0.056	0.056	0.086
Awash - Hombole	0.072	0.058	0.058	0.076
Keleta	0.084	0.053	0.057	0.061
Mojo	0.082	0.054	0.059	0.046
Kessem	0.084	0.064	0.067	0.069
Mille	0.082	0.057	0.057	0.093

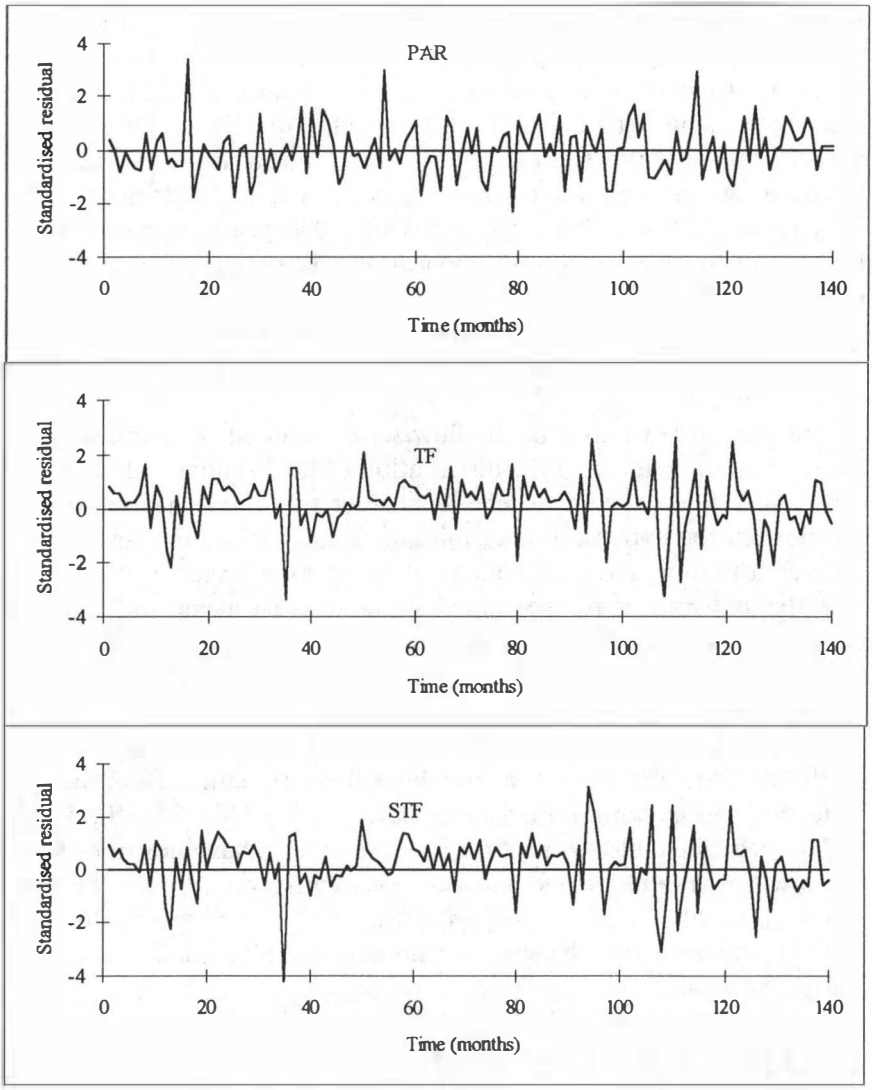


Fig. 3. — Time Series Plot of residuals from the three models for Mojo River at Molo.

4.5. Model Test on Simulation

After having calibrated the models, Monte Carlo simulation is possible by first generating an independent random variable which is normally distributed with mean zero and variance one. Then Z_{ij} are calculated using equations (3), (13) and (17) for PAR, TF and STF models respectively. Adding the seasonal mean to this series and eventual retransformation (if the original flow was transformed) result in a synthetic flow. Generated series of 1,000 years are sufficient to obtain a relatively good test for applications. To initialize the generation, the mean values of the first few seasons for the PAR model, the first season for TF and STF models are taken as known value. The first 50 years of generated data may be discarded to eliminate the effect of initialization.

The general behaviour of the flow series is tested by comparing the statistical parameters and the distribution of the original and generated series. It is also essential to check whether the model has reasonably reproduced the extreme flows : minimum and maximum flows within different duration and total volume of flow within a year. It is observed that the statistics of the generated flows such as mean and standard deviations are conserved. This also indicates that the stationary condition mentioned earlier is satisfied for each of the time series considered.

The three models have reproduced the same distribution for most of the months and both low and high flow extremes. Here also we note that the maximum deviations have smaller values for PAR and TF models (see tables 5 and 6). The three models have not reproduced the low flow events of one and two consecutive months for the Mille River (table 6). As far as the simulation test is concerned, the PAR and TF models show the same results and the STF model results are fairly similar also.

4.6. Tests on Forecasting

One of the applications of pure run-off models is to forecast the streamflows at time $t + h$ given flows on previous time points including time t. According to the model equations in section 2 the expectation of the stochastic term e_{ij} is zero ; hence the point forecasts for the three models are given as follows.

For the PAR model, let $Z_{ij}(h)$ be the forecast of $Z_{ij} + h$ with information on flow up to and including month j in the year i, then

Table 5

Kolmogorov-Smirnov tests of the distribution of extreme events with different durations generated from observed and simulated monthly flows. Critical deviation = 0.252 at 5 % significance level. Awash/Hombole

Duration (months)		Maximum observed deviation	
		PAR and TF	STF
Low flow	1	0.120	0.172
	2	0.082	0.100
	3	0.087	0.099
	6	0.072	0.144
	9	0.074	0.123
High flow	1	0.080	0.179
	2	0.085	0.194
	3	0.096	0.197
	6	0.102	0.188
	9	0.093	0.174
Annual flow		0.096	0.174

Table 6

Kolmogorov-Smirnov tests of the distribution of extreme events with different durations generated from observed and simulated monthly flows. Critical deviation = 0.290 at 5 % significance level. Mille river. The underlined values exceed the critical limit

Duration (months)		Maximum observed deviation	
		PAR and TF	STF
Low flow	1	<u>0.328</u>	<u>0.357</u>
	2	<u>0.304</u>	<u>0.336</u>
	3	0.175	0.203
	6	0.178	0.206
	9	0.066	0.104
High flow	1	0.134	0.210
	2	0.132	0.176
	3	0.102	0.150
	6	0.145	0.186
	9	0.124	0.155
Annual flow		0.113	0.117

h is the lead time or forecast horizon. By taking expectation, equation (3) is transformed into :

$$\hat{Z}_{ij}(h) = a_{1j+h-1}\,\hat{Z}_{ij}(h-1) + a_{2j+h-2}\,\hat{Z}_{ij}(h-2) + \ldots + a_{\omega j+h\omega_j}\,\hat{Z}_{ij}(h-\omega_j) \quad (20)$$

For the TF model this becomes :

$$\hat{Z}_{ij}(h) = a_{j+h-1}\,\hat{Z}_{ij}(h-1) \quad (21)$$

The above equation is equally valid for the STF model, where in this case the model parameter for each season is constant $a_{ij} = a$. It is clear that for $h\text{-}k \leq 0$, $\hat{Z}_{ij}(h\text{-}k)$ is observed, *i.e.* equal to Z_{ij+h-k}. By adding the seasonal mean $\bar{X}_{j+h}$ to $\hat{Z}_{ij}(h)$ a point estimate $\hat{x}_{ij}(h)$ of flow x_{ij+h} is obtained.

The quality of forecast is measured by the Root Mean Squared Error, RMSE. Since all models described are seasonal models, it is proposed that the RMSE of a model may be compared to the RMSE of the naive model which always gives the seasonal mean as point forecast. The RMSE is given as :

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(\hat{x}_t - x_t)} \quad (22)$$

where $\hat{x}_t$ and x_t are forecasted and observed flows at time point t respectively and n is the total number of point estimate obtained. Since the monthly flows are seasonal the RMSE of forecasts for only 9-month (October to June) low flow period is separately calculated (see table 7).

Table 7

Comparison of the RMSE of models and seasonal means for 1 and 2-month horizon forecasts on low flow period (9 months)

Catchment	Root mean squared error of forecasts by :						
	Seasonal mean	PAR		TF		STF	
		Hor. 1	Hor. 2	Hor. 1	Hor. 2	Hor. 1	Hor. 2
Awash/M.Kuntre	23.22	22.99	23.57	22.99	23.57	24.16	23.62
Awash/Hombole	14.98	13.28	13.07	13.28	13.07	13.58	14.23
Keleta	5.39	4.56	4.74	4.96	5.10	6.05	4.98
Mojo	5.27	3.63	3.99	4.00	4.78	6.07	5.71
Kessem	11.22	7.52	8.00	8.67	9.00	11.32	9.82
Mille	15.32	15.49	15.66	15.49	15.66	15.62	15.66

It is observed that the PAR and TF model forecasts are better than the seasonal mean forecasts for time horizon 1 month but not much improvement has been observed for time horizon 2 months. The STF model forecasts are resulting with RMSE of larger value than the seasonal mean forecast for time horizons 1 and 2.

4.7. Final Monthly Model Choice

4.7.1. Simulation

PAR and TF models generally show good results under the statistical tests considered with the exception of low flow extremes for Mille river. Maximum deviation observed in comparing the distribution of monthly flows and extreme events of observed and generated flows are systematically higher in STF than the PAR and TF but not significantly. The application of STF model in simulation, therefore, is limited. However, in preliminary studies the few STF parameters may be related to physical characteristics of catchments which then can be used for ungauged catchments.

4.7.2. Forecasting

STF model has nearly no improvement and often even worse forecast than seasonal mean. So the STF model has no forecasting ability at all which is attributed to highly seasonal variability of flow. The TF model and still more the PAR model show slight improvements for all basins except Mille, although sometimes the RMSE is higher than with the monthly means (especially with horizon 2). Hence the forecast is limited to one-month horizon.

5. Applications in Low Flow Studies

We have seen that the stochastic models are capable of generating longer simulated streamflow series which have the same statistical properties as the historical record. On the simulated series one can study the low flow duration and return periods without regulation of the river. In addition, when a river has to be subjected to regulation by building a dam, a reservoir capacity required to meet certain static or dynamic demand could be designed by using the generated flows. This section is devoted to show these two applications of the models.

5.1. Low Flow Duration - Return Period Curves

Low flow frequency analyses use data that are independent and homogeneous and therefore they can be used to determine the probability of occurrence of a flow event of specific magnitude. To obtain an independent series the annual minimum series are used for the analysis, which is valid for duration less than or equal to twelve months. For duration longer than twelve months a partial duration series is appropriate.

The low flow frequency analysis of the six selected streamflow series is performed for durations of one, two, three, six and nine months. The TF model is used to generate 1,000 years of simulated flow for all rivers except for Mojo river where the PAR model is used.

From the flow duration - return period relationships for the rivers studied (fig. 4), it is evident that for example the flow that could be available within a month, with an average failure of once in ten years, ranges from 0.15 million m^3 (Mojo) to 3 million m^3 (Awash at Hombole). This shows that even for relatively small demands of water from the river the reliability of the supply without regulation is very small for the rivers considered.

The Awash river at Hombole can cater for a limited amount of supply without any regulation of the river. The river can supply at least about 3 and 2 million m^3 per month with an average failure of once in ten and a hundred years respectively. Relatively speaking, the low flows of Mojo, Kessem and Mille rivers are very small, so that any project requiring reliable water supply needs a reservoir. The other two rivers, Awash at M. Kuntre and Hombole and Keleta, have at least some potential for diversion without regulation.

5.2. Reservoir Capacity Design

A comprehensive review and classification of most of the currently used reservoir capacity estimation procedures is given by MacMahon & Mein (1978) and Kachroo (1983). In this study the critical period method is used where the inflows are considered to be stochastic processes. Hence we use the simulated flows as inflow.

Let S_t = the storage at the beginning of month t, K = capacity of a reservoir, D_t = monthly demand and Q_t = generated monthly flow, where all the volumes are in the same units, for example million m^3. Then the storage at the beginning of month $t + 1$ is given as :

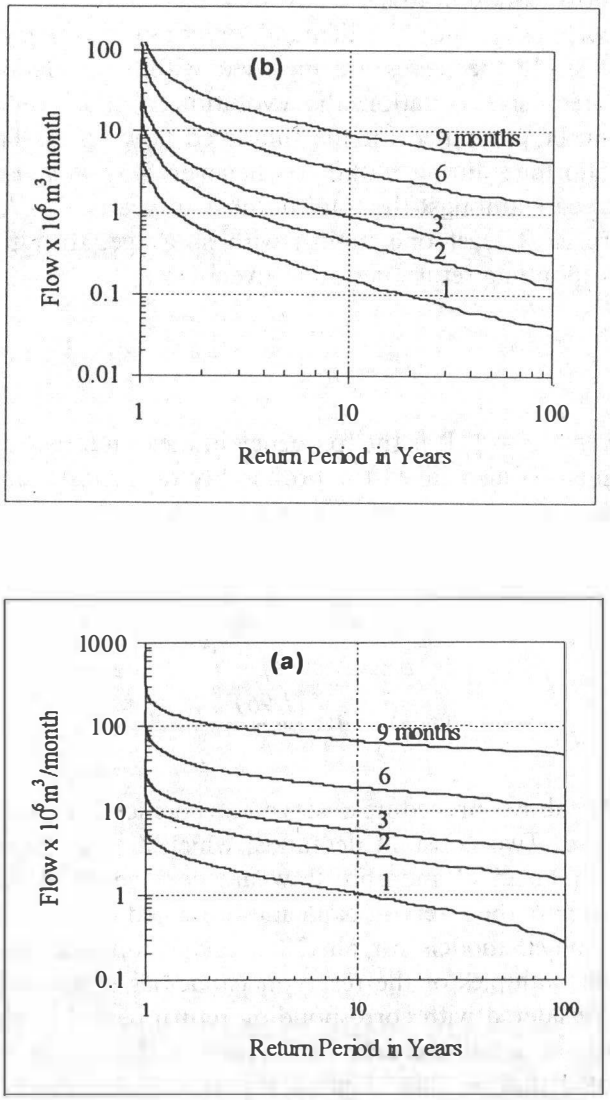


Fig. 4. — Low flow duration - return period relationships for a) Awash at Hombole and b) Mojo at Mojo.

$$S_{t+1} = \max (S_t + Q_t - D_t, 0) + \min (O, K - S_t - Q_t + D_t) \quad (23)$$

In the above equation losses from the reservoir such as evaporation can be incorporated into the demand or considered separately. For the present study the losses are included within the demand. Using the above recursive equation the evolution of the content of the reservoir can be computed for the simulated flow series. Then we say there is a shortage during month t whenever $S_{t+1} = 0$. Let s be the number of years amongst the total number of years $N = 1{,}000$ during which there is at least one month with shortage, then the estimate of the corresponding return period is given as :

$$R = \frac{N}{s} \quad (24)$$

and the inverse $F = 1/\mathrm{R}$ is the frequency in mean number of shortages per year and F is also called the probability of a shortage. The upper and lower boundaries of the 95 % confidence interval are approximately (VANDEWIELE *et al.* 1993) :

$$\frac{F + \frac{(1.96)^2}{2N} \pm 1.96 \sqrt{\frac{F(1-F)}{N} + \frac{(1.96)^2}{4N^2}}}{1 + \frac{(1.96)^2}{N}} \quad (25)$$

Using the above procedure reservoir capacities for the six stations are computed. Two constant demands, which are about 50 and 70 % of long-term mean of monthly flow are considered at each station. We also compare the reservoir capacities obtained from simulated flows using the studied models for all rivers under consideration. Figure 5 shows some examples of the reservoir capacities required for the two demands considered with corresponding return period of shortages for Awash river at Hombole and Mojo river at Mojo. At this stage it may be noted that, in these figures, the axis of the reservoir capacity can easily be transformed into height of the dam required at a selected dam site which in turn is transformed into the investment required. Hence this relationship is really a very important tool in making decisions at the planning stage both in technical and economic aspects.

The comparison of the results obtained by the PAR or TF and STF model shows that, for the first demand, *i.e.* 50 % of mean and

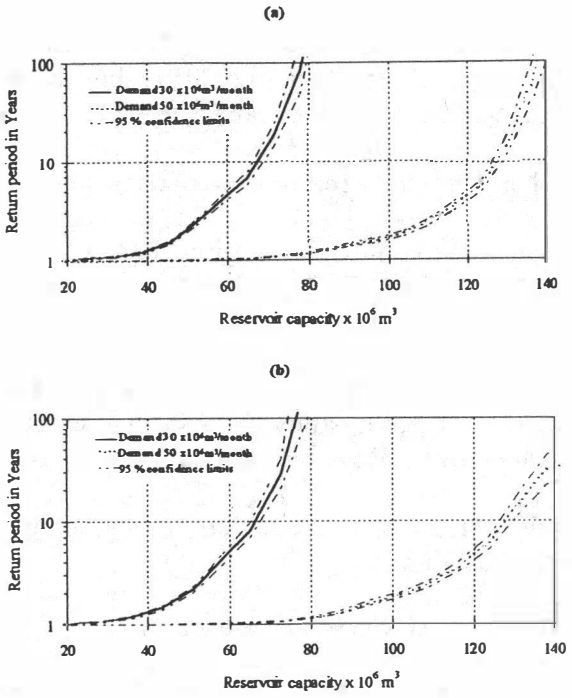


Fig. 5. — Return period versus reservoir capacity for given demands for Awash River at M. Kuntre using simulated flow by a) TF model and b) STF model.

smaller return periods less than ten to twenty years, the three models resulted in comparable reservoir capacities. But it is observed that for higher return periods and especially for the second demand the reservoir capacities are found to be higher for STF model than for PAR or TF model. Hence the STF model may be used to simulate flows for the purpose of reservoir design in cases of smaller demands and lower return periods. On the other hand, when the demand is high the application of the STF model is not recommended.

6. Conclusions

The following general conclusions are drawn from the study :

— In dealing with models requiring normally distributed series, the logarithmic flow transformation is found to be appropriate for the river flows considered.

— The TF model is good enough as compared to the PAR model except for Mojo river.
— Forecasting ability of the PAR and TF is limited perhaps due to physical characteristics of the catchments of having not much memory.
— STF model is bad in forecasting even compared to forecasts of monthly means.
— Reservoir capacity required for a given demand is overestimated by simulated flows from STF model as compared to the PAR or TF models, especially when higher demands and longer return periods are considered.
— For simulation purposes STF model may be used (with the above limitation) in a regional study in assessing water resources of ungauged catchments. However, more experience is needed in this regard.
— For Mille river all the three models are unsatisfactory in simulating low flows of short duration.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Hydrology Department of Ethiopian Water Resource Authority for providing the streamflow data. This study was carried out with grant of scholarship to the first author by the Vrije Universteit Brussel, Advice Councel for Development Co-operation (VUBAROS).

REFERENCES

ALEM, G. 1989. Monthly Pure Runoff Model for the Upper Awash River Catchment in Ethiopia. — M.Sc. Thesis, IUPHY, VUB, Brussels. 107 pp.

BOX, G. E. P. & JENKINS, G. M. 1976. Time Series Analysis, Forecasting and Control. — Holden-Day, San Francisco, 543 pp.

KACHROO, R. K. 1983. Storage Capacity and Yield Analysis. — Ph.D. Thesis, National University of Ireland, Galway, pp. 11-25.

KACHROO, R. K, BRUEN, M. & LIANG, G. C. 1991. Workshop on River Flow Forecasting. — Lecture Notes, Dept. of Engineering Hydrology, University College, Galway, Ireland.

KOTHYARI, U. C., ARAVAMUTHAN, V. & SINGH, V. P. 1993. Monthly Runoff Generation Using the Linear Perturbation Model. — *J. Hydr.*, **144** : 371-379.

MACMAHON, T. A. & ARENAS, A. D. 1982. Methods of computation of low streamflow — Studies and Reports in Hydrology, Unesco, 94 pp.

MacMahon, T. A & Mein , R. G. 1978. Reservoir Capacity and Yield. — Elsevier Scientific Publishing Company, Amsterdam.

Marien, J. L. & Vandewiele, G. L. 1986. A Point Rainfall Generator with Internal Structure. — *Water Resources Research*, **22** (4) : 475-482.

Obeysekera, J. T. B. & Salas, J. D. 1986. Modelling of Aggregated Hydrologic Time Series. — *J. Hydr.*, **86** : 197-219.

Thomas, H. A. & Fiering, M. B. 1962. Mathematical Synthesis of Streamflow Sequences for the Analysis of River Basin by Simulation. — *In* : Design of Water Resources Systems, Harvard University Press, Cambridge, Massachusetts, pp. 459-493.

Vandewiele, G. L. & Dom, A. 1989. A Non-Gaussian Multicomponent Pure Run-off Model. — *Water Resources Research*, **25** : 387-404.

Vandewiele, G. L., Xu, C.-Y. & Ni-Lar-Win 1993 Methodology for Constructing Monthly Water Balance Models in Basin Scale. — Publication of the Laboratory of Hydrology, No. 20, VUB, Brussels, 60 pp.

Wang, Z. M. & Vandewiele, G. L. 1994. Forecasting and Monte Carlo Simulation of Zaire River Flow. — *In* : Proceedings of the NATO ANSI Symposium on Coping with Floods, Erice, Italy.

Xu, C.-Y. 1992. Monthly Water Balance Models in Different Climatic Regions. — Ph.D. Thesis, IUPHY, VUB, Brussels, 214 pp.

Zebene, E. 1992. Generalization and comparative Study of the Non-Gaussian Multicomponent Models for River Flow. — Ph.D. Thesis, IUPHY, VUB, Brussels, 241 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 556-581 (1998)

Estimation of Latent Heat Fluxes with a Modified Jackson Model applied to Sparse Vegetation : Application to the Hapex Sahel Experiment

by

Bernard TYCHON * & Gabriele WOLLENWEBER **

KEYWORDS. — Jackson's Model ; Daily Evapotranspiration ; Hapex-Sahel ; Latent Heat Flux ; Remote Sensing ; Surface Temperature.

ABSTRACT. — The Jackson Model allows to estimate daily actual evapotranspiration from the integrated daily net radiation and from the difference between surface temperature and air near-midday. Accepting a few assumptions and after mathematical manipulations of the initial model, the daily evapotranspiration can be obtained if the near-midday instantaneous sensible heat fluxes and the daily and near midday net radiation are known. This paper focus on the estimation of the instantaneous sensible heat fluxes. Two approaches are used to estimate them : the first uses a classical approach which represents the surface with a homogeneous single layer. The second model approximates the surface with a double-layer. In the latter model, one layer represents the soil and herbaceous vegetation while the second layer is assumed to represent the foliage of trees or shrubs (high vegetation) depending on the site. Finally, this double-layer model is simplified to allow its use by remote sensors observations. These three models are compared with field measurements during the Hapex-Sahel 92 experiment in Niger. The results show that the classical one-layer model is unable to express the latent heat fluxes of this sparse vegetation while the two double-layer models appear promising and need further developments.

* Fondation Universitaire Luxembourgeoise, avenue de Longwy 185, B-6700 Arlon (Belgium).

** University of Reading, Department of Meteorology, 2 Early Gate, Whiteknights, P.O. Box 239, Reading RG6 6AT (United Kingdom).

MOTS-CLES. — Modèle de Jackson ; Evapotranspiration journalière ; Hapex-Sahel ; Flux de chaleur latente ; Satellite ; Température de surface.

RESUME. — *Estimation du flux de chaleur latente d'une végétation clairsemée par le modèle de Jackson modifié : Application aux expériences Hapex-Sahel.* — Le Modèle de Jackson estime l'évapotranspiration journalière réelle (ET_d) à partir du rayonnement net journalier et de la différence de température instantanée entre la surface et l'air aux environs de midi. Une autre expression de cette relation montre qu'il est possible d'obtenir ET_d si le rayonnement net journalier et instantané ainsi que le flux instantané de chaleur sensible sont connus vers midi. Cet article s'attarde sur l'estimation du flux instantané de chaleur sensible. Deux approches sont utilisées : la première décrit la surface en une seule couche homogène ; la seconde décrit la surface avec une double couche représentant respectivement le sol (ou la strate herbacée) et le feuillage des arbres ou arbustes. Ce modèle double couche est ensuite simplifié pour faciliter son utilisation par des approches satellitaires. Ces trois modèles sont comparés aux mesures de terrain prises pendant la campagne Hapex-Sahel 92. Les résultats obtenus sont médiocres pour le modèle à une seule couche et méritent des recherches complémentaires pour les deux modèles à double couche.

TREFWOORDEN. — Jacksons model ; Dagelijkse evapotranspiratie ; Hapex-Sahel ; Latente warmteflux ; Afstandswaarneming ; Oppervlaktetemperatuur.

SAMENVATTING. — *De schatting van de latente warmtefluxen met een vereenvoudigd model van Jackson toegepast op schaarse vegetatie : toepassing op het Hapex-Sahel Experiment.* — Jacksons model schat de dagelijkse reële evapotranspiratie vertrekkende van de dagelijkse nettostraling en van het verschil tussen de oppervlakte- en luchttemperatuur rond de middag. Een paar veronderstellingen toegelaten en na mathemathische bewerkingen van het initiële model, kan de dagelijkse evapotranspiratie bekomen worden wanneer de onmiddellijk latente warmtefluxen en de dagelijkse evenals de nettostraling rond de middag gekend zijn. Dit artikel spitst zich toe op de schatting van de onmiddellijk latente warmtefluxen. Twee benaderingswijzen worden gebruikt : de eerste gebruikt een klassieke benadering voorgesteld als de oppervlakte met een homogene enkele laag. Het tweede model beschrijft de oppervlakte met een dubbele laag. In het laatste model stelt één laag de bodem en de grasvegetatie voor, terwijl de tweede laag verondersteld wordt het lover van bomen of struiken (hoge vegetatie), afhangende van de site, voor te stellen. Ten slotte wordt dit dubbellagig model vereenvoudigd om het gebruik met afstandswaarnemingstechnieken te vergemakkelijken. Deze drie modellen worden vergeleken met terreinmetingen verkregen tijdens het Hapex-Sahel 92 experiment in Niger. De resultaten tonen aan dat het met het klassieke éénlagig model onmogelijk is de latente warmtefluxen van de schaarse vegetaties uit te drukken terwijl de resultaten van de dubbellagige modellen beloftevol schijnen en verder dienen onderzocht te worden.

Introduction

From 1991 to 1993, a large international experiment was carried out in Niger. This experiment, called HAPEX-Sahel (Hydrological Atmospheric Pilot Experiment), was designed to provide data to improve the parametrization of semi-arid land surface processes in General Circulation Models (GCM), because of the possible link between land degradation and climatic change in these regions. This campaign provided many data and observations on different scales to assess, among others, the actual evapotranspiration (ET), the most important parameter of the water balance in this part of the world (reaching values above 90 % of the precipitation). Most of the time, the ET distribution along the year is more important than the total annual ET for vegetation and it is crucial to know the ET at well-defined critical periods depending on phenolgical stages of the plant.

In the Sahel, cultivated crops behave like natural vegetation because they are limited by the amount of precipitation during the wet period and by the nutrients provided by soils. Such behaviour of the cultivated crops suits particularly well for a remote estimation of the ET. The main interest of the remote sensor can be found in its powerful way for extrapolating from point ground measurements to the regional scale, a scale used for the global monitoring and the food early warning systems.

This paper will analyse the aptitudes of a model adapted to remote sensors, derived from Jackson's model, to simulate or assess the daily latent heat fluxes of a surface covered with sparse vegetation, a typical case in the semi-arid and arid regions of the world.

Theoretical Bases

Description of the Jackson Model

One widely used model to describe latent heat fluxes with remote sensors is the Jackson Model (Jackson *et al.* 1977). It gives estimates of daily actual evapotranspiration of a site from the integrated daily net radiation and from the difference between surface temperature and air temperature near midday. It is restricted to use in cloud-free conditions if satellites are to be included.

$$ET_d = Rn_d + a - b\,(T_0\text{-}T_a)_t \quad (1)$$

where ET_d = actual daily evapotranspiration (W/m^2) ;
Rn_d = daily net radiation (W/m^2) ;
T_{0t} = surface temperature (or air temperature at the sink/source of sensible flux) near midday (K) ;
T_{at} = air temperature near midday (K) ;
a and b = fitted coefficients ;
t = instantaneous value ;
d = daily value ;
a and b are the fitted coefficient of the linear regression analysis.

Some authors (SEGUIN *et al.* 1983 , CASELLES *et al.* 1992, VIDAL & PERRIER 1989) gave a physical meaning to a and b.

If the daily ground heat flux (G_d) and advection are neglected in a surface energy balance

$$H_d = Rn_d - Et_d = a - b\,(T_0\text{-}T_a)_t \quad (2)$$

where H_d = daily sensible heat fluxes (W/m^2).

Unfortunately, H_d cannot be estimated from a single satellite overpass. Only instantaneous measurements of the sensible heat flux are available. But if we assume (SEGUIN *et al.* 1983) that there is a strong correlation between the ratios of daily to near-midday instantaneous sensible heat fluxes and net radiation, *i.e.* :

$$H_d/Rn_d = H_t/Rn_t \quad (3)$$

then

$$Rn_d - Et_d = H_d = H_t\,(Rn_d/Rn_t) = a - b\,(T_0 - T_a)_t \quad (4)$$

Having Rn_d and Rn_t, the estimation of Et_d will simplify to the estimation of the instantaneous sensible heat flux.

ESTIMATION OF THE INSTANTANEOUS SENSIBLE HEAT FLUX

Two approaches are used to estimate the instantaneous sensible heat flux near midday (fig. 1). The first uses the classical approach which simplifies the surface to a homogeneous single layer. The second model approximates the surface with a double layer. In the latter model, one layer represents the soil and herbaceous vegetation while the second layer is assumed to represent the foliage of trees or shrubs (high vegetation) according to the site. Some authors (CHOUDHURY &

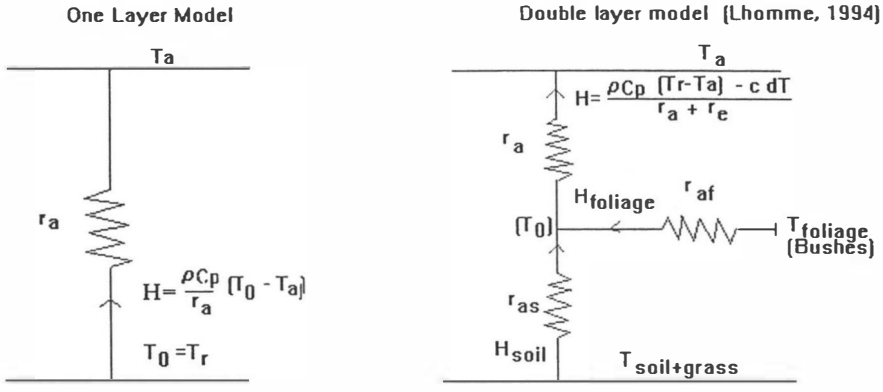


Fig. 1. — Schematic description of sensible heat fluxes models with one and two layers.

MONTEITH 1988) developed models with more than two layers but here, knowing the available data, the two-layer model was preferred.

The two-layer model is described as a look-like electrical schema with two resistances in parallel preceded by one resistance in series. The two parallel resistance (r_{as} and r_{af}) represent respectively the aerodynamic resistance between the substrate and the canopy source height and the bulk layer resistance of the foliage per unit ground area. The upper series resistance is the aerodynamic resistance (r_a) between reference height and canopy source height.

The potential differences which induce the fluxes (H_t) are the differences of temperatures between the different layers, *i.e.*, the foliage temperature and the soil + grass temperature and the air temperature. T_0 is the air temperature at the canopy source height. It is also called the aerodynamic surface temperature. Its value is *a priori* unknown but, as there is an equality between the fluxes leaving the canopy and the sum of the fluxes coming from the foliage and from the substrate, T_0 might be recovered by iteration, changing the estimated T0 until the equality of the fluxes is reached. For the single layer model, r_a has the meaning of the two-layer model and T_0 is equal to the surface temperature measured by a radiometer (T_r).

From these two models, two descriptions of the instantaneous sensible heat flux are obtained :

With the one-layer model

$$H_t = \frac{\rho Cp}{r_a} (T_r - T_a) \tag{5}$$

With the two-layer model (LHOMME *et al.* 1993)

$$H_t = \frac{\rho Cp\,[(T_r - T_a) - c\delta T]}{r_a + r_e} \tag{6}$$

where ρ = air density (kg/m^3) ;
Cp = specific heat of air (J/kg/K) ;
T_r = surface temperature (K) measured with a radiometer ;
T_a = air temperature (K) at the reference height ;.
$\delta T = T_s - T_f$;
T_f = shrubs foliage temperature (K) ;
T_s = average soil + grass temperature (K) ;
r_e = combined resistance of r_{as} and r_{af} (s/m) ;
r_a = aerodynamic resistance (s/m).

Equation (6) shows that H_t is not simply proportional to the temperature difference between the surface and the air. It must be corrected by a term proportional to the temperature difference between the substrate and the foliage. Obviously, with a homogeneous and dense cover (T and r_e are equal to 0 and equation (5) = (6)).

r_e is the resulting resistance of two resistances in parallel :

$$r_e = \frac{r_{as}\, r_{af}}{(r_{as} + r_{af})} \tag{7}$$

The parameter c is defined by :

$$c = \left[\frac{1}{(1 + r_{af}/r_{as})} \right] - f \tag{8}$$

with f = fractional vegetation cover.

The fractional cover is obtained by using the radiometric surface temperature being here either an aircraft or a satellite radiometric measurement. It is assumed to be the area-weighted mean of shrubs and grass (soil) temperatures (CHOUDHURY1989, KALMA & JUPP 1990, LHOMME *et al.* 1994). After some simple mathematical transformations f is defined as :

$$f = \frac{T_r - T_s}{T_f - T_s} \tag{9}$$

The bulk boundary layer resistance of the shrub canopy raf and the aerodynamic resistance between the substrate and the canopy r_{as} have been calculated according to developments from CHOUDHURY & MONTEITH (1988) and LHOMME *et al.* (1994).

In neutral conditions, the aerodynamic resistance r_a was estimated using a classical micrometeorological relationship. In non-neutral conditions, the ratio between the stability corrected aerodynamic resistance and the aerodynamic resistance in neutral situations is expressed as a function of the Richardson Number (VINEY 1991). As LHOMME *et al.* (1994), we have used the expression given by CHOUDHURY *et al.* (1986) and recommended by KALMA & JUPP (1990) for pasture with incomplete cover. These relationships were sucessfully applied to a sparse fallow site in Niger by LHOMME *et al.* (1994).

NEW ASSUMPTIONS

The application of the double-layer model with remote sensors requires information about high vegetation foliage and about soil + herbaceous vegetation. This problem might dramatically reduce the interest in this type of remote observation-based model. That is why an adaptation has been searched to avoid this inconvenience. A new double assumption is proposed :

$$T_s = T_r \tag{10}$$

$$T_f = T_a \tag{11}$$

These assumptions were taken because of the observed similarities between the air temperature and the surface temperature of the foliage and between the temperature of the soil and of the measured average surface temperature. This results mainly from the low vegetation fractional cover ($< 30\,\%$) of all three sites, a common situation in this part of the world. The lower the fractional cover, the closer will be surface temperature to soil temperature. Moreover, the very weak vegetation (not dense) will be unable either to confine air under its canopy or to put high quantity of water in the air. Consequently, air will keep its properties (temperature, humidity) and foliage temperature and air temperature will be close to each other. It is as if the surface foliage knew the way to reduce its temperature up to air temperature

(not below), by transpirating via its stomatal system. More research is required to state precisely when conditions are met to allow the above simplifications.

A less drastic assumption might have been taken, as the one from LHOMME *et al.* (1994) who considered a linear regression between the two different temperatures instead of a perfect equality. But this type of empirical relationships is difficult to use outside the site of its establishment. It comes mainly from the difficulties in measuring accurately, in the field, even average surface temperatures, average foliage temperature or average grass (or soil) surface temperature with radiometers on heterogeneous vegetation.

This double assumption impacts on a and b in the third line of table 1. This new model is called "Modified double layer model". The three different models were compared with the field measurements which, in the following, will be considered as the reference.

MATHEMATICAL DEFINITION OF A AND B IN THE JACKSON MODEL

To summarize, according to the models used to describe Ht, the regression coefficients a and b of equation (1) are given in table 1.

Table 1

Mathematical definition of the parameters a and b in the three Jackson Models

	a	b
Simple-layer model	$-\left(\frac{H_d}{Rn_d}-\frac{H_t}{Rn_t}\right)Rn_d - G_d$	$\frac{Rn_d}{Rn_t}\frac{\rho Cp}{r_a}$
Double-layer model	$\frac{Rn_d}{Rn_t}\frac{c\delta T\rho CP}{r_a+r_e}-\left(\frac{H_d}{Rn_d}-\frac{H_t}{Rn_t}\right)Rn_d - G_d$	$\frac{Rn_d}{Rn_t}\frac{\rho Cp}{r_a+r_e}$
Modified double-layer model	$-\left(\frac{H_d}{Rn_d}-\frac{H_t}{Rn_t}\right)Rn_d - G_d$	$\frac{Rn_d}{Rn_t}\frac{\rho Cp}{r_a+r_e}(1-c)$

Methodology

The objective is to find daily actual evapotranspiration by using the daily net radiation and the instantaneous temperature difference between air and surface. The remote estimation of net radiation has

been studied by numerous people (Li *et al.* 1993, Wollenweber *et al.* 1995) but in this paper, surface observations are preferred.

The first and probably most difficult step in the Jackson Model is to have an accurate estimation of an average surface temperature on a scale used by remote sensors and at the time of each satellite overpass (early to mid-afternoon). This estimation is a typical changing-scale problem : How to estimate the surface temperature of a large area from a few point measurements? Aircraft data, available during the Hapex-Sahel experiment, are the ideal intermediary to go from a field point measurement (from a few cm^2 to a few m^2) to a satellite pixel size area (> 1.2 km^2 for NOAA).

Moreover, in this study, field surface measurements ensure continuity in the observations. They are used to go from the aircraft (Piper), which gives the reference surface temperature (T_r), to the satellite because their time overpasses differ. This is done by using the relationship between the continuous surface temperature measurements on the ground and the Piper reference surface temperature. This relationship gives a continuous estimated average surface temperature (T_{fmod}) that will be assimilated to T_r for comparisons with values given by a satellite at the time of its overpass.

From this spatial averaged surface temperature, three instantaneous sensible heat fluxes from the three models defined above are calculated. Finally, three daily evapotranspirations are obtained by applying the three derived Jackson Models. The root mean square errors (RMSE) of the different results are calculated and compared. An attempt is made to partition the errors between the data quality and the different assumptions included in the three models.

Material

Site Description

This study applies to the Southern Supersite of the Hapex-Sahel Experiment reported by Wallace *et al.* (1994). The Supersite was located on the right bank of the river Niger, around the ICRISAT Sahelian Centre, about 45 km south of Niamey. The area consists of a broad sandy valley next to the river Niger, bordered to the west by extensive laterite plateaux.

Within the behaviour of three contrasting subsites, representing the predominant vegetation types in this area was studied.

1. The millet agricultural land which is used for growing traditionnal crops.
2. Fallow bush or fallow savannah, an agricultural land which has not been cropped since 1986, allowing the natural vegetation to regenerate.
3. Tiger bush, a type of natural open forest. The vegetation is confined to dense bands about 10-30 m wide by 100-300 m long, separated by completely bare crusted soil.

Period of Observation

The analysed days were chosen among the intensive observation period (15/08/92-15/10/92). Within this period days without clouds have been extracted as the Jackson method works only for days with clear sky. Finally, a subset of these days was chosen on the basis of the extent of field and remote observations. The following days were retained for the different subsites.

— Fallow bush subsite : 26/8,3/9,6/9,17/9,18/9,22/9,27/9,28/9 ;
— Millet subsite : 26/8,3/9,6/9,17/9,18/9,22/9,2/10 ;
— Tiger bush subsite : 26/8,3/9,6/9,17/9,18/9,22/9,27/9,28/9,2/10.

In addition, two cloudy days on which aircraft data were available were also analysed. These days are the 1/9 and the 26/9. The aircraft measurements were made below the clouds or during the cloud-free period of the day.

The Different Types of Measurements

Ground Measurements

Among the numerous continuous field measurements of the Hapex-Sahel experiment, the most retained were :

— Tree foliage and soil/grass surface temperature measured with radiometers Everest 4,000 infrared thermometer (8-14 μm) ;
— Net radiation measurements with Radiation Energy Balance Systems (REBS) dual hemisphere singel polyethylene dome Q*5 ;
— Ground heat fluxes with soil heat plates (Middelton) ;
— Sensible and latent heat fluxes, wind and temperature profiles with an adapted sonic anemometer, stability factor and air temperature (Sonic anemometer Hydra).

Some other punctual measurements were made with other instruments. A more detailed explanation of the material is given in the

different CD-ROM of the Hapex-Sahel Experiment (1994) and is summarized by TYCHON (1996).

Aircraft Measurements

A near-infrared radiometer (modified EVEREST 4,000-A with a wavelength window between 10.5 and 12.5 micron) was mounted onto a supporting frame designed to provide nadir and off-nadir (30) viewing directions. The aircraft flying height was 200 m (657 ft) above average ground level. Target speed was 90 knots (46 m/sec). The nominal field of view (at target height) of the Nadir-mounted Everest IRT is 70.5 m diameter. Radiometer measurements were made at 1-second intervals during passage over each subsite.

The Piper measurements avoid the sampling problems encountered with the field measurements concentrated on a few square meters. It also represents the subsite more effectively than can be achieved with the spatial resolution of NOAA data.

Satellite Measurements

In this paper, AVHRR NOAA measurements were not used to estimate average values of surface temperature. It will be limited to field-based average surface temperature.

Results and Discussion

THE SURFACE TEMPERATURE

The Piper aircraft measurements give the best spatial averaged surface temperature and is assumed to be T_r. The problem with the Piper comes from its low overpass frequency, which will need a procedure to estimate T_r at other periods, in particular when NOAA passes above the three subsites.

On the ground, for each subsite, different infrared thermometers measure points representing the two most typical cover situations (bare soil, bushes, grass, etc.). The procedure to get estimated continuous average surface temperature (T_{fmod}) comes from the extraction of T_r in equation 9.

$$T_{fmod} = f\,T_f + (1 - f)\,T_s \cong T_r \qquad (12)$$

Firstly, the fractional vegetation cover (f) will be estimated considering T_r as the Piper surface temperature measurements and taking T_f and

T_s respectively as the mean temperature of the foliage and soil (or grass, depending on the subsite). Afterwards, the three fractional vegetation covers are supposed to stay constant and are used to refind an estimated average surface temperature from the continuous foliage and soil surface temperatures at the time of satellite overpasses. It is called T_{fmod} instead of T_r to remind the way to obtain this average surface temperature. The constant value of the fractional vegetation cover (f) is a first approximation that might be improved in a next research.

In figure 2, the three points mean bushes surface temperature (T_f) and the three points mean grass surface temperature (T_s), both measured with IR thermometers surround, the Piper curve. The bushes that transpirate keep low temperature, part of the radiation received being used to transform liquid water into vapor. The soil behaviour depends on water content. With a high water content, its surface temperature is close to air temperature. Becoming drier, they will use the received energy to produce sensible heat fluxes by increasing the temperature gradient between the surface and the above air layer, thus by increasing their surface temperature.

The fractional vegetation covers of the three subistes obtained from equation 9 are given in table 2.

Table 2

Fractional vegetation cover (f) and statistical parameters describing the relationship between the Piper surface temperatures (T_r) and the surface temperatures of the different covers

	Fallow bush	Millet	Tiger bush
f	0.17	0.30	0.15
R^2	0.999	0.949	0.896
Relationship*	$T_{fmod} = 4.24 + 0.89T_r$	$T_{fmod} = 6.40 + 0.84T_r$	$T_{fmod} = -9.64 + 1.20T_r$
Std error (°C)	0.1	0.95	1.83
N. observation	3	3	3
RMSE (°C)	0.57	0.71	1.49

* T_{fmod} is the temperature obtained with the fractional vegetation cover model ; T_r is the measured surface temperature with the airplane.

Ideally, the average radiometric surface temperature derived from the fractional cover model (T_{fmod}) and the average surface temperature from the Piper (T_r) should be equal. This is not exactly the case but we will consider in the following sections that T_{fmod} is a good approximation of the average surface temperature of the subsite (T_r) and that it can be used in place of the Piper radiometric surface

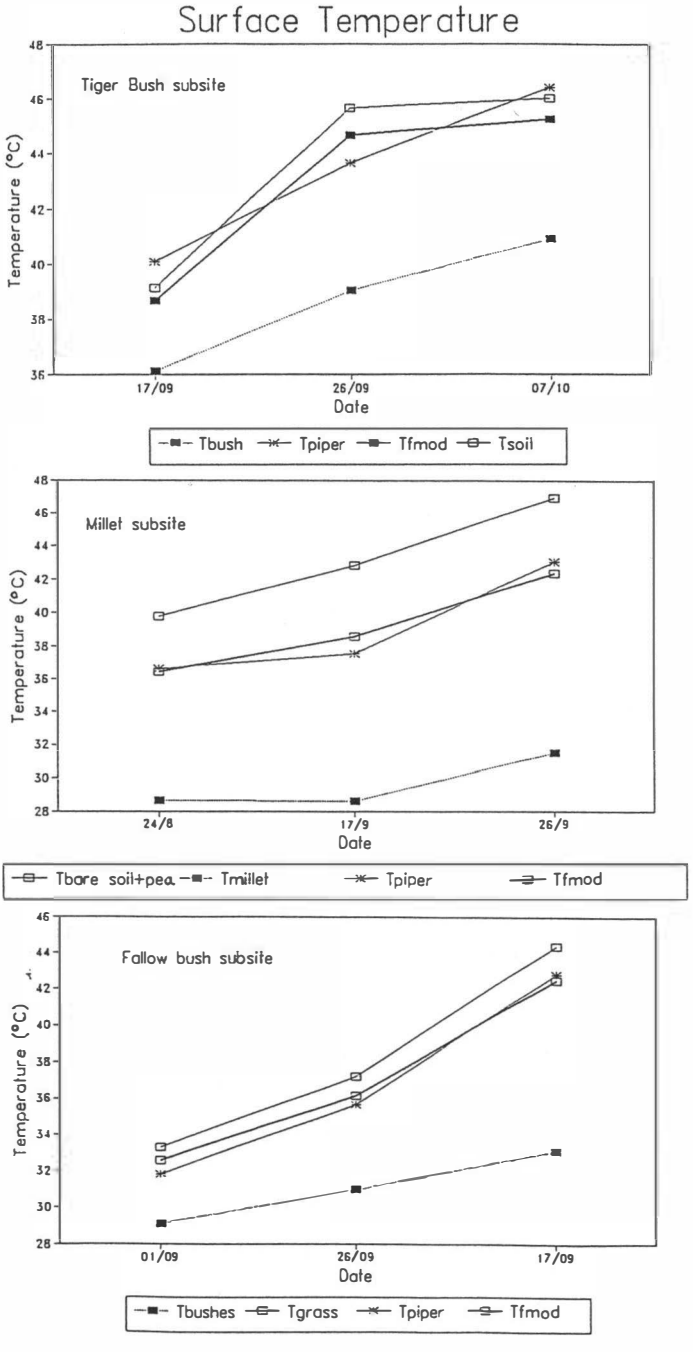


Fig. 2 a, b, c. — Relationships between the Piper radiometric temperature and the two main covers of the three subsites.

temperature measurements. More than three aircraft measurements should have been made for a robuster analysis but this situation is the reality met by people working with remote measurements. In the following, T_r and T_{fmod} will be synonym and will be used undifferently in the text.

The fractional vegetation covers obtained here with equation 9 are quite similar to those found by LHOMME *et al.* (1994) for millet and fallow bush subsites of the Central-West Supersite of the Hapex-Sahel 92 experiment. Concerning the tiger bush subsite, fractional cover estimation was two times lower than what had been calculated for the same subsite by CULF *et al.* (1993) in 1989 and 1990.

The tiger bush statistical results are not as good as the ones of the other subsites. It comes from the standard deviation error of the Piper measurements that are twice those of the other subsites (mean std error = 1.5 C instead of 0.75 C). This higher standard deviation error must be related to the structure of the cover with alternation of large bands of bare soil and equivalent length bands of vegetation. The size of the Piper measurement sample is close to the size of the bands. This can explain a higher heterogeneity in the sampling compared to the two other subsites. But the main reason must be assigned to the Piper 1 September measurement which was doubtful after HANAN (1994) who participated in the observations.

THE INSTANTANEOUS SENSIBLE HEAT FLUX (H_t)

Having obtained an estimation of the surface temperature, equations (5) and (6) and the relation coming from the simplifications of equations (10) and (11) are used to give the instantaneous sensible heat fluxes at the time of the satellite overpass. First, the sensible heat fluxes are estimated from field measurements of surface temperatures (T_{fmod}). The time of ground measurements of surface temperatures used in the method has been fixed to 15 h, the average time of NOAA overpass during this period. The three models presented in the theoretical part give three estimations of the instantaneous sensible heat flux. These heat fluxes are compared among themselves and with the actual measurements.

Several micrometeorological parameters used to describe the different resistances included in the models are given in table 3. Their values have been defined according to field observations or, when no observation was available, to classical relationships as the one from

Table 3

Micrometeorological parameters used in the three subsites

	Fallow bush	Millet	Tiger bush
Reference height (m)	9.9	5.25	18.3
Vegetation height (m)	2.5	2.2	4
Displacement height (m)	1.62	1.43	0.4
Roughness length (m)	0.25	0.22	2
Leaf Area Index	0.7	0.6	0.6

Monteith to recover roughness length and displacement height. The micrometeorological parameters keep their values during the two-month experiment.

The results are presented in figure 3 a, b and c considering the field measurements of the sensible heat flux as the reference. It appears clearly that the simple-layer model, which is the basic model, is unable to describe precisely the heat flux. Its overestimation raises up to 500 %. Such bad results applied to sparse vegetation have already been observed by LHOMME *et al.* (1994) and many others (STEWART *et al.* 1989, KALMA & JUPP 1990, STEWART *et al.* 1994).

The double-layer model fluxes are close to the field measurements for all the subsites. The simplified double-layer model is much closer to the measurements than the single layer-model. Its root mean square error is slightly higher than the non-simplified double-layer model (table 4). On two sites, the simplified model underestimates the fluxes and once it overestimates the observed values. These different behaviours can be explained by looking at the simplifications adopted with this last model. The temperature difference (δT) between bush foliage and grass (or bare soil) is replaced by the temperature difference between the air and the average estimated surface temperature. The use of this simplification with the data of the three subsites decreases T for the millet subsite and increase it for the two other subsites. The millet bare soil is always five to six degrees above the estimated surface temperature whereas this temperature difference is much lower for the two other subsites : around 0 to 1 degree.

Fortunately, the millet plant surface has a temperature above air temperature and thus, the δT difference between the double-layer model and the simplified one will not be as high as the 5 to 6 degrees noted for the soil-surface temperature differences.

Consequently, changing the value of δT in equation (6) changes the sensible fluxes in the same direction. The impact of δT change to the

aerodynamic resistance (r_a) is real but seems very low and can be neglected in a first assumption. In fact, as r_a depends on ($T_0 - T_a$) and as T_0 is obtained by iteration (from the equality of the fluxes from soil + foliage and of those leaving the canopy) it is clear that to take T_a and T_r respectively instead of T_f and T_s will change the value of T_0, and consequently of r_a. This aspect is developped by LHOMME *et al.* (1994).

A good expression of the discrepancies between the sensible heat fluxes measurements and their estimation is given by their root mean square error (RMSE) defined by

$$RMSE = (\sum_{i=1}^{n} (X_{est} - X_{meqs})^2 / n)^{1/2} \quad (13)$$

where X is here the instantaneous sensible heat flux.

Table 4 gathers the different RMSE for the three subsites. When RMSE is divided by the average value of the measurements during those days, it is called "relative RMSE". This last expression of the discrepancy is very interesting because it allows to follow its evolution along the different steps for the estimation of the actual evapotrans-

Table 4

Evolution of the RMSE and the relative RMSE during the different steps of the estimation of the actual evapotranspiration : all the fluxes RMSE and relative RMSE are in W/ m^2. The last three columns express average micrometeorological measurements of H_t, H_d and Et_d. For the fallow bushes, tiger bushes and millet subsites, nine, eight and seven days of data were available respectively

RMSE	Double-layer Model			One-layer Model			Simplified Double Layer Model			**Average Measurements**		
Subsite	H_t	H_d	ET_d	H_t	H_d	ET_d	H_t	H_d	ET_d	H_t	H_d	ET_d
Tiger bush	30.84	12.14	14.53	285.77	141.99	130.62	55.08	14.35	26.06	118.8	44.4	99.9
Millet	25.68	8.38	10.69	491.71	205.53	206.79	31.71	9.69	13.25	87.0	37.57	76.6
Fallow bush	16.70	5.50	6.67	214.84	90.28	89.15	28.56	9.71	27.34	67.5	27.24	113.9
Relative RMSE	Double-layer Model			One-Layer Model			Simplified Double Layer Model					
Subsite	H_t	H_d	ET_d	H_t	H_d	ET_d	H_t	H_d	ET_d			
Tiger bush	0.26	0.27	0.15	2.41	3.20	1.31	0.46	0.32	0.26			
Millet	0.30	0.22	0.14	5.65	5.47	2.70	0.36	0.26	0.17			
Fallow bush	0.25	0.20	0.06	3.18	3.31	0.78	0.42	0.36	0.24			

piration and to see the influence of each of them. The different RMSE and relative RMSE confirm the graphic analysis and give a quantitative expression of the discrepancies between the measurements and the different models.

The Daily Sensible Heat Fluxes (H_d)

To pass from near-midday instantaneous heat fluxes to daily heat fluxes, the assumption given in equation (3) is used. The instantaneous flux is multiplied by the ratio of daily to instanstaneous net radiation. This intermediate step allows to see the impact of the main assumption of Jackson and derived Jackson models. Figure 4 a, b and c is completed by table 6 to express quantitatively the differences of fluxes between the different models.

This step reduces sensibly the RMSE for the three models. This does not mean that this step has improved the quality of the models. One must expect a reduction of the differences between two sets of data when they are both reduced by $\pm$ 2.5, as it is the case here between the instantaneous and the daily values of the sensible heat fluxes. If this step had no effect on the model accuracy, the relative RMSE should stay the same as when calculated for the instantaneous sensible heat fluxes. This is not exactly the case. The relative RMSE is slightly reduced for the double and simplified double-layer models whereas it increases for the single-layer model. The reduction comes probably from the same reason that explains why monthly evapotranspiration can be estimated more precisely than daily evapotranspiration. There is an error compensation among the hourly measurements that give the daily values.

The trends observed in figure 3 a, b and c are still present in figure 4 but the data range is smaller. The measurements range between 20 and 40 W/m^2, 30 and 60 W/m^2, 30 and 45 W/m^2 respectively for the fallow bush, the tiger bush and the millet subsites. The range was 3 to 4 times higher with instantaneous values. This can once more be explained by the reduced dispersion of daily values compared to hourly values used to express instantaneous measurements.

The Daily Evapotranspiration (Et_d)

The objective of this paper is to approach the latent heat fluxes measurements by the three different models and to see how these models deviate from the measurements of the latent heat fluxes.

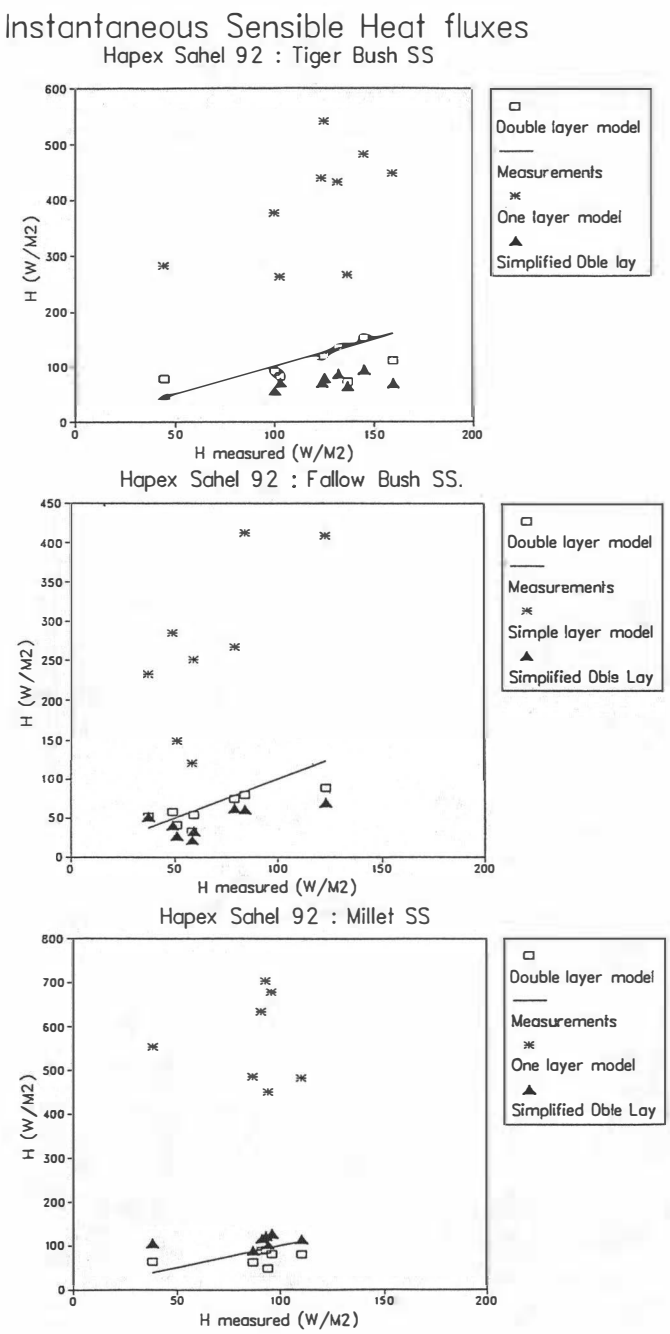


Fig. 3. — Instantaneous near-midday sensible heat fluxes of the three subsites.

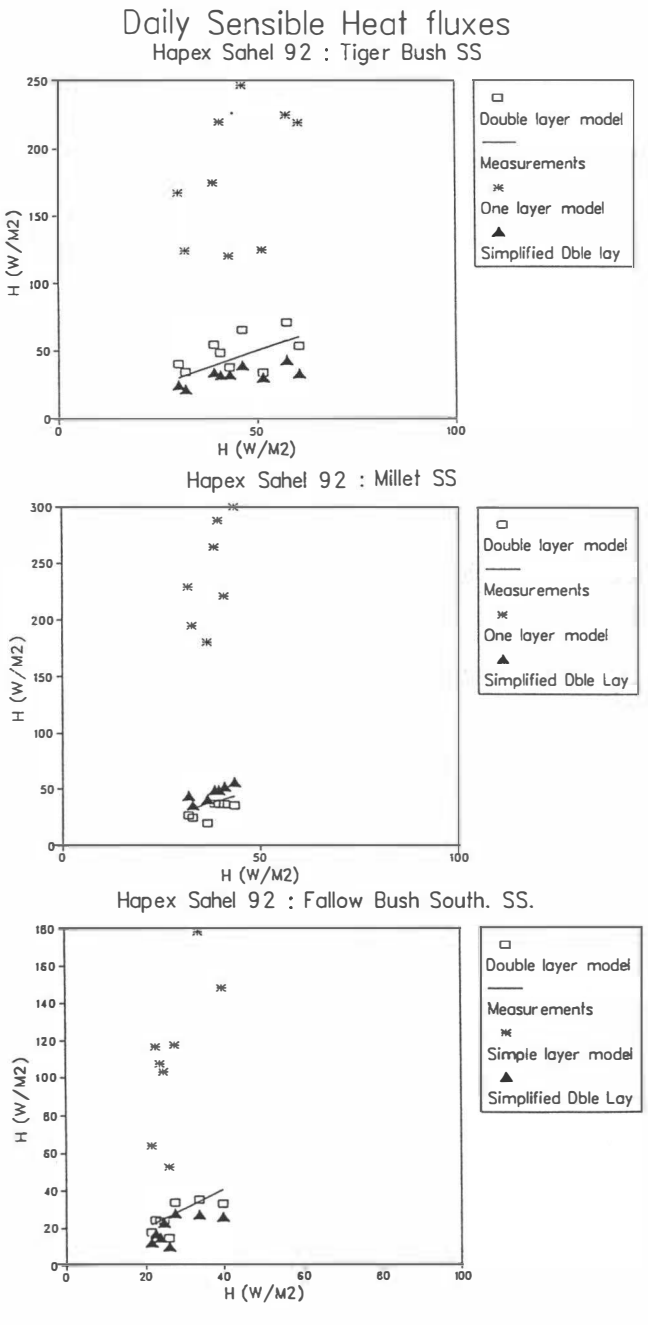


Fig. 4. — Daily sensible heat fluxes of the three subsites.

The daily evapotranspiration is calculated as in equation (1) with the different definitions of "a" and "b" in table 1 for the three models. These models explain the dispersion around an average value of a and b that are calculated for a linear regression.

These expressions of the models cannot be used for a "satellite-based" prediction of the actual daily evapotranspiration because parameter "a" of Jackson Model requires the measured value of the daily ground heat flux and the measurements of instantaneous and daily sensible heat fluxes to get "$H_d/R_{nd} - H_t / Rn_t$" (see table 1) that will be called "De" in the following.

Daily ground heat fluxes could be approached from the daily net radiation. CHOUDHURY *et al.* (1994) proposed to get it as 5 % of the daily net radiation. But this relationship could still be improved. "De" that we found inside parameter "a" of Jackson Model should also be estimated. From the measurements of this experiment, its mean values, multiplied by the average net daily radiation, are respectively 10.44, – 0.88 and 0.78 W/m² for the tiger bush, millet and fallow bush. The multiplication by Rn_d allows a comparison with the daily mean ground heat fluxes that are respectively equal to – 7.40, 7 and – 11 W/m². We have no idea how "De" could be evaluated.

The graphic and numeric expressions of the behaviour of the three models are given in figure 5 a, b, c and table 4. The graphic expression of the one-layer model is not presented because of its unability to express the parameters in the first two steps of the estimation of the daily evapotranspiration.

Both models are close to the measurements. More precisely, the double-layer model gives a RMSE equal to half the one of the simplified double-layer model. But their values are both low, respectively equal to 0.4 and 0.8 mm/day^{-1} (10 and 20 W/m²).

Finally, a reduction of the relative RMSE in this third and last step to estimate actual evapotranspiration is observed. This comes probably from the introduction of the exact net radiation in the calculation of the evapotranspiration. When you combine an accurate term to an estimated one, the sum of the two terms will have a lower relative RMSE than for the first estimated term alone.

COMPARISON BETWEEN PARAMETERS A AND B OF JACKSON MODELS OBTAINED BY THREE MODELS AND BY LINEAR REGRESSION

The three models' values of a and b are presented in table 5 as well as their values obtained by regression. The main thing to see here

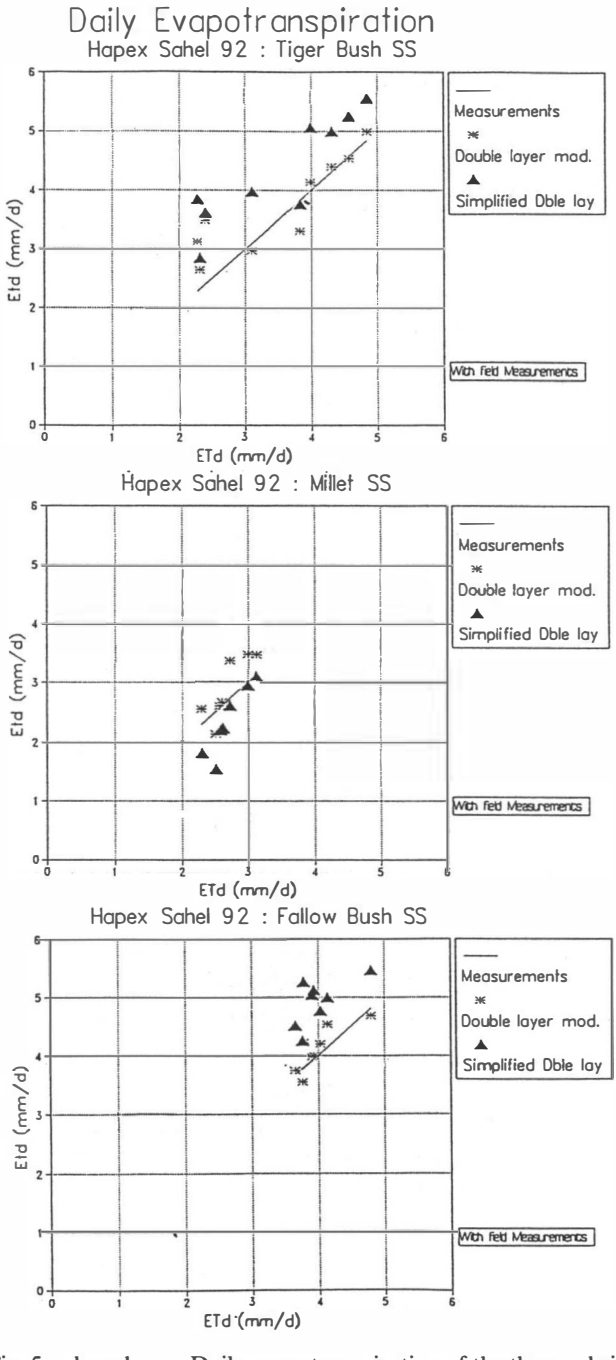


Fig. 5 a, b and c. — Daily evapotranspiration of the three subsites.

Table 5

Mean values and standard deviation of parameters a and b of Jackson Models obtained by different approaches

	Two-layer model		One-layer model		Simplified two-layers model		Linear regression
a ($mm.day^{-1}$)	Mean	Std	Mean	Std	Mean	Std	Mean
Tiger bush	1.373	0.345	0.626	0.602	0.626	0.602	– 2.118
Millet	1.046	0.422	– 0.277	0.426	– 0.277	0.426	– 2.395
Fallow bush	0.327	0.557	– 0.395	0.368	– 0.395	0.368	– 0.956
b ($mm/day^{-1}\ °C^{-1}$)	Mean	Std	Mean	Std	Mean	Std	Mean
Tiger bush	0.380	0.053	0.956	0.115	0.175	0.034	– 0.125
Millet	0.233	0.027	0.805	0.061	0.158	0.021	– 0.082
Fallow bush	0.276	0.050	0.656	0.081	0.115	0.030	0.073

are the values of the parameters that change with the cover. Each subsite seems to have its own behaviour. Both slope and offset are different for each type of vegetation. Nonetheless, we must be careful in our judgement because of the weak value of R^2 and of the important standard deviation of the data. But the influence of the type of cover has already been highlighted by VIDAL & PERRIER (1990). That means that, in the Sahel, to use this method on a scale of agrometeorological interest, let us say, to have an accurate estimation of the latent heat fluxes per 100 km^2, a field inquiry is required for the description and the classification of the type of covers. It would appear nonsense to evaluate the latent heat fluxes of a surface if the type of vegetation covering the studied surface is ignored. More experiments should be required to confirm this conclusion.

Figure 6a is a classical representation of the Jackson Model efficiency (SEGUIN *et al.* 1994) where $ET_d - Rn_d$ is on the y-axis while $T_r - T_a$ is on the the x-axis.

The one-layer model gives absurd results. It is impossible to have values of $ET_d - Rn_d$ below – 7 mm/day. That would mean a net radiation above 7 mm/day assuming a null evapotranspiration. Even in these regions, net radiation cannot reach such high values. The two other models are well centred in the middle of the data. A zoom with figure 6b highlights the high dispersion of the data and remember to be careful with the interpretation of the results. The results of the

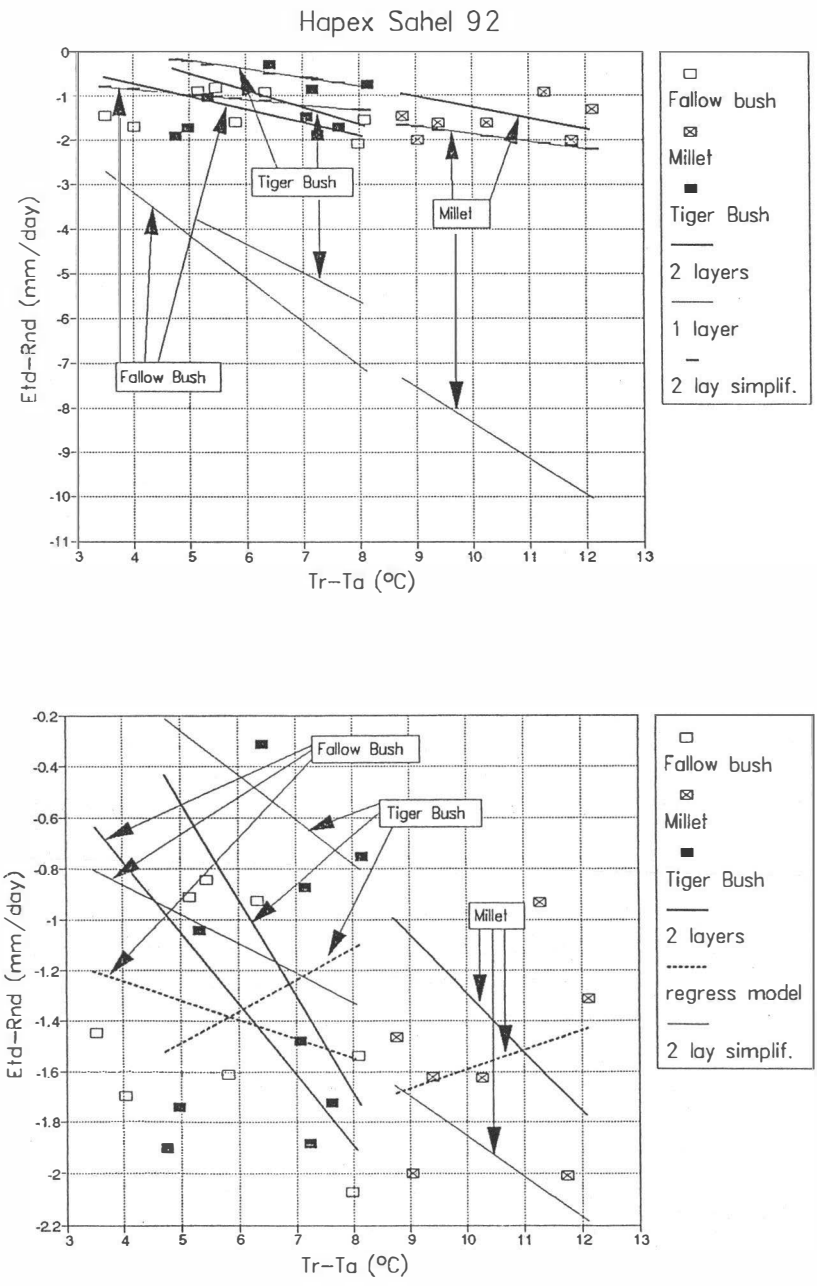


Fig. 6. — Relationships between ET_d-R_{nd} and T_r-T_a on a daily base for the three subsites ; fallow bush, millet and tiger bush. Data and three models (two double-layer models and the linear regression model).

regression are also in figure 6. Two times, the differences of temperature ($T_r - T_a$) are proportional to the differences between evapotranspiration and net radiation. This is nonsense. It should be the contrary after Jackson Model. It shows once more the importance to have enough data to make a robust analysis.

The linear regression model should have had a behaviour similar to (at least) the double-layer model. This is not the case : first, for the reason just mentioned (not enough data to get a robust linear regression), but probably also for some of the assumptions of this double-layer model, in particular its simplification of the actual flux-gradient relationship with two resistances in parallel model.

Conclusions

The one-layer model is unable to describe the latent heat fluxes in the Sahel.

The presented two-layer models seem to give estimations of fluxes accurate enough to pursue the study. Particularly, an analysis of sensitivity of the main parameters in these models is worthwhile and should easily be done.

The dispersion problems must be first due to the difficulty to get exact aerodynamic resistances. The relative RMSE ranges from 6 to 26 % for the double-layer models.

To forget the ground heat flux on a daily time step can lead to important errors.

The subsites have their own behaviour : Bowen ratio, daily ground heat fluxes, and net radiation differ from one site to the other. Furthermore, their aerodynamic characteristics are also different so that a field inquiry is necessary before starting any study like this one.

The ratio between usable to available data is extremely small. From the period observed (2.5 months), only 18 days with clear sky were extracted. From these days, those which could be controlled by field measurements and which were recorded by NOAA were kept for the present analyses. From the two months 1/2, only 7 to 9 days (depending on the subsites) satisfied all these points. If days with large viewing zenith angles of NOAA were rejected, the number would have dropped to 4 days. This problem explains the slowness of the development of this type of models.

However, all these mentioned problems must not change our mind that remote observations could be useful for the improvement and the control of classical methods used to estimate latent heat fluxes and also for their estimations in regions unreachable by man.

REFERENCES

CASELLES, V., SOBRINO, J. A. & COLL, C. 1992. On the use of satellite thermal data for determining evapotranspiration in partially vegetated areas. — *Int. J. Remote Sensing*, **13** (14) : 2669-2682.

CHOUDHURY, B. J. 1989. Estimating evaporation and carbon assimilation using I.R. temperature data : vistas in modelling. — *In* : ASRAR, G. (ed.), Theory and applications of optical Remote Sensing, Wiley, New York, pp. 628-690.

CHOUDHURY, B. J. & MONTEITH, J. L. 1988. A four-layer model for the heat budget of homogeneous land surfaces. — *Q. J. R. Meteorol. Soc.*, **114** : 373-398.

CHOUDHURY, B. J., REGINATO, R. G. & IDSO S. B. 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. — *Cultural and Forest Meteorology*, **37** : 75-88.

CULF, A. D. *et al.* 1993. Energy and water budgets of an area of patterned woodland in the Sahel. — *Agricultural and Forest Meteorology*, **66** : 65-80.

JACKSON, R. D., REGINATO, R. J., & IDSO, S. B. 1977. Wheat canopy temperature : a practical tool for evaluating water requirements. — *Water Resour. Res.*, **13** : 651-656.

KALMA, J. D. & JUPP, D. L. B. 1990. Estimating evaporation from pasture using infrared thermometry : evaluation of a one-layer resistance model. — *Agricultural and Forest Meteorology*, **51** : 223-246.

LHOMME, J. P., MONTENY, B. & AMADOU, M. 1994. Estimating sensible heat flux from radiometric temperature over sparse millet. — *Agricultural and Forest Meteorology*, **68** : 77-91.

LHOMME J. P., MONTENY B., CHEHBOUNI, A. & TROUFLEAU, D. 1993. Determination of sensible heat flux over sahelian fallow savannah using infra-red thermometry. — *Agricultural and Forest Meteorology*, **68** : 93-105.

LI ZHAO-LIANG & BECKER, F. 1993. Surface Net Solar radiation estimated from satellite measurements : comparison with tower observations. — *J. of Climate*, **6** : 1784-1792.

SEGUIN, B., COURAULT, D. & GUERIF, M. 1994. Surface temperature and evapotranspiration : application of local scale methods to regional scales using satellite data. — *Remote Sensing Environment*, **49** : 287-295.

SEGUIN, B. & ITIER, B. 1983. Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. — *Int. J. Remote Sensing*, **4** (2) : 371-383.

STEWART, J. B., KUSTAS, W. P., HUMES, K. S., NICHOLS, W. D., MORAN, M. S. & DE BRUIN, H. A. R. 1994. Sensible heat flux-radiometric surface temperature relationships for eight semi-arid areas. — *J. of Applied Meteorology*, **33** : 1110-1117.

STEWART, J. B., SHUTTLEWORTH, W. J., BLYTH, K. & LLOYD, C. R. 1989. Fife : a comparison between aerodynamic surface temperature and radiometric surface temperature over sparse prairie grass. — *In* : 19th Conf. Agric. and Forest Meteorology, Charleston, South Carolina, pp. 144-146.

TYCHON, B. 1996. Scientific final report of B. Tychon's mission in the Department of Meteorology (Tamsat group) of the University of Reading. — Fondation Universitaire Luxembourgeoise, 28 pp.

VIDAL, A. & PERRIER, A. 1989. Analysis of a simplified relation used to estimate daily evapotranspiration from satellite thermal I.R. data. — *Int. J. Remote Sensing*, **10** (8) : 1327-1337.

VIDAL, A. & PERRIER, A. 1990. Irrigation Monitoring by following the water balance from NOAA-AVHRR thermal infrared data. — *In* : IEEE Transaction on Geoscience and Remote Sensing, **28** (5) : 949-953.

VINEY, N. R. 1991. An empirical expression for aerodynamic resistance in the unstable boundary layer. — *Boundary Layer Meteorology*, **56** : 381-393.

WALLACE, J. S., BROUWER, J., ALLEN, S. J., BANTHORPE, B., BLYTH, E. M., BLYTH, K., BROMLEY, J., BUERKERT, A. C., CANTWELL, M., COOPER, J. D., CROPLEY, F. D., CULF, A. D., DOLMAN, A. J., DUGDALE, G., GASH, J. H. C., GAZE, S. R., HARDING, R. J., HARRISON, R. G., HOLWILL, C. J., JARVIS, P. G., LEVY, P. E., LLOYD, C. R., MALHI, Y. S., MASSHEDER, J. M., MONCRIEFF, J. B., PEARSON, D., SETTLE, J. J., SEWELL, I. J., SIVAKUMAR, M. V. K., SUDLOW, J. D., TAYLOR, C. M. & WILSON, A. K. 1994. HAPEX-Sahel Southern Supersite Report. — Published by the Institute of Hydrology, Wallingford, 55 pp.

WOLLENWEBER, G. C. K. & DE BRUIN, H. 1995. Combining NOAA-AVHRR and meteosat data to estimate net solar radiation balance at the surface, — International Conference "The meteorological satellite data users' conference : polar orbiting systems", Winchester, UK, September 1995, 8 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 582-592 (1998)

Non-Markovian Processes and the Statistical Prediction of River Flows

by

Stéphane VANNITSEM * & Catherine NICOLIS *

KEYWORDS. — Non-Markovian Processes ; River Discharges ; Symbolic Dynamics.

ABSTRACT. — A new method of analysis of hydrological data is proposed using the Zaire river discharges and the Nile river annual level minima as case studies. The data are grouped into two clusters associated to low and high values of the relevant variables and the transitions between the two "states" are analysed. Evidence that the dynamics of these transitions is not a first order Markov process is presented on the basis of the properties of the residence time distributions. A simple stochastic model of this behaviour is developed and compared to the intrinsic properties of the original time series. The consequences on the prediction of the evolution of such events are discussed.

MOTS-CLES. — Processus non markoviens ; Débits des cours d'eau ; Dynamique symbolique.

RESUME. — *Processus non markoviens et prévision statistique des débits des cours d'eau.* — Une nouvelle méthode d'analyse de données hydrologiques est proposée et appliquée aux cas du débit mensuel du fleuve Zaïre et du niveau annuel minimal du Nil. Les données sont séparées en deux groupes associés respectivement aux valeurs basses et élevées de la variable et les transitions entre ces deux états sont ensuite analysées. Au vu de la distribution du temps de résidence autour de ces deux états, il apparaît que la dynamique de ces transitions n'est pas un processus markovien. Un modèle stochastique simple est développé pour décrire cette dynamique et est comparé aux propriétés intrinsèques des séries originales. Les implications sur les prévisions de l'évolution de ces événements sont discutées.

* Royal Meteorological Institute of Belgium, av. Circulaire 3, B-1180 Brussels (Belgium).

TREFWOORDEN. — Niet-Markov processen ; Afvoeren ; Symbolische dynamica.

SAMENVATTING. — *Niet-Markov processen en de statistische voorspellingen van afvoeren van rivieren.* — Een nieuwe analysemethode van hydrologische gegevens wordt voorgesteld, gebruik makend van de afvoeren van de Zaïre-rivier en het jaarlijks minimumniveau van de Nijlrivier als modelstudies. De gegevens worden gegroepeerd in twee *clusters* geassocieerd met de lage en hoge waarden van de relevante variabelen en de overgangen tussen de twee „toestanden" worden geanalyseerd. Het bewijs dat de dynamismen van deze overgangen geen eerste orde Markovproces is, wordt uiteengezet op basis van de eigenschappen van de verblijvende tijdsverdelingen. Een eenvoudig stochastisch model van dit gedrag is ontwikkeld en vergeleken met de intrinsieke eigenschappen van de oorspronkelijke tijdreeks. De gevolgen van de voorspelling van de evolutie van zulke gebeurtenissen worden besproken.

1. Introduction

Floods and droughts are among the major causes of disasters in the world (LAMB 1977). During the year 1995, severe floods in South Asian regions, in Scandinavia and in North America were reported while long duration droughts in Morocco and the United Kingdom still persist (W.M.O. 1995). The prediction of these events constitutes an important challenge which requires both the qualitative understanding and the modelling of the underlying dynamics.

Ordinarily, the analysis and forecasting of floods is carried out by statistical methods. In this context, the main quantity of interest is the probability of occurrence of an event exceeding some threshold during a certain interval of time, typically a year (GUMBEL 1958, KOTTEGODA 1980, WILKS 1993, GUPTA *et al.* 1976, TODOROVIC 1978). The risk of occurrence of such an event is then expressed, for practical purposes, by the average return periods which are estimated, in turn, in terms of the associated probability. Probabilistic prediction algorithms have also been proposed on the basis of Markov chain models. For instance, first order Markov chains have been used to perform short-term flood forecasts and to solve decision problems (KRZYSZTOFOWICZ 1983, YAPO *et al.* 1993).

It is by now recognized that geophysical fields undergo complex spatio-temporal dynamics, originating from the highly non-linear character of the underlying processes. While stochastic processes may emulate, to some extent, this complexity it is far from clear that extreme

value statistics or Markov chains are representative models of the observed variability. As an example, the recurrence time for typical events in a non linear system giving rise to chaotic dynamics exhibits a dispersion around the mean comparable to the value of the mean, implying that average return times are poor predictors of the occurrence of the particular event under consideration (NICOLIS 1996). Furthermore, the lumping of states of a dynamical system into a limited number of regimes — the "states" of a probabilistic model — is known to give rise, in general, to non-Markovian dynamics (NICOLIS 1990). The development of methods of data analysis and modelling of hydrological processes allowing one to cope with some of these limitations is the principal objective of the present work.

In Section 2 the data pertaining to the monthly Zaire river discharges (BULTOT & DUPRIEZ 1987) and the annual Nile river level minima (FRAEDRICH & BANTZER 1991) are presented. Section 3 is devoted to the development of a non-Markovian model accounting for the data, based on the observation that the residence time distributions of the high and low discharge regimes are non-exponential. The main conclusions are drawn in Section 4.

2. The Data

The time series studied are the monthly discharges of the Zaire river and the Nile's annual level minima. These time series have been chosen because their dynamics are associated to the large-scale evolution of the tropical climate.

The monthly Zaire river discharges were estimated by BULTOT & DUPRIEZ (1987) using the daily river level measured at Kinshasa (Zaire) from 1903 to 1983 (MATEBA 1984). The Zaire river basin covers a large area of 3,747,320 km^2. One third of the basin lies in the north hemisphere and two thirds in the south hemisphere. The time series, comprizing 972 monthly values, is represented on figure 1a. It is worth noting the exceptional events which occurred at the beginning of the sixties, during which the Zaire's level was substantially larger than its long-term average (1961-1962, 1962-1963 and in December 1964).

The second set of data studied is the annual level minima of the river Nile starting in 715 and ending in 1470 (FRAEDRICH & BANTZER 1991). This time series, plotted on figure 1b, has been reconstructed from historical sources and corrected by POPPER (1951) by taking into

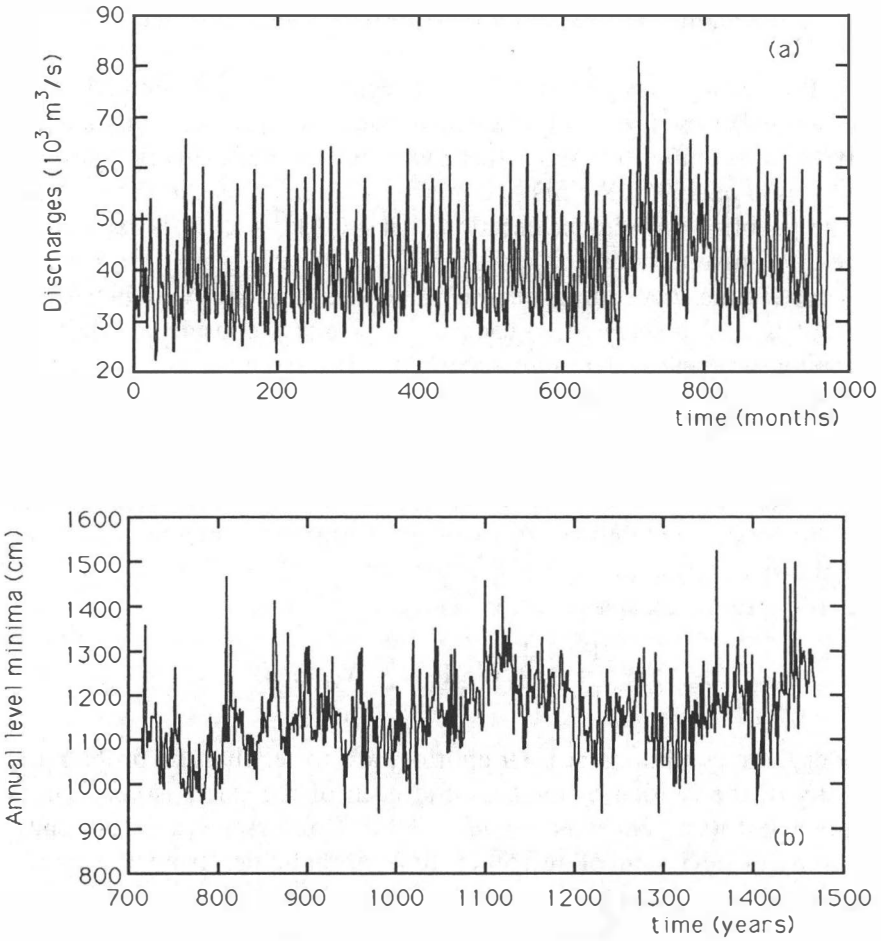


Fig. 1. — (a) The monthly Zaire river discharges (1903-1983) ; (b) the Nile annual level minima (715-1470).

account the changes in calibration of the Roda Nilometer near Cairo. The Nile receives the water from the White Nile in Equatorial Africa and from the Blue Nile in Ethiopia. The Ethiopian tributaries deliver an annual mean flow rate of the order of 1,600 m^3/s and, during the period July to September, flood peaks reach 5-6,000 m^3/s. Thereafter the Nile is mostly fed by the White Nile from tropical East Africa and is at the origin of the Nile annual level minima. It has been suggested that the dynamics of the Nile river is correlated to large-scale events such as the El Niño phenomenon (ELTAHIR 1996).

3. Probabilistic Prediction of Transitions between Regimes

In this section, we present a simple technique for the prediction of the long-term evolution of these processes which follows a method developed recently to study the dynamics of atmospheric clusters (NICOLIS *et al.* 1996). We first summarize the main ideas in the context of the problem under consideration. Let $\{X_k\}$ $k = 1, ..., N$ be a time series. We assume that at each time k, the state belongs to a certain type of regime, depending on the value taken by the variable X. A symbol is then associated to each of the regimes considered, thereby mapping the original data into a symbolic time sequence.

Assume that there are n different regimes R_i. The evolution of the system can then be viewed as a succession of halting periods around a particular state interrupted by rapid transitions between states. If the process were Markovian (first order), the time evolution of the instantaneous probabilities P_i to be in a particular regime could be computed in terms of the two-time transition probability matrix $W_{i,j}$, according to the master equation (GILLESPIE 1992),

$$\frac{dP_i}{dt} = \sum_{j \neq i}^{n} W_{j,i} P_j - \sum_{j \neq i}^{n} W_{i,j} P_i \qquad (1)$$

Under these conditions, it is straightforward to see that the probability density of the residence times around each of the states is necessarily exponential (see NICOLIS *et al.* 1996). Conversely, a statistically meaningful deviation of residence time probabilities from the exponential implies that eq. (1) no longer provides a full characterization of the process, which is now bound to exhibit memory effects.

NICOLIS *et al.* (1996) have proposed a Monte Carlo algorithm capable of generating this type of process on the basis of the two-time transition probabilities $W_{i,j}$ and of the (non-exponential) residence time distributions $p_i(r)$, both inferred from the data.

The algorithm may be summarized as follows :

— Firstly, one is given an initial regime R_i ;
— Secondly, one draws a random value from the residence time probability provided by the time series analysed ;
— Thirdly, when this time has elapsed, the process is switched from state R_i to another one, chosen according to the values of the transition probabilities $W_{i,j}$ $(i \neq j)$;
— Finally, once in the next state, the above algorithm is repeated.

One can associate a probability of occurrence of a particular realization on the basis of the true residence time probability around each regime ($p_i(r)$) and the two-time transition probabilities ($W_{i,j}$). If at a certain time t, the process lies in regime i, then the probability to have a particular realization is :

$$\pi\,(\text{Realization}) = p_i\,(\tau_1)\; W_{ij}\; p_j\,(\tau_2) \ldots p_k\,(\tau_{N-1})\; W_{k,s}\; p_S\,(\tau_N) \quad (2)$$

The method allows therefore for a probabilistic prediction of a typical sequence generated by the process.

We turn now to the analysis of the data summarized in Section 2 using this approach. We first note that the monthly Zaire river discharges display an important periodic component which masks the erratic part of the dynamics. Therefore, in order to get non-trivial results, we eliminate the annual cycle from the original time series by subtracting the monthly means and dividing by the monthly standard deviations.

Next, we define the various regimes through an approximate coarse graining of the original data set. For the two rivers studied here, we have divided the flows into two different regimes : a low regime, for which the values are less than the global average of the time series (state 1) and a high regime characterizing values higher than the mean (state 2). The coarse grained Zaire and Nile river time series are represented on figure 2. Clearly, the system spends a substantial time around each state before jumping rapidly to the other one.

The full lines of figure 3 display the residence time probabilities around each state of the two rivers, while the dashed lines correspond to the residence time probability distribution of a first-order Markov process corresponding to the transition matrices,

$$\mathbf{W}_{\text{Zaire}} = \begin{pmatrix} 0.847 & 0.153 \\ 0.174 & 0.826 \end{pmatrix} \quad (3)$$

and

$$\mathbf{W}_{\text{Nile}} = \begin{pmatrix} 0.712 & 0.288 \\ 0.267 & 0.733 \end{pmatrix} \quad (4)$$

Clearly, there is a large discrepancy between the natural distributions and the ones inferred from a first-order Markov process which is even more apparent in the tail of the distributions. This difference can be effectively quantified using the χ^2 test (EADIE *et al.* 1977), which shows that for the experimental residence time probability distributions

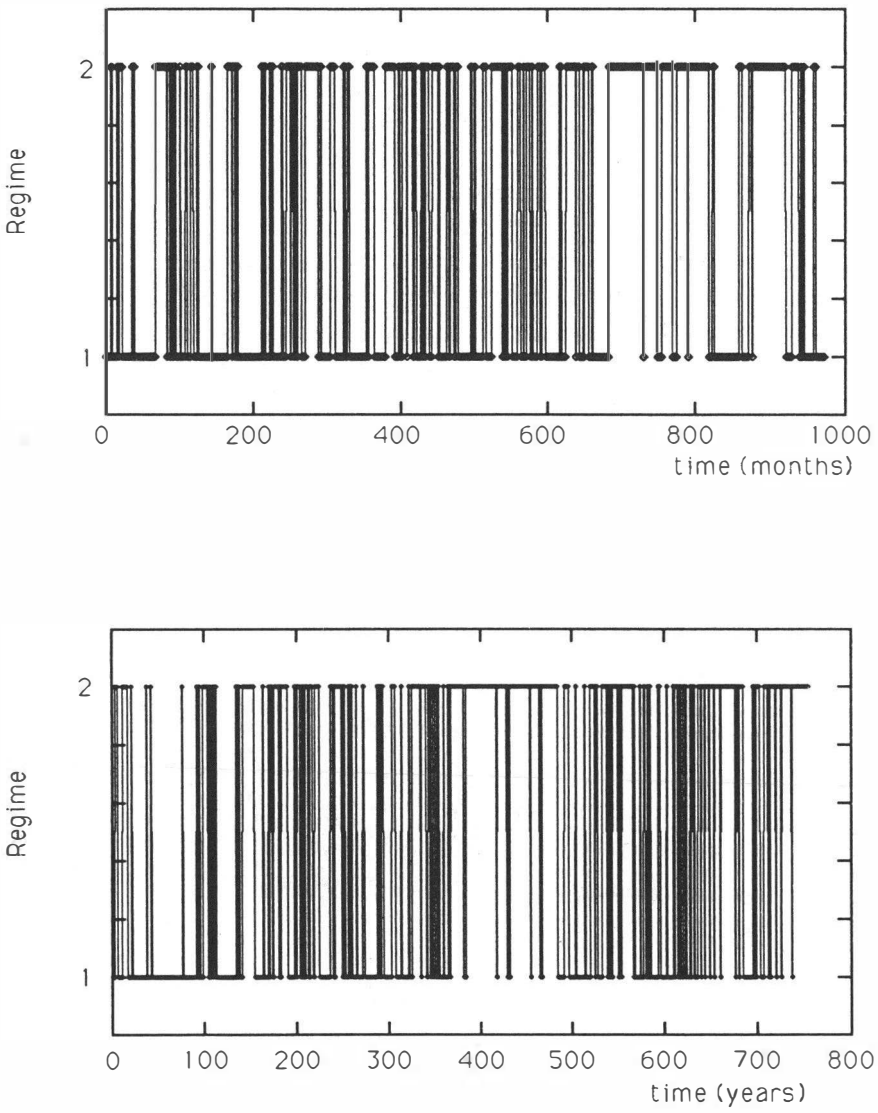


Fig. 2. — The coarse grained Zaire (top) and Nile (bottom) river time series.

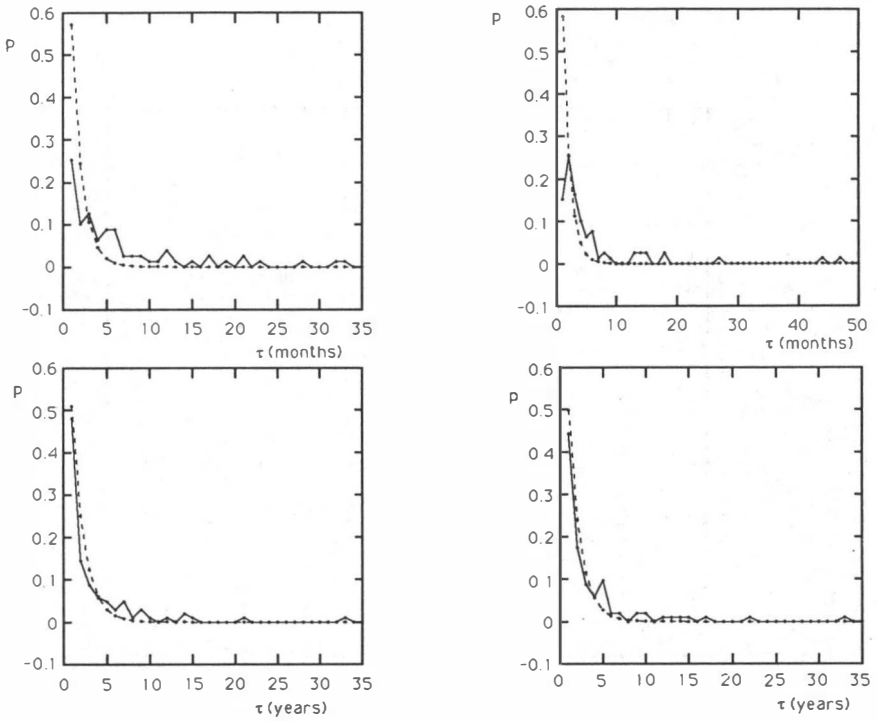


Fig. 3. — Residence time probability distribution (full line) for the two regimes of the Zaire river discharges (top panels) and the Nile annual level minima (bottom panels) as compared to the probability obtained from a first-order Markov process (dashed curve).

displayed on figure 3, the null hypothesis of equivalence of the experimental and the first-order Markov distributions is rejected with a confidence level smaller than 1 ‰, except for regime 1 of the Nile river time series for which the confidence level is of the order of 15 %. These results suggest that the dynamics of the transitions between regimes of these rivers are *not* first-order Markov.

Using the Monte Carlo algorithm described above, one can now generate a long time series of the associated processes. By construction, the asymptotic probability (for long time series) and the residence time distribution of the two regimes are strictly equal to the ones of the original time series. In order to further check the quality of the model, we compute the probability of occurrence of the various sequences of symbols appearing in the original and the simulated time series.

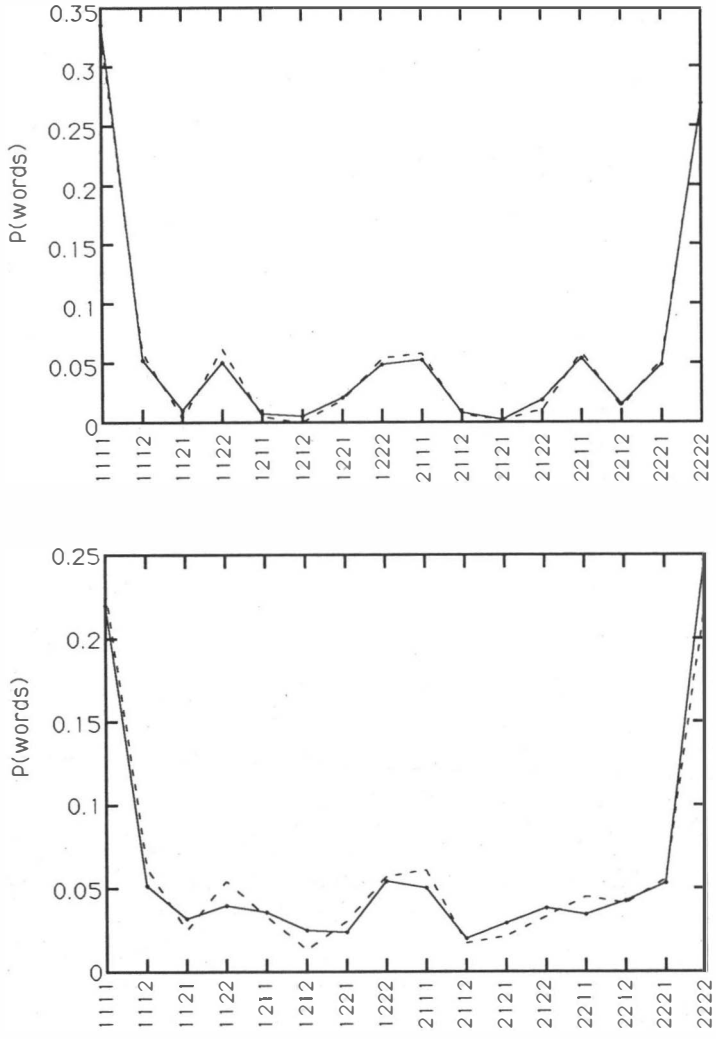


Fig. 4. — Probability of occurrence of a sequence of four successive states in the original (full line) time series and in a time series generated using the non-Markovian algorithm presented in Section 3 (dashed line). The top and the bottom panels correspond to the Zaire river discharges and the Nile annual level minima, respectively.

Figure 4 shows the probability of occurrence of words of four symbols (for instance, a sequence during which the process stays in regime 1 during four months/years : "1111") for the original and a generated time series with the same length. The agreement between the computed quantities is good suggesting that the model reproduces the statistical properties of the process.

4. Conclusions

In this work, we have proposed a new method of data analysis and long-term prediction of river flows. The first step has been to lump the initial time series into a small number (two in the present study) of regimes and to infer, from the resulting symbolic sequence, the transition probability matrix between states and the probability density of residence times around each state. In a second step, statistically significant deviations of the latter probability density from exponential have been identified, establishing the non-Markovian character of the process. Finally, a Monte Carlo algorithm has been developed enabling one to generate, on the sole basis of the data, plausible evolutionary scenarios and to identify their relevant statistical properties.

It should be interesting to apply these techniques to flow regimes characterized by high intermittency, such as flows of arid and semi-arid regions (CHEBAANE *et al.* 1995). This would provide useful information on the forecasting of extreme conditions such as the expected duration of extreme drought conditions.

ACKNOWLEDGEMENTS

We are indebted to Dr G. Demarée and Prof. K. Fraedrich for providing us with the data and to Mr A. Barbosa for a critical reading of the manuscript. This work is supported, in part, by the Federal Office for Scientific, Technical and Cultural Affairs (OSTC) of the Belgian government.

REFERENCES

BULTOT, F. & DUPRIEZ, G. L. 1987. Niveaux et débits du fleuve Zaïre à Kinshasa. — Académie Royale des Sciences d'Outre-mer, Mémoires in-4, t. VI, fasc. 2, Bruxelles, 49 pp.

CHEBAANE, M., SALAS, J. D. & BOES, D. C. 1995. Product periodic autoregressive processes for modeling intermittent monthly streamflows. — *Water Resour. Res.*, **31** : 1513-1518.

EADIE, W. T., DRIJARD, D., JAMES, F. E., ROOS, M. & SDOULET, B. 1977. Statistical Methods in Experimental Physics. — North-Holland, Amsterdam.

ELTAHIR, E. A. B. 1996. El Niño and the natural variability in the flow of the Nile river. — *Water Resour. Res.*, **32** : 131-137.

FRAEDRICH, K. & BANTZER, Ch. 1991. A note on fluctuations of the Nile river flood levels (715-1470). — *Theor. Appl. Climatol.*, **44** : 167-171.

GILLESPIE, D. T. 1992. Markov Processes. — Academic Press, San Diego.

GUMBEL, E. J. 1958. Statistics of Extremes. — Columbia University Press, New York.

GUPTA, V. K., DUCKSTEIN, L. & PEEBLES, R. W. 1976. On the joint distribution of the largest flood and its time of occurrence. — *Water Resour. Res.*, **12** : 295-304.

KOTTEGODA, N. T. 1980. Stochastic Water Resources Technology. — The MacMillan Press Ltd, London.

KRZYSZTOFOWICZ, R. 1983. A Bayesian Markov model of the flood forecast process. — *Water Resour. Res.*, **19** : 1455-1465.

LAMB, H. H. 1977. Climate : Present, Past and Future. Vol 2 : Climatic History and the Future. — Methuen, London.

MATEBA 1984. Observations limnimétriques à Kinshasa, Matadi et Boma : inventaire 1903-1984. — Labor. Recherches Hydrauliques, Min. belge des Trav. Publics, Navigabilité du bief maritime du fleuve Zaïre, n 22.

NICOLIS, C. 1990. Chaotic dynamics, Markov processes and climate predictability. — *Tellus*, **42A** : 401-412.

NICOLIS, C. 1997. Atmospheric analogues and recurrence time statistics : toward a dynamical formulation. — *J. Atmos. Sci.*, in press.

NICOLIS, C., EBELING, W. & BARALDI, C. 1997. Markov processes, dynamic entropies and the statistical prediction of mesoscale weather regimes. — *Tellus*, **49A** : 108-118.

POPPER, W. 1951. The Cairo Nilometer. — Berkeley : University of California Press.

TODOROVIC, P. 1978. Stochastic models for floods. — *Water Resour. Res.*, **14** : 345-356.

WILKS, D. S. 1993. Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series. — *Water Resour. Res.*, **29** : 3543-3549.

W.M.O. 1995. Le système climatique mondial en 1994. — *Bulletin*, **44** (3) : 279-283.

YAPO, P., SOROOSHIAN, S. & GUPTA, V. 1993. A Markov chain model for flood forecasting. — *Water Resour. Res.*, **29** : 2427-2436.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 593-606 (1998)

Deux systèmes hydrologiques mitoyens mais opposés du bassin du Congo-Zaïre : la Cuvette congolaise et les plateaux Tékés

par

Alain LARAQUE * & Jean-Claude OLIVRY *

MOTS-CLES. — Coefficient d'écoulement ; Congo ; Cuvette congolaise ; Débit spécifique ; Hydrogramme ; Module ; Plateaux Tékés ; Régime hydrologique.

RESUME. — Les affluents congolais du fleuve Congo-Zaïre se regroupent en deux systèmes hydrologiques mitoyens mais opposés : les «plateaux Tékés» et la «Cuvette congolaise». Leurs différentes dynamiques d'écoulement se caractérisent respectivement par des coefficients d'écoulement interannuel (rapport entre lame d'eau écoulée et lame précipitée) situés dans des gammes de valeurs moyennes allant de 45 à 60 % et de 20 à 30 % et par une variabilité saisonnière des débits, ou rapport dans une année hydrologique du débit mensuel maximum sur le débit mensuel minimum, variant de 1,1 à 1,5 et de 2,5 à 5,5. Cette classification hydrologique présente l'avantage d'être à la fois adaptée à ces contextes régionaux voisins, mais aussi de mettre en évidence dans son explication le rôle prépondérant des formations géologiques et de la couverture végétale sur les écoulements des cours d'eau concernés. Ces derniers s'opposent également par leurs caractéristiques biogéochimiques, induits elles aussi par les variations régionales de ces deux facteurs. Après passage au travers d'un important aquifère gréseux, dont les minéraux altérables ont été entièrement lessivés, les eaux des rivières Tékés font partie des «clear waters» remarquablement peu minéralisées mais relativement hypersiliceuses. Par contre, les «Coca Cola waters» de la Cuvette congolaise provenant du couvert forestier sont très riches en matière organique, donc très acides.

* Institut Français de Recherche Scientifique pour le Développement en Coopération, Laboratoire d'hydrologie, B.P. 5045, F-34032 Montpellier (France).

TREFWOORDEN. — Congo ; Congobekken ; Hydrogram ; Hydrologisch regime ; Module ; Afvoercoëfficiënt ; Specifiek debiet ; Tékés plateaus.

SAMENVATTING. — *Twee nevenliggende maar tegengestelde hydrologische systemen van het bekken van de Congo-Zaïre : de centrale Kuip en de Tékés plateaus.* — De bijrivieren van de Congo-Zaïrestroom groeperen zich in twee nevenliggende maar tegengestelde hydrologische systemen. Hun verschillende afvoermechanismen karakteriseren zich respectievelijk door interannuele afvoercoëfficiënten (verhouding tussen de afvoerlaag en de neerslaglaag) gelegen in de gamma's van de gemiddelde waarden gaande van 45 tot 60 % en van 20 tot 30 %, en door een seizoensvariabiliteit van de debieten, of de verhouding van een hydrologisch jaar van het maximum maandelijks debiet tot het minimum maandelijks debiet, variërende van 1,1 tot 1,5 en van 2,5 tot 5,5. Deze hydrologische klassificatie heeft het voordeel van tevens aangepast te zijn aan de regionale hydrologische toestanden, maar ook van in zijn verklaring de overwegende rol uit te drukken van de geologische formaties en de vegetatiebedekking op de beschouwde rivierafvoeren. Deze laatste onderscheiden zich tevens door hun biogeochemische karakteristieken tevens geïnduceerd door de regionale variaties van deze twee factoren. Na hun doortocht door een belangrijke zandsteenachtige watervoerende laag waarvan de verweerbare mineralen volledig uitgewassen werden, maken de waters van de Tékésrivieren deel uit van de „clear waters", opmerkelijk weinig gemineraliseerd maar relatief hypersiliceus. Daarentegen zijn de "Coca Cola waters" van de Congolese Kuip, komende van het regenwoud, zeer rijk aan organisch materiaal en dus zeer zuur.

KEYWORDS : Congo ; Congolese Basin ; Hydrograph ; Hydrological Regime ; Module ; Run-off Coefficient ; Specific Discharge ; Teke Plateaux.

ABSTRACT. — *Two Hydrological Systems Close but Opposite of the Congo-Zaire Basin : the Congolese Basin and Teke Plateaux.* — The Congolese tributaries of the Congo-Zaire river can be gathered in two hydrological systems close but opposite : the "Teke plateaux" and the "Congolese basin". We could make the difference between those from two hydrological criteria that we think are the most representative of their differences in their run-off dynamics. These criteria are the interannual run-off coefficient (ratio between the depth of run-off and the rainfall) and the seasonal variability of the monthly discharges, or ratio during an hydrological year of the monthly maximum and the monthly minimum discharge. In the first case, the rivers can be classified in the mean values range varying for these two parameters from 45 to 60 % and 1.1 to 1.5, and in the second group, they concern the values varying from 20 to 30 % and 2.5 to 5.5. This classification has the advantage of being adapted to these close regional contexts and to point out in its explanation the preponderant role of geological formation and vegetation on the run-off of the rivers concerned. The latter are also opposed by their

biogeochemical characteristics. After crossing an important sandy aquifer whose alterable minerals have been totally washed, the Teke rivers belong to the "clear waters", remarkably little mineralized but relatively hypersiliceous. But the "Coca Cola waters" of the Congolese Basin coming from the rain forest are very rich in organic material, therefore very acid.

1. Introduction

Les affluents congolais de la rive droite du Congo-Zaïre drainent toute la partie occidentale et septentrionale de son bassin versant. Leurs confluences se situent le long d'un tronçon de 600 km, de direction globale nord-sud, en amont de Brazzaville (fig. 1). Ils proviennent de deux régions bien individualisées dont nous présenterons les caractéristiques physiographiques avant d'aborder les particularités des régimes hydrologiques qu'elles induisent. L'étude de deux paramètres hydrologiques représentatifs de leurs différences nous permettra d'expliquer leur fonctionnement biogéohydrodynamique et la qualité de leurs eaux d'écoulement.

2. Physiographie régionale

Au nord de Brazzaville s'étend la région dite des «plateaux Tékés» dénommés aussi «Batékés», succession de collines très arrondies et de plateaux dont les reliefs inégaux avoisinent 700-800 m et sont constitués par les formations du Kalahari sablo-gréseuses du tertiaire de 200 à 400 m de puissance. Elles comprennent les deux niveaux Ba1 et Ba2 qui correspondent respectivement aux grès polymorphes (Paléogène) et aux sables ocre (Néogène) du Zaïre. Elles se prolongent dans les territoires gabonais et zaïrois pour couvrir environ 120 000 km^2. Elles forment un puissant aquifère à l'origine des régimes soutenus des cours d'eau qui en sont issus. Ces derniers s'écoulent au fond de vallées profondes qui entaillent ces plateaux où les écoulements superficiels sont inexistants. Leurs crues sont atténuées par le transfert des eaux d'infiltration dans l'aquifère et leurs étiages sont soutenus par la lente vidange de la nappe. Cela se traduit par des hydrogrammes particulièrement «monotones» (fig. 2a). Plusieurs auteurs déjà anciens (Babet 1947, Le Marechal 1966, Olivry 1967) et d'autres plus récents (Schwartz 1988, Laraque *et al.* 1995) ont mentionné la remarquable régularité de leurs régimes hydrologiques.

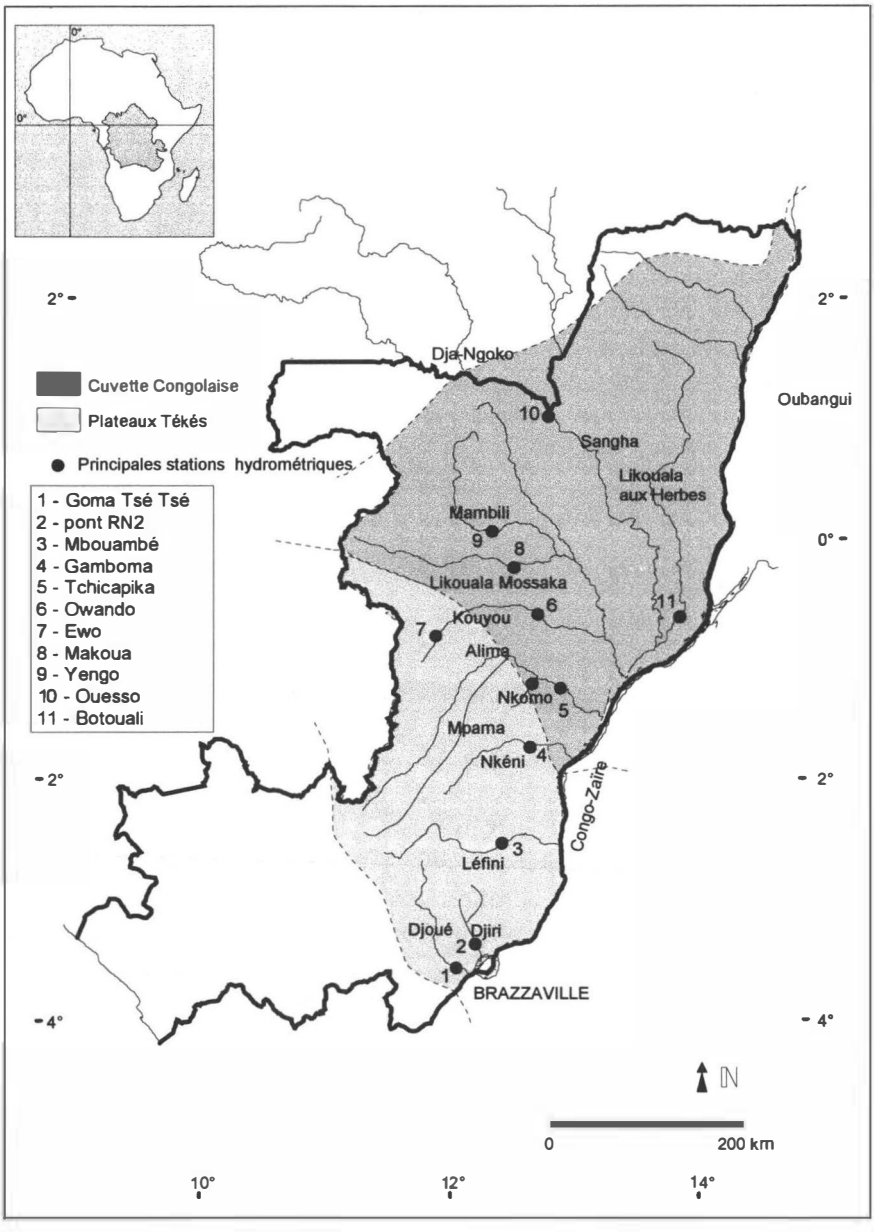


Fig. 1. — Affluents congolais du Congo-Zaïre et contours (lissés) des «plateaux Tékés» et de la «Cuvette».

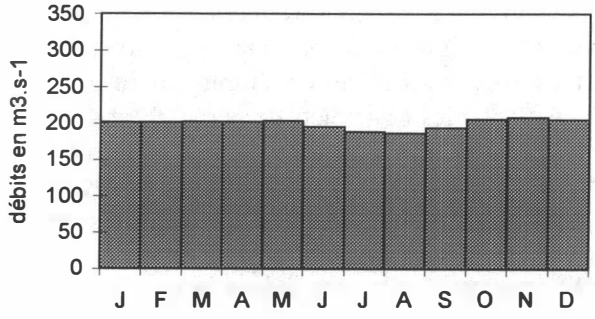


Fig. 2a. — Hydrogramme moyen de la Nkéni à Gamboma (période 1953-1993).

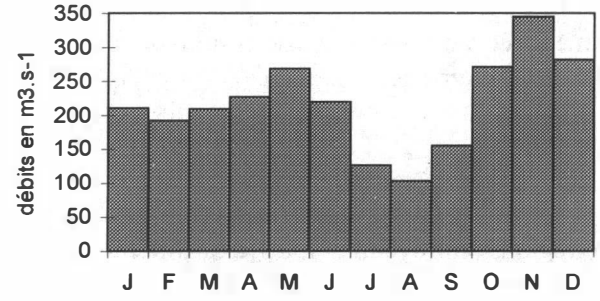


Fig. 2b. — Hydrogramme moyen de la Likouala Mossaka à Makoua (période 1953-1993).

Bien que la pluviométrie annuelle soit élevée (1 900 mm), le rôle déterminant des brûlis pratiqués par l'homme et l'infiltration facilitée par ces formations très perméables, limitent la végétation à une simple savane plus ou moins arbustive.

La région dénommée «Cuvette congolaise» s'étend autour de l'important «carrefour» de confluences entre le Congo-Zaïre, l'Oubangui, la Sangha, la Likouala aux Herbes et la Likouala Mossaka qui marque son point le plus bas à environ 400 m d'altitude. Elle est le prolongement de la vaste dépression zaïroise dont la seule partie inondable à 60 % couvre près de 220 000 km^2 selon BURGIS & SYMOENS (1987). Elle est recouverte de marécages, prairies et forêts pluviales en partie inondées en période de crue. Les cours d'eau qui sillonnent cette plaine inondable sont très sinueux, parfois anastomosés à proximité de leurs confluences et reliés entre eux par de nombreux chenaux naturels ou anthropiques,

où les courants s'inversent au gré des fluctuations de niveau des rivières qu'ils desservent. Les limites de partage des eaux entre deux bassins versants sont parfois très difficiles à établir en raison du faible relief de ce secteur. Au-delà des bourrelets de berge, il est par ailleurs difficile de différencier les eaux d'inondations du toit de la nappe alluviale qui affleure à maintes reprises et s'écoule lentement vers l'aval. POUYAUD (1970a-b) a déjà amplement décrit les particularités de ces bassins et surtout de celui très marécageux de la Likouala aux Herbes. Les formations de couverture de cette région sont constituées d'alluvions quaternaires fluviatiles argileuses ou sableuses et le climat passe du type équatorial, marqué par deux saisons de pluies à peu près identiques, à tropical humide de transition plus au nord. Excepté la présence au sud-ouest des plateaux Tékés, la Cuvette centrale est entourée d'une forêt ombrophile dense et humide recouvrant, de l'ouest au nord, des reliefs émoussés et peu élevés (400-800 m) où affleure le socle continental africain composé de roches cristallines et cristallophyliennes. Au sud et à l'est, cette forêt pluviale se prolonge au-delà de la dépression zaïroise pour couvrir dans son ensemble près de 48 % de la totalité du bassin du fleuve.

Ces deux régions, mitoyennes mais très différentes, présentent des caractéristiques hydrologiques contrastées avec des coefficients d'écoulement et des débits spécifiques dans les plateaux Tékés plus de deux fois supérieurs à ceux de la Cuvette. La seule et légère baisse de la pluviométrie, des plateaux (1 800 à 2 000 mm.an^{-1}) vers la Cuvette (1 600 à 1 800 mm.an^{-1}), ne semble pas suffisante pour expliquer de tels écarts (BULTOT 1971).

3. Caractérisation hydrologique régionale

Le type de regroupement régional que nous présentons, réalisé à partir de deux critères hydrologiques, est adapté à la physiographie des bassins versant de ces cours d'eau (fig. 3).

En fonction du coefficient d'écoulement interannuel (rapport entre lame d'eau écoulée et lame précipitée) et de la variabilité saisonnière moyenne des débits calculée sur la période 1953-1993 (rapport entre le débit mensuel maximum et le débit mensuel minimum), ces deux entités hydrologiques ont été isolées. Un premier nuage de points très compact, correspondant pour chaque cours d'eau, à des valeurs moyennes respectives des coefficients d'écoulement et de variabilité saisonnière de 45-60 % et de 1,1 à 1,5, se distingue d'un deuxième

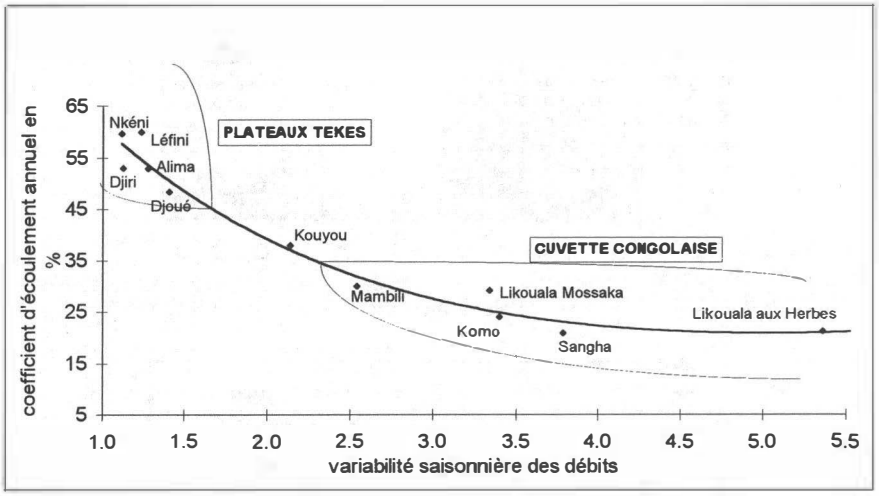


Fig. 3. — Classification hydrologique des affluents congolais du fleuve Congo-Zaïre.

groupe plus allongé, où ces mêmes paramètres varient respectivement entre 20-30 % et 2,5 à 5,5. Les variations saisonnières prises année par année sur la période d'étude sont bien moins dispersées pour le premier groupe avec des valeurs extrêmes de 1,04 et 1,7 contre 1,2 et 12 pour le second.

Pour la première catégorie correspondant aux rivières Tékés (Djiri, Léfini, Nkéni, Alima, Djoué), dont les modules se situent entre 25 et 600 $m^3.s^{-1}$ (LARAQUE & MAZIEZOULA 1995) pour des bassins couvrant des superficies de 1 000 à 20 000 km^2, le rôle régulateur de l'aquifère est mis en évidence par de faibles variations saisonnières des débits de ces cours d'eau. On ne distingue en effet ni crue ni étiage dans l'hydrogramme quasi «plat» de la figure 2a. Et cela malgré une importante variabilité saisonnière de la pluviométrie sur cette région qui présente une saison sèche bien marquée de juin à août (fig. 4a). Dans ces plateaux, l'infiltration est élevée et la majeure partie des précipitations météoriques est restituée aux cours d'eau à travers l'aquifère qui pondère les débits. Leur coefficient d'écoulement, et par conséquent leurs débits spécifiques, sont ainsi élevés (25 à 30 $l.s^{1}.km^{-2}$). Les cours d'eau parmi les plus réguliers de la planète (la Nkéni et la Léfini) en sont issus. Par la régulation des débits qu'il engendre sur les rivières qui s'en échappent, le puissant aquifère des plateaux Tékés explique également l'extraordinaire constance de leurs modules

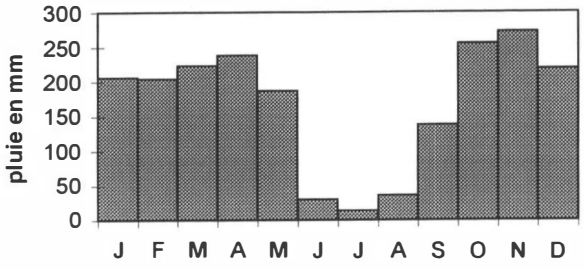


Fig. 4a. — Régime pluviométrique des plateaux Tékés.

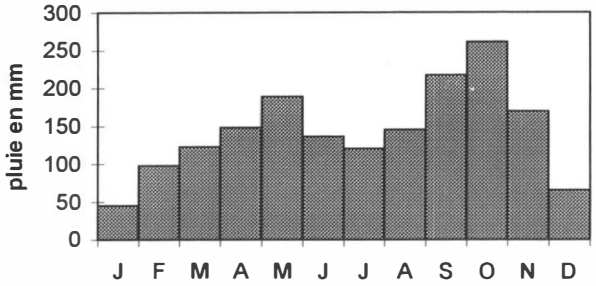


Fig. 4b. — Régime pluviométrique de la Cuvette congolaise.

annuels (fig. 5a), avec des rapports interannuels moyens n'excédant pas 1,4. L'écoulement montre en outre une certaine inertie face aux baisses des régimes pluviométriques de ces dernières années, plus modérées, il est vrai, que celles enregistrées dans la bande tropicale humide de transition de l'hémisphère nord (MAHE 1993).

C'est le contraire pour les cours d'eau du domaine forestier du deuxième groupe (Likouala aux Herbes, Komo, Likouala Mossaka, Mambili), dont les débits aux principales stations hydrométriques vont de 25 à 1 600 $m^3.s^{-1}$ pour des superficies variant de 1 000 à 160 000 km^2 (LARAQUE *et al.* 1995b). Les terrains moins perméables associés à une évapotranspiration plus élevée sur le couvert forestier et à une évaporation directe sur les zones inondables aux pentes quasi nulles et à l'écoulement très lent, voire inexistant dans les marécages, entraînent un déficit hydrique important. On obtient des coefficients d'écoulement et des débits spécifiques plus faibles de l'ordre de 10-15 $l.s^{-1}.km^{-2}$. En l'absence d'importants aquifères régulateurs, leurs régimes hydrologiques reflètent plus fidèlement le régime pluviométrique de cette région (fig. 2b et 4b) et leurs débits présentent des variabilités

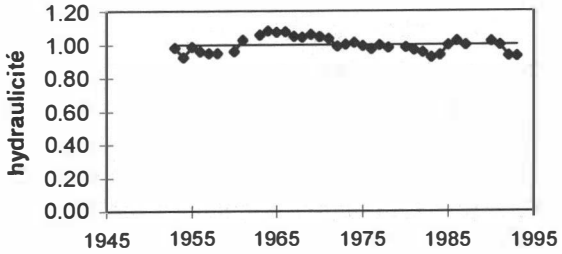


Fig. 5a. — Evolution de l'hydraulicité de la Nkéni à Gamboma.

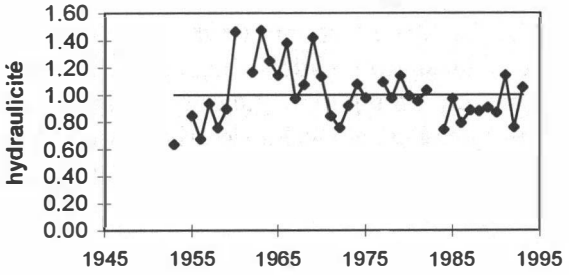


Fig. 5b. — Evolution de l'hydraulicité de la Likouala aux Herbes à Botouali.

saisonnières plus élevées alors que la pluviométrie y est bien moins contrastée que celle des plateaux Tékés.

Les variations interannuelles des modules sont également plus importantes (moyenne de 1,6 à 2,3 suivant les cours d'eau). En outre, ils ont été influencés depuis une vingtaine d'années par la péjoration climatique qui a fortement affecté les régions soudano-sahéliennes et, dans une moindre mesure, la partie septentrionale du bassin du Congo-Zaïre (fig. 5b), comme l'ont signalé SIRCOULON (1987), MAHE (1993), OLIVRY (1993), OLIVRY *et al.* (1993). Pour l'ensemble de la Cuvette congolaise, LARAQUE & OLIVRY (1996) ont calculé, à partir de la comparaison des modules des périodes 1987-1993 et 1953-1993, une baisse d'hydraulicité de 11 %.

Malgré la physiographie plus composite de son bassin amont très étendu (160 000 km²), la Sangha à Ouesso présente des comportements similaires. Ils sont dus en grande partie au sous-bassin forestier du Dja-Ngoko, affluent provenant du Cameroun et dont le cours inférieur marque la frontière avec le Congo. Il présente encore les caractéristiques hydrologiques observées dans la Cuvette avec des débits spécifiques

à sa confluence de 11,3 $l.s^{-1}.km^{-2}$ pour une variabilité saisonnière des débits un peu plus élevée, de l'ordre de 6,4.

Le Kouyou, quant à lui, mérite une attention particulière. Il se détache nettement du «noyau» des rivières Tékés et présente une variabilité saisonnière (2,14), un coefficient d'écoulement (40 %) et un débit spécifique (21 $l.s^{-1}.km^{-2}$) intermédiaires avec ceux du groupe des rivières forestières. L'influence régulatrice de l'aquifère Téké sur le flanc sud de son bassin et le début de la grande forêt équatoriale se font sentir simultanément. Ce cours d'eau marque la limite entre ces deux domaines aux fonctionnements biogéohydrodynamiques différents. Les courbes de la figure 6 montrent son changement de régime hydrologique entre les parties amont et aval de son bassin. Son cours supérieur (étudié à la station hydrométrique d'Ewo) provenant des plateaux Tékés présente un régime régulier qui leur est caractéristique, puis il acquiert progressivement celui des rivières de la Cuvette avec des variations saisonnières plus importantes au fur et à mesure qu'il s'y enfonce (station d'Owando).

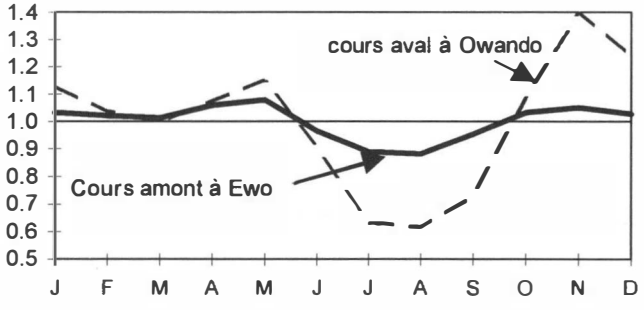


Fig. 6. — Variations saisonnières des régimes des cours supérieur et inférieur du Kouyou (période 1963-1977).

4. Typologie biogéochimique de ces eaux

Les deux groupes d'affluents précédemment individualisés par des critères hydrologiques s'opposent à nouveau, cette fois sous l'angle géochimique.

En effet, les rivières «*blanches*» à dominante siliceuse des plateaux Tékés sont très peu minéralisées (conductivités électriques de l'ordre de 5-8 µS.cm – 1 à 25 °C), tous les ions solubles ayant été pratiquement totalement lessivés. Certains éléments ont même des teneurs proches de celles des eaux de pluies. C'est le cas de la Léfini qui présente des teneurs en chlorures de 5 à 5,5 µmoles.l^{-1} (NEGREL 1992). C'est en raison de cette exceptionnelle pauvreté en ions minéraux (1 à 3 mg.l^{-1}!), que la proportion de silice est si élevée (75 %) alors que ses teneurs (8-10 mg.l^{-1}) restent voisines de la moyenne mondiale de 10,4 mg.l^{-1} (BERNER & BERNER 1987).

Ces eaux font face aux rivières de la cuvette congolaise, dites «*noires*» (ou Coca-Cola rivers) plus chargées surtout en bicarbonates. Elles présentent des pH pouvant descendre en dessous de 4, en présence des acides forestiers fulviques et humiques. Leurs teneurs en carbone organique total de 25,5 mg.l^{-1} contre 4,7 mg.l^{-1} (SEYLER *et al.* 1993) pour les plateaux Tékés, illustrent bien la différenciation forêt-savane de ces groupes de bassins.

La géologie plus hétérogène des bassins forestiers et la pédogenèse active sont à l'origine de leur charges ioniques plus élevées, situées en moyenne entre 11 et 28 mg.l^{-1}, à l'instar des conclusions de l'étude géochimique menée sur le Djoué (LARAQUE *et al.* 1996), affluent du Congo-Zaïre situé à la limite sud des plateaux Tékés et dont une partie du bassin versant est composée de formations géologiques plus variées. Par comparaison avec les cours d'eau Tékés, c'est leur plus grande richesse ionique qui explique le pourcentage plus faible (30-35 %) de silice dissoute (fig. 7).

Quant à la Sangha, de par l'extension de son bassin versant et son hétérogénéité physiographique, elle se détache quelque peu des grandeurs communément rencontrées dans la Cuvette inondable. Sa conductivité électrique moyenne est de 55 µS.cm^{-1} à 25 °C pour des pH oscillant autour de la neutralité entre 6,8 et 7,2, et ses eaux sont par conséquent bien plus riches en bicarbonates (près de 50 %).

Cependant, pour ces deux entités géographiques (Cuvette congolaise et plateaux Tékés), les différents taux d'exportations dissoutes spécifiques, tant minérales (10 t.km^2.an^{-1} contre 9,7 t.km^2.an^{-1}) qu'organiques (19,3 t.km^2.an^{-1} contre 13,5 t.km^2.an^{-1}), restent faibles et semblables malgré les importants écarts de concentrations correspondantes. Cela résulte de la compensation par les débits spécifiques élevés des plateaux Tékés (de l'ordre de 30 l.s^{-1}.km^{-2}).

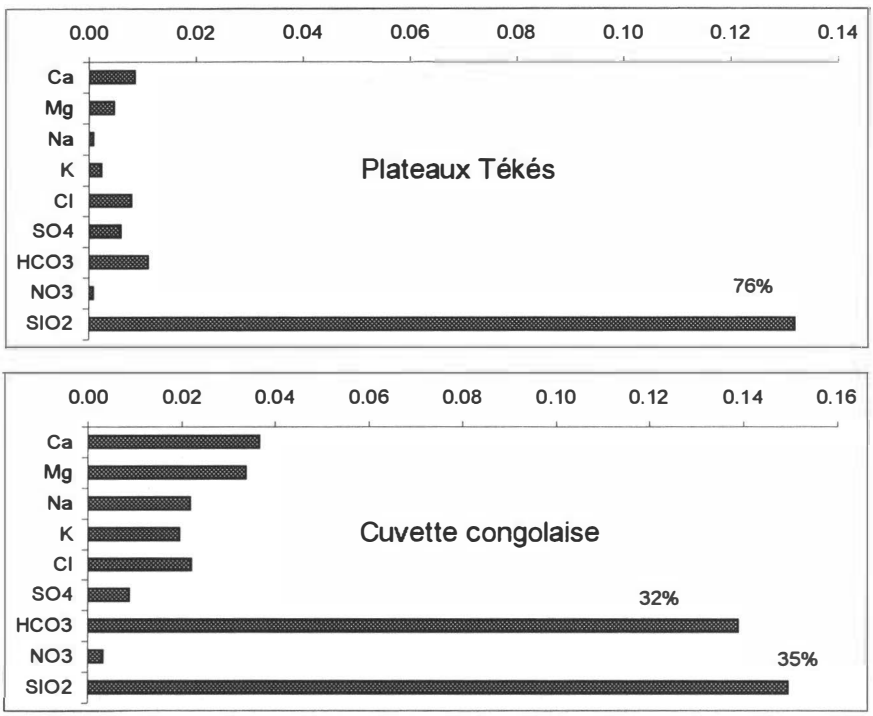


Fig. 7. — Composition des phases minérales des eaux des plateaux Tékés et de la Cuvette congolaise (concentrations moyenne en mmole.l^{-1}.

5. Conclusion

Parmi les affluents congolais de rive droite, deux familles se distinguent. Aux rivières claires très peu minéralisées des plateaux Tékés s'opposent les «Coca-Cola rivers» de la cuvette congolaise, aux eaux acides riches en matière organique. Les premières présentent des coefficients d'écoulement et des débits spécifiques particulièrement élevés avec des hydrogrammes très réguliers où les variations saisonnières des débits sont insignifiantes malgré un régime pluviométrique contrasté. C'est le contraire pour les secondes aux régimes pluviométriques et hydrométriques semblables. Formations géologiques et couvertures végétales de ces deux entités géographiques sont à l'origine de telles réponses à l'écoulement. Les rivières Tékés sont issues d'un important aquifère régulateur sablo-gréseux dénudé, tandis que les «Coca-Cola

rivers» circulent sous la dense forêt pluviale équatoriale et sur des alluvions à la lithologie plus variée, sans bénéficier d'une telle régulation hydrogéologique.

BIBLIOGRAPHIE

BABET, V. 1947. Compte rendu de la réunion des géologues du Congo occidental, tenue à Léopoldville les 10, 11 et 12 décembre 1945. *Bull. Serv. des Mines*, Paris, (3), 72 pp.

BERNER & BERNER 1987. The Global Water Cycle. Geochemistry and Environment. — Prentice Hall, 397 pp.

BULTOT, F. 1971. Atlas climatique du bassin congolais (t. 2) - les composantes du bilan de l'eau. — INEAC, Bruxelles.

BURGIS, M. J. & SYMOENS, J.-J. 1987. African Wetlands and Shallow Water Bodies — Zones humides et lacs peu profonds d'Afrique. — Orstom, Paris, 650 pp.

LARAQUE, A. & MAZIEZOULA, B. 1995. Banque de données hydrologiques des affluents congolais du fleuve Congo-Zaïre et informations physiographiques. — Rapport interne, lab. Hydr. Orstom, Montpellier, 250 pp.

LARAQUE, A. & OLIVRY, J.-C. 1996. Evolution de l'hydrologie du Congo-Zaïre et de ses affluents rive droite et dynamique de ses transports solides et dissous. — L'hydrologie tropicale : géoscience et outil pour le développement - Tropical Hydrology : a Geoscience and a Tool for Sustainability (Actes de la Conférence de Paris, mai 1995), IAHS Publ., n° 238, pp. 271-288.

LARAQUE, A., PANDI, A., BERTHELOT, M. & MIETTON, M. 1995. Ecoulement et transport de matière dans le bassin versant du Djoué : affluent du fleuve Congo-Zaïre. — *Hydrologie continentale*, Orstom, Paris, **10** (1) : 153-168.

LE MARECHAL, A. 1966. Contribution à l'étude des plateaux Batékés (géologie, géomorphologie, hydrogéologie). — Orstom, Brazzaville, 42 pp.

MAHE, G. 1993. Les écoulements fluviaux sur la façade atlantique de l'Afrique — étude des éléments du bilan hydrique et variabilité interannuelle, analyse de situations hydroclimatiques moyennes et extrèmes. — Thèse de doctorat, Coll. Etudes et Thèses Orstom, Paris, 438 pp.

NEGREL, P. 1992. Utilisation du Strontium, des alcalins et alcalino-terreux pour la détermination des bilans des éléments chimiques dans les fleuves : apports atmosphériques, altération des roches — exemple du bassin du Congo. — Thèse de doctorat, Univ. Paris 7, 249 pp.

OLIVRY, J.-C. 1967. Régime hydrologique des rivières Batéké. — Rapport Orstom, Brazzaville, nov. 1967, 27 pp.

OLIVRY, J.-C. 1993. Evolution récente des régimes hydrologiques des grands fleuves d'Afrique de l'Ouest et Centrale. — *In* : Les écosystèmes

intertropicaux, fonctionnement et usages, journées du programme Environnement CNRS/ORSTOM, 13, 14 et 15 janvier 1993, Lyon, 9 pp.

OLIVRY, J.-C., BRICQUET, J. P. & MAHE, G. 1993. Vers un appauvrissement durable des ressources en eau de l'Afrique humide? Hydrology of Warm Humids Regions, Proceedings of the Yokohama Symposium, IAHS, July 1993, 6 pp.

POUYAUD, B. & GATHELIER, R. 1970a. Les rivières du bassin de la Likouala Mossaka. — Orstom, Centre de Brazzaville, 48 pp.

POUYAUD, B. 1970b. La Likouala aux Herbes à Epéna et à Botouali. — Orstom, Centre de Brazzaville, 37 pp.

SCHWARTZ, D. 1988. Histoire d'un paysage : le Lousséké. Paléoenvironnements quaternaires et podzolisation sur sables Batéké (Quarante derniers millénaires, région de Brazzaville, R.P. du Congo). — Thèse doctorat ès Sciences, Univ. Nancy I, Coll. Etudes et Thèses, Orstom Paris, 285 pp.

SEYLER, P., ETCHEBER, H., ORANGE, D., LARAQUE, A., SIGHA-NKAMDJOU, L. & OLIVRY, J.-C. 1993. Contributions, fluctuations saisonnières et flux de carbone dans le bassin du Congo. — *In* : Actes du colloque PEGI, Grands bassins fluviaux periatlantiques : Congo, Niger, Amazone (Paris, 22-24 novembre 1993), Orstom, Paris, pp. 217-228.

SIRCOULON, J. 1987. Variations des débits des cours d'eau et des niveaux des lacs en Afrique de l'Ouest depuis le 20e siècle. — *In* : The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Ressources, Proceedings of the Vancouver Symposium (August, 1987), IAHS Public., **168** : 13-25.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 607-612 (1998)

Le projet FRIEND en Afrique de l'Ouest et centrale : l'expérience d'un réseau de recherche en partenariat dans le domaine de l'hydrologie régionale

par

Eric SERVAT *, Mamdou SAKHO **, Grégoire ALE ***,
Abel AFOUDA**** & Jean-Marie FRITSCH *****

MOTS-CLES. — Coopération scientifique ; Hydrologie régionale ; Partenariat ; Programme Hydrologique International ; Réseau scientifique ; UNESCO.

RESUME. — Sous l'égide du Programme Hydrologique International (PHI) de l'UNESCO, le programme FRIEND (Flow Regimes from International and Experimental Networks Data) existe depuis maintenant dix ans. Les groupes FRIEND NW (North-West Europe) et AMHY (Alpine and Mediterranean HYdrology) regroupent de nombreux hydrologues européens travaillant de concert et à l'échelle régionale sur des thèmes divers. Deux expériences similaires ont été lancées plus récemment en Afrique : les projets FRIEND Afrique Australe (SA), depuis 1992, et FRIEND Afrique de l'Ouest et Centrale (AOC), depuis 1994. Le projet FRIEND AOC est un réseau qui regroupe aujourd'hui plus de vingt pays et auquel participent des organismes à vocation régionale comme l'ORSTOM, l'EIER et AGRHYMET. Il s'articule autour de six thèmes de recherche qui privilégient la réflexion commune dans des domaines clés de l'estimation et de la gestion des ressources en eau. Après un peu plus d'un an d'existence, FRIEND AOC constitue une expérience intéressante de recherche en partenariat à l'échelle régionale. Les contacts pris à plusieurs niveaux se révèlent très prometteurs. Ils permettront de proposer, de comparer et d'éprouver des méthodologies, des techniques et des projets.

* ORSTOM Programme FRIEND AOC, 06 B.P. 1203 Cidex 1, Abidjan 06 (Côte-d'Ivoire).
** Direction de l'Eau, B.P. V161, Abidjan (Côte-d'Ivoire).
*** Direction de l'Hydraulique, B.P. 385, Cotonou (Bénin).
**** Université Nationale du Bénin, B.P.526, Cotonou (Bénin).
***** ORSTOM, B.P. 5045, 34032 Montpellier Cedex (France).

TREFWOORDEN. — Wetenschappelijke samenwerking ; Regionale hydrologie ; Partnerschap ; Internationaal Hydrologisch Programma ; Wetenschappelijk netwerk ; UNESCO.

SAMENVATTING. — *Het project FRIEND in West- en Centraal-Afrika : de ervaring van een netwerk van partners voor onderzoek in het domein van regionale hydrologie.* — Meer dan tien jaar geleden werd het programma FRIEND (Flow Regimes from International and Experimental Networks Data) opgestart in het kader van het Internationaal Hydrologisch Programma (IHP) van UNESCO. De NW (Noord-West Europa) FRIEND groep en de AMHY (Alpine and Mediterranean Hydrology) vertegenwoordigen vele Europese hydrologen die samenwerken op verschillende thema's en op regionale schaal. Twee gelijkaardige projecten werden recentelijk opgestart in Afrika : het zuidelijk Afrika FRIEND project, sedert 1992, en het OAC (Afrique de l'Ouest et Centrale) FRIEND project, sedert 1994. Het AOC FRIEND project, waaraan organisaties met regionale autoriteit zoals ORSTOM, EIER en AGRHYMET meewerken, vertegenwoordigt een netwerk van meer dan twintig landen. Het bestaat uit zes onderzoeksthema's die een gemeenschappelijke gedachtengrond bevorderen in sleutelgebieden zoals de schatting en het beheer van de waterbronnen. Niettegenstaande zijn korte bestaan, kan FRIEND AOC reeds interessante resultaten voorleggen op gebied van onderzoek in coöperatie op regionale schaal. De contacten gelegd op verschillende niveaus zijn beloftevol. Zij zullen toelaten om methodologieën, technieken en projecten voor te stellen, te vergelijken en te testen.

KEYWORDS. — Scientific Cooperation ; Regional Hydrology ; Partnership ; International Hydrological Programme ; Scientific Network ; UNESCO.

ABSTRACT. — *The FRIEND Project in West and Central Africa : the Experience of a Research Cooperation Network in the Field of Regional Hydrology.* — More than ten years ago, the FRIEND programme (Flow Regimes from International and Experimental Networks Data) was launched within the framework of the International Hydrological Programme (IHP) of UNESCO. The NW (North-West Europe) FRIEND Group and the AMHY (Alpine and Mediterranean HYdrology) FRIEND Group gather numerous European hydrologists working together on various topics and in a regional scale. Two similar projects have been launched more recently in Africa : the Southern African FRIEND project, since 1992, and the AOC (Afrique de l'Ouest et centrale) FRIEND, since 1994. The AOC FRIEND is a network that gathers more than twenty countries and in which organisms that have regional authority such as ORSTOM, EIER and AGRHYMET take an active part. It is made up of six research themes that give an important place to common thought on the main points of water resources assessment and management. In spite of its recent launching, AOC FRIEND can already show interesting results in the field of cooperation research on a regional

scale. The contacts made at different levels look very promising. They will allow to propose, compare and test methodologies, techniques and projects.

Introduction

Sous l'égide du Programme Hydrologique International (PHI) de l'UNESCO, le programme FRIEND (Flow Regimes from International and Experimental Networks Data) existe depuis maintenant dix ans.

Les groupes FRIEND NW (North-West Europe) et AMHY (Alpine and Mediterranean Hydrology) regroupent de nombreux hydrologues d'Europe et du bassin méditerranéen travaillant de concert et à l'échelle régionale sur des thèmes divers. Ces groupes sont aujourd'hui bien rodés et le travail qui s'y accomplit est d'un grand intérêt scientifique. Deux expériences similaires ont été lancées plus récemment en Afrique : les projets FRIEND Afrique Australe (SA pour Southern Africa), depuis 1992, et FRIEND Afrique de l'Ouest et centrale (AOC), depuis 1994. Un troisième groupe FRIEND africain est en cours de constitution, FRIEND NILE, qui regroupe les pays du bassin versant du Nil.

Problématique

La problématique scientifique qui est à la base des projets FRIEND, qu'ils soient européens ou africains, s'exprime selon plusieurs directions qui relèvent d'une approche régionale de l'Hydrologie :

— Approfondir la connaissance de la variabilité spatiale et temporelle des régimes hydrologiques au moyen d'ensembles de données régionales pour faciliter les recherches hydrologiques à l'échelle du continent ;
— Appréhender à l'échelle régionale les problèmes d'évaluation de la ressource en eau, et donc les problèmes complexes liés à la disponibilité et à la gestion de cette ressource ;
— Faire en sorte que les modèles régionaux soient élaborés plus en amont, de manière à pouvoir les comparer aux modèles de processus qui sont généralement construits à partir de travaux à l'échelle locale et contribuer ainsi à une désagrégation plus pertinente des données régionales ;
— Soutenir les réseaux d'observation en contribuant, en collaboration avec l'OMM, à la constitution de bases de données utiles, présentant un meilleur rapport «facilité d'emploi / haute technologie».

Structure du projet FRIEND AOC

Le projet FRIEND Afrique de l'Ouest et centrale (AOC), qui regroupe près d'une vingtaine de pays francophones et anglophones de cette partie du continent africain, s'est doté, en octobre 1994, d'un Comité de Pilotage constitué d'un Coordonnateur général (M. Sakho), des coordonnateurs de chacun des six thèmes de recherche, des représentants de l'UNESCO, de l'O.M.M., de l'ORSTOM, d'AGRHYMET et de l'EIER.

Il dispose désormais, et ce depuis juillet 1996, d'une banque de données inter-Etats gérée à l'aide d'un logiciel développé spécifiquement par l'ORSTOM. Les données de cette base (appelée BADOIE, pour BAnque de DOnnées Inter-Etats) seront accessibles à tous les membres du projet FRIEND recensés comme tels. Cette banque constitue l'élément fédérateur de FRIEND AOC car chaque pays est tenu d'y contribuer. C'est la condition *sine qua non* pour qu'en retour il puisse utiliser les données des autres participants et prendre part aux activités proposées par FRIEND AOC (animation scientifique, sessions de formation, etc.).

Comme tous les autres projets FRIEND, FRIEND AOC est structuré comme un réseau de recherche plurithématique. Chaque thème, à partir de la problématique générale qui précède, définit sa problématique scientifique propre.

Hormis la banque de données, les thèmes de Recherche du projet sont les suivants :

— Etiages	Coordonnateur : D. Sighomnou (Cameroun)
— Modélisation pluie-débit	Coordonnateur : A. Goula Bi (Côte-d'Ivoire)
— Régionalisation des paramètres hydrologiques	Coordonnateur : G. Alé (Bénin)
— Variabilité climatique	Coordonnateur : E. Servat (ORSTOM)
— Qualité des eaux	Coordonnateur : A. Afouda (Bénin)
— Gestion des ressources en eau	Coordonnateur : U. Nigg (EIER)

L'ORSTOM, de son côté, a mis en place un dispositif particulier pour le projet FRIEND AOC. Cela lui permet de mobiliser nombre de ses chercheurs et techniciens dans le cadre de ce projet et de soutenir des étudiants africains en formation de haut niveau (DEA et thèses).

Objectifs

Les objectifs poursuivis par le projet FRIEND AOC sont multiples. Répondant à la problématique définie ci-dessus, ils prennent également en compte le contexte local et la nécessité d'échanger des informations, de mettre en commun des acquis et d'assurer une formation :

— FRIEND AOC vise à promouvoir des thèmes de recherche utiles au développement dans une optique qui est celle des grands hydrosystèmes ou d'une approche régionale de l'hydrologie.
— Cet objectif principal passe par la mise en place d'un véritable réseau de recherche hydrologique en Afrique de l'Ouest et centrale. Ce réseau vise à rassembler, dans le domaine de l'hydrologie, des universitaires, des chercheurs et des hydrologues de type «recherche — développement» de structures plus opérationnelles.
— FRIEND AOC cherche à centraliser l'information disponible sous la forme d'une Base de Données Inter-Etats. Cette Base (BADOIE) permettra aux participants du projet d'avoir accès à une information régionale menant à une approche globale, comparative ou intégratrice, des phénomènes hydrologiques étudiés.
— Le projet FRIEND AOC a également pour ambition la mise en commun des connaissances, des méthodes et des techniques utilisées par les différents participants.
— FRIEND AOC cherche à favoriser au niveau de l'ensemble de la sous-région Afrique de l'Ouest et centrale l'échange d'informations scientifiques et la mise en commun des ressources documentaires et bibliographiques.
— Le projet FRIEND AOC doit être l'occasion pour les scientifiques africains d'échanges facilités avec leurs collègues du Nord par l'intermédiaire des autres projets FRIEND existant en Europe (FRIEND NW et FRIEND AMHY).
— FRIEND AOC doit permettre aux universitaires et chercheurs africains de sortir de leur isolement au niveau continental en leur offrant des possibilités de se rencontrer régulièrement. C'est dans cette optique que seront organisés chaque année des ateliers scientifiques FRIEND AOC.
— FRIEND AOC a également des objectifs de formation. Des sessions seront organisées chaque année, sur des sujets variables, qui permettront aux participants de compléter leurs connaissances dans des domaines utiles pour leurs recherches s'inscrivant dans tel ou tel thème.

— FRIEND AOC, de par son caractère multilatéral, de par l'importance des thèmes scientifiques étudiés, et de par ses actions de centralisation de l'information et de formation, doit pouvoir obtenir des financements internationaux. Ceux-ci permettraient à des équipes regroupant des participants de plusieurs pays d'obtenir les moyens nécessaires à la poursuite de leur activité scientifique dans de bonnes conditions.

Conclusion

Les deux premières années de fonctionnement de FRIEND AOC ont permis d'identifier et de préciser quels étaient les besoins d'un tel réseau de recherche en partenariat tant du point de vue financier que du point de vue organisationnel. La nécessité de procéder à des réunions de coordination pour chacun des thèmes de recherche, l'organisation de sessions de formation, la tenue régulière d'ateliers scientifiques, la participation de membres de FRIEND AOC aux manifestations internationales et la diffusion de l'information scientifique sont apparues comme les points sur lesquels faire porter nos efforts dans les mois et les années à venir. L'aide financière que la Coopération française a décidé d'apporter au projet FRIEND AOC permettra d'atteindre au mieux ces différents objectifs et de compléter ainsi le travail déjà accompli. Celui-ci se traduit par des études qui ont conduit à des publications et à des communications dans différents domaines. En outre, le groupe FRIEND AOC sera présent à la Conférence Internationale FRIEND qui se tiendra en octobre 1997 en Slovénie. FRIEND AOC participera également à la rédaction du rapport FRIEND quadriennal, apportant ainsi la contribution des scientifiques travaillant sur le continent africain.

Ces premières années de fonctionnement ont également permis de nouer des liens avec les autres Groupes FRIEND (NWE et AMHY). Les contacts pris sont importants dans la mesure où ils nous font bénéficier de l'expérience d'une pratique éprouvée en matière de fonctionnement d'un réseau scientifique. Par ailleurs, les relations établies avec les autres Groupes FRIEND africains (Afrique Australe et Nil, ce dernier étant en phase de démarrage) sont essentielles. Elles doivent permettre de multiplier les échanges entre les différentes communautés de scientifiques africains. Certains thèmes de recherche tels que «Modélisation pluie-débit» ou «Etiages» feront ainsi l'objet de travaux interconnectés à l'échelle du continent avec l'intérêt que l'on devine pour les méthodes utilisées et les résultats obtenus.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 613-637 (1998)

Les fluctuations du niveau du lac Tanganyika et les termes de surface de son bilan hydrique

par

Laurent BERGONZINI *

MOTS-CLES. — Niveau du lac ; Tanganyika ; *Water balance.*

RESUME. — Les données rassemblées ont permis d'évaluer les variations du niveau lacustre, du débit à l'exutoire, et d'un «niveau sans écoulement», de 1932 à 1995. L'évolution du niveau depuis 1932 se retrouve en partie dans la région des Grands Lacs d'Afrique intertropicale. Par contre, les écoulements à l'exutoire du lac, relativement plus importants de 1960 à 1990 que de 1932 à 1960 et diminuant après 1990, paraissent s'opposer à d'autres tributaires du fleuve Congo-Zaïre. Sur l'ensemble de la période, la hausse du «niveau sans écoulement» n'est pas régulière et est mise en relation avec la variabilité des abondances pluviométriques. A partir de ces observations, on estime qu'une diminution minimum de 11 % des précipitations entraînerait la fermeture du lac. La prise en compte de données d'écoulement pour vingt-six stations hydrométriques sur le bassin versant a également permis de caractériser les débits spécifiques des différentes rives et de localiser les zones d'alimentation en eau du lac. Ainsi, les termes de surface du bilan hydrique, évalué dans cette étude, et la partie atmosphérique, évaluées il y a plus de trente ans par BULTOT (1965), paraissent compatibles.

TREFWOORDEN. — Waterhoogte van het meer ; Tanganyika ; Waterbalans.

SAMENVATTING. — *De fluctuaties van het waterpeil van het Tanganyikameer en van de oppervlaktetermen van zijn waterbalans.* — De gegevens over het referentietijdvak 1932 tot 1995 hebben toegelaten de variaties van de waterhoogte van het Tanganyikameer, het debiet aan de uitlaat en van een „niveau zonder lozing" te schatten. De evolutie van het niveau sedert 1932 wordt gedeeltelijk herkend binnen het gebied van de grote meren van intertropisch Afrika. Anderzijds zijn de lozingen bij de uitlaat van het meer

* Laboratoire d'Hydrologie et de Géochimie Isotopique, Université de Paris-sud, Bât. 504, F-91405 Orsay Cedex (France).

relatief belangrijker van 1960 tot 1990 dan van 1932 tot 1960 en verminderen zij na 1990 ; zij blijken tegengesteld aan andere bijrivieren van de Congo-Zaïrestroom. Over het geheel van de periode is de stijging van het „niveau zonder lozing" niet regelmatig en wordt in verband gebracht met de variabiliteit van de overvloed aan neerslaghoeveelheden. Vertrekkende van deze waarnemingen veronderstelt men dat een vermindering van minimum 11 % van de neerslagen zou leiden tot de sluiting van het meer. Het in rekening brengen van de afvoergegevens van zesentwintig hydrometrische stations uit het stroombekken heeft eveneens toegelaten de specifieke debieten van de verschillende oevers te karakteriseren en de voedingszones aan water van het meer te lokaliseren. Aldus blijken de oppervlaktetermen van de waterbalans geëvalueerd in deze studie en het atmosferisch gedeelte, meer dan dertig jaar geleden geëvalueerd door Bultot (1965) overeen te stemmen.

Keywords. — Lake Level ; Tanganyika ; Water Balance.

Summary. — *The Fluctuations of the Water Levels of the Lake Tanganyika and of the Surface Components of its Water Budget.* — The data collected have allowed to evaluate the variations in the water levels, of the discharge at the outlet, and of a "level without discharge", from 1932 till 1995. The evolution of the level since 1932 is found all over the region of the intertropical large African lakes. On the contrary, the discharges at the outflow of the lake, relatively more important from 1960 till 1990 than from 1932 till 1960 and decreasing since 1990, seem to be opposed to the other tributaries of the River Congo-Zaire. Over the whole reference period, the increase of the "level without discharge" is not regular and is put in relationship with the variability of the abundant rainfall. From these observations, it is estimated that a minimum reduction of 11 % in the rainfall would cause the closure of the lake. Taking into account the discharge data from twenty-six hydrometric stations in the catchment has also allowed to characterize the specific discharges of different rivers and to localize the region of water input for the lake. In this way, the surface components of the water budget assessed in this study and the atmospheric parts, assessed more than thirty years ago by Bultot (1965) do look compatible.

1. Introduction

Les objectifs de cette étude sont, dans un premier temps, de caractériser les fluctuations du niveau du lac, de préciser les valeurs du débit à l'exutoire et d'évaluer l'excédent du bilan hydrologique. Dans un deuxième temps, on s'intéressera aux relations pouvant exister entre l'excédent et les précipitations. Enfin, la prise en compte des écoulements de surface à différentes stations hydrométriques permettra de caractériser

les différentes zones d'écoulement du bassin versant et de les comparer aux estimations existantes.

Cette note fait suite à la publication «des écoulements de la Lukuga à l'exutoire du lac Tanganyika» (BERGONZINI 1995), dont elle reprend quelques éléments et observations. Toutefois, l'obtention de nouvelles mesures de jaugeage à l'exutoire du lac, postérieures à 1964 (note personnelle de Crespin communiquée par Charlier), a permis de compléter cette première étude en rendant possible la réévaluation du débit de la Lukuga (exutoire du lac) après 1964 et une réactualisation des observations faites antérieurement. Par ailleurs, l'étude des cyclicités dans les enregistrements limnimétriques a fait apparaître des périodicités dans le bilan hydrologique du lac. Enfin, le traitement de données sur les écoulements de surface (vingt-six bassins versants qui alimentent le lac) a permis de caractériser le comportement des différentes zones du bassin versant.

Le lac Tanganyika s'étend du N-NO au S-SE sur 650 km, avec une largeur de 35 à 75 km, une surface de 32 600 km^2, un volume de 18 880 km^3 (fig. 1), et une profondeur maximum de 1 470 m (CAPART 1949). Limité par une série de failles et de hauts massifs, il fait partie du graben d'effondrement de l'axe central du continent africain. La surface du plan d'eau est sujette à une forte évaporation évaluée à 1 690 mm an^{-1}, les précipitations directes à la surface lacustre sont estimées à 1 000 mm an^{-1} (BULTOT 1965, 1993), le reste des apports provenant du bassin d'une superficie évaluée à environ 240 000 km^2 (GILLMAN 1933).

2. Variations du niveau lacustre

Une estimation du niveau du lac Tanganyika à l'échelle de Kalémie entre décembre 1992 et octobre 1995 a été ajoutée à la précedente étude (BERGONZINI 1995). Rappelons que les niveaux du lac Tanganyika ont été observés de façon irrégulière depuis 1846. Un certain nombre de voyageurs en ayant donné une description partielle au 20^e siècle, une courbe des variations moyennes a été reconstituée grâce à ces témoignages et aux récits recueillis auprès des habitants (DEVROEY 1938 ; Theeuws, note personnelle et inédite). Avant 1878, on était en présence d'un lac sans écoulement dont le niveau s'élevait graduellement et était d'environ 776,6 m en 1846. En 1878, il atteignait son maximum, soit environ 783,6 m (DEVROEY 1938). C'est en 1877-1878 que commence ce qu'on appelle «la débâcle» de la Lukuga. Celle-ci une fois amorcée,

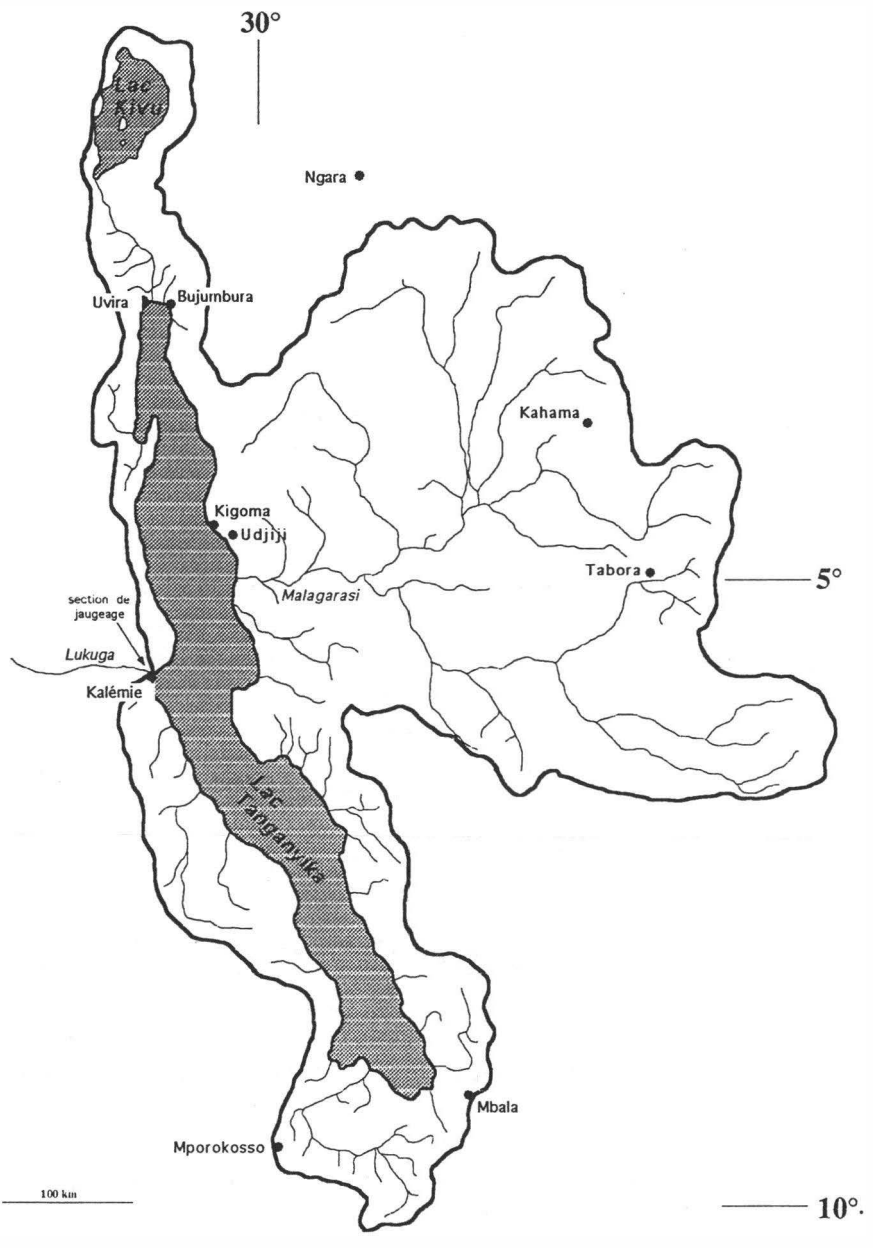


Fig. 1. — Le lac Tanganyika et son bassin versant.

les eaux passant par-dessus le barrage d'humus, emportèrent rapidement l'obstacle naturel qui limitait les écoulements du lac à la rivière. Les six premières années, le niveau baissa de 9 m, puis encore de 2 m les huit années suivantes, pour atteindre en 1894 la cote d'environ 772,5 m. Une première échelle fut installée en 1909 à Kigoma (Tanzanie). Des mesures ont été effectuées entre 1909 et 1933. Seules les valeurs des extrêmes annuels du niveau ont été conservées, et c'est uniquement depuis 1932 que l'ensemble des lectures journalières de l'échelle de Kalémie (Zaïre) est disponible (DEVROEY 1938). Cette échelle, installée en 1913, a son zéro positionné à une altitude d'environ 770 m. Les lectures des échelles font apparaître les variations annuelles, avec un maximum en avril-mai et un minimum en octobre-novembre (DEVROEY 1938). On constate par ailleurs que les différences de niveau d'un jour à l'autre ne dépassent pas quelques centimètres. L'alternance des saisons (apports pendant la saison des pluies et évaporation intense pendant la saison sèche) est la cause des marées annuelles. Il existe d'autres motifs de variations, soit accidentelles et dues à l'influence des vents, soit plus périodiques et en rapport avec la pression atmosphérique ou avec les phénomènes de seiches. Ces variations sont de l'ordre du décimètre. Quant aux variations cycliques, à périodicité plus longue, il semble établi qu'il existe un parallélisme entre les régimes du Tanganyika et des lacs Kivu, Albert et Victoria (DEVROEY 1949).

Nous avons utilisé l'enregistrement du niveau du lac au pas de temps mensuel à l'échelle du port de Kalémie entre 1932 et 1959 (DEVROEY 1948, 1952-60). Depuis 1959, ces enregistrements n'étant pas disponibles, il nous a fallu reconstituer la chronique après cette date. Cette reconstitution du niveau moyen mensuel du lac à Kalémie a été obtenue grâce aux enregistrements à l'échelle de Bujumbura (Burundi) de janvier 1950 à décembre 1992 (M. E. Coenen, communication personnelle). Suite à la comparaison entre les échelles de Kalémie, de Bujumbura, d'Uvira (Zaïre) et de Kigoma (Tanzanie), on a été conduit à éliminer les mesures effectuées à Bujumbura (de septembre 1955 à novembre 1956) qui paraissaient suspectes. Sur la période 1951-1959, entre les mesures de Kalémie et de Bujumbura, une relation linéaire traduit un décalage systématique des hauteurs enregistrées affecté par des variations saisonnières. Ce décalage entre les deux échelles est apparu plus important lors des étiages et semble tendre vers une valeur plus stable en période de hautes eaux. La relation choisie pour reconstituer le niveau à Kalémie prend donc en compte le facteur saisonnier de ces décalages.

$$H\,(Kal) = -4{,}84 + 0{,}98\,H\,(Buj) + 3{,}97\,\mathrm{Sin}\,(m\,\pi/6) + 3{,}39\,\mathrm{Cos}\,(m\,\pi/6)$$

$R^2 = 0{,}97$

écart type résiduel : 5 cm

avec : H (Kal) : le niveau moyen mensuel à l'échelle de Kalémie (cm),
H (Buj) : le niveau moyen mensuel à l'échelle de Bujumbura (cm),
m : un coefficient mensuel variant de 1 pour le mois de janvier à 12 pour le mois de décembre.

Au moyen de cette régression, la reconstitution à Kalémie est obtenue à partir d'estimations de l'espérance mathématique du niveau de H (Kal). On peut vérifier la précision de cette estimation grâce au calcul d'intervalles de confiance au niveau 90 % dont l'amplitude est de l'ordre de plus ou moins 3 cm. Cette relation permet donc de reconstituer, de façon relativement précise, le niveau du lac à Kalémie. La variabilité saisonnière entre les deux échelles H (Kal) et H (Buj) a été attribuée aux phénomènes de seiches, ainsi qu'à l'influence des vents. Quant aux résidus, ils correspondent aux difficultés de lecture sur ce plan d'eau sujet aux phénomènes de houle. Ajoutons que les cinq données mensuelles manquantes ont été évaluées graphiquement. Ne disposant pas des lectures du port de Bujumbura depuis décembre 1992, l'estimation du niveau du lac à l'échelle de Kalémie depuis cette date, et ce jusqu'en octobre 1995, a été obtenue grâce aux enregistrements satellitaires (Global Lake Catchment Conservation Database). Comme la période de recoupement entre les lectures hydrométriques et les mesures satellitaires n'est que de deux mois (d'octobre à décembre 1992), il ne s'agit là que d'une première approche permettant de mettre en évidence la tendance des variations depuis janvier 1993. L'étude des enregistrements aux échelles hydrolimnimétriques entreprise depuis janvier 1993 devrait permettre de préciser la relation entre niveau mesuré sur le terrain et par satellite. La courbe reconstituée du niveau moyen mensuel à Kalémie, pour la période 1932-1995, est représentée sur la figure 2a. Sur cette période, le niveau maximum a été observé lors des hautes eaux de 1964 (682 cm, environ 776,82 m), alors que le minimum s'est produit lors des basses eaux de 1949 (288 cm, environ 772,88 m). Ces extrêmes sont aussi enregistrés sur le lac Victoria, maximum depuis le début du siècle, lors des hautes eaux de 1964, et minimum depuis 1932, lors des basses eaux de 1949 (Sene & Plinston 1994). L'augmentation du niveau lacustre de presque 3 m,

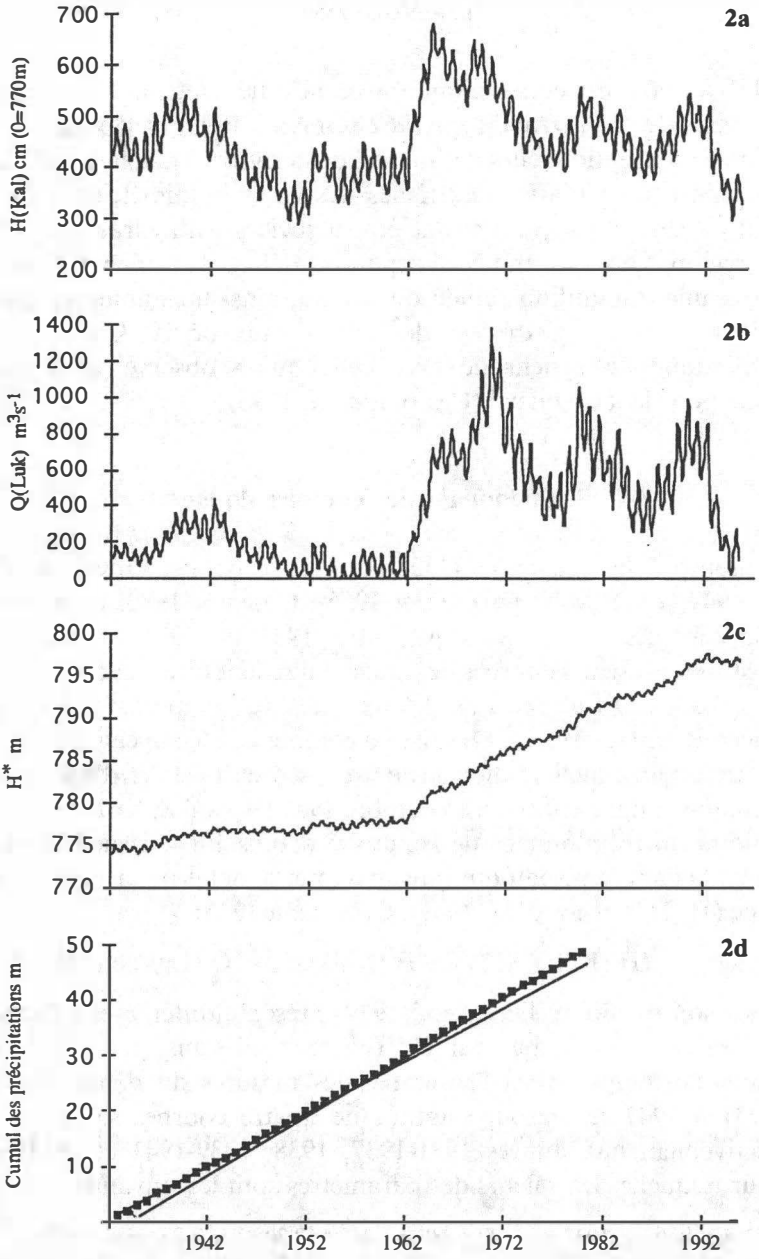


Fig. 2a. — Niveaux mensuels du lac Tanganyika, à l'échelle de Kalémie, H (Kal) en cm, enregistrés de 1932 à 1959 et reconstitués de 1960 à 1995.

Fig. 2b. — Reconstitution des débits mensuels de la Lukuga à Kalémie, Q(Luk) en m^3s^{-1}, de 1932 à 1995.

Fig. 2c. — Evolution de H*, «niveau sans écoulement» de 1932 à 1992.

Fig. 2d. — Cumul des pluies moyennes annuelles, reconstitué grace aux données des stations pluviométriques Bujumbura, Kigoma, Tabora, Ngara, Kahama, Mbala et Mporokosso, de 1932 à 1980.

de 1961 à 1964, est concomitante avec la crue centenaire du Congo-Zaïre observée à Brazzaville en 1962 (OLIVRY 1993) et l'extension sur des surfaces exceptionnelles des marais de la rivière Malagarasi (CAMUS 1965). Ainsi, les variations extrêmes des cotes limnimétriques du lac Tanganyika depuis 1932 peuvent être associées à l'hydraulicité d'une vaste région. Plus récemment, depuis le début des années 1990, on assiste à une diminution rapide du niveau, ainsi un minimum proche de 773 m a été enregistré lors des basses eaux de 1994. Cette chute limnimétrique est synchrone avec celle qu'on observe, à la même époque, pour le lac Malawi (CALDER *et al.* 1996).

3. Etalonnage de l'exutoire du lac

L'ensemble des jaugeages (135 mesures de débits, DEVROEY 1938, 1948, 1949, 1952-1960 ; CHARLIER 1955 ; CRESPIN 1980, note personnelle), effectués sur la Lukuga entre 1931 et 1971, a permis de reconstituer plusieurs courbes de tarage qui relient directement les débits de la Lukuga, Q(Luk) en m^3s^{-1}, aux cotes du lac mesurées à l'échelle de Kalémie, H (Kal) en m. La prise en compte de 26 jaugeages (CRESPIN 1980, note personnelle), effectués entre 1964 et 1971, et d'une mesure du débit instantané effectuée en octobre 1995 (BOMBI & KIHAKWI 1996), ont induit un réétalonnage de l'exutoire depuis 1964. Usuellement, les relations reliant le niveau du Tanganyika et le débit de la Lukuga sont de type (1) (DEVROEY 1938, 1949 ; CHARLIER 1955).

$$Q\,(Luk) = K\,(H\,(Kal) - H°)^{3/2} \quad H\,(Kal) \text{ en m} \quad Q\,(Luk) \text{ en } m^3s^{-1} \qquad (1)$$

Dans son mémoire, DEVROEY (1949) présente différentes valeurs du coefficient K et de la hauteur H° (hauteur du seuil) pour différentes périodes de temps. Ainsi l'ensemble des mesures du débit effectuées de 1931 à 1947 se regroupe autour de quatre courbes se rapportant respectivement aux années 1931-1937, 1938, 1939-1941 et 1941-1947, et pour lesquelles les valeurs des paramètres sont les suivantes :

de 1931 à septembre 1937	K = 60	H° = 2,70	(23 jaugeages, fig. 3a)
d'octobre 1937 à mai 1938	K = 67,5	H° = 2,70	(4 jaugeages, fig. 3b)
de juin 1938 à février 1941	K = 86	H° = 2,70	(5 jaugeages, fig. 3c)
de mars 1941 à janvier 1947	K = 112	H° = 2,70	(10 jaugeages, fig. 3d)

Cette dernière équation a été utilisée jusqu'en décembre 1951 (3 jaugeages). Pour la période allant de 1952 à 1954, CHARLIER (1955) avait proposé le même type de relation, mais avec les paramètres

suivants : $K = 265$ et $H° = 3,55$ (31 jaugeages). Après l'étude des jaugeages effectués après 1954, cette relation a été conservée pour les cotes inférieures à 4,30 m. Par contre, pour les hauteurs supérieures à 4,30 m, une relation de type (2), qui paraît plus adaptée pour les forts débits, a été établie :

$$Q\,(Luk) = K_2\,(H\,(Kal) - H_1)^{3/2} - Q\,(H_1) \quad Q\,(H_1) = K\,(H_1 - H°)^{3/2} \qquad (2)$$

Cette rupture dans la courbe de tarage avait déjà été observée par CHARLIER (1955) et correspond à un freinage de l'écoulement qui est entravé par les conditions en aval. Cette relation a été conservée jusqu'en octobre 1955. Il apparaît donc de février 1952 à octobre 1955 (36 jaugeages, fig. 3e) :

lorsque $H < 4,30$	$K = 265$	$H° = 3,55$	(32 jaugeages)
lorsque $H > 4,30$	$K_2 = 203$	$H_1 = 4,30$	(4 jaugeages)

De novembre 1955 jusqu'en mai 1964, le même type de relation est proposé (une relation de type (1) pour les faibles débits et une de type (2) pour les forts ; 35 jaugeages, fig. 3f) :

lorsque $H < 4,20$	$K = 265$	$H° = 3,55$	(16 jaugeages)
lorsque $H > 4,20$	$K_2 = 130$	$H_1 = 4,20$	(19 jaugeages)

A partir de juin 1964, on observe une augmentation régulière, au cours du temps, du paramètre K (CRESPIN 1980, note personnelle). La relation choisie prend donc en compte l'évolution temporelle de K :

de juin 1964 à mai 1966 $K = 78 + 1,5\,T$ $H° = 2,70$ (7 jaugeages, fig. 3g)

avec : $T = 1$ pour janvier 1964, $T = 2$ pour février 1964, ...

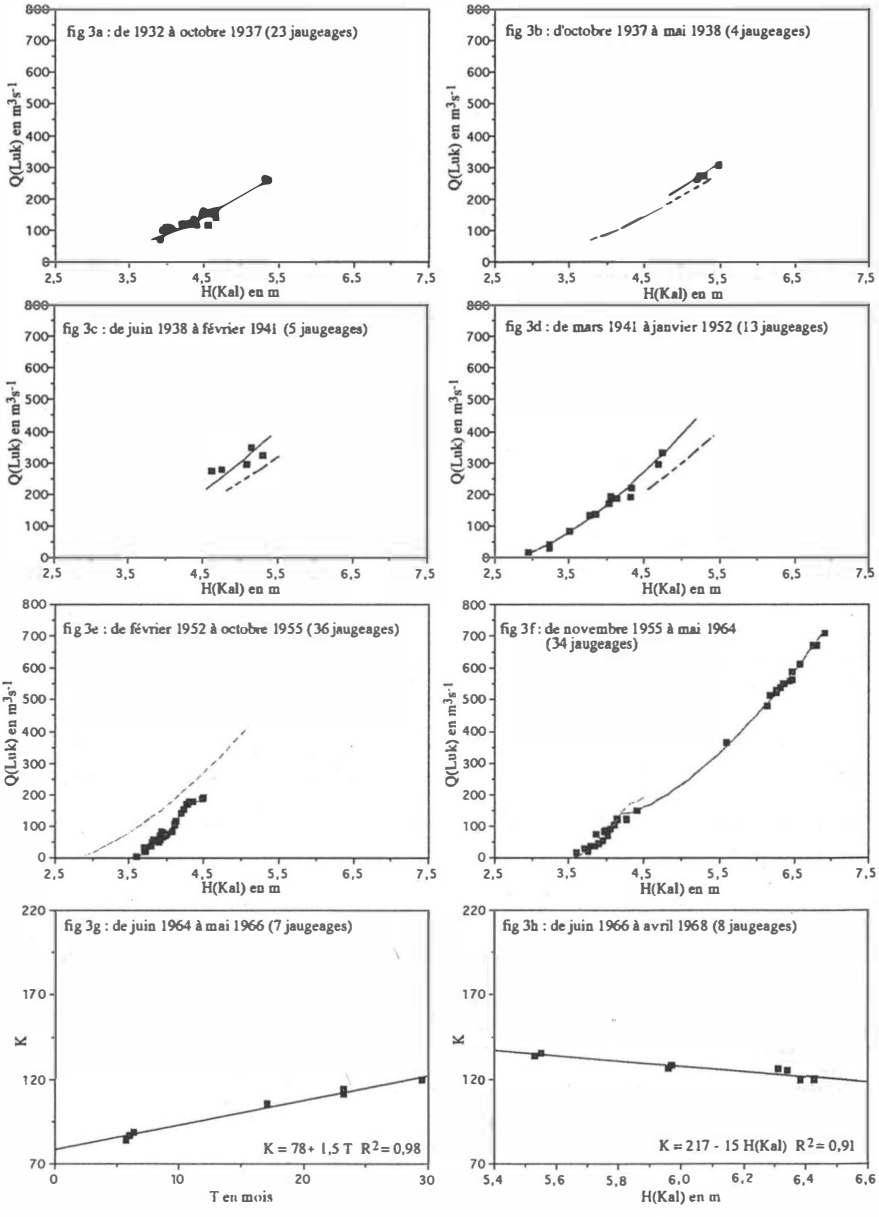
De juin 1966 à avril 1968, la courbe de tarage se stabilise, par contre le coefficient K varie en fonction de la cote du lac, H (Kal) (CRESPIN 1980, note personnelle, fig. 3h). Le paramètre K dépend donc du niveau lacustre :

de juin 1966 à avril 1968 $K = 217 - 15\,H\,(Kal)$ $H° = 2,70$ (5 jaugeages, fig. 3h')

Puis, à nouveau, on observe une augmentation au cours du temps du paramètre K. Une nouvelle relation prenant en compte cette évolution a donc été choisie :

de mai 1968 à avril 1970 $K = 90 + 4,2\,T$ $H° = 2,70$ (5 jaugeages, fig. 3i)

avec : $T = 1$ pour janvier 1968, $T = 2$ pour février 1968, ...


fig 3a : de 1932 à octobre 1937 (23 jaugeages)
fig 3b : d'octobre 1937 à mai 1938 (4 jaugeages)
fig 3c : de juin 1938 à février 1941 (5 jaugeages)
fig 3d : de mars 1941 à janvier 1952 (13 jaugeages)
fig 3e : de février 1952 à octobre 1955 (36 jaugeages)
fig 3f : de novembre 1955 à mai 1964 (34 jaugeages)
fig 3g : de juin 1964 à mai 1966 (7 jaugeages)
fig 3h : de juin 1966 à avril 1968 (8 jaugeages)
Q(Luk) en m3s-1
H(Kal) en m
K
T en mois
K = 78+ 1,5 T R2= 0,98
K = 217 - 15 H(Kal) R2= 0,91

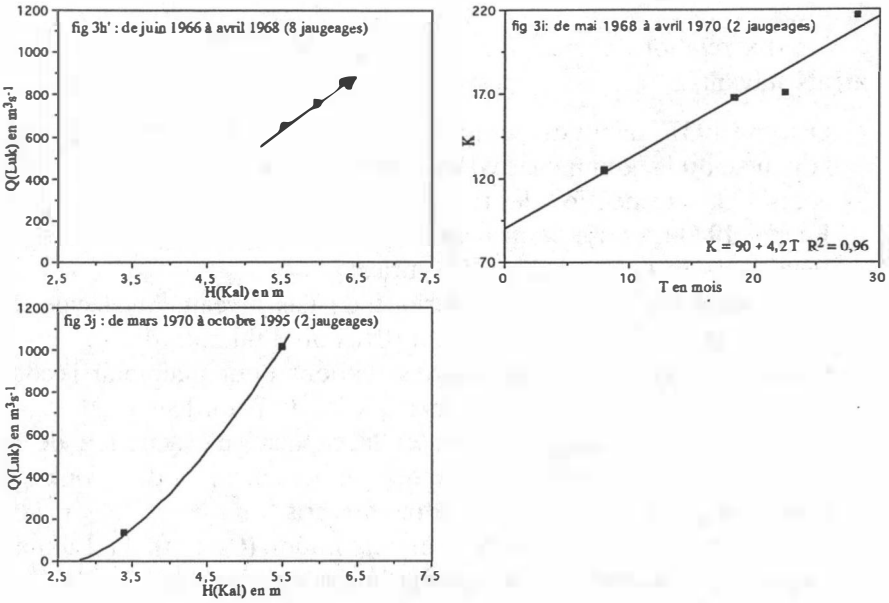


Fig. 3a, 3b, 3c, 3d, 3e, 3f, 3h et 3j. — Courbes d'étalonnages utilisées pour le calcul des débits instantanés de la Lukuga (en m^3/s), en fonction de la hauteur du lac Tanganyika à l'échelle de Kalémie (en m ; les courbes sont tracées des valeurs minimums aux valeurs maximums observées durant la période de validité de la relation).
Courbe de tarage utilisée pour la période : ———
Courbe de tarage antérieure à la période : — — —
Points de mesure du débit : •

Fig. 3g et 3i. — Evolution temporelle du paramètre F, fig. 3g pour la période allant de juin 1964 à mai 1966 (avec T = 1 le premier janvier 1964, T = 2 le premier février 1964, ...) et fig. 3i pour la période allant de mai 1968 à avril 1970 (avec T = 1 le premier janvier 1968, T = 2 le premier février 1968, ...)

Fig. 3h. — Evolution du paramètre K avec le niveau des eaux du lac Tanganyika à l'échelle de Kalémie pour la période allant de juin 1966 à avril 1968.

Depuis 1970, seulement deux mesures de débit sont disponibles, ce qui rend difficile l'étalonnage de l'exutoire du lac. Nous proposons malgré tout une relation du type :

de mai 1970 à octobre 1995 $K = 216$ $H° = 2,70$ (2 jaugeages fig. 3j)

Ces dix relations correspondent aux périodes associées aux événements suivants :

— Octobre 1937 : début du curage de la Lukuga entrepris pour enrayer la hausse du lac qui menace d'inonder les rives du lac ;
— Mars 1938 : suspension des travaux ;
— Février 1940 : reprise des travaux de curage ;
— Février 1941 : fin des travaux de curage ;
— Automne 1951 : suite à une période de bas niveau, on décide de soutenir le niveau du lac par la construction d'un batardeau ;
— Octobre 1954 : installation de trois syphons pour maintenir l'écoulement lors des niveaux inférieurs à la côte du batardeau ;
— Décembre 1955 : afin d'augmenter la capacité d'évacuation de la Lukuga lors des hautes eaux à venir, un dérochement de la Lukuga et un curage du lit de la rivière sont entrepris ;
— Mai 1964 : le niveau atteint son maximum (6,82 m), la Lukuga contourne le barrage provisoire, sur la rive gauche ;
— Octobre 1964 : le gouvernement du Zaïre fait débrousser, au grappin, l'exutoire ;
— 1966 et 1967 : les niveaux mensuels des hautes eaux de ces années ne dépassent pas 6,30 m à Kalémie ;
— 1968 et 1969 : le niveau mensuel du lac atteint, durant deux années, un niveau supérieur à 6,40 m à l'échelle de Kalémie ;
— Depuis 1970 : le niveau mensuel du lac n'a plus atteint une cote supérieure à 6,40 m.

Il est à noter que le découpage des quatre premières périodes (fig. 3a, b, c, et d) avait déjà été mis en évidence (Devroey 1949). Il montre l'augmentation de la capacité d'évacuation de la Lukuga, après les travaux de 1937 et de 1940. La dispersion des résultats, autour de ces courbes, fut à l'époque imputée au manque d'homogénéité des méthodes de mesure et à la diversité des opérateurs (Devroey 1949), ou à des erreurs de lecture d'échelles (Charlier 1955). Cette seconde hypothèse est la plus vraisemblable, car si l'on porte les débits en fonction du niveau à une échelle située en aval de l'exutoire, la dispersion des points s'atténue. Là encore, les mesures à l'échelle de

Kalémie sont relativement imprécises en raison de la houle. Après cette augmentation de la capacité d'évacuation de 1937 à 1941, il semble que la courbe de tarage se soit stabilisée (fig. 3d). En effet, les jaugeages effectués en septembre 1950 et en 1951 (3 jaugeages) semblent confirmer la courbe de tarage déterminée par Devroey pour la période 1941-1947 (10 jaugeages). Après l'établissement du barrage provisoire (1951), on remarque que le niveau du seuil est passé de 2,70 à 3,55 m (fig. 3e). Ce batardeau à l'entrée de la Lukuga semble avoir eu une influence immédiate sur le niveau du plan d'eau (fig. 2a). Les curages et dérochements de 1955 ne purent empêcher, pour une hauteur donnée, une diminution de la valeur du débit (fig. 3f). Cette variation de la courbe de tarage semble due à l'accumulation d'alluvions provoquée par la présence du batardeau. D'ailleurs, à l'encontre de ce que l'on observe sur l'exutoire de la plupart des lacs, la Lukuga a un débit solide important provenant de l'action de la houle et du vent sur les plages du lac (Camus 1965).

Lors des hautes eaux de juin 1964, le lac atteint le maximum enregistré (6,82 m). La Lukuga a contourné le batardeau par la rive gauche et a induit, progressivement, la remise en activité de l'ancien seuil (2,70 m ; Charlier, communication personnelle). La capacité de l'exutoire a alors augmenté de façon continue (fig. 3g). Un phénomène d'autocurage a donc modifié profondément l'écoulement de la rivière (Crespin 1980, note personnelle). Les avis furent partagés quant à l'efficacité des opérations d'octobre 1964 (Camus 1965), mais ce débroussage n'a pu qu'accélérer le processus enclenché. L'évolution a été rapide dans un premier temps, puis comme le niveau diminuait, le courant baissant, l'autocurage s'est interrompu. Cette stabilisation de la courbe de tarage de décembre 1965 à avril 1968 (fig. 3h') peut s'expliquer par la diminution du niveau lacustre. Quant à l'évolution de K en fonction du niveau lacustre (fig. 3h), elle s'explique par une influence croissante avec le niveau des conditions avales. Lors de cette période, et contrairement aux années 1964 et 1965, le niveau mensuel maximum n'a pas dépassé 6,30 m. Par contre, lors des hautes eaux de 1968 et 1969, les maximums des niveaux mensuels furent supérieurs à 6,40 m. De nouveau, le niveau et le courant augmentant, ce fut la reprise de l'autocurage de la Lukuga, et K augmenta à nouveau (fig. 3i). Il semble donc que l'autocurage de la Lukuga n'est induit que lorsque le niveau des hautes eaux est supérieur à 6,30-6,40 m.

Le peu de jaugeages (2 jaugeages) disponibles depuis 1970 rend aléatoire l'établissement d'une relation entre hauteur et débit. Mais,

on peut penser que, comme le niveau du lac est resté au cours de cette période inférieur à 6,30-6,40 m, la courbe de tarage n'a que peu été modifiée par des phénomènes d'autocurage. La relative constance du paramètre K entre les deux mesures de débits (K 1971 = 216 ; K 1995 = 225) laisse penser à une certaine stabilité de la courbe. Faute de mieux, on utilisera un coefficient K d'environ 216 (fig. 3j).

4. Débits de la Lukuga à l'exutoire du lac ou pertes de surface

Bien que les relations entre débits et hauteurs ne soient pas linéaires, nous avons utilisé les hauteurs moyennes mensuelles afin de déterminer le débit moyen mensuel (fig. 2b). Cette approximation reste ici justifiée car les variations des niveaux journaliers pour un mois donné sont très faibles. La Lukuga présente, elle aussi, un régime de type pondéré avec un maximum en avril-mai et un minimum en octobre-novembre. Le débit mensuel maximum s'est produit en mai 1970 (1 377 m^3s^{-1}) ; par contre, durant les basses eaux de 1954, 1955 et 1959, l'écoulement n'était dû qu'à la présence des siphons. Le plus fort débit mesuré n'étant que de 1 190 m^3s^{-1} (10/06/1966, note personnelle de Crespin 1980), il est possible que le débit maximum évalué soit surestimé, mais ce dernier est contemporain à l'enregistrement de forts débits sur le Congo-Zaïre ainsi que sur l'Oubangui (Olivry *et al.* 1993). Les différences entre les fluctuations du niveau et du débit s'expliquent par les aménagements à l'exutoire ainsi que les phénomènes d'autocurage du lit de la rivière. Sur la période 1932-1971 (40 ans), où de nombreux jaugeages sont disponibles, le module interannuel est d'environ 280 $m^3s - 1$, soit 9 km^3an^{-1}. Par contre, pour la période 1972-1995 (24 ans), où seulement deux jaugeages sont disponibles, le module passe à environ 540 m^3s^{-1} (17 km^3an^{-1}). Ces débits peuvent paraître considérables pour la Lukuga ; pourtant, lors de la grande débâcle entre 1879 et 1883, si on considère que le bilan hydrologique était excédentaire, l'écoulement était au minimum de 1 400 m^3s^{-1}. Sur l'ensemble de la période (1932-1995, 64 ans), le module interannuel est donc estimé à environ 380 m^3s^{-1} (12 km^3an^{-1}). Cette faible valeur s'explique par la forte évaporation à la surface du lac. En effet, pour la période 1932-1971, le débit spécifique du bassin versant est de 4,8 $l\,s^{-1}km^{-2}$, il tombe à 1,2 $l\,s^{-1}km^{-2}$ à l'exutoire. Par contre, sur l'ensemble de la période (1932-1995), le débit spécifique du bassin versant est d'environ 5,3 $l\,s^{-1}km^{-2}$, il tombe à environ 1,6 $l\,s^{-1}km^{-2}$ à l'exutoire du lac. Contrairement aux fleuves de l'Afrique intertropicale,

tributaire de la façade atlantique, Oubangui, Congo-Zaïre, Sangha (OLIVRY 1993), ou aux lacs d'Afrique de l'Ouest (SIRCOULON 1987), on n'assiste pas, à partir du milieu des années soixante, à une diminution des écoulements, mais au contraire à une augmentation de l'hydraulicité. Il est vrai que les débits de la période 1971-1995 sont sujets à caution, car nous n'avons que deux jaugeages qui ne nous permettent aucune certitude sur la courbe de tarage. Cette différence de comportement pourrait cependant s'expliquer par l'influence des masses d'air indienne et d'Afrique australe sur le bassin du lac Tanganyika, ainsi que par l'autocalibrage de la Lukuga. De plus, l'accroissement du module à partir des années soixante se retrouve à l'exutoire du lac Victoria (PIPER *et al.* 1986, SENE & PLINSTON 1994), au niveau des lacs Kyoga et Albert (CONWAY & HULME 1993), et coïncide avec l'augmentation des précipitations dans cette zone (CONWAY & HULME 1993). Plus récemment, depuis le début des années quatre-vingt-dix, on observe une diminution de l'écoulement. Le débit de la Lukuga retrouve des valeurs comparables à celles des années quarante et cinquante. Ce comportement s'inscrit probablement dans une évolution climatique globale de la région des Grands Lacs et semble s'opposer à l'évolution qu'on observe en Afrique de l'Ouest et dans toute la zone sahélienne au sens large.

5. Excédent hydrique à l'exutoire du lac

Afin d'étudier les variations du bilan hydrologique du lac, on a reconstitué les variations mensuelles du niveau telles qu'elles auraient été enregistrées si l'exutoire avait été obturé en 1932 («niveau sans écoulement» H*). Pour cela, l'ensemble des modules mensuels calculés, de 1932 à 1995, sont réintroduits dans le lac et induisent donc des hausses du niveau qui viennent s'ajouter aux variations observées en conditions naturelles (fig. 2c). Les variations du «niveau sans écoulement» laissent apparaître une périodicité annuelle, avec une montée des eaux d'octobre-novembre à mai qui signifie que l'excédent est positif, mais aussi une baisse de mai à octobre-novembre, où l'évaporation à la surface du lac l'emporte sur les apports. Pendant cette deuxième période, le «niveau sans écoulement» descend nonobstant l'obturation complète de l'exutoire. Dans l'hypothèse où la Lukuga aurait été obturée (depuis 1932), le lac aurait atteint, en octobre 1995, la cote de 796,7 m, ce qui correspond à une augmentation moyenne de 0,34 m an^{-1}. Cette hausse n'est pas régulière, on distingue plusieurs

périodes. De 1932 à 1961, cette augmentation est de 0,12 m an^{-1}, elle passe à 0,81 m an^{-1} entre 1961 et 1970, puis est estimée à 0,55 m an^{-1} pour la période allant de 1970 à 1992. Enfin, de 1992 à 1995, on observe une diminution moyenne de 0,17 m an^{-1} du niveau sans écoulement. Pour la première fois depuis 1932, le bilan hydrologique du lac a donc été déficitaire durant plusieurs années consécutives. Rappelons, à titre comparatif, que, durant la montée des eaux entre 1846 et 1878 (DEVROEY 1938), cet excédent était d'environ 0,21 m an^{-1}. Le temps de résidence des eaux dans le lac est lui d'environ 280 ans et le temps de résidence des eaux de surface d'environ 550 ans ; deux valeurs inférieures aux 430 et 1 000 ans proposés par DEGENS (1973).

La variation annuelle nette (H*) du «niveau sans exutoire» a été définie comme la différence entre les niveaux mensuels, H*, calculés entre les mois d'octobre de deux années consécutives. Cette variation représente, pour l'ensemble du bassin hydrographique du Tanganyika, l'excédent ou le déficit des apports sur l'évaporation selon qu'elle est positive ou négative. La définition de H* est associée à la sélection d'un mois de référence, dans le cas présent le mois d'octobre, à partir duquel s'effectue le calcul de la variation. Ce choix a bien évidemment un sens limnologique, mais c'est aussi celui qui conduit à établir la meilleure corrélation avec l'abondance pluviométrique annuelle associée (d'octobre à septembre), donc de relier sur un pas de temps de douze mois le bilan du lac et la pluviométrie, ce que nous ferons au paragraphe suivant. L'étude des périodicités dans l'enregistrement (63 ans) des variations annuelles nettes (H*) a fait apparaître plusieurs cyclicités de périodes supérieures à l'année. Des cycles d'environ 5, 9, et 11-12 ans semblent caractériser les oscillations du bilan hydrologique. De telles cyclicités de 5 et 10-11 ans ont déjà été mises en évidence dans les variations du niveau du lac Victoria (CRUL 1996). L'interprétation de ces cyclicités reste complexe ; elles peuvent avoir une origine atmosphérique globale, locale ou limnologique. Il est vrai qu'autrefois on se basait sur la périodicité des taches solaires pour prévoir les hausses et les baisses des Grands Lacs africains (GILLMAN 1933, DEVROEY 1949), mais cette relation ne semble pas si évidente. Une étude des relations pouvant exister entre l'excédent du bilan hydrologique et des indices globaux de la circulation intertropicale est actuellement en cours et devrait permettre de mieux comprendre l'origine et la signification de ces cyclicités. Certaines relations ont déjà été soulignées entre la pluviométrie et des indices caractérisant la circulation zonale cellulaire

de l'océan Indien (RICHARD 1992), ou l'oscillation australe (OGALLO 1988, RICHARD 1992).

6. Relation entre l'excédent hydrique et la pluviométrie annuelle

Cette partie rassemble le premier traitement de la relation entre variations du bilan hydrologique annuel H* et précipitations sur son bassin versant. On a calculé, par la méthode de Thiessen, pour chaque année (d'octobre à septembre), une pluie moyenne et ceci grâce aux enregistrements des totaux mensuels de sept stations pluviométriques (Bujumbura, Kigoma, Tabora, Mbala, Kahama, Ngara, Mporokosso, fig. 1). Seule la période 1932-1980 pour laquelle on disposait d'au moins 95 % des données mensuelles pour chaque poste pluviométrique a été considérée. Sur l'ensemble de la période, la pluviométrie présente une moyenne de 1 011 mm an^{-1}. L'évolution du cumul des précipitations depuis 1932 (fig. 2d) met en évidence l'augmentation de ces dernières depuis le début des années soixante. Une régression linéaire entre les variations annuelles du «niveau sans écoulements» et les précipitations a été calculée. La régression entre H* (en m an^{-1}) et la pluviométrie annuelle P (en mm an^{-1}) associée s'ecrit :

$$\Delta H^* = -2{,}42 + 0{,}0027\ P \qquad R^2 = 0{,}61 \text{ (48 points)}$$

Mais les résidus de la régression proposée sont fortement corrélés, ce qui signifie qu'il y a un effet récurrent de l'année précédente (niveau du lac et/ou pluviométrie) qui participe à l'évaluation de H*. Une étude est en cours pour préciser ce point.

D'autre part, l'étude du nuage de points suggère que le total annuel de la pluie calculé n'est pas le seul paramètre qui caractérise le bilan annuel du lac. Cette relation pourrait être améliorée en augmentant la densité des postes pluviométriques pris en compte, particulièrement dans le nord-ouest du bassin versant qui présente des débits spécifiques élevés. L'étude de la répartition des pluies, au cours de l'année, caractérisée par l'indice annuel de concentration des pluies mensuelles : Cp (ROCHE 1963) n'apporte pas d'amélioration significative à la corrélation. Ce qui s'explique par l'importance des précipitations à la surface du lac dont la répartition au cours de l'année n'influence pas les variations interannuelles du niveau. Il semble qu'une évolution progressive de la relation entre précipitations et bilan hydrique du lac caractérise le bassin. Ce type d'observation a déjà été fait sur le bassin

versant du lac Malawi et a été relié à l'augmentation de l'activité humaine (CALDER *et al.* 1995). L'étude de la portée de l'évolution de la relation entre précipitations et bilan hydrologique reste à démontrer et à quantifier.

Les résultats obtenus restent limités. Une grande prudence s'impose, mais il semble que, sur la période 1932-1980, les variations pluviométriques expliquent en grande partie l'évolution du niveau lacustre mieux que ne le font les variations des conditions de surface, la demande évaporatoire ou le régime hydrodynamique du lac. Si la relation se montre assez approximative, elle permet cependant d'estimer globalement la fonction reliant pluie et bilan du lac. Ainsi, on peut en déduire raisonnablement que seule une diminution de plus de 11 % des précipitations interannuelles pourrait entraîner la chute du niveau lacustre et sa fermeture. De la même façon, on estime à environ 976 $mm.an^{-1}$ (– 4 %) les précipitations lors de la montée du lac entre 1846 et 1878.

7. Ecoulements à la surface du bassin versant ou apports de surface

Les affluents du lac Tanganyika sont de types très variés ; la Malagarasi a un cours relativement lent, avec de nombreux méandres formant des zones de marais. La Ruzizi, déversoir du lac Kivu, a un cours supérieur torrentiel (la haute Ruzizi) et un cours inférieur relativement lent dans la plaine alluviale (la basse Ruzizi). Les grandes rivières : Ruzizi, Malagarasi, construisent presque toutes des méandres et des deltas importants. La Kalambo et d'autres rivières moins importantes, après un cours lent sur les hauts-plateaux, chutent de plus de 200 m jusqu'au niveau du lac (CAPART 1949). Le régime de ces rivières et torrents de montagne varie fortement au cours de l'année. Ils peuvent en effet connaître des crues d'une violence inouïe, qui leur font charrier d'importantes quantités de sédiments et contribuent à construire des cônes alluvionnaires.

Nous avons rassemblé les caractéristiques de vingt-six stations hydrométriques localisées sur le bassin versant du lac (tab. 1 et fig. 4). Ces stations se trouvent en Tanzanie, au Rwanda, au Burundi ou en Zambie ; aucune donnée du versant zaïrois n'a pu être obtenue. Ces bassins versants ont des surfaces très variables (entre 97 km^2 et 123 300 km^2), l'ensemble représentant 73 % de la surface totale du bassin versant du lac. Les périodes d'enregistrement disponibles pour chaque bassin n'étant généralement que de quelques années, aucune

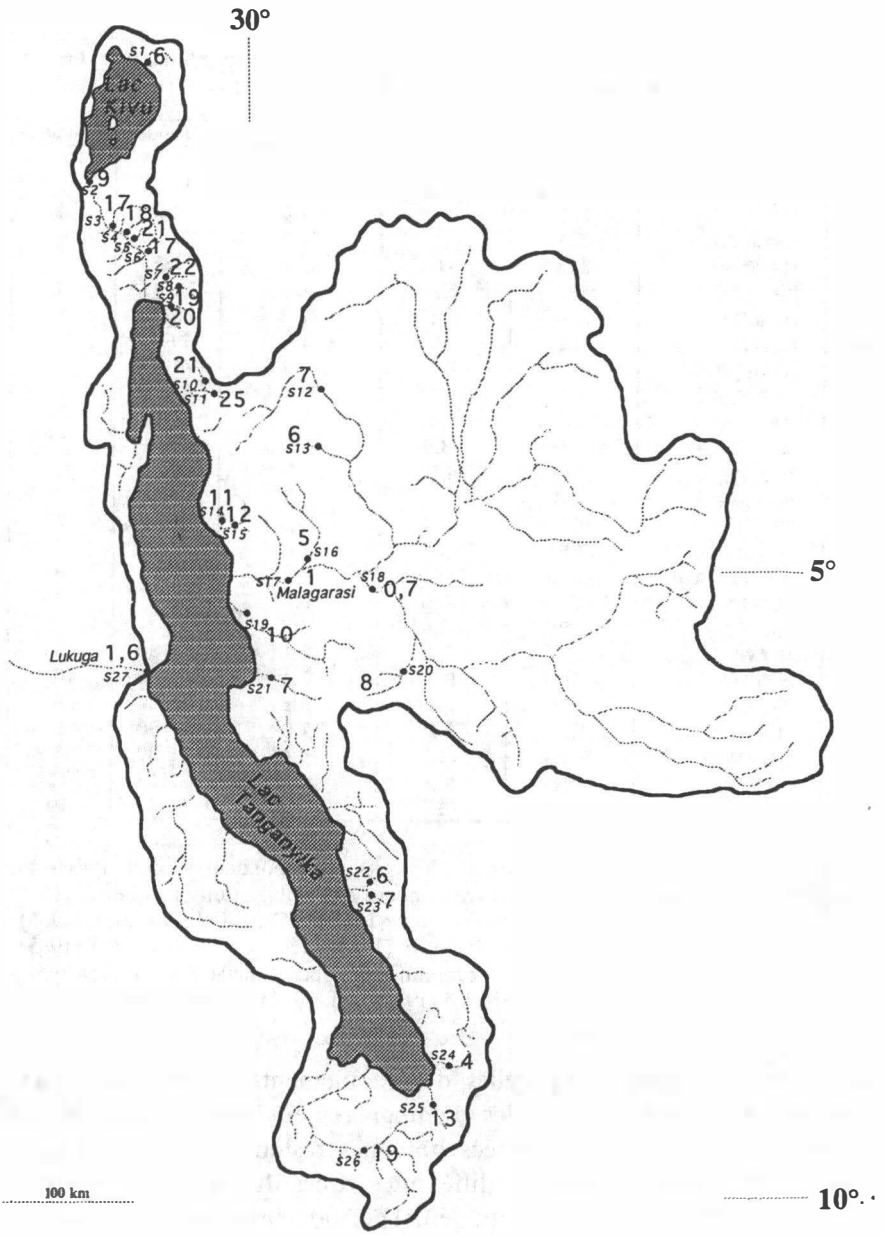


Fig. 4. — Sont reportés sur cette carte des débits spécifiques, en $l\ s^{-1}km^{-2}$, des 26 stations hydrométriques du tableau 1 (stations S1 à S26), ainsi que celui de l'exutoire du lac (station S27).

Tableau 1

Surface (en km²), débit moyen interannuel (en m^3s^{-1}) et débit spécifique ($l\ s^{-1}km^{-2}$) de 26 bassins versants contribuant à l'alimentation en eau du lac Tanganyika

n°	Rivière	Surface	Débit	Débit spécifique	Période	Référence
S1	SEBEYA	320	1,9	6,0	51-74	1 & 2
S2	RUZIZI	7600	70,0	9,2	42-59	3
S3	RUHWA	622	10,6	17,0	72-85	4
S4	NYAMAGANA	231	4,1	17,8	72-85	4
S5	MUHIRA	243	5,0	20,6	72-85	4
S6	KAGUNUZI	432	7,2	16,6	72-85	4
S7	MPANDA	214	4,8	22,3	69-71	5
S8	MUZAZI	102	1,9	19,0	69-73	5
S9	NTAHANGWA	97	1,9	19,6	71-73	5
S10	MURENBWE	299	6,3	21,0	84-85	6
S11	JIJI	197	4,8	24,6	84-85	6
S12	MALAGARASI	8525	63,5	7,5	-	7
S13	MAKERE	783	4,5	5,8	-	7
S14	MUNGONYA	128	1,4	11,2	-	7
S15	LUICHE	1626	19,4	11,9	-	7
S16	RUCHUGI	2989	15,5	5,2	-	7
S17	MALAGARASI	123300	135,8	1,1	75-88	8
S18	UGALLA	51775	33,9	0,7	-	7
S19	LUGUFU	4196	42,4	10,1	-	7
S20	MLAWEZI	951	7,7	8,1	76-80	9
S21	LUEGELE	1304	9,7	7,4	75-80	8
S22	SAMBA	353	2,0	5,6	75-80	9
S23	LUAMFI	531	3,7	7,0	77-80	9
S24	KALAMBO	3126	13,8	4,4	75-80	9
S25	LUNZUA	386	30,6	12,6	57-66	10
S26	LUFUBU	4090	76,7	18,8	57-66	10

Les codes des différentes stations hydrologiques correspondent à ceux utilisés sur la figure 4. Les références indiquées correspondent aux publications suivantes : réf. 1 : DEVROEY (1951-1960) ; réf. 2 : ANONYME n 1 (1961-1975) ; réf. 3 : BULTOT (1965) ; réf. 4 : ANONYME n 2 (1987) ; réf. 5 : PRUVOT (1974) ; réf. 6 : ANONYME n 3 (1985) ; réf. 7 : ANONYME n 4 (1989) ; réf. 8 : communication personnelle des services hydrologiques Tanzaniens ; réf. 9 : ANONYME n 5 (1982) ; réf. 10 : ANONYME n 6 (1957-1966).

étude des variations temporelles des écoulements de surface n'a été possible. Bien que les périodes d'enregistrement pour chaque bassin soient très variables, les données obtenues restent significatives pour qualifier le comportement des différentes zones du bassin. La figure 4 présente les différentes valeurs du débit spécifique aux vingt-six stations. Les débits spécifiques des différents bassins sont très variables, de $0,7\ l\ s^{-1}\ km^{-2}$ à $24,6\ l\ s^{-1}km^{-2}$. Si l'on compare cette carte à celle des écoulements établie par BULTOT (1965, 1971) à partir des cartes annuelles des pluies et de l'évapotranspiration réelle (résultat de la

méthode du bilan énergétique et hydrique de Thornthwaite), les débits observés apparaissent supérieurs aux estimations obtenues par bilan. Cette minoration des écoulements par la méthode du bilan hydrique peut être due à une appréhension inexacte du réservoir-sol ou à une surestimation de l'évapotranspiration potentielle. BULTOT (1965), dans sa note, émettait déjà des réserves sur l'estimation des écoulements issue des calculs effectués par la méthode du bilan, et basée sur un nombre trop restreint de postes de référence et des paramètres incertains (notamment la capacité du sol). Les valeurs de débits spécifiques interannuels observées (fig. 4) sont aussi supérieures, par deux fois au moins, à celles attribuées plus récemment à cette région (BRICQUET 1993). Elles sont en particulier beaucoup plus importantes à l'extrémité sud du lac (bassin de la Lufubu). L'ensemble de la surface jaugée (73 % du bassin) présente un débit spécifique de 3 l $s^{-1}km^{-2}$ (soit l'équivalent d'une lame d'eau de 69 mm an^{-1}). Si on considère l'ensemble de la surface jaugée, excepté la Malagarasi (qui à elle seule représente environ 60 % de la surface du bassin), soit 13 % du bassin, le débit spécifique est alors de 11,4 l $s^{-1}km^{-2}$ (371 mm an^{-1}). Par bilan hydrique on obtient pour le reste du bassin versant (27 % du bassin), dont la rive ouest du lac (15 % du bassin), un débit spécifique de 8,3 l $s^{-1}km^{-2}$ (264 mm an^{-1}), ordre de grandeur compatible avec les observations faites sur les 26 bassins versants. Avec un débit spécifique faible 1,1 l s^{-1} km^{-2} (dû à la présence de nombreuses zones marécageuses favorisant l'évapotranspiration) mais la surface drainée la plus grande, la Malagarasi reste, parmi les rivières qui alimentent directement le lac, l'une de celles qui lui apporte le plus d'eau (environ 4,3 km^3an^{-1}).

D'autres rivières apparaissent comme de premier ordre dans le bilan hydrologique du lac, la Ruzizi à l'extrême nord mais aussi la Lufubu à l'extrême sud. Les différences de comportement hydrologique proviennent de précipitations, de géologies et de reliefs différents pour chacun des bassins. Par ordre de débits spécifiques décroissants, on trouve d'abord l'extrémité nord du lac (bassin de la Ruzizi et rive burundaise du lac), la rive sud du lac (partie zambienne du bassin versant), puis l'ensemble du fossé bordant le lac et enfin la partie est du bassin (bassin de la Malagarasi). Notons que, si la carte de BULTOT (1965) indique des valeurs absolues d'écoulement inférieures aux observations, la variabilité spatiale de ce paramètre obtenu par la méthode du bilan correspond aux observations faites aux stations hydrométriques.

8. Conclusions

Cette étude a permis de préciser la valeur du module interannuel, 280 m^3s^{-1}, pour la période 1932-1971 où de nombreux jaugeages sont disponibles mais aussi d'estimer sa valeur, 380 m^3s^{-1}, pour l'ensemble de la période 1932-1995. Ces valeurs sont nettement supérieures aux estimations existantes (Bultot 1965, 1993 ; Devroey 1949). Il est aussi apparu que le bilan interannuel du lac, durant la période 1932-1995, n'a pas été constant. De 1932 à 1961, l'excédent moyen du bilan lacustre était de 0,12 m an^{-1}, il passe à 0,81 m an^{-1} de 1961 à 1970, pour être estimé à 0,55 m an^{-1} de 1970 à 1992. Depuis 1992, le bilan hydrologique du lac présente un déficit d'environ 0,17 m an^{-1}. Ce déficit en eau des dernières années a entraîné une chute brutale du niveau lacustre ; si cette situation tendait à perdurer, c'est à la fermeture du lac que l'on devrait assister assez rapidement. Des cyclicités, de périodes de 5, 9 et 10-11 ans, semblent caractériser le bilan hydrologique annuel du lac. L'origine de ces dernières n'a pas été étudiée mais pourrait être en rapport avec des phénomènes plus généraux à la zone intertropicale. Quant aux estimations du temps de résidence des eaux (280 ans) et des eaux de surface (550 ans), elles se sont avérées inférieures aux estimations antérieures (Degens 1973, Bergonzini 1995).

Une analyse plus fine des variations temporelles des régimes hydrologique et hydroclimatique, ainsi que des relations entre pluviométrie et bilan lacustre au pas de temps annuel et mensuel, devrait faire l'objet d'une étude ultérieure. Les résultats obtenus permettent déjà de caractériser la relation qui existe entre pluviométrie, niveau lacustre et débit à l'exutoire. Il apparaît ainsi qu'une diminution de la pluviométrie annuelle de 11 %, par rapport aux précipitations moyennes de la période 1932-1980 (1 010 mm an^{-1}), entraînerait la fermeture du lac. De plus, il a été possible d'estimer les précipitations pour la période 1848-1878 à environ 95 % (960 mm an^{-1}) des précipitations actuelles. Enfin, la prise en compte de données hydrométriques sur différents sous bassins du lac Tanganyika a permis de caractériser le comportement des différents versants du lac. Ainsi les débits spécifiques des différentes rives ont été approchés. Les données d'écoulement de surface obtenues pour le bassin versant du lac sont apparues compatibles avec les autres termes du bilan hydrologique du lac, mais supérieures aux valeurs généralement admises (Bultot 1965, Degens 1973, Bricquet 1993).

On aura pu se rendre compte que notre propos était la présentation de quelques remarques sur la variabilité temporelle et spatiale des

écoulements à l'exutoire du lac Tanganyika ainsi que sur son bassin versant. Il nous a paru propice de mettre en évidence certains problèmes que nous avons évoqués chemin faisant mais dont la résolution nécessiterait des études approfondies. Puisse quelqu'un ou quelqu'une y trouver intérêt.

REMERCIEMENTS

Mes remerciements s'adressent à J. Klerkx, qui m'a reçu à plusieurs reprises à Tervuren, à J. Charlier, qui m'a aidé dans l'acquisition des données et qui a relu et commenté la version finale de cette note. Je leur exprime ici ma gratitude.

BIBLIOGRAPHIE

ANONYME (n° 1). 1961-1975. Annuaire hydrologique du Rwanda de 1960 à 1974. — Bureau du Génie rural du Rwanda, Ministère de l'Agriculture, République rwandaise.

ANONYME (n° 2). 1987. Etude pour la mise en valeur de l'Imbo-nord, étude 1. 2 : hydrologie. — Publication de la Société pour l'Hydraulique et l'Equipement rural, Bujumbura, Burundi, 57 pp.

ANONYME (n° 3). 1985. Recueil de données hydrologiques, années 1984-1985. — Publication de l'Institut Géographique du Burundi.

ANONYME (n° 4). 1989. Kigoma Water Master Plan, Hydrology updated 1989. — Publication of the Ministry of Water, Tanzanian & Norwegian Agency for Development Co-opération, Oslo, Norvège.

ANONYME (n° 5). 1982. Rukwa Water Master Plan, Vol. 7, Hydrology. — Publication of the Norwegian Agency for Development Co-operation, Oslo, Norvège.

ANONYME (n° 6). 1957-1966. Hydrological Year-Book. — Prepared by the hydrological branch water affairs departement, Ministry of rural development, Republic of Zambia.

BERGONZINI, L. 1995. Les écoulements de la Lukuga à l'exutoire du lac Tanganyika. — Mus. Roy. Afr. Centr. Tervuren, Dept Géol. Min., Rapp. ann. 1993 & 1994, pp. 79-89.

BOMBI, K. & KILHAKWI, A. 1995. Water Discharge of Lukuga river. — *Lake Tanganyika Research Newsletter*, Bujumbura, Burundi, **16**, 12 pp.

BRICQUET, J.-P. 1993. Les écoulements du Congo à Brazzaville et la spatialisation des apports. — Actes du Colloque PEGI, Les grands bassins fluviaux périatlantiques : Congo, Niger, Amazone (Paris, 22-24 novembre 1993), ORSTOM, Paris, pp. 27-37.

BULTOT, F. 1965. A propos de l'évaporation du lac Tanganyika. — *Bull. Acad. R. Sci. Outre-Mer*, **4** : 1226-1241.

BULTOT, F. 1971. Atlas climatique du bassin Congolais, vol. 2. — Publ. INEAC.

BULTOT, F. 1993. Evaporation from a tropical lake : comparison of theory with direct measurements, comment. — *Journal of Hydrology*, **143** : 513-519.

CALDER, I., HALL, R., BASTABLE, H., GUNSTON, H., SHELA, O., CHIRWA, A. & KAPUNDU, R. 1995. The impact of land-use change on water resources in sub-Saharan Africa ; a modelling study of lake Malawi. — *Journal of Hydrology*, **170** : 123-135.

CAMUS, C. 1965. Fluctuations du niveau du lac Tanganyika. — *Bull. Séanc. Acad. R. Sci. Outre-Mer*, **11** : 1242-1256.

CAPART, A. 1949. Sondages et carte bathymétrique. Exploration hydrobiologique du lac Tanganyika (1946-1947). Résultats scientifiques. — *Inst. R. Sci. Nat. de Belgique*, **2** (2) : 16 pp.

CHARLIER, J. 1955. Etudes hydrographiques dans le bassin de Lualaba (Congo belge) (1952-1954). — Mém. Acad. R. Sci. Outre-Mer, Col. Sci. Techn. in-8, **1** (2) : 75 pp.

CONWAY, D. & HULME, M. 1993. Recent fluctuation in precipitation and runoff over the Nile sub-bassin and their impact on main Nile discharge. — *Climatic Change*, **25** : 127-151.

CRESPIN, 1980. Note personnelle et inédite.

CRUL, R. 1996. Limnology and Hydrology of Lake Victoria. — Studies and Reports in Hydrology, 53, UNESCO publ.

DEGENS, E. T. 1973. Palaeoclimatic reconstruction of late Pleistocene and Holocene based on biogenic sediments from the black sea and a tropical African lake. — Coll. Int. du Centre National de la Recherche Scientifique., Paris, **219**, 12 pp.

DEVROEY, E.-J. 1938. Le problème de la Lukuga exutoire de lac Tanganyika. — Mém. Inst. R. Colon. Belg., **1** (3) : 1-27.

DEVROEY, E.-J. 1948. Observations hydrographiques du Bassin congolais (1932-1947). — Mém. Inst. R. Colon. Belg., *Sci. Techn.*, in-8, **5** (1) : 163 pp.

DEVROEY, E.-J. 1949. A propos de la stabilisation du niveau du lac Tanganyika et de l'amélioration de la navigabilité du fleuve Congo (bief moyen du Lualaba, Kindu — Ponthierville). — Mém. Inst. R. Colon. Belg., *Sci. Tech.*, in-8, **5** (3) : 135 pp.

DEVROEY, E.-J. 1951. Observations hydrographiques au Congo belge et au Ruanda-Urundi. (1948-1950). — Mém. Inst. R. Colon. Belg., in-8, **6** (3).

DEVROEY, E.-J. 1952-1960. Annuaire hydrologique du Congo belge et du Ruanda-Urundi (années 1951 à 1959). — Mém. Acad. R. Sci. Colon., Bruxelles.

GILLMAN, F. 1933. Hydrology of lake Tanganyika. — *Bull. Geological Survey*, Dar es Salaam, **5** : 1-27.

Global Lake Catchment Conservation Database. La base de données peut être consultée sur le World Wide Web à l'adresse : http :// msslsp.mssl.ucl.ac.uk./orgs/un.

OGALLO, L. 1988. Relationships between seasonal rainfall in East Africa and the Southern Oscillation. — *Journal of Climatology*, **8** : 31-43.

OLIVRY, J.-C. 1993. Evolution récente des régimes hydrologiques en Afrique intertropical. — *In* : Au fil de l'eau, hommage à René Frecaut, Presses universitaires de Nancy, pp. 181-190.

OLIVRY, J.-C., BRICQUET, J.-P. & MAHE, G. 1993. Les études du PEGI sur le bassin du Congo-Zaïre dans le contexte déficitaire des ressources en eau de l'Afrique humide. — Actes du Colloque PEGI, Les grands bassins fluviaux périatlantiques : Congo, Niger, Amazone (Paris, 22-24 novembre 1993), ORSTOM, Paris, pp. 3-12.

PIPER, B., PLINSTON, D. & SUTCLIFFE, J. 1986. The water balance of Lake Victoria. — *Hydrological Sci. J.*, **31** (1, 3) : 25-37.

PRUVOT, P. 1974. Burundi, l'hydrologie de l'Imbo. — Document de travail de l'Organisation des Nations Unies pour l'alimentation et l'agriculture, FAO, Rome, 50 pp.

RICHARD, Y. 1992. Connexion entre le début de la saison des pluies en Afrique orientale méridionale et les circulations cellulaires zonales indienne et pacifique. — *Publ. Association Internationale de Climatologie,* **5** : 113-123.

ROCHE, M. 1963. Hydrologie de surface. — Gauthier Villars Ed., Paris, 430 pp.

SENE, K. J. & PLINSTON, D. T. 1994. A review and update of the hydrology of Lake Victoria in East Africa. — *Hydrological Sci. J.*, **39** (1) : 47-63.

SIRCOULON, J. 1987. Variation des débits des cours d'eau et des niveaux des lacs en Afrique de l'ouest depuis le début du 20e siecle. — *In* : The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Ressources, IAHS publication, **168** : 181-190.

THEEUWS, R. Note personnelle et inédite sur le problème de la Lukuga.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 638-640 (1998)

The Hydraulics Laboratory of U.M.S.S. at Cochabamba, Bolivia, and its Contribution to the Remediation of Topsoil Erosion

by

Jean BERLAMONT *

KEYWORDS. — Hydraulics Laboratory ; Cochabamba ; Topsoil Erosion.

ABSTRACT. — Within the framework of a VLIR-ABOS Inter-university Initiative in Supporting Developing Countries '94 a Hydraulics Laboratory was established from 1986 till 1990 at the "Universidad Mayor de San Simón" at Cochabamba, Bolivia. From 1990 till 1995 a support programme was active and currently an attempt is being made to transfer the Inter-university Programme in Water Resources Engineering (IUPWARE) '94 to the U.M.S.S. This project is supported by the W.H.O. and UNESCO. The philosophy behind the project and the reasons that have contributed to its success are briefly developed in this extended abstract.

MOTS-CLES. — Laboratoire hydraulique ; Cochabamba ; Erosion de surface.

RESUME. — *Le Laboratoire hydraulique à l'U.M.S.S. à Cochabamba, Bolivie, et son apport à la mitigation de l'érosion de la couche supérieure du sol.* — Dans le cadre d'une initiative interuniversitaire flamande de soutien aux pays en voie de développement, de 1986 à 1990, un Laboratoire hydraulique a été mis sur pied à l'Université Mayor de San Simón à Cochabamba en Bolivie. De 1990 à 1995, un programme de support a été actif et, actuellement, un effort est entrepris pour transférer l'«Inter-University Programme in Water Resources Engineering (IUPHWARE)» à l'U.M.S.S. Ce projet est soutenu tant par l'O.M.S. que par l'UNESCO. La philosophie de ce projet et les raisons qui ont contribué à son succès sont décrites dans ce résumé.

* Laboratorium voor Hydraulica, faculteit Toegepaste Wetenschappen, Katholieke Universiteit Leuven, W. de Croylaan 2, B-3001 Heverlee (Belgium).

TREFWOORDEN. — Hydraulisch Laboratorium ; Cochabamba ; Erosie van de bovenste bodemlaag.

SAMENVATTING. — *Het Hydraulisch Laboratorium gevestigd in de U.M.S.S te Cochabamba, Bolivië, en de bijdrage ervan tot het verhelpen van de erosie van de bovenste bodemlaag.* — Binnen het kader van een VLIR-ABOS „inter-universitair initiatief voor steun aan ontwikkelingslanden" werd van 1986 tot 1990 een Hydraulisch Laboratorium opgericht aan de „Universidad Mayor de San Simón" te Cochabamba, Bolivië. Van 1990 tot 1995 werd een „support" programma actief en tegenwoordig wordt een poging ondernomen om het „Inter-University Programme in Water Resources Engineering (IUPWARE)" over te hevelen naar de U.M.S.S. Dit project wordt zowel door de W.H.O. als de UNESCO ondersteund. De filosofie achter het project en de redenen die bijdroegen tot het succes worden in deze korte inhoud belicht.

Within the framework of (one of the first) VLIR-ABOS "Inter-University Initiatives in Supporting Developing Countries", a Hydraulics Laboratory was established at the "Universidad Mayor de San Simón" (U.M.S.S.) at Cochabamba, Bolivia, from 1986 till 1990. Subsequently a "support" program has been run (1990 till 1995), and actually an attempt is being made to transfer the Flemish ICP "Inter-University Program in Water Resources Engineering" (IUPWARE) to U.M.S.S. This project is supported both by W.H.O. and UNESCO.

The philosophy of the project has been :

— Rely as much as possible on the local involvement and initiatives ;
— Supply only the minimum necessary means to carry out (applied) hydraulic research (hydrometric equipment, basic laboratory equipment, books, software, computers,...) ;
— Invest in people and knowledge, rather than in fancy equipment ;
— Make the laboratory self-supporting by attracting projects from local authorities and international projects or agencies.

One such opportunity arose through the involvement of the Laboratory in the PROMIC project supported by the "Swiss Development Cooperation". PROMIC stands for "PROgrama Manejo Integral de Cuencas", and aims at preventing topsoil erosion on the steep hill sides surrounding the Cochabamba valley. The project is now also supported by the Belgian Government (ABOS).

The steep slopes of the Cochabamba valley, much like many other mountain slopes in Andes countries, were deforested in the past. Due to the high run-off velocities during the rainy season, surface erosion is very severe. The negative consequences are at least double : firstly,

the hills become less suited for agriculture, and secondly, the sediments of course finally arrive in the river, where they accumulate and are the cause of frequent flooding.

The PROMIC project thus aims at :

— Understanding the mechanisms of surface erosion, sediment transport *to* the rivers, and sediment transport *in* the (tributary) rivers. Therefore, an extensive hydrometeorological and sedimentological measuring campaign has been set up. Results now become available.
— Testing *in situ* a number of possible measures to reduce surface erosion, or to slow down sediment transport in rivers. A number of experimental devices are deployed and results are already available.
— Making the local "campesinos" feel responsible for the preservation of their own land, and teaching them how to use proper land working techniques and which crops to grow.

The Hydraulics projects in Cochabamba have shown how relatively small projects can have a substantial multiplicator effect, and how providing scientific and technical knowledge and research tools may lead on a short term to important improvements of the environmental and socio-economic conditions. The only prerequisite for success is that the local counterpart is fully aware of the importance of what is at stake, and is ready to make the necessary efforts.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 641-651 (1998)

Bilan hydrique climatique de la zone aride et de la zone de mousson en Asie

par

Barbara Olechnowicz-Bobrowska *,
Nguyen Can ** & Saadi Wahab ***

Mots-cles. — Bilan hydrique climatique ; Bilan thermique ; Evaporation potentielle ; Irak ; Vietnam.

Resume. — Le but de cette communication est la comparaison des structures du bilan thermique et du bilan hydrique de deux pays d'Asie, situés dans des conditions climatiques très différentes : l'Irak — climat aride, désertique ou semi-désertique et le Vietnam — climat de mousson. Les valeurs moyennes mensuelles et annuelles des principales composantes du bilan thermique et du bilan hydrique ont été calculées à partir des données météorologiques multiannuelles. On a determiné les termes suivants : rayonnement solaire global (Rg), rayonnement net (Rn), évaporation potentielle (Ep) et son équivalent énergétique (lEp), ainsi que précipitations atmosphériques (P). En utilisant les valeurs moyennes de ces termes on a calculé des indices numériques caractérisant quantitativement le climat de ces deux pays : le rapport lEp/Rn et la différence P - Ep («bilan hydrique climatique»). Tenant compte des indices énumérés, il était possible d'établir une classification climatique des deux pays étudiés. On a pris en considération non seulement les valeurs annuelles des indices, mais aussi leurs variations saisonnières, ce qui est important surtout dans les conditions du climat de mousson, caractérisé par deux saisons très marquées : la saison sèche et la saison humide.

Trefwoorden. — Klimatologische waterbalans ; Thermische balans ; Potentiële evaporatie ; Irak ; Vietnam.

Samenvatting. — *Waterbalans van de droge en van de moessonzone in Azië.* — Het doel van dit artikel is een vergelijking te maken van de water-

* Akademia Polnicza, H. Mickiewicza 24/28, PL-30059 Krakow (Poland).
** Institut de Géographie, Académie Polonaise des Sciences, Varsovie (Pologne).
*** Institut de Géophysique, Académie Polonaise des Sciences, Varsovie (Pologne).

en thermische balans van twee Aziatische landen gesitueerd in volkomen verschillende klimaatgordels : Irak : droog klimaat, woestijn tot semi-woestijn, en Vietnam : moessonklimaat. De maandelijkse en jaarlijkse gemiddelden van de belangrijkste componenten van de thermische en waterbalans werden berekend op basis van meerjaarlijkse meteorologische gegevens. De volgende gegevens werden geïdentificeerd : globale zonnestraling (R_g), nettostraling (R_n), potentiële evaporatie (E_p) en haar warmteëquivalent (lE_p), evenals de neerslag (P). Gebruik makend van de gemiddelde waarden van deze parameters werden numerieke indices berekend die kwantitatief het klimaat van deze twee landen kenmerken, met name de verhouding lE_p/R_n en het verschil $P-E_p$ (soms de klimatologische waterbalans genoemd). Door gebruik te maken van deze twee indices was het mogelijk een klimatologische classificatie van deze twee landen te bepalen. Deze classificatie is niet enkel gebaseerd op de gemiddelde jaarlijkse waarden van deze indices, maar ook op hun seizoenale variaties, wat zeer belangrijk blijkt te zijn in het geval van een moessonklimaat met twee uitgesproken seizoenen : een droog en een regenseizoen.

KEYWORDS. — Climatological Water Balance ; Heat Balance ; Potential Evaporation ; Iraq ; Vietnam

ABSTRACT. — *Climatological Water Balance in Arid and Monsoon Zones of Asia.* — The purpose of this paper is comparing the structure of both heat and water balances in two Asian countries situated in entirely different climatic conditions : Iraq — arid climate — and Vietnam — monsoon climate. Mean monthly and annual values of the main components of heat and water balances were calculated on the basis of multiannual meteorological data. Using multiannual meteorological data, mean monthly and yearly values of the main components of heat and water balances were calculated : global solar radiation (R_g), net radiation (R_n), potential evaporation (E_p) and its heat equivalent (lE_p), as well as rainfall (P). Those values were then used for evaluating two numerical indices which characterize quantitatively the climate of both countries. Those indices are : the ratio lE_p/R_n, and the difference $P - E_p$, sometimes called "climatological water balance". Taking into account those two indices, it was possible to establish a climatological classification of both countries. That classification was based not only on mean yearly values of indices, but also on their seasonal variations, which seem to be very important, especially for the conditions of monsoon climate with two distinct, dry and rainy seasons.

1. Introduction

Dans le cadre de la coopération scientifique et technique entre la Pologne et les pays en développement, on a effectué aussi des recherches climatologiques. Ces recherches ont concerné, entre autres, le problème

des bilans thermique et hydrique en Irak et au Vietnam, c'est-à-dire deux pays asiatiques situés dans des conditions climatiques très différentes. L'Irak appartient à la zone aride, désertique ou semi-désertique de l'Asie du sud-ouest, tandis que le Vietnam fait partie de la zone de mousson de l'Asie du sud-est. Les résultats de ces études ont été présentées dans deux thèses (CAN 1983, WAHAB 1987). Les méthodes appliquées sont rigoureusement semblables et permettent la comparaison des résultats.

Le but de cet article est la comparaison des principales composantes des bilans thermique et hydrique des deux pays mentionnés, ainsi que de certains indices du climat, basés sur la structure de ces deux bilans. Il s'agit donc de problèmes d'une grande importance pratique du point de vue des besoins de l'agrométéorologie et de la gestion de l'eau. Il faut souligner que différents climatologues, et surtout BULTOT (1971), ont maintes fois tiré l'attention sur ces problèmes.

2. Données de base

On a déterminé les valeurs moyennes, mensuelles et annuelles, des principales composantes des bilans thermique et hydrique au Vietnam à partir de données recueillies dans quatre-vingt-cinq stations météorologiques pendant une période de quinze ans (1960-1974). Les données pour l'Irak concernent la période 1971-1980 et proviennent de vingt stations météorologiques. Quoique les deux périodes ne soient pas les mêmes, une soigneuse analyse des données justifie leur comparaison. Le nombre des stations utilisées, beaucoup plus élevé dans le cas du Vietnam, a été nécessaire, compte tenu d'une grande diversité climatique au sein de ce pays par rapport à l'Irak.

Le Vietnam, avec sa superficie de 330 000 km², est situé entre $\varphi = 8°30'$ et $23°20'$ N, et $\lambda = 102°10'$ et $109°20'$ E. Le relief de ce pays est très diversifié : il s'étale des plaines littorales, comprenant aussi les vastes régions deltaïques du fleuve Rouge et du Mekong, jusqu'aux sommets des grandes chaînes montagneuses, atteignant l'altitude de 3 140 m. La montagne et les hauts-plateaux occupent une grande partie du territoire du Vietnam.

Le relief d'Irak ($\varphi = 38°50'$ et $48°40'$ N et $\lambda = 2910'$ et $37°20'$ E) est beaucoup moins différencié. La haute montagne, entre 1 000 et 3 600 m, au nord et nord-est du pays, n'occupe que 5 % de la superficie totale de 448 000 km². Entre la montagne et la plaine de Mésopotamie s'étale une zone de collines. La région centrale du pays forme une

plaine, contenant la Mésopotamie et la zone désertique au sud et sud-ouest, qui couvre plus de la moitié de la superficie totale de l'Irak. L'agriculture irakienne exige l'irrigation, une exception étant la zone montagneuse.

Le Vietnam est bordé tout le long de son territoire par la mer de Chine méridionale qui exerce une influence importante sur son climat, tandis que l'Irak possède un climat chaud et sec, marqué par la continentalité.

3. Méthode

Les principales composantes des bilans thermique et hydrique, sauf précipitations, ont été calculées à partir des données météorologiques. On a pris en considération les termes suivants : rayonnement solaire global (Rg), rayonnement net (Rn), évaporation potentielle (Ep) et son équivalent énergétique (lEp), ainsi que précipitations atmosphériques (P).

Pour déterminer le rayonnement net Rn, on a calculé séparément ses deux composantes : rayonnement net d'origine solaire et rayonnement net d'origine terrestre. Rg a été calculé en tant que fonction de la durée de l'ensoleillement, en utilisant la formule empirique de Black. Pour déterminer le rayonnement solaire absorbé, on a utilisé les valeurs de l'albedo (α) de la surface terrestre, en tenant compte de sa variabilité saisonnière. Au Vietnam, on a adopté $\alpha = 0{,}18$ pour la saison humide et 0,24 pour la saison sèche. Le rayonnement dans les grandes longueurs d'onde (infrarouge) a été calculé selon la formule empirique de Brunt, où ce rayonnement est fonction de la température et de l'humidité de l'air ainsi que de la nébulosité. De cette façon, on a obtenu des valeurs moyennes mensuelles, saisonnières et annuelles du rayonnement net Rn qui forme le terme principal des apports du bilan thermique.

L'évaporation potentielle a été calculée par la méthode de Penmann, modifiée par van Bavel et Morton. Un grand avantage de cette méthode repose sur le fait qu'elle est fondée sur des processus physiques fondamentaux, exprimés par l'équation du bilan thermique et par les deux équations aérodynamiques qui décrivent le transport vertical de la chaleur et de la vapeur d'eau dans la couche limite de l'atmosphère. Cette méthode est dépourvue de tout empirisme, ce qui lui donne un caractère général et la rend utile à la comparaison de l'évaporation potentielle dans différentes régions du globe. C'est à partir de ces

données de Ep qu'on a déterminé les valeurs moyennes du flux de chaleur latente de l'évaporation potentielle lEp.

L'évaporation potentielle ainsi définie exprime la quantité d'eau qui pourrait être évaporée dans l'atmosphère si la surface limite était toujours humide, c'est-à-dire couverte d'un film d'eau infiniment mince. Le principe posé est que les conditions météorologiques actuelles, comme la température de l'air, son humidité, la nébulosité, la vitesse du vent, ainsi que les propriétés physiques et l'état de surface, c'est-à-dire la température, la rugosité, la capacité et la conductivité thermique, l'albedo, l'émissivité, etc., ne varient pas lors du processus d'évaporation.

Il est clair qu'en réalité ce principe ne peut jamais être réalisé, parce que tout changement de l'humidité de la surface entraîne une modification d'un ou de plusieurs termes du bilan énergétique ainsi que des paramètres physiques énumérés. Cette méthode de détermination de l'évaporation potentielle permet néanmoins d'obtenir des valeurs bien définies et donc comparables.

Bien que l'évaporation potentielle ainsi déterminée soit une abstraction, sa connaissance peut être d'une grande importance scientifique et pratique. Elle peut être considérée comme un indice important du climat et a aussi servi à l'établissement de classifications climatiques.

4. Résultats

Les valeurs moyennes mensuelles, saisonnières et annuelles des éléments et des indices du climat ont servi à l'établissement de cartes représentant leur distribution géographique sur le territoire de l'Irak et du Vietnam. Nous nous limitons ici à la présentation des cartes des valeurs moyennes annuelles de :

— Somme des précipitations atmosphériques P ;
— Somme d'évaporation potentielle Ep ;
— Rapport lEp/Rn ;
— Différence P – Ep = bilan hydrique climatique.

La comparaison de ces valeurs entre l'Irak et le Vietnam indique l'existence de conditions climatiques tout à fait différentes entre ces deux pays.

Les sommes annuelles des précipitations P sont en Irak extrêmement basses. Elles tombent au-dessous de 100 mm par an dans la partie

méridionale du pays, et c'est seulement dans les montagnes du nord qu'elles dépassent 400 mm (fig. 1).

La distribution géographique des précipitations est au Vietnam beaucoup plus différenciée, ce qui est dû au relief très diversifié. Les sommes annuelles sont là-bas contenues dans l'intervalle allant d'un peu moins de 1 000 mm sur le littoral à un peu plus de 2 700 mm dans la montagne, au nord du pays.

L'évaporation potentielle Ep est en Irak contenue dans l'intervalle allant de 2 500 mm dans la région montagneuse du nord, à 2 900 mm dans la zone désertique du sud du pays (fig. 2). Les valeurs correspondantes au Vietnam sont inférieures à 1 100 mm dans les montagnes du nord et supérieures à 2 100 mm au sud du pays.

En ce qui concerne le rapport entre la chaleur latente de l'évaporation potentielle et le rayonnement net lEp/Rn, ses valeurs annuelles en Irak sont comprises dans l'intervalle 2,2 à 3,0 (fig. 3). Au Vietnam, les valeurs moyennes de ce rapport sont beaucoup moins élevées, et elles varient entre 0,8 au nord et 1,2 au sud. Ces différences entre les deux pays considérés résultent non seulement des valeurs inégales de lEp, mais sont aussi causées par le fait que les valeurs annuelles de Rn sont beaucoup moins élevées dans les conditions du climat désertique de l'Irak que dans les conditions du climat de mousson. Cette dernière différence est l'effet de valeurs relativement très élevées de l'albedo et des températures de surface dans le désert. C'est pour cette raison que les moyennes annuelles de Rn en Irak sont contenues dans l'intervalle 70 à 90 $W.m^{-2}$, tandis qu'au Vietnam elles varient entre 100 et 135 $W.m^{-2}$.

La différence P – Ep, appelée souvent «bilan hydrique climatique», a en Irak un caractère tout à fait différent de celui du Vietnam (fig. 4). Les valeurs annuelles de cet indice sont négatives sur tout le territoire irakien, étant comprises entre – 1 900 et – 2 700 mm par an. Au Vietnam, ces valeurs sont positives sur une grande partie du pays. C'est surtout dans les montagnes, sur les pentes exposées au vent, là où les pluies sont très abondantes, que cet indice peut atteindre 1 300 mm par an. Par contre, dans la partie méridionale du pays, il tombe à – 1 200 mm.

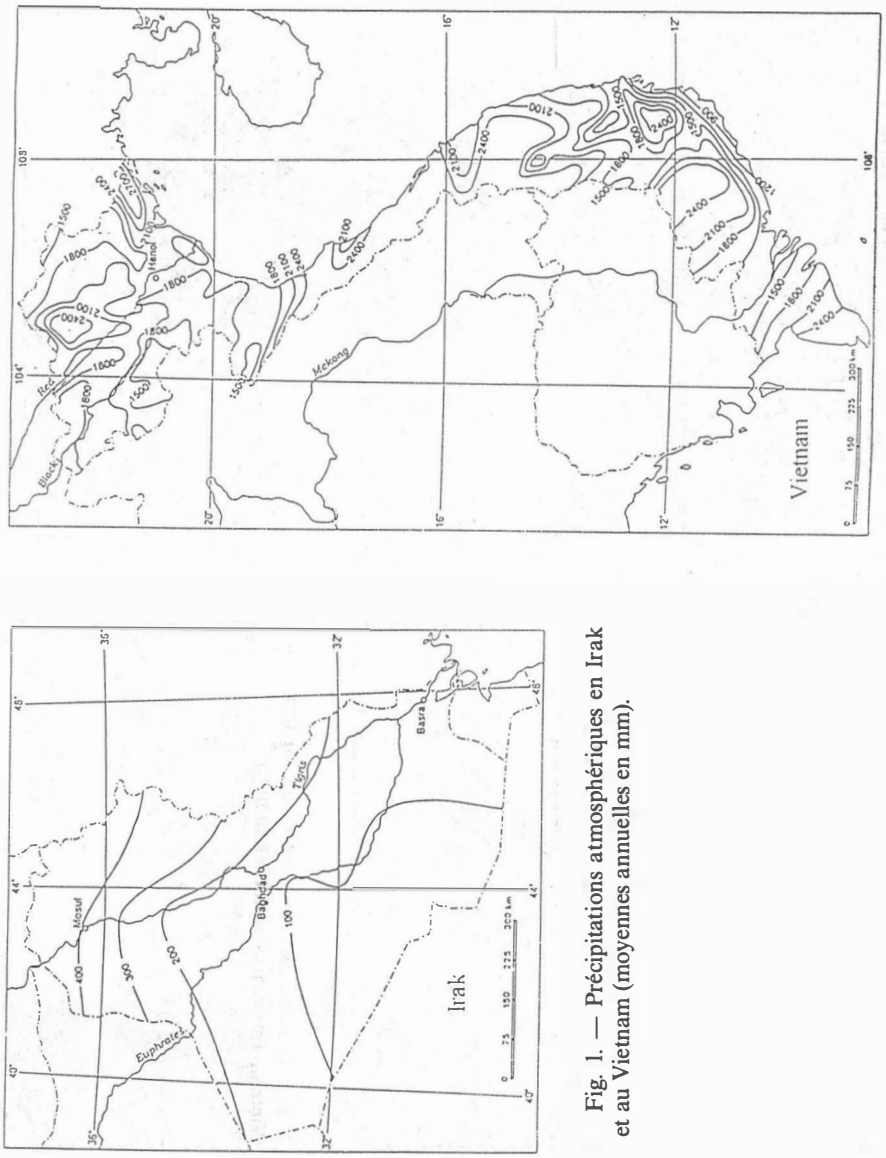


Fig. 1. — Précipitations atmosphériques en Irak et au Vietnam (moyennes annuelles en mm).

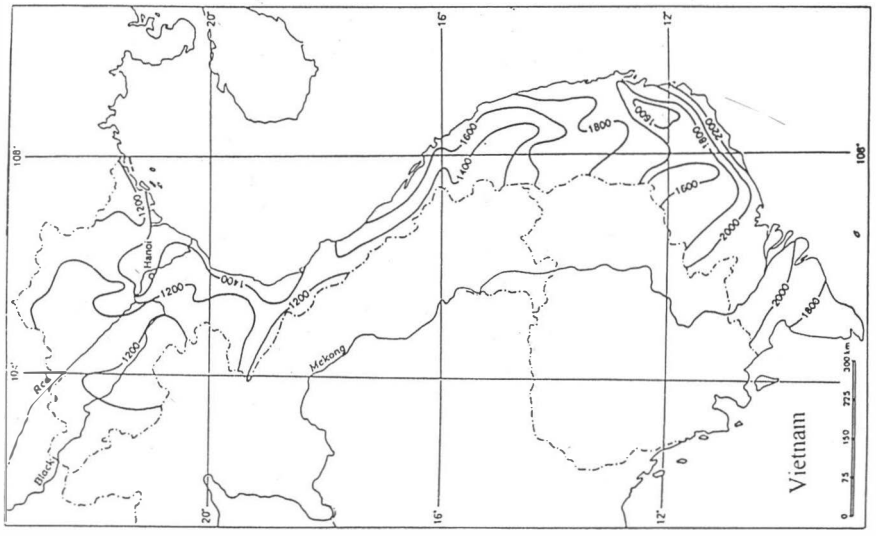
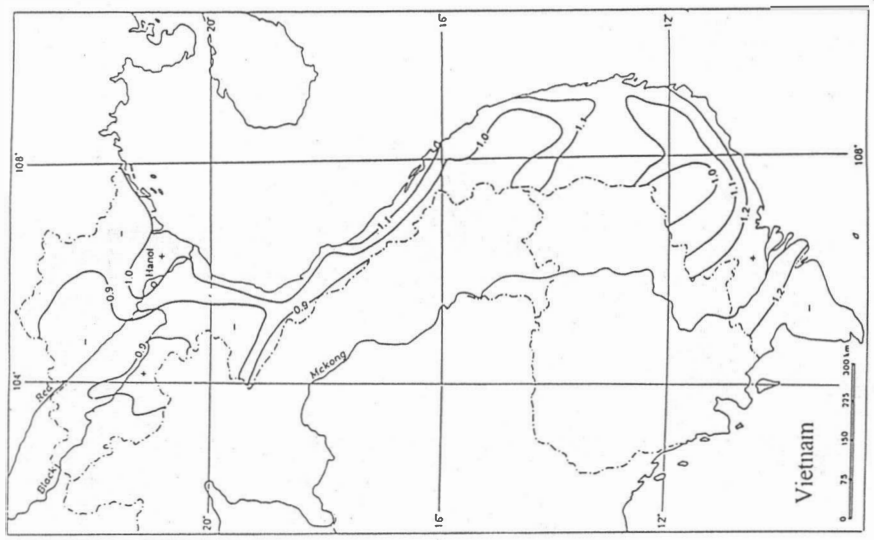


Fig. 2. — Evaporation potentielle en Irak et au Vietnam (moyennes annuelles en mm).



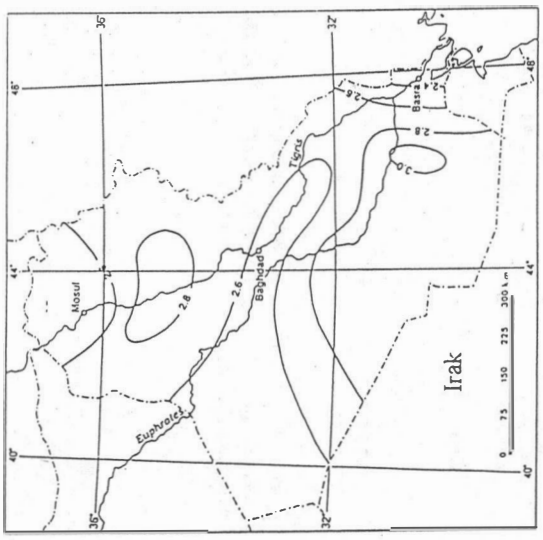


Fig. 3. — Rapport entre chaleur latente de l'évaporation potentielle et rayonnement net en Irak et au Vietnam (moyennes annuelles).

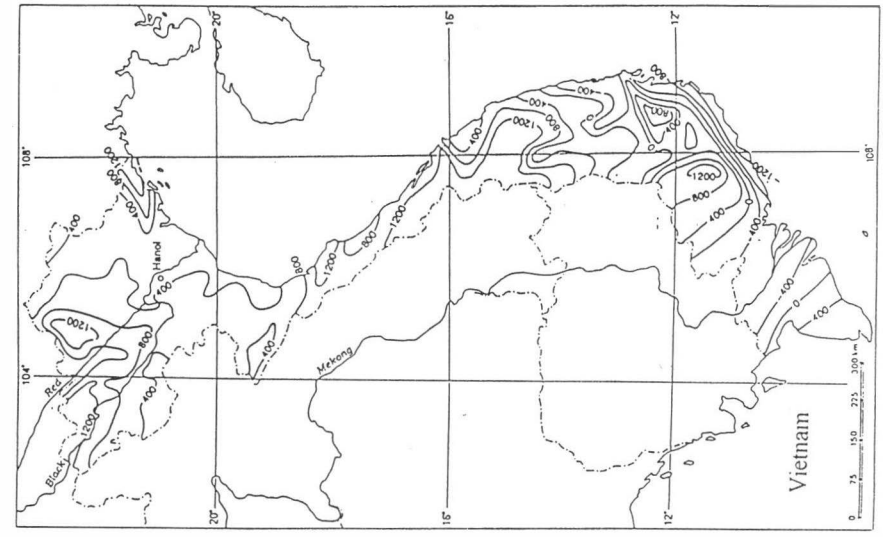


Fig. 4. — Différence entre précipitations atmosphériques et évaporation potentielle = «bilan hydrique climatique» (moyennes annuelles en mm).

5. Conclusions

Tenant compte des indices climatiques considérés, il était possible d'établir une classification climatique des pays étudiés (Paszynski & Can 1989). Dans une telle classification, on a pris en considération non seulement les valeurs annuelles des indices, mais aussi leurs variations saisonnières, ce qui est important surtout dans les conditions du climat de mousson caracterisé par deux saisons très marquées : la saison sèche et la saison humide.

Les résultats obtenus prouvent que les notions d'évaporation potentielle et de bilan hydrique climatique peuvent être utiles pour la description quantitative du climat. Elles permettent d'établir une nouvelle classification climatique, qui peut être d'une grande importance non seulement du point de vue de la science, mais aussi sur le plan pratique, surtout pour les besoins de l'agriculture et de la gestion de l'eau.

REMERCIEMENTS

Cet étude a été partiellement subventionnée par le Comité National Polonais des Recherches Scientifiques — KBN, le projet n 6 P202 040 07.

BIBLIOGRAPHIE

Bultot, F. 1971. Atlas climatique du Bassin congolais. — INEAC, 289 pp.

Can, N. 1983. Classification des climats du Vietnam à partir des bilans thermique et hydrique. — Académie Polonaise des Sciences, Institut de Géographie, Varsovie, 119 pp. (en russe)

Henning, J. & Henning, D. 1977. Klimatologische Wasserbilanz von Nordamerika. — *Archiv f. Meteorologie, Geophysik u. Bioklimatologie*, Ser. B, **25** : 92-98.

Olechnowicz-Bobrowska, B. 1978. Potential Evaporation in Poland. — Zeszyty Naukowe Akademii Rolniczej w Krakowie, Rozprawy, **67**, 173 pp. (en polonais).

Paszynski, J. & Can, N. 1989. Etudes agroclimatologiques au Vietnam. — *Publications de l'Association Internationale de Climatologie,* **2** : 277-280.

Wahab, S. A. 1987. The Variation of Evaporation in Iraq. — Polish Academy of Sciences, Institute of Geophysics, Warsaw, 140 pp.

AGROMETEOROLOGY

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 655-673 (1998)

Some Aspects of Climate Variability and Food Security in Sub-Saharan Africa

by

René Gommes *

Keywords. — Africa ; Climate ; Climate Variability ; Food Production ; Risk.

Abstract. — This paper focuses on some links between food security and climate variability in sub-Saharan Africa, essentially rainfall variability. As climate potentially affects the food chain from production to consumption, the different steps are succinctly described. Trends, seasonality and persistence are among the climate characteristics which display a most direct effect on food availability. More complex interactions are also examined, in particular situations where civil war (Rwanda), and demography and soil features amplify climate variability. An agroclimatic risk analysis is given for the production of cereals in Niger.

Mots-cles. — Afrique ; Climat ; Variabilité du climat ; Production alimentaire ; Risque.

Resume. — *Quelques aspects de la variabilité climatique et de la sécurité alimentaire en Afrique sub-saharienne.* — Le présent article met l'accent sur les liens entre la sécurité alimentaire et la variabilité du climat, essentiellement celle des pluies, en Afrique sub-saharienne. Etant donné que le climat peut affecter toutes les étapes de la chaîne alimentaire (de la production à la consommation), ces étapes sont succinctement décrites. Les tendances, l'alternance des saisons et la persistance sont quelques-unes des caractéristiques du climat qui affectent directement la sécurité alimentaire. On examine aussi quelques interactions plus complexes, celles où la guerre civile (Rwanda) ou la démographie et les caractéristiques du sol amplifient la variabilité du climat. Nous proposons ensuite une analyse du risque agroclimatique affectant la production céréalière au Niger.

* Coordinator, Agrometeorology Group, FAO, via delle Terme di Caracalla, Rome (Italy).

TREFWOORDEN. — Afrika ; Klimaat ; Klimaatwisseling ; Voedselproductie ; Risico.

SAMENVATTING. — *Enkele aspecten van de variabiliteit van het klimaat en de voedselzekerheid in sub-Sahariaans Afrika.* — In deze bijdrage staat het verband centraal dat in Afrika bezuiden de Sahara bestaat tussen voedselzekerheid en klimaatwisselingen die hoofdzakelijk betrekking hebben op neerslag. Vanwege het feit dat het klimaat van invloed kan zijn op de voedselketen (van productie tot consumptie), worden de verschillende stappen beknopt beschreven. Trends, seizoenswisselingen en aanhoudende weersomstandigheden zijn enkele klimaatfactoren die direct van invloed zijn op de beschikbaarheid van voedsel. Gecompliceerdere interacties worden ook meegenomen, in het bijzonder situaties waarbij burgeroorlog (Rwanda), demografie en bodemkenmerken klimaatwisselingen versterken. Tot slot wordt er een „agro-klimaat" risico-analyse gemaakt voor de graanproductie in Niger.

1. Introduction

Food security (and insecurity) is the result of the many factors that affect food availability, from production to consumption. The concept is not always easy to define and there are indeed many definitions. Most definitions mention that food supply must be regularly accessible in sufficient amounts, qualitatively adequate, obtained through conventional channels and culturally acceptable. The idea of most definitions is, of course, that food security is the basis of a healthy and active life.

Food problems used to be local ; they now tend to become global. This was exemplified by the rise in international wheat and maize prices in May 1996, the combined result of agricultural policies (both in the United States and in Europe) and the fear of poor crop prospects due to unusual weather conditions. The issue is thus complex and involves many economic and even psychological factors next to climate variability. It remains, though, that climate variability [1]* is still the predominant driving force behind the variability of food production.

It should be stressed that significantly more agricultural produce is lost through the "chronic" micro-variations of weather (local pockets of droughts, runs of excessively wet summers, ...) than through the often spectacular extreme events [2] which catch the attention of the media. A good example in point regards the 1993 Mississippi floods

* The numbers in brackets [ ] refer to the notes pp. 671-672.

where about three quarters of the damage occurred because of soil water logging due to excessive rain in non-flooded areas (IFMR 1994).

In the specific case of sub-Saharan Africa, it is also obvious that, with the exception of some areas in Southern Africa (*e.g.* Lesotho), rainfall is the main limiting factor in about 50 % of the continent. The paper therefore concentrates on rainfall.

2. The links between Climate Variability and the Variability of Food Availability

The availability of food depends not only on the amounts produced ("raw production"), but also on the amounts that will eventually become available for consumption.

Figure 1 schematically indicates the three stages of the food procurement, handling and consumption. Weather interacts with most steps in this graph, to varying degrees according to the level of development [3]. In addition, weather can affect most steps described below both directly and indirectly, where indirect effects are those like pests and diseases, landslides, fire, etc.

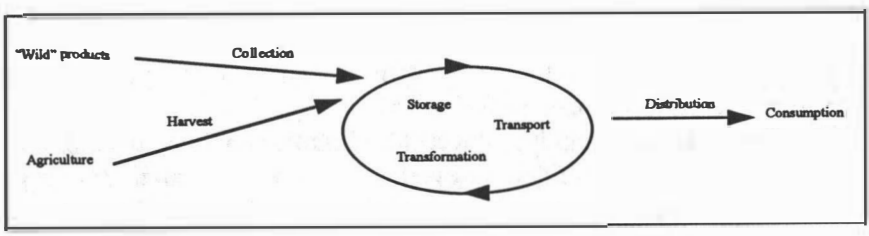


Fig. 1. — Schematic pathway of human food. Loops (e.g. cattle being fed cereals) are not shown.

Wild products (and semi-domesticated ones) still play an important role in many areas, one of the best examples being *fonio*, a small-grained *Digitaria* grass found in the Sahel. Management plays almost no role in the yield (tons/ha) of wild products (including fruits, river fish, etc.) : what is produced by unit area is the result of environmental conditions (soil, climate, vegetation), possibly including the effect of anthropogenic degradation of the environment and the competition with other consumers of the same products (wildlife, like birds). On the other hand, collection — mostly by hand — does depend on weather as it affects the accessibility and quality of the products. In many areas,

the collection "effort" does depend on the performance of crops, when the wild products are resorted to in bad years or in periods of food stress (for instance after household food stocks are depleted and the next crop has not reached maturity yet).

Agricultural production variability depends on the factors that affect yield, but also on the area planted and harvested. In fact, it is useful to distinguish between the "biological yield" (amount harvested divided by area planted) and the "statistical yield" (amount harvested divided by area harvested). It has been the practice of many national agricultural statistics services to report statistical yield, although the area harvested can be significantly less than the area planted, due to a number of reasons, one of them being the complete loss of the harvest due to unfavourable weather [4]. Obviously, such practices lead to overestimate the actual yield and constitute one of the difficulties in understanding the links between national crop statistics and weather.

The planted area also very much depends on economic factors (expected return), while yield is more complex when inputs are used. Particularly on soils with low water holding capacities, fertilizer can increase the vegetative growth **and the correlative water consumption** so much that it induces severe water stress. This is a first example of "non-climatic drought".

Harvest, like the collection of wild products, is not very dependent on climatic conditions, except for accessibility.

Post-harvest handling is subject to climatic impacts to different degrees in developing and developed countries. It is mainly storage that is likely to suffer from climatic conditions in developing countries : traditional storage structures are often fragile and easily attacked by a variety of pests and diseases, which are very weather-dependent. Needless to say, violent weather phenomena (including heavy rainfall leading to floods, wind — and their combination in tropical cyclones) also affect the general infrastructure (including farm buildings and other assets, roads, etc.). Recovery often takes several years in the case of plantation and tree crops.

Storage is particularly difficult in the case of animal products in tropical countries. In spite of traditional techniques (smoking, salting, drying), they are usually not stored over lengthy periods of time.

Distribution and consumption are exposed to several types of losses (like milling loss), but they are usually not very weather-sensitive. Distribution is singled out to stress the most important issue of actual access to food (which also includes prices, etc.)

3. Some Important Features of Climate Relevant to Food Security

3.1. Inter-annual Variability and Trends

Rainfall variability in Africa exhibits some consistent temporal and spatial patterns which can largely be accounted for by the movements of the Inter-Tropical Convergence Zone (I.T.C.Z.) and terrain features. For instance, good years in the Sahel (the I.T.C.Z. reaches high northern latitudes) usually correspond with a late start of the season in Southern Africa. The subject is covered with some details by Gommes & Petrassi (1994), to which the reader is also referred for literature on the subject. Some recent references include Bultot & Gellens (1994), Hess *et al.* (1995), Maloba Makanga (1995), Moron (1996) and Rojas (1995).

One of the most striking features of the second half of the century was the well-documented downward trend of rainfall in the "climatological Sahel" which extends from Cape Verde to Somalia (see e.g. fig. 2).

It should be mentioned that the trend ended in 1985, which was the worst year of the Sahelian drought. 1988 was the first year with rainfall amount comparable to the pre-1960 period. Since then, the Sahel has experienced only good to average years. It is worth noting that farmers have reacted very quickly to the new situation, for instance by growing groundnuts in areas where the crop had been abandoned a decade ago due to the unfavourable conditions.

Although it is not a form of "variability" due to its very regular behaviour, seasonality [5] plays an important part in the food supply of many populations. It is mentioned here because the dates of onset and end of the wet season(s) — or the end and beginning of the dry season — may vary by several weeks. This, of course, in turn affects the dates on farm operations and the time of harvesting. There are often difficult periods when stocks are depleted before the new harvest is in.

3.2. Persistence and Pseudo-Cycles

Climate is also characterized by persistence, *i.e.* the tendency for weather in successive time intervals to be correlated. Applied to rainfall, this means that dry and wet periods do not occur randomly but tend to occur in clusters, *i.e.* runs of dry (wet) days (weeks, months, years) are more likely than randomly distributed dry and wet days (weeks,

months, years). Needless to say, this behaviour is also present in crop production, and this has obvious implications for food security. Markov chains and transitional matrices are standard tools to simulate persistence (SHARMA 1996).

Table 1, taken from GOMMES (1985), illustrates this behaviour for an area south of lake Victoria. It reads as follows : a yield that falls in the lower quartile [6] class is followed during 34.8 % of the years by a yield in the same lower class, and during 20.6 % of the years by a yield in the highest class. In other words, a low yield is more likely to be followed by another low yield [7]. Similarly, a yield in the highest class is about two times more likely to be followed by a yield in the same class (0.404) than by a yield in the lowest class (0.242). This behaviour is responsible for the "pseudo-cycles" that are often apparent in climatological and agricultural time series. Note that, with the exception of 0.429, the highest values in the table are the top left (bad after bad) and bottom right (good after good). The implications of persistence are serious, as they are one of the main reasons why storage structures are so important.

Table 1

Probability of a maize yield in a given quartile class being followed the next year by a yield in any of the four classes (for a planting date in January)

		Year i + 1			
		Q1	Median		Q3
Year i	Q1	0.348	0.174	0.272	0.206
	Q2	0.305	0.158	0.196	0.341
	Q3	0.107	0.429	0.321	0.143
		0.242	0.192	0.162	0.404

Persistence is a particularly important feature for livestock populations : cattle suffers during runs of bad (dry) years, with increased mortality and decreasing populations. During the following episode of favourable range-land conditions (wet), the populations build up only gradually, with the consequence that it is often difficult to maintain herd size at a stable number. This is illustrated in figure 2 : livestock numbers in Mali, Niger and Chad follow an almost cyclical pattern driven by rainfall, indicated here by a rainfall index [8].

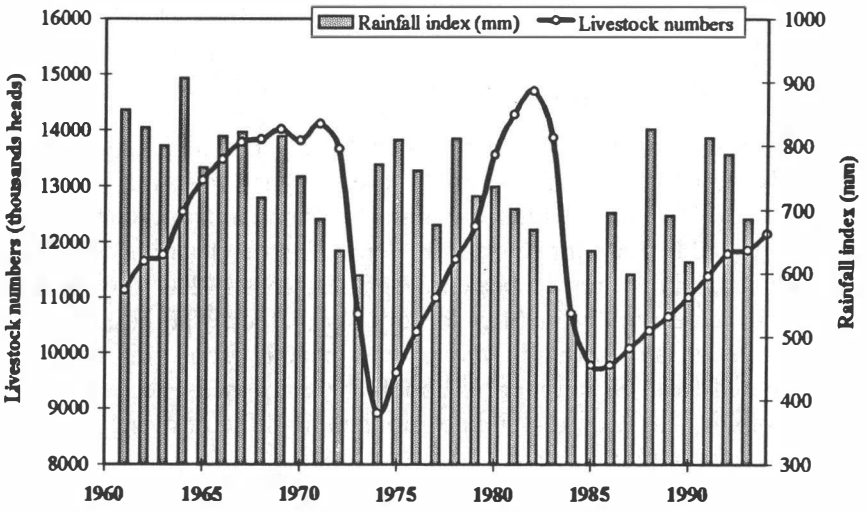


Fig. 2. — Livestock numbers (total of Niger, Mali and Chad) and rainfall indices between 1960 and 1994.

Livestock populations were on the increase during the early sixties, under relatively high rainfall indices, but they stabilized at about 14 million heads between 1965 and 1972, with decreasing rainfall. The first drought "peak" in 1973 was followed, with a time-lag, by a serious drop in numbers, which recovered slowly until 1982, to be followed, again, by a serious drop linked to the 1984 drought. Since 1987, the populations have been increasing again, although they are relatively stationary if expressed relative to the human population.

3.3. Complex Interactions

Two types of interactions are described below : the first refers to civil unrest and war, which has become a major factor of food insecurity over the recent decade. Climate and weather *per se* are not the causes of the phenomena, but they interact and often contribute to precipitating otherwise unstable situations. This will be illustrated with the Rwanda crisis of 1994, with particular emphasis on the timing of the events compared with the cropping calendar.

A second type of complex interaction is linked with population increase, which leads to cultivate less favourable land. Again, this increases the vulnerability to the variability of rainfall. A typical

situation will be described in the southern Lake Victoria area in Tanzania.

3.3.1. The 1994 Crisis in Rwanda [9]

Rwanda experiences an equatorial highland climate (fig. 3), with a relatively short "dry" season from June to August, followed by a first season with low and regular amounts of rainfall from October to January (at 60 to 100 mm per month, depending on elevation). Rainfall increases then in March to peak in April (at 150 to 200 mm/month) and to decrease rapidly in May to very low values. The best strategy to plant is usually around January, to benefit from soil moisture accumulated from September, although the combined effect of trends and variability has been making decisions more difficult over the recent years in the area (MUSITWA & KEATINGE 1996).

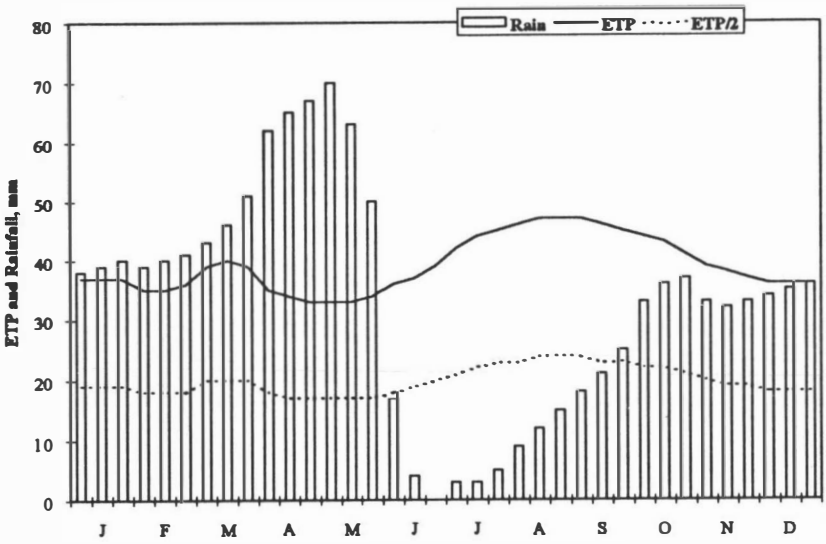


Fig. 3. — Average 10-day rainfall and evapotranspiration potential (ETP) patterns in Rubona, Rwanda, 1,706 m. ETP/2 is given as the value corresponding roughly to crop water requirements at early development stages. Planting can thus take place when rainfall exceeds ETP/2.

This leads to the following cropping seasons (cassava is also grown with no dominant harvesting period) :

— "A" season (September/October to January), where the main crops are cereals (maize, sorghum).

— B season (February to June), where the main crops are beans, sweet and white potatoes. About 40 % of the cereals and 60 % of the beans are grown in this season ;
— C season (June-September), when wet areas (valley bottoms and swampy areas) are used to grow vegetables, and sweet potato to be used as cuttings for the A season.

In August 1993, the rainy season started early (fig. 4), but September and October rains were low, which led to a reduction in planted areas as well as low yields. The first bean crop (a major staple) was lost, and could not be replanted due to insufficient rain.

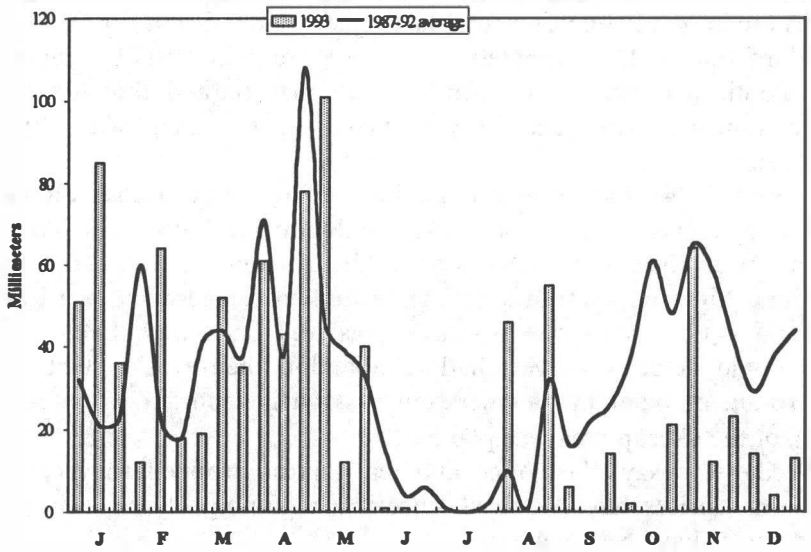


Fig. 4. — 1993 dekad rainfall in Butare (1,768 m), compared with the average of the previous 6 years.

In October 1993, a coup in Burundi was followed by large population movements (700,000 people) of which 400,000 entered Rwanda [10]. Following the poor harvest *prospects* and the increased demand, prices soared.

March witnesses a very critical food situation. The combination of a very unusual drought and the population movements creates a famine situation : the A season crop was down one third compared to the 1993 A crop. It is estimated at the time that the total output of the A and B seasons will be about 73 % of normal. The food deficit is

estimated at 300,000 tons. One of the difficulties is that some of the affected crops (tubers, plantain bananas) are difficult to substitute and to store.

The genocide erupted in April and May : numerous people were killed and about 2,000,000 were displaced. This very seriously reduces the expectations for the B season, combined with lack of seeds. It is all too obvious by now that the C crop will suffer as well, and that the early production deficit estimates have to be increased significantly.

A joint FAO/WFP mission visited the area in July 1994 and confirmed that a large proportion of fields were abandoned. B-season crops are in good condition (thanks to good rains), if not for excessive weed infestation. Unfortunately, no one is there to harvest. The mission also confirmed that the C crop was not planted and that livestock populations have dwindled. Very little land was prepared for the 1994/95 season.

August 1994 : the infrastructure has suffered very serious damage and it appears now that 10 % of the population was killed, that 700,000 people were displaced in Rwanda, while 2.2 million fled across the borders. Most population movements took place between April and July, at a time when the B season was well underway. Even those who could actually harvest had to abandon their stocks. Untimely harvesting of plantain bananas and cassava is reported. Only 30 to 50 % of the C-crop area was planted.

Needless to say, the coffee and tea harvest dropped to very low amounts ; prices have doubled since the beginning of the year, and food stocks have been depleted.

December 1994 reports indicate that less than 50 % of the A crop was actually planted, and all planning (including planning of relief operations) suffers from the lack of reliable data on demography, agriculture, meteorology [11]... In March 1995 planted areas were revised upward. After a slow start, the 1995 A season benefited from abundant and well-distributed rainfall.

The discussion above highlights the fact that climatic conditions often play an essential role in triggering and aggravating humanitarian crises. Climate and the crop calendar are closely linked, and information on both is essential in assessing the outcome of cropping seasons and the resulting food situation.

3.3.2. Climate-Soil-Demography Interactions

One of the most immediate results of population increase under relatively stable technology is the "horizontal" increase of cropped areas, roughly in direct proportion to population growth. Since there has also been a parallel trend of urbanization, there is a need for at least some intensification if the food production has to keep pace with requirements. Needless to say, the yield increases brought about by new varieties, fertilizer use, etc. have an often overlooked corollary in terms of water consumption : the higher the yield, the higher the water consumption. This means that, even under constant climate and on the same soil, intensification can, paradoxically, result in more frequent "droughts" and greater interannual variability of yields, even if the average levels of production improve. Ideally, improved practices should thus be accompanied by "response farming" techniques, *i.e.* improved management which takes into account the current weather.

A second, more serious and insidious mechanism which leads to greater vulnerability of food production systems to climate vagaries involves soils : when the agricultural area is expanded "horizontally", the "best" soils are usually cultivated first. "Best" here stands for soils with the highest natural fertility and high water-holding capacity.

Below is an example using data from east Mwanza region, south of Lake Victoria (mostly after GOMMES 1985), in which the author became interested in trying to understand why an area which had traditionally been considered a surplus maize producing area started experiencing food shortages.

As shown in table 2, only 25 % of the area has "good" soils. It is clear that the average yields and the interannual variability of yields

Table 2

Relative importance of soil types in east Mwanza region (Tanzania) according to water holding capacity (WHC)

WHC (mm)	Reference WHC (mm)	% of district	
15-35	30	40	"Poor soils"
35-50	40	32	
50-70	60	1	
70-90	80	2	"Good soils"
90-115	100	2	
115-160	130	5	
160-300	190	18	

are higher on the "poor" soils, and that the optimal planting dates vary as well.

The area experiences a climate which is transitional between unimodal and bimodal rainfall patterns, with a marked dry season (the general pattern is similar to Rwanda, with a longer main dry season, usually less reliable rain, and a more marked drop of precipitation in February). After a period of decreasing rainfall from 1930 to 1960 (fig. 5), the area recorded above-average rainfall during the sixties, which is also the period the traditional crops of bulrush millet, sorghum and cotton started being substituted with maize [12]. Maize is more water-demanding than the traditional cereal crops of the area, but this went unnoticed during the sixties as this also coincided with rainfall which improved over the previous decades.

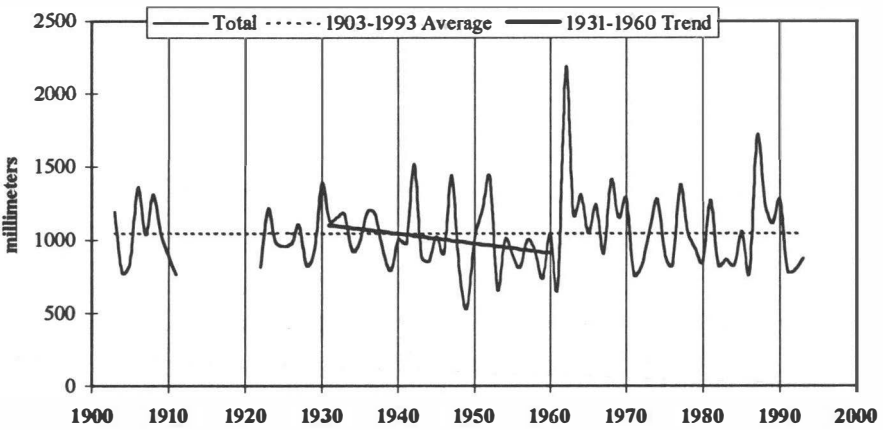


Fig. 5. — Annual rainfall pattern at Mwanza (lake Victoria) between 1903 and 1993 : annual total, average and downward trend between 1931 and 1960.

Food production shortages started occurring in the seventies and eighties, and this results from the combined effect of "normal" rainfall, a change in cropping pattern (maize) and the expansion into "poorer" soils.

This was simulated with a Monte Carlo approach in figure 6, under constant climate [13]. As population increases, the less favourable land is gradually cultivated from year 30 onwards (roughly corresponding to 1960 or 1970).

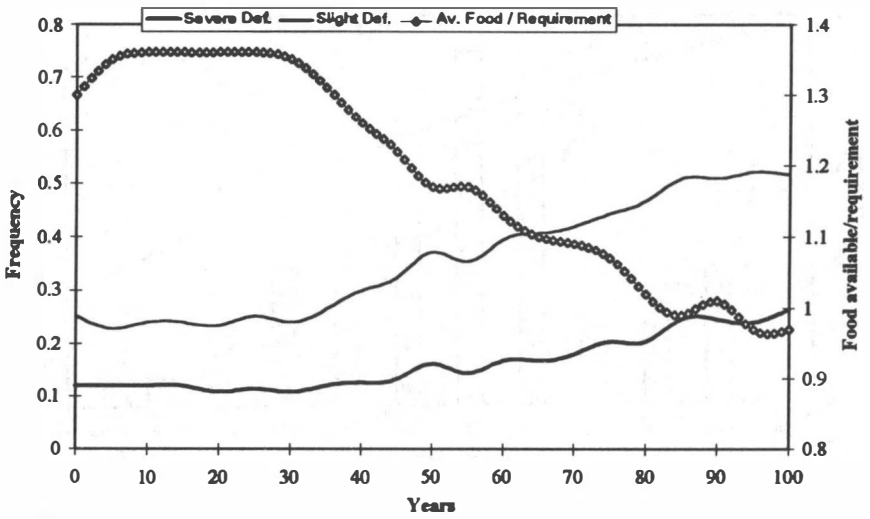


Fig. 6. — Monte Carlo simulated ratio between available (A) and required (R) food. A "slight deficit" occurs when food available (current season plus carry-over stocks) drops below requirement ($A < R$); a severe deficit is defined by $A < R/2$. Total area cultivated is assumed to be in direct proportion to the population. Refer to text for details.

4. Estimating Climatic Risk and Vulnerability

Climatic risk in agriculture is not easily defined. Economists tend to restrict the term to a probability of occurrence of a damaging event. Alternatively, risk can be defined as the product of the probability of a damaging event times the vulnerability (average loss) of the impacted system (ABBASPOUR 1994, WHITE 1994, NASH & NASH 1995). This notion is implicit in many situations, for instance, the risk is nil when either the probability is nil, or the expected loss is nil. Obviously, the vulnerability is a function of the intensity of the damaging event [14].

Given that many extreme events do not occur frequently (by definition), the corresponding risks may be difficult to assess in practice. This also stresses the need to conduct proper *post factum* damage assessments, which is seldom done in practice [15].

In the field of food security, it is obvious that the estimation of vulnerability and of the frequency of extreme and/or damaging factors as a function of their intensities is at the heart of the methodology of early warning systems.

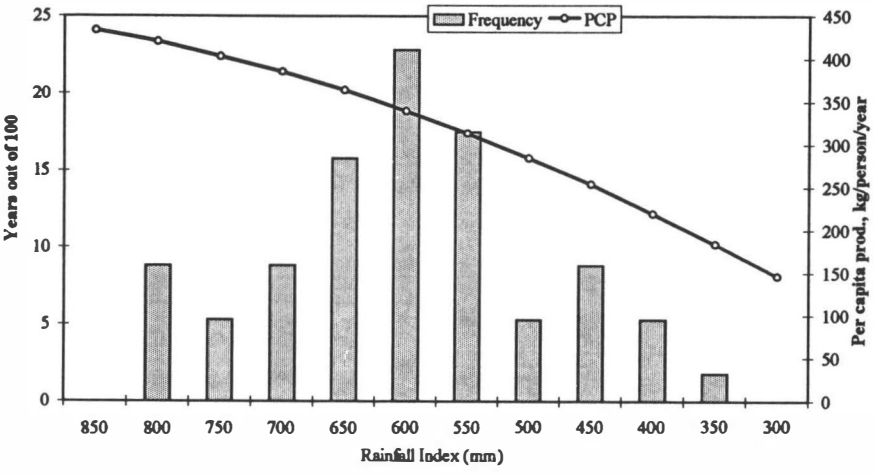


Fig. 7. — Some parameters used to assess the risk associated with growing cereals in Niger, based on 1932-93 rainfall (rainfall index frequency) and on 1961-94 cereal yields for *per capita* production (PCP, kg cereals person^{-1} year^{-1}). PCP values below 300 correspond to a deficit.

Below is an example of a climatic risk assessment in Niger. In the first graph (fig. 7) rainfall indices vary from 348 (1987) to 799 (1939) with a median of 570 and the following quartiles : Q1 = 507 and Q3 = 648.

Figure 7 shows the frequency of rainfall index classes : the most frequent value falls in the 600-class (600 to 649). The dotted line indicates how the *per capita* production (PCP : kg cereals person^{-1} year^{-1}) varies as a function of the rainfall index. With an assumed net *per capita* consumption rate around 240 kg person^{-1} year^{-1}, a PCP of about 300 kg is needed, assuming post-harvest losses of 20 %. This means that deficits will occur for rainfall indices below 500 mm, *i.e.* roughly during 25 % of the years (compare with Q1).

The numerical values corresponding to figure 7 are given in table 3. Food production surplus (+) and deficit (–) were computed by subtracting PCP (kg cereals person^{-1} year^{-1}) from the assumed gross requirement of 300 (240 net requirement). The risk is the product of S/D by the frequency per century. Deficits and surpluses were summed separately in the last column, in kg *per annum*. Obviously, the S/D variable satisfies the definition of vulnerability.

Table 3

Quantification of the risk associated with growing cereals in Niger. The frequency values corresponding to rainfall indices are based on the years 1932 to 1993 (57 years). They are given for the original period and per century (1 year in 57 is equivalent to 1.8 years in hundred, etc.). The *per capita* production PCP was estimated by regressing 1961 to 1994 values against rainfall index

Rainfall Index		Frequency		PCP	S/D	Risk	Accumulated risk
Interval	Midpoint value	Over 57 years	Over 100 years	kg person^{-1} year^{-1}	kg person^{-1} year^{-1}	kg person^{-1} (100 years)$^{-1}$	kg person^{-1} year^{-1}
301-350	325	0	0	146	– 154	0	
351-400	375	1	1.8	184	– 116	– 209	– 11.18
401-450	425	3	5.3	220	– 80	– 424	
451-500	475	5	8.8	254	– 46	– 405	
501-550	525	3	5.3	285	– 15	– 80	
551-600	575	10	17.5	314	14	245	
601-650	625	13	22.8	340	40	912	
651-700	675	9	15.8	364	64	1011	45.18
701-750	725	5	8.8	385	85	748	
751-800	775	3	5.3	403	103	546	
801-850	825	5	8.8	420	120	1056	
851-900	875	0	0	433	133	0	

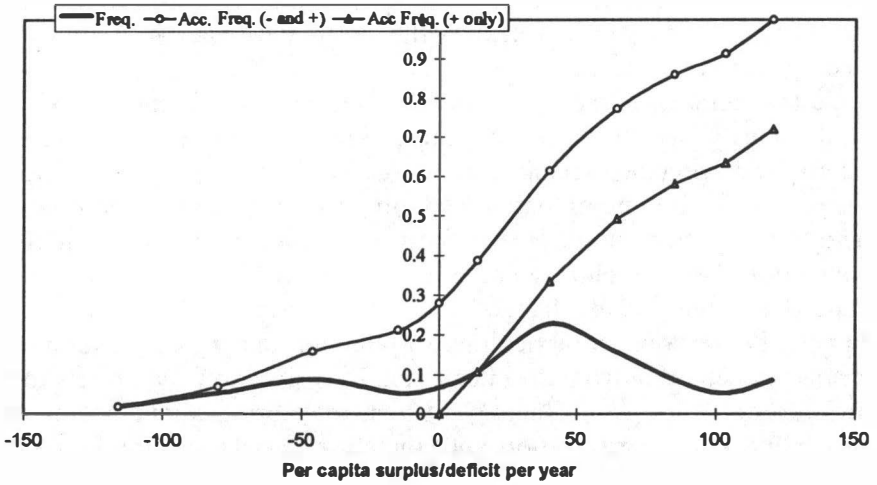


Fig. 8. — Accumulated frequencies of *per capita* cereal production surplus or deficit in Niger (based on the data in fig. 7). The "– and +" curve corresponds to the total range of values, from deficit to surplus. The "+ only" curve covers only positive values. The absolute frequency (derivative of the "– and +" curve) is represented on an arbitrary ordinate scale.

The average risk during deficit years which occur on average during about one year out of five (21.2 %) is 11.18 kg person^{-1} year^{-1}. An average surplus of 45.18 kg Pres.$^{-1}$ year^{-1} is available during 78.2 % of the years. Figure 8 shows accumulated frequencies associated with cereal production surpluses and deficits. The bimodal shape of the absolute frequency curve is particularly striking, and provides in fact another illustration of persistence : "neutral" years when production exactly covers requirements are less frequent than slight deficit (– 50 kg person^{-1} year^{-1}) and slight surplus years (50 kg person^{-1} year^{-1}). It remains that a situation where surplus years are only three times more frequent than deficit years is rather critical.

5. Conclusions

The regularity of food supply is one of the conditions of food security. As weather and climate are among the main direct factors behind the variability of agricultural production, they are also key factors in food security assessments and operational food early warning systems. Climate also indirectly affects production through pests, diseases, effects on the infrastructure and farm operations, human and animal health, etc. These aspects were not dealt with, but they do play an important role, especially at a local level.

Certain climate characteristics such as trends and persistence do affect food security *per se*, in other words, climate is not just a variable randomly driving the variability of production. On the contrary, it often forces certain dominant patterns upon food production variability. Another important point is that food production is the result of the interactions between climate and a food production system which itself undergoes continuous changes. Therefore, even under "constant" climate, the response of agricultural production undergoes interannual changes which result from the interaction. Intensification and population pressure are examples of changes which may bring about a greater variability of food production and, therefore, a deterioration of food security.

Over the last decade, war and civil unrest have also become major determinants of food security. The extent to which the destruction of the infrastructure and the disruption of civil life affects food security is also related, mainly through inadequate cropping calendars, to climatic conditions.

Finally, the recent evolution in sub-Saharan Africa appears to indicate that climate impact on food security is bound to increase in the future.

NOTES

[1] "Variability" is meant to include all scales of time, from hours to days (*e.g.* cold spells of a couple of days) to runs of years (*e.g.* dry years in the Sahel from about 1960 to 1987). No distinction is made according to the physical cause of the variability (random climatic noise, short-term fluctuation or climate change). Since both inter- and intra-seasonal variability result in inter-seasonal fluctuations in yields and production, the source of the variability is not so relevant for its impact on food security. This is now changing to some extent with the operational use of ENSO for seasonal forecasts (CANE *et al.* 1994, SELESHI & DEMAREE 1995, SISTEMA NACIONAL 1996).

[2] Extreme weather is defined by its statistical low frequency of occurrence rather than by the energies (cyclones, and other factors which severely affect the infrastructures), the magnitude of damage or by the size of the area affected (floods). The term "chronic" mostly characterizes damaging events with relatively high frequencies but usually low on the damage scale (compare with section 4 below).

[3] The author has noted that nationals from developed countries often do not understand the discussion that follows. It should, therefore, be recalled that the majority of African farmers live at the subsistence level, which, by definition, means that they grow their own food. Very little is sold or purchased or otherwise enters commercial channels. From there follow other semantic differences between developing and developed countries, for instance as regards "cash crops" . To the farmer in developed countries, all crops are "cash crops", but in developing countries, farmers — very often women — must decide whether they can afford to grow crops for their food and crops they will sell. The decision is based on the manual labour that is available (including children), the access to buyers and the prospective price at the time of harvest. Cash crops can be food crops (after making allowance for domestic consumption and carry-over stock) or industrial crops. In some areas (Sukumaland in Tanzania), cotton is grown as an insurance against good years, *i.e.* during excellent years, maize price will drop so low that only cotton can be sold with some benefit. The area under cotton is kept low, as the crop increases vulnerability during bad years.

[4] For instance, in Thailand, an average of 12.6 % of the rice land is not planted, and 20.8 % is not harvested due to adverse weather (SINGH 1989). This results in only 66.6 % of the potential rice area being actually productive in a given year.

[5] Seasonality describes the fact that wet (rainy) and dry seasons occur alternately. This is a very predictable behaviour from a climatic perspective.

[6] Definition of a quartile : assume a variable (say, June rainfall) was measured over a number of years ; the values are obviously distributed over a range. The values can be ranked from the smallest to the highest, with usually some identical values in-between. The value which is exactly in the middle is the median, *i.e.* 50 % of the values are below the median, and 50 % are above it. Similarly, the quartiles subdivide the interval into four groups containing each 25 % of the values. The four groups are separated by the lower quartile Q1, the middle quartile (Q2, which is the same as the median), and the upper quartile.

[7] The values in the lines obviously add up to 1.

[8] The index is defined as the national average of the total annual precipitation weighted, for each station, by its long-term average. This index is biased towards agriculture, *i.e* rainfall is given a low weight in the driest areas which are also characterized by a low rainfall-climatic agricultural potential.

[9] The description of the crisis is taken mainly from the FAO Global Information and early Warning System on Food and Agriculture special alerts and other UN documents (UNHCR, WFP).

[10] About 400,000 refugees were already living in camps due to previous problems in the area (1990 and 1993).

[11] The destruction of the meteorological network is one of the factors which makes it difficult to forecast crop production.

[12] The issue is more complex, as this is also the period immediately after independence, when farmers tended to abandon the "colonial" cotton crop. Maize, like cotton, is also easy to market and fetches better prices than sorghum and millet. Other food crops grown in the area include sweet potatoes and cassava.

[13] The "constant climate" under consideration corresponds to the 1932-85 conditions. The transition matrix in table 1 was used to simulate 500 cropping seasons (crop planted in January).

[14] Another advantage of this definition is that it provides a straightforward approach to "vulnerability" : the average loss (which can be measured) associated with a given damaging event. Risk is thus expressed as the "average loss over a given time interval", for instance in US $/year or number of homeless people per year, thus *Loss/year = Number of events/year * Loss/Event*. As most damaging events can occur at different intensities, this can be reformulated as $Total\ risk_{(loss/year)} = \Sigma_i\ (Frequency_i * Vulnerabilty_i)$ where *Frequency* is measured in number of events per year and *Vulnerability* in loss/event. The summation index i corresponds to different intensities or even categories of events.

[15] The impact of tropical cyclones on agriculture constitutes a good example of lost data and missed opportunities. In most instances meteorological stations are not cyclone-proof and essential data are never recorded, for instance maximum wind speed. It is therefore most difficult to "categorize" the cyclone. Similarly, a proper description of the impacted system is necessary.

REFERENCES

ABBASPOUR, K. C. 1994. Bayesian risk methodology for crop insurance decisions. — *Agric. For. Meteorol.*, **71** :297-314.

BULTOT, F. & GELLENS, D. 1994. Sur le caractère stationnaire et cyclique des précipitations au Rwanda. — Acad. R. Sci. Outre-Mer, Cl. Sci. Techn., Mém. in-8, N. S., **19** (1), 53 pp.

CANE, M. A., ESHEL, G. & BUCKLAND, R. W. 1994. Forecasting Zimbabwean Maize yield using eastern equatorial Pacific sea surface temperature. — *Nature*, **370** :204-205.

GOMMES, R. 1985. Rainfed food-crop production in east Mwanza region. A semi-quantitative risk analysis. — Workshop on Food security and Nutrition education, Mikumi, Tanzania, 27-31 May 1985 : IRA/UDSM/IUNS/DIDA/UNICEF/UTAFITI, 28 pp.

GOMMES, R. & PETRASSI, F. 1994. Rainfall variability and drought in sub-Saharan Africa since 1960. — FAO Agrometeorology Series, Working Papers No. 9, 100 pp.

HESS, T. M., STEPHENS, W. & MARYAH, U. M. 1995. Rainfall trends in the North East arid zone of Nigeria 1961-1990. — *Agric. For. meteorol.*, **74** :87-97.

IFMR 1994. Sharing the challenge : floodplain management into the 21st century. — Report of the Interagency Floodplain Management Review Committee to the Adminstration Floodplain Management task Force, Washington.

MALOBA MAKANGA, J. D. 1995. Variabilité pluviométrique du Gabon (1951-1990). — *Veille Clim. Satell.*, **52** : 43-57.

MORON, V. 1996. Régionalisation et évolution des précipitations tropicales annuelles (1946-1992). — *Sécheresse*, **7** (1) : 25-32.

MUSITWA, F. & KEATINGE, J. D. H. 1996. Fitting annual cropping systems in the bimodal rainfall regions of Uganda. — In print.

NASH, J. C. & NASH, M. M. 1995. Managing Risks. — *Chance*, **8** (4) : 25-31.

ROJAS, O. 1995. O impacto climático sobre a produção de milho em Moçambique. — Estudo de sensibilidade e cenários. Sistema Nacional de aviso prévio para a segurança alimentar, GCPS/MOZ/049/EC, Maputo, 19 pp.

SELESHI, Y. & DEMAREE, G. R. 1995. Rainfall Variability in the Ethiopian and Eritrean highlands and its links with the Southern Oscillation Index. — *J. Biogeogr.*, **22** : 945-952.

SHARMA, T.C. 1996. Simulation of the Kenyan longest dry and wet spells and the largest rain-sums using a Markov model. — *J. Hydrol.*, **178** : 55-67.

SINGH, R. B. 1989. Contingency Crop Planning for rainfed areas. — *In* : Rainfed Agriculture in Asia and the Pacific Region, FAO Regional Office for Asia and the Pacific, Bangkok, pp. 49-59.

Sistema Nacional 1996. Estudio agroclimático da precipitação e sua aplicação na segurança alimentar. — Sistema Nacional de aviso prévio para a segurança alimentar, GCPS/MOZ/049/EC, Maputo, 27 pp. (text) & 65 pp. (tables and graphs).

WHITE, D. H. 1994. Climate variability, ecologically sustainable development and risk management. — *Agric. Systems and Information Technology*, **6** (2) : 7-8.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 674-684 (1998)

Monsoon Prediction in Bangladesh : a Preliminary Study

by

Rafique AHMED *

KEYWORDS. — Bangladesh ; Monsoon Arrival Dates ; Monsoon Variability ; Monsoon Prediction.

ABSTRACT. — Arrival dates of the summer monsoon in Bangladesh vary from place to place, and from year to year. An empirical/statistical model has been developed for the prediction of the arrival dates of the summer monsoon in the country. Daily rainfall amount and mean wind direction (azimuth) at nineteen stations, for the period May 1 through October 31, for each of the 30-year period from 1958 through 1987, were used to determine the arrival dates of the summer monsoon. Statistical relationship between the arrival date of the summer monsoon at Cox's Bazar (a station in the south-eastern coastal area) and the Temperature Gradient Index (T.G.I.), expressed as the ratio between temporal temperature changes at Rajshahi (an interior station) and at Chittagong (a coastal station) during the early part of the pre-monsoon season, has been used to predict the arrival date of the summer monsoon at Cox's Bazar in a given year. Arrival dates of the summer monsoon at other stations were predicted by projecting the subsequent location of the isoline of the advancing monsoon based on its normal (or mean) progression.

MOTS-CLES. — Bangladesh ; Dates d'arrivée de la saison des moussons ; Variabilité de la mousson ; Prévision de la mousson.

RESUME. — *La prévision des moussons au Bangladesh : une étude préliminaire*. — Les dates d'arrivée des moussons d'été au Bangladesh varient d'un lieu à l'autre et d'une année à l'autre. Un modèle empiro-statistique a été développé pour la prévision des dates d'arrivée des moussons d'été dans ce pays. Des cotes pluviométriques journalières et la direction moyenne du

* Department of Geography and Earth Science, University of Wisconsin-La Crosse, La Crosse, Wisconsin, 54601 (U.S.A.).

vent (azimuth) de dix-neuf stations, pour la période du 1er mai au 31 octobre et pour chaque année de la période de référence (de 1958 à 1987), ont été utilisées pour déterminer les dates d'arrivée des moussons d'été. La relation statistique entre les dates d'arrivée des moussons d'été à Cox Bazar (poste dans la région sud-est de la côte) et l'index du gradient de la température (T.G.I.), exprimé comme la proportion entre les changements temporels de la température à Rajshahi (poste à l'intérieur des terres) et à Chittagong (poste côtier) au début de la saison des moussons, a été utilisée pour prévoir les dates d'arrivée des moussons d'été à Cox Bazar pour une année précise. Les dates d'arrivée des moussons d'été à d'autres stations sont prévues en projetant la position de l'isoligne de la mousson en progression sur sa progression normale (ou moyenne).

TREFWOORDEN. — Bangladesh ; Begindata moessonseizoen ; Moessonvariabiliteit ; Moessonvoorspelling.

SAMENVATTING. — *Moessonvoorspelling in Bangladesh : een voorbereidende studie.* — Het begin van het zomermoessonseizoen in Bangladesh verschilt van plaats tot plaats, en van jaar tot jaar. Een empirisch/statistisch model werd ontwikkeld voor de voorspelling van de begindata van de zomermoesson in het land. Dagelijkse neerslaghoeveelheden en gemiddelde windrichting (azimuth) van negentien stations, voor de periode 1 mei tot 31 oktober, voor de 30-jarige periode 1958 tot 1987 werden gebruikt om de begindata van de zomermoesson te bepalen. Statistische relaties tussen de begindata van de zomermoesson te Cox's Bazar (een station in het zuidoostelijke kustgebied) en de temperatuursgradiëntindex (T.G.I.), uitgedrukt als de verhouding van tijdelijke temperatuurschommelingen te Rajshahi (een station in het binnenland) en te Chittagong (kuststation) gedurende het beginstadium van het premoessonseizoen, werden gebruikt om de aanvangsdatum van de zomermoesson te Cox's Bazar te voorspellen in een gegeven jaar. Aanvangsdata van de zomermoesson voor andere stations werden voorspeld door de subsequente ligging van de isolijn van de vooruitschreidende moesson te projecteren, gebaseerd op haar normale (of gemiddelde) vooruitgang/progressie.

1. Introduction

Geographically, Bangladesh is located in the tropical region that extends from 20°45′ N to 26°40′ N, and from 88°05′ E to 92°40′ E. Climatologically, it is located at the entry and exit point of the Bay of Bengal branch of the South Asian monsoon (SPATE & LEARMONTH 1984), thereby making it one of the most important monsoon regions in the world. The rainy season coincides with the summer monsoon season, which prevails from early June through mid-October, when

it is dominated by the south-westerly winds from the Bay of Bengal (AHMED & KARMAKAR 1993).

The summer monsoon season has a profound influence on the agriculture, hydrology and drainage systems of Bangladesh, all of which, in turn, influence the economy of the country (JOHNSON 1982). This season accounts for 75-80 % of the total annual rainfall of the country. The arrival date of the summer monsoon is very important from the agricultural point of view because it affects two crop seasons : harvesting period of aus (local name for the summer rice), and planting period of aman (local name for the autumn rice). Moreover, every year several floods occur during this season which cause extensive damage to crops, livestock, life and properties (JOHNSON 1982, AHMED 1989, AHMED & KARMAKAR 1993). Sometimes floods may reach calamity proportions, such as those of 1987 and 1988 (BRAMMER 1990), requiring large-scale international relief efforts.

Although Bangladesh is located in a major monsoon region of the world, very little is known about the various characteristics of its summer monsoon. Especially, no studies have been done on the prediction of monsoon in Bangladesh. This paper presents the results of an empirical study on the prediction of the arrival date of the summer monsoon season in Bangladesh.

2. Methodology

Methodology included the (a) determination of the arrival dates of the summer monsoon, and (b) the determination of the temperature gradient index between Rajshahi (an interior station) and Chittagong (a coastal station) during the pre-monsoon season. These were used for the prediction of the arrival date of the summer monsoon in Bangladesh.

2.1. Determination of the Arrival Dates of the Summer Monsoon

The arrival dates of the summer at various stations were determined by using the method described by AHMED & KARMAKAR (1993). According to this method, the arrival date of the summer monsoon is given by the first day of a period of three or more consecutive days of rainfall, with daily rainfall of 5 mm or more, accompanied by southerly or south-westerly winds which prevailed through the rest of

the season. For the ease of statistical analysis, the arrival date of the summer monsoon in a given year has been expressed as the Index of Monsoon Arrival date. This has been counted as the number of days elapsed since April 30. For example, Index 1 means May 1, 29 means May 29, and 40 means June 9, etc.

2.2. Determination of the Temperature Gradient Index (T.G.I.) during the Pre-Monsoon Season

The pre-monsoon season (March through May) in Bangladesh is the transition period between the northerly or north-westerly winds of the winter monsoon and the southerly or south-westerly winds of the summer monsoon. As the season progresses, a centre of thermal low temperatures develops and intensifies in the west-central part of India (Ahmed 1989, Ahmed & Karmakar 1993). Also, as the pre-monsoon season progresses, temperature in Bangladesh continues to rise differentially — the west-central part gains temperature at a faster rate than the south-eastern coastal areas. As a result, a spatial temperature gradient is created between the warmer west-central part and the south-eastern coastal area of Bangladesh, which intensifies with the progression of the pre-monsoon season (fig. 1).

In this study, the pre-monsoon hot season (March through May) was investigated for meteorological signals that might indicate when the monsoon may arrive in Bangladesh in a given year. This was done on the basis of the statistical relationship between the arrival date of the summer monsoon at Cox's Bazar and the Temperature Gradient Index (T.G.I.) between Rajshahi and Chittagong during the early pre-monsoon season. The rate of temporal temperature change at Rajshahi (an interior station) and Chittagong (a coastal station in the south-east) during the early pre-monsoon has been expressed as the ratio between the two, and is called the Temperature Gradient Index (T.G.I.) :

$$\text{T.G.I.} = (T_{R6\&7} - T_{R1\&2}) \,/\, (T_{C6\&7} - T_{C1\&2}),$$

where T is the average temperature of a two-week period in a given year, subscripts R and C represent the stations Rajshahi and Chittagong, respectively ; and subscripted numbers 6 & 7 and 1 & 2 represent the respective two-week long period of the pre-monsoon season, with March 1 as the beginning of the first week of the season.

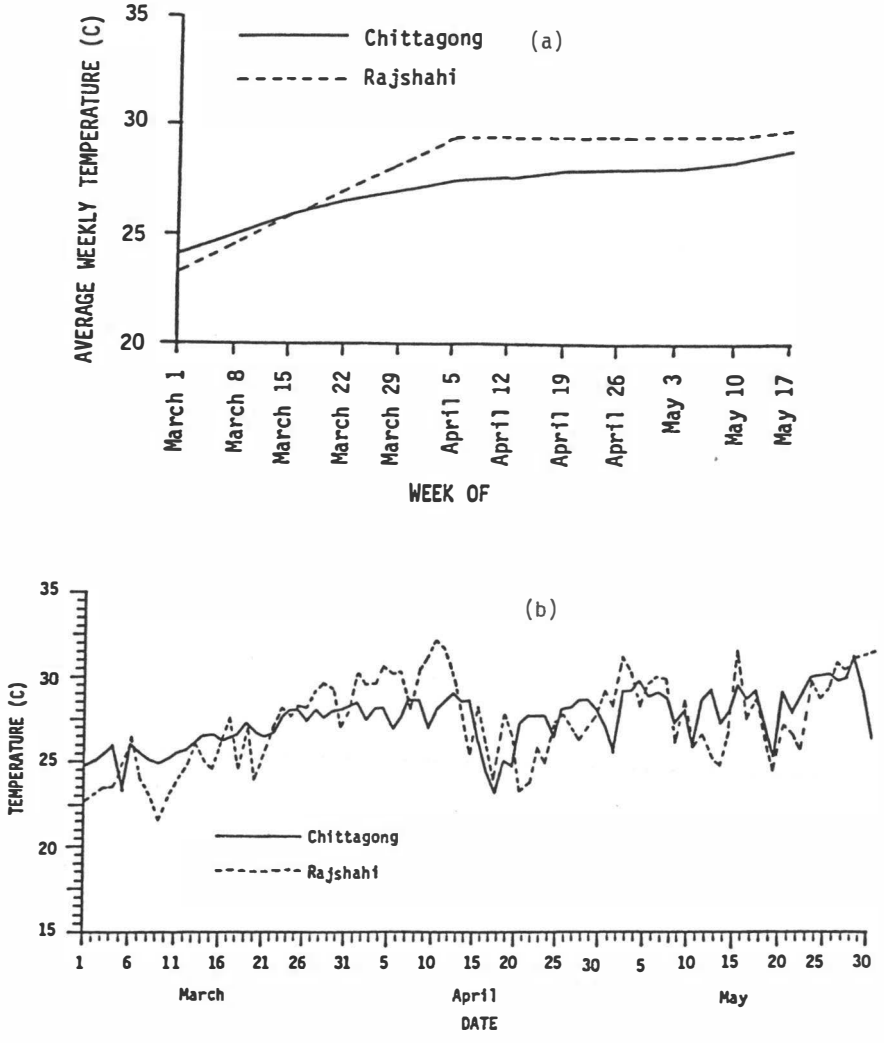


Fig. 1. — (a) Trends of the mean weekly temperatures at Chittagong and Rajshahi from the week of March 1 through the week of May 17 (1958-1987 mean), and (b) plots of daily mean temperatures for Chittagong and Rajshahi for the period March 1 through May 30, 1964.

2.3. Statistical Model of the Monsoon Arrival Date

The date of the monsoon arrival at Cox's Bazar has been used as the dependent variable and the Temperature Gradient Index between Rajshahi and Chittagong (T.G.I.) has been used as the independent variable. Arrival date of the summer monsoon at Cox's Bazar in different years of the 30-year period from 1958 through 1987, and the T.G.I. for each of those 30-year period are shown in table 1. The statistical model for the prediction of the arrival date of the summer monsoon is given as :

$$y = 54.535 - 11.179 \text{ T.G.I., with } r = -0.73035, \text{ and } n = 21,$$

where y is the predicted index of the monsoon arrival date, r is the correlation coefficient, and n is the number of paired observation of both T.G.I. and observed index of monsoon arrival date.

It was observed that the arrival date of the summer monsoon in Bangladesh varies from year to year. In the thirty-year period of observation (1958-1987) at Cox's Bazar, monsoon arrived as early as May 11 (in 1968) and as late as June 17 (in 1958).

3. Data

Daily rainfall (mm) and daily prevailing wind direction (azimuth) data for the months May through October for the period 1958 through 1987, for nineteen stations in Bangladesh were used in this study to determine the arrival date of the summer monsoon in the country. The location of the stations are shown in figure 2a. These stations were selected to portray the geographical and climatological variations in the country. Besides these, mean daily temperatures for Chittagong and Rajshahi, for each day of the three months of the pre-monsoon season (March through May), for the above-mentioned 30-year period, were used to determine T.G.I. All data were obtained from the Bangladesh Meteorological Department. It may be noted that Rajshahi station was not operational before 1964. As a result, T.G.I. could not be determined for the period 1958 through 1963. Besides these, there were also other cases of missing data which were marked missing (M) in table 1.

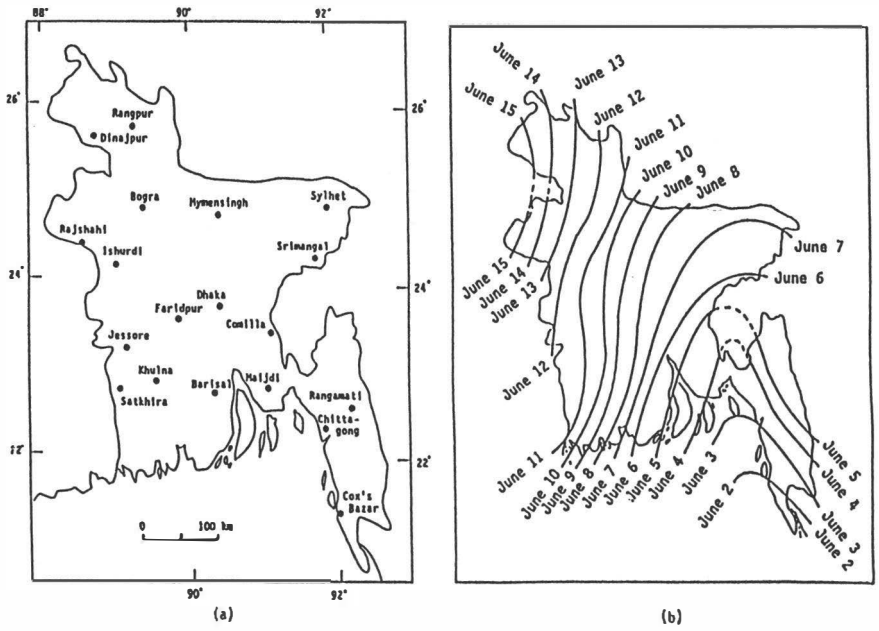


Fig. 2. — (a) Location of stations, and (b) spatial pattern of the mean arrival dates of the summer monsoon in Bangladesh (after AHMED & KARMAKAR).

4. Results and Discussion

The summer monsoon, on an average, arrives at Cox's Bazar on June 2, and reaches the north-western part of the country by June 15 (fig. 2b). The relationship between the arrival date of the summer monsoon at Cox's Bazar and the pre-monsoon Temperature Gradient Index (T.G.I.) between Rajshahi and Chittagong is given as $y = 54.535 - 11.179$ T.G.I., with a correlation coefficient (r) of -0.73035 (fig. 3). This relationship has been used for the prediction of the arrival date of the summer monsoon at Cox's Bazar. Comparison of the time series of the observed and predicted dates of the summer monsoon at Cox's Bazar are shown in figure 4. It appears that the absolute error between the observed and predicted dates of monsoon arrival varies from 0 to 9 days, with an average error of 5 days.

Once the arrival date of the summer monsoon at Cox's Bazar is predicted, then the arrival dates over the rest of the country can be projected by using the subsequent location of the isoline of the advancing monsoon, following the method described by AHMED &

Table 1

Index of monsoon arrival date at Cox's Bazar, Temperature Gradient Index (T.G.I.) between Rajshahi and Chittagong, predicted arrival date of the summer monsoon, and the absolute error between observed and predicted monsoon arrival date indices at Cox's Bazar during the 30-year period (1958-87)

Year	Monsoon Arrival Index (y_I)	Temperature Gradient Index (T.G.I.) between Rajshahi and Chittagong	Predicted Monsoon Arrival Index (y)	Absolute Error between y_I and y (days)
1958	48	M	—	
1959	23	M	—	
1960	37	M	—	
1961	28	M	—	
1962	25	M	—	
1963	34	M	—	
1964	29	2.800	23	6
1965	28	1.715	35	7
1966	42	M	—	—
1967	39	1.830	34	5
1968	11	3.800	12	1
1969	34	M	—	—
1970	23	2.270	29	6
1971	34	M	—	—
1972	43	1.279	40	3
1973	41	2.030	32	9
1974	27	1.750	35	8
1975	35	2.218	30	5
1976	35	1.740	35	0
1977	30	1.730	35	5
1978	36	1.873	34	2
1979	39	1.646	36	3
1980	27	1.860	34	7
1981	26	2.069	31	5
1982	40	1.840	34	6
1983	44	1.582	37	7
1984	32	1.460	38	6
1985	23	2.120	31	8
1986	43	1.131	42	1
1987	42	1.710	35	7

Note : M represents missing data.

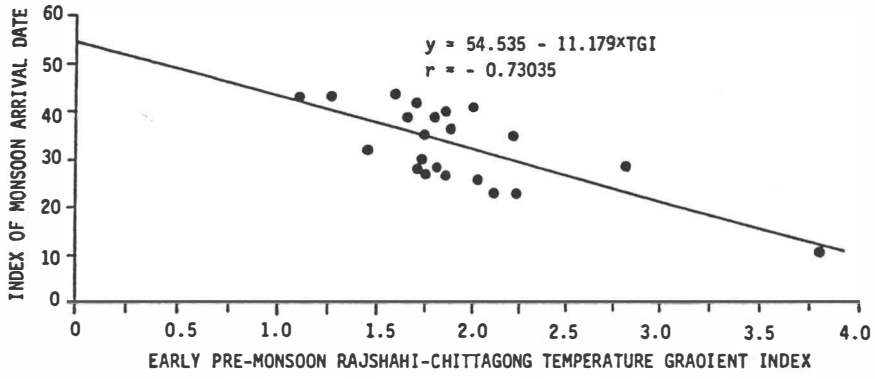


Fig. 3. — Relationship between the Index of Monsoon Arrival Date and Temperature Gradient Index between Rashahi and Chittagong during the early pre-monsoon season.

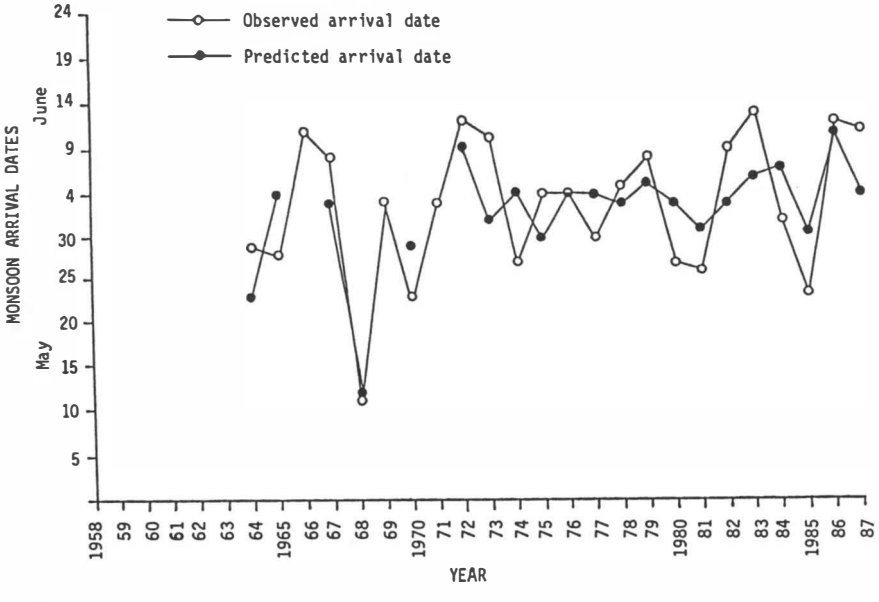


Fig. 4. — Comparison between the observed and predicted arrival dates of the summer monsoon at Cox's Bazar.

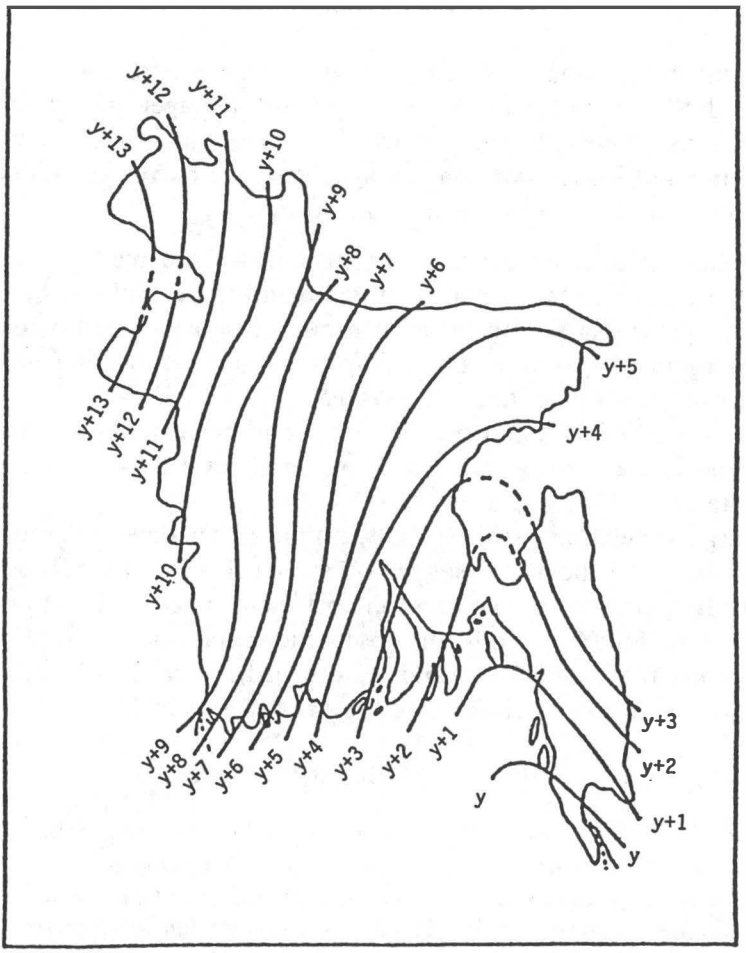


Fig. 5. — Spatial pattern of the predicted arrival dates of the summer monsoon in Bangladesh. The label y denotes the predicted arrival date of the summer monsoon at Cox's Bazar in a given year, and the labels y + 1, y + 2, etc. denote the progression of the predicted arrival dates after 1 day, 2 days, etc., since its arrival at Cox's Bazar.

KARMAKAR (1993). Spatial pattern of the predicted dates of the summer monsoon in Bangladesh has been shown in figure 5.

5. Conclusions

Results of an empirical study for the prediction of the monsoon arrival date in Bangladesh are presented in this paper. The difference between the observed and predicted monsoon arrival dates ranges between 0 and 9 days, with an average difference of 5 days. Important aspects of this study are summarized below :

1. It relies on meteorological parameters which are readily available in the country. Only mean daily temperature data of the first half of the preceding season (March through May) are needed for two stations only — one in the west-central interior location and the other in the south-eastern coastal area.
2. Arrival date of the summer monsoon in a given year can be predicted by the end of the second week of April (at least four weeks in advance).
3. A large correlation coefficient between the arrival date of the summer monsoon and the T.G.I. suggests a strong relationship between the two. But, perhaps the correlation coefficient (r) could be improved. Probably longer periods of observation and inclusion of other variables (*e.g.*, dew point and wind speed), in a stepwise multiple regression model, could be used for a better prediction.

REFERENCES

AHMED, R. 1989. Probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season. — *Indian Geographical J.*, **64** : 39-53.

AHMED, R. & KARMAKAR, S. 1993. Arrival and withdrawal dates of the summer monsoon in Bangladesh. — *International J. Climatology*, **13** (7) : 727-740.

BRAMMER, H. 1990. Floods in Bangladesh : Geographical background to 1987 and 1988 floods. — *Geographical J.*, **156** (1) : 283-296.

JOHNSON, B. L. C. 1982. Bangladesh. — Heinemann, London.

SPATE, O. H. K. & LEARMONTH, A. T. A. 1984. India and Pakistan : A General and Regional Geography. — Munshirakm Manoharilal Publishers, New Delhi (and South Asia Books, Columbia, Missouri, USA).

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 685-692 (1998)

L'enseignement en agrométéorologie pour les ressortissants des pays en voie de développement

par

Victor TONNARD * & Bernard TYCHON *

MOTS-CLES. — Agrométéorologie ; Enseignement ; Pays en développement.

RESUME. — Depuis 1979, la Fondation Universitaire Luxembourgeoise (Arlon, Belgique) organise une formation en agrométéorologie. Cette formation s'adresse aux agronomes et météorologues de niveau universitaire des pays en développement. Elle dure douze mois et est subsidiée par l'A.G.C.D., via l'O.M.M. qui propose les candidats. Les auteurs, responsables de cet enseignement, présentent la formation, en retracent l'évolution et en soulignent les originalités

TREFWOORDEN. — Agrometeorologie ; Onderwijs ; Landen in ontwikkeling.

SAMENVATTING. — *Het onderwijs in de agrometeorologie voor onderhorigen van landen in ontwikkeling.* — Sedert 1979 organiseert de „Fondation Universitaire Luxembourgeoise" (Arlon, België) een opleiding in landbouwmeteorologie. Deze opleiding richt zich tot landbouwdeskundigen en meteorologen van universitair niveau uit de ontwikkelingslanden. De opleiding duurt twaalf maanden en wordt gesubsidieerd door het ABOS via de W.M.O. die de kandidaten voordraagt. De verantwoordelijken van dit onderwijs presenteren de opleiding door het schetsen van de evolutie en het onderstrepen van de originaliteiten.

KEYWORDS. — Agrometeorology ; Education ; Developing Countries.

ABSTRACT. — *The Teaching of Agrometeorology for People from Developing Countries.* — Since 1979, the "Fondation Universitaire Luxembourgeoise" (Arlon, Belgium) has designed a course in agrometeorology intended for university graduates in agronomy and meteorology for developing countries. The programme lasts twelve months and is subsidized by the General

* Fondation Universitaire Luxembourgeoise, Agrométéorologie, av. de Longwy 185, B-6700 Arlon (Belgique).

Administration of Cooperation for Development (A.G.C.D.) via the World Meteorological Organization (W.M.O.) which selects the candidates. The authors in charge of the teaching programme outline the course and its updating and emphasize its originality.

Introduction

Dans leurs tentatives d'autosuffisance alimentaire, les P.V.D. sont tributaires des aléas météorologiques. En région tropicale, ils sont soumis à l'irrégularité des saisons sèches et pluvieuses. Les pays du CILSS sont, de plus, confrontés à la lente dégradation climatique actuelle. Dans ces conditions, il est inévitable que surgissent des périodes d'insuffisance alimentaire, voire de famine, avec leur cortège de souffrances, d'errance et de déstabilisation politique.

Il apparaît donc indispensable que ces pays organisent des centres agrométéorologiques opérationnels et efficaces pilotés par du personnel qualifié qui contribueront à prévoir et prévenir les risques de pénurie alimentaire. L'aide et le soutien des pays du Nord sont, dans ce domaine, indispensables.

«La prévention de la violence repose avant tout sur un effort à l'éducation et à la formation» rappelait le Secrétaire d'Etat R. Moreels lors d'un récent débat tenu à la Faculté des Sciences agronomiques de Gembloux (22.04.96). C'est dans cet esprit, pour améliorer d'éventuels services existants et pour créer une véritable «veille agrométéorologique», que l'O.M.M., à l'initiative d'anciens agents de l'INEAC, avec des fonds de l'A.G.C.D., organise une formation de haut niveau en agrométéorologie.

Historique

En 1979, forts de l'expérience agronomique et météorologique de la Belgique acquise dans son ancienne colonie, des scientifiques belges, proches de l'O.M.M. et de l'I.R.M., créent à la Fondation Universitaire Luxembourgeoise (Arlon), avec l'aide de l'A.G.C.D., un centre de formation en agrométéorologie. Plusieurs critères justifient cette implantation :

— Le caractère interuniversitaire de cette Fondation fait appel à des professeurs de plusieurs universités belges et étrangères et à des membres des instituts scientifiques nationaux ou privés. Ceci permet un choix de compétences particulièrement large.

— Sa multidisciplinarité convient particulièrement à l'agrométéorologie, science de synthèse.
— Dotée d'un système de fonctionnement très souple, la F.U.L. peut s'adapter à l'évolution rapide des besoins en agrométéorologie.
— Enfin, les chercheurs et enseignants de la F.U.L. sont des spécialistes de l'environnement, préoccupation à l'époque moins fréquemment répandue qu'à l'heure actuelle mais proche des démarches de l'agrométéorologie.

Le 1er octobre 1979, les premiers étudiants, fonctionnaires détachés des Services nationaux, se retrouvent à Arlon pour une première année académique. Depuis lors, et sans interruption, entre sept et quinze étudiants (Maîtrise et Certificat) séjournent chaque année à la F.U.L. Jusqu'à présent, cent cinquante-neuf étudiants répartis en quarante-trois nationalités ont fréquenté les auditoires de l'agrométéorologie : Afrique : 26 nations ; Asie : 5 nations ; Amérique latine : 6 nations ; Europe et Amérique du Nord : 6 nations.

En 1990, deux modifications importantes interviennent, suite aux recommandations de consultants extérieurs. Un *coordinateur* est désigné qui se préoccupera essentiellement du suivi scientifique des étudiants et veillera à la réalisation des projets pédagogiques décidés en réunion des enseignants. D'autre part, on crée le poste d'*assistant permanent* occupé par un ingénieur-docteur qui, au contact *journalier* des étudiants, les assiste dans les travaux pratiques, les oriente dans les recherches bibliographiques, les aide à assimiler les principes, les théories, les techniques indispensables à une activité scientifique d'un certain niveau.

La formation est actuellement intégrée aux trois autres orientations assurées par la F.U.L. Elle est sanctionnée, pour les maîtrisants, par un diplôme D.E.S.

Organisation

La formation est accessible à deux niveaux :

— *La Maîtrise (D.E.S.)* s'adresse aux détenteurs (agronomes, biologistes, géographes) d'un diplôme Bac + 4 ou météo classe 2. Elle dure une année académique (de septembre à juin) mais douze mois en pratique.
— *Le Certificat* s'adresse aux détenteurs d'un diplôme Bac + 3 ou météo classe 3 minimum. Il dure six mois (de janvier à juin).

Les deux niveaux reçoivent les enseignements suivants :

— Initiation multidisciplinaire à l'environnement ;
— Cours généraux et spécialisés en agrométéorologie ;
— Cours complémentaires d'agronomie ou de météorologie selon la formation initiale ;
— Entraînement intensif à la mesure, la collecte et au traitement des données chiffrées et imagées ;
— Travaux pratiques de terrain, excursions, visites didactiques de sites ou laboratoires ;
— Un travail de fin d'étude est demandé aux maîtrisants.

Ces enseignements sont dispensés par une dizaine de professeurs venus des universités francophones et des institutions scientifiques du pays.

On rappelle qu'un coordinateur supervise la formation et qu'un assistant est quotidiennement à disposition des étudiants.

De plus, le parc didactique comprend : stations météo manuelles et automatiques, batterie d'ordinateurs et imprimantes, imagerie satellitaire (capture et traitement), parcelles d'analyses phénologiques, bibliothèque, salles de lecture et de travail.

Pédagogie

Ce n'est un secret pour personne que, dans les P.V.D., la formation scientifique de niveau universitaire est hétérogène, voire hétéroclite. Bien que recrutée en principe parmi les meilleurs éléments des Services nationaux, notre population étudiante n'échappe pas à cette réalité. Si la formation professionnelle est souvent satisfaisante, beaucoup n'ont que des connaissances très fragmentaires dans des domaines cependant très proches.

Un météorologue ignore presque tout des bases physiologiques et des pratiques de l'agronomie ; un agronome a peu de notions de la physique de l'atmosphère. Des pans entiers de formation sont à édifier sur des bases qu'il faut, au préalable, renforcer.

Il faut encore admettre et tenir compte de ce que ces auditeurs, envoyés en formation intensive après plusieurs années de service dans des administrations parfois déficientes, ont un certain âge et mettent du temps à reprendre le rythme d'un travail intellectuel exigeant et soutenu.

Comment compenser rapidement ces lacunes de formation avec un auditoire si particulier? C'est le défi pédagogique, d'ailleurs passionnant, que doivent relever enseignants, coordinateur et assistant. Depuis 1979, les approches didactiques ont profondément changé. Elles évoluent encore chaque année à la lumière des succès ou échecs rencontrés.

Ce n'est pas ici le lieu de détailler ce point important qu'est la pédagogie à développer dans ces conditions. Cependant, l'un de nous (V.T.), après une carrière pédagogique de quarante ans devant de tels auditoires, souhaite vivement qu'un séminaire ou un colloque rassemble ceux qui vivent cette pratique. Il y a beaucoup à faire et à corriger en ce domaine, à la veille d'une ère où se multiplieront les transferts technologiques.

Un autre défi de taille est l'évolution des matières à présenter. Certes, les bases de la physiologie animale ou végétale restent semblables au cours des années ; il en est de même pour les bases de la physique de l'atmosphère, de la physique des sols ou des statistiques descriptives. Des sciences plus appliquées comme la phytopathologie, le calcul des rations alimentaires, l'inférence statistique évoluent déjà plus rapidement.

Mais l'intrusion des techniques informatiques et des applications électroniques a créé de tout nouveaux outils qu'il importe de présenter, de démystifier et d'apprendre à manipuler. Installation et maintenance des stations automatiques, exploitation des logiciels généraux et spécialisés, gestion des données, analyse des images satellitaires sont des sujets à présenter pour préparer et soutenir d'ultérieurs efforts de transferts.

Les banques de données

Ceci nous amène à parler de la présentation des banques de données et logiciels y afférents. Ce point est l'un des plus évolutifs dans la formation.

Le projet I.D.C.C. a, selon nous, rempli une mission d'un inestimable intérêt : sauver, sous forme cohérente et standardisée, les archives météorologiques éparses dans les caves ou hangars des services nationaux des P.V.D. Pendant des décennies, les climatologues rendront grâce à cette initiative de l'I.R.M.

Pour que cette sauvegarde se prolonge au profit des données actuelles, il reste à sensibiliser et former les météorologues et singu-

lièrement les agrométéorologues à l'archivage électronique des données sous forme exportable, exploitable et cohérente.

Si, en amont de la constitution de ces banques, nous devons former les étudiants à la saisie et l'archivage (stations automatiques, capteurs, transmission, stockage), nous devons aussi, à l'aval, les former à l'exploitation de celles-ci et surtout à l'exploitation raisonnée. En effet, le développement explosif et la convivialité sans cesse croissante des logiciels généraux et spécialisés sont générateurs d'une exploitation aveugle conduisant à des résultats aberrants quoique apparemment corrects si on ne se réfère régulièrement et rigoureusement qu'aux bases théoriques de manipulation des données. Or, en ce domaine, la matière est à la fois diffuse et confuse.

Le format des bases n'est pas standardisé et les exportations et importations sont parfois malaisées. C'est la règle pour les bases climatologiques, pédologiques, économiques, agro-alimentaires ou de télédétection. En 1993, une réunion des experts de la FAO a déjà souligné ce fait (FAO 1995).

Les logiciels standard (Quattro, Excel, Lotus, Multiplan, Works, etc.) sont nombreux et conviviaux. Mais ils sont encore limités dans les possibilités d'importation et de traitements statistiques (mentionnons, en passant, la disparition de Graph-in-the-Box qui semblait pourtant promis à un beau développement).

Les logiciels spécialisés sont soit commerciaux (Minitab, TableCurve, Statistix, Idrisi, Tosca), très conviviaux, performants mais peu utilisés par les techniciens des P.V.D., soit distribués par la FAO ou l'O.M.M. (Clicom, Instat, Faostat, Faomet, Ecopro, Ida, etc.). A leur sujet également, la dernière réunion des experts tenue à Rome par la FAO a reconnu l'urgence d'un effort de standardisation.

Devant cette profusion, un peu anarchique, les formateurs doivent garder à l'esprit que toute exploitation efficace et fiable passe par une maîtrise suffisante en statistique et en informatique. Il est indispensable d'asseoir solidement ces bases. Un lieu de formation comme celui de la F.U.L. peut constituer un site privilégié en ce domaine. La durée de formation et le public-cible, scientifiquement et politiquement placé à des postes importants, nationaux ou internationaux, sont des atouts à exploiter. Un tel centre pourrait même servir de champ de test pour les entreprises publiques ou privées qui élaborent de nouveaux produits.

Projets et conclusions

Parce qu'elle est un projet pédagogique, la formation en agrométéorologie a évolué et évoluera sans cesse. D'année en année, elle a abandonné un caractère quelque peu académique pour s'orienter vers une formation pratique, consciente des réalités des P.V.D. et soucieuse de préparer les transferts technologiques. Pour ce faire, elle a bénéficié de l'expérience de collaborateurs chevronnés issus des universités, des facultés d'agronomie, des institutions nationales et internationales. Ils connaissaient bien le contexte africain pour l'avoir vécu. Mais encore et surtout, il faut et gérer le présent et préparer l'avenir qui s'annonce plein de bouleversements.

Si on suit les prévisions, très optimistes mais plausibles, de KHALILII & MELLAERT (1996) ou les possibilités présentées par BOUMAN (1995), on doit préparer les agrométéorologues à de rapides et profondes modifications dans l'acquisition et l'exploitation des données. Dans ce domaine, toute une série de techniques existent qui ne sont pas encore ou peu exploitées :

— Le développement des stations automatiques est inéluctable et il faudra prévoir les modes de passage du manuel aux méthodes électroniques. On en est à ce stade dans nos pays et la manière de gérer cette conversion sera un enseignement pour les P.V.D.
— L'acquisition, le traitement et la dissémination se feront en temps réel, ce qui sera significatif pour la phase de contrôle.
— Les S.I.G. seront de plus en plus fréquemment utilisés aux fins d'extrapolation si importante en agrométéorologie et en dissémination.
— Les données seront calibrées, croisées et exploitées en temps réel ; l'indice NDVI de ARTEMIS est un précurseur en ce domaine.
— L'affinement des modèles permettra les prévisions de rendement à plus long terme.
— Les possibilités interactives d'Internet et des E-mails seront exploitées plus largement.

Une large panoplie d'outils s'ouvre donc pour l'agrométéorologue qui aura la chance de travailler dans le cadre des institutions internationales.

Par contre, quoique connaissant l'existence, les possibilités et les limites de ces techniques évoluées, l'ingénieur ou le technicien rivé à son poste local, limité par le politique et les financements régionaux,

confronté aux difficultés de contact avec le paysannat, continuera longtemps encore à devoir se contenter de moyens que d'aucuns qualifieront d'archaïques. Notre enseignement devra toujours tenir compte de cette double réalité.

Pour répondre aux besoins actuels et futurs de la coopération et améliorer les conditions de transfert technologique, les responsables du Projet «enseignement en agrométéorologie» proposent d'engager en outre un partenariat avec le centre Agrhymet de Niamey (Niger).

Avec l'accord de l'A.G.C.D. et de l'O.M.M., deux missions ont déjà, sur place, établi un projet de formation jumelée, d'échange d'enseignants et de recherches appliquées complémentaires. Le politique décidera de la viabilité de cette proposition.

Ce politique devra aussi tenir compte de ce que, si l'enseignement évolue rapidement comme nous l'avons montré, deux faits restent constants :

— Le rendement scientifique de la formation est plus que satisfaisant, puisque au moins 75 % des anciens étudiants restent dans le domaine de l'agrométéorologie. Ce sont des fonctionnaires détachés qui réintégreront leur département.
— Parmi ceux-ci, beaucoup occupent actuellement des postes à hautes responsabilités dans des services qu'ils ont souvent créés eux-mêmes. Dans bien des pays, ce sont ces cellules agrométéorologiques qui représentent la plus grosse part de l'activité scientifique des Services nationaux et — à côté des travaux de routine — leur raison d'être.

Ce faisant, l'enseignement de l'agrométéorologie à la F.U.L. continuera à maintenir l'image de marque de la Belgique dans un domaine où elle fit école, domaine très étroitement lié à la vie économique, sociale et politique des jeunes nations et à nos relations avec elles.

BIBLIOGRAPHIE

BOUMAN, B. A. M. 1995. Crop modelling and remote sensing for yield prediction. — *Neth. Journal of Agric. Science*, **43** : 143-162.

FAO 1995. Coordination and Harmonisation of Databases and Software for agroclimatic applications, Working Paper no. 13.

KHALILII, A. & MELLAART, E. A. R. 1996. Towards an object-based, GIS-linked meteorological data organization for agriculture in third world countries.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 693-709 (1998)

Water Scarcity and Sustainable Agricultural Development in the Drought-prone Semi-Arid Zone of West Africa

by

Daniel Davou DABI * & William ANDERSON *

KEYWORDS. — Agriculture ; Drought-prone ; Economy ; Environment ; Resources ; Rural ; Scarcity ; Sustainable ; Water.

ABSTRACT. — This paper considers the potential water availability for sustainable agricultural development in drought-prone areas of West Africa. It provides overviews of hydro-climatological characteristics of the region, land-use practices, and technological development. The first (rainfall, streamflow and groundwater) provides valuable information on water resources availability while the latter two provide the necessary information on human activity and its effect on the environment. Five different conditions responsible for the increasing severity of water scarcity are identified : aridity and intermittent droughts, attributed to climatic change and natural environmental conditions ; land degradation ; population growth ; and weak economic, institutional and technological bases. These conditions are viewed to be mutually inclusive and operating in a form of vicious circle. A survey of human activities from a selected rural area in semi-arid northern Nigeria supports this assertion. It is concluded that within the existing climatic, environmental and human conditions, these areas will experience severe water scarcity, unsustainable agricultural development, and subsequent food and economic insecurity unless stringent water and environmental management strategies are developed. The paper suggests an integrated (multidisciplinary) approach to ensure sustainable agricultural development in the area.

MOTS-CLES. — Agriculture ; Sensibilité à la sécheresse ; Economie ; Environnement ; Ressources ; Rural ; Rareté ; Durable ; Eau.

RESUME. — *Pénurie d'eau et développement agricole durable dans les régions sensibles à la sécheresse en Afrique de l'Ouest semi-aride.* — Cet article

* Department of Geography, McMaster University, Hamilton, Ontario L8S 4K1 (Canada).

considère la disponibilité potentielle de l'eau pour le développement agricole durable dans les régions sensibles à la sécheresse de l'Afrique de l'Ouest. Il donne des vues d'ensemble des caractéristiques hydro-climatiques de cette région, des pratiques de l'usage de la terre et du développement technologique. La première (pluie, cours d'eaux et eaux souterraines) donne des informations importantes sur la disponibilité des ressources en eau nécessaires pour l'agriculture, tandis que les deux autres procurent des informations nécessaires sur l'activité humaine et ses effets sur l'environnement. Cinq conditions différentes sont tenues pour responsables du manque accru d'eau : l'aridité et les sécheresses intermittentes, attribuées aux changements de climat et aux conditions naturelles de l'environnement ; la dégradation de la terre ; la croissance de la population ; et des bases économiques, institutionnelles et technologiques faibles. Ces conditions sont considérées comme étant mutuellement incluses et exploitables sous forme de cercle vicieux. Une enquête des activités humaines dans une région rurale du nord-est du Nigeria semi-aride confirme cette assertion. Il est conclu que, dans les conditions climatiques, environnementales et humaines existantes, ces régions subiront de graves pénuries d'eau, un développement agricole non durable et une insécurité alimentaire et économique subséquente, à moins que des stratégies rigoureuses de gestion de l'eau et de l'environnement soient développées. Cet article propose une méthode intégrée (multidisciplinaire) pour assurer un développement agricole durable dans la région étudiée.

TREFWOORDEN. — Landbouw ; Droogtegevoelig ; Economie ; Milieu ; Rijkdommen ; Platteland ; Zeldzaamheid ; Duurzaam ; Water.

SAMENVATTING. — *Schaarste aan water en duurzame landbouwkundige ontwikkeling in de droogtegevoelige semi-aride zone van West-Afrika.* — Dit artikel bespreekt de mogelijke beschikbaarheid van water, voor langdurige landbouwkundige ontwikkeling in de droogtegevoelige gebieden in West-Afrika. Het geeft overzichten van de hydro-klimatologische kenmerken van het gebied, de manier waarop het land gebruikt wordt, en de technologische ontwikkeling. Het eerste (regen, rivieren en grondwater) geeft waardevolle informatie over de beschikbaarheid van water dat nodig is voor landbouw, terwijl de laatste twee noodzakelijke informatie verschaffen over de menselijke activiteiten en hun effect op het milieu. Vijf verschillende omstandigheden worden verantwoordelijk geacht voor het verergeren van het watergebrek. Deze zijn dorheid en afwisselende droogtes, als een gevolg van klimaatveranderingen en natuurlijke milieu-omstandigheden ; degradatie van het land ; bevolkingstoename ; en een zwakke economische, institutionele en technologische basis. Deze omstandigheden worden gezien als elkaar omvattend en werkende in een vicieuze cirkel. Een onderzoek naar de menselijke activiteiten in een geselecteerd landelijk gebied in semi-aride noord-oostelijk Nigeria bevestigt deze constatering. Het staat vast dat binnen de bestaande klima-

tologische, milieu- and menselijke omstandigheden, deze gebieden met een gebrek aan water, een onstabiele landbouwkundige ontwikkeling en, daaruitvolgend, voedings- en economische onzekerheden zullen geconfronteerd worden tenzij strenge water- en milieubeheerstrategiëen worden ontwikkeld. Dit artikel stelt een integrale (multidisciplinaire) benadering voor om een langdurige landbouwkundige ontwikkeling in dit gebied te verzekeren.

1. Introduction

Sub-tropical regions of the world have marked dry and wet climatic conditions and experience drought-related problems, aridity and water scarcity. FALKENMARK (1989) observed that most of the less developed countries (LDCs) are located in the water-scarce regions of the tropics and subtropics (arid and semi-arid regions, ASA). They have three basic characteristics : (i) located where water is scarce for most or part of the year ; (ii) experience intermittent drought years ; and (iii) experience a high evaporative demand, which prevents much rainfall from being used for human activities (FALKENMARK & LINDH 1993, CLARKE 1993). A larger part of the African continent, including the semi-arid (Sahelian) belt of West Africa, which depends on agriculture, lies in this zone where most of the year is arid with recurrent droughts which severely impede agriculture.

The impact of the intermittent droughts, particularly those of 1968-1973 and 1984-1985, coupled with rapid population growth in the arid and semi-arid (ASA) regions of Africa, have led to severe water shortages, environmental degradation and the consequent outcry for food security in the affected areas. However, food aid and other relief measures from various international donor agencies have not solved the problem. This has necessitated more internal investigations of Africa's water scarcity problems using micro-scale approaches (RUDDLE & RONDINELLI 1983, FALKENMARK *et al.* 1989).

This paper reviews issues of water scarcity in the ASA zone of West Africa and points to new research directions. An ongoing study of Katarko village in northern Nigeria is used to illustrate the problem of water-scarce regions and provide an example of a research agenda for addressing human-environment interactions using micro-scale and integrated approaches (see fig. 1).

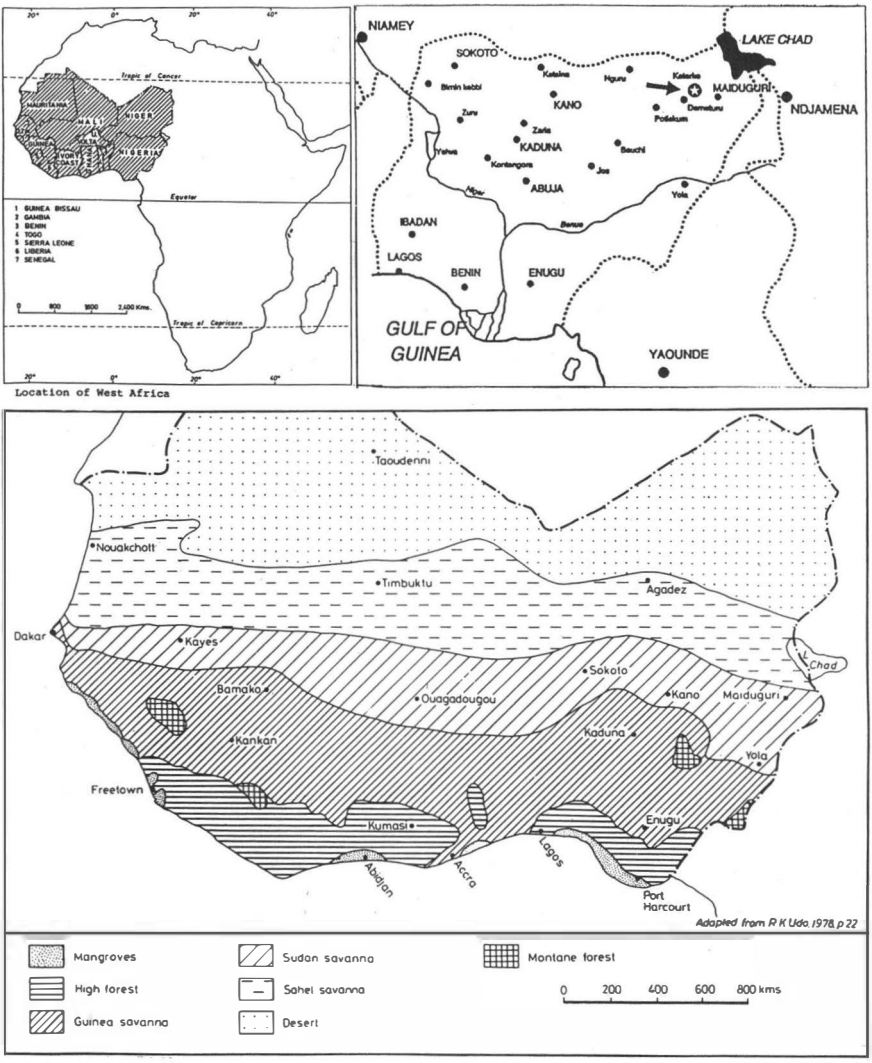


Fig. 1. — General reference map showing location of West Africa and study area.

2. Water Scarcity

Water scarcity is defined here as the difference between water availability and water demand. That is the shortfall in the amount of water available for human use. Significant water shortages (shortfalls) in most parts of Africa led the United Nations at the end of 1984 to declare most of sub-Saharan Africa as countries lying within the verge of aridity and to be suffering from "abnormal food shortages". However, as CLARKE (1993) rightly argues, the real truth is that Africa was not so much short of food as of water. Although this water scarcity was related to droughts, controversial but exceptional meteorological events, water shortage in much of Africa and elsewhere is not exceptional but endemic, a part of everyday life (FALKENMARK 1989).

2.1. WATER AVAILABILITY

There are three basic sources of water for human use : rainfall, streamflow and groundwater. These can be assessed through meteorological, hydrological and geologic surveys, and water balance studies (MUTISO & THOMPSON 1987). However, it is not the amount of water available in the seas or ground storages that determines the availability of water resources for withdrawal but the amount in circulation, that is freshwater flow in rivers and streams, and groundwater flow. The gross amount of water available can be divided into two categories : exogenous supply in cross boundary aquifers and rivers from upstream countries or regions, and endogenous supply through precipitation over the territory in question (FALKENMARK 1989).

FALKENMARK *et al.* (1989) and CLARKE (1993) identified four causes of water scarcity : (i) aridity as a permanent shortage of water caused by a dry climate ; (ii) droughts as an irregular phenomenon occurring in exceptionally dry areas ; (iii) desiccation as a drying-up of the landscape, particularly soil, resulting from activities such as deforestation and overgrazing ; and (iv) water stress which is due to increased *per capita* demand over fixed levels of water supply. These can be regrouped in two categories : the first two are climatic and the latter are due to human activity.

West Africa's mean annual rainfall varies from more than 3,500 mm in coastal (rainforest) areas of the south and south-west to less than 500 mm in the desert fringe of the north. Although its semi-arid zone is endowed with many river systems and lakes : notably the rivers Niger,

Senegal, the Gambia, and Volta, surface water (streamflow) is limited. This is because many of the rivers and tributaries traversing the region carry less water and easily dry up during the dry season due to high evaporative demand and siltation. The same problem in association with human activities is attributable to the shrinkage of Lake Chad in West Africa (HUTCHINSON *et al.* 1992). The region relies to a great extent on the groundwater found in fractures, joints and partially decomposed rocks (AGBOOLA 1979).

Studies have indicated a progressive decline in the availability of water in the region. For example, GLANTZ (1987) observed that desertification has occurred due to incidence of drought. WOO & TARHULE (1994) and HESS *et al.* (1995) reported the seasonality, reduction in duration and amount of rainfall in northern Nigeria (see fig. 2 and table 1). Similar conditions were explained for Sierra Leone (BAH 1987).

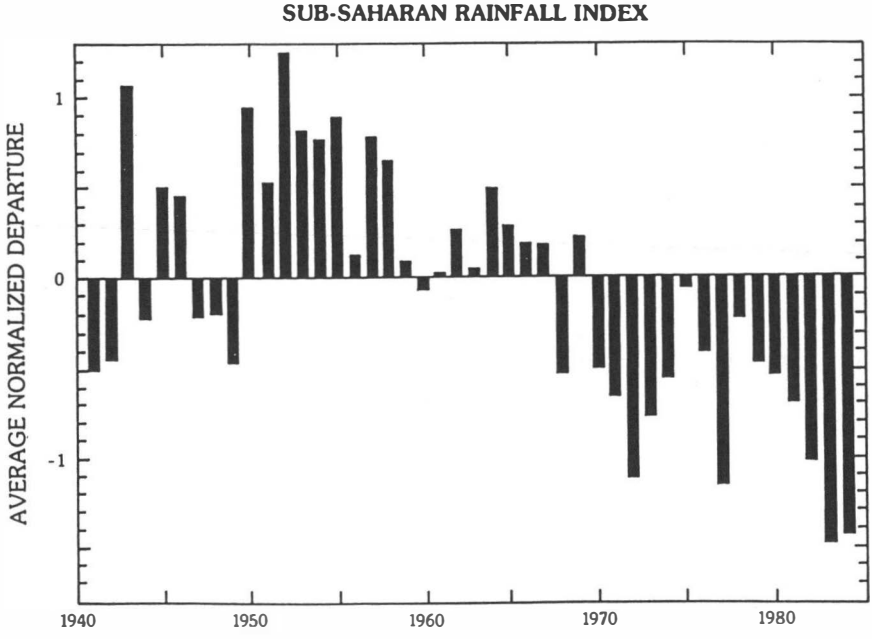


Fig. 2. — Rainfall index for 20 sub-Saharian stations in West Africa west o 10 E between 11 N and 19 N (developed by LAMB 1985). *Source* : GLANTZ (1987).

Table 1

Number of rain-days per year and average rain per day for 1961-1970, 1971-1980 and 1981-1990

Station	No rain-days			Mean rain per rain-day (m)		
	1961-1970	1971-1980	1981-1990	1961-1970	1971-1980	1981-1990
Potiskum	53	42	29	14.2	13.6	16.9
Maiduguri	47	35	30	12.0	14.1	12.5
Nguru	36	27	20	12.7	13.6	13.5
Maine Soroa	26	25	20	13.5	11.3	10.3

2.2. Water Demand

Water is demanded for three major functions : household (domestic), industrial and agricultural uses. Increasing water demand has been attributed to three major factors : rapid population growth ; increased consumption due to improved standards of living ; and expansion in water-related commodity production and service industries (United Nations 1976). Relating population growth and water scarcity, Falkenmark (1990) developed a hypothetical model on water availability and population size and constructed a global water scarcity index. By her projections, Nigeria, among other West African countries, would be experiencing "absolute" water scarcity by the year 2025. A situation beyond the limits of water stress resulting from excess demand over water availability from the water cycle.

3. Human Activities and the Environment

Agriculture (animal and crop production) is the predominant human and economic activity in the semi-arid zone of West Africa. It provides the means of livelihood (food) and employment for the ever-increasing population. The relative decline in *per capita* food production in this region (see figs. 3-4) may be attributed in part to the recurrent droughts experienced in the zone and partly to other "man-induced" problems as discussed below.

Sub-Saharan Africa suffers from endemic environmental problems which include deforestation, overgrazing, soil erosion, ecological degradation, and desertification. Although these are blamed on rapid population growth and poverty, there is no conclusive evidence to show that the people have been unconcerned with the quality of their environment. Rather, the problems are more insidious than meets the

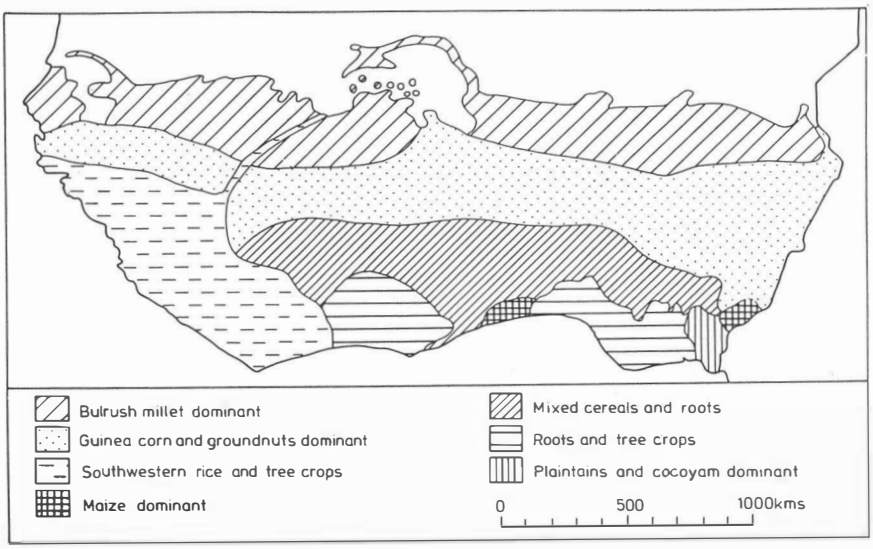


Fig. 3. — General pattern of crop production in West Africa.

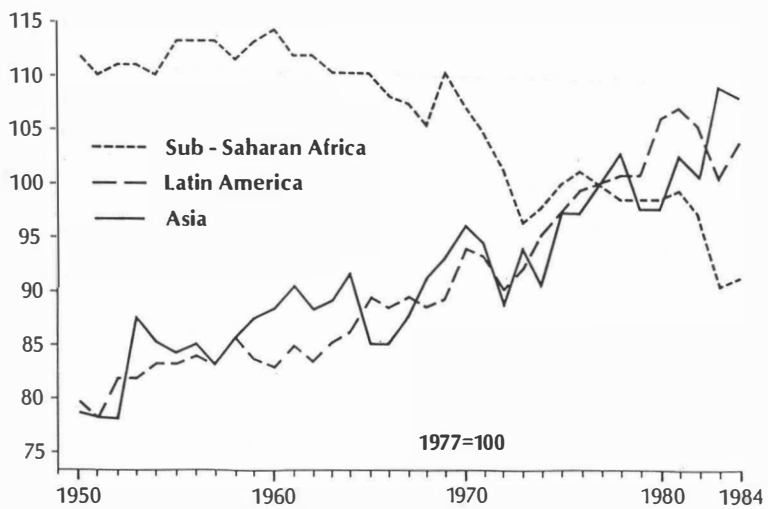


Fig. 4. — Regional trends in *per capita* food production. *Source* : GUTHRIE (1986).

eye. Three factors : population pressure, heavy foreign debt burden, and political instability have impeded economic development in the region. It is confronted with consequences of inappropriate policies, poor economies and managerial incapabilities, as well as an increasingly hostile external economic milieu. Poverty has forced families to develop simple but problematic survival strategies, overexploitation of natural resources : subsistence farming and grazing on marginal lands, overuse of surface water sources and wetlands, and fuelwood harvesting. Consequently, acute pressure is exerted on the environment leading to eventual degradation (World Bank 1989, MABOGUNJE 1995).

WATTS' (1987) review of the ecological context and conditions of operation, human knowledge and effort geared towards food production under environmental uncertainty, and the socio-political and economic changes in semi-arid West Africa, summarized as follows : "peasant knowledge and practice is overridden by forces that compel peasants and pastoralists to destroy their own environment in attempts to delay their own destruction".

3.1. SUSTAINABLE AGRICULTURE

Declining water availability in semi-arid West Africa has serious repercussions on the agricultural development of the area. Rainfed farming is adversely affected, while irrigated agriculture and animal rearing are facilitated only at locations accessible to surface and groundwater sources. Otherwise, up to eight months of the year become an idle period for most of the rural population, except for those engaged in other non-farm economic activities (rural industry). Therefore, the demand for water for agriculture, rural industry, and domestic uses exerts tremendous pressure on the limited water resources and the environment.

Because water is a major input in the agricultural sector, which provides employment and food to the rural and urban populations, water must be exploited to facilitate agriculture. But in order to avoid the stated repercussions, there is need for better management of water resources to enhance sustainable agriculture and rural development in this semi-arid environment. The question may then arise "How sustainable can agriculture be in the ASA areas of LDCs?" The lack of a precise definition of the concept of "sustainable development" makes the question difficult to answer. However, a considerable consensus has evolved in support of the main idea that it is both morally

and economically wrong to consider the world (natural resources) as a business liquidation (DALY 1991, CALDWELL 1994), and this implies an increasing consensus on the need for sustainable development (KUMAR *et al.* 1993).

A generally acceptable connotation of "agricultural sustainability" is feasible following DOUGLAS' (1984) work. He identified three schools of thought regarding agricultural sustainability: (i) the economists' viewpoint which is concerned with greater production efficiency and considers agriculture primarily as an instrument for food sufficiency; (ii) the ecological viewpoint that sees agriculture as being unsustainable because it depletes, pollutes, or disrupts the ecological balance of natural systems, but subscribes to ecological stewardship; and (iii) the "alternative" agriculturalists whose ideas are similar to the second group but promote vital and coherent rural cultures for environmental preservation. Compromising these schools of thought, Douglas conceptualized that "agriculture will be found to be sustainable when ways are discovered to meet future demands for foodstuff without imposing on society real increases in social costs of production and without causing the distribution of opportunities or incomes to worsen". However, it is evident that current production structures are unsustainable.

VAN KOOTEN (1993) quoted Hileman's definition of sustainable agriculture as follows:

> Sustainable agriculture is a system approach to farming that seeks to develop a multiyear practice that takes advantage of whatever is produced or can be produced on the farm, including naturally occurring beneficial biological interactions, to ensure soil fertility and keep losses from pest, weeds, animal diseases within acceptable levels. The aims are adequate productivity and profitability, conservation of resources, protection of the environment, and assured food safety (HILEMAN 1990, p. 27).

This definition seems to embrace the three schools of thought noted by Douglas (increased productivity, stewardship, and preservation) and tends to relate sustainability with conservation. It is also in line with the doctrines of sustainable development (World Commission on Environment and Development 1987). Therefore, it presents an acceptable definition of "agricultural sustainability" for use in this study.

4. Towards a Sustainable Agricultural Development

The growing concern over water scarcity and its effects on the world's population, particularly the developing countries, has called for better water management strategies. These have been viewed from different perspectives by various workers. For example GUSTAFSSON (1980) suggested an ecological approach to water management which incorporates spatial variability in both water availability and population distribution on a regional rather than global scale. MUTISO & THOMPSON (1987) advocated an integrated rural-water resource development management strategy through the determination of water balance. It provides qualitative information on water resources potential, including spatial and temporal distribution of untapped water resources, possible resource exploitation, and optimal utilization. FALKENMARK (1989) suggested an integrated soil-water-nutrient-vegetation conservation approach. And MITCHELL (1990) documented comprehensively the various approaches to integrated water management.

Since agriculture is still the predominant economic activity, the relationship between water and development is strong. Agriculture is the largest consumer of water and water is the most crucial input for agricultural production. Thus, water scarcity is a major impediment to agricultural development with a resultant food shortage and insecurity. In order to achieve sufficiency in food production, the available water resources have to be augmented for both rainfed and irrigated agriculture. This must be carried out in a manner which ensures agricultural sustainability without jeopardizing future food production. Unlike water-rich developing countries, especially south-east Asia, where improved crop varieties have been the major technological breakthrough in agricultural advancement, existing water management practices in irrigated agriculture, the only option for water deficit areas, must be ameliorated.

PRADHAN (1993) observed that irrigated agriculture is "a strategically important sector of the Nigerian economy" and the need for its expansion. Since this may lead to drastic increase in water demand within limited supply, it can only be sustained by good water management and conservation strategies. Most efforts at managing the water resources in the drier parts of developing countries have been through the construction of large-scale dams along major rivers for the provision of municipal water supply and irrigation development. Unfortunately, most of the river basin development projects, for

example the Sokoto Rima river basin development (Bakolori dam) project in Nigeria, have not performed to expectation due to managerial and institutional bottlenecks, and operational constraints among others (MITCHELL 1994). Rather, they have contributed to more environmental problems, degrading wetland ecosystems and depriving water to users downstream (ADAMS 1986, SCUDDER 1989, MABOGUNJE 1995).

Although small-scale irrigation initiatives have been introduced, they have faced similar problems with the large-scale schemes, particularly technological fixes (KIMMAGE 1991) and adverse effects on traditional activities (KIMMAGE & ADAMS 1992). However, many contributors have written in favour of small-scale irrigation projects and the need for farmer participation in decision-making (ADAMS 1986, GLADDEN & PHILLIPS-HOWARD 1992). Small-scale irrigation initiatives, if properly harnessed, will provide the most viable and sustainable agricultural development in this semi-arid zone. Efforts at rainwater harvesting and rainwater farming in water-scarce North and East Africa have been reported by ASSWAD (1995) and ARNTZEN (1995) respectively.

5. Case Study : Katarko Village

Katarko is a village of about 3,000 people located in semi-arid north-eastern Nigeria. Rainfall, streamflow, groundwater data for the village is not yet available. But it has similar environmental characteristics and human activities as the rest of northern Nigeria or the Sahel. Our literature suggests that most studies related to water resources in this region have been discipline-specific and more generalized. A multidisciplinary perspective and on a micro-scale has therefore been taken to investigate the situation in this area. This will facilitate an understanding of the direct and indirect effects of this man-environment relationship and measures adopted by the people in coping with declining water availability, declining agricultural productivity and degrading environment, towards sustainability.

The study investigates the nature of water demand in the entire economy with two main objectives : (i) establishing the relationship between the production of goods and services (commodities) and the use of ecological commodities (water, land and vegetation) in the economy ; and (ii) ascertaining the total water requirement (direct and indirect) of the different sectors of the economy (particularly in agricultural-related activities). In other words, determine the effect of

each activity on water availability, their impact on the environment and interrelationships in the local economy. This will be investigated using the model parameters and indigenous knowledge systems.

This approach follows the framework of the input-output (commodity-by-industry economic-ecological) model. It considers the interactions within the economic system and between it and the ecological system with particular reference to water. This framework facilitates the projection of water demand by estimating water requirements in the various use sectors. By incorporating the environmental (ecological) sector, the source of water and other environmental factors (ecological commodities) into the accounting system, it is possible to determine the total water requirement of the region (community) by means of computer simulations. Indigenous knowledge systems will help elucidate the nature of the problem and coping strategies. Under drought conditions, agricultural activities, for example, will be constrained due to water scarcity. Farmers may develop water conservation strategies or adopt new technologies. Under such circumstances, the production process will be affected and thus the technical coefficients of the model (use and make matrices). Consequently, the coefficients of the model will be adjusted to fit such changes (Dabi 1996).

Preliminary results from field data indicate that agriculture is the highest consumer of water compared to domestic and industrial uses in the village (see fig. 5). Agricultural water is demanded mostly for irrigated farming and for watering animals. Existing technologies for water collection, storage, delivery and use are basically traditional. Few dry season farmers use machines to pump water from wash bore-holes to irrigate swamp rice and wheat for external markets. Generally, crops grown are traditional market garden vegetables consumed locally. Olsson (1993) and Hess *et al.* (1995) indicated a close association between crop (grain) yield and the number of rainy days ; therefore, rainfed farmers who grow staple crops may be forced to engage in some form of irrigation if the rate of rainfall decline in the region continues.

The model described above is being constructed by the authors to determine the transactions between the economy and the environment with particular reference to agriculture and water use. The research requires further field investigations. Thus, a second field season aimed at developing scenarios of water-use efficiency has been scheduled for the next dry season.

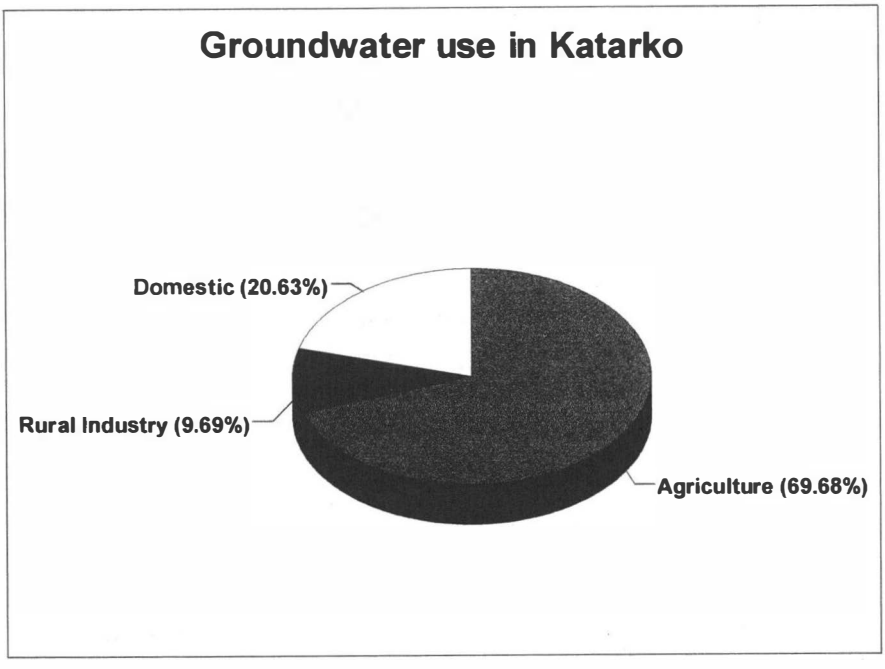


Fig. 5. — Pattern of water use in Katarko village, Nigeria. *Source* : Field survey (1995).

6. Concluding Remarks and Suggestions

This paper identifies five interrelated conditions of water scarcity as follows : (i) aridity, a permanent shortage of water caused by a dry climate ; (ii) droughts, irregular phenomena occurring in exceptionally dry areas ; (iii) desiccation, drying-up of the soil and landscape, due to deforestation and overgrazing ; (iv) water stress, due to increased *per capita* demand over fixed levels of water supply ; and (v) inaccessibility, due to adverse economic, institutional (socio-political and educational), and technological bases to harness and manage the potential water available. These can be regrouped into two ; the first two are climatic and the latter three man-made.

Further, the paper identifies three problems of unsustainable agricultural development and environmental degradation emanating from this water scarcity : (i) a relative decline in *per capita* food production ; (ii) continued poverty and food insecurity ; and (iii) endemic environ-

mental problems which include deforestation, overgrazing, soil erosion, ecological degradation, and desertification.

In order to achieve a sustainable agricultural development policy in the region, the following suggestions are advanced : (i) development of small-scale irrigation schemes and maintainance of relatively high but sustainable levels of productivity ; (ii) cultivation of drought resistant crop varieties with high-utility value, adaptable to the natural and socio-economic setting ; (iii) facilitate the use of local inputs, organic manures and other farm nutrients in order to optimize the rate of turnover and enhance the recycling of matter ; (iv) development and adoption of appropriate technologies suitable to meet the needs of farmers and pastoralists ; (v) development of rainwater harvesting and farming practices to maximize the use of water normally lost to evaporation ; (vi) encourage better water management strategies during withdrawal, storage, delivery and use ; (vii) establishment of an enabling political environment and will-power for and participation by the inhabitants ; and (viii) conduct micro-scale multidisciplinary research such as the one outlined for Katarko village to establish the possibility of attaining these suggestions. Authors of this paper are currently working along those lines. Their findings will be reported elsewhere.

ACKNOWLEDGEMENTS

This work has been supported by the Jos-McMaster drought and rural water-use project (funded by the Canadian International Development Agency) and the Department of Geography, McMaster University, Canada.

REFERENCES

ADAMS, W. M. 1986. Traditional agriculture and water use in the Sokoto valley, Nigeria. — *The Geographical J.*, **152** (1) : 30-43.

AGBOOLA, S. A. 1979. An Agroclimatological Atlas of Nigeria. — Oxford University Press, Oxford.

ARNTZEN, J. 1995. Economic instruments for sustainable resources management : the case of Botswana's water resources. — *Ambio*, **24** (1) : 7-15.

ASSWAD, R. M. 1995. Agricultural prospects and water resources in Libya. — *Ambio*, **24** (6) : 324-327.

BAH, O. 1987. Rural water supply development in Sierra Leone. — *Singapore Journal of Tropical Geography*, **8** (2) : 84-96.

CALDWELL, L. 1994. Sustainable development : viable concept and attainable goal? — *Environmental Conservation*, **21** (3) : 193-195.

CLARKE, R. 1993. Water : the international crisis. — The MIT Press, Cambridge, Massachusetts.

DABI, D. D. 1996. Water demand and use in the rural economy of a semi-arid environment : a northern Nigeria case study. — A Doctoral research proposal presented in the Dept. of Geography, McMaster Univ. (Hamilton, Canada, 22 September 1996), 36 pp.

DALY, H. E. 1991. The steady-state economy. — *In* : DOBSON, A. (ed.), The Green Reader. Andre Deutsch, pp. 145-151.

DOUGLAS, G. K. 1984. The meanings of agricultural sustainability. — *In* : DOUGLAS, G. K. (ed.), Agricultural Sustainability in a Changing World Order. Westview Press, Boulder, Colorado.

FALKENMARK, M. 1989. The massive water scarcity now threatening Africa : why is it not being addressed? — *Ambio*, **18** (2) : 112-118.

FALKENMARK, M. 1990. Rapid population growth and water scarcity : the predicament of tomorrow's Africa. — *In* : DAVIS, K. & BERNSTAM, M. (eds.), Resources, Environment and Population : present knowledge and future options, Oxford Univ. Press, New York, pp. 81-94.

FALKENMARK, M. & LINDH, G. 1993. Water and economic development. — *In* : GLEICK, P. H. (ed.), Water in crisis : a guide to world's freshwater resources. Oxford Univ. Press, Oxford, pp. 80-91.

FALKENMARK, M., LUNDQVIST, J. & WIDSTRAND, C. 1989. Macro-scale water scarcity requires micro-scale approaches : aspects of vulnerability in semi-arid development. — *Nat. Res. Forum*, **13** : 285-267.

GLADDEN, J. N. & PHILLIPS-HOWARD, K. D. 1992. Policy approaches to agricultural development in Nigeria : transfer of technology and farmer first. — Paper presented at the National Workshop on strategies for agricultural development (Univ. of Agric., Makurdi, April 8-10, 1992).

GLANTZ, M. H. 1987. Drought and Hunger in Africa : denying famine a future. — Cambridge Univ. Press.

GUSTAFSSON, Y. 1977. Variations in rainfall as a natural constraint on agriculture. — *Ambio*, **6** (1) : 34-35.

HESS, T. M., STEPHENS, W. & MARYAH, U. M. 1995. Rainfall trends in the North-Eastern Arid zone of Nigeria. — *Agric. & Forest Met.*, **74** : 87-97.

HILEMAN, B. 1990. Alternative agriculture. — *Chemical Engineering News*, **68** (March) : 26-40.

HUTCHINSON, C. F., WARSHALL, P., ARNOLD, E. J. & KINDLER, J. 1992. Development in arid lands : lessons from Lake Chad. — *Environment*, **34** (6) : 16-20, 40-43.

KIMMAGE, K. 1991. Small-scale irrigation initiatives in Nigeria : the problems of equity and sustainability. — *Appl. Geography*, **11** : 5-20.

KIMMAGE, K. & ADAMS, W. 1992. Wetland agricultural production and river

basin development in the Hadejia-Jama'are valley, Nigeria. — *The Geographical J.*, **158** (1) : 1-12.

KUMAR, R., MANNING, E. W. & MURCK, B. 1993. The Challenge of Sustainability. — Don Mills, Ont., Centre for a sustainable future, Foundation for training.

MABOGUNJE, A. L. 1995. The environmental challenges in sub-Saharan Africa. — *Environment*, **37** (4) : 4-9, 31-35.

MITCHELL, B. 1990. Integrated Water Management : international experiences and perspectives. — Belhaven Press, London.

MITCHELL, B. 1994. Addressing the "edge" problems in land and water management in the Sokoto-Rima river basin, Nigeria. — *Geoforum*, **25** (2) : 133-143.

MUTISO, S. K. & THOMPSON, R. D. 1987. Future water supply in the Machakos District of Kenya. — *Ambio*, **16** (6) : 322-325.

OLSSON, L. 1993. On the causes of famine - drought, desertification and market failure in the Sudan. — *Ambio*, **6** : 395-403.

PRADHAN, P. 1993. Research priority of irrigation in Nigeria. — *In* : NWA, E. & PRADHAN, P. (eds.), Proceedings of a National Seminar on irrigation research priorities for Nigeria (Univ. of Ilorin, Nigeria. IIMI, Kano), pp. 19-32.

RUDDLE, K. & RONDINELLI, D. A. 1983. Resources, environment, and development policy : a resource system framework. — *Resource Management and Optimization*, **3** (1) : 1-22.

SCUDDER, T. 1989. Conservation versus development : river basin projects in Africa. — *Environment*, **31** (2) : March, 1989.

United Nations 1976. The Demand for Water : procedures and methodologies for projecting water demands in the context of regional and national planning. — Nat. Resour./Water Series 3, New York.

VAN KOOTEN, G. C. 1993. Conservation and sustainable development. — *In* : VAN KOOTEN, G. C. (ed.), Land Resource Economics and Sustainable Development : economic policies and the common good. UBC Press, Vancouver, pp. 164-187.

WATTS, M. J. 1987. Drought, environment and food security : some reflections on peasants, pastoralists and commoditization in dryland West Africa. — *In* : GLANTZ, M. H. (ed.), Drought and Hunger in Africa : denying famine a future. Cambridge University Press, Cambridge.

WOO, M.K. & TARHULE, A. 1994. Streamflow droughts of northern Nigerian rivers. — *Hydrol. Sciences J.*, **39** (1) : 19-34.

World Bank 1989. Sub-Saharan Africa : from crisis to sustainable development : a long-term perspective study. — World Bank, Washington, D.C., 22 pp.

World Comm. on Environment & Development 1987. Our Common Future. — Oxford Univ. Press, Oxford.

SUSTAINABLE DEVELOPMENT

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 713-729 (1998)

The Convention on Biological Diversity and the Role of the Royal Belgian Institute of Natural Sciences in Biodiversity Research

by

Jackie VAN GOETHEM *

KEYWORDS. — Biodiversity Research ; Biology ; Convention on Biological Diversity ; Royal Belgian Institute of Natural Sciences.

ABSTRACT. — In 1987, the Governing Council of the United Nations Environment Programme recognized the need to increase and streamline international efforts to protect biological diversity. After many sessions of different bodies and strong negotiations, the Convention on Biological Diversity was opened for signature at the United Nations Conference on Environment and Development, on 5 June 1992, in Rio de Janeiro, Brazil. The Convention came into force on 29 December 1993. A brief history of the Convention and of the preliminary work which led to the First Conference of the Parties at the end of 1994 is given. The character of the Convention is briefly analysed while some definitions of biodiversity are mentioned and commented. Initiatives taken on a broad scale and with worldwide impact are summarized. Finally, many aspects of biodiversity research at the Royal Belgian Institute of Natural Sciences are highlighted. In 1995, this Institute was commissioned as the Belgian National Focal Point to follow up activities for the United Nations Convention on Biological Diversity.

MOTS-CLES. — Recherche en biodiversité ; Biologie ; Convention sur la diversité biologique ; Institut royal des Sciences naturelles de Belgique.

RESUME. — *La Convention sur la diversité biologique et le rôle de l'Institut royal des Sciences naturelles de Belgique dans la recherche sur la biodiversité.* — En 1987, le Conseil directeur du Programme des Nations Unies pour l'environnement (PNUE) a reconnu le besoin d'augmenter et de modeler les efforts internationaux pour protéger la diversité biologique. Après maintes

* Department of Invertebrates, Royal Belgian Institute of Natural Sciences, Vautierstraat 29, B-1000 Brussels (Belgium).

sessions de corps divers et des négociations difficiles, la Convention sur la diversité biologique fut soumise à la signature lors de la Conférence des Nations Unies sur l'Environnement et le Développement (CNUED), le 5 juin 1992, à Rio de Janeiro au Brésil. La Convention entra en vigueur le 29 décembre 1993. Une histoire brève de la Convention et du travail préliminaire qui a mené à la première Conférence des Parties est relatée. Le caractère de la Convention est analysé brièvement en mentionnant et en commentant quelques définitions de la biodiversité. Des initiatives prises à grande échelle et à impact mondial sont résumées. Finalement, des aspects de recherche en biodiversité à l'Institut royal des Sciences naturelles de Belgique sont mis en valeur. En 1995, cet Institut fut désigné comme le point focal national belge pour le suivi de la Convention des Nations Unies sur la diversité biologique.

TREFWOORDEN. — Biodiversiteitsonderzoek ; Biologie ; Verdrag inzake biologische diversiteit ; Koninklijk Belgisch Instituut voor Natuurwetenschappen.

SAMENVATTING. — *Het verdrag inzake biologische diversiteit en de rol van het Koninklijk Belgisch Instituut voor Natuurwetenschappen in onderzoek over biodiversiteit.* — In 1987 erkende de Administratieve Raad van het Milieuprogramma van de Verenigde Naties de noodzaak om de internationale inspanningen om de biologische diversiteit te beschermen, te verhogen en te coördineren. Na vele vergaderingen van verschillende instanties en moeilijke onderhandelingen werd het Verdrag inzake biologische diversiteit geopend ter ondertekening op de Conferentie van de Verenigde Naties over Milieu en Ontwikkeling, op 5 juni 1992 in Rio de Janeiro, Brazilië. Het Verdrag trad in werking op 29 december 1993. Er wordt een kort overzicht gegeven van het Verdrag en het voorafgaandelijk werk dat heeft geleid tot de Eerste Conferentie van de Partijen eind 1994. De aard van het Verdrag wordt kort geschetst terwijl sommige definities van biodiversiteit worden aangehaald en becommentarieerd. Initiatieven genomen op een brede schaal en met wereldwijde impact worden opgesomd. Ten slotte worden vele aspecten van het onderzoek over biodiversiteit op het Koninklijk Belgisch Instituut voor Natuurwetenschappen in de verf gezet. In 1995 werd dit Instituut aangesteld als het Nationaal Belgisch Knooppunt om de activiteiten onder het Verdrag van de Verenigde Naties inzake biologische diversiteit op te volgen.

1. The Crisis

Simply defined, biological diversity, or *biodiversity*, is the total sum of all life forms on Earth. It is the variety and the variability of all species of plants, animals and micro-organisms, as well as the ecosystems they are part of. Some twenty-two ecological processes provided by

biodiversity, such as oxygen production, water purification, nitrogen fixation, erosion control, decomposition and humus production, serve and sustain our lives in countless ways. Also, biodiversity provides enormous direct and indirect economic benefits. In agriculture, disease- and pest-resistant crop varieties are continually derived from wild relatives of domestic crops. Nearly half the prescriptions worldwide are for medicines based on compounds extracted from wild plants, animals, or micro-organisms. Other major resource-based industries, such as forestry, fisheries and tourism, depend heavily on biodiversity. And local and indigenous communities throughout the world depend on biological resources for their sustenance and traditional lifestyles.

Tragically, the Earth's biological diversity is being lost at a rate unprecedented in human history. Leading scientists predict that at current rates of extinction, the Earth could lose about 20 % of all its living species by the year 2020 and about 50 % two or three decades later. Moreover, losses of species and ecosystems are being accompanied by dramatic losses of genetic diversity within species. Also, activities causing biodiversity loss take a tremendous toll on communities living close to these resources and relying on them for daily needs. The primary causes underlying the loss of biodiversity are well known : they are demographic, economic, political and technological.

The fact that biological diversity is unevenly distributed around the globe is also important : the North, biologically poorer, has depleted its biodiversity reserves over time, but such reserves are still found in the biologically rich South. If biodiversity is to be conserved, this imposes a heavier burden on the South, at a time when the use of biological resources is of utmost importance for developing countries in achieving development. This burden, in turn, can only be alleviated by additional contributions (not only financial) from the industrialized North and through increased partnership between both developed and developing countries (IUCN 1993).

2. Brief History of the Convention on Biological Diversity

2.1. *Ad hoc* Working Group of Experts on Biological Diversity

Long before the governmental negotiations began under the United Nations Environment Programme (UNEP), international experts had been promoting the idea of a global convention on biodiversity.

Following recommendations from its General Assemblies in 1984 and 1987, The World Conservation Union (I.U.C.N.) had been

exploring the possibilities for a treaty on the subject, and had prepared successive drafts of articles for inclusion in a treaty.

In 1987, the UNEP Governing Council recognized the need to increase and streamline international efforts to protect biological diversity. It therefore established an *Ad hoc* Working Group of Experts. The first meeting of the group in November 1988 concluded that the existing conventions addressed specific questions of biodiversity conservation but did not adequately meet the needs of conserving biodiversity worldwide. At the global level, the existing conventions covered only : internationally important natural sites (the World Heritage Convention), the specific threat of trade in endangered species (CITES or the Washington Convention), a specific ecosystem type (the Ramsar or Wetlands Convention) and a group only of species (the Migratory Species Convention or the Bonn Convention).

By the summer of 1990, a new "Sub-Working Group on Biotechnology" was established to prepare terms of reference on biotechnology transfer. Other aspects of biodiversity were included, such as *in situ* and *ex situ* conservation of wild and domesticated species, access to genetic resources and technology, including biotechnology, new and additional financial resources, and safety of release or experimentation on living genetically-modified organisms (L.M.O.'s), also known as "biosafety".

2.2. Intergovernmental Negotiating Committee

By February 1991, the former *Ad hoc* Working Group had become known as the Intergovernmental Negotiating Committee (I.N.C.). After many sessions and very difficult, hardly progressing negotiations its work culminated on 22 May 1992 with the Nairobi Conference in Kenya for the adoption of the final text of the Convention on Biological Diversity (the Nairobi Act).

The Convention on Biological Diversity was opened for signature at the United Nations Conference on Environment and Development (UNCED), the so-called Rio Earth Summit in Brazil, on 5 June 1992. It remained open for signature for one year, by which time it had received 168 signatures. The Convention came into force on 29 December 1993, which was 90 days after the 30th ratification.

To date, September 1996 at the time this text was submitted for printing, 158 Parties — 157 countries and the European Union — have ratified the Convention, which contains three national level obligations :

— The conservation of biological diversity ;
— The sustainable use of its components ;
— The fair and equitable sharing of the benefits arising out of the utilization of genetic resources.

2.3. Intergovernmental Committee on the Convention on Biological Diversity (I.C.C.B.D.)

In May 1993, UNEP's Governing Council established the Intergovernmental Commission on the Convention on Biological Diversity to prepare for the first meeting of the Conference of the Parties and to ensure effective operation of the Convention upon its enforcement.

The I.C.C.B.D. met in two sessions, the first one in October 1993, the second one in June 1994. The negotiations suffered from conflicting points of view between the South and the North. Some progress was only made on pure technical issues, such as : rules of procedure, the Subsidiary Body on Scientific, Technical and Technological Advice (S.B.S.T.T.A.) and the Clearing-House Mechanism (C.H.M.).

2.4. First Conference of the Parties

The first meeting of the Conference of the Parties (COP-1) took place in Nassau, the Bahamas, from 28 November until 9 December 1994. During the course of the meeting, delegates reached agreement on basic machinery for the Convention's implementation. Some of the key decisions taken by COP-1 included : adoption of the medium-term work programme, designation of the Permanent Secretariat, establishment of the Clearing-House Mechanism and the Subsidiary Body on Scientific, Technical and Technological Advice, and designation of the Global Environment Facility (GEF) as the interim institutional structure for the financial mechanism.

2.5. Second Conference of the Parties

The second Conference of the Parties (COP-2) to the Convention on Biological Diversity (C.B.D.) met in Jakarta, Indonesia (6-17 November 1995). The theme of the session was "Biodiversity for Equitable Welfare of all People".

If COP-1 established the basis machinery for the Convention's implementation, COP-2 initiated this process. Some of the key decisions taken by COP-2 include : designation of the permanent location of the Secretariat at Montreal, Canada, agreement to develop a protocol

on biosafety ; operation of the Clearing-House Mechanism, adoption of a programme of work funded by a larger budget, designation of the GEF as the continuing interim institutional structure for the financial mechanism, consideration of its first substantive issue : conservation of marine and coastal biodiversity, and agreement to address forests and biodiversity, including the development of a statement from the C.B.D. to the Commission on Sustainable Development's (C.S.D.) Intergovernmental Panel on Forests (I.P.F.).

2.6. To Resume

Given the dramatic loss of biological diversity worldwide, and given a predicted doubling of the world population within the next fifty years, the Convention on Biological Diversity was inspired by the world community's growing commitment to sustainable development.

In Rio, over one hundred and fifty nations signed the legally-binding Convention on Biological Diversity, the first international agreement obligating governments to conserve and sustainably use their biological resources, and ensure the equitable sharing of their benefits. The signing of the C.B.D. has set an enormous long-term process in motion under the Convention involvement, among other things : development and implementation of national biodiversity strategies and action plans, regular meetings of the Parties of the C.B.D. to review compliance and consider actions for implementing the Convention, cooperative partnerships on research, technology transfer and benefit sharing, and the provision of new funding to developing countries to implement the C.B.D.

3. The Character of the Convention on Biological Diversity

The Convention on Biological Diversity is a framework agreement, leaving it up to individual countries to determine how most of its provisions are to be implemented. In turn its provisions are mostly expressed as overall goals and policies, rather than as hard and precise obligations, as in, for example, the Convention on International Trade in Endangered Species (CITES). Nor does it tend to set targets, as does, for example, the recent Habitats, Flora and Fauna Directive of the European Union, which lists hundreds of species that should be brought back to "satisfactory levels". Instead, the emphasis on the

Convention on Biological Diversity is to place the main decision-making at the national level. Unlike other conservation conventions, there are no lists, no annexes of accepted sites, or of species to be protected (I.U.C.N. 1993).

With regard to the provisions on conservation and sustainable use, the focus on action at the national level is emphasized by two crucial articles : article 1, which sets out the objectives agreed by the Parties, and article 6, which requires each State to develop a national strategy, plan or programme for the conservation of biodiversity and the sustainable use of biological resources. It will often be the case that the national strategy or plan will have to go beyond the substantive provisions in the later articles, to achieve the overall objectives in article 1 that Parties will accept by ratifying the Convention (UNEP 1994).

Further articles set out the policies to be followed. Article 8 sets out the major policies for effective *in situ* conservation of biodiversity, giving States a set of goals, against which to match their own laws and policies. Article 9 does the same for *ex situ* conservation, article 10 for sustainable use of biological resources and article 14 for environmental impact assessment. These goals are buttressed by less detailed commitments on research and training (article 12), and on education and awareness (article 13).

The later articles on access to genetic resources (article 15) and access to and transfer of technology (article 16), complex and imprecise as they are, also leave much to each Contracting Party to decide regarding their implementation. The financial articles (article 20, 21 and 39) were, to an extent, purposely left vague for the Conference of the Parties to later clarify ; this part of the Convention's text simply reflects the level of agreement that could be achieved in time for the deadline of signature at UNCED in Rio de Janeiro on 5 June 1992.

The ultimate success of the C.B.D. will depend on effectively addressing some very difficult issues, such as priority-setting (in the context of the C.B.D.), underlying causes of biodiversity loss, funding issues, access to genetic resources, benefit sharing arrangements and biosafety. Clearly, governments alone cannot adequately address these issues, nor achieve the objectives of the C.B.D. Substantive and active involvement and support (at all levels) of e.g. non-governmental organizations (N.G.O.'s), and the private sector as well, will be necessary.

4. Biodiversity : Definitions — Scope

Since the publication in 1988 of *Biodiversity*, the book edited by WILSON & PETER, there has been an exponential rate of articles on biodiversity. They do not refer necessarily to the same aspects, and there is a real need for a better understanding of what is biodiversity in reality.

At least fourteen recent definitions of biodiversity are commonly used. The more extended one is that of the United Nations included in the Convention on Biological Diversity (UNEP, 1992). According to it, biological diversity means : "The variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part ; this includes diversity within species, between species and of ecosystems". A more lyric definition is : "Complex beyond understanding and valuable beyond measure, biodiversity is the total variety of life on Earth" (RYAN 1992). The shortest definition of all is that of the Global Biodiversity Strategy (W.R.I./I.U.C.N./UNEP 1992) : "Biodiversity is the totality of genes, species, and ecosystems in a region".

It is interesting to note that most definitions do refer to the three main components of biodiversity : genes, species and ecosystems. Diversity within species is the *genetic* diversity, between species is the *species* or *taxonomic* or *organismal* diversity, and of ecosystems is the *ecological* or *habitat* diversity.

Unfortunately, the definitions pay little attention, if any to the interactions within, between and among the various levels of biodiversity. And interaction is the main intrinsic mechanism to shape the characteristics and the functioning of biodiversity. Another shortcoming is that the notion of scale seems to have been ignored.

To meet these shortcomings DI CASTRI (1995) proposed the following definition : "Biodiversity is the ensemble and the interactions of the genetic, the species and the ecological diversity, in a given place and at a given time".

Hierarchy is a central phenomenon of biodiversity. In this way biodiversity, rather than amalgamating disconnected pieces of scientific research, will become a transdisciplinary scientific field on its own.

Biodiversity can become a much needed unifying leitmotiv providing a continuum within the biological world. At present, biology is fragmented in a large number of disciplines with little or no connection among them, and too often competing and underestimating each other.

In most countries, molecular biology is the most appealing field, while taxonomy is neglected and holds little or no career incentives. Still, both disciplines are equally needed in a close cooperation and interaction if we are to successfully address the problems of biodiversity. The same applies to ecology when it is rightly taken as a scientific discipline with its own logic, and not as an emotional position or a political ideology. Working together towards a common goal, with compatible methods and approaches, can lead to a kind of cultural revolution of the current sectoral mechanisms and institutional patterns, breaking up the existing barriers to research and training in biology. This is not a dream. The "Centre National de la Recherche Scientifique" (C.N.R.S.) in France has decided to establish biodiversity as the core activity of its department of Life Sciences. A direct result is a renewed dialogue between previously separated scientists and disciplines (DI CASTRI & YOUNES 1996).

5. Global Biodiversity Assessment

UNEP has played a key role in the development of issues relating to biodiversity. An essential element is the collection and dissemination of knowledge generated by scientific research. In this regard the scientific community is a key partner to UNEP.

In this spirit UNEP commissioned the Global Biodiversity Assessment (G.B.A.) project. Underlying this endeavour was an attempt to mobilize the global scientific community to analyse the present state-of-the-art knowledge and understanding of biodiversity and the nature of our interactions with it. The document produced is the result of an ambitious scientific endeavour, the outcome of the invaluable contributions of more than a thousand experts worldwide. It reflects a broad spectrum of views (HEYWOOD & WATSON 1995).

Based on the approach used by the Inter-governmental Panel on Climate Change, the G.B.A. aims to provide an independent, critical, peer-reviewed scientific analysis of the current issues, theories and views regarding the main global aspects of biodiversity. The G.B.A. addresses more fundamental issues such as : How does one measure biodiversity in terms of species, genes and ecosystems? What is the ecosystem function of biodiversity? How may these different attributes be monitored? What are the issues involved in predicting probable extinction rates and their impacts on people? How can biodiversity be valued in economic terms? What are the human and economic

limitations involved? What are the implications of modern biotechnology for biodiversity? What is the role of humans in the loss of biodiversity, and what can people do to conserve biodiversity? The solid baseline of information generated by the G.B.A. provides the objectivity necessary for progress in conserving biodiversity.

The Global Biodiversity Assessment was officially presented in Jakarta in November 1995 at COP-2. This impressive volume counts 1,140 pages and is the one indispensable reference for scientists. A concise and very clear summary edition for policy-makers is also available. It is a general hope that decision-makers will find the time to go through those very 46 pages only (WATSON *et al.* 1995).

Many other initiatives were and are being taken to summarize knowledge regarding biodiversity. Another impressive volume is the "Global Biodiversity : Status of the Earth's living resources" compiled by the World Conservation Monitoring Centre (1992). In the same year a "Global Biodiversity Strategy" was also published (W.R.I./ I.U.C.N./UNEP 1992).

"Systematics Agenda 2000 — Charting the Biosphere" is a long-term initiative launched by a consortium of Biologist Associations. It is a global call for action during the next twenty-five years to :

— Discover, describe and inventory global species diversity ;
— To analyse and synthesize the information derived from this global discovery effort into a predictive classification system that reflects the history of life ;
— To organize the information derived from this global programme in an efficiently retrievable form that best meets the needs of science and society.

The Species 2000 Programme was established by I.U.B.S., CODATA and I.U.M.S. with the central aim of indexing the world's known species. It was subsequently endorsed by UNEP in its Biodiversity Work Programme 1996-1997, and associated with the Clearing-House Mechanism of the U.N. Convention on Biological Diversity.

Diversitas is a partnership of inter-governmental and non-governmental organisations (I.U.B.S., SCOPE, UNESCO, ICSU, I.G.B.P.-G.C.T.E., I.U.M.S.) to promote, facilitate and catalyse scientific research on biological diversity — its origin, composition, functioning, maintenance and conservation. *Diversitas* is conducting research on many subjects directly related to the Articles of the Convention on Biological Diversity.

Finally, it is impossible not to mention the abundance of initiatives to create and develop electronic networks and databases on biological diversity issues. Many of these will in the near future undoubtedly be linked to a metadata system known as Clearing-House Mechanism under the C.B.D. The establishment of a Clearing House is for mutual benefit :

— Developing countries gain access to data and technology from developed countries and as well as from other nations that have comparable ecological, social and economic conditions and, importantly, gain a forum for articulating priority needs for scientific and technical exchange ;
— Developed countries gain increased ability to form partnerships in sustainable development, to exchange expertise and information, and to more efficiently respond to identified needs for data and technology transfer.

6. Biodiversity Research at the Royal Belgian Institute of Natural Sciences

6.1. Introduction

Much of the focus on biodiversity science to date, has emphasized ecology, systematics, conservation, and to a lesser degree, evolution. There is a good reason for this : those elements of biology provide both basic and applied information in direct and crucial ways.

Zoological research at the Royal Belgian Institute of Natural Sciences deals with the three levels of hierarchy in biodiversity, the *species* and *species-group level* being the most investigated, the *ecosystem level* being for a long time a major concern towards conservation and studied since the early 80s, and finally the *genetic* and *molecular level* being studied intensively some six years onward.

6.2. The Ecosystem Level

Scientists of this Institute have explored during more than one century many terrestrial, marine and other aquatic ecosystems throughout the world (IRScNB 1996).

They observed and collected countless components of biodiversity in these ecosystems. After study, they were preserved and stored, building up a major zoological reference collection of which specialized

parts belong to the top five of the world. These collections are an invaluable archive of biodiversity which constitutes some thirty million components of ecosystems, some of which have disappeared today (VAN GOETHEM *et al.* 1995).

The concern for nature conservation at the Institute goes back to its early history. It culminated in the creation, shortly after the First World War, of the National Parks in Zaïre and later in 1959 by the founding in Brussels of the Charles Darwin Foundation for the conservation of fauna and flora on the Galápagos Archipelago. Both were initiatives of Victor Van Straelen, a former director of the Institute.

Since the early 80s research has started towards the study of evaluating habitats and ecosystems and the dynamics of protected sites, first in Europe, later on in other continents. In recent years, emphasis has been put on the development of methodologies concerning the evaluation of biodiversity richness of habitats and ecosystems (DEVILLERS & BEUDELS 1995).

6.3. THE SPECIES AND SPECIES-GROUP LEVEL

Since the early 80s research has been carried out on threatened wildlife, e.g. the Mediterranean Monk Seal, savanna, steppe and desert ungulates, bats, forest and migratory birds, amphibians, insects, spiders, crustaceans, snails and clams. This research focuses on evaluation of population status, identification of risk factors and conception of conservation measures.

Several researchers spent part of their lifetime in studying a species-group, mostly at family level. They became experts in each group and are known worldwide, and consulted therefore. Sometimes, less than three experts are known for a particular group. The use of scanning electron microscopy can lead to the discovery of unknown cells or organs. One of my colleagues studies on a world scale parasitic micro-wasps. They exhibit interesting anatomical features, among others the so-called Waterston's organ : a small reticulated area on an abdominal tergite ; it is thought improving the evaporation of pheromones. Discovery of such organs can in turn contribute to a better understanding of the interactions within and between species or with the ecosystem they share.

Interstitial habitats are water-filled cavities between the sediment particles. This realm is the place of an astonishing wealth of micro-invertebrates. Microcrustaceans as ostracods and copepods, as well as

nematodes, are studied by our scientists. Interstitial habitats are present in all major aquatic systems, but show their highest diversity of organisms in the coastal subtidal and intertidal zone. Contamination and urban impacts can cause severe damage on this fragile world resulting in the disappearance of a unique fauna which often represents the basic step in the aquatic trophic food webs.

Another example of biodiversity research at the Institute is the study of the economically important group of plant-parasitic nematodes, the family Trichodoridae. These ectoparasites not only cause direct damage to the root system of various crops and other plants, but they also act as vectors of three plant viruses, the tobacco rattle virus (T.R.V.) being the most widely spread (DECRAEMER 1995).

The majority of the twenty-five scientists of the Institute involved with the study of elements of biodiversity collaborate in international projects, some of which I will mention here.

6.4. SPECIATION IN ANCIENT LAKES

Ancient lakes like Tanganyika, Nyasa/Malawi and Baikal are characterized by their extraordinary extant animal and plant diversity and endemicity. About 1,300 animal species have so far been reported from Lake Tanganyika, of which more than 50 % are endemic, although several groups show 90 to even 100 % endemicity.

These ancient lakes are few, each is unique and they are highly vulnerable because they suffer from resource-use pressure as other lakes. Their conservation is of particular concern.

6.5. LAKE BAIKAL

Lake Baikal in eastern Siberia is the oldest, the most voluminous and the deepest (1,637 m) of all extant lakes. It contains about one fifth of the planet's unfrozen surface fresh water. Due to its size and age, the rich and diverse life of the lake contains numerous endemic species, e.g. giant Gammaridae and Turbellaria and a particular species of seal. The fact that even the deepest waters of Lake Baikal are well oxygenated, makes this lake unique, but also vulnerable to organic pollution. The lake is still well preserved ; local pollution, however, has already touched certain areas.

Since 1989 international research on the lake has been stimulated. A scientific collaboration between the Limnological Institute in Irkutsk and our Institute was established. Belgium belongs also to the founding

members of the "Baikal International Centre for Ecological Research" (BICER).

Research topics in which our Institute is involved are dealing with benthic invertebrates such as midge larvae, worms and crustaceans. These studies can give basic information for appropriate conservation measures to be taken (MARTENS *et al.* 1994).

6.6. GALAPAGOS ISLANDS

The Galápagos Islands are truly an exquisite field laboratory for the study of evolution. Scientists of the Institute started in the 80s a detailed investigation of the spider and carabid beetle fauna of the islands. So far, thirty-seven scientific papers have resulted from these studies. They contribute to a better understanding of radiation, speciation and endemicity on archipelagos as shown by the beetle genus *Pterostichus*. All species found are endemic, this means limited to one island only or even to a part of it (DESENDER *et al.* 1992).

6.7. ANTARCTICA

Belgian involvement in Antarctic research goes back a hundred years ago with Adrien de Gerlache who was the first to overwinter in the Antarctic ice, on board the "Belgica".

Current research is intensely woven within a broad international collaboration. It focuses on the structural and functional roles of the peracarid crustaceans in Antarctic benthic shelf communities (DE BROYER & JAZDZEWSKI 1996). It deals, among others, with the characterization and comparison of the trophodynamic structure of the amphipod taxocoenosis in the Eastern Weddell Sea and King George Island shelf benthos.

A recent new topic is the comparative study of diversity and gigantism among Antarctic and Lake Baikal amphipods.

6.8. PAPUA NEW GUINEA

Coral reefs constitute extremely complex ecosystems with the most diversified marine fauna, from which local people draw an important part of their food. The existence of these ecosystems is nevertheless seriously compromised by pollution, overfishing and large-scale tourism.

In 1976, the King Leopold III Biological Station was founded by the "Université Libre de Bruxelles" on Laing Island at the north coast of Papua New Guinea. It has welcomed many researches from the

Institute, dealing with marine, freshwater and terrestrial faunas, including biodiversity canopy research in the rain forest. To date the Institute researchers have published more than one hundred scientific papers on Papua New Guinea fauna in internationally refereed journals.

6.9. Abyssal Depths

The Institute is also participating in international research programmes in the Caribbean, where living fossil sponges are found in dark biotopes such as underwater caves or at depths unreachable by scuba divers. These organisms contribute to build up the deep fore reef framework by laying down a massive calcareous skeleton, the growth rate of which is being measured here to understand their function in those endangered biotopes.

Abyssal depths are also explored for new sponges containing bioactive compounds investigated by the pharmaceutical industry for their antibacterial, antiviral, antifungal, antimalarial, or antiparasitic therapeutic properties.

6.10. The Genetic and Molecular Level

Molecular techniques were introduced at the Institute some six years ago. Protein electrophoresis is an excellent tool to distinguish cryptic species and to recognize genetically distinct populations from a same species (Backeljau *et al.* 1992). Such information is highly relevant to recognize "Evolutionarily Significant Units" and to predict possible problems of outbreeding depression during species reintroduction programmes.

The possibility to amplify the D.N.A. from museum specimens has recently stimulated our Institute to develop the use of D.N.A. sequence data in systematical research. This technique validates the existing major reference collections in musea (Winnepenninckx *et al.* 1993).

Mitochondrial D.N.A. is the most widely used molecular marker for phylogenetic and population level studies. At our Institute the technique is intensely used in studies on prehistoric man, rodents, molluscs, insects, crustaceans, worms, and on Tanganyikan cichlid fishes, the latter presenting the most spectacular example of adaptive radiation and speciation within the confines of a single lacustrine system. Extensive fieldwork is as always required ; so, over the past few year, cichlids were collected over a distance of 800 km shoreline of Burundi, Tanzania and Zambia (Meyer *et al.* 1996).

7. Conclusion

Many disciplines of biological science have a major role to play in the analysis and understanding of biodiversity and in the assessment of its importance to human society. A synthesis and integration of several approaches to research in biodiversity science will provide better understanding than unidirectional pathways. Education in the several spheres of biology not in the least by the Institute's Natural History Museum will allow the public to have a realistic basis for assessing the significance of biodiversity to their lives.

REFERENCES

BACKELJAU, T., BRITO, C. P., TRISTAO DA CUNHA, R. M., FRIAS MARTINS, A. M. & DE BRUYN, L. 1992. Colour polymorphism and genetic strains in *Arion intermedius* from Flores, Azores (Mollusca : Pulmonata). — *Biological Journal of the Linnean Society*, **46** : 131-143.

DE BROYER, C. & JAZDZEWSKI, K. 1996. Biodiversity of the Southern Ocean : towards a new synthesis for the Amphipoda (Crustacea). — *Bolletino del Museo Civico di Storia Naturale di Verona*, **20** : 547-567.

DECRAEMER, W. 1995. The Family Trichodoridae : Stubby Root and Virus Vector Nematodes. Developments in Plant Pathology. Vol. 6. — Kluwer Academic Publishers, Dordrecht, Boston, London, XVI + 360 pp.

DESENDER, K., BAERT, L. & MAELFAIT, J.-P. 1992. Distribution and speciation of carabid beetles in the Galápagos Archipelago (Ecuador). — *Bulletin van het Koninklijk Belgisch Instituut voor Natuurwetenschappen, Entomologie*, **62** : 57-66.

DEVILLERS, P. & BEUDELS, R. C. 1995. Espaces protégés et petites populations : une gestion intégrée du Patrimoine naturel. — *Nouvelles de la Science et des Technologies*, **13** (2/3/4) : 211-216.

DI CASTRI, F. 1995. The hierarchical uniqueness of biodiversity. — *Biology International* (Special Issue), **33** : 54-57.

DI CASTRI, F. & YOUNES, T. 1996. Introduction : Biodiversity, the Emergence of a New Scientific Field - its Perspectives and Constraints. — *In* : DI CASTRI, F. & YOUNES, T. (eds.) Biodiversity, Science and Development. Towards a New Partnership. CAB International, Paris, pp. 1-11.

HEYWOOD, V. H. & WATSON, R. T. 1995. Global Biodiversity Assessment. — UNEP, University Press, Cambridge, XI + 1140 pp.

IRScNB 1996. Du Musée à l'Institut : 150 ans de Sciences naturelles de Belgique. — Bruxelles, 112 pp. (exists also in a Dutch version).

I.U.C.N. The World Conservation Union/Environmental Law Centre 1993. The Convention on Biological Diversity. An Explanatory Guide. — IUCN/ELC, Bonn, IV + 142 pp.

MARTENS, K., GODDEERIS, B. & COULTER, G. (eds.) 1994. Speciation in Ancient Lakes. — *Archiv für Hydrobiologie, Beiheft, Ergebnisse der Limnologie,* **44** : X + 508 pp.

MEYER, A., KNOWLES, L. L. & VERHEYEN, E. 1996. Widespread geographic distribution of mitochondrial haplotypes in rock-dwelling cichlid fishes from Lake Tanganyika. — *Molecular Ecology*, **5** : 341-350.

RYAN, J. C. 1992. Life Support : Conserving Biological Diversity. — Worldwatch Paper 109. Worldwatch Institute, Washington, D.C.

UNEP 1994. Convention on Biological Diversity. Text and annexes. — The Interim Secretariat for the Convention on Biological Diversity, Geneva Executive Center, Châtelaine, 34 pp.

VAN GOETHEM, J. L., BACKELJAU, T. & WOUTERS, K. 1995. The Royal Belgian Institute of Natural Sciences and the role of natural history collections in biodiversity research. — *Nouvelles de la Science et des Technologies*, **13** (2/3/4) : 205-209.

WATSON, R. T., HEYWOOD, V. H., BASTE, I., DIAS, B., GAMEZ, R., JANETOS, T., REID, W. & RUARK, G. 1995. Global Biodiversity Assessment. Summary for Policy-Makers. — UNEP, University Press, Cambridge, VII + 46 pp.

WILSON, E. O. & PETER, F. M. (eds.) 1988. Biodiversity. — National Academy Press, Washington, D.C., XIII + 521 pp.

WINNEPENNINCKX, B., BACKELJAU, T. & DE WACHTER, R. 1993. A simple method for the extraction of high molecular weight DNA from molluscs. — *Trends in Genetics*, **9** : 407.

World Conservation Monitoring Centre 1992. Global Biodiversity : Status of the Earth's Living Resources. — Chapman & Hall, London, XX + 594 pp.

W.R.I./I.U.C.N./UNEP 1992. Global Biodiversity Strategy : Guidelines for Action to Save, Study, and Use Earth's Biotic Wealth Sustainably and Equitably. — World Resources Institute Publications, Baltimore, VI + 244 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 730-744 (1998)

Importance of Organic Matter for Sustainability of Agro-Ecosystems in Lower Zaire

by

Geert BAERT * & Eric VAN RANST *

KEYWORDS. — Cation Exchange Capacity ; Organic Matter ; Sustainable Agriculture ; Soil Management ; Zaire.

ABSTRACT. — "Sustainable agriculture" involves site specific farming systems that maintain or improve profitability while conserving natural resources. In natural systems, losses of nutrients due to leaching, run-off or erosion are small enough to be compensated by addition from the natural vegetation, atmospheric addition or weathering of minerals. However, more losses occur in agro-ecosystems because of : (1) the removal of crop harvests, (2) the accelerated breakdown of organic matter (O.M.) related to changes in the pedoclimate and the soil hydrology. In this paper, we will focus on the role of O.M. in the sustainable cultivation of three soils in Lower Zaire, containing mainly kaolinite and iron oxides, but having varying contents in O.M. The charge properties were determined by the "Charge Fingerprint" method. The results clearly show the impact of O.M. on the chemical fertility status of highly weathered soils. Since the pHo of O.M. is much lower (3.5-4) than of Fe and Al oxides (6.5-9.5), the CEC in the topsoils with high O.M. contents sometimes exceeds up to five times the CEC of the subsoil. In soils nearly devoid of O.M., top and subsoils show similar and low CEC values. Management of highly weathered soils should therefore be oriented towards maintaining and, if possible, increasing the level of O.M.

MOTS-CLES. — Capacité d'échange de cations ; Matière organique ; Agriculture durable ; Gestion des sols ; Zaïre.

RESUME. — *L' importance de la matière organique dans la durabilité des systèmes agro-écologiques du Bas-Zaïre.* — «L'Agriculture durable» comprend des systèmes de production qui visent à maintenir et/ou améliorer la rentabilité,

* Laboratory of Soil Science, University of Gent, Krijgslaan 281 (S8), B-9000 Gent (Belgium).

en préservant les ressources naturelles. Dans les systèmes naturels, les pertes des éléments nutritifs par lessivage, ruissellement ou érosion sont généralement faibles et sont compensées par des apports de végétation naturelle, atmosphériques ou par l'altération des minéraux. Cependant, plus de pertes sont enregistrées dans les systèmes agricoles en raison de (1) l'exportation des éléments nutritifs dans les parties végétales récoltées, (2) la dégradation rapide de la matière organique (M.O.) suite aux changements des conditions pédoclimatiques et hydriques du sol. Cet article a pour objectif d'asseoir le rôle que la M.O. pourrait jouer dans l'exploitation durable de trois types de sol du Bas-Zaïre. Ces sols sont caractérisés par des taux élevés de kaolinite et des oxydes de fer ; cependant, leur teneur en M.O. est variable. La caractérisation de la charge a été réalisée par la méthode «Charge Fingerprint». Les résultats obtenus ont montré l'importance de la M.O. dans la fertilité chimique des sols. Du fait que le pHo de la M.O. est plus faible (3,5-4) par rapport au pHo des oxydes de Fe et Al (6,5-9,5), la CEC des couches superficielles des sols ayant des teneurs élevées en M.O., peut atteindre cinq fois celle des couches inférieures. Cependant, dans les sols qui sont presque dépourvus de M.O., la CEC reste faible à travers tout leur profil. La gestion rationnelle des sols fortement altérés devrait se fixer comme objectif l'amélioration du niveau de la M.O.

TREFWOORDEN. — Kationen uitwisselingsvermogen ; Organisch materiaal ; Duurzame landbouw ; Bodembeheer ; Zaïre.

SAMENVATTING. — *Het belang van organisch materiaal in de duurzaamheid van agro-ecologische systemen in Beneden Zaïre.* — „Duurzame landbouw" omvat specifieke landbouwsystemen gericht op het behoud of de verbetering van de rentabiliteit, met behoud van de natuurlijke rijkdommen. In natuurlijke systemen zijn verliezen van voedingsbestanddelen door uitloging, afspoeling of erosie minimaal genoeg om gecompenseerd te worden door inbreng van de natuurlijke vegetatie en/of de atmosfeer, of door verwering van mineralen. Daarentegen treden grotere verliezen op in agro-ecosystemen door : (1) het verwijderen van de gewasoogst, (2) de versnelde afbraak van organisch materiaal (O.M.) te wijten aan veranderingen in pedoklimaat en bodemhydrologie. In dit artikel zullen we ons toespitsen op de rol van O.M. in het duurzaam verbouwen van drie bodems van Beneden Zaïre, die vooral kaoliniet en ijzeroxiden bevatten, maar met een variërende hoeveelheid O.M. De ladingskenmerken werden bepaald met de „Charge Fingerprint" methode. De resultaten tonen duidelijk de impact van O.M. op de chemische fertiliteitstoestand van sterk verweerde tropische bodems. Gezien de pHo van O.M. veel lager (3,5-4) is dan die van Fe en Al oxiden (6,5-9,5), overschrijdt de CEC van de bovengrond met veel O.M. soms tot vijfmaal de CEC van de ondergrond. In humusarme bodems vertonen de boven- en ondergrond gelijkaardige en lage CEC waarden. Beheer van sterk verweerde bodems dient

daarom te steunen op een behoud en, indien mogelijk, een verhoging van het gehalte aan O.M.

Introduction

Soil organic matter maintains an equilibrium with climate, vegetation and other environmental conditions. It depletes rapidly if this equilibrium is disturbed by inappropriate management practices. After clearing of the natural vegetation, soils are exposed to erosion and high temperatures that accelerate the decomposition of organic matter. Also, when cultivated, the rate of organic matter return is much lower, so that organic matter will fall to lower equilibrium levels than in comparable arable soils in the temperate zone (VAN WAMBEKE 1992).

Organic matter exerts a profound influence on soil properties, including productivity. It helps to develop and maintain a good soil structure, water-holding capacity, aeration, permeability and resistance to erosion. Its major contribution, however, lies in the supply of nitrogen and in the raising of the capacity of the soil to retain cations necessary for plant growth.

In this paper, we will focus on the role of organic matter in the sustainability of the traditional cultivation of the highly weathered soils in Lower Zaire, with predominantly variable charge minerals, kaolinite and iron oxides, and limited amounts of permanent charge minerals (2/1 phyllosilicates) in the clay fraction. The contribution of organic matter to the exchange capacity will be investigated in detail. The impact of organic matter on the soil fertility status and management of highly weathered soils will be discussed.

Geographic Setting

Lower Zaire represents the western part of the Republic of Zaire, *i.e.* the region between Kinshasa and the Atlantic Ocean. Geologically, the study area consists of a Precambrian basement, covered over vast areas by Post-Palaeozoic sediments. The Precambrian basement is composed of igneous rocks and strongly metamorphosed crystalline rocks in its western part and of sedimentary rocks in its eastern part. The landscape is very diversified as a result of the various lithologies of the geologic materials. Several erosion cycles have occurred since the Cretaceous, which resulted in a series of, often laterized, peneplains.

In the western part, a strong rejuvenation of the relief took place following the incision of the Zaire river.

The climate belongs to the Aw4 type of the Köppens' climatic classification system, *i.e.* a humid, tropical climate with a marked dry season of 4 months. The rainfall decreases gradually from east to west ; from 1,500 mm y^{-1} east of Kinshasa to 800 mm y^{-1} at the coast. The mean annual temperature is approximately 24 °C.

Only the Mayumbe area is covered by a tropical forest, with some important industrial plantations of perennial crops as oil palm, rubber, coffee and cocoa. The remaining part of Lower Zaire consists of an anthropogenic savanna. The valleys are often covered with gallery forests. In the savanna area, the dominant crops, grown under shifting cultivation, are cassava, maize, groundnuts, sweet potato and cajan pea.

Materials and Methods

The soils of Lower Zaire were mapped at reconnaissance level (Baert *et al.* 1991). Over 90 % of Lower Zaire consists of highly weathered soils, with a colloid fraction predominated by kaolinite and sesquioxides (Baert 1995).

For this study, soil samples of A and B horizons were collected from three representative highly weathered soils in the savanna area of Lower Zaire :

— Profile BO5 : Rhodic Kandiustalf (Soil Survey Staff 1994), on basic rock ;
— Profile SB31 : Humic Haplustox, on basic rock ;
— Profile MT2 : Typic Haplustox, on granite.

The electrochemical properties were determined by the "Charge Fingerprint" method, developed by Gillman (1984), later revised by Gillman & Sumpter (1986). The method allows the determination of the cation and anion exchange capacity (designated as CEC and AEC, respectively), the point of zero charge of the variable charge components (pHo), the relative amount of permanent charge (σ_p). Briefly, the soils were Ca saturated and brought to equilibrium with 0.002 M $CaCl_2$. The pH was adjusted to a number of values between 3 and 7, and 1 M NH_4NO_3 was then used to extract Ca, Al and Cl from the soils. The amounts adsorbed were calculated, allowing for entrained species. The method allows the determination of :

— The Total Cation Exchange Capacity (CEC_T), defined by the Ca + Al adsorbed. The CEC_T denotes the amount of basic and acid cations that can be retained.
— The Basic Cation Exchange Capacity (CEC_B), which is the Ca adsorbed. The CEC_B relates to the retention of only the basic cations ; it is of considerable agronomic significance.
— The AEC, defined by the Cl adsorbed, and reflecting the amount of exchangeable anions.

The permanent charge refers to the difference between CEC_T and AEC at pHo.

The other analyses are limited to those properties which have a direct impact on the exchange capacity of the soil : O.C. clay content and dithionite-citrate-buffer (DCB) extractable Al and Fe. The methods used are described in PAUWELS *et al.* (1992).

Results and Discussion

CHARGE COMPONENTS

The capacity of a soil to retain and exchange cations and anions largely depends on the nature of the soil colloids, in particular their charge properties. This subject is of great interest in the tropics because highly weathered tropical soils behave differently from most temperate soils. In Lower Zaire, the young soils behave electrochemically in a similar way as most soils in the temperate regions, as their colloid fraction is dominated by permanent charge minerals (2/1 phyllosilicates). In this case, the charge on the surface of the minerals originates from defects in the interior of the crystal. However, most soils of Lower Zaire are highly weathered and have a colloid fraction predominantly composed of variable charge components. Contrary to permanent charge minerals, the "variable" charge of colloids as organic matter, sesquioxides and kaolinite arises from adsorption of potential determining (P.D.) ions, mainly H^{+k+} and OH^-, on functional groups. Carboxyl (– COOH), amine (– NH_2) and phenol (– C_6H_3OH) are the main functional groups of organic matter. The charge is variable because it depends on several factors, as expressed by the Gouy-Chapman equation, based on the double-layer theory (UEHARA & GILLMAN 1981) :

$$\sigma_v = \left(\frac{2\pi\varepsilon RT}{\Pi} \right)^{1/2} \sinh 1.15\, z\, (pHo - pH)$$

with :

σ_v = variable charge (C/cm^2) ;
n = counterion concentration in the equilibrium solution (ion/cm^3) ;
ε = dielectric constant (C^2/Jm) ;
R = gas constant (8.314×10^3 JK^{-1} $kmol^{-1}$) ;
T = temperature (298 K) ;
z = counterion valence ;
pH = pH of the bulk solution (soil pH) ;
pHo = pH at which the net charge of the potential determining ions is zero.

From this equation, it is clear that the magnitude of the variable charge will be determined mainly by the ionic strength of the soil solution, the valence of the counterions, and by the difference between pHo and pH. This difference will also determine the sign of the variable charge. The total surface charge of the soil colloids comprises the sum of the permanent and variable charge, and is an expression of the cation exchange capacity.

The equation also shows that at some point on the pH scale, σ_v can be zero. This pH value at which the sum of charges due to adsorption of P.D. ions equals zero is indicated as pHo of the solid. In other words, equal amounts of positive and negative charges are present on the colloid surfaces. If $\sigma_v = 0$ in a mixed charge soil system, the remaining charge is the net permanent charge. When soil pH $<$ pHo, the variable charge sites carry a net positive charge, and conversely they are net negatively charged when soil pH $>$ pHo.

In tropical soils, the variable soil colloids are predominantly organic matter, and iron and aluminium (hydr)oxides, with minor contributions of the edges of silicate clay minerals, in particular kaolinite. These various colloids have individual pHo values, *i.e.* 6.5-9 for iron and aluminium (hydr)oxides and $\pm$ 4 for organic matter (Greenland & Mott 1978, Uehara & Gillman 1981). The proportions of the different colloids in the soil will determine the overall pHo value. Iron-rich soils with low organic matter contents will have high pHo values, while high organic matter contents will decrease the pHo.

Charge Properties of Highly Weathered Soils in Lower Zaire

Point of Zero Charge

Some selected parameters of the studied soils having an impact on

the charge properties are summarized in table 1. The surface charge properties of those soils are presented in table 2.

Table 1

Selected soil parameters and clay mineralogical composition of the studied soils

Profile	Horizon	Depth (cm)	O.C (%)	Clay (%)	DCB clay (%)		Phyllosilicates*			
					Fe_2O_3	Al_2O_3	C-S	M-S	S	K
Rhodic Kandiustalf (BO5)	Ah	0-15	2.2	24	14.0	2.1	(+)	+	(+)	+++
	Bt2	53-110	0.4	67	13.5	2.0	(+)	+	—	+++
Typic Haplustox (MT2)	Ah	0-15	1.1	39	9.7	1.5	—	(+)	—	+++
	Bws2	56-95	0.2	40	10.0	1.5	—	(+)	—	+++
Humic Haplustox (SB31)	Ah	0-12	3.9	61	10.8	3.0	—	(+)	—	+++
	Bws1	65-114	0.4	70	12.9	3.0	—	(+)	—	+++

* C-S : chlorite-smectite ; M-S : mica-smectite ; S : smectite ; K : kaolinite (based on XRD interpretation) ; +++ : dominant ; ++ : important ; + : minor ; (+) : traces ; — : absent.

Table 2

Selected surface charge properties of the studied soils

Hor.	soil pH	pHo	σ_p	Charges at soil pH*				I** (M)
			clay	soil	CEC_T	CEC_B	AEC	
			cmol(c) kg^{-1} soil					
Rhodic Kandiustalf (BO5)								
Ah	6.1	5.0	NA	10.4	12.6	12.6	0.2	0.007
Bt2	5.1	6.6	7.5	5.1	5.1	5.1	1.4	0.005
Typic Haplustox (MT2)								
Ah	4.7	5.8	NA	1.8	1.7	1.5	0.5	0.007
Bws2	4.5	7.0	6.0	2.4	1.6	1.4	1.1	0.004
Humic Haplustox (SB31)								
Ah	5.5	3.4	NA	4.8	11.0	11.0	0.3	0.005
Bws1	4.8	7.3	3.4	2.4	1.7	1.6	1.3	0.002

* "Charge Fingerprint" method.

** Ionic strength of soil solution calculated from the 1 :5 soil extract by the equation $I_{soil\ solution} = 0.0446EC_{1:5}\ 0.000173$ (GILLMAN & BELL 1978).

σ_p clay in cmol(+) kg^{-1} clay.

The studied soils are highly weathered, as indicated by a clay mineralogy predominated by kaolinite. Minor amounts of interstratified minerals formed out of mica are observed in profile BO5. Only traces of those minerals are present in the other profiles (table 1). The A and B horizons within the same profile have a similar clay mineralogical

composition and nearly equal amounts of DCB extractable Fe and Al.

All surface horizons show a lower pHo value compared to the underlying B horizons (table 2), clearly illustrating the impact of organic matter on the charge properties. GILLMAN (1985) reported that pHo is reduced by about 1 pH unit for each 1 % increase in organic carbon. As the organic matter decreases with depth, the pHo of the subsoil is determined by the other variable charge components. The high pHo of the studied B horizons is related to the high iron oxide content. The B horizon of profile BO5 shows the lowest pHo, although it has the highest iron content of all studied subsoils (table 2). Here, the pHo is lowered by the presence of 2/1 phyllosilicates in the clay fraction. In profile SB31, the high pHo may be, to some extent, linked to the high Al-for-Fe substitution, resulting in a lower degree of crystallinity of the iron oxides.

CHARGE CURVES

The "Charge Fingerprint" method allows the determination of the variation of CEC_T, CEC_B and AEC in a 0.002 M $CaCl_2$ solution over a pH range of 3 to 7. The ionic strength of the $CaCl_2$ solution, *i.e.* 0.006, approaches the ionic strength of the soil solution of the studied soils (table 2). The charge curves of both A and B horizons of the studied profiles are illustrated in figure 1. The Ah horizons, having a similar mineralogical composition as the subsoils within the same profile (table 1), show higher CEC values related to the higher content in organic matter. The higher the organic matter content, the higher the difference between CEC compared to the underlying subsoil. This is illustrated in figure 2, showing the influence of organic matter content and its related pHo value on the magnitude of CEC. The charge curve of the Ah horizon of profile MT2, relatively poor in organic matter, nearly overlaps with the curve of the subsoil. This clearly reflects the impact of organic matter on the fertility status in Oxisols. Maintaining high levels of organic matter in such soils is of uppermost importance. The strong variation in CEC, particularly of the agronomically important CEC_B, in the Ah horizons reflects the considerable variable charge character of organic matter. ABRUNA & VINCENTE-CHANDLER (1955) measured an exchange capacity of 260 cmol(+) kg^{-1} O.C at pH 7, which dropped to 65 cmol(+) kg^{-1} O.C at pH 4.5.

At pH values below 4, CEC_T tends to run parallel to the pH axis (fig. 1). However, CEC_B still decreases depicting the preferential

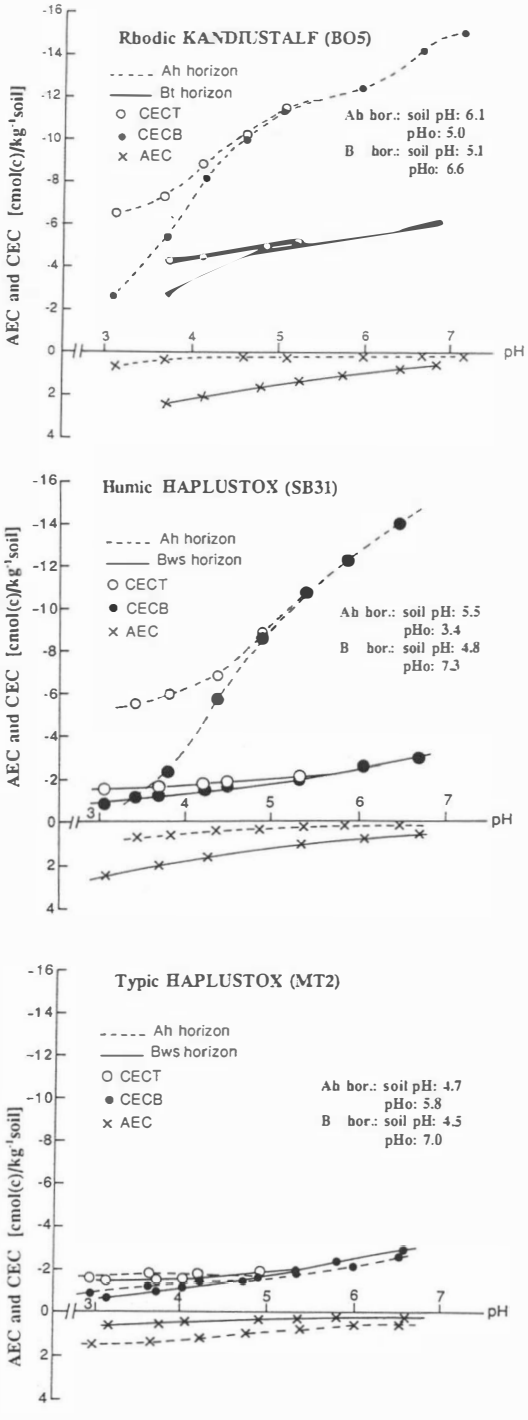


Fig. 1. — Charge curves of the studied soils.

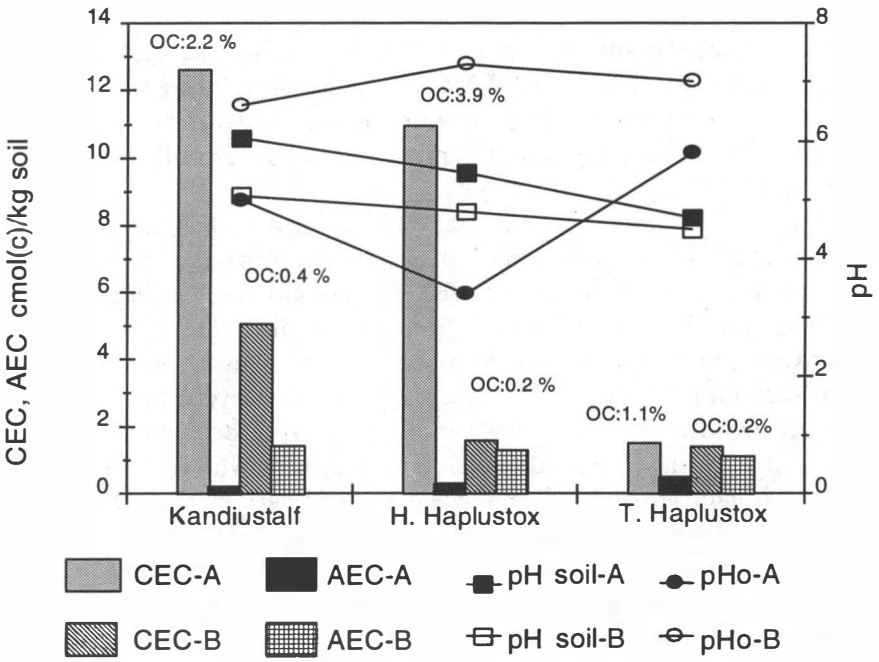


Fig. 2. — Variation in O.C, pH soil, po and of CEC and AEC at pH soil of A and B horizons.

adsorption of Al on the exchange complex at low pH values. Thus in very acid soils, the capacity of the soils to hold nutrients necessary for crop growth is very limited. The CEC_B at low pH of profile BO5 is double that of the other profiles, and is related to the presence of higher amounts of permanent charged minerals, having a higher cation exchange capacity. The highest Al adsorption at low pH is observed in Ah horizons rich in organic matter (SB31), and in B horizons containing substantial amounts of open 2/1 phyllosilicates (BO5).

Implications for Sustainable Agriculture

The above results have clearly shown the impact of organic matter on the chemical fertility status of highly weathered soils. Organic matter does not only supply nitrogen, phosphorus and sulphur to the crops, but it also has an important contribution to the cation exchange capacity of the soil, and thus to the amounts of nutrients the soil can store. Since the pHo of organic matter is much lower ($\pm$ 4.0) than

of Fe and Al oxides (6.5-9.5), the CEC in the Ah horizon with high organic matter contents may exceed several times the CEC of the B horizon. In highly weathered tropical soils, most plant nutrients are present in the topsoil, where they are associated with organic matter. In soils nearly devoid of organic matter, top and subsoils show similar and low CEC values.

The amount of organic matter present in a soil at any one time is the result of addition and loss. Under natural vegetation the rate of input will be high, so that the equilibrium level is high in spite of the fact that the decomposition rate is also rather high. When cultivated, the rate of organic matter return is much lower, so that organic matter will fall to lower equilibrium levels. The nutrient-supplying power of highly weathered tropical soils declines very rapidly within two or three years after clearing, coinciding with the rapid decline in the organic matter content when the soils are cultivated (ALEGRE & CASSEL 1986, JENKINSON 1990, GREENLAND *et al.* 1992).

Management of highly weathered soils should therefore be oriented towards maintaining and, if possible, increasing the level of organic matter. The management of such soils has therefore often been called "management of organic matter" (VAN WAMBEKE 1992). Addition of high amounts of organic matter will lead to an overall lowering of the soil pHo, resulting in a higher CEC. Addition of organic material also reduces the harmful effects of Al toxicity in acid soils (AHMAD & TAN 1986). It is believed that Al ions are detoxified by interactions with organic matter in the form of complex reactions, complex coagulation, chelation, and peptization reactions (CABRERA & TALIBUDEEN 1977). This results in the formation of Al-organo chelates or complexes followed by a reduction of the Al-ion concentration to levels thought to be beneficial to plant growth. According to AHMAD & TAN (1986), organic matter is as effective as lime in reducing Al toxicity.

However, soil organic matter is not easily increased above a level which is mostly determined by climatic factors and management practices. Given the high mean annual temperature and seasons of extreme desiccation in Lower Zaire, in combination with inappropriate management practices, high levels of soil organic matter are difficult to maintain. Addition of manure, crop residues or mulches can make significant contributions to soil organic matter in relative terms. In practice, a shortage or absence of manure and the inefficiencies of unproductive green fallows suggest that organic matter should be

maintained by the return to the soil of all crop residues. Management practices increasing the amount of crop residues will also increase the soil organic matter content, provided these practices do not expose the land to higher temperatures leading to faster decomposition rates and increasing the risks of accelerated erosion (VAN WAMBEKE 1992). Where a continuous cover is maintained, such as pasture, it should be possible to maintain higher levels of organic matter and, consequently, the capacity of a variable charge soil to retain cations (UEHARA & GILLMAN 1981).

Also fertilization leads to a better conservation of the organic matter level in soils. ALEGRE & CASSEL (1986) observed that the original soil organic matter content, after clearing of a 20-year-old secondary forest, was preserved by appropriate fertilization and liming during a 23-month experiment with annual crops. On the other hand, the unfertilized fields showed a decline in organic carbon from 1.04 to 0.80 % during the same period.

In Lower Zaire, the purchasing power of the rural population is very poor and farmers rely mainly on "shifting cultivation". This system exploits the nutritional value of organic matter since no mineral fertilizers are used to supply plant nutrients. Shifting cultivation has evolved as a means of using soils with an inadequate capacity to hold nutrients, including cations. The stability of such crop production systems depends on replenishing nutrients in the soil organic matter and in the biomass by allowing vegetation to regenerate naturally for several years (FOX 1980).

Shifting cultivation can only be practised when the population density is low. A 2 to 3 year-cropping period alternates with long periods of fallow (7-10 years), during which the natural fertility may be re-established (VAN WAMBEKE 1992). Shifting cultivation is thus an acceptable land-use alternative as long as there is enough land. However, this practice becomes impossible when the population pressure is such that insufficient land is available to keep it under fallow for long periods. To maintain a more intensive use of the land on a sustainable basis, additional inputs, among which organic matter, are needed. Cultural practices should take into account a need to maintain and, if possible, to increase the levels of organic matter in soils.

In the major part of Lower Zaire, enough land is still available for shifting cultivation. However, tradition rather than need demands an annual burning of the fallows. These bush fires, exerted at the end

of the dry season, lead to a bare soil surface at the beginning of the rainy season. This results in a very strong erosion, removing large quantities of soil and organic matter. Furthermore, erosion is enhanced by the traditional farming system, whereby burning is usually carried out parallel rather than perpendicular to the slope direction. This has led to a permanent loss of large amounts of arable land.

A sustainable farming system in Lower Zaire will require a complete change in mentality of the rural population. Cultural practices should take into account soil conservation and erosion control measures, and adapted cropping systems. On the other hand, it is very difficult to maintain constant organic matter levels under sustainable agriculture. Other (inorganic) amendments will have to be considered to increase the nutrient retaining capacity, in a similar way as organic matter, thus by lowering the pHo. The most promising method is the addition of silicate and phosphorus. However, silicate or phosphate fertilization of highly weathered soils is a capital investment, due to the adsorption capacity of iron-rich soils. In capital deficient societies, a sensible approach would be to use existing native fertility to the extent that it can produce capital, to finance programmes of fertility build-up. This can be achieved by cultivating in a first stage crops that are well adapted to highly weathered soils and having low P requirements. Once a certain capital is produced, other amendments can be applied.

Conclusions

Climate is to a large extent, through its impact on vegetation, determining the organic matter content. In a natural ecosystem, an equilibrium exists between input and mineralization rate of organic matter. In agro-ecosystems, disturbing this equilibrium leads to a decrease in organic matter content, particularly due to changes in soil climate-hydrology, and losses through erosion. In highly weathered tropical soils, this is translated by a gradual decrease of the soil fertility, as organic matter largely determines the soils' capacity to retain nutrients. Management of such soils on a sustainable basis should therefore be oriented towards maintaining or increasing the organic matter content.

ACKNOWLEDGEMENT

The authors are gratefull to the National Science Foundation (Belgium) for the financial support of this investigation, which is part of the research program "Mineralogy and fertility of tropical soils" (N.F.W.O. no. 2.0017.93).

REFERENCES

ABRUNA, F. & VINCENTE-CHANDLER, J. 1955. Organic matter activity of some tropical soils of Puerto Rico. — *J. Agric. Univ. Puerto Rico*, **39** : 65-76.

AHMAD, F. & TAN, K. H. 1986. Effect of lime and organic matter on soybean seedlings grown in aluminium-toxic soils. — *Soil Sci. Soc. Am. J.*, **50** : 656-661.

ALEGRE, J. C. & CASSEL, K. K. 1986. Effect of land-clearing methods and post-clearing management on aggregate stability and organic carbon content of a soil in the humid tropics. — *Soil Sci.*, **142** : 289-295.

BAERT, G. 1995. Properties and chemical management aspects of soils on different parent rocks in the Lower Zaire. — Ph.D. thesis, Univ. of Gent, Belgium, 316 pp.

BAERT, G., EMBRECHTS, J., DE DAPPER, M. & MAPAKA, M. 1991. Cartographie du Bas-Zaïre : sols et évaluation des terres, feuille de Matadi. — Univ. of Gent, ABOS, Belgium, 177 pp.

CABRERA, F. & TALIBUDEEN, O. 1977. Effect of soil pH and organic matter on labile aluminium in soils under permanent grass. — *J. Soil Sci.*, **28** : 259-270.

FOX, R. L. 1980. Soils with variable charge : agronomic and fertility aspects. — *In* : THENG, B. K. G. (ed.), Soils with Variable Charge. New Zealand Soc. Soil Sci., Lower Hutt, N.Z., pp. 195-224.

GILLMAN, G. P. 1984. Using variable charge characteristics to understand the exchangeable cation status of oxidic soils. — *Aust. J. Soil Res.*, **22** : 71-80.

GILLMAN, G. P. 1985. Influence of organic matter and phosphate content on the point of zero charge of variable charge components in oxidic soils. — *Aust. J. Soil Res.*, **23** : 643-646.

GILLMAN, G. P. & BELL, L. C. 1978. Soil solution studies on weathered soils from tropical north Queensland. — *Aust. J. Soil Res.*, **16** : 67-77.

GILLMAN, G. P. & SUMPTER, E. A. 1986. Modification to the compulsive exchange method for measuring exchange characteristics of soils. — *Aust. J. Soil Res.*, **24** : 61-66.

GREENLAND, D. J. & MOTT, C. J. B. 1978. Surfaces of soil particles. — *In* : GREENLAND, D. J. & HAYES, M. H. B. (eds.), The Chemistry of Soil Constituents, John Wiley & Sons, Chichester, pp. 321-353.

GREENLAND, D. J., WILD, A. & ADAMS, D. 1992. Organic matter dynamics in soils of the tropics — From myth to complex reality. — *In* : LAL, R. & SANCHEZ, P. A. (eds.), Myths and Science of Soils of the Tropics. SSSA Special Public. no. 29, Soil Sci. Soc. Am., Madison, Wisconsin, pp. 17-33.

JENKINSON, D. S. 1990. Turnover of organic carbon and nitrogen in soil. — *Phil. Trans. R. Soc. London*, Ser. B, **329** : 361-368.

PAUWELS, J. M., VAN RANST, E., VERLOO, M. & MVONDO, Z. E. A. 1992. Manuel de laboratoire de pédologie. — Publ. Agric. n 28, AGCD, Bruxelles, 265 pp.

Soil Survey Staff 1994. Keys to Soil Taxonomy, sixth edition. — Soil Conservation Service, USDA, Washington D.C. ,305 pp.

UEHARA, G. & GILLMAN, G. P. 1981. The mineralogy, chemistry, and physics of tropical soils with variable charge clays. — Westview Trop. Agric., Series n. 4, 170 pp.

VAN WAMBEKE, A. 1992. Soils of the Tropics, Properties and Appraisal. — McGraw-Hill Inc., 343 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 745-751 (1998)

Desertification in the Republic of Sudan. Some Recommendations for the Sustainable Utilization of Sahelian Resources

by

Mariam AKHTAR *

KEYWORDS. — Drought ; Land Degradation ; Desertification ; Land Uses ; Sahel ; Sustainable Development.

ABSTRACT. — Long-term ecological surveys in the Sahelian zone of the Republic of Sudan revealed that the abolition of tribal land-use regulation systems in the early seventies and the unilateral promotion of land cultivation have marginalized the ecologically adapted, but more traditional land uses. The increasing cleavage between the socio-economic and the ecological factors has induced land degradation up to the point of desertification. A pronounced decline in perennial and often important dry season grazing plants (e.g. *Blepharis edulis*), and the increase in noxious annual species were recorded in core areas of agro-pastoral activities. Degradation processes were however aggravated by the incessant dry periods of the eighties and the early nineties. The promotion of sustained land management programmes to the Sahel necessitates the incorporation of more flexibility into the existing land-use systems. Land use control measures must consider (re)introducing a controlled accessibility to the regional water resources.

MOTS-CLES. — Sécheresse ; Dégradation ; Désertification ; Utilisation des sols ; Sahel ; Développement durable.

RESUME. — *Désertification dans la République du Soudan. Quelques conseils pour une utilisation durable des ressources sahéliennes.* — Dans la République du Soudan, des études sur le terrain à long terme (cartographie de la végétation, analyse des données hydrologiques et météorologiques, étude des sols) et des recherches interdisciplinaires ont montré que l'abolition des systèmes tribaux de régulation de l'utilisation des sols au début des années soixante-dix, d'une part, et la promotion unilatérale de la culture (système

* Technical Highschool Berlin, Schillerpromenade 26, G-12409 Berlin (Germany).

d'irrigation, mécanisation de l'agriculture pluviale), dautre part, ont de plus en plus marginalisé les systèmes traditionnels d'utilisation des sols, pourtant mieux adaptés écologiquement. Le clivage croissant entre les facteurs socio-économiques et écologiques a amené le processus de dégradation des terres au stade de désertification. On a constaté dans les principales régions agro-pastorales une nette diminution des plantes fourragères des saisons sèches, vivaces et souvent importantes (p. ex. *Blepharis edulis*), et une augmentation des espèces annuelles nocives. La dégradation des sols a été de plus aggravée par les périodes continues de sécheresse dans les années quatre-vingt et au début des années quatre-vingt-dix. La mise en œuvre de programmes de gestion durable des sols dans la zone du Sahel nécessite une plus ample flexibilité dans les systèmes actuels d'utilisation des sols. Les mesures de contrôle de l'utilisation des sols devraient envisager la (ré)introduction d'un accès aux ressources régionales en eau inspecté au niveau communal.

TREFWOORDEN. — Droogte ; Landdegradatie ; Desertificatie ; Bodemgebruik ; Sahel ; Duurzame ontwikkeling.

SAMENVATTING. — *Desertificatie in de Republiek Soedan. Enkele aanbevelingen voor het duurzaam gebruik van de Saheliaanse hulpbronnen.* — Langdurige ecologische terreinstudies in de Sahelzone van de Republiek Soedan hebben aangetoond dat de afschaffing van de tribale geregulariseerde systemen van bodemgebruik in het begin van de jaren zeventig, en de unilaterale promotie van bodembewerking, het ecologisch aangepaste maar meer traditionele bodemgebruik gemarginaliseerd hebben. De toenemende splitsing tussen de socio-economische en de ecologische factoren heeft landdegradatie teweeggebracht tot op het punt van desertificatie. Een uitgesproken vermindering van de overblijvende en veelal belangrijke voederplanten in het droge seizoen (bvb. *Blepharis edulis*) en een toename van de schadelijke jaarlijkse soorten werd waargenomen in kerngebieden van agro-pastorale activiteiten. Degradatieprocessen werden daarenboven nog verergerd door de onophoudende droogteperiode van de jaren tachtig en het begin van de jaren negentig. De bevordering van duurzame bodembeheerprogramma's in de Sahel noodzaakt de incorporatie van een grotere flexibiliteit ten opzichte van de bestaande bodemgebruikssystemen. Maatregelen voor controle op het bodemgebruik dienen een (her-)introductie van een gecontroleerde toegankelijkheid tot de regionale beschikbare waterhoeveelheden in acht te nemen.

1. Introduction

The unpredictability in the commencement, and in the length of the summer rains in the Sahel, resulted in the development of nomadic animal husbandry systems which could react quickly to the climate-

induced fluctuations in the available vegetal and water resources. Especially in years with below-average rainfall, the extensive southerly migrations of nomads, and also traditional land-use rights prevented the overexploitation of the plant cover; hence, averting an extensive and irreversible degradation of the vulnerable Sahelian pastures.

Long-term ecological field investigations in the north-eastern Sudan were carried out in wet and dry years, thus recording the impact of rainfall amounts and its variability on plant cover, and on the land-use patterns. An interdisciplinary approach was indispensable in order to identify the major causes of land degradation and desertification. As the grasslands of the Sahelian zone are still the economic backbone of a large majority of the people living in this zone, field investigations were carried out with socio-economists, ethnologists, and with specialists on animal production. The multitemporal analyses of remote sensing data (M.S.S., T.M., NOAA and aerial photographs) supplemented the field observations, and enabled the delineation of geomorphic, vegetation, land-use and desertification maps.

2. Causes of Land Degradation and Desertification

Besides the climate-induced flexibility in the traditional land husbandry, the natural regeneration of the vegetal resources of frequently utilized Sahelian resources was — until a few decades ago — also actively supported by tribal resource control and management systems. Thus, until recently, in the Butana region (north-eastern Sudan), a marked land degradation or desertification was limited to locations with constant water resources (cf. also Harrison 1955).

Since the 1920s, the colonial policies, and then the Republic of Sudan, have gradually marginalized the indigenous land-use and resource control mechanisms. This process supported the promotion of stationary agricultural activities to the southern Sahel. In the early seventies, the state's declaration of the natural resources as free goods led to the expropriation of exclusive tribal rights, and culminated in the introduction of the open access system to the Sudan. This induced the uncontrolled accessibility to the natural resources. The average rainfall events of the seventies could maintain a high grazing potential. The extensive pastoral resources of that decade retarded any irreversible ecological effects of the uncontrolled exploitation. The meagre resource capacity prevailing in the dry period of the eighties and the early nineties, and the reduced regenerative forces within the plant cover

lastly revealed the environmental consequences of the open access system.

3. Indicators of Land Degradation and Desertification

The absence of land control regulations triggered off the following regressive and negative changes to the vegetal resources in the investigated areas of the central and southern Sahel :

— Retarded or even lacking vegetal regeneration ;
— Limited rejuvenation of perennial plants ;
— Decrease in slow-growing plants ;
— Increase in annual, and very often noxious species in the herb-layer ;
— Overall reduction in the biomass production.

In the eastern Sahel, *i.e.* in the Butana region, the interdependence between the extent of the plant cover transformation and the seasonal length of the water supply have emphasized that the changes to the plant cover are the effects of land mismanagement. The dry period of the eighties and the early nineties (fig. 1), with its marked drought events of 1984/85 and 1990/91, led to a natural decline in the regeneration capacity of the plant cover, thus aggravating the effects of the pastoral overexploitation.

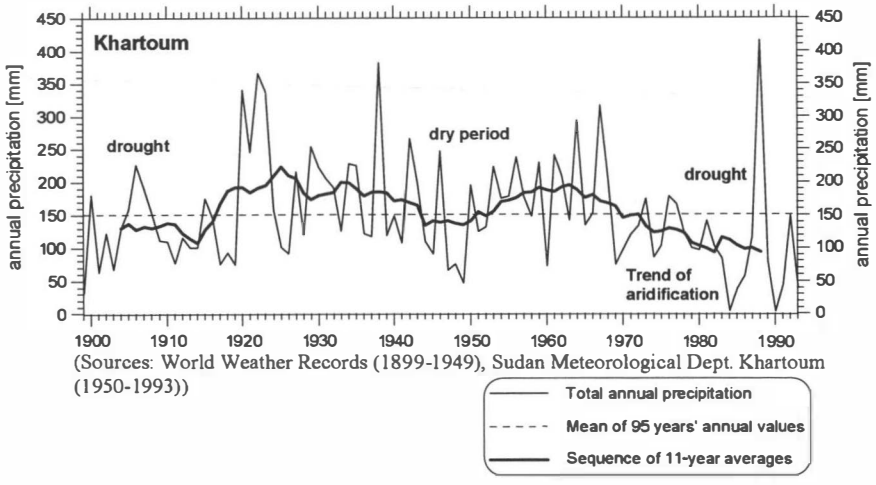


Fig. 1. — The long-term rainfall structure in the north-eastern Sahel, Khartoum meteorological station. *Source* : Data of the meteorological station Khartoum. *Draft* : M. Akhtar 1994.

Field studies in the early 1989 also showed that an isolated humid year, such as the very wet year of 1988 (in this year the total annual rainfall at the meteorological station of Khartoum exceeded the long-term average by more than twofold) is not capable of restoring a sufficient regeneration, especially to the heavily exploited and slow-growing plants.

During the recent dry period in the Butana region, a remarkable pasture potential was generally restricted to the south of the 15° latitude (fig. 2), hence, spatially limited to the dry season grazing areas. However, the rainfed cultivation, after its mechanization, expanded considerably at the cost of these dry season pasture lands. In the eighties and early nineties, the remaining grazing areas were exposed to a high concentration of animal herds, as long as the migratory routes to the more southerly pastures remained closed because the fields had not yet been harvested.

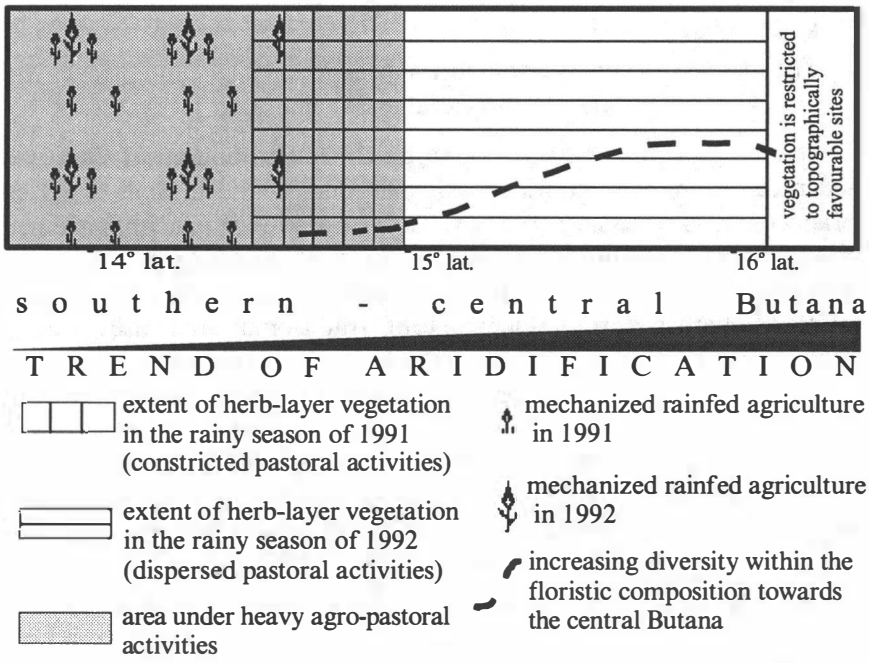


Fig. 2. — The distribution of pastures in wet and dry years, and the areas under frequent agro-pastoral activities. *Source* : Field surveys from 1991 up to 1992 by M. Akhtar. *Draft* : M. Akhtar 1994.

In the Butana region, the regular overstocking of the vulnerable pastures led to the decrease in the floristic diversity of the herb-layer. Simultaneously, a marked decline in very important dry season grazing plants (e.g. *Blepharis edulis*) could be recorded. Annual and often noxious species have started spreading (*Urochloa trichopus*, *Aristida* spp.) in areas under heavy agro-pastoral activities (fig. 2).

The vegetation degradation has enhanced the seasonal variations in the availability of the biomass. Subsequently, due to this degradation, livelihoods, which depend mainly on animal husbandry, are increasingly exposed to the unpredictable Sahelian environment, with its markedly contrasting inter- and intra-annual bioclimatic fluctuations.

4. Proposals for the Development of Sustainable Land Husbandry Systems

The recent trends in the utilization of Sahelian resources are governed by two major principles :

— The individual maximization of the resource utilization (*cf.* also KIRK 1994) ;
— The increase in stationary land-use practices which cannot react with flexibility or mobility to the variable Sahelian rainfall events.

Changing norms and values among the local population show that sedentarization will continue to marginalize the mobile land-use practices. It is necessary to examine the traditional land management strategies, *i.e.* the indigenous environmental knowledge, prior to the development of modern resource management measures. It should be studied whether certain elements of traditional land uses can be modified and integrated into the present land-use systems.

Especially in years with below-average rainfall events, innovative approaches must be developed which discuss corrective measures to the water management in highly exposed agro-pastoral lands. Field surveys showed that traditional types of water regulation systems did support a controlled accessibility to the biomass in the specific tribal areas. It should be discussed whether in lean years tribes, whose former tribal lands now also contribute to the agro-pastoral core areas, should again obtain some exclusive rights over their former lands.

This would imply that farmers from the irrigation schemes and the mechanized rainfed agricultural areas would not any more have an unlimited access to the free-of-charge grazing and browsing resources in these lands. Instead, they would have to link their animal husbandry

more to their lands that are under cultivation (*e.g.* forage production and crop residues). Thus, the vulnerable pasture resources of dry years will only be exposed to a tolerable exploitation, and tribal/community regulation mechanisms would guarantee a sustained utilization.

It should be investigated whether during the dry season, traditional livestock holders can obtain a comparatively free access to the crop residues in the rainfed agricultural areas. This had been the case up to the beginning of the eighties. This measure would relieve the strain of the dry season pastures during the second half of the dry season.

Vegetation mappings in wet years indicated an emergence of extensive high quality pastures up to about 16°30′ latitude. Hence, in humid years exclusive land-use rights would only be necessary during the second half of the dry season.

5. Conclusions

The weather-related variations in the biomass productivity are a consistent characteristic of the Sahel. This aspect has to be emphasized in the development programmes. The non-symbiotic relationship between mobile animal husbandry and stationary agricultural systems has led to an uncontrolled exploitation of the free-of-charge resources, and has triggered off an alarming qualitative and quantitative decline in the natural resources.

The need to strengthen community awareness towards degradation processes by establishing institutions for resource management is a major step in order to promote a sustained utilization to the Sahel. An important resource regulation mechanism could imply the reintroduction of a collective control of the local/regional water resources.

REFERENCES

AKHTAR, M. 1995. Degradationsprozesse und Desertifikation im semiariden randtropischen Gebiet der Butana / Rep. Sudan. — Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen, Göttingen, 105 : 166 pp.

HARRISON, M. N. 1955. Report on grazing survey of the Sudan. — *In* : Proceedings of the Department of Animal Production, Khartoum, pp. 1-21.

KIRK, M. 1994. Property rights in resources, pluri-activities and socio-economic differentiation : livestock production in the Butana today. — *In* : Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen : Interdisciplinary Research on Animal Production in the Sahel. Symposium (Göttingen, 28-29 October 1993), 98, pp. 125-149.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 752-767 (1998)

The Implementation of the Rio Conventions and Agenda 21 in the European Union and in Belgium

by

Luc HENS *

KEYWORDS. — Agenda 21 ; Biodiversity Convention ; Climate Convention ; Desertification Convention ; Global Environmental Facility (GEF) ; UNCED-Conference.

ABSTRACT. — This paper gives an overview of the implementation of Agenda 21 and its related documents by international organizations, the European Union and Belgium. At the international level, attention is paid to the implementation of national plans for sustainable development and to the financing of Rio's follow-up. The paper describes to which extent the Climate Convention, the Biodiversity Convention, the Forests Declaration, the Desertification Convention and Agenda 21 have influenced the (environmental) policy of the European Union. The overall picture which emerges shows that this influence is more coincidental than systematic. The Belgian government has established a National Council for Sustainable Development and (independently of Agenda 21) a product tax environmental legislation.The Climate Change Convention was ratified in January 1996. For the Biodiversity convention the ratification process is still going on. In this way, the legacy of Rio is characterized both by coincidence and fragmentation. Some of the main fundamental reasons for this situation include the concept of sustainability which opens up the possibility of an insufficient social basis for taking the measures which are rationally of critical importance. More research on sustainability and an intensive programme to raise public awareness and concern for the environment are advocated as elements of key importance to revive "the spirit of Rio".

MOTS-CLES. — Agenda 21 ; Convention sur la biodiversité ; Convention climatique ; Convention sur la désertification ; *Global Environmental Facility* (GEF) ; UNCED-conférence.

* Human Ecology Department, Vrije Universiteit Brussel, Laarbeeklaan 103, B-1090 Brussel (Belgium).

RESUME. — *La mise en œuvre des conventions de Rio et l'Agenda 21 dans l'Union Européenne et en Belgique.* — Cette contribution donne un aperçu de la mise en œuvre de l'Agenda 21 et des autres documents issus de la Conférence de Rio par des organisations internationales, l'Union Européenne et la Belgique. Sur le plan international, l'accent est mis sur l'application de différents plans nationaux pour le développement durable et le financement des actions résultant des discussions de Rio. Nous avons recherché dans quelle mesure la convention relative au climat, celle relative à la biodiversité, à la désertification, et l'Agenda 21 ont influencé la politique environnementale de l'Union Européenne. L'image générale ressortant de cette analyse indique plus des coïncidences que les résultats d'une application systématique. En Belgique, le gouvernement a créé le Conseil National pour un Développement Durable. De plus, il considère la législation sur les écotaxes comme un élément clé d'une société durable (même si cette législation a été établie indépendamment de l'Agenda 21). La convention sur le climat a été ratifiée en janvier 1996. La convention sur la biodiversité n'est pas encore ratifiée et la Belgique n'appartient pas aux nations intéressées par la convention sur la désertification. Nos données indiquent que l'héritage de Rio est souvent une question de hasards ; il s'agit d'une politique fragmentaire, plutôt que le résultat d'une politique bien établie. On peut citer différentes causes à cette situation : l'une a certainement trait au caractère vague et peu défini du concept de durabilité. C'est aussi une des raisons qui explique qu'il y a un manque de support social permettant d'appuyer des mesures nécessaires à l'environnement. Plus de recherches et plus de programmes de formation de l'opinion publique apparaissent nécessaires afin de revitaliser «l'esprit de Rio».

TREFWOORDEN. — Agenda 21 ; Biodiversiteitsconventie ; Klimaatconventie ; Conventie over de verwoestijning ; *Global Environmental Facility* (GEF) ; UNCED-conferentie.

SAMENVATTING. — *De implementatie van de Rio conventies en Agenda 21 in de Europese Unie en in België.* — Deze bijdrage biedt een overzicht van de inwerking van Agenda 21 en de andere documenten die voortgekomen zijn uit de Rio Conferentie in internationale organisaties, de Europese Unie en in België. Internationaal is er aandacht voor de implementatie van nationale plannen voor duurzame ontwikkeling en de financiering van de follow-up van Rio. Deze bijdrage beschrijft in welke mate de klimaatconventie, de conventie over de biodiversiteit, de conventie over verwoestijning en Agenda 21 het (milieu)beleid in de Europese Unie hebben beïnvloed. Het algemene beeld dat naar voor komt wijst op een eerder coïncidentele dan systematische impact. In België heeft de overheid een „Nationale Raad voor Duurzame Ontwikkeling" geïnstalleerd en schuift de „ecotaxwetgeving" (hoewel onafhankelijk van Agenda 21 tot stand gekomen) naar voor als een belangrijk element voor een meer duurzame samenleving. De klimaatconventie werd geratificeerd in

januari 1996. De biodiversiteitsconventie wacht nog op ratificatie en België is geen partner in de conventie over de woestijnen. Deze gegevens tonen aan dat de erfenis van Rio een zaak is van toeval en fragmenten. Hiervoor bestaan verschillende oorzaken. Eén ervan heeft te maken met het etherisch karakter van het begrip duurzaamheid. Mede daardoor is het sociale draagvlak om de voor het milieu noodzakelijke maatregelen te nemen, te gering. Meer onderzoek en meer programma's om de openbare mening te vormen lijken meer dan ooit noodzakelijk om de „geest van Rio" te doen herleven.

Introduction

When the participants at the United Nations Conference on Environment and Development (UNCED) and those at the parallel N.G.O. conference, the "Global Forum", left Rio de Janeiro, Brazil, on June 14th, 1992, they had mixed feelings.

On the one hand, they had accomplished a major task. They reached consensus on Agenda 21, an international plan for environmental management in close relationship with development. With its fourty chapters, it was and still is the largest and most comprehensive international agreement the U.N. has ever negotiated. Agenda 21 was accompanied by the "Declaration of Rio". This basic document lists the principles and fundamental rights human beings worldwide have to environment and development. Moreover, the most pressing issues of Agenda 21 were converted into two conventions, one on climate changes and the second one on biodiversity. By March, 1994 this series was also complemented by a convention on desertification. Once the conventions are signed by the U.N. member states (and almost 160 out of the 176 represented at the Rio Conference did so), they have to be converted into national laws providing them with a legal basis. This contrasts with Agenda 21 as a whole which has a moral, non-legally binding basis. The series of agreements was completed by a declaration on the management of forests. In short, they had accomplished a major job in defining sustainability and sustainable development on a worldwide basis in 1992 and for the (five) years to come.

On the other hand, they left Rio with major doubts on how to put the numerous suggestions into practice. Doubts raised by the tensions which became clear during the negotiations and which were sometimes diplomatically but not fundamentally dealt with. Doubts also about how the numerous projects and programmes which should put the agreements into practice can be financed. There was a general

feeling among the participants that the real work had yet to start, that only the fundamentals for the construction of sustainable development had been outlined, but that the hard core building work still had to start (HENS 1996).

In May 1996, almost four years after Rio, it is worthwhile making an interim balance sheet for this process. What has been achieved in the ambitious programme which was set out? What are the main obstacles? How can the process be optimized? This paper deals with these questions by analysing the influence of Rio on environmental policy at three levels : international worldwide implementation, the European Union and, in particular, the repercussions for Belgium. The picture which emerges from this analysis is not only informative about the characteristics of the implementation of the UNCED agreements but also makes possible some recommendations for making the process effective and efficient.

World-wide Initiatives

Systematically reviewing what international organizations, multilateral agencies and international N.G.O.s did during the past four years to apply the Rio agreements in environmental and developmental policies is beyond the aims and the possibilities of this paper. I will focus on two particular aspects which clearly illustrate the post-Rio process and difficulties :

— National Plans for Sustainable Development (N.P.S.D.) ;
— The Global Environmental Facility (GEF).

National Plans for Sustainable Development

The main objectives for the National Plans for Sustainable Development (N.P.S.D.) were given in Chapter 8 of Agenda 21 which states : "Governments ... should adopt a national strategy for sustainable development .. This strategy should build upon and harmonise the various sectoral, economic, social and environmental policies and plans that are operating in the country .. Its goals should be to ensure socially responsible economic development, while protecting the resource base and the environment for the benefit of future generations. It should be developed through the widest possible participation. It should be based on a thorough assessment of the current situation and initiatives".

In this way Agenda 21 sets out a general set of guidelines for an intellectually attractive (but not legally mandatory) instrument for

sustainable development. Leaving Rio however, few participants had any ideas about how to set up such a N.P.S.D. in practice.

The O.E.C.D. lent the planners a hand by organizing a workshop in Ottawa, Canada from 13th until 15th October 1993 on "Planning for Sustainable Development" (O.E.C.D. 1995). The aim was to discuss past experiences and future strategies of national governments and international organisations with respect to preparing and implementing N.P.S.D.. It is interesting to note here some of the conclusions :

— No unique model for a country-based N.P.S.D. exists. Each case must be tailored to the particular situation.
— Emphasis should be laid on the process of working out a strategy or a plan rather than a plan for its own sake. The process has a value in itself.
— Undue speed to produce a document rather than using the exercise as a vehicle for achieving more fundamental objectives would frustrate the process and prevent it from being really country-driven.
— Planning ambitions should be realistic, based on existing plans or starting with local planning exercises. Environmental planning experiences might form the basis of sustainable development plans.

No guidelines were prepared at this workshop nor were any structures set up for countries which were in the main willing to deal with the issue but were confronted with technical and practical difficulties. Particular attention was paid to listing these problems but little was done to solve them. The general atmosphere was one of turning the ambitious ideas of Agenda 21 into more realistic and modest actions.

The technical difficulties listed are enforced by a political argument : many countries fear that providing the public with data about its activities relating to sustainable development might threaten their national sovereignty. The end result is that by 1994, only fifteen countries had submitted a national report to the Commission for Sustainable Development (C.S.D.) which invites the governments of all U.N. member states to submit such a report. In 1996 the C.S.D. is still struggling finding the parameters to measure sustainable development in the different U.N. member countries worldwide.

The Global Environmental Facility (GEF)

In Rio, rich countries committed themselves, at least morally, to provide the poor countries with the necessary means to combat poverty

and to promote sustainable development. Quantitatively, the estimated cost of the implementation of Agenda 21 was estimated to be US$ 562 billion (bn) for developing countries alone, of which US$ 125 bn should be new, additional money.

Different means of achieving these goals were suggested :

— By increasing development aid. It is a long-standing ambition of the U.N. that rich countries should spend at least 0.7 % of their G.N.P. in supporting development in poor countries. This goal was reconfirmed in Rio. It can be shown that achieving this goal would raise US$ 70 bn of the US$ 125 bn which is estimated to be needed.
— Cancelling the debts of poor countries. The "Debt Swaps for Nature" system was especially recommended in Rio.
— Economic measures. Improvement in international trade giving special benefit to poor countries, *e.g.* by GATT agreements such as the "Trade Before Aid" principle and increases in investments in developing countries.
— The GEF. In 1991, one year before the Rio Conference, the World Bank and the U.N. set up an international financing mechanism known as the Global Environmental Facility (GEF). Funded by a small number of O.E.C.D. donor states, GEF was designed to provide less industrialized countries with small but additional financial incentives for tackling global environmental problems. The creation of such an international environmental finance agency arose from a growing appreciation of the need to provide developing countries with the means to leapfrog the polluting and wasteful stages of industrialization.

In 1992, following the financial discussions on the implementation of the Conventions and Agenda 21 in Rio, GEF emerged as one of the main candidates for the management of the money pledged by the donor countries. The operation of the GEF has two phases : an initial, pilot phase from July 1991 to June 1994 (the so-called GEF P) and a phase with new tasks, the post-pilot GEF 1, which operates from mid-1994 to mid-1997.

GEF P had access to funds of about US$ 12 billion. This money was provided by donations from 28 countries including 12 from the developing world. This "core fund" was supplemented by US$ 200 million from the Multilateral Ozone Fund (established by the partners to the Montreal Protocol). By the end of the pilot phase in 1994, US$ 742.1 million from the core fund had been allocated to 117 projects.

After an evaluation procedure, GEF phase 1 could start as a result of an agreement reached on March 16th, 1994. The management is still with the World Bank. There is a "Government Council" of 32 members, half of which are from developing countries, and both U.N.D.P. and UNEP continue to act as working agencies.

None of these instruments, apart from the GEF, were really new. On the other hand, their effective application could potentially enable the goals of Rio to be established. Therefore, it is important to evaluate their current status.

In the post-Rio period, the rich countries did not spend more on development aid. Due to so-called "periods of crisis", they often spent even less. In 1992, bilateral aid at the global level decreased by 6 % (Bureau Européen de l'Environnement 1995). As a rule, the 0.7 % objective has not been achieved ; none of the main O.E.C.D. donors spends more than 0.5 % of its G.N.P. on development aid : US 0.2 % ; Japan, 0.2 % ; the EU, 0.4 % on average although some countries spend much more, *e.g.* the Netherlands, 0.8 % and Sweden more than 0.7 %. Belgium, on the other hand, spent only 0.3 % in 1994 or less than half of what it donated twenty years ago.

As far as debts are concerned, they continue to increase in spite of the measures which were taken over the past three years. Between 1991 and 1992, global debt increased from US$ 1.479 billion to US$ 1.542 billion (Bureau Européen de l'Environnement 1995). On the other hand, the possibility of alleviating the debts to both the EU and the US of the poorest African countries is being studied.

As far as economic relationships are concerned, the GATT agreement of 1994 is an important new element. The new possibilities for more liberal worldwide trade encourage in particular a number of "promising" South American and Far-Eastern countries. On the other hand, there is substantial doubt over whether GATT will help sustainable development in Africa's poorest countries. Moreover, growing divergencies between the G77 countries (the "club" of the poorest countries in the world) also result in the political fragmentation of this group (DUMONT 1995).

The GEF is characterized by three main points of inertia. The first one is mainly psychological in nature. The World Bank has a poor reputation when it comes to sustainable development. In the past, it financed projects which have resulted in the deterioration of the environment and there are many examples which show that in their

evaluation of projects, economic considerations prevail over care for the environment. Moreover, the first phase of GEF was severely criticized for a lack of transparency and operational inertia. It is clear that some antipathy towards the World Bank has developed internationally. In spite of this psychological problem, the World Bank is still the main actor as the GEF is sure of its funding only until 1997.

The second problem has to do with the functioning of GEF P. In this phase, 115 projects which committed US$ 732.6 M were officially approved. But only a few projects have in fact started and only US$ 60 M have been distributed. This lag in project implementation was severely criticized during the 1994 evaluation. Even the most convinced defender of the GEF nowadays agrees that continued and enforced monitoring of its activities is necessary (HENS 1996).

The third problem is the amount of money that the GEF has available. Even when this was increased by US$ 2.02 bn after March 1994 and the money from Phase P never allocated to a project is included (out of the US$ 1,300 M available, only US$ 732.6 M were allocated), the amount of money available still remains relatively low compared to the amount needed. This is especially true in view of the fact that up to now, the projects which have been funded have mainly concerned global warming, biodiversity and international water management. Desertification and projects dealing with the many other important issues cited in Agenda 21 still remain low on the list of priorities for funding.

Implementation of Rio in the European Union (EU)

Political decision-making at the supra-national level has been particularly influential in determining environmental policy in the member states. More specifically, the most important policy issues in relation to the Rio Conference which have been dealt with at the European level of the Union are the Climate Treaty, the Biodiversity Treaty, the Declaration on the Forests, the Desertification Convention and Agenda 21. A summary of what has been achieved by the EU on these different issues will now be given (Bureau Européen de l'Environnement 1995).

The Climate Treaty

In Rio, 154 U.N. member states and the European Community signed the Convention on Climate Change. On December 13th 1993, the EU ratified this Treaty, although there was substantial disagreement

on the strategies for reducing CO_2 in the member states. On March 21st 1994, the Treaty came into force. The main aim is that, by the year 2000, CO_2 emissions should have been reduced to the levels present in 1990.

At present the EU has adopted three elements of an overall energy policy. A fourth element, a CO_2 tax, is still to be adopted. These four elements are :

— The SAVE Directive by which the member states have agreed to limit CO_2 emissions by improving their energetic capacity in areas such as the insulation of buildings, changes in the cost of energy and investments in rational energy use.
— The ALTENER programme for the promotion of renewable energy sources.
— A monitoring system for CO_2 and other greenhouse gases which imposes an obligation on the member states not only to monitor global change gases but also to plan for reductions in their emission.
— In contrast to the three elements given above, the energy or CO_2 tax still remains to be adopted. It is the most heatedly debated element of the EU's energy policy. It divides the northern from the southern states of the EU and the main fossil energy suppliers. It is also a preferred field of lobbying for the energy industry which does not like (environmental) taxes at all.

Biodiversity

The Biodiversity Convention was signed in Rio by 156 countries and by the European Community. It was ratified by all the EU member States except Belgium and Ireland, and came into force on December 29th, 1993.

An important EU policy element in this context is the directive on the conservation of natural habitats and wild fauna and flora (92/43/C.E.E.) which was adopted in May 1992 and came into effect in June 1994. This directive is the basis for a common policy on animal, plant and habitat conservation.

As far as the biotechnology part of the Biodiversity Convention is concerned, the EU's policy is based on two directives : one on the voluntary release of genetically modified organisms into the environment (90/220/C.E.E.) and a second one on the use of genetically modified organisms (90/219/C.E.E.).

It should be noted however that, although the EU's policy contains elements which are of key importance within the Biodiversity Convention framework, these policy elements do not cover the scope, specific aims and instruments foreseen by the Convention. A key element in the Convention concerns, for example, the establishment of national plans for the conservation and sustainable use of biodiversity. In this field, there is no union-wide strategy and only a few member countries (such as the UK and Italy) have finalized their national strategies.

Although there are different policy elements in the EU legislation which are important for the Biodiversity Convention, one cannot say that the EU played a stimulating and guiding role in the implementation of the Convention by the member states.

Forests

Since the EU had already enacted legislation for the conservation of both tropical and temperate region forests before the Rio Conference, it was not surprising that, during the preparation of the Declaration on Forests, the Community supported (and still supports) the necessity of a convention on forests which would co-ordinate conservation efforts and rational management at a global level. This also explains why the environment ministers decided to "work actively" on the implementation of the declaration immediately after Rio.

This "active work" consists of different elements. Although the list is not exhaustive, the elements are important :

— A permanent committee for forests (DG VI, the Agriculture Directorate) ;
— National plans for forest management ;
— Support for tropical forest conservation (since 1979) and rules for tropical forest conservation which are based on the guidelines given in Rio's Declaration on Forests ;
— Different initiatives to stimulate the setting-up of an European "eco-label" for (tropical) wood.

Desertification

The Desertification Convention was planned by the UNCED Conference and is the first convention to have been negotiated after the Rio Conference was over. The text was finalized in June 1994, and the convention was signed in Paris in October 1994. All EU member states except Belgium and Austria signed the convention.

Although there are no specific EU initiatives for putting this convention into practice, 10 member states have decided to allocate special funds to support programmes in the regions affected especially in Africa.

It is however too early to evaluate the results of this convention which was signed only last year.

Agenda 21

In May 1992, environment ministers already considered Agenda 21 to be one of the essential results of the Rio Conference. Shortly after Rio, the heads of state and government declared in June 1992 in Lisbon that they would establish national strategies for putting Agenda 21 into practice.

It is clear that, as far as the contents are concerned, the EU agreed to do this according to the main guidelines of Agenda 21. A remarkable document in this context is the white paper by EU Commission President Delors (1993) in which he advocates :

— A political strategy which allows the integration in a systematic way of all externalized costs into the market price ;
— Macro-economic instruments (indirect fiscal instruments, fiscal regulations, etc.) to reach the same target ;
— Sectoral policies having sustainability as one of their targets.

In practice, the main instruments which were produced to make these political ambitions concrete are the EU's State of the Environment Report (1993) and the Fifth Action Programme (1990) which is called "Towards Sustainability". This Fifth Action Programme proposes a set of approaches, instruments and principles which were completely new at the time the programme was launched : shared responsibility, subsidiarity and the precautionary principle next to fiscal and educational instruments which promote public participation. The programme is to be put into action using two basic mechanisms :

— As an important source of inspiration for the establishment of national environmental plans ;
— As the basis for a set of directives in different sectors such as agriculture, water, industry, transport, waste and energy.

In conclusion, although the environmental policy lines coincide at different points with "the spirit of Rio", there has not been, to date,

any particular action taken to implement Agenda 21 in a systematic way. In a descriptive analysis such as this one, it is impossible to determine which elements are just coincidentally in line with the Rio documents and which ones have really been influenced by the conference outcome. However, the lack of a specific implementation policy has resulted in some important lacunae. They have to do with aspects of the different parts of Agenda 21 :

Part 1 : the EU's policy is characterized by a failure to make the concept of sustainability operational and by its limited effort in redirecting consumer patterns towards the principles of the Rio Declaration.

Part 2 : environmental problems are probably covered the best by the EU's policy. On the other hand, its weak position in the discussion on desertification and on the implementation of this convention indicates the low priority given by the EU in its international policy to some of the most important environmental problems.

Part 3 of Agenda 21 promotes the idea of consensus between target groups as a necessary basis for environmental policy. Currently, this is one of the weakest elements. Everyday experience proves that it is not because people rationally agree that long-term thinking on environmental issues is necessary or that a general air or water quality level should be reached that they are prepared to match the action necessary to protect the environment with (short-term) industrial, agricultural, tourism or consumer targets. Much more attention needs to be paid to policies promoting the social basis for the implementation of Agenda 21. If not, energy taxes may never be imposed and a decline in existing standards in, for example, water quality for recreation and consumption is likely.

Part 4 : in this instrumental part, the EU is decidedly remiss in not having taken a leading role in the implementation of Agenda 21 despite the avowed desire by the heads of the member states for it to do so.

In the different areas where the EU's policy is at work, there is a distinct heterogeneity among the different initiatives : some directives or programmes have already been implemented. Others proceed slowly and the discussions seem to be far from reaching a conclusion. The slow EU decision-making procedures and a misinterpretation of the "subsidiarity" principle are often cited as reasons for this heterogeneity.

Belgium

At the Belgian federal level, the most important post-Rio action up to now has been the creation of the National Council for Sustainable Development. After long discussions behind closed doors, the federal government decided to establish this council during the second half of 1993. The inauguration took place on October 13th 1993. The presidency of the council by his Royal Highness, Prince Philip of Belgium, and the different ministerial addresses delivered on the occasion of the inauguration of the council, point to the importance Belgium formally wished to give to its activities. According to Chapter 38 of Agenda 21, this National Council has to work on the implementation of the concept of sustainable development in general and the results of the Rio Conference in particular.

On the other hand, the Council has to operate with some difficulties built in to its structure. Its composition is one of them. Noticing on the one hand that most environmental issues are under the authority of the regions and, on the other hand, that the representation of the regions in this National Council is rather limited (6 representatives out of 56 members), it is doubtful whether the composition of the Council is appropriate for dealing with most of the concepts and issues of sustainable development in an adequate way. In particular, the absence of representatives from the existing regional councils for environmental advice (who are specialists in these matters) is an important drawback.

Although the National Council is chaired by an important member of the Royal Court, the government apparently does not have significant ambitions for the Council. In 1996 a new Royal Decree has been proposed which specifies the tasks of the council. Setting up a federal plan for sustainable development and producing a state of the Belgian environment will be central in its forthcoming activities.

Another initiative by the federal government is the implementation of an eco-tax system. Although such a system theoretically fits within the targets of Agenda 21, its practical organization in Belgium is particularly inefficient. It was set up under great political duress in a manner that is typical for the Belgian federal government. It was clear from the beginning that the government was not at all enthusiastic about these eco-taxes. The rules for the taxes have proved to be very difficult to implement and no opportunity is lost to delay the implementation of this system. The result is that a theoretically

promising instrument for environmental policy is almost completely ineffective due to a lack of commitment on the part of the government itself which is under great pressure from industry and business on this matter.

Table 1

Status in May 1996 of the acts Belgium undertook to follow up the UNCED Conference (Rio de Janeiro, Brazil, June 1992)

	Status	**Remarks**
Climate Change Convention	Signed June 1992 Ratified January 1996 Party to the convention April 1996	No specific environmental policy to realize 5 % reduction target (2000-1990)
Biodiversity Convention	Signed June 1992 Not ratified	
Global Environmental Facility (GEF)	GEF-pilot phase (GEF-P) (July 1991-June 1994) Notification of participation GEF-restructured (GEF-1) February 1995 (July 1994-June 1997)	242 million BEF 1.1 billion BEF
Desertification Convention	Not signed Not ratified	Procedure to access is going on 2.10^6 BEF will be contributed to secretariat costs in 1996
Commission for Sustainable Development (CSD)	Belgium is one of the 50 members of the CSD since its inauguration in September 1992	
National Council for Sustainable Development	Installed by Royal Decree of October 1993	To be restrucured by 1/1/1997

Table 1 summarizes the state of the art of the administrative acts Belgium undertook to following up UNCED (Status May 1996). It took three years and a half to ratify the Climate Change Convention, which is not followed up by a specific rational energy use policy. The Biodiversity Convention has not been ratified yet and the country is not a partner in the Desertification Convention. On the other hand, the country is one of the fifty members of the New York-based Commission for Sustainable Development since its establishment in 1992. After important initial difficulties it also acts as a partner in the Global Environmental Facility.

Conclusion

More than four years after the Rio Conference, there is little doubt that the ideas and the documents of the conference have influenced environmental policy in the European Union and its member states. This influence is mainly of moral and inspirational nature and not the result of a policy which aims to achieve the systematic implementation of Agenda 21 and its Conventions.

This lack of a policy for systematic implementation of Agenda 21 explains why implementation appears highly fragmented ; both the EU and its member states are prepared to implement bits and pieces in line with the guidelines of Agenda 21 but whether this will be sufficient for sustainability is very questionable.

This paper has uncovered at least two main reasons for this situation :

— Sustainability as a concept is still much too vague and thus too difficult to make operational. There is still no agreement on how to measure sustainable development. This partly explains the inertia which plagues the setting-up of national plans for sustainable development and it causes major difficulties for the C.S.D. in attempting to follow up the process. This difficulty in making the concept operational also explains why sustainable development is often mentioned as a benchmark for (environmental) policies but why so few fields of actions can be found which really put the concept into practice. Inertia is often at the root of the lack of policy momentum which environmental issues have faced since the Rio Conference.

— Implementation of sustainability is not the duty of policy-makers alone. Issues of environment and development have such far-reaching effects in society that every group has to take up its own responsibilities and do its part of the job. Although in this post-Rio era, farmers, industrialists and consumers are more often confronted with questions on environmental issues than before, as a rule, environmental concerns are not given priority in the decision-making process. A "business as usual" reaction explains both why the EU and a country such as Belgium seems to be unable to implement eco-taxes. The lack of a broad public support for sustainability also explains why, for example, the Belgian government can be so negligent in ratifying conventions, why it did not sign the Desertification Convention and why it did not contribute initially

to the GEF 1 phase. In general, it also explains, at least in part, the worldwide lack of financial resources for implementing Agenda 21.

These findings force to the conclusion that more attention must be paid to explaining to all the target groups why environmental care is of crucial importance for society. Only with this knowledge is sufficient public impetus likely to be generated for converting the currently widespread practice of only paying lip service to the concept of sustainable development into truly sustainable behaviour on the part of all the target groups concerned.

REFERENCES

Bureau Européen de l'Environnement 1995. La mise en œuvre des accords de Rio et la Communauté Européenne. — Bureau Européen de l'Environnement, Brussels, Belgium, 48 pp.

DUMONT, H. 1995. De zoektocht van de Verenigde Naties naar duurzame ontwikkeling. — *In*: Openbare zitting, Koninklijke Academie voor Overzeese Wetenschappen, Brussel, Belgium, pp. 29-54.

HENS, L. 1996. The Rio Conference and Thereafter. — *In*: NATH, B., HENS, L. & DEVUYST, D. (eds.), Textbook on Sustainable Development. VUB Press, Brussels, Belgium, pp. 81-110.

O.E.C.D. 1995. Planning for Sustainable Development, Country Experiences. — O.E.C.D. Publications, Paris, France, 98 pp.

International Conference
"Tropical Climatology, Meteorology and Hydrology"
(Brussels, 22-24 May 1996)
Proceedings edited by
G. Demarée, J. Alexandre and M. De Dapper
pp. 768-785 (1998)

Water for Sustainable Development in Tropical Areas

by

Zbigniew W. KUNDZEWICZ *

KEYWORDS. — Sustainable Development ; Water Resources ; Water Management ; Tropical Areas ; Drought and Desertification ; Observation Networks.

ABSTRACT. — Availability of freshwater in sufficient quantity and quality is an indispensable condition for sustainable development. Water availability influences demography, health, agriculture, rural and regional development, biological diversity, transport, consumption and production patterns. This general truth is of particular importance in tropical areas, where scarcity, abundance or pollution of water cause destruction and human suffering. In the present contribution, discussion focuses on notions and conditions of sustainable water resources development in tropical areas, as outlined in Agenda 21. Knowledge of water resources is seen as an indispensable component of sustainability. That is why water resources assessment in tropical areas, understood as examination of availability and use of freshwater, including quantity and quality aspects, is so important.

MOTS-CLES. — Développement durable ; Ressources en eau ; Gestion de l'eau ; Régions tropicales ; Sécheresse et désertification ; Réseaux d'observations.

RESUME. — *De l'eau pour un développement durable en région tropicale.* — La disponibilité de l'eau douce en quantité et en qualité suffisante est une condition indispensable pour le développement durable. La disponibilité de l'eau influence la démographie, la santé, l'agriculture, le développement rural et régional, la diversité biologique, le transport, la consommation et les modèles de production. Cette vérité générale revêt une importance particulière dans les zones tropicales où la rareté, l'abondance ou la pollution de l'eau sont cause de destruction et de souffrance humaine. Dans cette note, la discussion se concentre sur des notions et des conditions de développement durable de ressources en eau dans les régions tropicales comme il a été souligné dans

* Research Centre of Agricultural and Forest Environment Studies, Polish Academy of Sciences, Poznan (Poland).

l'Agenda 21. Le savoir en ressources hydriques est reconnu comme une composante indispensable de développement durable. Pour cette raison, la détermination des ressources hydriques, entendue comme une évaluation de la disponibilité et l'usage de l'eau douce, y compris les aspects de quantité et de qualité, est d'une telle importance.

TREFWOORDEN. — Duurzame ontwikkeling ; Waterbronnen ; Waterbeheer ; Tropische gebieden ; Droogte en verwoestijning ; Meetnetten.

SAMENVATTING. — *Water voor duurzame ontwikkeling in de tropische gebieden.* — De beschikbaarheid van zoetwater in voldoende hoeveelheid en van goede kwaliteit is een onvoorwaardelijke conditie voor duurzame ontwikkeling. De beschikbaarheid van water beinvloedt demografie, gezondheid, landbouw, rurale en regionale ontwikkeling, biologische diversiteit, transport, consumptie en productiepatronen. Deze algemene waarheid is van bijzonder belang in tropische gebieden, waar zeldzaamheid, overvloed of verontreiniging van water de oorzaak zijn van destructie of menselijk leed. In deze bijdrage wordt aandacht besteed aan de grondbeginselen en condities van de ontwikkeling van duurzame waterreserves in tropische gebieden, zoals uitgelegd in Agenda 21. De kennis van waterreserves wordt aanzien als een onmisbare component van de duurzaamheid. Om die reden is de beoordeling van waterreserves in tropische gebieden, begrepen als onderzoek voor de beschikbaarheid en gebruik van zoetwater, inclusief kwantiteit en kwaliteit, zo belangrijk.

Introduction — Concepts of Sustainability

Although the term "sustainable development" is broadly used worldwide nowadays, there is still no common understanding of this notion ; the concept may mean different things to different people. Because of ambiguity and self-contradiction in the term "sustainable development" (oxymoron?), it is difficult, if at all possible, to delineate the borders between "sustainable" and "non-sustainable" in a unique way. However, it is important to try and unify the notions contained in several available definitions and to translate them into concrete measures, criteria and controls applicable to specific issues.

The adjective "sustainable" stems from a Latin verb *sustinere* (to uphold). The corresponding English verb, "to sustain", has such meanings as : to maintain, to keep going, to keep in being, to keep from falling, to carry on, to withstand, to bear, to support life, to provide for the life or bodily needs, to furnish with the necessarities of life (LITTLE 1972). Many of these meanings are encapsulated in the term "sustainable development" being broadly used nowadays.

In fact, "sustainable development" is an old concept that has been used in management of renewable natural resources to ensure that the rate of harvesting a resource is smaller than the rate of its renewal. There have been a number of available definitions among which the one from Brundtland Report (W.C.E.D. 1987) is commonly known : "humanity has the ability to make development sustainable — to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs". This aim should be achieved while minimizing the losses (maximizing the gains) to economic, social and environmental systems. A sample of alternative definitions read :

— Living on the "interests" from the Earth "capital" without depleting the possessions inherited from former generations ;
— Improving the quality of human life within the carrying capacity of supporting ecosystems ;
— Keeping dynamic equilibrium of the Earth system over a long (theoretically infinite) time ;
— Property of the system whose essential features remain within satisfactory domain over a long time ;
— Development minimizing probable future regret for decisions taken today.

The common element contained in the above definitions is the postulate that the inter-generational equity cannot hold unless the natural ecological systems are conserved.

Availability of water in adequate quantity and quality is a necessary condition for sustainable development. Water, the basic element of the life support system of the planet, is indispensable to sustain any form of life and virtually every human activity. U.N. Water Conference in 1977 agreed that "all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs". Access to safe water has therefore become a kind of human right. The International Drinking Water Supply and Sanitation Decade, proclaimed by the United Nations in the 1980s, provided access to potable water (understood as a source of water supply of fifty litres of drinking quality water within two kilometres from home) to 1.3 billion human beings. However, despite this achievement of the Decade, there is still a number of the same order of magnitude of those lacking access to clean and safe water. After estimates by WHO, about 80 %

of all diseases and one-third of all deaths in developing countries are related to water. Water-related diseases, such as diarrhoea, malaria, schistosomiasis, river blindness, Guinea worm, and others kill globally perhaps 25,000 human beings a day that is over seventeen people in one minute. Heads of states and governments gathered at the World Summit for Children in September 1990 declared that the universal access to water supply and sanitation should be reached by the year 1995. Yet, adequate and reliable supply of water of proper quality for the entire population of the Globe and for preserving hydrological, biological and chemical functions of ecosystems is still a remote goal.

Global water consumption has increased about eightfold since the beginning of the 20th century. This has been caused by population growth and increase of the *per capita* water use. The continuing population growth with consequences for food production, and justified aspirations of nations and individuals towards better living conditions, will undoubtedly cause the demand for water to grow further.

The problems of water shortage are likely to be the most dominant water problems in the forthcoming century. In a number of countries a dramatic drop of the *per capita* availability of water, to largely below the level recognized now as the threshold of scarcity, is foreseen. In order to manage water in the age of scarcity, assessment of available water resources is indispensable. This refers both to characteristics of mean values and of variability, and both to water quantity and quality aspects.

How can the sustainable development of water resources be achieved? A set of answers to this question is proposed in Agenda 21 (UNCED 1993) bearing a subtitle "Programme of Action for Sustainable Development". In this "comprehensive blueprint for action to be taken globally", freshwater resources issues are dealt with in Chapter 18, entirely devoted to this topic, and in a number of other chapters dedicated to several aspects of sustainable development where water components play a significant role. Agenda 21 (UNCED 1993) emphasizes sustainability of vulnerable areas, such as arid and semi-arid lands suffering from frequent and severe droughts and jeopardized by desertification (Chapter 12), and vulnerable mountainous environment (Chapter 13).

In Chapter 18 of Agenda 21, seven principal programme areas are proposed for the freshwater sector, as given in table 1. Table 1 also shows the estimates of the average total annual expenditures that have to be borne in the time interval 1993-2000 in order to implement the

Table 1

Estimated annual costs of implementation of objectives of Agenda 21 (Chapter 18) in million US$ (of 1992)

Programme area	Costs for international community	Total costs
Integrated water resources development and management	115	
Water resources assessment	145	355
Protection of water resources, water quality and aquatic ecosystems	340	1,000
Drinking-water supply and sanitation	7,400	20,000
Water and sustainable urban development	4 ;500	20,000
Water for sustainable food production and rural development	4 ;500	13,200
Impacts of climate change on water resources	40	100
Total for all programme areas identified in Chapter 18	**17,040**	**63,770**

activities deemed necessary in Agenda 21. These costs have been suggested by the Secretariat of UNCED and, as noted in Agenda 21, they are "indicative and order-of-magnitude estimates only and have not been reviewed by Governments. Actual costs and financial terms, including any that are non-concessional, will depend upon, *inter alia*, the specific strategies and programmes Governments decide upon for implementation".

The estimated costs of implementing Agenda 21, as listed in table 1, are given in two categories: expenditures of the international community on grant or concessional basis and total costs for both international and national communities. It results from table 1 that the three major expenditures in the freshwater sector are related to such programme areas as drinking water supply and sanitation, water for sustainable urban development and for rural development and food production. Each of these objectives requires support in excess of 10 billion US$ a year. However, it may well be that the investments in one of the less costly areas such as integrated water resources management and water resources assessment could have a strong leverage effect with excellent cost-benefit rates.

An estimate of the overall average annual costs of implementing all, not only water-related, areas listed in Agenda 21 in developing countries is 600 billion US$ including about 125 billion US$ on grant and concessional basis. Notwithstanding the activities of multilateral

development banks and funds, bilateral assistance programmes, debt relief, innovative funding (*e.g.* re-allocation of resources committed at present to military purposes), the sums really disbursed at the global level are largely below the above estimates of necessary cost of implementation.

A recent imperative for sustainable development and management is the worldwide acceptance of the integrated approach. This notion is based on the perception of water as an integral part of the ecosystem, a natural resource and a social and economic good. It embraces quantity and quality aspects of surface and groundwater, and multi-interest competing demands. It should enhance the efficiency of water use, sustainable water utilization patterns, water conservation, and wastage minimization. Rational land use and the landscape planning should play an important role in controlling the water distribution, and abatement of pollution and eutrophication of freshwater bodies.

Water Resources for Sustainability of Vulnerable Areas

The word "tropical" is sometimes misinterpreted as hot and humid. Indeed, a large part of tropical areas are humid tropics, but a significant portion of the belt between the Tropics of Cancer and of Capricorn is not humid.

In humid tropics, many water-related problems are linked with water excess : destructive floods. For example, Cotonou, the capital city of Benin, suffered severe floods in 1988 and 1991 which made the economic life stop for a week. Floods are recurrent there and 56 % of houses are flooded regularly. Poor water quality is another severe problem. Even when perennial surface water is available, its consumption in an untreated state presents a serious risk to human health because of contamination by pathogens or waste. Burning water-supply problems occur in unsustainable human settlements, such as slums around mega-cities, where the poor have no access to public, hitherto safer, tapwater. They may have to buy poor quality water from vendors and pay much more than the price charged to more wealthy inhabitants who have access to public water supplies.

In arid, semi-arid and dry sub-humid parts of the tropical belt precipitation is typically short- lasting (rainy season or short rain events scattered unevenly) followed by a long no-rain hot period with high evaporation. The rain typically falls as a violent shower of high amplitude and uneven spatial distribution.

Sahelian and Central Africa, that is a vast belt stretching from Cape Verde Islands to the east of Sudan, has been hit by severe and long-lasting drought since the beginning of 1970s. A sharp decrease in rainfall has been observed, accompanied by significant reduction of river flow. For example, since 1970 the mean discharge of the River Niger in Koulikoro has nearly halved from its levels in the sixties, and nearly dried up at Niamey in 1984 and 1985. The Niger recovered somewhat after 1990 but has not reached its former flows. Figure 1 (data from CHEREL-GEFFARD & ALBERGEL 1996) shows the observed changes in seasonal flow distribution of the River Senegal at Bakel, averaged for different time periods. In 1974, 1982, 1984 and 1985 the river nearly stopped flowing (SEHMI & KUNDZEWICZ 1997).

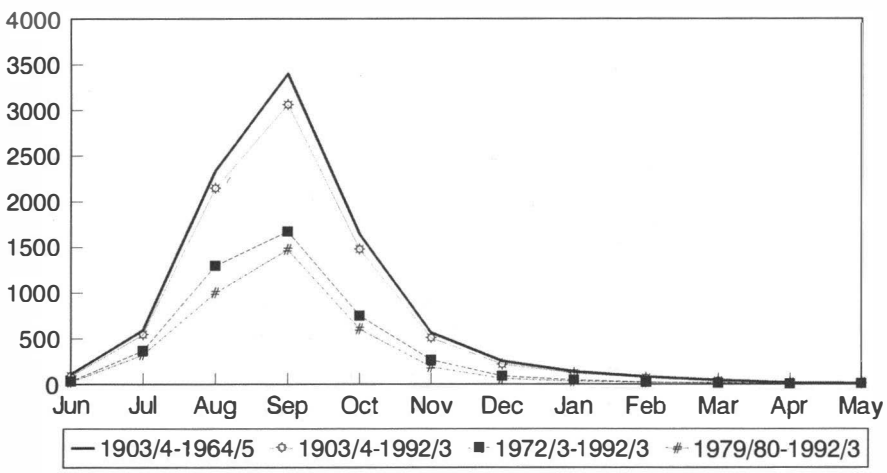


Fig. 1. — Time series of monthly mean flow [in m^3/s] in Senegal at Bakel. Data from CHEREL-GEFFARD & ALBERGEL (1996).

A drought, an eternal plague endured repeatedly by mankind, can be defined as the naturally occurring phenomenon of prolonged and severe water deficits ; that is, periods during which the natural water availability is significantly below the normally recorded level. This notion should not be confused with aridity where water is always in short supply ; that is, a "permanent drought" is a normal feature. Droughts may hit large areas (up to sub-continental scale) and, by their nature, extend in time, lasting months through years to decades.

A drought manifests itself by low values of such hydrological variables as precipitation, river flow, river and lake level, soil moisture and groundwater level.

Prolonged droughts which frequently hit large tropical areas, in combination with human activities, may lead to desertification of vulnerable areas and to degradation of soil and bio-productive resources. According to FALKENMARK (1988), soil permeability and water retention capacity which secure availability of water for an adequate production of biomass are conditions of sustainability. The extent of the problem of drought and desertification in general, and in Africa in particular, has raised a global concern. It has forced the international community to adapt the "United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa". The Convention refers to "arid", "semi-arid" and "dry sub-humid" areas where "the ratio of annual precipitation to potential evapotranspiration falls within the range from 0.05 to 0.65".

Drought may trigger desertification but human factors play a significant role (GLANTZ 1994). Overcultivation, overgrazing, deforestation and poorly drained irrigation can destroy the soil at a very fast pace. It takes a long time for the soil to form, but little time to be destroyed. The present annual rate of global soil loss reaches 24 billion metric tons.

The non-availability or near-absence of water resources is the primary element of desertification (SEHMI & KUNDZEWICZ 1997). Therefore, all action plans to combat drought and desertification must be geared around the possibilities of extending the availability of water. All means which could serve this aim have to be considered. Some of the technical measures of water conservation and augmentation are : improved land-use practices ; conjunctive use of surface and groundwater ; watershed management ; rainwater/run-off harvesting ; recycling water ; water transfer studies ; erosion control and sand dune fixation ; development of water allocation strategies among competing demands. Not least, improvement of water conservation via reduction of the non-accounted for water (which soars to 60 % and more in several locations in Africa) deserve attention. Using groundwater reservoirs (aquifers) to store water, when available, is more advantageous than surface water storage which is subject to very high evapotranspiration loss. Non-technical human factors reducing anthropogenic pressure on the environment such as population dynamics (birth control), legislation, organization, and education are of primary importance. Other controls of drought

and desertification embrace : afforestation or reforestation, soil conservation policy, and control of grazing.

In order to combat desertification and promote development, a major input of financial and human resources is necessary. If such an input is not available, there is little hope of halting the process of desertification or mitigating the ravages caused by long droughts. It is worth applauding the desire of several developing countries who wish to break the dependency syndrome, i.e. not to count entirely on the uncertain external aid (W.M.O. 1995a).

Water resources management has traditionally been based on the assumption of stationarity, that is one of unchanged climate. However, the drought anomaly of exceptional magnitude and duration observed in the last decades in the Sahel makes many a specialist question the stationarity assumption. Several studies indicate changing frequency of dominating weather circulation patterns. Insurance industry is being concerned with the increase of compensations following natural water-related disasters.

If the long-term climate change studies augur sharpening hydrological extremes in the warmer World, then the consequences for reservoir design codes of practice would be severe. One would have to design and build bigger storage volumes to accommodate larger flood waves and to better fulfil the growing demand for water during the prolonged and more frequent droughts of increasing severity. Existing infrastructure may not guarantee the adequate level of protection and may need to be re-developed. There is however an insufficient knowledge of future climate variability and no firm message referring to the future can be addressed to water management specialists.

A fair measure of sustainability of water use is the ratio of annual water withdrawals to internal renewable supplies (use to resource ratio). One can define a value (*e.g.* of 25 %) which can be accepted as the lower limit of water stress. According to Gleick (1993), Libya is withdrawing 374 % of its internal renewable supply. There are abundant reserves under the Sahara Desert in Southern Libya, of the order of many tens cubic kilometres, partially at the depth of 2,000 m and more. Mining fossil water reserves at considerable depths is not a sustainable policy, as it means irreversible exploitation of a non-renewable resource. This fossil water is mostly between 14 and 38 thousand years old ; i.e. dates back to the time when the climate was wetter.

When discussing examples of unsustainable policies one can recall the practical question posed by Loucks (1997). Should humans strive

to sustain every region, every small piece of land, or else, perhaps some areas should be sacrificed for the benefit of the whole? It is easy to criticize the concept of sacrifice but, as mentioned earlier, resources for achieving sustainability of the whole of the planet are not available anyway. Even if consumption of non-renewable resources is considered unsustainable per definition, LOUCKS (1997) suggests that use of such resources may "improve technology, enhance our knowledge, create a greater degree of societal stability and harmony and contribute to our culture". Thus, there may be a number of advantages to compensate the loss of a portion of a non-renewable resource. It is not excluded that use of a non-renewable resource may enhance the welfare of future generations thus fulfilling one of the conditions of sustainability.

Hydrological Data for Sustainable Development

Hydrological information on water levels, discharge, sediment and water quality is necessary for a range of projects, whereas in particular applications information on time series, maxima or minima of the variable may be needed (cf. W.M.O. 1994). Examples of such projects for which hydrological information is indispensable comprise water engineering works (dams, reservoirs, spillways, canals, diversions, hydropower, etc.) as well as quality considerations, zoning, insurance, standards and legislation. Moreover, availability of hydrological data in the real time is needed for management of water resources, and flood forecasting and control.

The basic component of water management is a water storage reservoir typically serving multiple purposes, such as flood protection, water supply, power. Hydroclimatological information plays a significant role in both reservoir design and operation. In the design phase, estimating of the necessary reservoir capacity is based on time series of inflows and evaporation. Estimating evaporation losses from a reservoir is of extreme importance in hot and dry climates, where the annual total of free-water evaporation may be as high as 2,500 mm. The very issue of feasibility of a reservoir potentially subject to excessive evaporation is at stake. Hydroclimatic information is also necessary to dimension the size of spillway to discharge a flood wave and this has to be done based on the available data.

Without adequate knowledge and understanding, uninformed decisions are made that may lead to unsustainable situations. In order to minimize the chances of inadequate design, construction or operation

of water systems or other hydrological projects, an adequate level of basic data collection is required. Therefore, hydrological observations should be recognized as an essential component of sustainable development and management of water resources. If the hydrological cycle is not monitored with appropriate spatial and temporal coverage, decision-makers and the general public may not be informed of water problems until late, when consequences are already severe and straightforward solutions cannot be implemented. Hydrological observations provide the basis for essential early warnings in case sustainable development is threatened. These can allow effective actions to be taken without having to wait for great material losses and human suffering.

Before launching a freshwater-related project, or considering forecasts and response strategies, it is essential to know how much water and of what quality has been available in the past-to-present. The basic hydrological network should therefore provide a level of hydrological information that would preclude gross mistakes in decision-making related to freshwater.

The quality of design of a dam depends on the availability and accuracy of information available for the site-relevant conditions. It is estimated that a number of dam failures have occurred due to inadequacy of the available data. Even major projects have been launched with meagre hydrological background, the typical excuse being the lack of time for data collection programmes. The Akosombo dam on the river Volta was claimed to have a potential production of 5,000 GWh, whereas these calculations were based on a relatively short time series with particularly high flows. In the eighties, only 60 % of this power was reached in the average with the lowest annual mean of 1,468 Gwh in 1994 (W.M.O. 1996).

Already the U.N. Water Conference in 1977, and many other meetings and bodies since, have recognized the inadequacy of hydrological networks. This inadequacy is growing. Recent studies in Africa (*e.g.* Sub-Saharan Africa Hydrological Assessment financed by the World Bank and the U.N.D.P.) have demonstrated that the phase of expansion of networks of hydrological observing stations that took place in the 1970s had passed long ago. Now, hydrological networks are in decline. When confronted with budgetary cuts, it is not a standard practice to strive towards an optimal reduction of a network, minimizing the information loss. More common is elimination of observation stations which are difficult to access and expensive to run, even if loss of such stations may be highly detrimental to the global monitoring

and to the state of our knowledge. Even stations where long time series of observations have been carried out may urgently require up-grading or revitalization.

Since the early 1980s hydrological data collection and analysis worldwide have not been keeping pace with the actual water development and management needs. Despite the increasing demands for water and the growing water stress, calling for improved and scientifically-based water management, the largely inadequate funds available for maintenance and operation of Hydrological Services are being further reduced. Governments are not able or are not willing to adequately fund National Hydrological Services. It is a paradox that Governments are willing to invest many millions in projects with fragile hydrological data foundations, ones which may not be sustainable, but they are unwilling to spend the very much smaller sums needed to ensure that data are collected to meet current and future needs and to demonstrate the sustainability of projects.

The situation is particularly sensitive in the conflict-prone areas where a number of countries are largely dependent on international rivers. Maintenance of good quality hydrological observation networks and arranging for data to be internationally exchanged is an imperative.

In order to mitigate the impacts of drought and desertification, strengthening the knowledge base of water resources is necessary (SEHMI & KUNDZEWICZ 1997). This embraces, first of all, the revitalization of networks of hydrological observing stations. The necessary knowledge base should extend beyond the classical water sciences, embracing also economic, political and social systems that are intimately interlinked. Such socio-economic targets as eradication of poverty and alternative livelihood systems, which may largely contribute to combating desertification, require a substantial knowledge base.

Information about hydrological networks in countries of Africa is compiled in INFOHYDRO (W.M.O. 1995). One can note, for example, that Chad of the area of 1,284,000 km^2 has only three stations where water levels are monitored (1987). As far as the number of water level and discharge stations with longer time series of records (more than or equal to 30 years) is concerned, according to INFOHYDRO (1995), Botswana has no such stations (1985) and Burkina Faso has one water level and three discharge stations (1983).

Table 2 shows W.M.O. recommendations on minimum network density or maximum area per station (W.M.O. 1994, PERKS *et al.* 1995) for selected hydrological variables (precipitation, evaporation, discharge

Table 2

WMO recommendation of minimum density of hydrological networks (maximum recommended areas per station [in km^2])

	Polar/arid	Coastal	Hilly	Interior plains	Mountainous
Non-recording precipitation	10,000	900	575	575	250
Recording precipitation	100,000	9,000	5,075	5,075	2,050
Evaporation	100,000	50,000	50,000	50,000	50,000
Discharge	20,000	2,750	1,875	1,875	1,000
Water quality	100,000	7,500	7,500	7,500	3,000

and water quantity) for different physiographies. Comparison of these recommendations with the actual figures for particular countries given above clearly documents how inadequate hydrological observation networks are in tropical Africa.

The results of B.N.A.P. (PERKS *et al.* 1996) show that the area per one precipitation station in Senegal is 7,855 km^2 ; in Chad : 6,429 km^2 ; in Mali : 3,381 km^2 ; in Rwanda : 2,745 km^2 ; and in Côte-d'Ivoire : 1,918 km^2. For water quantity observations (water level and discharge) the areas per station read : in Chad : 17,450 km^2 ; in Namibia : 6,379 km^2 ; in Guyana : 6,323 km^2 ; and in Mali : 5,292 km^2. As far as evaporation stations are concerned, in Namibia, Senegal, Chad, Guyana, Ghana, Rwanda and Mali the densities of evaporation stations are among the lowest worldwide, as reported by PERKS *et al.* (1996), with areas per station which are in excess of 20,000 km^2. On the average, the area per water quality station is 10,318 km^2 in Senegal.

The need for enhancement of collection, storage, and processing of data calls for undertaking further multi-disciplinary large-scale research and monitoring programmes and experiments concentrated on energy and water fluxes. Rise of understanding of the availability of water in both quantity and quality dimensions is a prerequisite for prediction of changes of the hydrological cycle and their impacts. In order to gather high quality uninterrupted stream of data on freshwater resources on the global scale, the World Hydrological Cycle Observing System (WHYCOS) is being launched jointly by the World Meteorological Organization and the World Bank. WHYCOS would consist initially of about 1,000 reference stations (hydrological observatories) worldwide sited on major rivers. Each station would monitor about 15 variables such as flow, water chemistry and on-bank meteorological

variables, and then transmit the data through satellites to national, regional and global data centres. In WHYCOS use will be made of those existing observing stations and databases which meet the required specifications. Actual rehabilitation and expansion of operational monitoring and assessment programmes are being developed as regional components of WHYCOS. Those regional components are at different levels of development. Implementation of the MED-HYCOS in the Mediterranean Rim is most advanced. Tropical areas of Africa are in the focus of interest during the planning phases of the regional implementation of WHYCOS. Such regional projects as SADC-HYCOS in countries of Southern Africa Development Community, AOC-HYCOS in West and Central Africa, Congo-HYCOS in the Congo River Basin, IGAD-HYCOS in Eastern Africa are in different stages of preparation or implementation. Moreover, plans are being made for Nile-HYCOS and Lake Victoria-HYCOS.

In Agenda 21 (UNCED 1993), the blueprint for sustainable development, a concern was expressed that commonly used indicators do not provide adequate measures of sustainability. Chapter 40 of Agenda 21 devoted to information for decision-making contains a recommendation that indicators of sustainable development "need to be developed to provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems". In consequence, a number of endeavours have been undertaken aimed at proposing measures which could be used to quantify sustainable development. The United Nations Commission on Sustainable Development established a multi-year thematic programme on indicators for sustainable development.

One of candidate indicators being proposed by W.M.O. is the density of hydrological networks (KUNDZEWICZ 1996) defined as the average area served by one hydrological station. Density of hydrological networks is an indicator illustrating the importance which is attributed in a given country to information for sustainable development. It indicates a government policy response to the need to monitor hydrological variables for relation to the assessing, developing and managing freshwater resources. Information on density of hydrological observation networks may be viewed as one of the building blocks which form the foundation of a sound decision-making procedure in the water sector, and also as an insurance which is obtained to protect against an uncertain future.

Concluding Remarks

As outlined in the Agenda 21, sustainable development requires an integrated and holistic approach to the development and management of water resources unlike the fragmentation of perspective on water which has dominated until recently. An integrated and holistic perspective should embrace protection of water resources and aquatic ecosystems, sustainable agriculture and consideration of climate change impacts. There is a clear need for close international cooperation over shared bodies.

A recent study (KULSHRESHTHA 1993) has shown that food insecurity is a major water-resource related issue in the ASAL of Africa, noting that about a third of the population lives in that region. The study shows that over a dozen countries in Africa are already under water stress, or water scarcity, if they were to attain the goal of food self-sufficiency alone. Dynamic increase in population at the rate of 3.5 % in Sub-Saharan Africa, as compared to the global rate of 1.7 %, leads to increased pressure on land. There is an urgent need to feed the ever-increasing number of humans and irrigation, although inefficient, seems indispensable.

In the developed world, droughts hit but do not kill. There is a whole spectrum of measures which can be taken in response to a drought forecast. GLANTZ (1982) mentioned a case of a drought forecast in a US basin that triggered such activities as : digging wells (removing limits for permits), leasing water rights (between cultivators of annual and perennial crops) ; transplantation of perennial crops to other areas ; developing subsidized water bank that would buy water from farmers' growing annual crops and resell it to others at a subsidized price ; subsidizing farmers with annual crops to leave their land fallow ; hauling water by trucks, encouraging water conservation (lining, cleaning, inspection of ditches). Moreover, a number of further options have been considered, such as the suggestion of pumping dead storage from reservoirs ; additional storage sites ; weather modification. Is it possible that these drought mitigation measures can be used in the case of Africa? Unfortunately not at the present time, due to poverty, illiteracy, population dynamics, warfare and lack of adequate structures, institutions, legislation, etc. That is why, in his earlier work, GLANTZ (1977) gave a gloomy yet sober, realistic statement on the situation in the West African Sahel : "Even if a six-month forecast of weather

were available few of the areas could have responded in any different way to that which actually happened".

The main obstacles for water resources assessment (W.R.A.) are the fragmentation of institutional responsibilities and the low level of priority given to W.R.A. at the national level. Recent cutbacks have taken their toll both in terms of the poor operation and maintenance of networks, and the availability and lack of reliability of water information. A theme common to many countries is that of problems in training and retraining W.R.A. staff, and in updating their abilities to implement more advanced technologies and equipment. From a global perspective, there is, in consequence, a serious concern about the ability of the national agencies which are responsible for W.R.A. to meet the growing needs for data and information, especially as these relate to sustainable development.

Fragmentation of water matters is not endemic in tropical areas. In the W.M.O.'s survey INFOHYDRO (W.M.O. 1995), 175 countries reported on hydrological data collection activities. However, among the respondents were 480 agencies, that is on the average nearly three agencies per country. A similar fragmentation of water affairs can be also observed at the international level. There exists no powerful intergovernmental water agency. Even if there are some two dozen agencies of the United Nations family dealing with water, their water units are usually outsiders, appendices of secondary (at best) importance.

Water is not a free good any more but rather an economic good. A future-oriented philosophy of water resources management dwells more on shaping demands than on supply extension. One should strive towards increasing the efficiency of water use trying to "do more with less". Financial instruments, such as water pricing not only granting full cost recovery but also accounting the cost of the resource, in the sense of foregone opportunities, require thorough consideration. Such non-investment reserves as water conservation measures, institutional changes, broad consultation with people affected (local community groups) need to be carefully studied.

It is proposed (cf. UNCED 1993) to base sustainable development on the principles of : decentralization and devolution of responsibility in water and environmental matters to the parties involved at the lowest feasible level in society (subsidiarity principle) ; local and private sector participation ; a demand-driven cost recovery approach and equitable charging to enhance sustainability, and enforceable legislation at all

levels. Further, it is essential to reach significant portions of communities and involve them in the process of consultation, to make them understand, accept and support plans. The principles of decentralization and involvement of communities pose ambitious challenges for education and training.

The developed world has developed numerous principles that help strive towards sustainable development. Such principles as "polluter pays", "source control rather than end-of-pipe", "participatory approach", "subsidiarity principle", "improve efficiency of water use" are really useful. These principles are also valid in the developing world. However, one cannot expect that they appeal to those not having one decent meal a day...

Despite virtually no success in building a sound water base for sustainable development in tropical areas, a clear message can be delivered. It is still worthwhile revisiting Agenda 21, whose statements have not lost anything of their validity.

REFERENCES

CHEREL-GEFFARD, S. & ALBERGEL, J. 1996. Le bassin versant du Sénégal. — *In* : Water Resources Management and Desertification : Processes and Challenges, W.M.O., Geneva, pp. . 97-108,

FALKENMARK, M. 1988. Sustainable development as seen from a water perspective. — *In* : Perspectives of Sustainable Development, Stockholm Studies in Natural Resources Management, No. 1, Stockholm, Sweden, pp. 71-84.

GLANTZ, M. H. 1977. The value of a long-range weather forecast for the West African Sahel. — *Bull. Amer. Met. Soc.*, **58** : 150-158.

GLANTZ, M. H. 1982. Consequences and responsibilities in drought forecasting : the case of Yakima, 1977. — *Water Resour. Res.*, **18** : 3-13.

GLANTZ, M. H. (ed.). 1994. Drought Follows the Plow. — Cambridge University Press, Cambridge, UK.

GLEICK, P. (ed.) 1993. Water in Crisis : a Guide to the World's Fresh Water Resources. — Oxford University Press, New York, USA.

KULSHRESHTHA, S. N. 1993. World Water Resources and Regional Vulnerability : Impact of Future Changes. — IIASA, RR-93-10, Laxenburg.

KUNDZEWICZ, Z. W. 1996. Density of hydrological networks as indicator of sustainable development. — *In* : Proc. Intern. Conf. on Water Resources and Environment Research : Towards the 21st Century, Kyoto, 29-31 Oct. 1996.

LITTLE, W. 1972. The Shorter Oxford English Dictionary on Historical Principles. — Third edition revised and edited by C. T. Onions, Oxford at the Clarendon Press.

LOUCKS, D. P. 1997. Quantifying system sustainability using multiple risk criteria. — Paper presented at the Third Kovacs Colloquium in Paris, 19-21 September 1992 (to be published in 1997).

PERKS, A., WINKLER, T. & STEWART, B. 1996. The adequacy of hydrological networks : a global assessment. — HWR-52, WMO-740, W.M.O., Geneva, Switzerland.

PIEYNS, S. A. & SEHMI, N. S. 1995. Water resources monitoring system for the Aral Sea. — *WMO Bull.*, **44** (1) : 64-66.

SEHMI, N. S. & KUNDZEWICZ, Z. W. 1997. Water, drought and desertification in Africa. — Submitted for presentation and possible publication in Proc. of Symp. on Sustainability of Water Resources under Increasing Uncertainty at 5th IAHS Scientific Assembly, Rabat, 23 April - 3 May 1997.

UNCED (UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT) 1993. Agenda 21 : Programme of Action for Sustainable Development. — United Nations Publications No. E.93.1.11, New York, USA.

WCED (WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT) 1987. Our Common Future (The Brundtland Report). — Oxford University Press, Oxford, UK.

WMO (WORLD METEOROLOGICAL ORGANIZATION) 1994. Guide to Hydrological Practices. — WMO-164, WMO, Geneva (5th edition), WMO-No. 168, Geneva, Switzerland.

WMO 1995. INFOHYDRO Manual, Hydrological Information Referral Service. — Operational Hydrology Report No. 28, WMO-No. 683.

WMO 1995a. African Conference on Water : Policy and Assessment. — Addis Ababa, Ethiopia, 20-25 March 1995, Report of the Conference, WMO, Geneva, Switzerland.

WMO 1996. Water Resources Management and Desertification : Processes and Challenges. — WMO, Geneva.

MEDEWERKERS — CONFERENCIERS — CONTRIBUTORS *

H. R. H. Prins Laurent, Voorzitter van het Koninklijk Instituut voor het duurzaam Beheer van de natuurlijke Rijkdommen en de Bevordering van de schone Technologie / Président de l'Institut Royal pour la Gestion durable des Ressources naturelles et la Promotion des Technologies propres, E. Jacqmainlaan 157, North Plaza Building — 8 ste verd., B-1210 Brussels (Belgium).

Afouda A., Université Nationale de Bénin, B.P. 256, Cotonou (Bénin).

Ahmed Rafique, Department of Geography and Earth Sciences, University of Wisconsin-La Crosse, La Crosse, 54601 Wisconsin (U.S.A.).

Akhtar Mariam, Technical Highschool Berlin, Schillerpromenade 26, G-12409 Berlin (Germany).

Alderweireld Serge, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Alé G., Direction de l'Hydraulique, B.P. 385, Cotonou (Bénin).

Alexandre Jean, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, Sart Tilman, B-4000 Liège (Belgium).

Anderson William, Department of Geography, McMaster University, 1280 Main Street West, L8S 4K1 Hamilton, Ontario (Canada).

Assani Ali Arkamose, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, B-4000 Liège (Belgium).

Astafyeva N., Space Research Centre, 88/32, Profsoyuznaya st., Moscow, 117810 (Russia).

Baert Geert, Laboratory of Soil Science, Universiteit Gent, Krijgslaan 281 (S8), B-9000 Gent (Belgium).

Bauwens Willy, Laboratory of Hydrology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

Bergonzini Laurent, Laboratoire d'Hydrologie et de Géochimie Isotopique, Université de Paris-Sud Orsay, Bât. 504, F-91405 Orsay, Cedex (France).

Berlamont Jean, Faculteit Toegepaste Wetenschappen, Departement Burgerlijke Bouwkunde, Laboratorium voor Hydraulica, Katholieke Universiteit Leuven, W. De Croylaan 2, B-3001 Heverlee (Belgium).

Bernard Etienne, avenue W. Churchill 253, B-1180 Brussels (Belgium).

Birkett Charon, Dept. of Space and Climate Physics, University College London, Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, RH5 6NT Surrey (United Kingdom).

---

* Sommige medewerkers hebben hun tekst niet ingediend voor publicatie / Certains conférenciers n'ont pas introduit leur texte pour publication / Some contributors did not introduce their paper for publication.

Boekaerts Piet, Departement Elektronika, Faculteit Toegepaste Wetenschappen, Vrije Universiteit Brussel, Gebouw K — niveau 5, Pleinlaan 2, B-1050 Brussels (Belgium).

Bound Alice, Dept. of Space and Climate Physics, University College London, Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, RH5 6NT Surrey (United Kingdom).

Brasseur Olivier, Institut d'Astronomie et de Géophysique Lemaître, Université Catholique de Louvain, chemin du Cyclotron 2, B-1348 Louvain-la-Neuve (Belgium).

Bricquet J. C., ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).

Bryson Robert, Archaeoclimatology Consultants, P.O. Box 2084, Davis, CA 95617 (USA).

Can Nguyen, Institut de Géographie, Académie Polonaise des Sciences, Varsovie (Poland).

Cayanan Esperanza, PAGASA, 1424 Quezon Ave., 1104 Quezon City (Rep. of the Philippines).

Ceuppens Johan, Institute for Land and Water Management, V. Decosterstraat 102, B-3000 Leuven (Belgium).

Charlier Jean, Grand'route 176, B-1428 Lillois (Belgium).

Chinthalu G., Indian Institute of Tropical Meteorology, Pune-411008 (India).

Colman Andrew, Hadley Centre, Meteorological Office, Room H006, RG12 2SY Bracknell Berkshire (United Kingdom).

Cornelis Jan, Department of Electronics (ETRO), Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

Corten-Gualteri Pascale, Koninklijk Belgisch Instituut voor Natuurwetenschappen/ Institut Royal des Sciences Naturelles de Belgique, rue Vautier 28, B-1040 Brussels (Belgium).

Crommelynck Dominique, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Dabi Daniel Davou, Department of Geography, McMaster University, 1280 Main Street West, L8S 4K1 Hamilton, Ontario (Canada).

Daouda Mamadou, Direction Météorologie Nationale, B.P. 218, Niamey (Niger).

Debruyn W., VITO, Centrum voor Teledetectie, Boeretang 200, B-2400 Mol (Belgium).

De Cauwer Vera, Department Forest and Water Management, Universiteit Gent, Coupure Links 653, B-9000 Gent (Belgium).

Decleir Hugo, Geografisch Instituut, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

De Deken Reginald, Institute of Tropical Medecine, Nationalestraat 155, B-2000 Antwerpen (Belgium).

Demarée Gaston, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Demeyere Frank, Adjunct Kabinetschef, Wetstraat 66, B-1040 Brussels (Belgium).

Derasse Slavica, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

De Troch François, Faculty of Agricultural and Applied Biosciences, Universiteit Gent, Coupure Links 653, B-9000 Gent.

Dewitte Steven, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Diaradouno Daniel, Direction Nationale de la Météorologie, B.P. 566, Conakry (République de Guinée).

Dinku Tufa, National Meteorological Service Agency, P.O. Box 1090, Addis Ababa (Ethiopia).

Erpicum Michel, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, B-4000 Liège (Belgium).

Fink Andreas, Institut für Geophysik und Meteorologie der Universität zu Köln, Kerpener Str. 13, D-50923 Köln (Germany).

Feyen Jan, Institute for Land and Water Management, V. Decosterstraat 102, B-3000 Leuven (Belgium).

Fink Andreas, Institut für Geophysik und Meteorologie der Universität zu Köln, Kerpener Str. 13, D-50923 Köln (Germany).

Fritsch Jean-Marie, ORSTOM, B.P. 5045, F-34042 Montpellier, Cedex 1 (France).

Gallée Hubert, Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, chemin du Cyclotron 2, B-1348 Louvain-la-Neuve (Belgium).

Goma Willy, Department of Meteorology, P.O. Box 310095, 15301 Lusaka (Zambia).

Gommes René, FAO, Environment and Natural Ressources Service, Agrometeorology Group, Viale delle Terme di Caracalla, I-00100 Roma (Italy).

Grove Alfred, Department of Geography, University of Cambridge, Downing Place, CB2 3EN, Cambridge (United Kingdom).

Griguolo Silvio, DAEST, Co' Tron, Santa Croce 1957, I-30135 Venezia (Italy).

Guschchina Daria, Meteorological Department, Moscow State University, Leninskie gory, 117899 Moscow (Russia).

Hall, Dept. of Space and Climate Physics, University College London, Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, RH5 6NT Surrey (United Kingdom).

Harris A., Dept. of Space and Climate Physics, University College London, Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, RH5 6NT Surrey (United Kingdom).

Hendrickx Guy, GCP/TOG/013/BEL, B.P. 114, Sokodé (Togo).
Hennon C., Institut für Geophysik und Meteorologie der Universität zu Köln, Kerpener Str. 13, D-50923 Köln (Germany).
Hens Luc, Faculty of Medicine and Pharmacy, Vrije Universiteit Brussel, Laarbeeklaan 103, B-1090 Brussel (Belgium).
Hulme Mike, Climate Research Unit, School of Environmental Sciences, University of East Anglia, NR4 7TJ Norwich (United Kingdom).
Huttula T., Regional Environmental Agency of Häme, PL 297, 33101 Tampere (Finland).
Hulme Mike, Climate Research Unit, School of Environmental Sciences, University of East Anglia, NR4 7TJ Norwich (United Kingdom).
Hus Jozef J., Centre de Physique du Globe de l'I.R.M., B-5670 Dourbes (Belgium).
Jelinek Jan, Antropos Museum, P.O.Box 14, Kniničky-Chřiby 831, 63500 Brno (Czech Republic).
Kalombo Kamutanda, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, Sart Tilman, B-4000 Liège (Belgium).
Kundzewicz Zbigniew, Research Centre of Agricultural and Forest Environment Studies, Polish Academy of Sciences, Poznan (Poland).
Lakeev S. G., Karpov Institute of Physical Chemistry, 10 Vorontsovo pole st., Moscow, 103064 (Russia).
Lao Carina, PAGASA, 1424 Quezon Ave., 1104 Quezon City (Rep. of the Philippines).
Laraque Alain, ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).
Lebarbe L., ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).
Li Qinghong, Centre for Ocean-Land-Atmosphere Studies, 4041 Powder Mill Road, Suite 302, 20705 Calverton (USA).
Mahajan P.N., Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune — 411008 (India).
Mahé Gil, ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).
Manalo-Smith N., Analytical Services and Materials, Hampton, VA 23666 (USA).
Marieu B., ORSTOM, Laboratoire d'Hydrologie, B.P. 5045, F-34032 Montpellier (France).
Mason I., Dept. of Space and Climate Physics, University Colleges London, Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, RH5 6NT Surrey (United Kingdom).
MBaye Cheikh Amadou Tidiane, Všk, Blok A1, Vinaršká 5, 60300 Brno (Czech Republik).

Mhita M. S., Directorate of Meteorology, P.O. Box 3056, Dar es Salaam (Tanzania).

Michel Raymond, Ministère de la Région Wallonne, Direction Générale de l'Aménagement du Territoire du Logement et du Patrimoine, 1 rue des Brigades d'Irlande, B-5100 Jambes (Belgium).

Moeyersons Jan, Royal Museum of Central Africa, Leuvensesteenweg 13, B-3080 Tervuren (Belgium).

Moons Xavier, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Moreda Fekadu, Laboratory of Hydrology, Vrije Universiteit Brussel, Pleinlaan 2, B-1180, Brussels (Belgium).

Morel Robert, 19 rue Henri Lot, F-91860 Epinay Sous Senart (France).

Muchinda Maurice, Zambia Meteorological Department, Haile Selassie, 30200 Lusaka (Zambia).

Muys Bart, Koninklijk Instituut voor het duurzaam Beheer van de natuurlijke Rijkdommen en de Bevordering van de schone Technologie / Institut Royal pour la Gestion durable des Ressources naturelles et la Promotion des Technologies propres, E. Jacqmainlaan 157, North Plaza Building — 8ste verd., B-1000 Brussels (Belgium).

Napala Ayitou, GCP/TOG/013/BEL, B.P. 114, Sokodé (Togo).

Nicolis Catherine, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Ntezimana V., Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, chemin du Cyclotron 2, B-1348 Louvain-la-Neuve (Belgium).

Obasi Godwin, Secretary-General World Meteorological Organization, 41 av. Giuseppe-Motta, Case Postale n° 2300, CH-1200 Genève 2 (Switzerland).

Olechnowicz-Bobrowska Barbara, Akademia Rolnicza Katedra Meteorologii i Klimatologii, Al. Mickiewicza 24/28, 30-059 Kraków (Poland).

Olivry Jean-Claude, ORSTOM, Laboratoire d'Hydrologie, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).

Olszewski Krzysztof, Faculty of Geography and Regional Studies, University of Warshaw, ul. Krakowskie Przedmiescie 30, 00-927 Warshaw (Poland).

Orange Didier, ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).

Ozer Pierre, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, Sart Tilman, B-4000 Liège (Belgium).

Paepe Roland, Earth Technology Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).

Pajunen Hannu, Geological Survey of Finland, P.O. Box 1237, Fin-70211 Kuopio (Finland).

Peirsman Kristel, Department Forest and Water Management, Universiteit Gent, Coupure Links 653, B-9000 Gent (Belgium).

Petit-Maire Nicole, URA164 — CNRS, Case 907, F-13288 Marseille (France).
Plisnier Pierre-Denis, rue du Spinea 19, B-5080 Emines (Belgium).
Podsetchine Victor, Regional Environmental Agency of Häme, Rautatienkatu 2LB, P.O. Box 297, Fin-33101 Tampere (Finland).
Przybylak Rajmund, Department of Climatology, Nicholas Copernicus University, Danielewskiego 6, Toruń (Poland).
Raes Dirk, Institute for Land and Water Management, V. Decosterstraat 102, B-3000 Leuven (Belgium).
Rajamani S., Indian Institute of Tropical Meteorology, Prune-411008 (India).
Ridder Taeke, Julianalaan 232, NL-3722 GW Bilthoven (The Netherlands).
Roche Emile, Musée Royal de l'Afrique Centrale, Leuvensesteenweg 13, B-3080 Tervuren (Belgium).
Rogers D., Department of Zoology, South Parks Road, Oxford OX1 3PS (England).
Runge Jürgen, Universität Paderborn, Warburger Strasse 100, D-33098 Paderborn (Germany).
Sakho Mamadou Adama, Direction de l'Eau, B.P. V161, Abidjan (Côte-d'Ivoire).
Santacroce Paolo, DAEST, Ca' Tron, Santa Croce 1957, I-30135 Venezia (Italy).
Santiago Armelle, chemin du Renard, F-01600 Saint Didier de Formans (France).
Savijärvi H., Department of Meteorology, University of Helsinki, 00100 Helsinki 10 (Finland).
Schayes G., Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, chemin du Cyclotron 2, B-1348 Louvain-la-Neuve (Belgium).
Schietecat Günther, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Schrage Jon, Institut für Geophysik und Meteorologie der Universität zu Köln, Kerpener Str. 13, D-50923 Köln (Germany).
Seleshi Yilma, Faculty of Technology, P.O. Box 385, Addis Ababa University, Addis Ababa (Ethiopia).
Semenov E. K., Meteorological Department, Moscow State University, Leninskie gory, Moscow, 117899 (Russia).
Servat Eric, ORSTOM, Programme Friend AOC, 06 B.P. 1203 Cedex 1, Abidjan 06 (Côte-d'Ivoire).
Simón Allen, Institute of Hydrology, Wallingford, Oxfordshire, OX10 8BB (United Kingdom).
Sircoulon Jacques, ORSTOM, 211 rue Lafayette, F-75480 Paris, Cedex 10 (France).
Slingenbergh J., FAO, Via delle Terme di Caracalla, I-00100 Rome (Italy).
Suchel J. B., Université Jean Monnet, F-42000 Saint-Etienne (France).

Szöllösi-Nagy András, International Hydrology Programme, Director Division of Water Sciences, 7 place de Fontenoy, F-75352 Paris 07 SP (France).
Tapsoba Dominique, ORSTOM, avenue Agropolis 911, B.P. 5045, F-34032 Montpellier, Cedex 1 (France).
Tarhule Aondover Augustine, Department of Geography, McMaster University, 1280 Main Street West, L8S 4K1 Hamilton, Ontario (Canada).
Tonnard Victor, Fondation Universitaire Luxembourgeoise, avenue de Longwy 185, B-6700 Arlon (Belgium).
Tricot Christian, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Troch Peter, Faculty of Agricultural and Applied Biosciences, Universiteit Gent, Coupure Links 653, B-9000 Gent (Belgium).
Tychon Bernard, Fondation Universitaire Luxembourgeoise, avenue de Longwy 185, B-6700 Arlon (Belgium).
Van Damme Patrick, Faculty of Agricultural and Applied Biological Sciences, Universiteit Gent, Coupure Links 653, B-9000 Gent (Belgium).
Vandewiele Georges, Centre for Statistic and Operational Research, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).
Van Goethem Jackie, Koninklijk Belgisch Instituut voor Natuurwetenschappen/Institut Royal des Sciences Naturelles de Belgique, rue Vautier 28, B-1000 Brussels (Belgium).
Van Gompel Bruno, L. Titecastraat 46, B-1150 Brussels (Belgium).
Van Haver Philippe, Koninklijk Belgisch Instituut voor Natuurwetenschappen / Institut Royal des Sciences Naturelles de Belgique, rue Vautier 28, B-1000 Brussels (Belgium).
Vannitsem Stéphane, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Van Overloop Elfi, International postgraduate training course on Fundamental and Applied Quaternary Geology-IFAQ, Earth Technology Institute, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).
Van Ranst Eric, Laboratory of Soil Science, Universiteit Gent, Krijgslaan 281 (S8), B-9000 Gent (Belgium).
Van Rensbergen J., VITO, Centrum voor Teledetectie, Boeretang 200, B-2400 Mol (Belgium).
van Scherpenzeel Cees, Royal Netherlands Meteorological Institute, P.O. Box 201, 3730 AE De Bilt (The Netherlands).
Vanzeer Frank, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Venäläinen Ari, Finnish Meteorological Institute, P.O. Box 503, Fin-00101 Helsinki (Finland).
Verheijen Y., VITO, Centrum voor Teledetectie, Boeretang 200, B-2400 Mol (Belgium).

Vermeulen Hendrik, Faculty of Agricultural and Applied Biological Sciences, Universiteit Gent, Coupure Links 653, B-9000 Gent (Belgium).

Veroustraete Frank, VITO, Centrum voor Teledetectie, Boeretang 200, B-2400 Mol (Belgium).

Vincent Dayton, Department of Earth and Atmospheric Sciences, Purdue University, CE 1397, West Lafayette, Indiana 47907-1397 (U.S.A.).

Vits Catherine, Department Forest and Water Management, Universiteit Gent, Coupure Links 653, B-900 Gent (Belgium).

Wahab Sàadi A., Institut de Géophysique, Académie Polonaise des Sciences, Varsovie (Poland).

Wollenweber Gabriele, Department of Meteorology, 2 Earley Gate, Whiteknights, P.O.Box 239, Reading, RG6 6AU (United Kingdom).

Xue Yongkang, Centre for Ocean-Land-Atmosphere Studies, 4041 Powder Mill Road, Suite 302, 20705 Calverton (U.S.A.).

DEELNEMERS — PARTICIPANTS — PARTICIPANTS

Mme Alexandre, Département de Géographie Physique, Université de Liège, allée du 6 Août, Bât. 11, Sart Tilman, B-4000 Liège (Belgium).

Beghin Ivan, President of the Royal Academy of Overseas Sciences, rue de Bordeaux 53, B-1060 Brussels (Belgium).

Berger André, Université Catholique de Louvain, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve (Belgium).

Bouquegneau Christian, Prorector Fac. Polytechnique de Mons, rue de Houdain 9, B-7000 Mons (Belgium).

Brouyaux François, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Mme Bultot-Neirinck Lydie, bd G. Van Haelen 198 Bte 1, B-1190 Brussels (Belgium).

Cahen Daniel, Director Koninklijk Belgisch Instituut voor Natuurwetenschappen/Institut Royal des Sciences Naturelles de Belgique, rue Vautier 28, B-1000 Brussels (Belgium).

Chevalier, rue P. Van Dijck 37, B-1310 La Hulpe (Belgium).

Cockshaw Pierre, Bibl. Royale de Belgique, bd de l'Empereur 4, B-1000 Brussels (Belgium).

Crabbé Marcel, avenue du Château 6/10, B-1081 Brussels (Belgium).

Dautrebande Sylvia, Faculté des Sciences Agronomiques de Gembloux, Passage des Déportés 2, B-5030 Gembloux (Belgium).

Decadt Brigitte, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1000 Brussels (Belgium).

De Corte Marc, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Decrock-Beyrus Jobine, Adviseur-generaal, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1000 Brussels (Belgium).

De Cuyper Jacques, Member of the Royal Academy of Overseas Sciences, rue J. Jordaens 30, B-1000 Brussels (Belgium).

De Dapper Morgan, Vakgroep Geografie, Laboratorium Fysische Geografie, Universiteit Gent, Krijgslaan 281 (S8), B-9000 Gent (Belgium).

Delmer J., avenue Col. Daumerie, B-1160 Brussels (Belgium).

Dereymaeker Els, Royal Academy of Overseas Sciences, Defacqzstraat 1, bus 3, B-1000 Brussels (Belgium).

de Potter d'Indoye N., Pater Devroyestraat 74, B-1150 Brussels (Belgium).

Desmeth Monnik, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1040, Brussels (Belgium).

De Swert Christiane, Régie des Voies Aériennes, Aéroport de Bruxelles National, B-1930 Zaventem (Belgium).
Devorst Monique, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Devorst Nicole, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
D'Hoore Jules, Schoonzichtlaan 94, B-3020 Herent (Belgium).
Drachoussoff Vladimir, rue Général MacArthur 48, B-1180 Brussels (Belgium).
His Excellency M. B. Ekpang, Ambassadeur du Nigeria, avenue de Tervuren 288, B-1150 Brussels (Belgium).
El Houssein Taleb, Geografisch Instituut, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels (Belgium).
Eyckmans Luc, Royal Academy of Overseas Sciences, Eredirecteur Prins Leopold Instituut voor Tropische Geneeskunde, Wildenhoge 26, B-3020 Winksele (Belgium).
Evrard Pierre, Mierchamps 19, B-6985 La Roche-en-Ardenne (Belgium).
Gellens Daniel, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Gellens-Meulenberghs Françoise, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Sir John Gray, British Ambassador, rue d'Arlon 85, B-1000 Brussels (Belgium).
Grotard Claudette, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Grove Jean, Department of Geography, University of Cambridge, Downing Place, CB2 3EN, Cambridge (United Kingdom).
Gysels H., Universiteit Gent, Apotheekstraat 5, B-9000 Gent (Belgium).
Heremans Ria, Officer in Charge U.N. Information Centre, de Broquevillelaan 40, B-1200 Brussels (Belgium).
Heylen Jos, Hoofd Dienst Hydrologisch Onderzoek, W.T.C.-toren 3, S. Bolivarlaan 30, B-1000 Brussels (Belgium).
Hubert Pierre, Ecole des Mines de Paris, Comité Français des Sciences Hydrologiques, 35 rue Saint Honoré, F-77305 Fontainebleau (France).
Jadin Jean-Marie, Royal Academy of Overseas Sciences, av. de l'Ermitage 8, B-5000 Namur (Belgium).
Jaumotte André, Royal Academy of Overseas Sciences, av. Jeanne 33/17, B-1050 Brussels (Belgium).
Joukoff Alexandre, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).
Kraemer Dieter, World Meteorological Organization, av. Giuseppe Motta, Case Postale 2300, CH-1211 Genève 2 (Switzerland).
Lederer André, Royal Academy of Overseas Sciences, rue de la Tarantelle 15, B-1050 Brussels (Belgium).

Lema Inge, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Lens-Declerck J., Zilverstraat 26, B-1850 Grimbergen (Belgium).

Lingier Jean, Algemeen Bestuur voor Ontwikkelingssamenwerking/Administration Générale de la Cooperation au Développement, Brederodestraat 6, B-1000 Brussels (Belgium).

Locquin Marcel, Secrétaire perpétuel de l'Académie francophone d'Ingénieurs, av. de Colmar 59b, F-92500 Rueil-Mailmaison (France).

Maenhout André, Opvoedingsstraat 153, B-9000 Gent (Belgium).

Major, bd. A. Reyers — Radio RTBF, B-1044 Brussels (Belgium).

Malcorps Henri, Director Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Mann Samuel, First Secretary, Ambassade de la République Coopérative de Guyana, av. de Brésil 12, B-1000 Brussels (Belgium).

Matthys Georges-Marie, av. E. Max 76, B-1030 Brussels (Belgium).

His Excellency Mumbengegwi Simbarashe, Ambassador of the Republic of Zimbabwe, Square J. Charlotte 11, B-1200 Brussels (Belgium).

Nemeghaire Jean, rue Col. Chaltin 32, B-1180 Brussels (Belgium).

Nicolaï Henri, Université Libre de Bruxelles — Royal Academy of Overseas Sciences, bd A. Reyers 41, Boîte 6, B-1040 Brussels (Belgium).

His Excellency P. M. Nwanzia, Ambassador of Kenya, rue W. Churchill 208, B-1180 Brussels (Belgium).

Nzima-Ntsekhe, bd Gen. Wahis 45, B-1030 Brussels (Belgium).

Osterrieth An, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1000 Brussels (Belgium).

Ozer André, Président du Département de Géographie Physique, allée du 6 Août, Bât. 11, Sart Tilman, B-4000 Liège (Belgium).

Paelinck Honoré, Royal Academy of Overseas Sciences, Hof ter Delftlaan 40, B-2180 Antwerpen (Belgium).

Paquet Paul, Director Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Paszyński Janusz, Institute of Geography, Polish Academy of Sciences, ul. Krakowskie Przedmieście 30, Warszawa (Poland).

Quinet Alfred, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Rabenowicz Henri, Sq. Hoedemaeckers 24/51, B-1140 Brussels (Belgium).

Raymaekers Paul, Royal Academy of Overseas Sciences, av. des Chênes 23, B-1640 Rhode-St-Genèse (Belgium).

Roberti Christine, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Roulin Emmanuel, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Schoofs Ria, Algemeen Bestuur voor Ontwikkelingssamenwerking / Administration Générale de la Cooperation au Développement, Brederodestraat 6, B-1000 Brussels (Belgium).

Simonet Maurice, Royal Academy of Overseas Sciences, av. Col. Daumerie 7, B-1150 Brussels (Belgium).

Smolders Myriam, Abdijstraat 20, B-1850 Grimbergen (Belgium).

Sokal Raoul, Royal Academy of Overseas Sciences, rue du Marteau 55, B-1040 Brussels (Belgium).

Symoens Jean-Jacques, Erevast Secretaris Royal Academy of Overseas Sciences, St.-Quentinstraat 69, B-1000 Brussels (Belgium).

Symoens Berthe, St.-Quentinstraat 69, B-1000 Brussels (Belgium).

Thonnard Robert, Royal Academy of Overseas Sciences, Pré au Bois 3, B-1640 Rhode-St-Genèse (Belgium).

Trapenard Chantal, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Turcios Díaz Marlen, Secretaría de Relaciones Exteriores de la República de Honduras, Tegucigalpa (Honduras).

Vaasen Raf, rue du Tilleul 13, B-1332 Genval (Belgium).

Vanderborght Oscar, Kraaibossen 24, B-2440 Geel (Belgium).

Van der Slagmolen Nancy, Royal Academy of Overseas Sciences, Defacqzstraat 1 bus 3, B-1000 Brussels (Belgium).

van de Vyvere Didier, TCO, World Meteorological Organization, Case Postale 2300, CH-1211 Genève 2 (Switzerland).

Vandiepenbeeck Mark, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels (Belgium).

Vanderstraeten Martine, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1000 Brussels (Belgium).

van Engelen Aryan, Koninklijk Nederlands Meteorologisch Instituut, P.O. Box 201, 3730 AE De Bilt (Nederland).

Van Langenhove Luk, Adj. Secretaris-generaal, Federale Diensten voor Wetenschappelijke, Technische en Culturele Aangelegenheden, Wetenschapsstraat 8, B-1140 Brussel (Belgium).

Van Malderen Denise, Groenstraat 80, B-1740 Ternat (Belgium).

Van Noten Francis, Royal Academy of Overseas Sciences — Hoofdconservator Koninklijke Musea voor Kunst en Geschiedenis, Jubelpark 10, B-1000 Brussels (Belgium).

Van Twembeke Urbain, Royal Academy of Overseas Sciences, Kruisbooglaan 11, B-3210 Linden (Belgium).

Vanwormhoudt Marc, St.-Pietersnieuwstraat 41, B-9000 Gent (Belgium).

Verhasselt Yola, Permanent Secretary Royal Academy of Overseas Sciences, Defacqzstraat 1 bus 3, B-1000 Brussels (Belgium).

Von Frenckell Maryanne, Fondation Universitaire Luxembourgeoise, av. de Longwy 185, B-6700 Arlon (Belgium).