

Impact modeling of climate change from the global to the local scale

Piet Termonia and Daniel Gellens

Abstract

The societal impact of weather and climate phenomena is mainly felt through the occurrence of extreme events (storms, extreme precipitation, floodings, heat waves, hail). Processes at the short time scales (ranging from a few hours to a few days) play an important role for the estimation of the impact of climate change at the long time scales (next century). The Royal Meteorological Institute (RMI) provides both operational weather forecasts and climate advice. To do so, numerical computer models are used. It is shown here how scientific advances in numerical weather prediction can lead to better climate information.

Samenvatting

De maatschappelijke impact van weer- en klimaatfenomenen laat zich voornamelijk voelen in het voorkomen van extreme weersituaties (stormen, hevige neerslag, overstromingen, hittegolven en hagel). Processen die zich voorstellen op korte tijdschalen (gaande van een paar uur tot een paar dagen) spelen een belangrijke rol voor het inschatten van klimaatimpact op de lange tijdschalen (komende eeuw). Het Koninklijk Meteorologisch Instituut (KMI) levert zowel operationele weersvoorspellingen als klimaatadvies. Daarvoor worden numerieke modellen gebruikt. In dit artikel tonen we aan hoe wetenschappelijke vooruitgang in het domein van de numerieke weersvoorspellingen kan leiden tot betere klimaatinformatie.

Résumé

L'impact sociétal des phénomènes météorologiques et climatiques se fait principalement sentir par l'apparition d'événements extrêmes (tempêtes, précipitations extrêmes, inondations, vagues de chaleur, grêle). Les processus à court terme (allant de quelques heures à quelques jours) jouent un rôle important pour estimer l'impact du changement climatique à long terme (siècle prochain). L'Institut Royal Météorologique (IRM) fournit à la fois des prévisions météorologiques opérationnelles et des avis sur le climat. Pour ce faire, des modèles numériques sont utilisés. Nous montrons ici comment les progrès scientifiques dans le domaine des prévisions numériques du temps peuvent conduire à une meilleure information climatique.

1. Introduction

Weather events represent some of the most severe natural risks. For instance, the floods that took place in Belgium from 12 November to 15 November 2010 led to 180 million Euro of damage claims. Another example is the so-called Pentecost storm in 2014, for which the damage claims summed up to about 650 million Euro. During the 2003 European heat wave, eight consecutive days occurred with temperatures higher than 40 °C in several places in Europe. The death toll of that heat wave exceeded 70,000 in Europe (Robine *et al.*, 2008).

The mission of the Royal Meteorological Institute (RMI), as the Belgian National Meteorological Service (NMS), is to provide permanent services to insure the Belgian national security, to provide meteorological information to the population and to support the political authorities (Royal Decree of 31 December 1986). The weather office of the RMI issues warnings in case of extreme weather events and monitors the meteorological situation on a 24/7 basis.

Extreme weather events do not only have an important societal impact today. It is expected that under a changing climate, some of those events may become more extreme or may occur more frequently. Climate change has been quantified in the latest Assessment Report Nr. 5 (AR5) of the Intergovernmental Panel for Climate Change (IPCC) according to so-called Representative Concentration Pathways (RCPs) that express climate change as a function of the radiative forcing of the scenarios ranging from 2.6 to 8.5 W/m² at the end of the century (van Vuuren *et al.* 2011). According to the AR5 (IPCC, 2013), under the most severe RCP8.5 scenario, one expects a global warming of about 3.7 °C (with an uncertainty ranging from 2.6 °C to 4.8 °C) by the year 2100. However, the impact of that change will be manifested through extreme natural events (Fig. 1; IPCC, 2014). This figure shows the change of the key risks for Europe, in the current climate, for the mid-

century and by the end of the 21st century for Europe. It includes the major natural risks related to heat and cold spells and extreme precipitation (or lack thereof) that the NMSs are forecasting and monitoring today.

Extreme events take place at smaller spatial scales than the global scale. So in order to increase our scientific knowledge about them, it is necessary to rely on the same modeling tools that are used for Numerical Weather Prediction (NWP). Here we give a brief overview of the history and challenges of NWP and we will then explain how the RMI expertise on NWP has been used to compute high-resolution climate change scenarios for Belgium. The same model is also used for overseas applications as will be shown below.

2. Numerical Weather Prediction

Numerical weather prediction consists of computer models that numerically solve the dynamical equations of the atmosphere (Bauer *et al.* 2015). The planet is covered with a three-dimensional grid and the spatial derivatives are approximated by using the information in the neighboring grid boxes. By carefully discretizing the time derivatives, the state of the atmosphere can be computed a time step ahead into the future. Phenomena that are smaller than the size of the grid boxes are *parameterized* by empirical relations. For models running at resolutions of about 10 km, this is done for the following processes: turbulence, deep convection, radiation, phase transitions of water and interactions with the topography.

The discretized equations are then reduced to a set of numerical operations that can be executed on a computer. The bigger the computing power, the more grid boxes can be computed and the higher the resolution of the model can be. By increasing the resolution more phenomena become explicitly resolved by the model equations and one can expect that the model becomes more precise. Historically the science of NWP has followed the progress in computing science and this has led to a substantial improvement of the forecast skill of today's NWP models.

Fig. 2 shows the progress of the global model of the European Centre for Medium Range Weather Forecasts (ECMWF). It depicts the so-called anomaly correlation [the anomaly is the difference with the mean value] between the predicted 500 hPa geopotential height [this is the height where the pressure is 500 hPa] by the model and the one obtained from the observations. It can be seen from this figure that at three days lead time the model was reaching an accuracy of 90% around 1990, whereas the same 90% is reached for five days lead time since 2010. One can roughly state that a decade of research and development on climate modelling has increased the forecast skill of one day lead time further into the future.

The atmosphere is a non-linear system (Lorenz, 1963). Small errors in the initial conditions will grow in time until the forecast becomes unreliable. The corresponding uncertainties are estimated by Ensemble Prediction Systems (EPSs). EPSs compute a numerical forecast, then perturb the model and its initial state a number of times to introduce artificial errors and run it again with these perturbations. This delivers for each model output variable a probability distribution of the predicted variables. The spread of this distribution is an indicator of the uncertainty of the forecast. For instance, the ECMWF provides twice a day an EPS with one unperturbed and 50 perturbed model runs.

The resolution of the ECMWF model is currently 8 km. This is not enough to properly resolve deep convection systems that are responsible for thunderstorms. To go to higher resolution one relies on specialized models that run on limited geographical areas, the so-called Limited-Area Models (LAMs). By limiting the domain one reduces the necessary computing resources, and one can spend the computing power on computing more details with higher resolution.

The RMI is a member of the ALADIN Limited-Area Model consortium (Termonia *et al.* 2018). This is an international consortium of 16 NMSs that develops and maintains a state-of-the-art LAM NWP system, called the ALADIN System. The consortium includes 13 European and 3 North-African countries. The ALADIN System is operationally used in each of the countries to provide high-resolution NWP forecasts to satisfy their national needs. The operational model configuration runs at resolutions of the order of 1 km, which allows to improve the realism of extreme precipitation events. The RMI runs the ALADIN System on its own HPC infrastructure. The model outputs are used by the forecasters. The output is post-processed and disseminated, for instance on the RMI website. See Fig. 3 for an illustration on this.

3. Climate change simulations

The same type of models is used for climate simulations. The main specificity of climate models is the radiative forcing which follows the prescribed pathways as put forth by the IPCC. Climate simulations cover more than a century, so given the limitations in computing power, they can only run with resolutions of the order of about 100 km. This means that Belgium is covered by only a few grid boxes, which is too coarse to simulate the extreme weather phenomena that were mentioned above.

Using the ALADIN System, the RMI developed a regional climate model that can be run with spatial resolution of a few kilometers. The parameterizations are adapted to give a better representation of the deep convective systems, thus providing details at the so-called convection permitting scales, which are the scales at which the processes for extreme precipitation take place. This model called ALARO-0 (De Troch *et al.* 2013 and Giot *et al.* 2016) has also been used to analyze the urban heat island effects and to downscale the coarser scale climate model outputs. In a recent Belgian project COmbining Regional climate Downscaling EXpertise in Belgium (CORDEX.be) this model was used, together with three other regional climate models run by the universities KU Leuven, UCLouvain and ULg. The CORDEX.be project was funded by the Belgian Science Policy Office (Belspo) and provided a set of high-resolution climate scenarios for Belgium. The project also performed a number of impact studies (Termonia *et al.* 2018).

The four climate models of the CORDEX.be project have been validated with respect to the observations from the climatological observation network of the RMI. To this end the models were run for the past period 1980-2010. Fig. 4 shows some of the validation maps. While the models slightly differ in the precise quantities they nevertheless reproduce the observed spatial pattern over Belgium in a qualitatively satisfactory manner. Subsequently, the models were run for 100 years in the future, till the end of the 21st century. The data were archived and various climate change signals were computed. Figure 5 shows the example of increase of the winter precipitation by the end of the century.

Within the CORDEX.be project, the scenarios were used to compute climate impact with Local Impact Models (LIMs) for heat waves (Hamdi *et al.* 2016), urban-heat island effects (Lauwaet *et al.* 2015), impacts on crop growth (Gobin 2012), impacts on isoprene emissions (Bauwens *et al.* 2018) and on storm surges and wave heights for the North Sea, see the project's website, <http://www.euro-cordex.be/>, for more detailed information. Focusing on the end of the 21th century using a scenario with the largest greenhouse gas emissions (RCP8.5), the most prominent impacts of climate change for Belgium were identified; they include: (i) a strong increase in number of tropical days and heat wave days; e.g. an increase of a factor 3 to 4 in the number of heat waves in the Brussels urban environment; (ii) an increase in winter precipitation and long extremely wet periods, (iii) an intensification of summer precipitation extremes, especially in urbanized areas; e.g. the precipitation intensity with hourly time scale and 10-year return period may increase up to 100%; (iv) an increased variability for biomass production and yields; and (v) severely reduced winter snow height maxima.

The atmospheric dynamics is a complex system. Explaining the scientific basis of climate change, including the related scientific uncertainties is often a challenge. By relying on ensembles of climate model runs that are provided by climate research centers worldwide, one can quantify the uncertainties. Based on those uncertainty estimates, climate change signal can be separated from the noise. Such a quantification has been done for Belgium within the CORDEX.be project by KU Leuven, see table in Termonia *et al.* (2018). A similar study has been performed for the northwest of Ethiopia by van Vooren *et al.* (2019) in a collaboration between RMI and UGent and shows how parameterization of the orography can impact the simulated precipitation.

The second challenge of science communication is to properly explain what the impact numbers mean in practice. Since climate change impact is felt through similar extreme weather events as forecasted today, the CORDEX.be project disseminated its results on the climate change impacts on heat waves in a format that is similar to the one used for weather forecasts. Fig. 6 shows one of the future heat waves simulated by the ALARO-0 model under the RCP8.5 scenario, presented in the format of a weather forecast as it would be communicated on the RMI website. The heat wave takes place at 2063 and lasts for 13 days. However, a word of caution should be given here: the forecasted event will not happen literally on 6 July 2063. In climate simulations the model output does not correspond to the real weather at the exact place and time, but the long-term climate runs reproduce the climate, including the amplitudes and the occurrence frequencies of the

weather phenomena. Nevertheless, this kind of presentation demonstrates climate change in a more tangible way than the climate change impact statistics do.

The ALARO-0 model of the RMI has been used recently over Central Asia. For instance, Cai *et al.* (2019) used this model to study the circulation within the Mountain-Oasis-Desert System (MODS) in the region. During the 31 summers (1986–2016), two simulations have been performed: (i) a control simulation (CTL) where the land use/cover presents the current situation of the oasis areas in the study region, and (ii) a simulation where the oasis areas have been replaced by the surrounding desert (NO_OASIS). The difference of the two runs is used to detect the potential effect of oasis expansion on the summer precipitation. The result is shown in Fig. 7 indicating that the presence of the oasis is responsible for an increase of the total summer precipitation with quantities up to about 40 mm.

Currently, the ALARO-0 model is being used in the H2020 AFTER project (Kotova *et al.* 2018) to study climate-change impact over Central Asia. This project has similar goals and structure as the Belgian CORDEX.be project. First a limited number of climate runs are being performed over the region of interest of Central Asia, following the IPCC AR5 prescribed RCP scenarios. The used models are the REMO model of the HZG-GERICS climate center of Germany and the ALARO-0 model of the RMI, the latter being exactly the same model as the one used for the CORDEX.be project. The guidelines of the CORDEX project are followed. Considerable attention will be payed to model validation and bias correction. Subsequently, the outputs of these models will be used to run LIMs for biomass production, similarly as done for Belgium in the CORDEX.be project. The project will also include a stakeholder dialogue. Since the CORDEX-Central Asia domain covers the Xinjiang region, these scenarios will be used later to study the MODS effect under a changing future climate.

5. Discussion

In 2009, the World Meteorological Organization (WMO) organized the third World Climate Conference (WCC-3) to establish a global network for climate services. Climate services are services that allow to disseminate climate information to the public and to specific socioeconomic users. This requires a strong partnership between the providers of climate services and the stakeholders. Climate services are needed for policy making and sustainable development by providing reliable climate projections and climate information. WCC-3 led to the creation of several climate centers worldwide. In Belgium such a climate center does not yet exist. Instead the Royal Meteorological Institute (RMI) started to develop its own climate services in strong partnership with the universities.

This paper illustrates how longstanding advances in weather forecasting by means of numerical weather prediction models has helped the RMI to build climate change scenarios for Belgium. This work was done in close collaboration with the climate modeling groups at the universities. The climate data is now archived and may serve to develop further climate services.

References

1. Bauer, P., Thorpe, A., Brunet, G., 2015. The quiet revolution of numerical weather prediction. — *Nature*, 525, 47–55.
2. Bauwens, M., Trissevgeni, S., Jean-François, M., Van Schaeybroeck, B., De Cruz, L., De Troch, R., Giot, O., Hamdi, R., Termonia, P., Laffineur, Q., Amelynck, C., Schoon, N., Heinesch, B., Holst, T., Arneth, A., Ceulemans, R., Sanchez-Lorenzo, A., Guenther, A., 2018. Recent past (1979–2014) and future (2070–2099) isoprene fluxes over Europe simulated with the MEGAN–MOHYCAN model. — *Biogeosciences*, 15: 3673–3690.
3. Cai, P., Hamdi, R., Luo, G., He, H., Zhang, M., Termonia, P., & De Maeyer, P., 2019. Agriculture intensification increases summer precipitation in Tianshan Mountains, China. *Atmospheric Research*. — 227, 140–146.

4. De Troch, R., Hamdi, R., Van de Vyver, H., Geleyn, J.-F. & Termonia, P.. 2013. Multiscale Performance of the ALARO-0 Model for Simulating Extreme Summer Precipitation Climatology in Belgium. — *Journal of Climate* 26 (22): 8895–8915.
5. Hamdi, R., Duchêne, F., Berckmans, J., Delcloo, A., Vanpoucke, C., Termonia, P., 2016. Evolution of urban heat wave intensity for the brussels capital region in the arpege-climat A1B scenario. — *Urban Clim.* 17: 176–195.
6. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
7. IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 688.
8. Giot, O., Termonia, P., Degrauwe, D., De Troch, R., Caluwaerts, S., Smet, G., Berckmans, J., Deckmyn, A., De Cruz, L., De Meutter, P., Duerinckx, A., Gerard, L., Hamdi, R., Van den Bergh, J., Van Ginderachter, M. & Van Schaeybroeck, B., 2016. Validation of the ALARO-0 Model Within the EURO-CORDEX Framework. — *Geoscientific Model Development* 9 (3): 1143–1152.
9. Gobin, A., 2012. Impact of heat and drought stress on arable crop production in belgium. — *Nat. Hazards Earth Syst. Sci.* 12 (6): 1911–1922.
10. Kotova L., Aniskevich, S., Bobylev, L., Caluwaerts, S., De Cruz, L., De Troch, R., et al., 2018. A new project AFTER investigates the impacts of climate change in the Europe-Russia-Turkey region. — *Climate Services*, 12:64–6.
11. Lauwaet, D., Hooyberghs, H., Maiheu, B., Lefebvre, W., Driesen, G., Van Looy, S., De Ridder, K., 2015. Detailed urban heat island projections for cities worldwide: dynamical downscaling cmip5 global climate models. — *Climate* 3 (2): 391–415.
12. Lorenz, E.N., 1963. Deterministic Nonperiodic Flow. — *Journal of the Atmospheric Sciences.*, 20 (2): 130-141.
13. Robine, J.-M., Cheung, S.L.K. Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P. & Herrmann, F.R. 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. — *C. R. Biologies*, 331 (2): 171-178. <https://doi.org/10.1016/j.crvi.2007.12.001>.
14. Termonia, P., Fischer, C., Bazile, E., Bouyssel, F., Brožková, R., Bénard, P., Bochenek, B., Degrauwe, D., Derková, M., El Khatib, R., Hamdi , R., Mašek, J., Pottier, P., Pristov, N., Seity, Y., Smolíková, P., Španiel, O., Tudor, M., Wang, Y., Wittmann, C., and Joly, A., 2018. The ALADIN System and its canonical model configurations AROME CY41T1 and ALARO CY40T1. — *Geosci. Model Dev.*, 11, 257-281, <https://doi.org/10.5194/gmd-11-257-2018>.
15. Termonia, P., Van Schaeybroeck, B., De Cruz, L., De Troch, R., Caluwaerts, S., Giot, O., Hamdi, R., et al. 2018. The CORDEX.be Initiative as a Foundation for Climate Services in Belgium. — *Climate Services*, 11, 49-61.
16. Van Vooren, S., Van Schaeybroeck, B., Nyssen, J., Van Ginderachter, M., & Termonia, P. 2019. Evaluation of CORDEX rainfall in northwest Ethiopia : sensitivity to the model representation of the orography. — *International Journal of Climatology*, 39(5), 2569–2586.
17. van Vuuren, D.P., Edmonds, J., Kainuma, M. et al., 2011. The representative concentration pathways: an overview. — *Climatic Change* (2011) 109: 5. <https://doi.org/10.1007/s10584-011-0148-z>.

Climate-related drivers of impacts					Level of risk & potential for adaptation	
Key risk	Adaptation issues & prospects		Climatic drivers	Timeframe	Risk & potential for adaptation	
<p>Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (<i>high confidence</i>) [23.2-3, 23.7]</p>	<p>Adaptation can prevent most of the projected damages (<i>high confidence</i>). <ul style="list-style-type: none"> Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands High costs for increasing flood protection Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns </p>			Present Near term (2030–2040) Long term 2°C (2080–2100) 4°C	 	
<p>Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (<i>high confidence</i>) [23.4, 23.7]</p>	<p>Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) <ul style="list-style-type: none"> Implementation of best practices and governance instruments in river basin management plans and integrated water management </p>			Present Near term (2030–2040) Long-term 2°C (2080–2100) 4°C	 	
<p>Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (<i>medium confidence</i>) [23.3-7, Table 23-1]</p>	<p>Implementation of warning systems <ul style="list-style-type: none"> Adaptation of dwellings and workplaces and of transport and energy infrastructure Reductions in emissions to improve air quality Improved wildfire management Development of insurance products against weather-related yield variations </p>			Present Near term (2030–2040) Long term 2°C (2080–2100) 4°C	 	

Figure 1: Key risks from climate change in Europe and the potential for reducing risk through mitigation and adaptation. Risk levels are presented in three time frames: the present, near-term (2030–2040), and longer term (2080–2100). For each time frame, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions. Key risks were identified based on assessment of the literature and expert judgment. Table taken from the WGII report of the AR5 (IPCC, 2014).

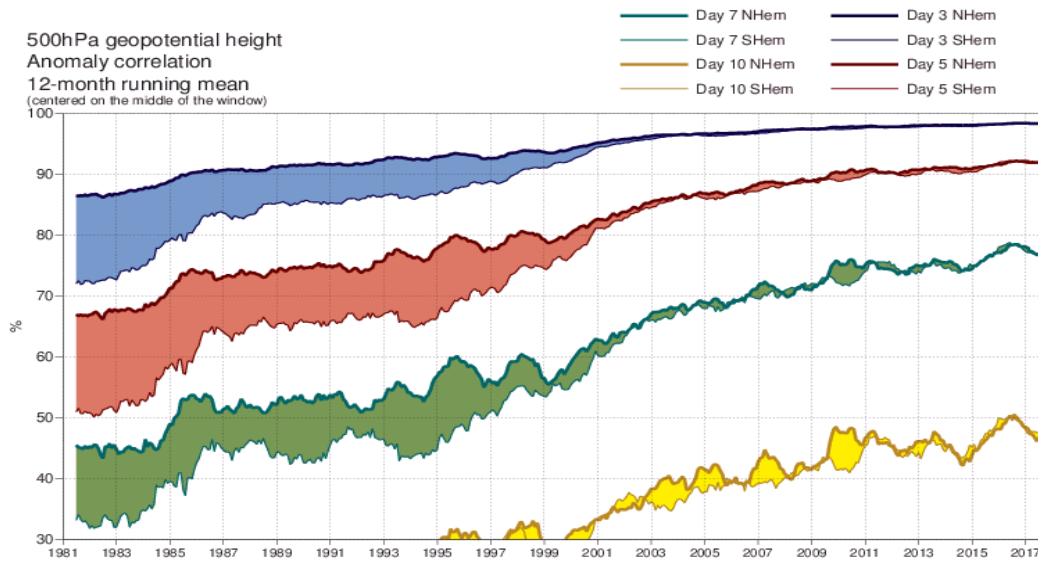
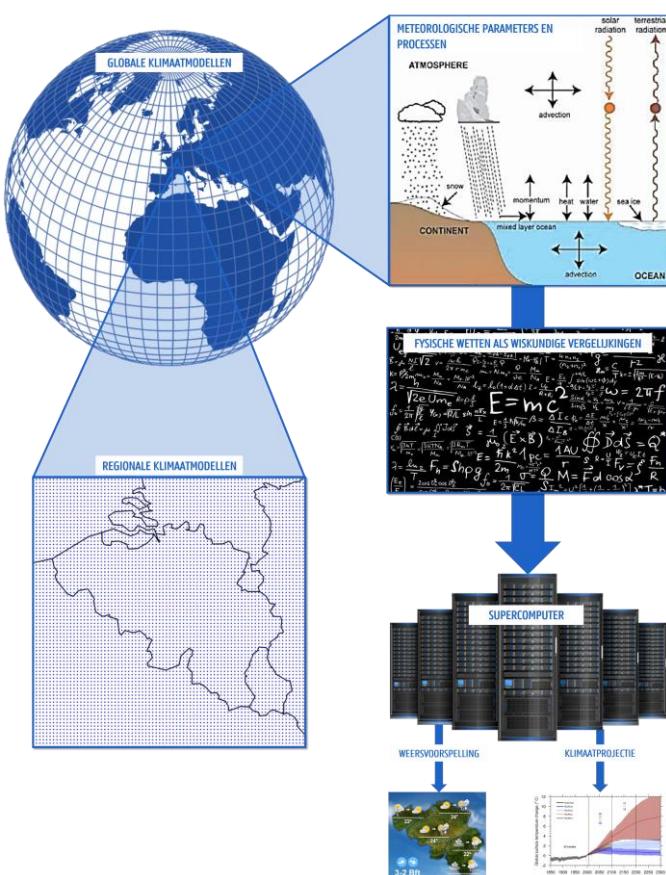


Figure 2: The anomaly correlation between the 500 hPa geopotential height (i.e. the height where the pressure is 500 hPa) predicted by the global model of the ECMWF and the observations. The thick lines represent the anomaly correlation for the Northern Hemisphere, whereas the thin lines represent the one for the Southern Hemisphere. One notices a progressive improvement of the forecast skills in the Southern Hemisphere that is slowly converging to the performance in the Northern Hemisphere.



	morgen +	vrijdag +	zaterdag +
Kust Oostende, Knokke-Heist, Nieuwpoort, De Panne, ...	15°	12°/15°	11°/15°
Centrum Brussel, Antwerpen, Gent, Leuven, Mechelen, Kortrijk, Lier, Charleroi, Nijvel, Namen, Bergen, ...	15°	9°/15°	8°/16°
Kempen Turnhout, Hasselt, Genk, Heist-op-den-Berg, Brasschaat, Mol, ...	14°	9°/16°	7°/17°
Ardennen Neufchâteau, Marche-en-Famenne, Bastogne, ...	11°	6°/13°	5°/14°
Belgisch Lotharingen Arlon, Virton, ...	13°	8°/15°	6°/15°

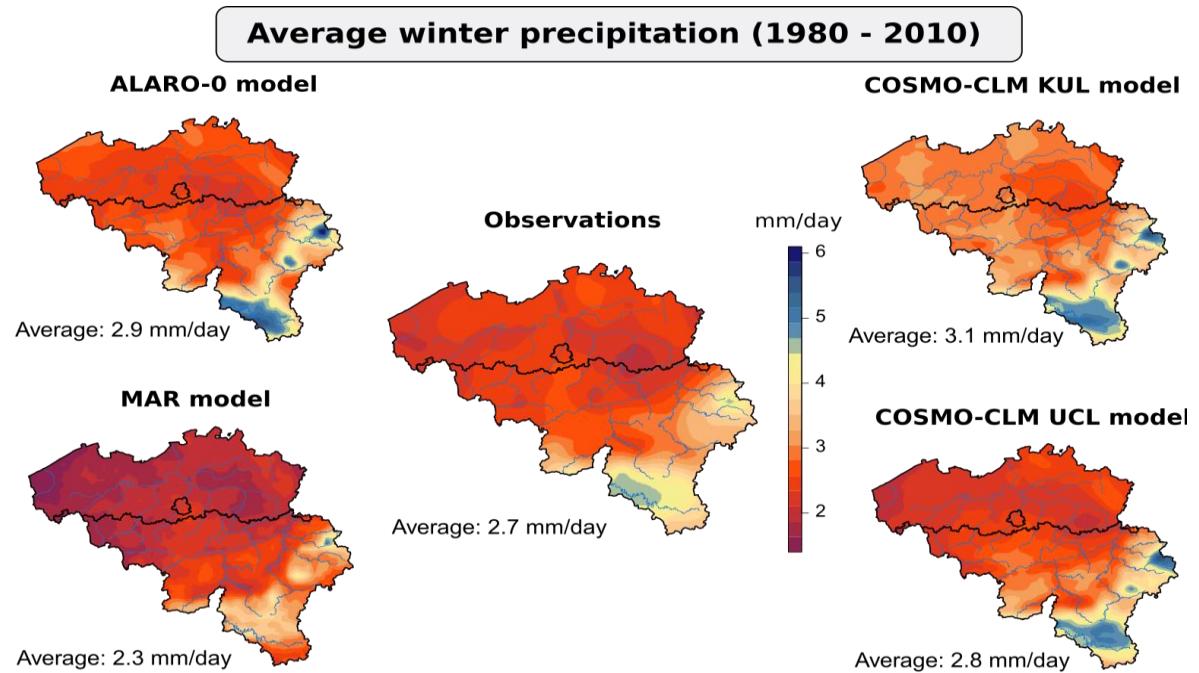


Figure 4: Validation of the winter precipitation for the four regional climate models used in the CORDEX.be project as described by Termonia et al. (2018) compared to the climatology from the RMI observation network.

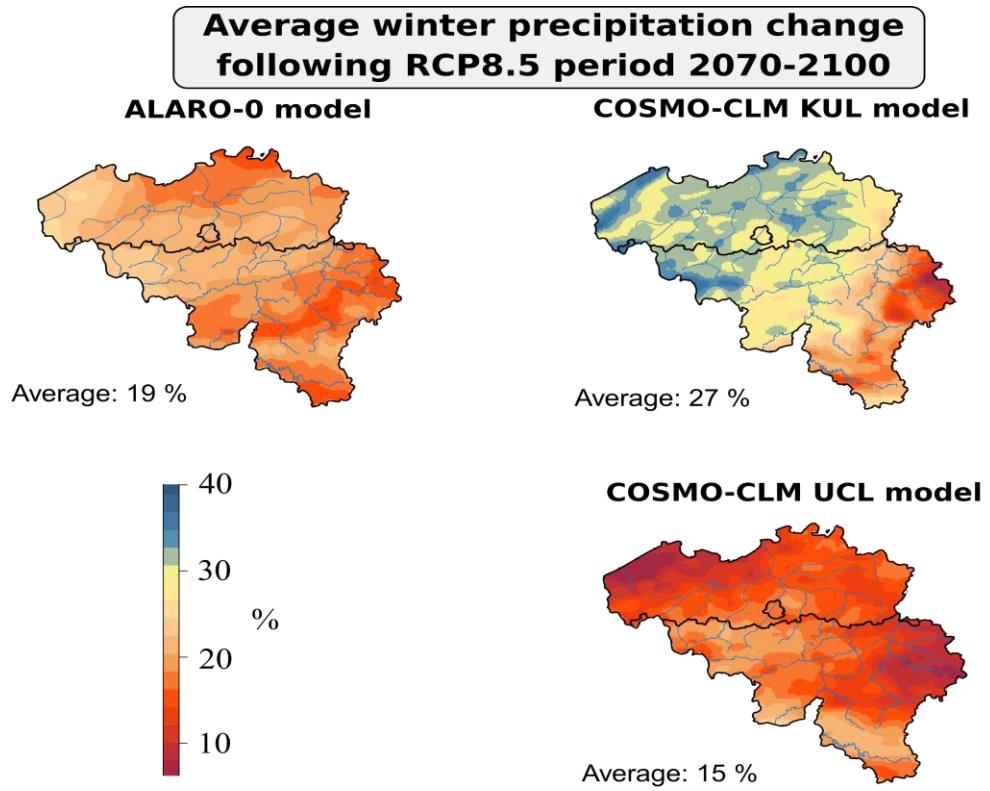


Figure 5: Climate change of the winter precipitation in Belgian according to three of the CORDEX.be climate models. All three models give climate change signals of the same order of magnitude.

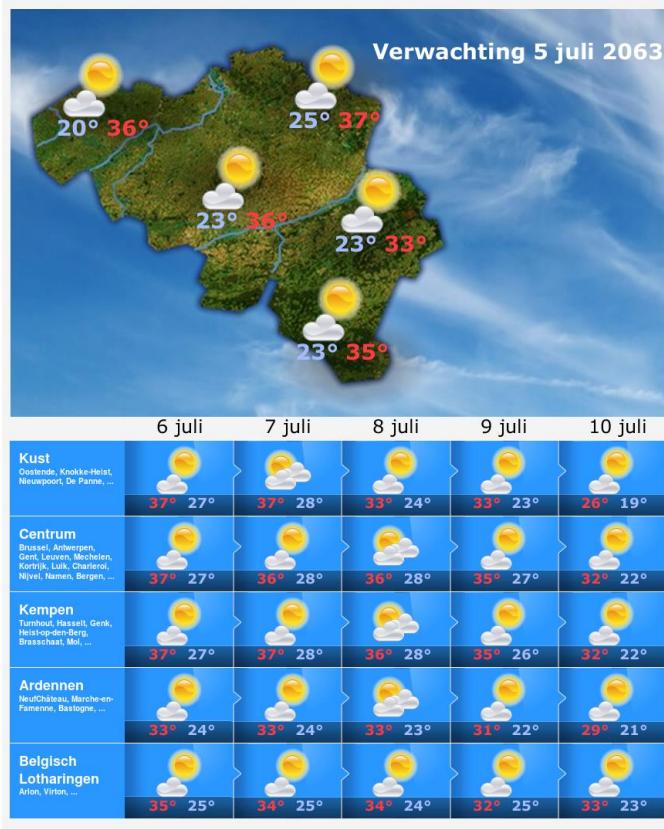


Figure 6: One of the future heat waves found within the ALARO-0 RCP8.5 simulation, presented here in the format of a weather forecast as it could be communicated on the RMI website.

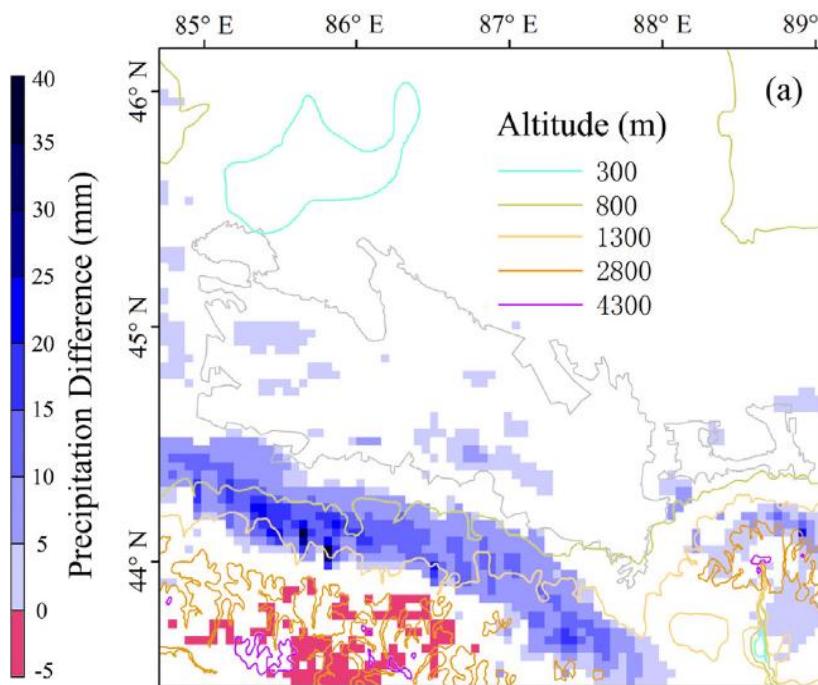


Figure 7: The total averaged summer precipitation during the period 1981–2016 computed from the difference between the model simulation with oasis and the model simulation without oasis present. The oasis considerably increases the total precipitation with up to about 40 mm. The area of the oasis is indicated by the gray line. The colored lines indicate the height contour of the mountains.