Towards better future climate information over Central Asia*

by

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KEYWORDS. — regional climate modelling; climate projections; climate change

SUMMARY. — Unprecedented, widespread and rapid changes in the climate system have been observed in every region across the globe. Moreover, the increase in global near surface temperature is projected to continue until at least 2050, which will lead towards more extreme events. Regional climate models (RCMs) are used to downscale the information of global circulation models (GCMs) over particular regions of interest to study the effect of global warming at higher spatial and temporal resolutions. Such high-resolution climate information is still scarce for Central Asia, while this region covers a large range of climatic zones and comprises some densely populated cities. High-resolution climate projections over Central Asia are presented, under 1.5 °C, 2 °C and 3 °C global warming.

Op naar betere, toekomstige klimaatinformatie over Centraal Azië

TREFWOORDEN. — regionale klimaatmodellering; klimaatprojecties; klimaatverandering

SAMENVATTING. — Ongeziene, uitgebreide en snelle veranderingen in het klimaat zijn waargenomen in elke regio van de wereld. Bovendien wordt tot minstens 2050 een verdere toename van de globale temperatuur verwacht, wat zal leiden tot meer extreme gebeurtenissen. Regionale klimaatmodellen worden gebruikt om informatie van globale modellen om te zetten naar data met een hogere ruimtelijke en temporele resolutie over een beperkt studiegebied om zo het effect van klimaatverandering gedetailleerder te kunnen bestuderen. Dergelijke hoge resolutie klimaatinformatie over Centraal Azië is echter schaars, terwijl deze regio een groot aantal klimaatzones vertegenwoordigt en enkele steden met een zeer hoge bevolking omvat. Hoge resolutie klimaatprojecties over Centraal Azië zullen worden toegelicht bij een globale klimaatopwarming van 1,5 °C, 2°C en 3 °C.

Vers une meilleure information sur le climat de l'Asie Centrale

MOTS-CLÉS. — modélisation climatique régionale; projections climatiques; changement climatique

RÉSUMÉ. — Des changements inédits, étendus et rapides du système climatique ont été observés dans toutes les régions du monde. De plus, il est prévu que la température de surface mondiale continue d’augmenter au moins jusque 2050, ce qui provoquera davantage d’événements plus extrêmes. Les modèles de climat régionaux sont utilisés pour améliorer l’information des modèles globaux en se focalisant sur des régions d’intérêt, particulières pour étudier l'effet du réchauffement climatique avec des résolutions spatiales et temporelles plus fines. Ces informations climatiques à haute résolution sont encore rares pour l'Asie Centrale. En plus, cette région couvre beaucoup de zones climatiques et comprend quelque villes densément peuplées. Par suite des projections climatiques à haute résolution sur l'Asie Centrale sont présentées pour un réchauffement climatique de 1,5 °C, 2 °C et 3 °C.

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Introduction

Extreme events such as heatwaves, heavy precipitation, droughts, and tropical cyclones become more intense and occur more frequently (IPCC 2021). These observations have been linked to the unprecedented and rapid changes in the climate system (IPCC 2021). In 2020 a global near surface temperature rise of 1.26 °C (1.12 °C - 1.37 °C) relative to the baseline period 1850-1900 was reached (IPCC 2021, p. 191). This stands for the approximate temperature rise since the pre-industrial period. Parties all over the world pledged in 2016 in the Paris Agreement to pursue a limitation of the global warming to 1.5°C or to stay well below 2 °C with respect to the pre-industrial temperature levels. The IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial level (IPCC, 2018) states with high confidence that global warming will reach 1.5 °C between 2030 and 2052 if greenhouse gas concentrations continue to increase at the same rate. The increase in global temperature is moreover projected to continue at least until 2050 under the socio-economic scenarios that are considered as feasible (IPCC 2021). A global warming of 2 °C will therefore be exceeded during the 21st century unless greenhouse gas emissions are drastically reduced in the coming decades. A further ongoing global warming will lead towards even more extreme events and will for example induce more frequent exceedance of human health heat thresholds, causing reduced wellbeing, labour productivity and an excess in mortality (Casanueva et al. 2020; IPCC 2021).

In order to study the potential future climate pathways and their impacts, future climate simulations are necessary. Global circulation models (GCMs) make such simulations possible by including physical laws to describe the atmosphere and its interactions. They simulate global climate information at a coarse resolution of typically ~100 km by ~100 km, with 25 km being the finest resolution currently reached (Demory et al. 2020). Regional climate models (RCMs) consists similarly to GCMs out of physical laws, but the physical laws of RCMs describe smaller scale processes that cannot be resolved by the coarse resolution of GCMs. RCMs are therefore used to downscale the data of GCMs over particular regions of interest to study the effect of global warming at higher spatial and temporal resolutions. The spatial resolution is typically 25 km by 25 km or finer. Such high-resolution climate information is still scarce for Central Asia(Kotova et al. 2018). Additionally, the Central Asia region covers a large range of climatic zones and comprises some densely populated cities, which increases the potential value of high-resolution climate information when it would be available for this region (IPCC 2021). Moreover, high-resolution climate information is needed to study the possible impact of climate change on for example the crop yields (Vannoppen et al. 2020), ecosystems (Cai et al., 2020), urban climate (Cugnon et al. 2019), building materials (Hedayatnia et al. 2021) etc. The following sections describe therefore the method and outcomes of the future climate projections that have been produced with the RCMs ALARO (Giot et al., 2016) and REMO (Jacob & Podzun 1997). ALARO was developed and maintained by the Royal Meteorological Institute of Belgium (RMIB) (Termonia et al., 2018), while REMO was developed at the Max Planck Institute for Meteorology and is maintained and utilized by the Helmholtz-Zentrum Hereon Climate Service Center Germany (HZH-GERICS) (Jacob et al., 2012).

Before presenting the outcomes of the climate projections, the first section explains how regional climate modeling works, why we can trust the results and which methods were applied to obtain the results described in the following sections. The second and third section present the future changes in respectively temperature and precipitation over Central Asia, together with their uncertainties. In this way we reduced the gap in high-resolution climate data and knowledge of the possible future climate evolutions under 1.5 °C, 2 °C and 3 °C over this region.

Regional climate modelling over Central Asia

The model domain applied over Central Asia, as depicted in Fig. 1, was defined by the Coordinated Regional Climate Downscaling Experiment (CORDEX). This international initiative was initiated with the aim of designing and conducting several high-resolution experiments over prescribed spatial domains across the globe. Further, CORDEX creates a framework to perform downscaling towards high-resolution climate data, to evaluate these downscaled data, and to characterise uncertainties of regional climate change projections by combining data of different RCMs into ensemble projections (Giorgi & Gutowski, 2015). Although this initiative resulted in an added value since the joint agreements and modelling efforts led towards large multi-model ensembles over several regions produced by different modelling groups, some regions such as Central Asia are until today sparsely covered by high-resolution climate data. Therefore climate data with the unprecedented spatial resolution of 25 km by 25 km was produced over this region in the course of the AFTER-project (Kotova et al. 2018). The evaluation data, historical runs and future projections can be retrieved from the ESGF data nodes (website: http://esgf.llnl.gov/, last access: 31 August 2022) and can be freely used for further research.

Fig. 1: IPCC6 subregions in the CORDEX Central Asia (CAS-CORDEX) domain (based on Top 2022).

Before the RCMs can be trusted for producing climate projections and their data can be applied in impact models, a model evaluation is needed to retrieve possible model errors or biases and to gain confidence in the RCM downscaling procedure. Top et al. (2021) evaluated both ALARO and REMO over the Central Asia CORDEX domain (CAS-CORDEX) (Fig. 1) by comparing their downscaled results to observed and reanalysis data. Top et al. (2021) concluded that the RCMs ALARO and REMO are able to capture the general climate, but both models have however some deficiencies for a certain variable over particular parts of the modelling domain. For example, ALARO is subject to significant positive temperature biases in winter, followed by large negative biases in spring for the northern part of the CAS-CORDEX domain and REMO simulated excessive precipitation amounts over the Tibetan Plateau during all seasons. These shortcomings have to be taken into account when using and interpreting the data of these RCMs for climate projections.

To downscale future climate data of a GCM to a finer grid the dynamical downscaling procedure was applied. Hereby data produced by a GCM of the fifth Coupled Model Intercomparison Project (CMIP5) cycle was used as the lateral boundary condition to force an RCM that produces climate data at higher spatial and temporal resolutions. The RCM ALARO was forced by the GCM CNRM-CM5, while REMO was forced by three GCMs, namely: HadGEM2-ES, MPI-ESM-LR and NorESM1-M. In this way a small ensemble of four GCM-RCM members was created to reduce biased conclusions. The multi-model mean of the ensemble is obtained by taking an equal average over the four members. The variation between the outcomes of the different GCM-RCM members was quantified by calculating the standard deviation between the different members to see whether the general outcome is supported by each GCM-RCM combination and whether a particular change in temperature or precipitation is likely to occur or not under a 1.5 °C, 2 °C and 3 °C warmer world. A larger spread between the GCM-RCM members in the ensemble means that there is a higher uncertainty in the future prevalent temperature or precipitation at that location. Since the ensemble only consists of four members, one should keep in mind that only a small part of the full uncertainty range will be covered.

Climate projections are always conditional on the considered future socio-economic scenario. To determine possible future climate outcomes different shared socio-economic pathways (SSPs) are combined with representative concentration pathways (RCPs) to include time series of emissions and concentrations of all greenhouse gases, aerosols and chemically active gases, as well as land use/land cover changes. The RCPs prescribe these possible future changes in time by using radiative forcing values. For example, in the RCP2.6 scenario the radiative forcing peaks to 3 W m^{-2} before 2100 and then declines to 2.6 W m^{-2} by the end of the century (Van Vuuren et al., 2011). Future simulations were run from 2006 to 2100 and are for all GCM-RCM members performed for a low and very high emission scenario, RCP2.6 and RCP8.5 respectively. RCP8.5 represents rather an unlikely high-risk future scenario since it assumes a fivefold increase in coal use by 2100, while coal use peaked in 2013 (Hausfather & Peters 2020). This scenario is however taken into account to identify all potential risks and to be prepared for extreme cases since it includes for example the uncertainty of important feedback effects that might be underestimated by the current climate models, such as the carbon cycle feedbacks. By using the low and very high RCPs as boundary condition for climate projections, both the optimistic and worst case climate change scenario are taken into account.

To investigate how the temperature and precipitation patterns will evolve over time, the period 1976-2005 is selected as historical modelling period. The climate change signal with respect to the near past is then obtained by subtracting the historical 30-year mean from a future 30-year mean. To present the spatial variation in climate change under a global warming of 1.5 °C, 2 °C or 3 °C with respect to the pre-industrial era, the 1850-1900 period has to be used as reference period as done by the IPCC (IPCC 2021). To obtain the results under a 1.5 °C, 2 °C or 3 °C warmer world, the warming from 1850-1900 until the historical period 1976-2005 has to be taken into account and amounts 0.69 °C (0.52 °C - 0.82 °C) (Jacob et al., 2018; IPCC, 2021). The central years and 30-year periods when the different GCMs coupled to the RCMs reach 1.5 °C, 2 °C and 3 °C were determined using the method of Vautard et al. (2014) and are presented in Tables 1, 2 and 3 respectively. The 1.5 °C, 2 °C and 3 °C periods differ for each RCP scenario because human induced emissions evolve differently under these scenarios (Tables 1, 2 and 3). These years in Tables 1, 2 and 3 make it possible to trace back when changes in temperature and precipitation patterns, described in the following sections, will likely take place given a certain emission scenario. Some GCMs do not reach the 2 °C and/or 3 °C global warming threshold by 2085 under RCP 2.6, which makes it impossible to define the 30-year period for these GCMs, indicated by “inf” in Tables 2 and 3.

Table 1: Central year and 30-year period when global warming is reaching +1.5 °C for used general circulation models (GCMs) under different representative concentration pathways (RCPs) (adopted from Top 2022).

	RCP 2.6		**RCP 8.5**	
GCM	**+1.5 °C central year**	**+1.5 °C period**	**+1.5 °C central year**	**+1.5 °C period**
CNRM-CM5-r1i1p1	2040	2026-2055	2029	2015-2044
HadGEM2-ES-r1i1p1	2019	2005-2034	2018	2004-2033
MPI-ESM-LR-r1i1p1	2049	2035-2064	2026	2012-2041
NorESM1-M-r1i1p1	2063	2049-2078	2031	2017-2046

Table 2: Central year and 30-year period when global warming is reaching +2 °C for used general circulation models (GCMs) under different representative concentration pathways (RCPs) (adopted from Top 2022). “inf” indicates that the warming level was not reached by 2085.

	RCP 2.6		**RCP 8.5**	
GCM	**+2 °C central year**	**+2 °C period**	**+2 °C central year**	**+2 °C period**
CNRM-CM5-r1i1p1	inf	inf	2044	2030-2059
HadGEM2-ES-r1i1p1	2037	2023-2052	2030	2016-2045
MPI-ESM-LR-r1i1p1	inf	inf	2044	2030-2059
NorESM1-M-r1i1p1	inf	inf	2046	2032-2061

Table 3: Central year and 30-year period when global warming is reaching +3 °C for used general circulation models (GCMs) under different representative concentration pathways (RCPs) (adopted from Top 2022). “inf” indicates that the warming level was not reached by 2085.

	RCP 2.6		**RCP 8.5**	

GCM	+3 °C central year	+3 °C period	+3 °C central year	+3 °C period
CNRM-CM5-r1i1p1	inf	inf	2067	2053-2082
HadGEM2-ES-r1i1p1	inf	inf	2051	2037-2066
MPI-ESM-LR-r1i1p1	inf	inf	2067	2053-2082
NorESM1-M-r1i1p1	inf	inf	2072	2058-2087

Under RCP8.5 1.5 °C, 2 °C and 3 °C global warming is reached by all four GCMs (Tables 1, 2 and 3). The fact that this is the only scenario that makes it possible to investigate which regional changes will take place under an extreme global warming of 3 °C is an additional reason to take this scenario into account. In Table 2, the 2 °C level is not reached under RCP2.6, except for the GCM HadGEM2-ES. The central year when 1.5 °C is reached for the GCMs CNRM-CM5 and MPI-ESM-LR lies between 2030 and 2052, which is according to the IPCC the period when it is very likely that 1.5 °C global warming will be reached, while NorESM1-M reaches 1.5 °C global warming later (Table 1). According the observations within the framework of the IPCC (IPCC 2021) the steep warming trend of HadGEM2-ES, reaching 1.5 °C in the central year 2019 (Table 1) is too fast compared to the observed global warming. Different to NorESM1-M, CNRM-CM5 and MPI-ESM-LR, the GCM HadGEM2-ES simulates a positive shortwave cloud radiative forcing which can partly explain the strong climate sensitivity of HadGEM2-ES (Andrews et al., 2012).

In the following sections the spatial differences in future and historical climate are presented based on the changes in the multi-model mean of temperature and precipitation. The multi-model mean of the 30-year periods representing a 1.5 °C, 2 °C and 3 °C global warming since the pre-industrial period are compared to the historical period 1976-2005. Since the 1976-2005 period already experienced a warming of 0.69 °C, the differences between the 1.5 °C, 2 °C and 3 °C scenarios show the effect of 0.81 °C, 1.31 °C and 2.31 °C global warming when compared to the historical 1976-2005 period. To define whether changes in the distribution of the simulated variables under 0.81 °C, 1.31 °C and 2.31 °C global warming are significant, a Mann-Whitney U-test, also named the Wilcoxon rank sum test, at a 95% significance level is performed. This test puts the values of both, historical and future, periods into one sample with an indication to which period the values belong. When the historical and future values are randomly ranked, then the values of the two periods are not different and no increase or decrease is found and vice versa (Corder & Foreman, 2011). A one-sided test is applied for temperature since a warming trend is expected over the CAS-CORDEX domain (IPCC, 2021) and a two-sided test is used for precipitation because an increasing or decreasing precipitation trend is expected depending on the region (IPCC, 2021).

Future change in temperature over Central Asia

Figure 2 shows the spatial distribution of the multi-model mean for temperature during the historical period 1976-2005 and presents the regional warming under different global warming levels. The Wilcoxon signed-rank test at a 95% significance level shows at annual level and for each season that the complete CAS-CORDEX region is projected to undergo a significant warming under all three investigated global warming levels when compared to the temperature distribution during the historical 1975-2005 period. Further, it can be derived from Fig. 2 that a more severe regional warming will take place under more severe global warming. Moreover, the regional warming trend is steeper than the global warming trend since an increase in 0.81 °C globally leads to a change of 1 °C to 3 °C over most of the CAS-CORDEX domain. Further, the northern region of the CAS-CORDEX domain will undergo a faster temperature increase than the mean warming trend over the CAS-CORDEX domain, while Southeast-China experiences a slower warming. When seasons are compared, then the warming trend is more prominent during autumn and winter over most parts of the domain.

Fig. 2: Spatial variability in the annual and seasonal temperature means for the historical period (1976-2005) and temperature change under 1.5 °C, 2 °C and 3 °C global warming showing the effect of 0.81 °C, 1.31 °C and 2.31 °C global warming with respect to the historical period shows that additional global warming causes a significant additional warming over the Central Asia domain (based on Top 2022).

Figure 3 presents the spread between the different model members of the ensemble for the three warming scenarios. The very similar patterns in spread that appear for each warming scenario (columns in Fig. 3) show that the dissimilarities between the models stay the same over time. This implies that the dissimilarities between the models are mainly due to the inter-model uncertainty on regional processes that do not change over time. Over the northeastern region of the CAS-CORDEX domain there is a large standard deviation up to 5 °C, indicating a large uncertainty at annual level (Fig. 3). This corresponds with the region for which a large deviation with the reference datasets was found during the evaluation of the RCMs and for which ALARO had a cold bias, while REMO had a warm bias (Top et al 2021). Large uncertainties are also found during winter over the full domain, with the highest uncertainty in the eastern part of the domain up to a standard deviation of 10 °C in northern China, Mongolia and eastern Russia. Also during spring there is a large model spread in the northern part of the region, with the largest standard deviation being up to 7 °C over eastern Russia. These large uncertainties can again be linked to the deficiencies that were reported in the evaluation study of the RCMs. The variation between the models is smaller during summer with values up to 3 °C, except for some parts in East-Europe and Lake Baikal in southeastern Russia. During autumn the RCMs had the best performance during the evaluation study (Top et al. 2021) and this results in a small standard deviation up to 2 °C between the models over most of the region, except for northern China, Mongolia and eastern Russia. This makes the resulting significant regional warming during the autumn very robust and likely to occur. The variation between the model outcomes of the different GCM-RCM members is small during the seasons and over the regions for which the two RCMs performed well (Top et al., 2021). This is remarkable since the different ensemble members could project different future climates. The deficiencies that were reported during the evaluation of the RCMs lead to a larger spread between the model outcomes for the future projections, which causes an increase in the uncertainty. Therefore, the RCMs should be improved or a bias adjustment should be executed to reduce the uncertainty in the future projections.

Fig. 3: Spatial variability in the annual and seasonal spread, quantified by the standard deviation, between temperatures of the different ensemble members and RCP scenarios under global warming of 0.81 °C, 1.31 °C and 2.31 °C with respect to the historical period (1976-2005) or 1.5 °C, 2 °C and 3 °C global warming with respect to the pre-industrial baseline period (based on Top 2022).

Future change in precipitation over Central Asia

Figure 4 shows the spatial changes of the multi-model mean in relative precipitation amounts under the three different global warming levels compared to the historical period 1976-2005. Based on the Mann-Whitney U-test with a 95% significance level not all parts of the CAS-CORDEX will experience a significant change in precipitation under 0.81 °C, 1.31 °C and 2.31 °C global warming, which is indicated with the grey dots on Fig. 4. Further, the projections in Fig. 4 show that a more pronounced global warming causes a larger area of significant changes in precipitation. At annual level, significantly increased precipitation amounts are projected over the northern and central regions of the CAS-CORDEX domain for all warming levels, covering parts of Russia, Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, Tajikistan, Mongolia and western China. Contrary, a decrease in precipitation is projected over the Middle East and northern India, but this decrease is only significant under a global warming of 1.31 °C and 2.31 °C for Syria, northern Iraq and southern Afghanistan, while it is only significant under a 1.31 °C global warming for East-Europe and northern India. Additionally, there is no clear change in annual precipitation over eastern China under all three warming levels.

Fig. 4: Spatial variability in the annual and seasonal precipitation amounts for the historical period (1976-2005) and change in precipitation amounts under 1.5 °C, 2 °C and 3 °C global warming showing the effect of 0.81 °C, 1.31 °C

and 2.31 °C global warming with respect to the historical period. The grey dots, on top of the precipitation difference class, indicate where the precipitation does not differ significantly between the historical and future period over the Central Asia domain(based on Top 2022).

For all seasons except for summer a significant increase in precipitation is projected over the northern and central regions of the CAS-CORDEX domain, with the strongest increase and largest region of significant increase occurring during the winter. Under more severe global warming, the increase in precipitation during winter is steeper for the northeastern part of the domain compared to the rest of the CAS-CORDEX domain. During spring and summer large, however insignificant relative precipitation changes are found over the Middle East. This is due to the small precipitation amounts that this region experiences. Further, a significant decrease in precipitation is projected over East China for all global warming levels during summer and under 1.31 °C and 2.31 °C global warming during autumn. During summer there is also a significant decreasing precipitation trend projected for East-Europe under a global warming of 1.31 °C, while under a global warming of 2.31 °C this is only the case for southeastern Europe. During winter, East-Europe is projected to experience a significant increase in precipitation under the 2.31 °C warming level, which explains why at annual level the decreasing precipitation trend is only projected under a global warming of 1.31 °C.

Figure 5 shows large variations in precipitation between the projections model members over the southeastern part of the domain and East-Europe, resulting in a large uncertainty for the future precipitation amounts. Over Kazakhstan and regions with small precipitation amounts, namely the Arabian Peninsula, East-Iran and the Gobi Desert the standard deviation between the different model simulations is small, which indicates that the models agree well. Compared to the autumn and winter the standard deviation in the northwest and northeastern part of the CAS-CORDEX domain indicates a larger uncertainty between the modelled precipitation during spring and summer. Top et al. (2021) revealed that not all members of the ensemble simulate the East Asian monsoon equally well and this probably causes the larger uncertainty over southeastern China except during winter since there is no East Asian monsoon precipitation during winter. Similar as for temperature, the standard deviation remains more or less the same for the three global warming levels indicating that the dissimilarities between the model outputs are mainly due to the inter-model uncertainty on regional processes that do not evolve over time.

Fig. 5: Spatial variability in the annual and seasonal spread, quantified by the standard deviation, between regional precipitation amounts of the different ensemble members and RCP scenarios under global warming of 1.5 °C, 2 °C and 3 °C (based on Top 2022).

Conclusion

Highly needed high-resolution climate data over Central Asia was produced, evaluated, studied and made available for the scientific community through the ESGF data nodes (website: http://esgf.llnl.gov/, last access: 31 August 2022). Hopefully this effort will enhance the creation of more high-resolution climate information and increase the number of climate impact studies over this region, so there is more certainty on how the future climate will evolve over this region and what the potential impacts of ongoing global warming are.

The future temperature projections showed that the warming rate differs depending on the location in the Central Asia domain, with in general a faster warming in the north. Future changes in precipitation amounts will also depend on the location e.g. an increase in annual precipitation is expected in the northern and central part of the CAS-CORDEX domain, while a significant decrease is expected for the Middle East and northern India under an additional global warming of 1.31 °C and 2.31 °C compared to the historical period 1976-2005, or 2 °C and 3 °C when compared to the 1850-1900 period. For both temperature and precipitation larger regional changes in Central Asia are expected under more severe global warming. Reducing the greenhouse gas emissions is thus of major importance for limiting the adverse impacts of climate change within Central Asia.

The variation between the model members remained smaller for the regions where both RCMs performed well during the evaluation study and variations in projected temperature and precipitation between the different model members are mainly due to the inter-model uncertainty on regional processes that do not evolve over time. For future research an improvement of the RCMs in simulating the current climate features or a bias adjustment is therefore recommended since this will probably reduce the uncertainty in the future projections, which is important for impact studies.

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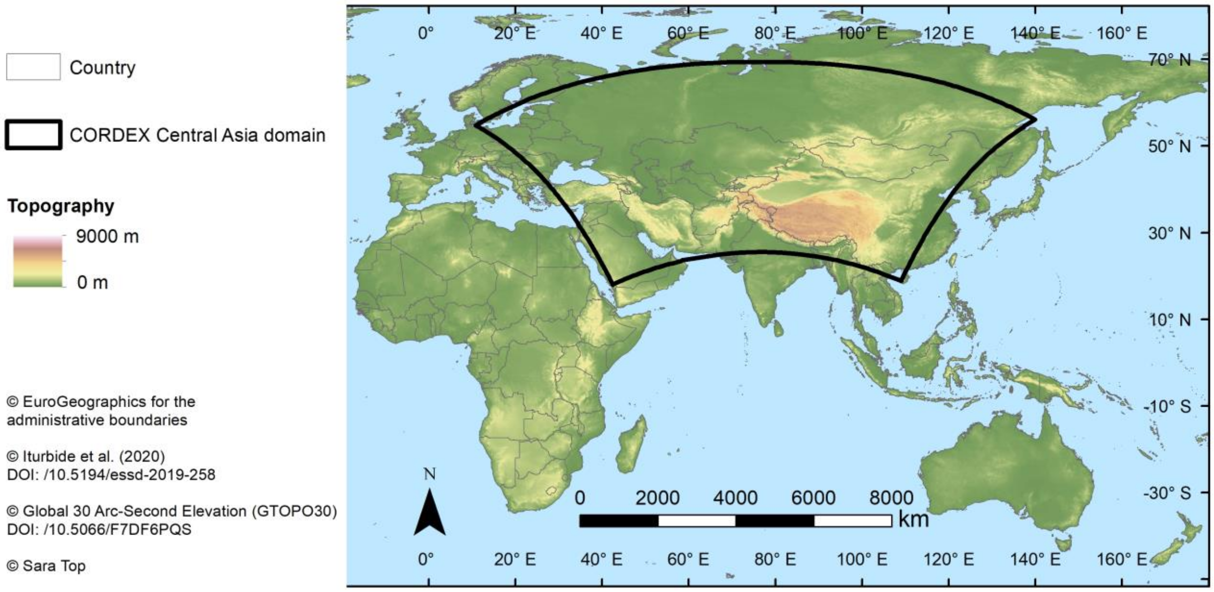

Fig. 1: IPCC6 subregions in the CORDEX Central Asia (CAS-CORDEX) domain (based on Top 2022).

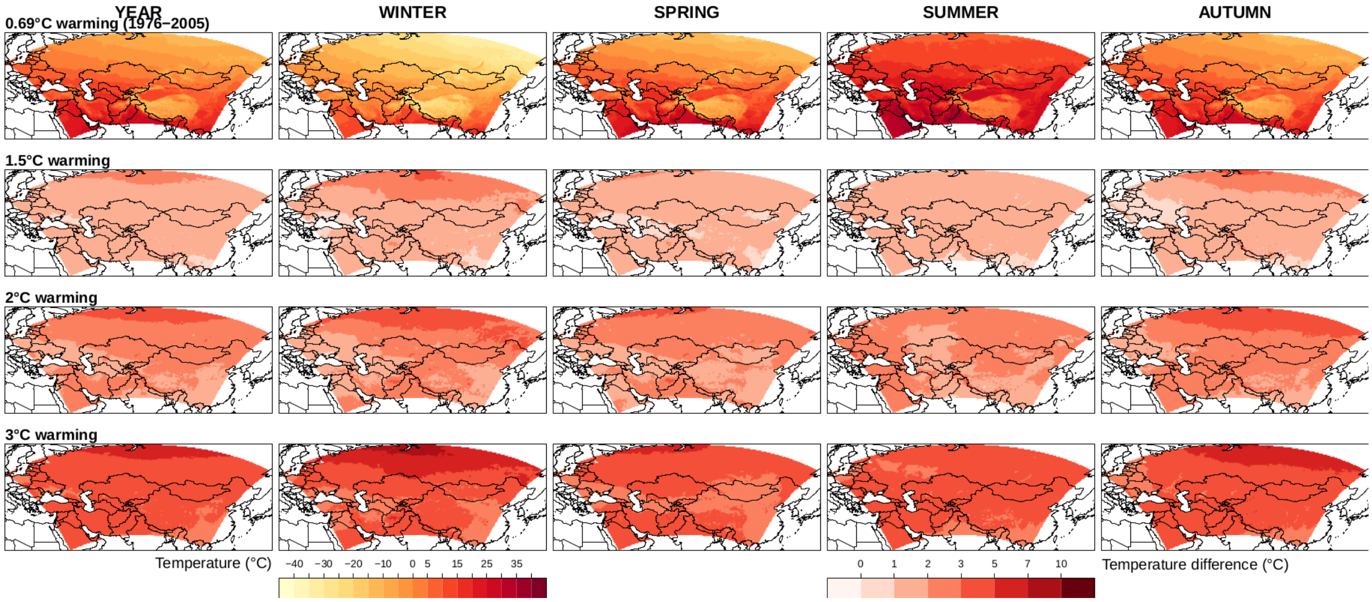

Fig. 2: Spatial variability in the annual and seasonal temperature means for the historical period (1976-2005) and temperature change under 1.5 °C, 2 °C and 3 °C global warming showing the effect of 0.81 °C, 1.31 °C and 2.31 °C global warming with respect to the historical period shows that additional global warming causes a significant additional warming over the Central Asia domain (based on Top 2022).

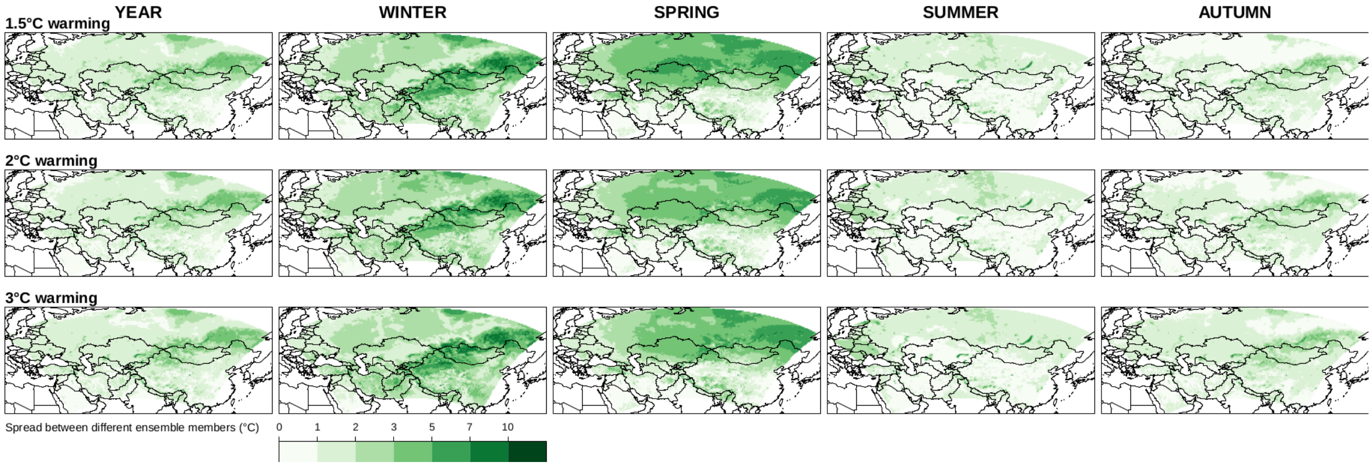

Fig. 3: Spatial variability in the annual and seasonal spread, quantified by the standard deviation, between temperatures of the different ensemble members and RCP scenarios under global warming of 0.81 °C, 1.31 °C and 2.31 °C with respect to the historical period (1976-2005) or 1.5 °C, 2 °C and 3 °C global warming with respect to the pre-industrial baseline period (based on Top 2022).

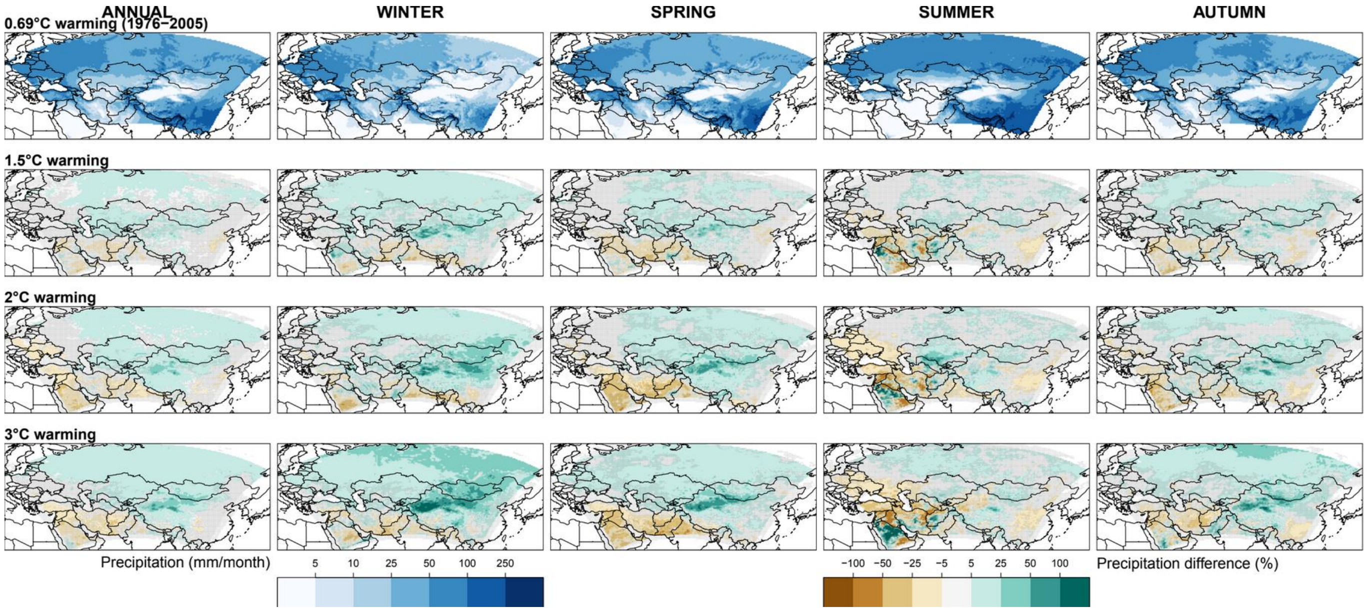

Fig. 4: Spatial variability in the annual and seasonal precipitation amounts for the historical period (1976-2005) and change in precipitation amounts under 1.5 °C, 2 °C and 3 °C global warming showing the effect of 0.81 °C, 1.31 °C and 2.31 °C global warming with respect to the historical period. The grey dots, on top of the precipitation difference class, indicate where the precipitation does not differ significantly between the historical and future period over the Central Asia domain(based on Top 2022).

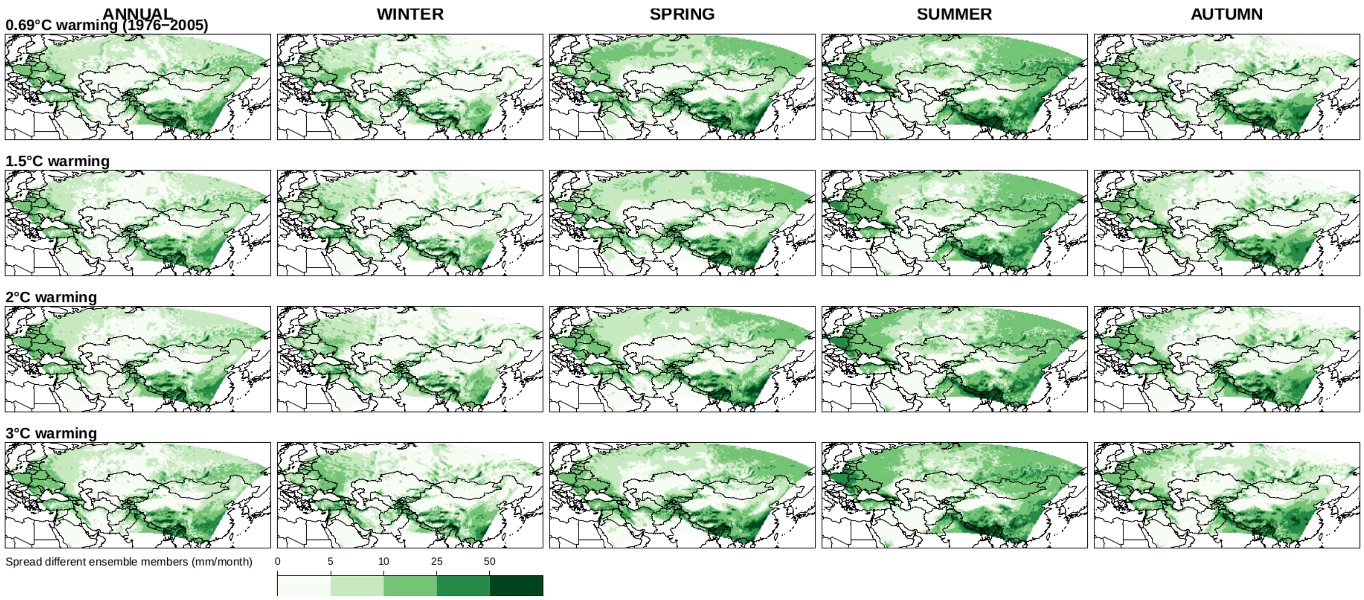

Fig. 5: Spatial variability in the annual and seasonal spread, quantified by the standard deviation, between regional precipitation amounts of the different ensemble members and RCP scenarios under global warming of 1.5 °C, 2 °C and 3 °C (based on Top 2022).