Dynamical downscaling of climate change in Central Asia

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ABSTRACT

The high-resolution regional climate model (RCM) REMO has been implemented over the region of Central Asia, including western China. A model run forced by reanalysis data (1/2° resolution), and two runs forced by a GCM (one run with 1/2° and one run with 1/6° resolution) have been realized. The model has been evaluated regarding its ability to simulate the mean climate of the period 1971–2000. It has been found that the spatial pattern of mean temperature and precipitation is simulated well by REMO. The REMO simulations are often closer to observational data than reanalysis data are, and show considerably higher spatial detail. The GCM-forced simulations extend to the year 2100 under the A1B scenario. The climate change signal of temperature is largest in winter in the northern part of the study area and over mountainous terrain. A warming up to 7 °C is projected until the end of the 21st century. In summer, warming is strongest over the southern part of Central Asia. Changes in precipitation are spatially more heterogeneous.

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1. Introduction

The region of Central Asia is characterized by a highly continental climate. The northern part of the region is even supposed to have the highest degree of continentality in the world. In addition to high amplitudes in the seasonal cycle of temperature, this implies semiarid to arid conditions with a constant moisture deficit and low relative humidity. The Caspian Sea and Aral Lake do not attenuate these extreme conditions beyond the directly adjacent areas (Lydolph, 1977). Despite these drawbacks in environmental conditions, the region has been cultivated for thousands of years. In the past decades the intensification of agriculture, namely overgrazing and an irrigation policy based on water mismanagement, resulted in desertification processes. Albeit this antagonism of water demand and availability is obvious, only when the desiccation of the Aral Sea since the early 1960s became impressively visible in the late 1980s, the subject has been attracting worldwide attention. Nevertheless, the public and scientific interest was focused on the Aral Sea region. Today, the water balance of the lake and the relation between the massive irrigation of (mainly cotton) fields and the desiccation of the lake is well documented (Micklin, 1988, 2007; Glantz, 1999). However, interest in understanding and quantifying the elements of the hydrological cycle on a larger scale, i.e. in the entire region of Central Asia, has occurred in more recent years only. Thus, it is still rather rudimentary (Lioubimtseva et al., 2005; Schiemann et al., 2008; Ozturk et al., 2012). In the part of Central Asia located in the former Soviet Union water-related problems have arisen due to irrigation and have been investigated at least to a certain degree for some decades. This is not the case for the eastern part of Central Asia, i.e. North-West China, which is also faced with substantial anthropogenic water demand in a context of scarce water resources. But here, in addition to agriculture, urbanization is the key challenge. While the actual urbanization level is still one of the lowest globally, the expected increase in the world’s urban population is predicted to be concentrated in China. In fact, the last two decades have already shown a rapid urbanization (Liu et al., 2003; United Nations, 2008). This means that population will be concentrated in areas with sparse water supply. Furthermore, urbanization usually leads to deteriorated water quality, which aggravates this problem (Foley et al., 2005). There are some studies on large-scale climate variations (e.g. Hu et al. (2003)), but apart from some Chinese catchment-related work, only few studies concerning the water cycle on the regional scale exist (Aizen et al., 1997).

For human activity water availability is of crucial importance, and the outlined issues of water demand and pulsing development in the study area strongly indicate the need of a sound knowledge of the water cycle on a regional scale. For a sustainable development it is necessary to adapt both to the present situation and to possible future changes in hydrological conditions. Observations have revealed an

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increase in temperature during the twentieth century. The heterogeneity of the region, which includes high mountain ridges as well as vast planes, does not only lead to a high spatial precipitation variability, but also to opposite precipitation trends on small scales (Lioubimtseva et al., 2005). Anthropogenic forcing as known from the global change discussion, and the possibility that global warming may intensify the water cycle and thus alter the spatial and temporal distribution of water (Bosilovich et al., 2005; Giorgi et al., 2011), strongly indicate the possibility of substantial future changes in the water cycle. The mentioned developments in the past seem to confirm this assumption.

Regional climate models allow to investigate the climatic side of the outlined problems on the regional scale. Thus, in this paper we present model simulations of present and future temperature and precipitation in Central Asia at different resolutions. This allows for a comprehensive study of Central Asian climate. The capability of the model to simulate the present climate is validated by different observational and reanalysis data. Furthermore, future climate changes can be investigated on a detailed spatial scale which is not captured by global climate model simulations (Tebaldi et al., 2005). This is even more important as the heterogeneous terrain of the study region requires the consideration of spatial details.

The following section presents the considered data sets and the model setup. Section 3 deals with the model validation, and Section 4 presents the model future scenarios. Finally, the results are summarized and discussed in Section 5.

2. Data

2.1. Observational data

For temperature and precipitation, the gridded global data set of the Climate Research Unit (CRU) is used. The monthly CRU data represent one of the most comprehensive observational data sets available and have been widely used for former studies. For precipitation, we included two additional gridded data sets: a climatology of monthly precipitation provided by the Global Precipitation Climatology Centre (GPCC), and the daily precipitation data set. An overview of these data and related references are given in Table 1.

All these observational data sets are based on statistical interpolation methods, which are used to retrieve a comprehensive gridded data set. An overview of these data and related references are given in Table 1. Additionally, in Section 3.4, we use some station data of the National Climatic Centre of the China Meteorological Administration (see Table 3).

2.2. Reanalysis data

Central Asia is a region with sparse data availability, but it is located downstream of the dense observation networks of Europe and the Middle East. Thus, data assimilation methods may deliver additional information and may constitute a more accurate picture of the real climate. We included two widely-used reanalysis data sets in our study: the ERA-40 data of the European Centre for Medium-Range Weather Forecasts, and the NCEP/NCAR data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research. The ERA-40 data has originally a T159 resolution (~125 km). We used a version which is interpolated to 2.5°, because it is freely available from http://www.ecmwf.int/products/. Note that while temperature data is assimilated from observations, precipitation is a fully independent model product in both reanalyses. Again, a summary of the data is given in Table 1.

2.3. ECHAM

The model ECHAM5/MPI-OM is a coupled global General Circulation Model (GCM). It delivers the boundary conditions for our regional model and will be referred to simply as “ECHAM” further on. Its atmospheric component ECHAM is used in its fifth generation. The model uses spherical harmonics with a truncation at wavenumber 63 (T63) which corresponds to a Gaussian grid of 192 × 96 grid boxes (Roeckner et al., 2003), i.e. a mesh width of 1.875°. The ocean/sea-ice component of the coupled model is called MPI-OM. It includes a dynamic and thermodynamic sea ice model. The horizontal resolution of the ocean/sea-ice component is 1.5° (Roeckner et al., 2003). The ECHAM simulations start in 1860 but end in different years between 2000 and 2300. We only used the time frame covered by REMO as well.

2.4. REMO

Regional climate models (RCMs) are useful tools for the projection of climate change on regional scales (Déqué et al., 2005; Jacob et al., 2007). Unlike GCMs, the model domain of an RCM does not cover the entire globe. It is restricted to a certain area of regional scale. This restriction allows for long-term simulations with higher resolutions. On the other hand this implies that information about the lateral and lower boundary conditions (LBCs) has to be provided. These LBCs can be derived from GCM simulations or from observational data sets (usually reanalysis products).

The modeling tool used for the regionalization of the Central Asian climate is based on the regional climate model REMO, version REMO 5.7 or REMO 2009 (further information: http://www.remo-rcm.de).

From a model physics point of view, REMO is a three-dimensional, hydrostatic atmospheric circulation model (Jacob and Podzun, 1997; Jacob et al., 2001). The atmospheric prognostic variables of REMO are the horizontal wind components, surface pressure, temperature, specific humidity and cloud liquid water. For horizontal discretization REMO uses a Arakawa-C grid where most of the variables are defined on the center of the grid boxes (Kotlarski, 2007). The grid box centers are defined on a rotated coordinate system. The influence of the LBCs can lead to boundary effects at the 3 to 8 outermost grid cells of the REMO domain. At the lower boundary, REMO is forced by the land surface characteristics, which are derived from FAO-soil type data sets, USGS land-cover classification and GTOPO30 topography. The original datasets have a resolution of 30 arc-seconds (approximately 1') and are interpolated to the respective REMO resolution.

Denis et al. (2003) found that a maximum spatial resolution jump of factor 12 between the RCM and its driving field is desirable to obtain satisfactorily dynamical downscaling results. Thus, in order to reduce the resolution jump from ECHAM at 1.75° to REMO at 0.166°, we adopted a double nesting strategy using an intermediate REMO simulation at 0.5° to drive REMO at 0.166°.
The REMO simulations used in this study are (please note, that the geographical boundaries of the domains only give a rough idea of the area covered since due to rotated coordinates the real model domain is not rectangular) as follows:

(1) REMO (ERA-40) has a resolution of 0.5° and covers an area of 91 × 65 grid points. The domain covers roughly 25°N to 60°N and 40°E to 90°E. This is the only available run with a forcing by observations using ERA40 as lateral and lower boundary conditions. The simulation covers the period from 1958 to 2000. The simulation was realized with the version REMO 5.7.

(2) REMO (ECHAM, 1/2°) is defined by a 0.5° resolution but a larger domain. It covers 163 × 121 grid points which is roughly from 5°N to 65°N and 30°E to 111°E. The simulation is realized with REMO 2009 and covers the years 1950 to 2100 and is driven by a run of the GCM ECHAM (Roeckner et al., 2003). The forcing until the year 2000 is a standard C20 scenario of observed greenhouse gas concentrations. The transient forcing during the period 2001–2100 corresponds to the Special Report of Emissions Scenario A1B (Nakicenovic and Swart, 2000). The forcing is the same as for REMO (ECHAM, 1/2°).

(3) REMO (ECHAM, 1/6°) is a two step-nesting product derived from REMO (ECHAM, 1/2°). The resolution is 0.166° with a model domain covering 181 × 121 grid points which is roughly from 25°N to 45°N and from 55°E to 85°E. The time range is from 1961 to 2100, and the forcing is the same as for REMO (ECHAM, 1/2°).

The different REMO model domains and their corresponding model topography are shown in Fig. 1. For comparison, the ECHAM model topography is shown, too.

3. Model validation

RCMs have emerged over the last 20 years. They have proven to be useful for climate impact studies, where detailed spatial patterns of meteorological variables are required and the influence of larger-scale variability on the local-to-regional climate processes is of interest. As RCMs allow for a more detailed spatial and temporal representation of climate processes than GCMs, they typically improve the simulation of extreme events, humidity and precipitation, because these are strongly influenced by small-scale processes (Feser, 2006; Paeth and Mannig, in press). Dynamical downscaling, as presented in this study, has the disadvantage that it is computationally more expensive than statistical downscaling. But it leads to more comprehensive and consistent data sets. Furthermore, statistical downscaling is always based on empirical relationships between local predictors and the variables of interest. Thus, firstly it is highly dependent on the quality of the empirical data, and secondly, statistical downscaling cannot simulate a climate outside the range of instrumental observations. For climate change studies, this is the crucial advantage of dynamical downscaling. However, the quality of the boundary conditions and the physical parameterizations are limiting factors of dynamical RCM simulations (Paeth et al., 2005, 2009; Rummukainen, 2010). In the present study we use boundary conditions from the GCM ECHAM5/MPIOM and the ERA40 reanalysis. The resulting REMO output is compared with each other in order to assess systematic biases arising from the different driving data. Therefore, particular emphasis is on the validation of REMO in light of existing observations.

3.1. Temperature climatology

As Central Asia includes both high mountain ranges and flat low-level planes, the spatial temperature variability is very high. This can be seen in Fig. 2, where the long-term mean of annual 2 m-temperature (1971–2000) is shown. The spatial resolution of the datasets differs widely; all climatologies are depicted in their original resolution. Thus, the different characteristics and advantages of the data emerge. The area shown corresponds to the model domain of the REMO (ERA40)
Fig. 2. Annual temperature means (in °C) 1971–2000 of ECHAM, different observational, reanalysis and REMO data sets.
simulation. The REMO (ECHAM, 1/6°) simulation is depicted in its original (much smaller) model domain. To neglect the influence of the forcing field, which decreases exponentially from the outer limits of the model domain, at each side of the area the three outer grid rows are skipped.

The annual temperature means show a clear north-south temperature gradient, which is modified by orographic effects. The overall spatial pattern is consistent in all data sets. Highest temperatures are achieved in the northern planes of India and Pakistan, with a steep temperature gradient among the southern slopes of the Himalaya. Lowest temperatures are achieved at the western Tibetan Plateau with means around −10 °C. This is expected as elevations in this area are generally above 5000 m. The Central Asian Planes and the basin of the Taklamakan Desert (Tarim Basin) in the North are distinctly warmer. The Tarim Basin has a considerable elevation, roughly around 1000 m. This is why the planes of Central Asia at the same latitude are warmer than the Tarim Basin. North of the Tien Shan mountains the latitudinal temperature gradient dominates. Another visible feature is a southward shift of the isotherms towards the East, and two cold cores in the East, which are due to the Altai Mountains. The southward shift of the isotherms reflects the gradient in continentality.

Pattern similarity in terms of these large scale features has been expected; interesting are the differences in regional details. Here, the most striking feature is the differences in the northern parts of India and Pakistan and the northerly adjacent mountainous regions with the enclosed Tarim Basin. Amongst all data, the model simulations (ECHAM and REMO) have the largest, and the CRU data the smallest temperature range over these regions. The latter may be influenced by orographic effects. The overall influence of orography is consistent in all data sets. The highest-resolution model data. It has to be considered that the dynamical downscaling process results in the heterogeneous pattern of mountain precipitation. This is especially true for the highest-resolution model data. It has to be considered that the reanalysis and ECHAM data have the coarsest resolution, which hampers the ability to simulate precipitation in heterogeneous terrain. The Taklamakan desert does not show up in the pattern of NCEP precipitation, compared with both reanalysis data and observations. This is due to winter precipitation (not shown).

Comparing the reanalysis precipitation data with three different observational and reanalysis data. While all data sets capture the main features of the precipitation pattern, namely a belt of very high precipitation along the southern slopes of the Himalaya, the dry areas of the Tarim Basin and the Central Asian planes and higher precipitation in all further mountain ranges, there are considerable differences between the data sets even on larger scales. The mentioned high–precipitation belt is broader in both reanalysis data sets. The same is true for the higher precipitation at the Tien Shan mountains. All observational data show more spatial details than the reanalysis data, but the precipitation pattern is more differentiated in the APHRODITE and GPC data than CRU. In REMO the dynamical downscaling process results in the heterogeneous pattern of mountain precipitation. This is especially true for the highest-resolution model data. It has to be considered that the reanalysis and ECHAM data have the coarsest resolution, which hampers the ability to simulate precipitation in heterogeneous terrain. The Taklamakan desert does not show up in the pattern of NCEP precipitation, compared with both reanalysis data and observations. This is due to winter precipitation (not shown).

All data sets show the dry area across the Central Asian plains, although amplitudes and extent are different. ECHAM and REMO driven by ECHAM simulate considerably less precipitation than shown in the observations. This may reflect a dry bias from the GCM. In the North-West of the REMO (ERA40) model domain, more precisely north of the Caspian Sea, all model simulations produce too much precipitation compared with both reanalysis and observations. This is due to winter precipitation (not shown).

Comparing the reanalysis precipitation data with three different observational data sets, they do not seem to be very reliable in our model domain. This is especially true for all mountain ranges and for NCEP in general (see also Schiemann et al. (2008)). Overall, in the very dry and very wet regions differences between all data sets are most obvious. Nonetheless, the absolute differences in precipitation are not very high in the dry regions (note the nonuniform graduation of the scale bar). The Tibetan Plateau even the structure of the precipitation pattern differs between the different observation data. This is most likely due to the scarce station availability and the different interpolation methods. There, REMO has a considerable wet bias, to a lesser degree it also exists in ECHAM. This bias is mainly due to summer precipitation, where the observation datasets show nearly no precipitation at all over the entire central and eastern model domain (not shown). No other data set shows as much spatial detail as the highest resolution REMO data. Especially in winter precipitation (not shown) in the REMO (ECHAM, 1/6°) simulations single large valleys can be identified due to the windward and leeward effects. It cannot be ruled out that the RCM simulations are closer to the real climate system than any other data set considered here. In such orographically complex areas with sparse station coverage it is
Fig. 3. Same as Fig. 2, but for annual precipitation and two additional observational data sets (cf. Section 2.1).
nearly impossible to sensibly validate high-resolution model data. As a general validation result, the ECHAM and REMO simulations seem to have a wet bias over mountain ranges and a dry bias over dry areas, and especially the wet bias is more pronounced in the higher resolution model simulations.

3.3. Seasonal cycle

The seasonal cycle in the region is controlled by larger-scale circulation patterns, especially the jet stream. Its location changes over the year. In summer, it is located over the northern part of the model domain, and in winter it moves to the south of Central Asia. Thus, in winter the Siberian High extends into the northern model domain, while the southern part is influenced by less stable weather conditions generated by the overlying jet stream. In summer strong heating leads to the formation of heat lows over the entire region (Lydolph, 1977; Schemm et al., 2008). This means that besides the differences in terrain, the model domain is too large to have a uniform seasonal cycle. Therefore, prior to the examination of seasonal temperature and precipitation variations some kind of regionalization is necessary. This was achieved by performing a cluster analysis which is based on variables derived from the CRU data. These were 30-year means of annual temperature, annual temperature amplitudes, monthly maximum and minimum temperatures, annual mean precipitation, January and July precipitation. The cluster analysis has been performed following the approach of Fovell and Fovell (1993): a principal component analysis has been performed over a data matrix containing the mentioned mean values at each grid box. The rotated eigenvectors serve as input of a k-means cluster approach. With eight clusters prescribed, the best compromise between clustering and segmentation was achieved. For the analysis, monthly long-term means (1971–2000) were built for all regions.

The result of the regionalization is shown in Fig. 4. It reflects the growing continentality from west to east as well as the north-south gradient and the main orographic features. The regions are sorted by the annual mean temperature. Cluster 1 is the region with the lowest annual mean temperature (always referring to the long term mean 1971–2000), and cluster 8 in northern India the cluster with the highest annual mean temperature. Table 2 provides a brief climatological overview of the different clusters.

The individual diagrams in Fig. 5 show the mean annual temperature cycle for the different regions and data sets. The REMO (ECHAM, 1/6°) run is omitted, as it does not cover all regions. The continentality of the entire REMO (ERA) model domain is indicated by large annual temperature amplitudes in all regions. High summer insolation leads to strong surface heating, and in winter, the northern part is dominated by clear sky conditions associated with the influence of the Siberian High. In the southern part, more turbulent weather conditions with milder winter temperatures prevail, as indicated by the temperature cycle of clusters 7 and 8. Cluster 8 has the lowest yearly amplitude, which still equals nearly 20. The spread between the different data sets is largest for cluster 1, 2 – which are both highly mountainous regions – and 8. In cluster 1, both NCEP and REMO (ECHAM, 1/2°) deviate slightly from annual cycle of the other data. Compared to ERA and CRU, REMO as well as NCEP seem to underestimate temperatures of the Tibetan Plateau (cluster 2). NCEP shows this underestimation throughout the year, but REMO only in winter and especially in spring. But again, this is a high mountain area and REMO is the only data set which is dynamically downscale to a high resolution. REMO (ECHAM, 1/2°) seems to slightly underestimate temperature in the north-eastern part of the model domain (see clusters 1 and 3). In the northwest, agreement between the datasets is high, only in late autumn REMO (ECHAM, 1/2°) is too warm and NCEP colder than the other data. CRU, ERA, ECHAM and REMO (ERA40) are in almost perfect accordance. Summer temperatures in clusters 5 to 7 are overestimated by both ECHAM and REMO. In cluster 5 deviations are rather small. The cluster includes miscellaneous areas mountainous and flat areas, so not much information can be gained from this. But in cluster 6 and especially 7 the deviation in summer temperatures is considerably larger. These clusters comprise the dry plains of Central Asia (6 and 7), the area south of those plains and the Punjab area (cluster 7) as well as the Tarim Basin and Gobi desert (cluster 6). So there might be a certain systematic bias.

For the small cluster 8, REMO as well as ECHAM simulate clearly too high temperatures in late spring and REMO has also slightly too high temperatures throughout the year, while ECHAM has too cold winter months, thus overestimating the seasonal cycle. Similar to Section 3.1, for clusters 1 to 4 both REMO simulations lie within the range of uncertainty derived from the observational and reanalysis data. Existing biases, especially in clusters 1 and 2, may arise from differences in cloudiness, mountain effects or simply from model deficiencies with regard to the physical parametrization. A possible reason for the low spring temperatures in cluster 2 is too much snow cover in winter or too much precipitation in spring. Then, a large part of the insolation is used as latent energy for melting and evaporation and is not available for heating. This hypothesis seems to be supported by the fact that in this region, the wet bias of ECHAM is slightly lower, and so is its cold bias. High summer temperatures in late spring and summer in clusters 5 to 8 may be due to land use and irrigation: ECHAM and REMO neither contains a coupled land use model nor additional water due to irrigation nor the true land use of the validation time period; firstly because land use varies often on small scales the models cannot resolve, and secondly because land use is handled as a fixed boundary condition which does not change in time, as it does in reality.

For precipitation, the seasonal cycles of the different regions show a broad range of characteristics (see Fig. 6). The mountainous regions (clusters 1 and 2) and the region influenced by the Indian monsoon (cluster 8) show the most pronounced seasonal cycle with large precipitation peaks during the summer months and very little precipitation in winter (especially clusters 1 and 8). Clusters 5 (miscellaneous,
but mainly southern mountainous regions) and 7 (the southern part of Central Asia) have a precipitation maximum in March and minimums in summer and early autumn. The magnitude of variability is somewhat larger in region 5, which includes more mountainous territory and is located mostly north of cluster 7. The central dry region (cluster 6, including the dry core of Central Asia and the Tarim Basin) has very low precipitation amounts in all months, thus showing very little variation throughout the year.

Precipitation amounts of CRU, GPCC, and APHRODITE are generally very much alike in all months and for all regions. An exception is the summer precipitation in cluster 8, where CRU and ERA-40 have the best match. The reanalysis data, especially NCEP, show large deviations from the other observational data sets in its absolute values, although the general characteristic of the seasonal cycle is reproduced in all regions. REMO is usually closer to observations than the NCEP data. Only in the region consisting mainly of the Tibetan Plateau (cluster 2), the NCEP data is closer to observations than both ECHAM, REMO and ERA-40 data. The ERA-40 data severely overestimate the seasonal cycle. It is the only region where REMO performs poorly in comparison with ECHAM and the observational data, simulating too much precipitation throughout the year. The ECHAM driven REMO run shows a sharp second precipitation minimum in May, which is also slightly indicated in ECHAM and the CRU data set. In this high mountain region the largest differences between all considered data sets occur. This may not serve as an alibi for the poor performance of REMO. Nonetheless, station coverage is very low in this area and hence, no reliable ground truth for model validation is given.

Generally, in all regions with a summer precipitation maximum (clusters 1–4, 8), REMO (but not always ECHAM) has a wet bias. The reason lies within the upwind effect, which is stronger the better topography is resolved. While REMO driven by ECHAM simulates too high precipitation rates throughout the year, REMO (ERA40) precipitation is close to observations in winter but does generate too much summer precipitation. Thus, it exaggerates the seasonal cycle. This is especially true for cluster 8. There, the REMO (ECHAM, 1/2°) is very close to the CRU and ERA-40 precipitation from January to
August, but overestimating precipitation from September to December. The three driest regions (clusters 5 to 7) have an annual cycle of precipitation, with comparatively wet springs and a minimum of precipitation in late summer and autumn. For cluster 5, ECHAM is in perfect accordance with APHRODITE, which itself differs from CRU and GPCC. REMO is closer to the latter two. Cluster 7 embraces the Southern part of Central Asia, where land cover and irrigation have strong effects on precipitation (Lioubimtseva et al., 2005). So possibly shortcomings in the simulation of precipitation are not necessarily due to parameterization, but to bad representation of land surface characteristics. Here, REMO is closer to observations than ECHAM. In cluster 6, REMO (ECHAM), and more so ECHAM, overestimate winter precipitation and slightly underestimate summer precipitation.

Only in some cases REMO (ERA40) is closer to observations than REMO (ECHAM). Typically, this is for situations where the larger-scale circulation pattern governs precipitation events. An example is winter precipitation in cluster 7, where ECHAM and REMO (ECHAM) both underestimate precipitation. Earlier studies have shown that ECHAM and other GCMs have poor simulation skill in terms of Central Asian winter precipitation (Tippett et al., 2003). So we assume that at least partly the errors are inherited from the driving model.

Neither for temperature nor for precipitation REMO simulations are generally closer to observations. This is at least partly due to the lack of stations in the regions of highest elevation (that matters mostly in cluster 2). Therefore, effects of highest topography which influence the spatial mean do not emerge in the gridded observation data, but in high-resolution model simulations.

3.4. Weather stations

Our previous analysis has shown that in mountainous regions all data sets differ considerably in their precipitation amounts (cf. cluster 2 in Section 3.3). In the dry regions REMO (ECHAM, 1/2°) seems to overestimate winter precipitation (cf. cluster 5). We use station data, which is supposed to represent the “ground truth”, to examine the REMO (ECHAM) performance in more detail. Therefore we choose...
a subset of the region where we have a transition between high precipitation regimes in the mountains to the dry Taklamakan desert basin (see Fig. 7).

The most prominent feature is that both REMO runs simulate too little precipitation in the dry basin and too much precipitation in the northwest and mountain regions. This confirms our findings from Section 3.2. However, it appears that the bias is slightly lower in the higher-resolution simulation (Table 3). Table 3 also reveals that the model biases are not height dependent. Some of the deviations could be due to the fact that we compare local station data with model grid boxes in a rough terrain. We did not include an elevation model in our study, so we have no information about the exposition of the locations of the weather stations. Doing so could give some explanations, because we would see which stations are in the rain shadow and which are particularly exposed.

4. Future climate change

In this section we analyze projected temperature and precipitation changes until the end of the twenty first century under the assumption of the IPCC A1B emission scenario. Therefore, we build differences between the means 2071–2100 and 1971–2000 and test the statistical significance by means of a t-test for independent random samples.

Simulations of GCMs suggest that the study area is prone to a warming above global average in the future. The region is isolated from maritime influences from the West and South, and the temperature change will be strongly affected by the winter Arctic warming in the North and local snow cover feedbacks. Changes in precipitation will be linked to changes in moisture transport from the northwest by westerlies and polar fronts and in the context of the South Asian monsoon system. However, it is known that GCMs perform poorly in this area of complex topography (Christensen et al., 2007). REMO simulates temperature changes between approx. 2 and 7 °C in the region for both summer (JJA) and winter (DJF), changes in winter temperature as simulated by ECHAM exceed even 8 °C (see Fig. 8). The climate change pattern is similar in all three simulations. All changes are statistically significant, at least at the 5% level.

Temperature changes in summer are smallest in the northwest of the region, where the westerly influence is strongest. Changes as simulated by REMO generally increase towards the southeast, but some hot spots of warming are over the mountainous regions of Iran, the Tibetan Plateau and the Pamir and Tien Shan Mountains and over the Taklamakan desert basin. The latter is more pronounced in the REMO (ECHAM, 1/6°) simulation. REMO (ECHAM, 1/2°) shows some hot spots of warming in the Tien Shan, the Karakorum and western Tibetan Plateau that do not appear in the high-resolution warming pattern. Those small structures do not appear in ECHAM, and neither does the intensified warming in the Taklamakan desert basin. Nonetheless, the general warming pattern coincides with that of REMO. Simulated changes are app. 1 °C warmer than those by REMO. In winter, the snow-albedo effect clearly leads to the strongest warming in the northwest and mountain regions. The magnitude of warming is nearly everywhere above 3 °C and exceeds 5 °C in large areas. REMO (ECHAM, 1/6°) is not fundamentally different to the coarser resolution simulation, but shows a more detailed spatial pattern in the Tibetan Plateau and the Tarim Mountains. In ECHAM, warming is generally stronger then in REMO. There are too few details seen for a genuine comparison with the REMO warming patterns. But two hot spots of warming exist, one is in the north, similar to REMO, but more centered. The second is clearly concentrated in the Himalayan Mountain Range. Different from REMO, the entire eastern depicted model domain has a more or less uniform warming, the Tibetan Plateau does not emerge in the warming pattern. Only in the southeast are the warming amplitudes the same in the RCM and GCM.

Until now, we have realized only one simulation per model domain. Thus, we cannot estimate the uncertainty of climate change by a probabilistic approach. The IPCC range of projected temperatures at the end of the 21st century according to the SRES A1B scenario is above 4 °C for the northern part of our model domain, 2–3 °C for the Tibetan Plateau and the Central Asian core region; ECHAM is close to the IPCC multi-model ensemble mean (Christensen et al., 2007).

Table 3

<table>
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Fig. 7. Comparison of station data and simulated annual precipitation in a subset of the model domain for both REMO resolutions.
Most GCMs simulate reduced precipitation in summer for Central Asia, and increased winter precipitation for northern Asia and the Tibetan Plateau (Christensen et al., 2007). Others find a tendency towards a warmer and wetter climate in Northwest China (Shi et al., 2007). ECHAM shows opposing trends in Central Asian summer precipitation and agrees with those trends regarding winter precipitation in northern Asia, but not necessarily in the Tibetan Plateau, where ECHAM simulates weak opposing tendencies, and a strong drying of the South Himalayan Mountain slopes. The tendencies for Northwest China are only confirmed in winter precipitation.

The REMO simulations are similar to ECHAM in the moistening of the very north and in the location of the hot spots of drying (see Fig. 9). All further changes are very small. The REMO (ECHAM, 1/2°) simulations indicate slightly dryer summer conditions for a large part of Central Asia. Again, the largest changes emerge over mountainous regions. But in the Tibetan Plateau small areas with a strong drying tendency of more than 100 mm within a season are neighboring regions with a simulated increase of the same amount. Those regions represent a narrow band of increasing precipitation along the highest elevations of the Himalayas mountain range. This is a small scale phenomenon which cannot be resolved by ECHAM, it shows the strong drying solely. The pattern is also shown by REMO (ECHAM, 1/6°), but the drying effects are stronger. The drying south of the band belongs to an expanded area of distinctly decreasing precipitation over Pakistan and India. The opposing effects are both statistically significant. A similar pattern was found in a regional climate model study by Rupa Kumar et al. (2006), although their simulations show a smaller magnitude of precipitation decrease and the area with decreasing precipitation north and south of the Himalayas mountain range has a smaller extent.

During winter, the area with an increase of precipitation extends farther south and covers entire Kazakhstan. The increase in precipitation does not exceed more than 25 mm in the South and is only significant in the northern part. Further north, increases in precipitation are larger (up to 100 mm). In the southwest there remains a small drying tendency, only pronounced over the Zagros Mountains. Along the southern fringe of the Himalayan Mountains there is a moderate decrease in precipitation, which is stronger in the ECHAM simulations. But as winter precipitation is low in this region (see cluster 8 in Fig. 6), this decrease may have considerable impact. However, it is not statistically significant everywhere. Furthermore, the 1/2° resolution REMO shows a small area in the Tien Shan mountains with decreasing precipitation and a decrease over the Lake Balkhash in southern Kazakhstan.

Fig. 8. Temperature change in °C: Mean 2071–2100 to 1971–2000, summer and winter, all changes are significant at the 95%-level (two-sided t-test). Top: ECHAM, middle: REMO (ECHAM, 1/2°), bottom: REMO (ECHAM, 1/6°).
The transition to wetter conditions in the Pamir and Tien Shan Mountains is more pronounced in the high-resolution simulations, and cannot be seen in the GCM simulation, which shows weak drying tendencies. The decrease in precipitation along the southern fringe of the Himalaya and in the Hindu Kush is strongest in ECHAM, but simulated by all models. Both REMO simulations show a similar moderate increase in winter precipitation in the northern part of the Tibetan Plateau and the Tarim Basin, whereas the ECHAM simulation reveals very weak tendencies of different sign.

The proposed transition from a warm-dry to a warm-wet climate in northwest China (Shi et al., 2007) is verified by our simulations and by ECHAM for the winter months only. REMO agrees to a certain degree with further GCM simulations, more so than ECHAM: dryer summer conditions for most of Central Asia and an increase in winter precipitation for the northern part of the area and large parts of the Tibetan Plateau. Noteworthy is the small-scale spatial heterogeneity of precipitation changes in this region.

The IPCC results show a large uncertainty regarding the changes in precipitation in this area (Christensen et al., 2007). In summer, the models differ even in the direction of precipitation changes (increase vs. decrease) over the entire REMO model domain, and ECHAM shows a more extended drying tendency than the IPCC multi-model ensemble mean. In winter, ECHAM is close to this mean. Most models predict an increase of precipitation in the northern model domain, but further south (a large area including inner Central Asia and the Tibetan Plateau), approximately half of the models predicts an increase, while the other half an decrease.

5. Discussion and conclusions

In summary, the simulated large scale precipitation and temperature patterns are in good agreement with observations. In the high altitudes of the mountainous regions in the east of the study area, REMO (all versions) simulates colder temperatures than observed. The same is true for the NCEP data. ECHAM has this cold bias only where the model resolution allows for high elevations, i.e. some parts of the Tibetan Plateau. In Northern India and Pakistan as well as in the Central Asian plains both ECHAM and all REMO versions simulate warmer temperatures than observed, as does ERA-40. For precipitation, the pattern of the NCEP precipitation climatology deviates from the precipitation of the other data sets. The pattern of REMO precipitation is quite close to observations. Due to the higher
resolution, the spatial details of the REMO simulations agree better with observations than ECHAM or the reanalysis data do. Nonetheless, the magnitude of spatial variability is larger than for the observations, and for the Tibetan Plateau simulated precipitation is clearly above observed precipitation, although it has to be considered that much of the precipitation at the Plateau comes as snow, which is difficult to measure. ECHAM also shows this moist bias, but it has a much smaller extent. The REMO (ECHAM, 1/6°) simulation reveals the most details, topography related effects emerge clearly. It is difficult to evaluate the true information content of these details, because the model simulations have a higher resolution than the observational data, and station coverage is low. Those stations which exist are usually situated in valleys, and not the high elevations. This means that effects from high altitudes might not emerge in the observation data, which could explain why in some mountainous regions the simulation of the highest resolution has the largest bias, if compared to the gridded observation data.

The validation of the seasonal cycle confirms that simulated temperatures are within the range of uncertainty of the different observational and reanalysis data for a large part of the model domain. There are two obvious and severe shortcomings. Firstly, REMO simulations underestimate the spring temperature for the Tibetan Plateau. This is most likely due to snow cover effects. If the winter precipitation is too high (which is the case), the snow cover is larger than in reality. Then in spring more energy is used for melting and thus not available for sensible heat fluxes. ECHAM does not have this cold bias, which might be explained by the fact that precipitation is closer to the observations in the Tibetan Plateau. The second obvious bias in the REMO and ECHAM simulations is the high summer temperature in Northern India, Pakistan and the Central Asian irrigated cropland. The problem here is the inadequate land surface forcing for the REMO simulations. In reality, irrigation during the dry season leads to enhanced evapotranspiration and thus lower temperatures. This remains unaccounted for in both the REMO and ECHAM simulations.

For precipitation the regionalization reveals that REMO is able to reproduce the seasonal cycle well for most of the area. The exception is the region including the Tibetan Plateau and part of the Tien Shan mountains. Here, precipitation amounts are not only too high throughout the year, but REMO simulates an artificial second precipitation maximum in spring. ECHAM also indicates this second maximum, but the wet bias is smaller, as it mainly occurs above the Himalayan Mountain Range, and not the entire Plateau. These validation results reveal some biases of REMO. Nonetheless, final conclusion concerning the quality of the RCM remains difficult. Although logically we would expect an added value of a RCM, it might not be possible to verify it. A large part of the region is data sparse (see e.g. Schiemann et al. (2008) or the CRU cell-station data set). All the used gridded observational data sets use statistical interpolation methods between the station observations, which tend to smooth the climatological patterns. Especially in the seasonal precipitation climatologies, the different observational datasets vary clearly. The ERA-40 and more so the NCEP data are not closer to the observational data sets than the REMO data. In some extent this is certainly due to the complex terrain and the low resolution of the reanalysis data, but it also leads to the question how reliable our validation data base is. While ECHAM is closer in the spatial means to the observations in some cases (see Section 3.3), the more detailed patterns of REMO coincide better with observations than ECHAM does (e.g. the Tien Shan mountains or the Taklakaman desert basin).

With the exception of the too low spring temperature in the Himalayan Plateau mentioned above, no bias interrelationships between mean values and seasonal cycle or between temperature and precipitation are obvious. For example, in the northwestern part of the study area the REMO (ECHAM, 1/2°) simulation follows almost perfectly the observed seasonal cycle of precipitation, but shows too high mean values throughout the year. The Tibetan Plateau region is characterized by a remarkable bias in precipitation, although the REMO (ERA-40) run simulates the seasonal cycle in agreement with the observations, albeit at a too high level.

In a comparison of model precipitation with station data, we find that for the selected subregion REMO simulates too low precipitation in dry regions, and too much precipitation in the adjacent mountainous regions. For this small-scale analysis, the advantage of REMO (ECHAM, 1/6°) emerges, as its simulated precipitation values are closer to station measurements. For improvements in the simulation of both precipitation and temperature, a more comprehensive land surface forcing is necessary. Important human impacts like irrigation and land use changes have to be considered (cf. Paeth et al. (2009), Saeed et al. (2009)).

The climate change scenarios show a warming which is above global average in the largest part of the model domain. The warming peaks during winter at high elevations sites and the northern part of the region. The REMO (ECHAM, 1/6°) run reveals the spatial structure of this warming in more detail. For most of the area, the projected warming is more pronounced than predicted by the IPCC multimodel projections, as are the seasonal differences in the warming rate (Christensen et al., 2007). It is likely that the warming affects on the summer monsoon precipitation, because it intensifies the summer thermal low over the Tibetan Plateau. However, our simulations predict a decrease in summer precipitation in the monsoon region. This is not necessarily a contradiction. Douville et al. (2000) found a weakening of the monsoon circulation for greenhouse gas induced climate change scenarios. They conclude that changes in atmospheric water content, precipitation and land surface hydrology could have greater influence than the increasing land–sea thermal gradient. Others attribute the decrease in monsoon precipitation to the effect of aerosols (Mudur, 1995). The simulated increase in winter precipitation over the northern part of the model domain is in accordance with previous findings. In summer, our simulated changes are small and mostly not significant, but the dominant drying tendency is also confirmed by earlier studies (Christensen et al., 2007). To assess the uncertainties of our findings, additional model runs are necessary. The REMO (ECHAM, 1/6°) simulation depicts an impressive degree of spatial details, both in climatologies and in climate change signals. Nonetheless, for applications even higher resolution information is necessary. These may be gained by dynamical or statistical downscaling approaches, or a combination of both. Such approaches have been successfully applied for a region of similar terrain (Haas and Born, 2011). A further possibility to obtain precipitation data of high spatial and temporal resolution, e.g. for impact studies, is the setup of a weather generator. Another feasibility to pave the way for impact studies and enhance RCM simulations is a coupling to glacial and hydrological models.

Acknowledgments

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