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QUANTIFICATION OF UNCERTAINTIES IN REGIONAL CLIMATE AND CLIMATE CHANGE SIMULATIONS (QUIRCS)

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Summary

The comparison of multi model runs of the reference period 1979-1993 with different observational data sets for several climate parameters enables the quantification of the model uncertainties in representing present-day climate conditions for Central Europe. The quantification is based on a number of objective distance measures which detect differences in the spatial and temporal structures of the data sets being compared. Additional climate change simulations of two 30-year periods (control and scenario simulation) are performed for the SRES B2 global change scenario. They indicate a severe warming for Germany with values of up to 4 K in summer which is much higher than the quantified uncertainty range of the regional models for this climate parameter. For precipitation in Germany, a weak reduction during the summer months is overcompensated by an increase in winter and fall. However, the simulated changes are smaller than the quantified uncertainty range for the regional models so that in particular a significant reduction of the annual precipitation in Germany cannot be stated on basis of the current simulations for the B2 scenario.

Aim of the research in the context of DEKLIM

A reliable assessment of possible future climate developments requires an improved understanding of climate and its variability as well as a detailed knowledge of the uncertainties of climate simulations which provide the requested information about the potential degree of future changes. The project QUIRCS focuses on the climate patterns of Central Europe and investigates the quality of currently used regional climate models and regionalization techniques by a model inter-comparison, a substantial model evaluation, additional sensitivity studies and an extensive analysis of climate data. The major scientific aims are

- to quantify the uncertainties of regional climate simulations and of observed climate data,
- to provide a regional climate change scenario for Europe with a particular focus on Germany,
- to assess the reliability of the produced climate change signals with respect to the quantified uncertainties.

A set of common model experiments and data evaluations have been realized by the six project partners to achieve these aims. Additional contributions of associated partners from PIK and GKSS, who have joined the project during the last year, have substantially enlarged the data basis for the quantification of potential model uncertainties.

Principal results

The quantification of model uncertainties and the associated assessment of simulated climate change signals in QUIRCS are based on a number of climate simulations for Central Europe with different regional climate models at a horizontal resolution of about 18 km (Fig. 1). In the evaluation runs, the period between 1979 and 1993 was simulated to determine how good the climate conditions during that period can be reproduced by the regional models. The models being used are two versions of the regional climate model REMO (Jacob, 2001), the mesoscale model MM5 (Grell et al., 2000), two climate versions of the weather forecast model LM (Boehm et al., 2004), and a statistical-dynamical approach (Busch and Heimann, 2001) which uses the results of selected episodes from one of the continuous REMO simulations for a statistical recombination of the climate conditions of the reference period. The other 5 model versions are directly nested into six-hourly ECMWF reanalyses of the actual weather conditions of the regarded 15-year period (ERA15, Gibson et al., 1997).

The resulting climate parameters are compared with corresponding reference data (Table 1) which have been prepared from surface and satellite observations. A number of objective keyparameters like the BIAS or the spatial and temporal correlations of annual or monthly means over certain subregions are used to measure the distances between model results and reference data. The range of values for each of these distance measures quantifies the uncertainty by which the regional climate models are able to reproduce special characteristics like the long term means, or the spatial and temporal structures of a certain climate parameter.

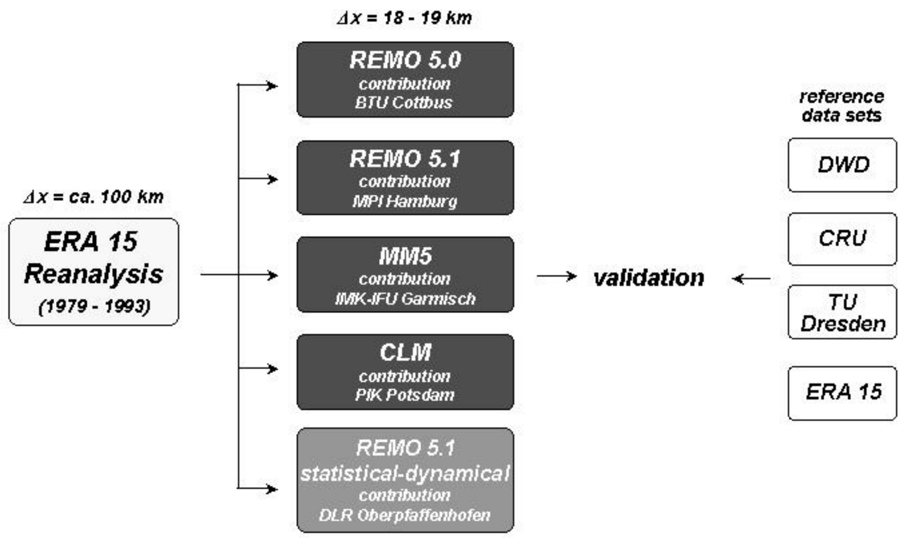

Figure 1. Downscaling and validation concept in QUIRCS.

In a next step, two further time-periods were simulated with different regional models. The first period (control run) represents a fictive present-day control climate. The lateral forcing is provided by a global climate simulation with ECHAM4. The second period (scenario run) represents a future climate scenario simulated by the same global climate model but according to a prescribed global increase of greenhouse gas concentrations (IPCC SRES B2). The differences between the regional simulations of the scenario and the control period provide the climate change signals. They are quantified by the same distance measures (e.g. the BIAS) that are used to determine the deviations of the evaluation runs from the observed climate.

Variations of these measures from model to model yield the potential uncertainty of the simulated changes due to the influence of the model characteristics. If for a certain climate parameter the climate change signal is larger than the uncertainty range of the evaluation runs the simulated changes can be seen as a reliable regional response of the investigated region to the assumed global climate change.

Uncertainties in the reconstruction of present-day climate conditions

For the period from 1979 to 1993 monthly means of a number of climate parameters (Table 1) were interpolated from the surface observation network of the German Weather Service (DWD) onto a regular grid across the area of Germany by a combination of inverse distance weighting with horizontal and vertical regression methods (Dittmann et al., 1999) to provide the necessary reference data for the model evaluations (Fig. 1). For some of these parameters the climate data sets by New et al. (2000) from the Climate Research Unit (CRU) can be used as an additional reference for the European land areas. Furthermore, the colleagues from the Technical University of Dresden (TUD) have calculated area wide upward and downward radiant fluxes at the top of the atmosphere and at the earth's surface by radiation transfer simulations using ISCCP (Rossow and Schiffer, 1999) satellite observations. The horizontal resolution of all data sets is comparable to the resolution of the regional climate simulations.

Climate parameter	provided by	DWD	CRU	TUD
Mean sea level pressure	MSLP	X		
Near surface air temperature	T2m	X	X	
Total precipitation amount	Pre	X	X	
Daily maximum and minimum temperature	Tmax, Tmin	X		
Diurnal temperature range of 2m-temperature	DTR	X	X	
Wind speed 10 m above ground	V10m	X		
Specific humidity/vapor pressure near the surface	qv, e	X	X	
Frequency of summer, frost, and ice days	Ns, Nf, Ni	X		
Frequency of significant and intensive rain days	Nsr, Nir	X		
Long- and shortwave radiation fluxes at top of atmosphere	Q-TOA			X
Long- and shortwave radiation fluxes at the earth surface	Q-SF			X

Table 1. High resolution reference data for model evaluation provided by the German Weather Service (DWD), the Climate Research Unit (CRU, version TS 1.2), and the Technical University of Dresden (TUD). Significant/intensive rain days are defined as days with more than 1mm/10mm of precipitation. Summer, frost, and ice days are days with Tmax>25°C, Tmin<0°C, and Tmax<0°C, respectively.

A set of keyparameters was introduced in order to enable an objective quantification of the distances of the model results from the reference data for a given region (e.g. systematic and absolute deviation of area averages, relation of temporal and spatial variability, and conformance of spatial and temporal structures).

The deviations (BIAS) of all simulated climatological (15-year averaged) annual means of the 2m temperature from DWD and CRU data are shown in Figure 2 for 8 different subregions in the reference domain of Central Europe (see Fig. 4). Some models systematically overestimate the annual mean temperature for all subregions and some models underestimate it. For Germany, the deviations of the simulated annual mean temperature from the reference data vary between -1.7 K and +1.4 K. The range of the temperature BIAS slightly varies from region to region and is greatest with values between ±2 K for the area around Munich. The two reference data sets agree quite well with a maximum difference of 0.5 K for the subregion Munich.

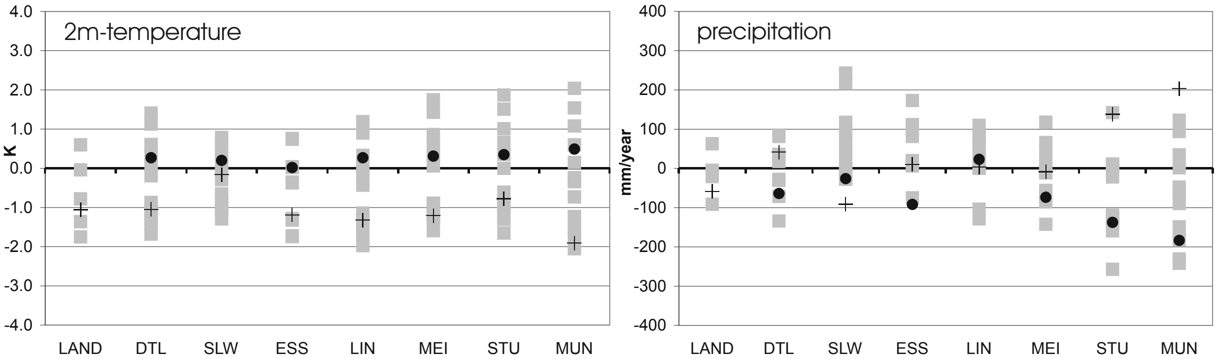

Figure 2. BIAS of climatological annual means of temperature and precipitation for 8 subregions: the entire land area of the reference domain (LAND), the area of Germany (DTL), and 6 subareas of Germany with an approximate size of 125x125 km^2 located around the cities of Schleswig (SLW), Essen (ESS), Lindenberg (LIN), Meiningen (MEI), Stuttgart (STU), and Munich (MUN). Each square represents the deviation of one of the six model simulations from one of the two reference data sets. The circles indicate the BIAS between the two reference data sets (CRU-DWD) and the crosses mark the deviation of the corresponding ECMWF reanalysis values from CRU data.

The deviations in the climatological annual precipitation (Fig. 2) are smallest if the total land area is considered. For smaller regions the uncertainty increases. The deviations of the annual mean precipitation for Germany are in the range of -134 to + 85 mm/y. The largest deviations again occur in the foothills of the Alps represented by the subregion Munich. Here, deviations rise to more than 200 mm/y. However, the difference between the two reference data sets also amounts up to 200 mm/y. The strong discrepancy between CRU and DWD data for the subregion Munich is the reason why all regional climate models overestimate the precipitation amount with respect to CRU data but underestimate it if DWD data is used as reference. In order to value the quality of the deviations, the same climatological means have been calculated for ECMWF reanalysis which force the regional climate simulations at their lateral boundaries. The deviations from the corresponding CRU data are indicated in Figure 1 by small crosses. Obviously, the regional climate models do not produce larger deviations from the known reality than already inherent in the three dimensional daily weather analyses.

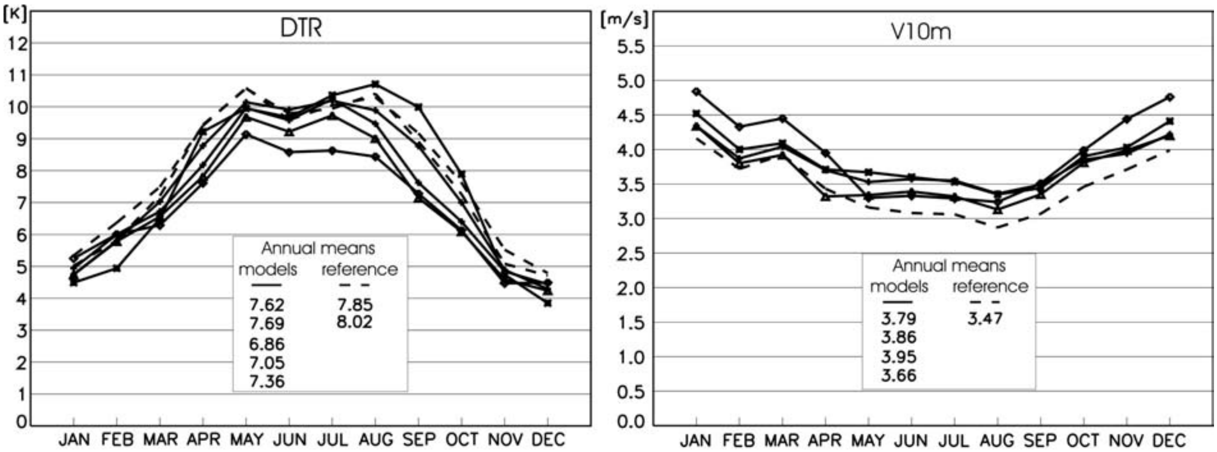

Figure 3. Climatological cycles of monthly means of diurnal temperature range and 10m wind speed for the area of Germany. Solid lines are model results dashed lines are reference data (for v10m only DWD data available).

The simulated climatological diurnal temperature ranges (DTR) and the 10m hourly wind speed, both averaged over Germany, show the same annual cycles as the available reference data (Fig. 3). Only one simulation has significantly weaker daily temperature amplitudes during summer. For this simulation, the mean absolute monthly difference (MAMD[1]) of the

[1] Annual average of the absolute differences between the monthly means of two climatological annual cycles

climatological annual cycle to the reference data of DWD is 1.2 K. The corresponding distance between CRU and DWD data is only 0.2 K. The MAMD for the 10m wind speed lies between 0.2 and 0.5 m/s. That means that the models are capable to reproduce the climatological monthly means of wind speed for Germany with an uncertainty of less than 0.5m/s. For smaller subregions like MUN or STU (not shown here) the deviation slightly increases to a little more than 1.0m/s. The temporal correlation of the monthly means of all simulated 15-year time series with the corresponding reference data for Germany is higher than 0.87 for both the diurnal temperature range and the 10m wind speed.

An important parameter for the assessment of future climate changes is the frequency of extreme events. Therefore, the capability of the regional models to reproduce the number of summer and frost days as well as the number of days with significant and intensive precipitation was investigated. The differences in the number of summer and frost days between models and DWD reference data for Germany are rather large in many cases (Fig. 4). Some models systematically overestimate the number of events. As the analysis shows, these models generate warmer summer (up to +1.4 K) and colder winter temperatures (up to -1.8 K) so that their annual mean temperature agrees very well with the observations, but the number of extreme temperature events is overestimated by up to 30 days in some areas. For subregion Germany the simulations produce up to 17 summer days and 29 frost days more than observed which corresponds to a maximum relative deviation of 64 % and 36 %, respectively.

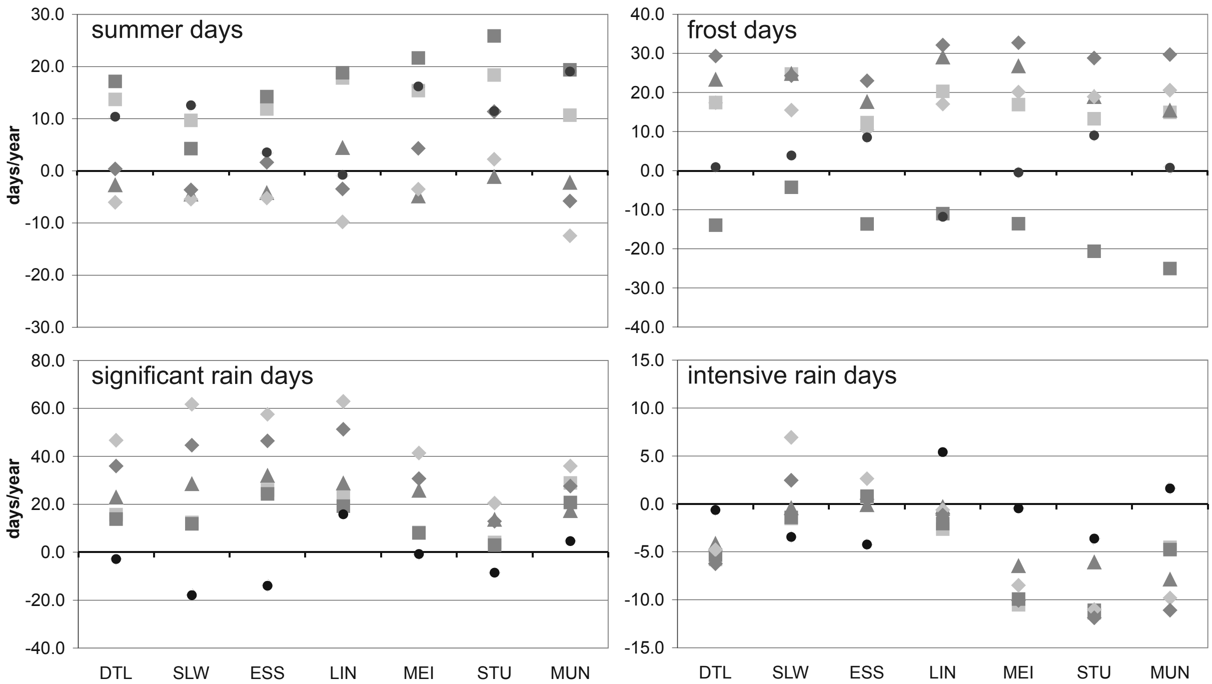

Figure 4. BIAS of climatological annual frequencies of summer days (with Tmax>25°C), frost days (Tmin<0°C), and days with significant (>1mm/d) and intensive (>10mm/d) precipitation for 8 subregions (see Fig. 2). Grey markers indicate the deviations of different model results from DWD reference data. The black circles show possible variations of the reference data for different interpolation methods.

For precipitation, the number of days with significant rainfall is larger for all models than the DWD values indicate. The method of interpolating observed frequencies into the area can cause differences in the area average over Germany of up to 20 days. But this uncertainty is in all cases smaller than the deviations of the regional models. However, the reference statistic is based on uncorrected rain gauge measurements, which probably leads to a systematic under-estimation of events with more than 1 mm/d due to sampling errors in particular for days with weak snow fall or strong wind. Intensive rain days are partly underestimated by up to 10 days/y especially in the mountainous subregions of Meiningen, Stuttgart, and Munich. For Germany all models show a similar deviation of about -5 days. With an average of 23 events per year for this area the uncertainty of the models to reproduce intensive rain days is about 20 %. The interpolation/regression method itself can affect the area means by up to 5 days, too, so that the uncertainty of the preparation method is in the same range as model uncertainties.

Uncertainties in the simulation of climate change signals

The control and the scenario runs are based on two 30-year time-slices of a 250-year global transient simulation with the coupled global climate model ECHAM4+OPYC (Roeckner et al., 1999). In this simulation, the increase of greenhouse gas concentrations follows the IPCC SRES B2 scenario (Nakicenovic and Swart, 2000) up from 1990. The two time-slices cover the years 1960 to 1989 as the control period for present-day climate conditions and 2070 to 2099 as the scenario for future climate conditions. Both periods are simulated by 5 different regional climate models and nesting strategies. So far, two of these simulations (REMO 5.0 and REMO 5.3) are completed so that first results of the projected regional changes can be presented.

Figure 5 shows the climate change signal (difference scenario-control) of the 30-year annual mean 2m-temperature for the simulation with REMO 5.0. A severe increase in temperature is found over the whole model domain. A relatively moderate warming appears in the north-western part with 2K. The strongest warming with more than 4K can be found in the Alps, the Pyrenees, and in parts of Spain. In Germany the temperature increases in average by up to 3.2K. The model version REMO 5.3 shows the same performance with respect to the regional distribution and the magnitude of the temperature rise. Besides changes in the annual mean values, seasonal or monthly changes are also of interest. Figure 6 shows the difference of the climatological monthly mean values of the two 30-year periods and of the annual means for Germany. The magnitude of the warming varies throughout the year with a maximum in summer of almost 4 K in the REMO 5.3 simulation. The changes of the 2m-temperatures are significant on a 95% confidence level for all months and the annual mean. The differences between the results of the two models which indicate the possible uncertainty of the regional signal are relatively small (below 0.5 K).

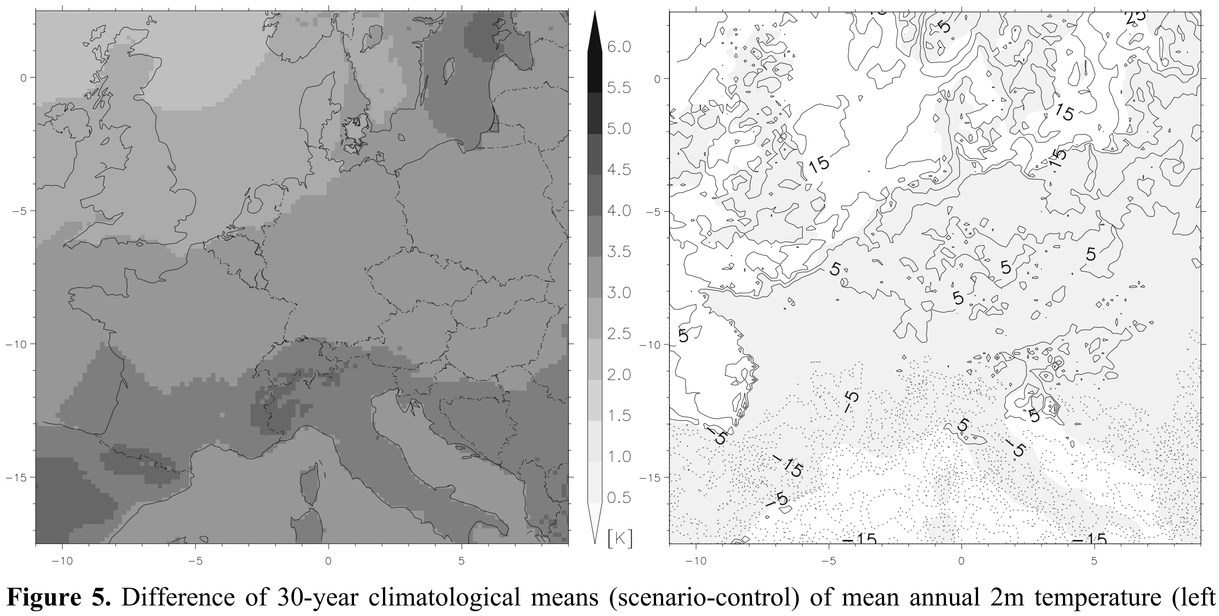

Figure 5. Difference of 30-year climatological means (scenario-control) of mean annual 2m temperature (left panel) with absolute differences in K and of mean annual precipitation (right panel) with relative differences in % and positive deviations with solid and negative with dotted contours for the simulation with REMO 5.0. Areas between the first solid and dotted line have relative deviations in the range of ±5%.

The relative changes in the annual sum of precipitation between the scenario and the control period (Fig. 5, right hand side) show no consistent trend for the whole domain. Precipitation increases over the northern part of the model domain, whereas the southern part is dominated by decreasing values. The differences are in the range of +/-25%. A tendency to an increase of precipitation can be found in northern Germany. For the southern part, however, the projected changes are in an indifferent range between ± 5%. In total, the area mean yields a weak increase of 55 mm for the annual precipitation sum over Germany. These findings are confirmed by the second REMO simulation which yields an increase of 63 mm for annual precipitation in Germany. In contrast to the increase of annual means, both simulations show a weak reduction of precipitation in Germany for spring and summer (Fig. 6). However, this decrease is significant in both model versions only for July. A significant increase of precipitation can be found in January (only REMO 5.3) and in February, October, and November (both models). The increase of annual precipitation is significant for both models.

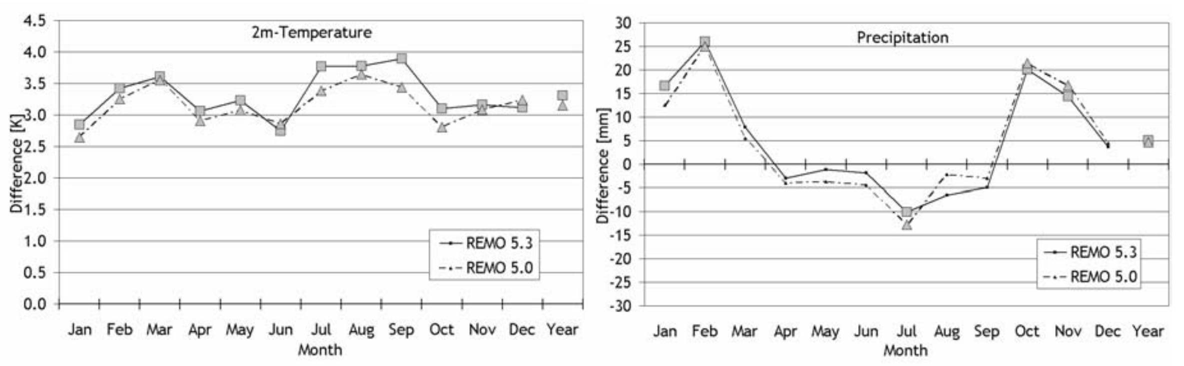

Figure 6. Climate change signals of monthly and annual means of 2m temperature and precipitation from two different REMO simulations. The values represent spatial means over the area of Germany. Highlighted symbols denote significant changes on a 95% confidence level.

Conclusions

A comprehensive method was developed enabling an objective quantification of differences between the results of regional climate simulations and corresponding reference data sets. A set of distance measures is used to provide quantitative information about the deviations of different temporal and spatial characteristics of simulated climate means and variances from interpolated climate observations on a monthly basis. Additional reference data for monthly means of near surface climate parameters, annual frequencies of extreme events, and radiant fluxes at the surface and the top of the atmosphere were generated on regular grids with a high horizontal resolution and were compared with the results of 6 different regional simulations. The range of values for the calculated distance measures represents the range of uncertainty by which the applied regional models are able to reproduce present-day climate conditions. As an example, the annual mean 2m temperature and mean annual precipitation over Germany can be reproduced with an uncertainty of 1.5 K and 110 mm/y, respectively. Simulated climate changes should be larger than these ranges to be regarded as a reliable regional response to an assumed global change. The two scenario simulations analysed so far indicate that the SRES B2 scenario will lead to a substantial warming in Germany with maximum values of up to 4 K in summer. No reliable evidence can be found, however, that the amount of annual precipitation will decrease in this scenario. In contrast, the tendency to a weak reduction of summer precipitation seems to be overcompensated by higher amounts in winter and fall. But the resulting increase of the annual precipitation is much smaller than the model uncertainty and therefore, from our perspective, cannot be regarded as a reliable change. For a final conclusion, however, the results of the three outstanding scenario runs still have to be analysed.

QUIRCS also shows that significant differences can exist between independently generated reference data sets - a fact that additionally broadens the measured ranges of uncertainty. A further improvement of model quality therefore requires additional high resolution gridded reference data sets especially for corrected precipitation values and near surface energy fluxes. Furthermore, the ensemble size of model to reference data comparisons must be increased so that the pure min-max-ranges for the measured deviations can be replaced in near future by probability density functions.

Next steps and completing activities

In addition to the evaluation of classical near surface climate parameters it is also important to assess the ability of regional climate models to reproduce the vertical structure of the atmosphere. Therefore vertical profiles of temperature, moisture, and wind together with some vertical keyparameters like the precipitable water content, the height of the freezing level, and the height of the tropopause are prepared from radiosonde measurements at the six reference locations in Germany listed in the context of Figure 2. The monthly means and temporal variations of these profiles will be compared with corresponding model results of the evaluation runs.

The results of three additional simulations of the control and the scenario period with different regional models and nesting strategies still have to be analyzed. The entire ensemble of 5 regional realizations of the same global climate change scenario will finally provide an estimation of the uncertainty or variability of the simulated changes due to the influence of different regional model characteristics. A comparison of the derived climate change signals with the uncertainty ranges from the evaluation runs will then allow an assessment of the reliability of the generated climate change patterns for different regions in Germany and Central Europe.

Policy relevance and application

The project QUIRCS provides one possible climate change scenario for Central Europe with the highest horizontal resolution that is presently available. Together with the quantified uncertainties the results can support political and economic decision makers to develop and implement further mitigation and adaptation strategies in order to minimize the regional consequences of increasing global greenhouse gas concentrations.

The results can further be used for detailed regional impact studies. In this context it will be of major interest how the quantified uncertainties of the climatological input affect the response of the investigated ecological and socio-economic systems. This, in return, will tell us whether the accuracy of the climate simulations is sufficient for the investigated problems or must be further improved.

Finally, QUIRCS provides additional high resolution gridded reference data sets which can be used together with the extensive results of the numerous regional climate simulations for additional investigations of local and regional climate variability and trends. The continuation of this fundamental climate research is essential for an ongoing improvement of our understanding of the climatologically relevant regional processes and for a further reduction of potential uncertainties of simulated and observed climate.

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