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Article

Ensemble simulations for the RCP8.5-Scenario

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Abstract

The mean climatic development for Germany was investigated within the period 2031/60 in comparison to the situation in the observational period 1981/2010. The RCP8.5-Scenario of the IPCC was used because it reflects the actual CO_2-emissions very well. On this basis the temperature trend for Germany was estimated using 21 GCM runs up to the year 2100. This temperature trend was the driving force for the statistical regional climate model STARS. 100 ensemble runs of the model STARS were compared with the scenario period and with the observational period. Temperature, precipitation, climatic water balance and some additional parameters were analyzed. One important result is the change in the distribution of precipitation in Germany during the year – decrease in summer, increase in winter. Finally the future climate development leads to a negative climatic water balance over the whole year.

Keywords: Climate development Germany, Scenario, climate model STARS, climatic water balance

1 Introduction

It is the aim of this article to outline potential mean climatic developments in Germany by means of a scenario for which an ensemble of model calculations was compiled. The RCP-Scenarios (RCP = Representative Concentration Pathway) which were set up for the 5th IPCC Assessment Report served as the initial point for these analyses. Fig. 1 shows the radiative forcing of the different scenarios (see MEINSHAUSEN et al., 2011).

For the following analyses, the scenario with the strongest emission of greenhouse gases (RCP8.5) was chosen. Fig. 2 illustrates the reason why. It shows the CO_2 development presumed for this scenario and for the period 2001/05 which has the same behaviour as the factually estimated CO_2 emissions. This implies that the RCP8.5-Scenario, which was ranked extreme by IPCC, has already been equaled respectively outpaced by reality. Hence, scenario RCP8.5 is closest to the present development in emissions.

As a rule, a single scenario run cannot be taken as representative, so the practice has changed in recent years and ensembles of climate model runs are employed for interpretation. Studies on the future climatic development in Germany have merely been published for the so-called SRES (Special Report on Emissions Scenarios). However, these results fail to meet the current state of research. As an example, the report “Climate impacts and adaptation in Germany – stage 1: The building of regional climate scenarios for Germany” (JACOB et al., 2008) by the Federal Environment Agency does not base the analysis of results on ensemble-run data – as customary today – but is based only on one global climate model (ECHAM5/MPI-OM) and one regional climate model (REMO). Both models have been developed at Max Planck Institute for Meteorology (MPI) Hamburg. The same holds true for the statistical regional model WETTREG (SPEKAT et al., 2007). Although, this model enables to calculate ensembles of up to 10 runs per scenario, however, this can only be operated on the basis of a global climate model. There are two ways to solve the problem: one either combines as many models as possible in an ensemble or one uses one model to calculate one scenario under varying initial conditions as often as necessary to cover the scope of uncertainties. For the study presented, the second method was chosen. With the regional climate model STARS (see Chapter 2) a validated model was at hand which could cover the scope of uncertainties of the RCP8.5-Scenario (see Chapter 4). This was one reason to choose the second method. (Moreover, there were no validated scenario runs from the EURO CORDEX program available (http://www.euro-cordex.net).) With these ensemble results, the whole span of potential climatic developments was covered, the resulting uncertainties were qualified and the parameters needed for the impact models were provided and described in their climatic development.

2 The regional climate model STARS

The STARS (**ST**atistical **A**nalog **R**esampling **S**cheme) model is a statistical regional climate model. It is the advancement of the model STAR and calculates regional climate projections of daily meteorological variables up to 100 years. The model uses historical observations

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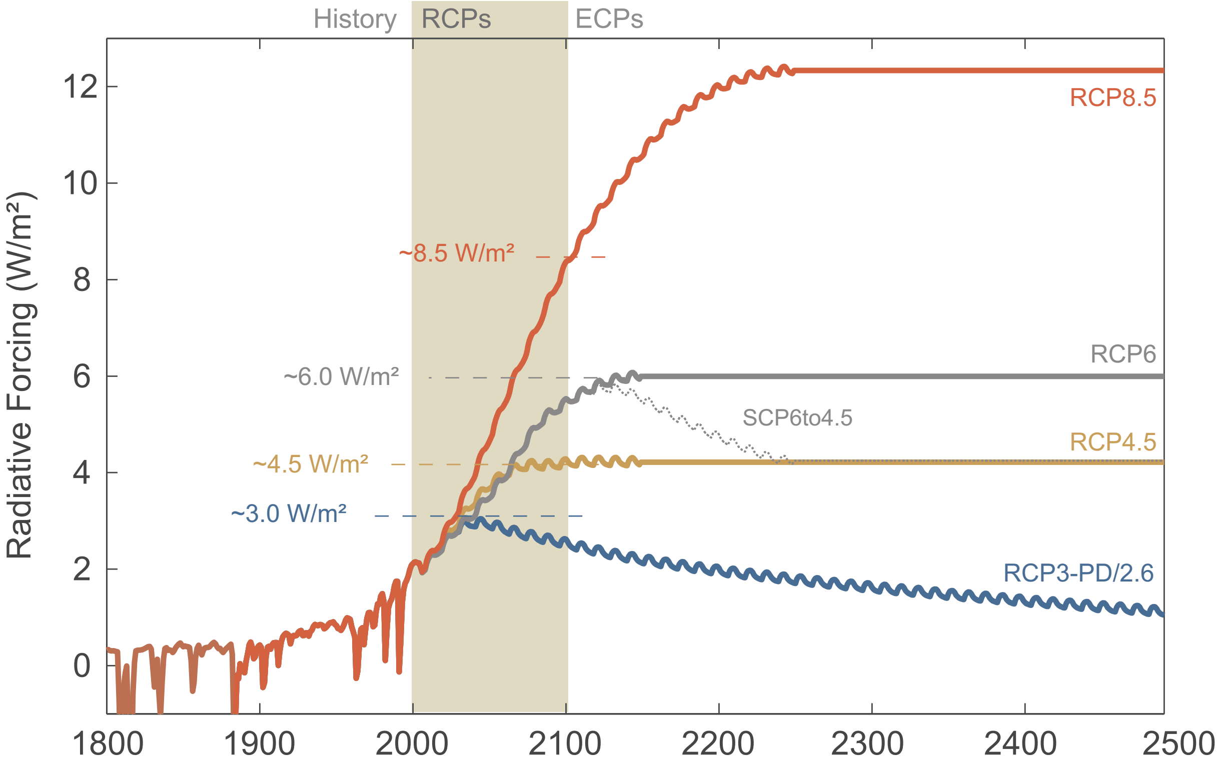

Figure 1: Global Anthropogenic Radiative Forcing for the high RCP8.5, the medium-high RCP6, the medium-low RCP4.5 and the low RCP3-PD. In addition, two supplementary extensions are shown, connecting RCP6.0 levels to RCP4.5 levels by 2250 (SCP6TO45) or RCP4.5 levels to RCP3PD concentrations and forcings (SCP45to3PD). No uncertainty ranges are shown and reported, as for creating the recommendation datasets for CMIP5, central estimates have been assumed closely in line with central estimates in IPCC AR4 (Meinshausen et al., 2011).

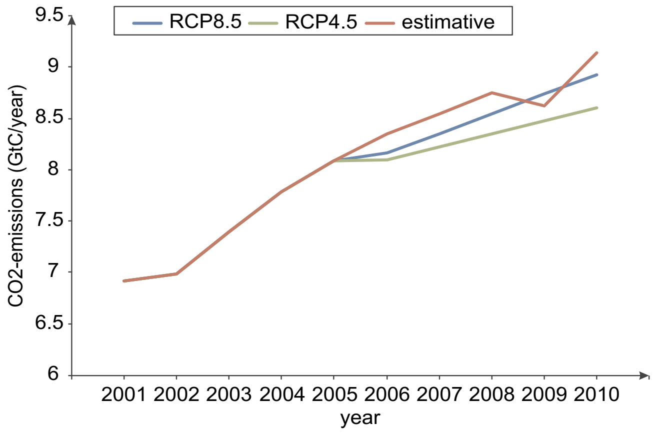

Figure 2: Observed and calculated CO_2-emissions for the RCP-Scenario 8.5 and 4.5 for the period 2001/10 (see Gerstengarbe and Welzer, 2013).

from weather stations and a prescribed future trend of a meteorological variable (in this case the annual mean of the air temperature, spatially distributed in the area of interest) in order to assemble a new meteorological data set that fulfills the trend prescription. Observed meteorological data associated with the trend variable are maintained, so temporal and spatial consistency in the future data set is assured. Because of the very modest demands in computational resources, the STARS model is able to simulate a large number of such data re-assemblies, called realizations, for a given future trend of a meteorological variable. This allows one to assess the model uncertainties. The basic idea and methodology can be described as follows:

Under the assumption that the climatic conditions in the near future are not very different from conditions that have been observed in the past, it can be assumed that past weather situations will occur again in the future, or that a future weather situation will be similar to past ones. The task of the STARS model is to find those weather situations and re-arrange their time sequence in such a way that it results in a plausible climatic development. The larger the number of past observations, the better the result is because of the fact that a larger sample reproduces the climate variability more exactly. Pre-analyses have shown that the duration of the simulation period should not significantly exceed that of the observation period. Fig. 3 shows the model scheme which can be described as follows: In a first step, the station data from the observation period are re-arranged by means of a random number generator in such a way that the resulting mean annual air temperature fulfills the prescribed temperature trend as accurately as possible. The first realization of the scenario is successful if this re-

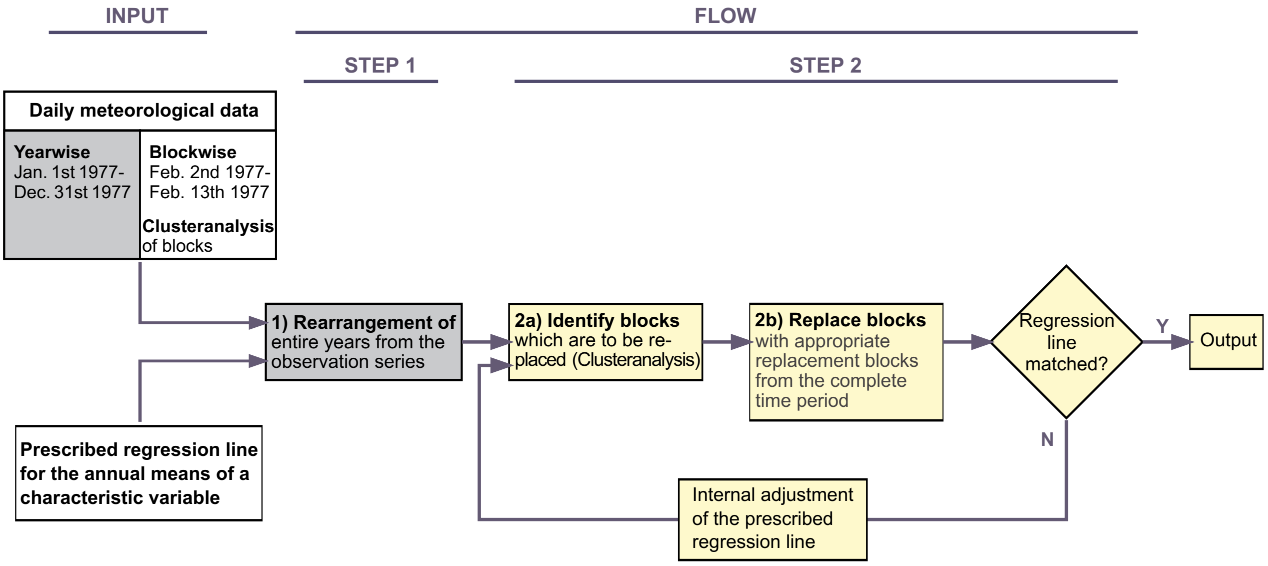

Figure 3: Model scheme for the regional climate model STARS.

arrangement of the data "hits" the trend exactly. This is usually not the case and the simulated temperature trend has to be adjusted to the prescribed trend. This is done by exchanging so called "data blocks" within the simulated future years. The "blocks" are mean temperature data for 12-day time periods, grouped by means of cluster analysis according to their temperature characteristics. To prevent using blocks with a circulation pattern not adapted to the situation, i) a data window is provided which has to contain the exchange block, ii) the blocks are applied in overlapping mode (Orlowsky et al., 2008). This data exchange allows the mean annual air temperatures of individual years to be adjusted in such a way that the future temperature trend is met by the simulations as closely as possible. The procedure is carried out in an iterative manner in space for certain reference stations until the temperature trend is met with a prescribed accuracy it means the deviation from the trend (for instance 0.1 degree). The reference stations are preselected, also through cluster analysis, and represent the climatology of a sub-region. Every "data block" is tied to an actual date in the past. For each realization, the STARS model delivers a time sequence of dates in addition to the temperatures. The meteorological variables other than air temperature that are associated with those dates are also attributed to the future data. In a last step all meteorological stations within a cluster are adjusted to the simulated development of the particular reference station. For every further realization, the same procedure will be repeated with a varying composition of the synthetic row. This procedure ensures that the meteorological data for each realization of the scenario are consistent with respect to observations. A detailed description of the STARS model including its validation can be found in Orlowsky et al. (2008).

3 Data

Observed data from 1218 stations were used for Germany over the period 1901/2010. It's about 180 climate stations and 1038 precipitation recording stations. The data set comprised 11 daily values of the following parameters:

Daily maximum of the air temperature (°C)
Daily mean of the air temperature (°C)
Daily minimum of the air temperature (°C)
Daily sum of precipitation (mm)
Daily mean of the relative humidity (%)
Daily mean of the air pressure on station level (hPa)
Daily mean of the vapor pressure (hPa)
Daily sum of the sunshine duration (h)
Daily mean of the cloud cover (eighth)
Daily mean of the global radiation (J/cm^2)
Daily mean of the wind velocity (m/s)

These data were provided by the German Weather Service. At the Potsdam Institute for Climate Impact Research the data were checked for completeness, supplemented if necessary, tested for homogeneity and homogenized if necessary (Österle et al., 2006). 10 of the parameters were interpolated at precipitation recording stations. The basic version of the interpolation method (Shepard, 1968) was made available by the German Weather Service. This method is based on the weighting of the inverse distance and considers the dependency on the height. Because the global radiation is measured only at 42 climate stations, the values for the other stations were calculated using a special regression model under consideration of the sunshine duration (Österle, 2001). An improvement of the results was possible if further parameters like cloudiness, relative humidity and

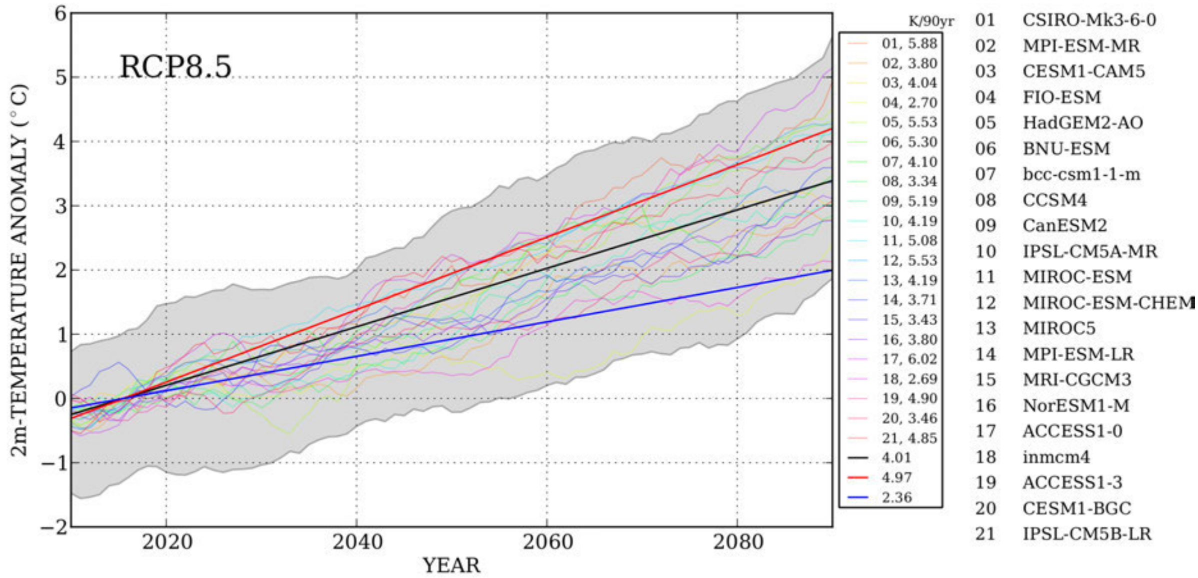

Figure 4: Linear temperature trends for the 21 GCMs (blue – minimum; black – mean; red – maximum).

the daily range of the temperature were implicated. Furthermore the daily sum of the climatic water balance (i.e. precipitation – evapotranspiration) was calculated. The evapotranspiration was calculated using the method of Turc/Ivanov (Wendling and Müller, 1984). For the period 1901/50 only a small number of stations were available, sometimes without the complete data set of all 11 parameters. On this account a synthesized data set was calculated using a special analogy method (Österle, 1992). Before this calculation was carried out, the method was extensively tested with the data of the 11 parameters of the period 1951/2010.

4 The RCP8.5-Scenario for Germany

As already outlined in Chapter 1, the RCP8.5-Scenario was chosen as a basis to estimate the future climate development. Since the STARS model requires a temperature trend as a driver, this trend had to be derived from the respective runs of several GCMs for Germany. For this, 21 model runs which had been calculated in the CMIP5 program were used on a standard grid of 0.11 °×0.11 ° (http://cmip-pcmdi.llnl.gov/cmip5/availability.html). For the period 2011/2100, the temperature trend of these 21 models ranges from 2.36 °C (minimum), 4.01 °C (median) and 4.97 °C (maximum) for Germany (Fig. 4). These trends vary for individual reference stations.

Precipitation varies in the range from −180 mm to +150 mm. This span is so wide that it must be clarified if any of the models is capable at all of determining the precipitation development in an almost realistic way, as it is for the rise in temperature. To answer this question, it was checked to what extent the models simulate the change in precipitation at the condition of a concurrent change in temperature in the observation period 1950/2005. The result is presented in Fig. 5. It turns out that none of the global climate models is able to even roughly simulate the measured precipitation trend in relation to the temperature trend. Hence, the prerequisite (although not sufficient) condition that, at least in ensemble modus, a climate model has to exactly reproduce the past except for a tolerable error is not fulfilled. This result is relevant for the nesting of regional climate models into GCMs since the GCM error will be transferred to the regional climate model. This finding is important for the application of the STARS model since only the temperature trend is prescribed.

However, with respect to the simulation of precipitation, it has to be clarified if the STARS model shows similarly grave deviations from reality like the GCMs. To do so, 100 realizations were calculated (as described in Chapter 2) according to the trend given from the observations for the period 1950/2005, and the particular precipitation trend was plotted to the temperature trend. The result is illustrated in Fig. 6. It is obvious that the temperature trend (since it is given) is reproduced exactly within the defined margins of deviation. Nevertheless, the associated precipitation trend oscillates between −100 mm and +100 mm. The major part of realizations lies within the negative area of the precipitation trend, and this is due to the fact that, within the training sample, weather situations with high temperatures come along with lower precipitation, whereas the test sample shows a positive temperature trend. This must be considered when analyzing the results. Three ways to analyze the result are possible:

1. The observed temperature-precipitation trend lies within the upper range of the simulated values. This means, with regard to the ensemble of 100 realizations, that the STARS model simulates the observa-

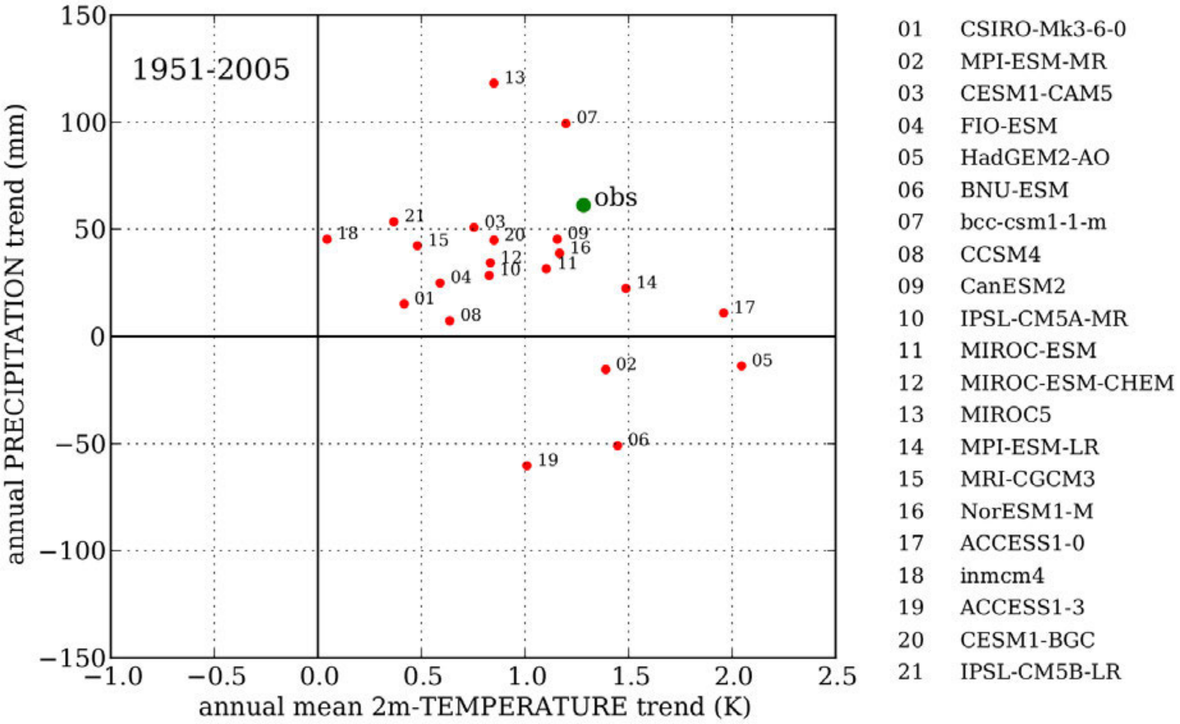

Figure 5: Temperature-precipitation relations for 21 GCM runs for Germany, time period 1950/2005.

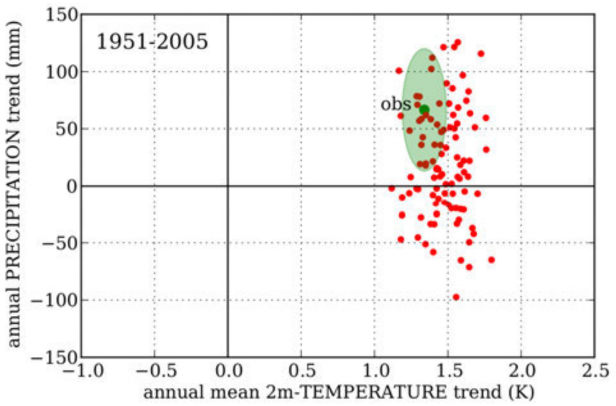

Figure 6: Temperature-precipitation relations for 100 STARS realizations for Germany, time period 1950/2005 (green field = 1σ-area of the variance).

tion within a defined an uncertainty area around the observation very well (for instance $\pm 1\sigma$). This model characteristic has to be taken into account when calculating future scenarios under the assumption that a model has to simulate the past accurate enough. On this assumption the solution for this problem will be quite simple:

- An uncertainty area around the observed trend values of temperature and precipitation must be defined where all simulated trend values do not differ significantly from the observation value ($\pm 1\sigma$ barrier, e.g.).
- The number of simulations lying within this uncertainty area must be defined and put into proportion to the whole number (in Fig. 6 30 out of 100 simulations are in the uncertainty area, e.g.).
- If an ensemble of 100 realizations shall be set up in future scenario calculations, the number of realizations must be increased from 100 to $\sim$ 350 for the example given. From the 350 realizations, 100 realizations must be selected for further analyses according to the given uncertainty area.

With this method further regression relations such as temperature, global radiation etc. can be examined. This opens the way to validate all parameters carried in the model.

2. To investigate very dry situations within the 100 calculated realizations one can select all those below the -1σ-limit of the observational values. If this number is too small the algorithm described above can be used to increase the number of realizations.

3. To get an overview on the uncertainty of the model of possible future scenario developments one has to analyze the complete set of realizations.

The last way was taken for the further investigations.

5 Evaluation process

The temporal changes and the spatial distributions were investigated by means of selected meteorological parameters like temperature, precipitation, climatic water

Table 1: Different meteorological parameters: mean values for the period 1981/2010 and mean values for the period 2031/60 related to the q50-quantile of the 100 realizations of mean temperature trend, all changes are statistical significant (Wilcoxon-Test).

Parameter	**Season**	**Period**		**Difference**
		1981/2010	**2031/60**	**2031/60 – 1981/2010**
Precipitation (mm)	Year	863.6	832.5	−31.1
	Summer JJA	252.6	207.6	−45.0
	Winter DJF	203.2	229.5	26.3
Climatic water balance (mm)	Year	250.9	145.8	−105.1
	Summer JJA	−61.4	−139.0	−77.6
	Winter DJF	175.3	198.1	22.8
Days without precipitation	Year	180.7	198.1	17.4
Days with strong precipitation	Year	24.3	23.2	−1.1
Daily maximum of the air temperature (°C)	Year	13.1	15.1	2.0
Daily mean of the air temperature (°C)	Year	8.8	10.5	1.7
Daily minimum of the air temperature (°C)	Year	4.8	6.2	1.4
Daily sum of the sunshine duration (d)	Year	4.4	4.8	0.4
Daily sum of the global radiation (J/cm^2)	Year	1023.4	1071.9	48.5
Summer days	Year	34.6	51.9	17.3
Hot days	Year	6.2	9.4	3.2
Ice days	Year	23.0	10.3	−12.7
Frost days	Year	87.1	61.5	−25.6

balance, sunshine duration and global radiation. These parameters were calculated both for the whole year and the seasons for each station. In the next step the data were interpolated on a 0.11 ° longitude and latitude grid. The interpolation method used is based on the weighting of the inverse distance under consideration of the geographical height. To represent the range of a possible future development three temperature trends were given for the period 2011/2100 (see Fig. 4) and each meteorological reference station (see Chapter 4). In the next step 1000 realizations were calculated for each of the temperature trends by the model STARS. From these realizations 100 were selected using the weighted trends of the climatic water balance. This selection was fulfilled in such a way that the complete range of the 1000 realizations was captured. The most important reason for this step was the reduction of data without a loss of information. For the analysis of possible climate changes, the period 1981/2010 was defined as the reference interval and the period 2031/60 as the future scenario interval. The period 2031/60 was selected from the period 2011/2100 because it is a frequent planning horizon for climate impact investigations.

To describe the future climate changes the two time periods were compared. Therefore mean values for the year, summer and winter and the frequency of special occurrence days were derived. For the observational period 30-year means as well as the minimum and maximum values were calculated for each parameter. For the scenario period the quantiles $q = 5\,\%$, $q = 50\,\%$ and $q = 95\,\%$ were estimated for the 100 realizations and the 30-year period ($100 \times 30 = 3000$ values). To present a manageable number of Figs, only the maps related to the median of the 100 realizations for the mean temperature trend were prepared for the analysis. A selected number of additional parameters were presented in tabular form.

6 Results

As mentioned above, from the high number of results only a selection of results can be presented and discussed[1]. On that condition, the focus was aimed on developing the parameters temperature, precipitation, climatic water balance and global radiation, which are important for hydrology, agriculture, forestry and the energy sector.

Fig. 7a shows the spatial distribution of the annual mean of the air temperature for the observational period 1981/2010 and Fig. 7b for the difference 2031/60 – 1981/2010. One can see the typical structure of the temperature distribution for Germany – the coastal region, the interior land, the region in front of the low mountain range, the low mountain range and the Alps. The warmest region of Germany is situated along the river Rhine with mean values between 12 and 14 degrees. In the difference Fig. we see a positive temperature gradient from north to south. These differences range from about 1 up to 2 degrees. The mean value amounts 1.7 degree and corresponds exactly with the presetting trend for the model STARS.

A view on the Figs 8a and 8b provides information on the development of the mean annual precipitation sum in Germany. Principally, three relatively consistent regions can be identified (see Fig. 8a): the dry eastern part of Germany including the lee of the low mountain ranges, the Alps and low mountain ranges with high precipitation sums and the remaining regions of Germany characterized by a moderate precipitation sum per year. Even though the mean annual sum of the period 2031/60 is

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[1] (Remark: The complete results in higher temporal and spatial solution for the scenarios RCP8.5 and RCP2.6 can be recalled via the internet platform www.klimafolgenonline.com.)

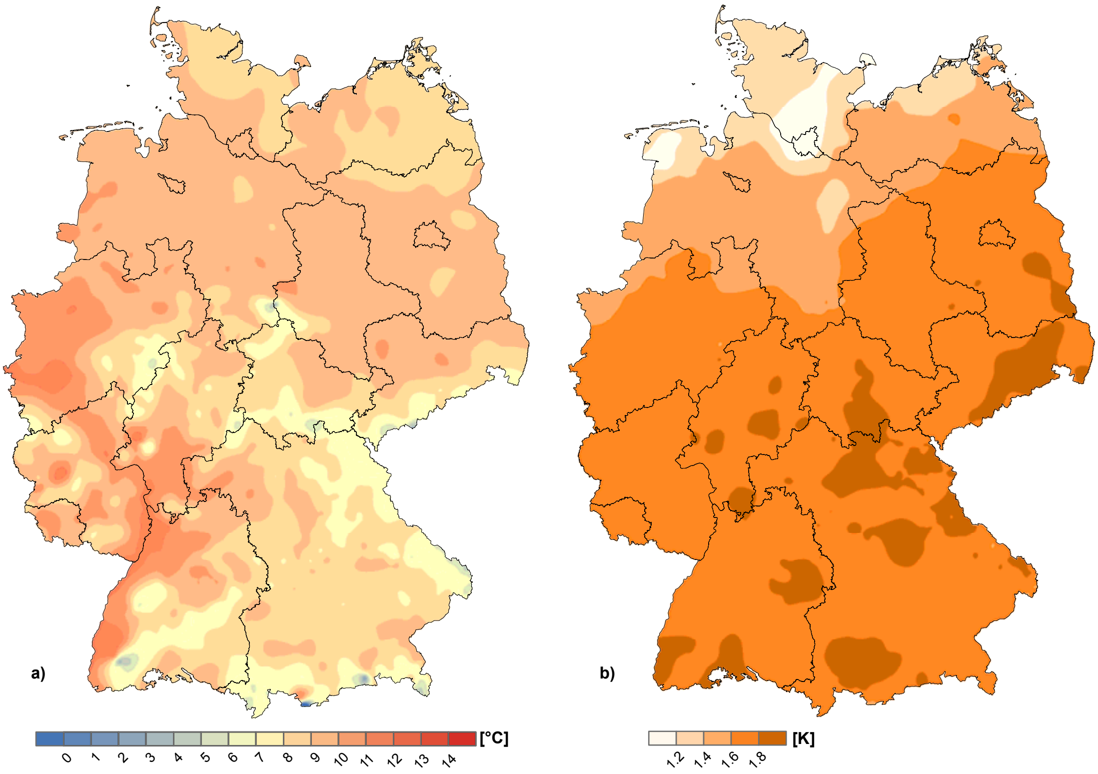

Figure 7: a) Mean spatial distribution of the temperature for Germany for the period 1981/2010 and b) for the difference 2031/60 – 1981/2010.

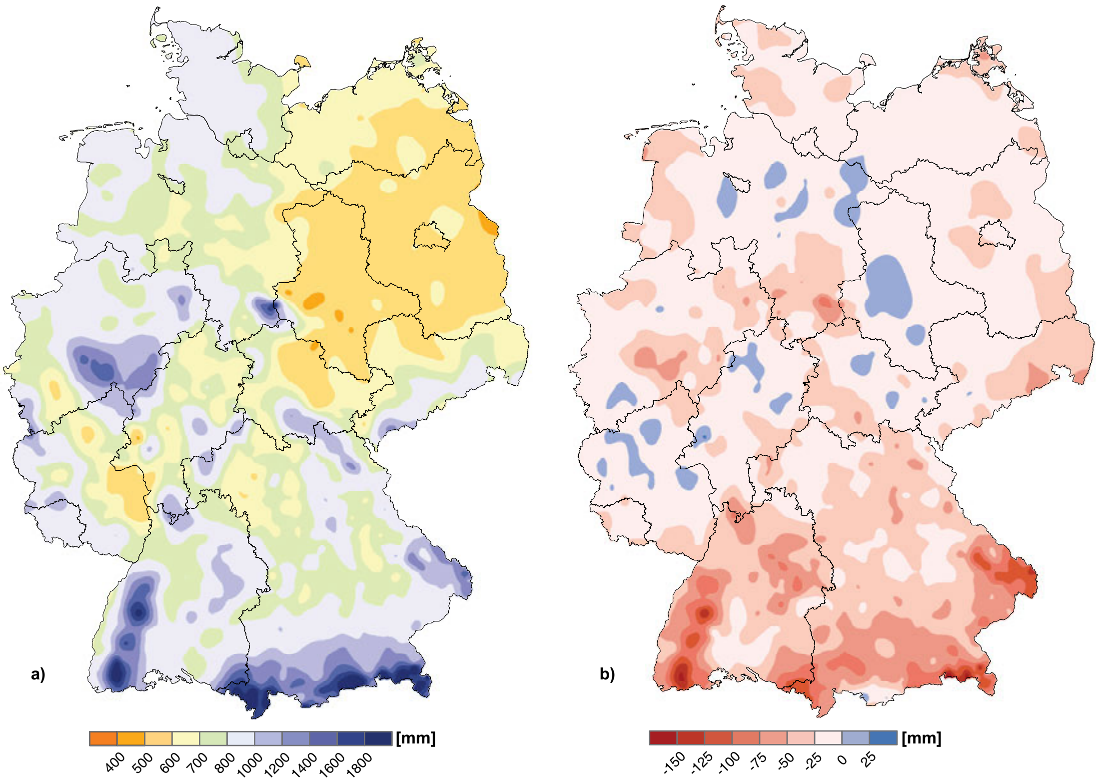

Figure 8: a) Mean spatial distribution of the precipitation for Germany for the period 1981/2010 and b) for the difference 2031/60 – 1981/2010.

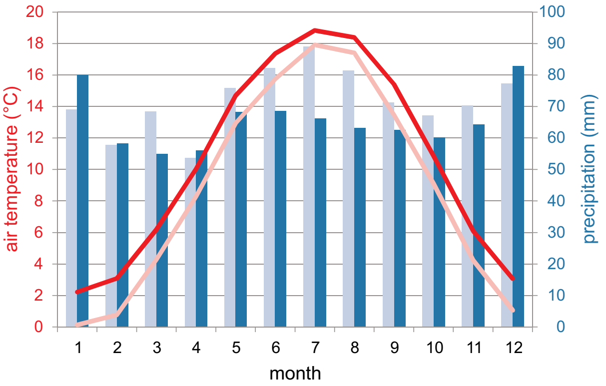

Figure 9: Annual course of the temperature and precipitation for the periods 1981/2010 (light red and blue) and 2031/60 (dark red and blue).

only −31.1 mm less than those of the observational period (see Table 1) obvious spatial changes in the distribution of the precipitation are visible. So the most important reduction occurs in the southern part of Germany.

This situation changes deeply if one investigates the precipitation distribution within the annual course (see Fig. 9). For the observational period the maximum of precipitation can be observed with the summer months (light blue columns). The inverse situation can be stated for the scenario period (dark blue columns): The precipitation sum in summer decreases, while a strong increase can be observed with the winter months December and January. The annual course of temperature is also given in Fig. 9, showing that in 2031/60 the monthly mean temperature is about 2 degrees higher in winter and 1 degree higher in summer, compared to the observed period 1981/2010. Connected with this development is an obvious increase of days without precipitation from 181 days to 198 days (see Table 1).

This development has obvious consequences on the climatic water balance. Two thirds of Germany has a positive climatic water balance in the observational period. Negative values are manifested mainly in the eastern part (Fig. 10a). In the period 2031/60 the climatic water balance decreases from 250.9 mm to 145.8 mm (Fig. 10b). The decline has a value of about −105 mm, but with 145.8 mm the climatic water balance stayed in the positive range. This situation changes if one analyze the summer months. Fig. 11a and 11b illustrates this development. In the observational period the climatic water balance is −61.4 mm negative. This tendency is strengthened within the scenario period with a value of −139 mm (see Table 1). The main causes for this development are the previously discussed decline of precipitation in the summer months, as well as the higher temperatures connected with a higher insolation resulting in increased of the evaporation.

We will now discuss the remaining parameters of Table 1. There are only non-significant changes between the two time periods for the days with strong precipitation, sunshine duration and global radiation parameters. A strong increase in the summer days and hot days as well as a decrease of the number of ice and frost days can be seen. All these changes are in accordance with the warming during the next decades.

7 Conclusions

It is shown that the available GCM runs do not provide sufficient results to reproduce the climate development in Germany for the past period 1901/2005. In this case the use of the regional statistical STARS delivers more satisfying results. A high number of ensemble calculations with STARS give the possibility to estimate the uncertainty of the model as well as to analyze possible future climate developments within the range of different temperature trends. For the RCP8.5-Scenario the mean temperature in Germany will increase about 1.7 degree for the period 2031/60. This development is coupled with a strongly negative climatic water balance in summer and an increase of hot and summer days. Parallel to this a reduction in ice and frost days will be observed. As mentioned above the complete set of results can be reviewed via the internet: www.klimafolgenonline.com.

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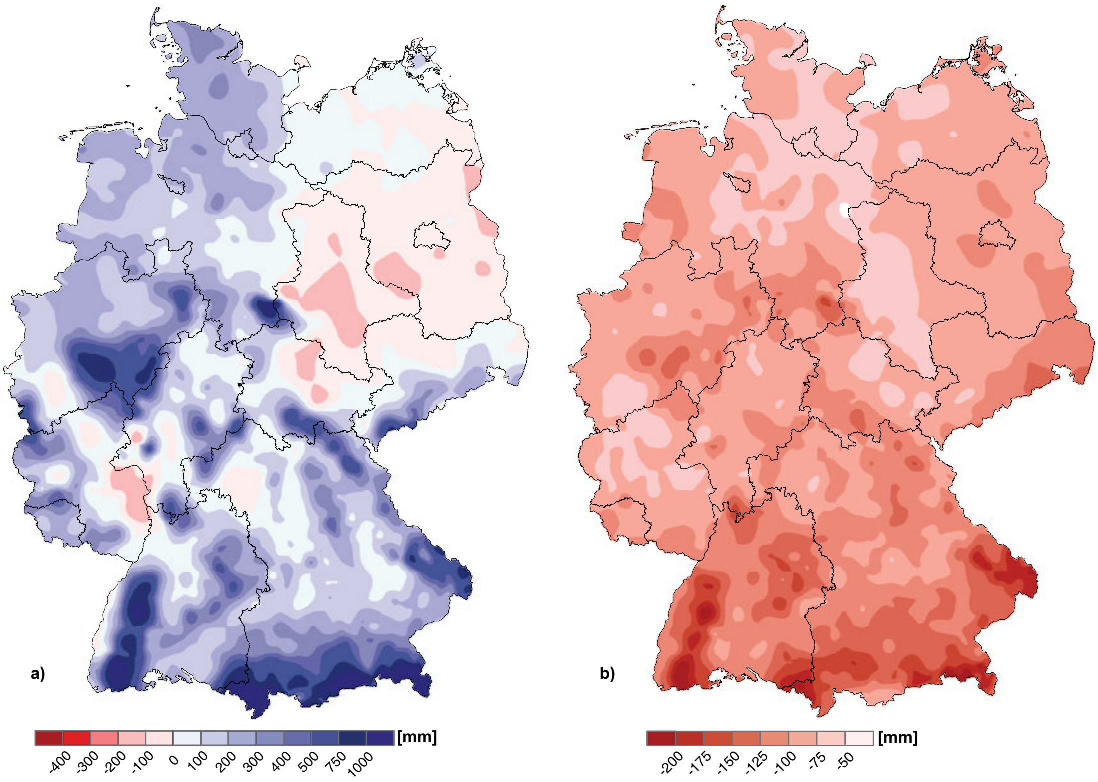

Figure 10: a) Mean climatic water balance for Germany (year) 1981/2010 and b) for the difference 2031/60 – 1981/2010.

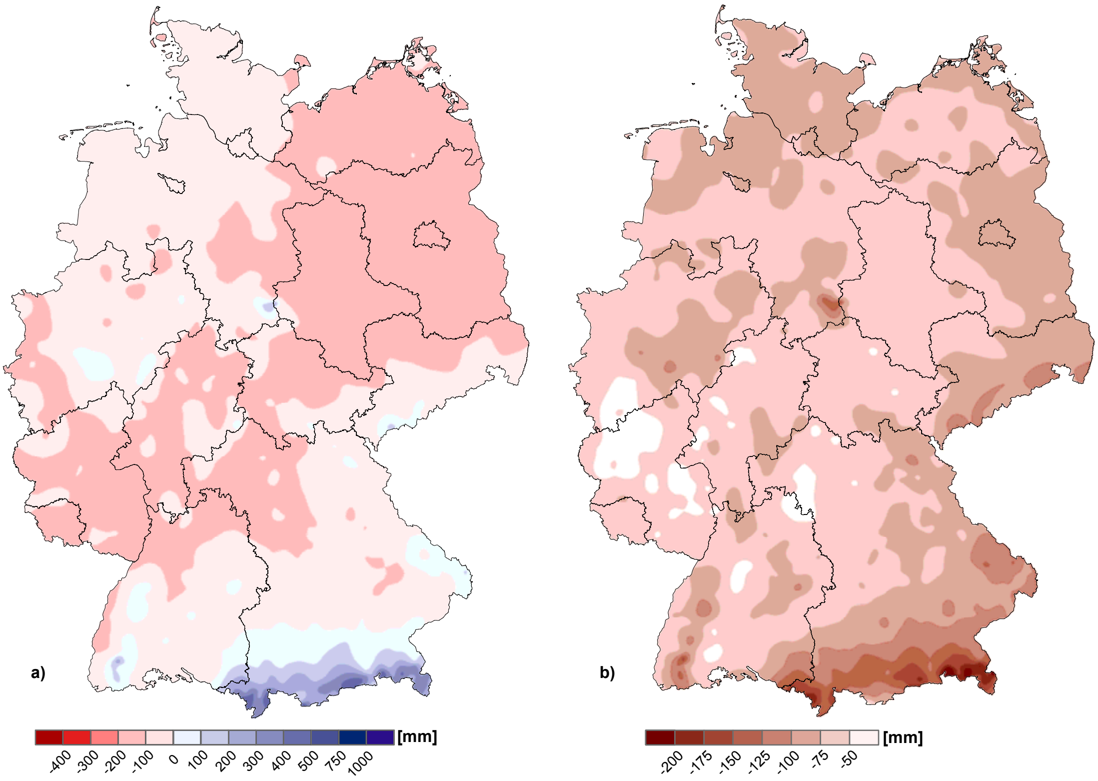

Figure 11: a) Mean climatic water balance for Germany (JJA) 1981/2010 and b) for the difference 2031/60 – 1981/2010.

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