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Water supply patterns in two agricultural areas of Central Germany under climate change conditions

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Abstract

Increasing emissions of greenhouse gases and increasing prices for fossil fuels have highlighted the demand for CO_2 “neutral” renewable energy sources, e.g. short rotation forestry systems used for bioenergy. These systems might be vulnerable to changes in temperature, precipitation and occurrence of extreme weather events. To estimate success or failure of such short rotation coppices in a certain area we need regional climate projections and risk assessment. Changes of water supply patterns in two agriculturally extensively used regions in Central Germany (around Göttingen and Großfahner) with different climate conditions but both in the temperate climate zone are explored. The study is carried out under present conditions as well as under projected climate change conditions (1971–2100) using A1B and B1 climate scenarios downscaled for Europe. Analysis of precipitation bias shows regional differences: a strong bias in Göttingen area and a weaker bias in the Großfahner area. A bias correction approach, Quantile mapping, is applied to the ensemble results for both areas for winter and summer seasons. By using quantile regression on the seasonal Standardized Precipitation Indices (SPIs) as indicator for water supply conditions we found that precipitation is expected to increase in winter in all quantiles of the distribution for Göttingen area during the 21th century. Heavy precipitation is also expected to increase for Großfahner area suggesting a trend to wetter extremes in winter for the future. This winter precipitation increase could trigger runoff and soil erosion risk enhancing the severity of floods. Increasing winter availability of water could enhance local water supply in spring. For both areas no significant change in summer was found over the whole time period. Although the climate change signal of the SPI indicate mild dryer conditions in summer at the end of the 21st century which may trigger water shortage and summer drying associated with above–average temperatures in the future. Even though both study areas are close together Großfahner area was found to be the least affected one by changes indicating that small spatial scale differences matter. These developments were found in all examined simulation runs. This study highlighted the regional differences in the vulnerability

to water surplus or deficit risks in a temperate system which emphasizes the need in impact studies to focus on proper consideration of local and regional environmental conditions as well as adaption and mitigation of management for agriculture.

1 Introduction

Ongoing increases in the atmospheric CO_2 concentration and associated climate changes are real. Furthermore, global climate models show that the annual mean temperature may increase by 2.5 °C to 4.5 °C depending on scenario until the end of this century (IPCC, 2007). Projected mean precipitation is expected to decrease in mid-latitudes and to increase in high latitudes (Christensen et al., 2007) with precipitation shifting seasonally and changing regionally rising the risk for extremes such as droughts in one area and floods in the other. Recent extreme events have highlighted Europe's vulnerability to this natural hazards (Lloyd-Hughes and Saunders, 2002; Zaitchik et al., 2006). Continued occurrence of such weather events may result in possible crop failure and decrease in yield (Leilah and Al-Khateeb, 2005), run off and erosion risks, forest fires (Pausas, 2004), increase of pollutants in water bodies, social alarm (Palutikof et al., 2004), illness and increasing irrigation (Schär et al., 2004; Bartholy et al., 2009). A decrease of water resources due to decreasing precipitation (DeGaetano, 1999) and increasing evapotranspiration can significantly influence the drinking water supply which is relevant for agricultural management (Wilhite et al., 2000; Kundzewicz, 2003).

Increasing emissions of greenhouse gases and increasing prices for fossil fuels have highlighted the demand for CO_2 "neutral" renewable energy sources as bioenergy, e.g. agro-forestry systems or short-rotation poplar coppices. These systems may be "neutral" for carbon dioxide. However, their productivity is depending on changes in temperature, precipitation and extreme weather events which can have destructive impacts and reduce the carbon sequestration potential of these systems. For estimating success or failure of such systems in the future we need climate projections and risk assessment. It is still debated where potential areas for bioenergetic use exists taking into account cropping and climatic requirements. Therefore, in combination with new trends in agricultural and forest management, e.g. the demand of biomass for energetic and material resources, adequate assessment of future water surplus or deficit risks plays an important role in the development of adaptation and mitigation strategies. Therefore, within the framework of the joint research project BEST (BioEnergy regions STrenghtening) investigations are started aimed at estimating the success of various bioenergy plantations in Germany based on the example of two areas. The success is evaluated from different view points including the interaction with climate at local and regional scales.

Studies with regional climate models for Europe based on the PRUDENCE data set (Christensen et al., 2007) showed an increase of winter precipitation and a decrease of summer precipitation in Germany with an increased frequency of both extreme precipitations and droughts (Gerstengarbe et al., 2003). It is acknowledged that climate change may alter the potential of hydrological risks over large regional scales, although the impact on smaller regional scale is less demonstrated in the scientific literature so far. The analysis of recent precipitation trends in Lower Saxony was presented in the study of Haberlandt and Belli (2010). One of the indicators for the description of water supply is the Standardized Precipitation Index (SPI) after McKee et al. (1993). Many studies using the SPI focused mainly on Boreal and Mediterranean regions (Galos et al., 2007; Anav and Mariotti, 2011). Hirschi et al. (2011) were the first who compared the impact of moisture deficit on hot extremes between a temperate and Mediterranean area using the SPI. They found an overestimation of the seasonal moisture deficit in Central Europe. The projected seasonal climate variability required for impact analysis and adaption strategies needs to be considered also on regional scale, e.g. Olesen et al. (2007), as the regional and local climate beside the quality of the location constitutes a major component of farming.

The outputs of the high resolution regional climate model COSMO-CLM (Will et al., 2006) is used in this study which precipitation change is average compared to other state-of-the-art regional models over Europe (Christensen et al., 2007; Jaeger et al., 2008; Jacob et al., 2012). However, Kjellström et al. (2007) and Jacob et al. (2007) report of a cold and wet bias in the COSMO-CLM on a large scale.

Here, we are interested in biases in modeled data compared to observations of two local bioenergy areas using the COSMO-CLM. These nearby agriculturally extensively used areas are both in the temperate region in Central Germany, but with different climate conditions. Using bias correction on the COSMO-CLM output we investigate in water supply patterns using the SPI of these two study areas as a case study, both under present and under future projected climate conditions. For future water availability and its surplus or deficit over the two regions the SPI is analysed using quantile regression.

2 Study areas and methods

2.1 Sites

The two agricultural study sites chosen for a case study for analyses are located in Central Germany in the northern fringe of the Central-German low mountain range, henceforth Göttingen area (9°9′3″ E, 51°5′3″ N) in the state Lower Saxony with a size of around 1100 km^2 and Großfahner area (10°8′3″ E, 51°0′6″ N) in the state Thuringia with a size of around 500 km^2 as in Fig. 1. Göttingen area is characterised by a combination of stretched hillsides which intermediate between various basins (e.g., Leinetal valley) and hilltops of the surrounding low mountain range, resulting in altitudes ranging from 105–586 m. The undulating terrain of the Großfahner area is shielded by mountain ridges towards North (Harz mountain), South (Forest of Thuringia) and West (Hesse hillsides) with altitudes ranging from 600–1100 m. The soils of these areas consists mainly of sandy loam formed during the last glacial period and includes some weathered black earth. These conditions serve these areas as a diverse agricultural base. Both field areas are considered as wet soil–moisture regimes (energy limited evapotranspiration) after Hirschi et al. (2011) where soil moisture does not impact evapotranspiration variability (Seneviratne et al., 2010).

The rivers Aller and Leine flow within the Göttingen area and the smaller rivers like Unstrut, Gera and Nesse drain the Großfahner area. Both study sites are dominated by a temperate humid climate (Cfb according to Köppen) i.e. a humid seasonal climate where the general weather situation is characterized by advective rainfall originating from the Atlantic with its maximum during the summer. Due to the considerable distance to the sea of 500 km and 600 km, respectively, the study sites are located in a transition zone where the oceanic climate-aspects diminish and the continental characteristics gain more impact. Thus, the climate could be specified as sub-oceanic in the Göttingen area and sub-continental in the Großfahner area (Liedtke and Marcinek, 2002).

Apart from this overall climatic boundary conditions, rainfall patterns and temperature levels are mainly driven by the landform configuration. A variation of large valleys, hillsides and hilltops result in both, rain shadow and relief rainfall effects, triggers convective rainfall patterns during summer and is additionally influeneced by altitude.

According to the data of the German Weather Service (DWD) mean annual precipitation (1971–2000) of 730 mm in the Göttingen area ranges from 617 mm (e.g., Basin of Eichsfeld) to around 900 mm (Forest of Kaufung). Average annual temperature of 8.2 °C ranges between 6.6 °C and 8.8 °C.

The rain shadow effect in the Großfahner area is even more pronounced since major wind directions for advective rainfall are blocked by mountain ridges, resulting in mean annual precipitation of only around 540 mm. Due to orographic rainfall effects, the hills ridge (300–400 m), called “Fahner Höhe” shows up to 650–700 mm of annual precipitation (1971–2000). The overall intra-regional differentiation of precipitaion is, however smaller compared to the Göttingen area and ranges from 470 mm to 618 mm. Average annual temperature of 8.3 °C varies between 7.2 °C and 8.7 °C.

2.2 Scenarios and model

Multiple IPCC/AR4 control (C20) and emission scenarios (SRES) A1B and B1 and two realizations of these scenarios (IPCC, 2007) modeled with ECHAM5/MPI-OM (MPI-M, 2006; Roeckner et al., 2006) and downscaled with the non-hydrostatic regional climate model COSMO-CLM (CCLM) (Will et al., 2006) to a 18 km horizontal resolution are used for analysis depending upon availability. This ensemble of simulations enables a more robust evidence of climate change relative to single realizations.

2.3 Bias correction

Precipitation simulated by climate models might deviate from observations. This systematic deviation is usually called bias. The bias indicates the necessity of model improvements. It could be argued that the model bias influences only the absolute model values and the simulated relative climate change signal can be used. However, many climate impact studies need the real range of changes. Therefore, different correction methods are applied by the scientific community for successful impact modelling (Mudelsee et al., 2010). In the present study a bias correction method (Quantile mapping) after Piani et al. (2010) is applied to the modeled data. This climate model bias correction may be useful for long-term statistical analysis to quantify changes in precipitation. The correction method constructs a transfer function which maps the cumulative distribution function of the simulated daily precipitation sums to the one of a given observational dataset in the control period of the climate simulation. This transfer function is then applied to the entire climate scenario simulation under the assumption of stationarity. The gridded daily precipitation data set REGNIE (R, Regionalisierung von Niederschlagshöhen) (DWD, 2009) was aggregated to the CCLM grid and used for bias corretion and for validation of the model results. The effect of bias correction on regional scale is explored.

2.4 Standardized precipitation index

To assess deficit or excess of moisture conditions in the aforementioned regions the Standardized Precipitation Index (SPI) after McKee et al. (1993) is applied to the precipitation time series. This dimensionless index can quantify the precipitation deficit or surplus for multiple time scales based on the long-term probability distribution of precipitation in a grid cell by using the two-parameter Gamma distribution estimated by the maximum likelihood method. This commonly used index has been shown to be relevant for drought reconstruction and drought monitoring and can be derived for different time and spatial scales (Lana et al., 2001; Lloyd-Hughes and Saunders, 2002; Wu et al., 2005). Here, the SPI is calculated for summer and winter for a 6-month time scale (covering agricultural and meteorological drought) similar to the approach of Hirschi et al. (2011). For a stable estimation of the gamma distribution parameters, the required length of record needs to be longer than 80 yr (Wu et al., 2005), therefore, the period 1971 to 2100 is used for estimating SPI. Positive SPI values between 0.5 and 2 indicate wetter than median precipitation, and above 2 corresponds to extremely wet conditions. Whereas negative values between −0.5 to 2 indicate less than median precipitation, and values below −2 correspond to extremely dry conditions.

2.5 Quantile regression

For estimating trends in all parts of the variable distribution in the seasonal SPI time series for winter and summer quantile regression is applied. This method identifies not only the response in the mean of the variable distribution of some predictor variables as in ordinary least squares regression, but in all quantiles of the distribution of the response variable. In classical linear regression, the response variable Y is related linearly with X by $Y = \beta X + \gamma$ where the coefficients β and γ are the slope and the intercept, respectively. In this case the coefficient values for β and γ are found by "minimizing the sum of squared residuals". For quantile regression each quantile λ of the response variable Y is determined by estimating each quantile slope β_λ and intercept

γ_λ by minimizing the asymmetrically weighted sum of absolute residuals (Koenker and Hallock, 2001). Standard deviations of the estimated trend coefficients for each year are derived with bootstrapping by taking into account the three consecutive winter or summer months of each year. Significance of the slopes were estimated at the 5 % significance level (two-tailed test).

Climate change impacts on water supply patterns are investigated by comparing SPI characteristics of the two study areas during the reference period 1971–2000 with those of future scenarios over the period 2071–2100.

3 Results

For the identification of biases in model data to observations and for exploring the effect of the bias correction method we compared median seasonal sums of observed precipitation of the REGNIE data set (R) with simulated precipitation of the COSMO-CLM (CCLM) and for the latter with bias corrected simulated precipitation of the COSMO-CLM (CCLMBC) averaged over the two sub-regions (Göttingen and Großfahner area) with the associated standard deviations for the reference period 1971–2000 for summer and winter (see Fig. 2 DJF and JJA). Simulated precipitation is overestimated by the model for the Göttingen area and the variance is underestimated for both study areas relative to the observations for both seasons. The bias correction improves the simulated precipitation values over the area of Göttingen compared to the observations. The original CCLM values over the Großfahner area are quiet similar in the mean to the observations, and the bias correction can not provide as much improvement as in the case of Göttingen area.

Ranking the model precipitation (CCLM) and the bias corrected model precipitation (CCLMBC) to the observed data for winter and summer, respectively, shows that the correction improves to a great extent the model precipitation for Göttingen area whereas for Großfahner area the values are close to the observations with marginal improvement (see Table 1). Examining the effect of the bias correction to the scenarios for both field areas shows that the seasonal bias corrected model precipitation (A1BBC and B1BC) of Göttingen area deviates more from the seasonal model precipitation (A1B and B1) than the values for the Großfahner area as shown in Table 2 and Fig. 3. For further analysis the corrected model values which are significantly not different from the observational values in the mean (5 % significance level, two-tailed t- and U-test) are taken into account.

In order to identify trends in all quantiles of the precipitation distribution the ensemble mean slopes of the 130 yr SPI values (C20 and A1B) are determined with quantile regression analysis as demonstrated in Fig. 4. Values with a star mark denote significant slopes. SPI trend coefficients of 0.2–0.8 quantiles of SPI winter time series for the period 1971 to 2100 depict future wetter winters for the Göttingen area. The quantiles of the upper distribution are significant also for Großfahner area suggesting a trend to wetter extremes in winter for the future. Drying of the land surface in summer for both areas are less marked and almost invisible compared to the winter season showing only marginally insignificant drying in the lowest quantile distribution for Göttingen area. The quantile regression results for the B1 scenarios are identical to A1B and therefore not shown.

The climate change signal on water supply patterns is investigated by comparing SPI characteristics of the two study areas during the reference period 1971–2000 with those of future scenarios over the period 2071–2100. The difference of future SPI values (2071–2100) to the control period (1971–2000) calculated with data of the CCLM scenario runs SRES A1B and B1 are presented in Fig. 5a–d winter and summer. Changes in precipitation for SRES A1B and B1 in Göttingen and Großfahner area are less marked compared to the whole area (see Fig. 5a–d) in both seasonal time period differences. Of the two regions Großfahner area is the least effected one to changes. Marked increases in precipitation in winter are identified at the edge of the Harz mountain ridge (Northeast) and in front of the Thuringia forest (Southwest). Mildest changes in winter were found behind (East) the forest of Thuringia. Highest values for drying in summer were found at the edge of the Harz mountain and minor changes were found behind the Harz mountain and the Thuringia forest in the last 21st century. Changes in SPI for SRES B1 compared to the control period are lower than those for SRES A1B in general (see Fig. 5a–d). The spatial pattern in winter for SRES B1 is similar to SRES A1B, but show a quite different picture in summer with wetting in the Northeast at the edge of the Harz mountain for 2071–2100. The climate change signal of SPI shows an overall wetting in winter for 2071–2100 and drying in summer.

4 Discussion and conclusions

Here we present water supply patterns of two agriculturally extensively used temperate regions in Central Germany, Göttingen area and Großfahner area, with different climate characteristics both under present as well as under future climate change conditions taking bias correction into account.

The effect of the bias correction method on regional scale is explored and demonstrated for two regions being close together. Generally, the median and the variance (to some extent) of the model precipitation values relative to the observations are improved with the quantile mapping transfer function. More specific to the regions, the correction method improves the bias in the Göttingen area to a large extent suggesting that bias correction is an added value to this region. However, the model control values in the case of Großfahner area are already close to the observations meaning that they are more accurate than the ones of Göttingen area, see also Hagemann and Jacob (2007). It may be the result of the less topographic gradients and less heterogeneous land cover in this basin, suggesting that even small differences in spatial scale play an important role (Samuels et al., 2011). It is arguable to what extent the correction method helps to improve the variance especially regarding outliers, see also Mudelsee et al. (2010). On the one hand, it is quite difficult to assess the true quality of the bias corrected data since they are limited by the quality of the observations, and further the climate models do not reproduce all observed features (Dosio and Paruolo, 2011) which cannot be accounted for by the bias correction method used for this study.

A possible improvement could be achieved by a cascade bias correction method which accounts for the fluctuations on different timescales, as was suggested by (Haerter et al., 2011) for temperature and could be extended for precipitation. Another approach of bias correction using weather type classes may be an alternative accounting for realistic representation of extreme events (Bissoli and Dittmann, 2001).

The spatial differences in the climate change signal conform with the in the IPCC report depicted physical background of getting more moisture in the studied area through the westerly wind system. Changes in the SPI-based values follow the modeled changes in precipitation for both study areas. We found significant wetting in winter in all quantiles for Göttingen area which is line with the literature (Christensen et al., 2007; Gerstengarbe et al., 2003), although significant wetting was only found in the higher tails of the distribution for Großfahner area. This increase of extreme precipitation in winter for both study areas could trigger runoff and soil erosion risk (Zhai et al., 2010) enhancing the severity of floods. For that agro-forestry systems could level off erosion which should be considered for agricultural management.

Contradictory to the literature (e.g., Gerstengarbe et al., 2003) suggesting an overall drying in summer in Germany we found no significant change for summer for both areas. In general Großfahner area is less affected to changes both in summer and winter. Quantile regression results show that severe shortage of precipitation in summer is not expected in both study areas although mild drier conditions may occur in both areas at the end of the 21st century according to the climate change signal. This circumstance may trigger water shortage and summer drying associated with above–average temperatures in the future (Hirschi et al., 2011). The same combination may induce increases of potential plant stress. Water stress affects the agricultural sector then first because of its dependence on stored soil water, which is rapidly depleted during extended dry periods. The surplus of precipitation in winter may level off these circumstances. For short-rotations poplar coppices a high water gauge would be beneficial.

The future increased winter storage of water in the soil via precipitation surplus introduces long-term memory effects with timescales of several months (Vautard et al., 2007) which may lead to more water availability in spring. This winter soil water surplus could enhance local convective cloud formation and local latent heat fluxes (Schär et al., 1999) thereby decreasing sensible heat fluxes in winter and early spring. As a result soil drying may be delayed to late spring extending into the summer period being an important effect on sensible heat fluxes (Seneviratne et al., 2002).

Upward trends in winter wetness occur in both regions agreeing with the IPCC findings on the regional impacts of climate change (IPCC, 2007). The higher water availability in winter due to increased rainfall may ensure that soil moisture will not be a limiting factor in early spring. Consequently, evapotranspiration cooling may continue at the beginning of the growing season. The water availability may indeed increase in the vertical soil profile due to increasing storage in winter based on the 6 month SPI (Vicente-Serrano and Lopez-Moreno, 2005) and may favor soil nutrient leaching. This is ongoing impact research and will be analysed within BEST with a hydrological model combining precipitation, evapotranspiration and runoff to affect the vertical soil moisture memory in the next study.

This study highlighted the regional differences in the vulnerability to water surplus or deficit risks on an example of two areas in the temperate climate zone and emphasizes the need in impact studies to focus on proper consideration of local environmental conditions as well as adaption of management for agriculture.

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Table 1. Magnitude of the difference in percent between the mean model precipitation (CCLM) and the bias corrected model precipitation (CCLMBC) with the observed data for winter and summer of 1971–2000.

Model	Göttingen area	Großfahner area
Winter		
CCLM	8 %	3 %
CCLMBC	−12 %	−4 %
Summer		
CCLM	16 %	2 %
CCLMBC	3 %	0 %

Table 2. Magnitude of the difference in percent between the bias corrected mean model precipitation (A1BBC and B1BC) and the model precipitation for winter and summer of 2001–2100.

Model	Göttingen area	Großfahner area
Winter		
A1BBC	–21 %	–5 %
B1BC	–21 %	–7 %
Summer		
A1BBC	–17 %	–2 %
B1BC	–17 %	–3 %

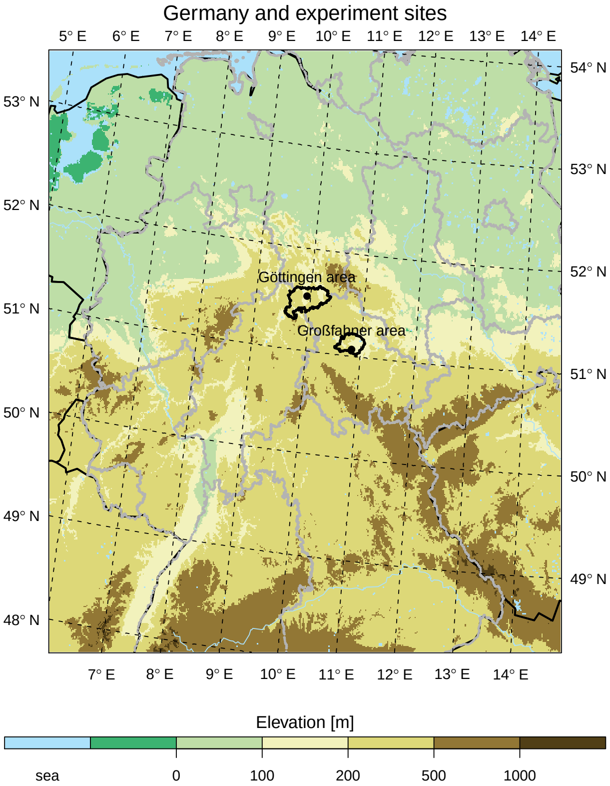

Fig. 1. The country Germany in its elevation and the experimental sites: Göttingen area and Großfahner area.

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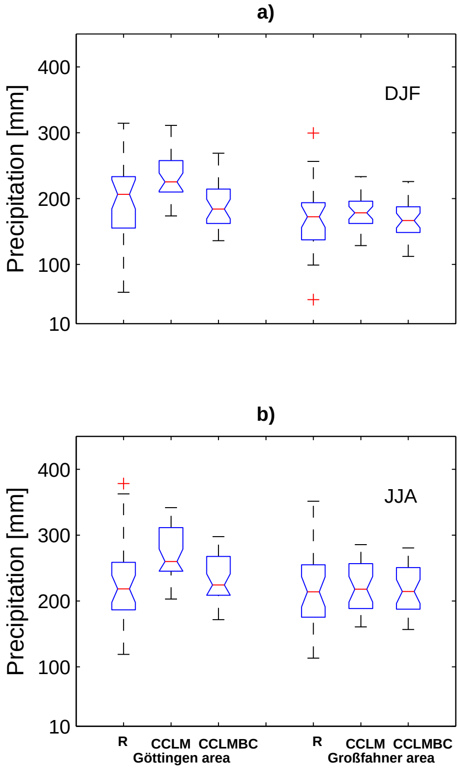

Fig. 2. (a) Seasonal winter (DFJ) sums of observed REGNIE (R), simulated precipitation (CCLM), and bias corrected simulated precipitation (CCLMBC) averaged over the two sub-regions (Göttingen and Großfahner area) with the associated standard deviations for the reference period 1971–2000. **(b)** Seasonal summer (JJA) sums of observed REGNIE (R), simulated precipitation (CCLM), and bias corrected simulated precipitation (CCLMBC) averaged over the two sub-regions (Göttingen and Großfahner area) with the associated standard deviations for the reference period 1971–2000. Central line: median; bottom and top of box: 25th and 75th percentiles; whiskers: data range; crosses: outliers.

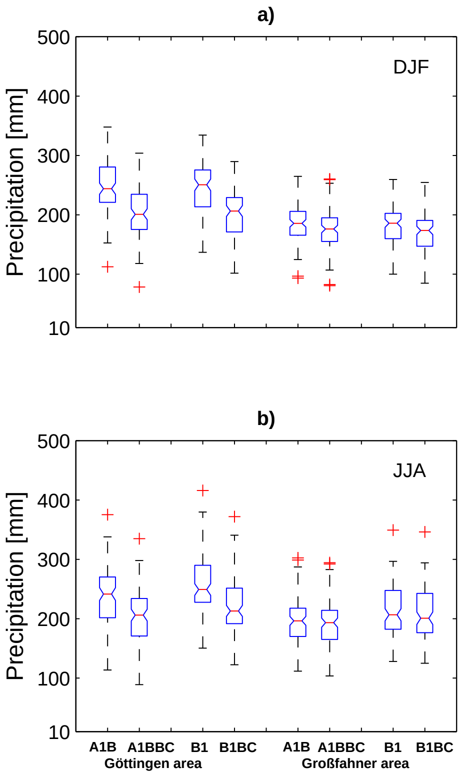

Fig. 3. (a) Seasonal winter (DFJ) sums of future projected precipitation (A1B and B1) and bias corrected projected precipitation (A1BBC and B1BC) averaged over the two sub-regions (Göttingen and Großfahner area) for the period 2001–2100. **(b)** Seasonal summer (JJA) sums of future projected precipitation (A1B and B1) and bias corrected projected precipitation (A1BBC and B1BC) averaged over the two sub-regions (Göttingen and Großfahner area) for the period 2001–2100. Central line: median; bottom and top of box: 25th and 75th percentiles; whiskers: data range; crosses: outliers.

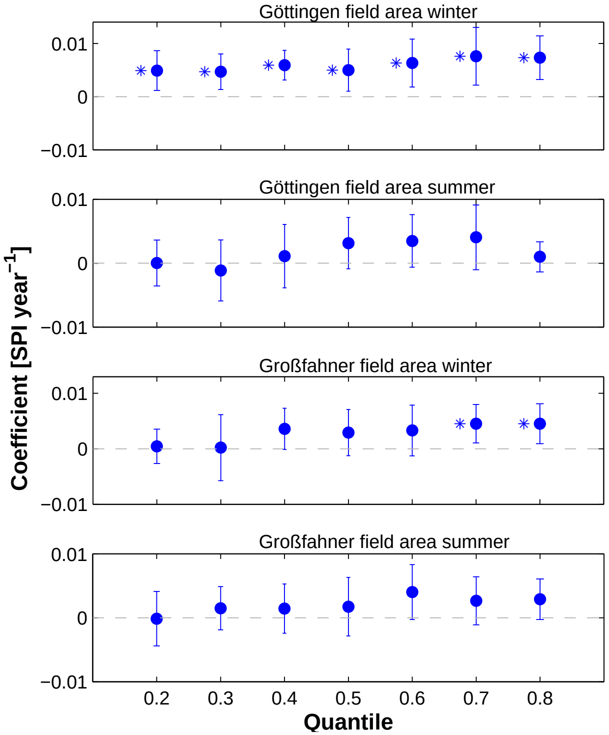

Fig. 4. Quantile regression analysis. Trend coefficients of 0.2–0.8 quantiles of quantile regression analysis of SPI winter and summer time series of Göttingen and Großfahner area for the period 1971 to 2100 (C20 and A1B). Standard deviations of the estimated trend coefficients are shown derived with bootstrapping. Star marks indicate significant trends.

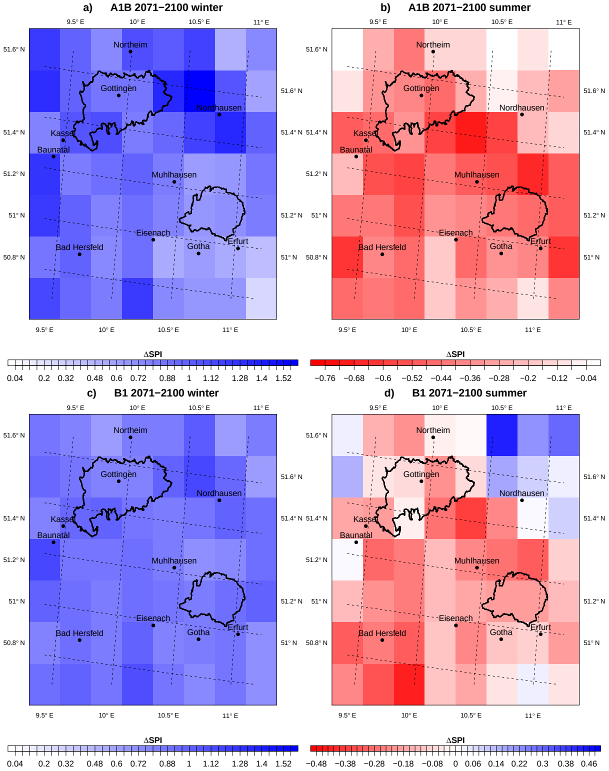

Fig. 5. Climate change signal: difference of SPI between 2071–2100 and 1971–2000 for winter and summer of SRES A1B and B1 to C20. Black line: Göttingen area and Großfahner area.