Evaluation of a climate simulation in Europe based on the WRF–NOAH model system: precipitation in Germany

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Abstract The Weather Research and Forecast (WRF) model with its land surface model NOAH was set up and applied as regional climate model over Europe. It was forced with the latest ERA-interim reanalysis data from 1989 to 2008 and operated with 0.33° and 0.11° resolution. This study focuses on the verification of monthly and seasonal mean precipitation over Germany, where a high quality precipitation dataset of the German Weather Service is available. In particular, the precipitation is studied in the orographic terrain of southwestern Germany and the dry lowlands of northeastern Germany. In both regions precipitation data is very important for end users such as hydrologists and farmers. Both WRF simulations show a systematic positive precipitation bias not apparent in ERA-interim and an overestimation of wet day frequency. The downscaling experiment improved the annual cycle of the precipitation intensity, which is underestimated by ERA-interim. Normalized Taylor diagrams, i.e., those discarding the systematic bias by normalizing the quantities, demonstrate that downscaling with WRF provides a better spatial distribution than the ERA interim precipitation analyses in southwestern Germany and most of the whole of Germany but degrades the results for northeastern Germany. At the applied model resolution of 0.11°, WRF shows typical systematic errors of RCMs in orographic terrain such as the windward–lee effect. A convection permitting case study set up for summer 2007 improved the precipitation simulations with respect to the location of precipitation maxima in the mountainous regions and the spatial correlation of precipitation. This result indicates the high value of regional climate simulations on the convection-permitting scale.

Keywords Regional climate model · Germany · Precipitation · Convection-permitting simulation

1 Introduction

Climate change will induce not only modifications of temperature statistics and trends but also of the water cycle. This will result in spatial and temporal changes of soil, cloud, and precipitation patterns. It will be connected with variations of weather statistics, particularly of extreme precipitation events and heat waves (e.g., Meehl and Tebaldi 2004; Schär et al. 2004).

In order to react and to adapt to these changes, regional climate simulations down to the scales essential for decision models of policy makers and end users are required. Dynamical downscaling of global climate models using regional climate models (RCMs) is considered to be the most promising means in this context. Changes in the statistics of synoptic conditions due to climate change are simulated in the GCMs driving the RCMs. The interaction and feedbacks between large-scale and small-scale conditions are simulated in detail on a physical basis in the RCMs. This approach requires the verification and continuous improvements of model physics prior to their application for climate projections.

In recent years, various RCMs have been developed and applied for simulating the present and future climate of Europe. The performance of the RCMs to successfully reproduce the observed regional climate characteristics within the last decades was extensively assessed. Within

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the EU projects ENSEMBLES and PRUDENCE, ensemble simulations of RCMs were executed and analyzed with a grid resolution of the order of 25 and 50 km (Christensen and Christensen 2007; Christensen et al. 2007). These models were able to reproduce the pattern of temperature distributions reasonably well but a large scatter was found with respect to the simulation of precipitation. The results of ENSEMBLES and PRUDENCE are in accordance with a variety of studies of RCMs at the order of 25–50 km (e.g., Kotlarski et al. 2005; Beniston et al. 2007; Déqué et al. 2007; Jacob et al. 2007; Jaeger et al. 2008).

RCMs with even higher grid resolutions of 10–20 km were developed and extensively verified e.g., in southwestern (SW) Germany, Feldmann et al. (2008) and Früh et al. (2010) studied the consortia runs of the climate version of the COSMO model (COSMO–CLM) of the German Weather Service (DWD) and the REMO model of the Max Planck Institute for Meteorology. However, even at this resolution, several systematic errors were remaining. For instance, the "windward–lee effect" (Schwitalla et al. 2008; Wulfmeyer et al. 2008) is visible at mountain ranges showing a strong overestimation of precipitation on the windward side and an underestimation on the lee side. Heikkilä et al. (2011) studied the impact of grid resolution on simulation results of precipitation in Norway applying the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) forced with ERA-40 reanalysis on 0.33° and 0.11°. Despite the inaccuracies of the coarse forcing data that were transferred to the results, all simulations indicated a gain from high resolution due to better resolution of orographic effects. These include an improved simulation of the spatial distribution of precipitation, wet day frequency and extreme values of precipitation, but three major systematic errors remained: the windward–lee effect, phase errors in the diurnal cycle of precipitation (Brockhaus et al. 2008), and biased precipitation return values, especially on longer return periods (Früh et al. 2010).

Due to their bias in precipitation and temperature, the RCM results are commonly statistically bias-corrected prior to applying their climate data to force hydrological and impact models (e.g., Dobler and Ahrens 2008; Piani et al. 2010). The bias correction is based on the past and current climate and may be applied for the past e.g., in hydrological and ecological modeling. However, this method is highly questionable. Correlations between land-surface and atmospheric variables are generally not considered to cause inconsistencies between the driving data and the end user models. Moreover, bias correction can be questionable under changing climate conditions in climate projections (e.g., Teutschbein and Seibert 2010; Maraun 2011, 2012; Ehret et al. 2012). This is especially important for hydrological impact studies, since hydro-meteorological atmospheric and land-surface processes interactions are complex and non-negligible.

In order to reduce or to avoid bias-correction, the development of a model system providing simulations with improved statistics is essential. The performance of the RCMs is strongly dependent on its ability to simulate the combination of forcing events leading to precipitation, which on the other hand is feeding back to land-surface properties such as soil moisture. A suitable forcing concept for mid-latitude precipitation can be found in Wulfmeyer et al. (2011). For instance, if precipitation is due to strongly forced conditions such as large-scale synoptic events, the downscaling results are mainly controlled by the quality of boundary forcing. Therefore, systematic errors corresponding to the boundary forcing will remain. If precipitation is driven by local forcing e.g., by orography or land-surface heterogeneity, the benefit of downscaling should become more visible, as higher resolution models have better capability to simulate convection initiation, organization, and decay (Rotach et al. 2009; Wulfmeyer et al. 2011). Particularly in summer time, is it expected that downscaling will also lead to improved simulations of the spatial distribution and the diurnal cycle of precipitation. It can be expected that the performance of downscaling on the convection-permitting scale will lead to a significant advance in the quality of the simulation of precipitation (e.g., Bauer et al. 2011).

The purpose of this work is to evaluate the potential of downscaling of large scale climate data applying a regional climate model like the WRF–NOAH model system. This is reasonable as this model system has advanced description of physical processes such as land-surface–vegetation–atmosphere interaction, dynamical processes, and it can be operated down to the convection-permitting scale. WRF–NOAH offers multiple parameterizations e.g., for microphysics, turbulence, radiation transfer and boundary layer physics. So the best set of a combination of state of the art parameterizations can be chosen for each model domain WRF–NOAH is applied to. Alternatively, an ensemble of WRF–NOAH simulations can be run with different combinations of parameterizations.

For this investigation, it is essential that the WRF–NOAH model system is driven by the best reanalysis. So far, the NCEP, ERA-15 and ERA-40 reanalysis have been downscaled over Europe. Recently the third generation of the ECMWF reanalysis, ERA-interim (Simmons et al. 2007; Uppala et al. 2008) became available. The ERA-interim reanalysis corrects some of the errors of the ERA-40 reanalysis and is available from 1979 onwards on a T255 spectral grid (i.e., approx. 0.75°). In order to provide high-resolution ensembles and comparisons of regional climate simulations, the World Climate Research Program (WCRP) initiated the COordinated Regional climate

Downscaling EXperiment (CORDEX) (Giorgi et al. 2009). At that time ERA-interim data was available from 1989 to 2008, and therefore the a verification run is performed for a 20-year period (1989–2008) driven by the ERA-interim data. In our study, a verification run for Europe with 0.11° ($\sim$12 km) resolution was performed with WRF–NOAH.

This study analyzes the precipitation results for Germany, and in more detail for southwest (SW) Germany and the lowlands of northeastern (NE) Germany. SW-Germany has been the focus of weather forecasts (e.g., Bauer et al. 2011; Schwitalla et al. 2011) and climate studies (e.g., Feldmann et al. 2008; Früh et al. 2010) due to (1) its interesting orography formed by the Rhine valley between the Vosges and Black Forest mountain ranges, the Neckar valley and the Swabian Jura, (2) readily available high quality observational data, (3) its vulnerability to floods, and (4) its importance for agriculture and industry. NE-Germany is one of the driest regions in Germany.

The article is structured as follows. First, the applied model configuration and data sets are introduced. Thereafter, an overview of the landscape and climate of Germany is given. This is followed by the evaluation of the precipitation simulation and a discussion of the results in a larger context. Finally, conclusions are drawn.

2 A downscaling experiment for Europe with WRF–NOAH

2.1 Configuration of WRF–NOAH for the simulation

Version 3.1.0 of the WRF model has been applied to Europe on a rotated latitude–longitude grid with a horizontal resolution of 0.11° and with 50 vertical layers up to 20 hPa with the land surface model NOAH (Chen and Dudhia 2001a, b). The model domain (red frame in Fig. 1) covers the area specified in CORDEX. ERA-interim forcing data is available at approx. 0.75°, and WRF was applied, one-way nested, in a double nesting approach on 0.33° (black frame in Fig. 1) and 0.11°. In an additional experiment for summer 2007, when the Convective and Orographically-induced Precipitation Study (COPS) (Wulfmeyer et al. 2011) took place, a third domain with 0.0367° ($\sim$4 km) resolution was nested into the 0.11° domain (white frame in Fig. 1), and a convection permitting simulation was performed. From experience with previous applications of WRF in Central Europe in the weather forecast mode (Schwitalla et al. 2011), it was decided to use the Morrison two-moment microphysics scheme (Morrison et al. 2009) and the YSU atmospheric boundary layer parameterization (Hong et al. 2006). Further, the Kain–Fritsch–Eta convection scheme (Kain 2004)

and the CAM shortwave and longwave radiation schemes (Collins et al. 2004) were chosen.

2.2 Data for model simulation

The ERA-interim data set is the latest ECMWF global atmospheric multi-decadal reanalysis using a 6-h 4D-Var data assimilation system. Dee et al. (2011) give a detailed description and analysis. At the time of the beginning of the simulations, ERA-interim data was available from 1989 to 2008. The WRF simulation was carried out from 1989 to 2008, forced with 6-hourly analysis data at the lateral boundary and daily sea surface temperatures- both from ERA-interim. Soil moisture and temperature profiles were initialized from ERA-interim at the 1st January 1989, interpolating the data to the NOAH model. Wu and Dickinson (2004) studied the time scales of layered soil moisture memory in the context of land–atmosphere interaction and found a memory of 2.6–4 months in the root zone for the mid and high latitudes. To reduce at least some spin-up effects that may disturb the model results, 1989 is omitted in the evaluation and only the period of 1990–2008 is investigated.

For vegetation type and soil texture the following data sets included in the pre-processing package of WRF are used. For vegetation this is the 30″ MODIS land-cover data, classified according to the International Geosphere–Biosphere Programme (IGBP), which was adapted to NOAH. For the soil, the 5 min. UN/FAO data is used.

3 Germany and its climatology

3.1 Landscape and climate

Germany has a typical mid-latitude moderate climate, characterized by a westerly flow with rainfall associated with frontal systems in winter and more convective precipitation in summer (Wulfmeyer et al. 2011). The North Sea and Baltic Sea further influence the climate in northern Germany. Germany is characterized by its flat terrain in the north, the low mountain ranges of the Harz and Thüringer Wald in the center and the mountain ranges of the Black Forest, Swabian Jura, Bavarian Forest and the Alps in the south. Mixed Forests, needle leaf forests, cultivated grasslands and croplands characterize the landscape.

The SW-German study area is located between 7.5° and 11°E and 47° and 50°N. It covers the Rhine, Neckar and upper Danube river valleys, the Black Forest and the Swabian Jura. The Black Forest is a mountain range with a south–north orientation with elevations up to almost 1,500 m above mean sea level (Feldberg). The Swabian Jura which has a southwesterly–northeasterly orientation and elevations up to 1,000 m above mean sea level, is
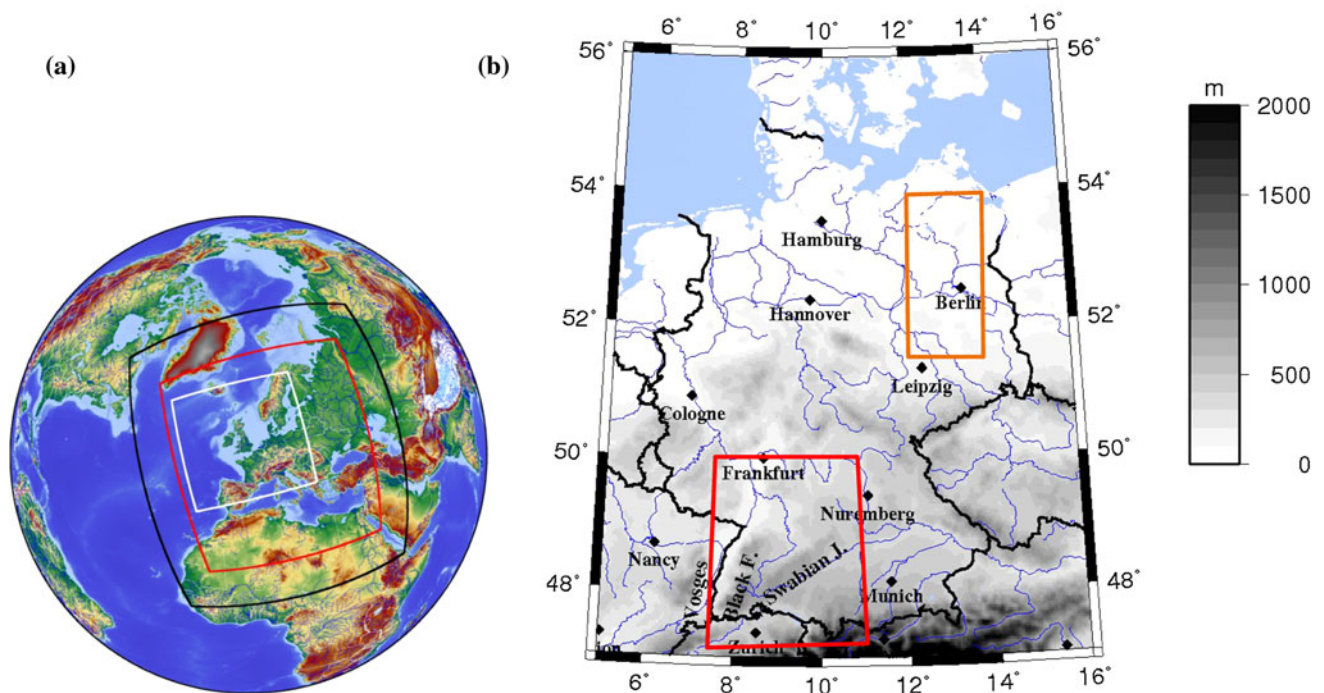
Fig. 1 **a** Domain of WRF–NOAH for CORDEX Europe on a rotated grid with 0.33° (*black frame*), 0.11° resolution (*red frame*) and 0.0367° (*white frame*), **b** Map of Germany, the evaluation area of SW-Germany and NE-Germany are indicated by a *red* and *orange frame*

characterized by steep orography at its boundaries and a high plateau. The valleys and the high plateau of the Swabian Jura are dominated by agriculture and beech trees while the Black Forest is dominated by evergreen needle trees. Dominant soil textures are loamy silt in the Swabian Jura and alpine upland, sandy loams in the Black forest and sandy and silty soils in the river valleys.

The NE-German study area is located between 12° and 14°E and 51.5° and 54°N, the city of Berlin is located in its center. The lowlands are characterized by the rivers Elbe and its contributory Havel and the lakelands of Mecklenburg. Sandy soils dominate NE-Germany, and agriculture with large fields and deciduous forests characterize the landscape. Through the sandy soils the water drains rather quickly leading to a limitation of transpiration due to low soil water availability.

3.2 Precipitation climatology

For Germany, the DWD processed a consistent 1 km^2 gridded dataset of daily precipitation (REGNIE = Regionalisierung von Niederschlagsdaten) from 1961 to 2009. REGNIE is generated from about 1,200 precipitation measurement stations interpolated on a 1 × 1 km^2 grid

over Germany. During the interpolation, also the station elevation and exposition are considered.

In Germany, the annual mean precipitation between 1961 and 2009 varied between 584 mm in 1976 and 1,005 mm in 2002. During this period, the annual mean precipitation increased by 7 % (at the 90 % confidence interval). The monthly precipitation has no significant trend except in June, July and December. In June a significant (90 % confidence interval) decrease of about 16 % is observed between 1961 and 2009. July and December show a very significant (95 % confidence interval) increase of about 27 % in July and 2 % in December.

In SW-Germany, the annual precipitation between 1961 and 2009 varied between 662 and 1,248 mm with a mean of 920 mm. The monthly precipitation has no significant trend except in June, when a very significant (95 % confidence interval) decrease of about 25 % is observed.

In NE-Germany the annual precipitation from 1961 to 2009 varied between 408 mm in 1982 and 793 mm in 2007 with a mean of 571 mm. The monthly precipitation had no significant trend except in February, when a significant (90 % confidence interval) 45 % increase is observed, however, it is not yet known, if this trend is subject to climate change or natural variability.

4 Evaluation

4.1 Evaluation metrics of this study

To compare the REGNIE dataset with simulation results, the observations were interpolated to the model grid with a simple weighted squared distance approach as applied in Schwitalla et al. (2008). Richter (1995) gives the climatological (1961–1990) monthly mean undercatch of the German precipitation gauges used in the REGNIE data. The lowest undercatch is found in very protected locations in southern Germany in July (5.6 %). With an undercatch of up to 33.5 % in February largest values occur in February at non-protected gauges in eastern Germany (Richter 1995). In summer Berg et al. (2011) found the EOBS data have an undercatch of 10–27 % with respect to corrected precipitation data in the Ammer, Ruhr and Mulde catchments. In these regions the non-corrected gauge data have an undercatch of 7.3–10.8 % in summer (Richter 1995). This means that the REGNIE is not only available at a higher resolution than the commonly applied European gridded precipitation observational data EOBS (Haylock et al. 2008), it also has a significantly reduced undercatch. We evaluated the temporal and spatial distribution of the annual, seasonal and monthly precipitation calculated in a climate simulation from 1990 to 2008. The spatial distribution of the seasonal mean precipitation is studied with 2D-maps and probability density functions (pdf). Further, the time series and the climatologic annual cycle of the areal mean precipitation, wet day frequency, daily precipitation intensity and the 90 % quantile of daily precipitation amounts are analyzed. Following Frei et al. (2003) a threshold of 1 mm/day was chosen discriminate between wet days and dry days. The skill of the model in simulating the observed spatial seasonal mean is assessed here through Taylor diagrams (Taylor 2001). The normalized Taylor diagram is a method to evaluate a model against observations discarding the systematic bias by normalizing the quantities. Taylor diagrams can provide a brief statistical outline of how well patterns match each other in terms of their correlation, their root-mean-square difference, and the ratio of their variances. The distance from the origin is the standard deviation of the field. If the standard deviation of the model is same as that of the observation, then the radius is 1. The distance from the reference point to the plotted point gives the root mean square difference (RMSE). The nearer the plotted point is to the reference point, the lesser will be the RMSE. The correlation between the model and the climatology is the cosine of the polar angle (if the correlation between the model and observation is 1, then the point will lie on the horizontal axis). Thus the model which has largest correlation coefficient, smaller RMSE and comparable variance will be close to the reference

point (i.e., the observation) is considered to be the best among all (Joseph et al. 2010).

4.2 Germany

Figure 2 shows the seasonal precipitation climatology of 1990–2008 in Germany for the simulations [ERA-interim and WRF–NOAH (0.11° and 0.33°)] and the observation (REGNIE) for spring (March–May), summer (June–August), autumn (September–November) and winter (December–February).

While WRF–NOAH is wetter in all seasons than REGNIE and ERA-interim, WRF–NOAH generally meets the heterogeneous structures in the precipitation distribution whereas ERA-interim smoothes out most structures over Germany due to its coarse resolution. However, ERA-interim delivers the observed precipitation gradient declining from the Alps in the south to the lowlands in the north and from the North Sea coast in the west to the continental climate in the east.

WRF–NOAH-0.33° shows more structure than the 0.75° resolving ERA-interim data. But the model is not able to resolve the finer observed precipitation patterns, namely around the low-mountain ranges. These get better resolved by WRF–NOAH-0.11°. The most obvious precipitation difference between WRF–NOAH at 0.33° and 0.11° is the windward–lee-effect which is apparent in the WRF–NOAH-0.11° results, namely in the Black Forest region.

The WRF–NOAH-0.11° overestimates precipitation almost everywhere in Germany both in spring and in winter by 0.75–1.75 mm/day (Fig. 3). ERA-interim precipitation agrees to within ±0.25 mm/day in most of the lowlands in spring and winter, but shows a negative bias of 1–2 mm in the mountains and an equally positive bias in the Rhine valley and between the Swabian Jura, the Alps and Bavarian Forest.

In summer, not only is the precipitation pattern more variable, but also the bias of the simulated precipitation of WRF–NOAH-0.11° is more distributed. Clearly the windward–lee effect of regional models causes biases at the mountain ranges. In the lowlands of northern Germany WRF–NOAH-0.11° shows a wet bias of 0.25–1.5 mm/day, namely at coastal areas which suffer from an overestimation in precipitation. The ERA-interim data shows a negative bias of 0.25–1.5 mm/day mostly in the orographically structured terrain.

In autumn the differences between the model simulations and observation are similar to the summer but the bias is higher. The windward–lee effect is no longer pronounced in autumn.

The spatial probability density functions (pdf) of the mean seasonal precipitation (1990–2008) is displayed in Fig. 4. WRF–NOAH-0.11° shows a similar pdf shape to
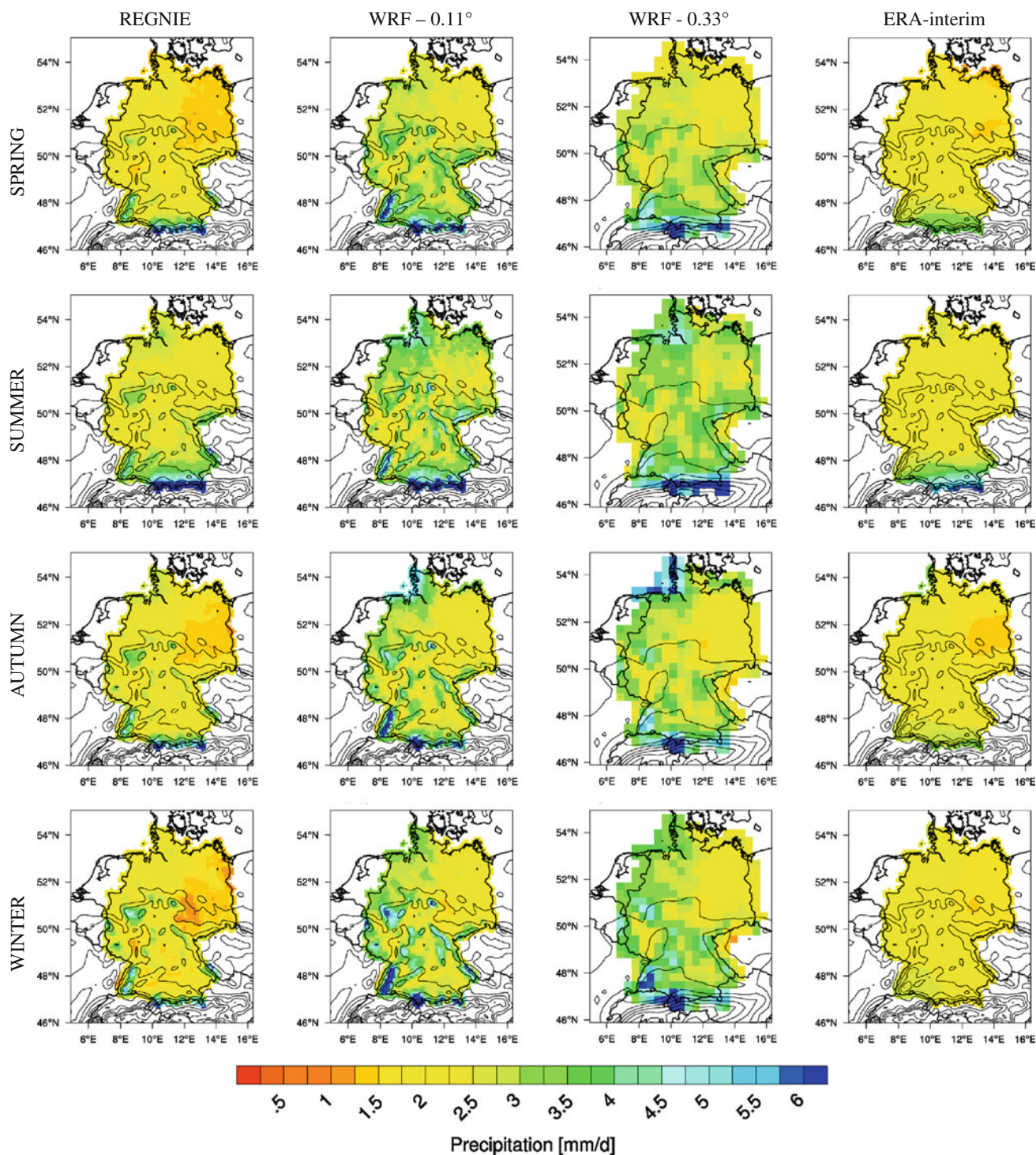
Fig. 2 Seasonal precipitation climatology of 1990–2008 in Germany for the observation (REGNIE) and the simulations (WRF–NOAH-0.11°, WRF–NOAH-0.33° and ERA-interim) for spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). *Black thin contour lines* show the orography

REGNIE in spring, autumn and winter but a bias towards stronger precipitation. ERA-interim overestimates precipitation in all seasons except spring in the 200 mm/season intensity class and underestimates stronger precipitation classes. Discarding the wet bias of WRF–NOAH, WRF–NOAH's pdf shape agrees well with REGNIE's in spring, autumn and winter. In summer both, WRF–NOAH-0.11° has a broader pdf shape than REGNIE, while ERA-

Fig. 3 Difference of seasonal precipitation (1990–2008) between WRF–NOAH (0.11°) and REGNIE and ERA interim and REGNIE in Germany for spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). *Black thin contour lines* show the orography
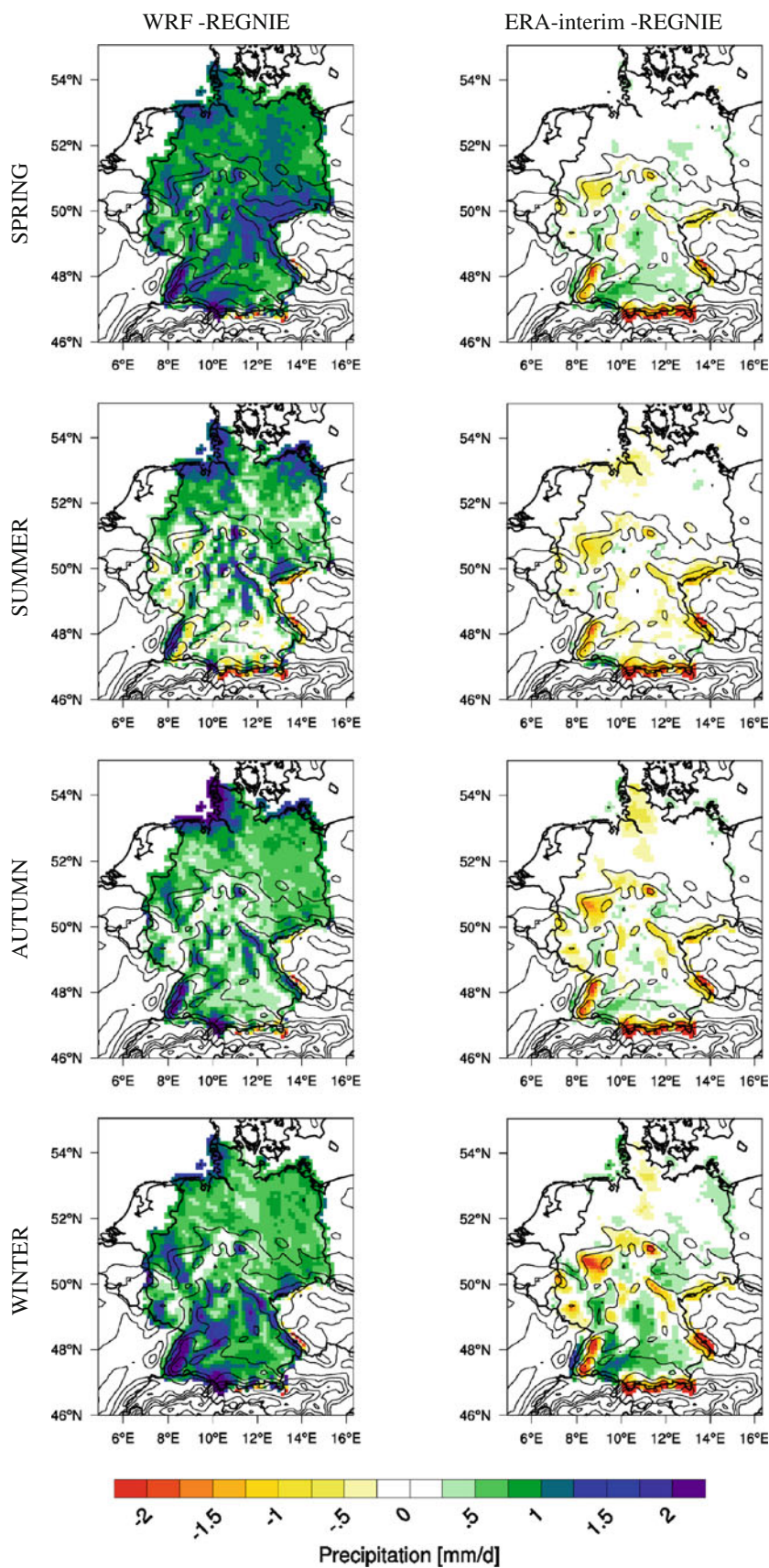
interim's pdf is too tight with an overestimation of the frequency of the 210 mm/season intensity class. Figure 5 shows scatter plots of simulated versus observed mean seasonal grid precipitation. Except for summer, ERA-interim is not capturing the larger intensity classes (above 300 mm/season) while WRF–NOAH has a wet bias but captures the larger precipitation classes. In the lower precipitation classes WRF shows a larger scatter than ERA-interim. The regression lines of WRF–NOAH show an offset but similar slope like REGNIE, while ERA-interim deviates from REGNIE due to the missing high intensities. In summer both, ERA interim and WRF–NOAH have a dry bias in the larger precipitation classes. The results underline, that information about the spatial distribution of precipitation intensities is gained by dynamical downscaling. However, this in case of WRF–NOAH includes a wet bias.

Figure 6's normalized spatial Taylor diagram shows deficiencies and benefits of the simulated seasonal precipitation climatology by downscaling with WRF–NOAH. In spring WRF–NOAH shows a smaller standard deviation (STD), root mean square error (RMSE) and a slightly better correlation than ERA-interim. In summer ERA-interim shows a better performance than the downscaling experiment: while the normalized STD is 1 mm/day for WRF–NOAH in summer, it is lower (0.5 mm/day) in ERA-interim. The RMSE is larger and the correlation is lower in WRF–NOAH's summer precipitation than in ERA-interim. Autumn has a similar performance in ERA-interim and WRF–NOAH. In winter, the correlation is a lot worse in ERA-interim (0.34) than in WRF–NOAH (0.86).

Figure 7 shows the time series of Germany's mean seasonal precipitation from 1990 to 2008 for REGNIE, ERA-interim, WRF–NOAH-0.11° and WRF–NOAH-0.33°. ERA-interim's mean precipitation agrees well in all years and seasons with REGNIE's. Note that ERA-interim is a reanalysis product and even rain-affected radiances are assimilated (Dee et al. 2011). Dee et al. (2011) show a good agreement between ERA-interim's precipitation and precipitation data from the Global Precipitation Climatology Project (Dee et al. 2011). WRF–NOAH on the other hand is only forced by reanalysis data at its lateral boundaries and the oceans. Thus a model-specific climate evolves within the model domain in a climate simulation. WRF–NOAH's time-series show a wet bias, except in the summers from 2005 to 2007, autumn 1998 and winters 1994, 1995 and 2001 when precipitation agrees well with REGNIE. In general, at 0.33° WRF–NOAH has the same or a stronger wet bias in Germany than at 0.11°. Only a few years in spring and summer WRF–NOAH-0.11° has the wetter bias. The general shape of the time-series is reproduced relatively well by WRF–NOAH for winter precipitation and even summer and autumn show a similar shape with only a few exceptional years.

The mean annual cycle of precipitation (Fig. 8) shows the wet bias of WRF–NOAH-0.11° of up to 35 % in Germany, but the mean annual cycle of precipitation is well reproduced except for a relative minimum observed in October which occurs in September in WRF–NOAH and also that the amplitude is smaller in WRF–NOAH. The mean annual cycle shows a good agreement between ERA-interim and REGNIE in winter and spring. In summer and autumn ERA-interim has a dry bias of approximately 10 % in Germany.

The annual cycle of daily precipitation statistics for the areal mean of Germany is displayed in Fig. 9 for REGNIE, WRF_NOAH-0.11°, WRF–NOAH-0.33° and ERA-interim. The observed annual cycle of wet-day frequency fraction ranges between 0.3 and 0.4 and is overestimated by both WRF simulations and the ERA-interim data. ERA-interim's range is between 0.4 and 0.5 while WRF ranges between 0.43 and 0.6. While ERA-interim shows just an offset from REGNIE, WRF–NOAH-0.11° has a larger frequency fraction difference with respect to REGNIE between October and May than from June to September. The 0.33° WRF simulation shows the largest wet day frequency throughout the year. With respect to the mean daily precipitation intensity ERA-interim is underestimating the amount while WRF–NOAH-0.11° follows the observation except from July to September, when the mean precipitation intensity is overestimated. WRF–NOAH-0.33° shows mean precipitation intensities between ERA-interim and WRF–NOAH-0.11°. Comparing the mean precipitation, wet day frequency and mean precipitation intensity it can be summarized that in Germany the models simulate too many precipitation days. While ERA-interim has lower intensities—and meets the mean precipitation—WRF–NOAH-0.11° meets the observed intensities and consequently overestimates the mean precipitation. The downscaling from WRF–NOAH-0.33° to 0.11° improves the performance. The annual cycle of heavy precipitation (as revealed by the 90 % quantile) shows a peak in July. Throughout the year the 90 % quantile of precipitation amounts is reflecting the wet bias introduced by the downscaling of ERA-interim with WRF. Only in July—when the peak occurs—the 90 % quantile shows an agreement between REGNIE and WRF while ERA-interim has too low values. In July precipitation in Germany is dominated by convection induced strong precipitation. This is mainly driven by local forcing e.g., by orography or land-surface heterogeneity. Under such conditions downscaling ERA-interim with WRF improves the 90 % quantile of precipitation amount simulation. However, they are overestimated in WRF in June.
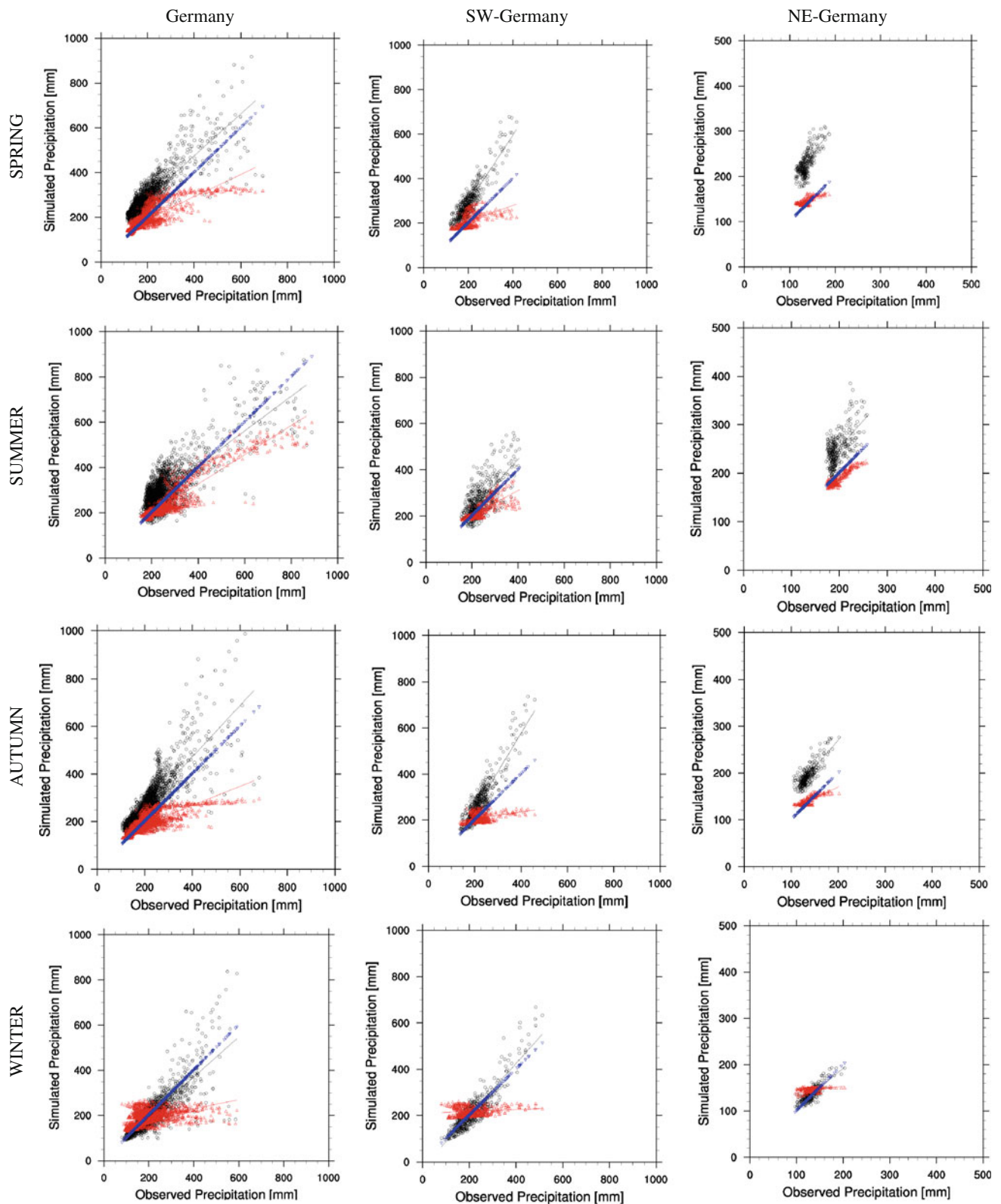
4.3 SW-Germany

SW-Germany is dominated by its orographic structures and precipitation fields look different than throughout
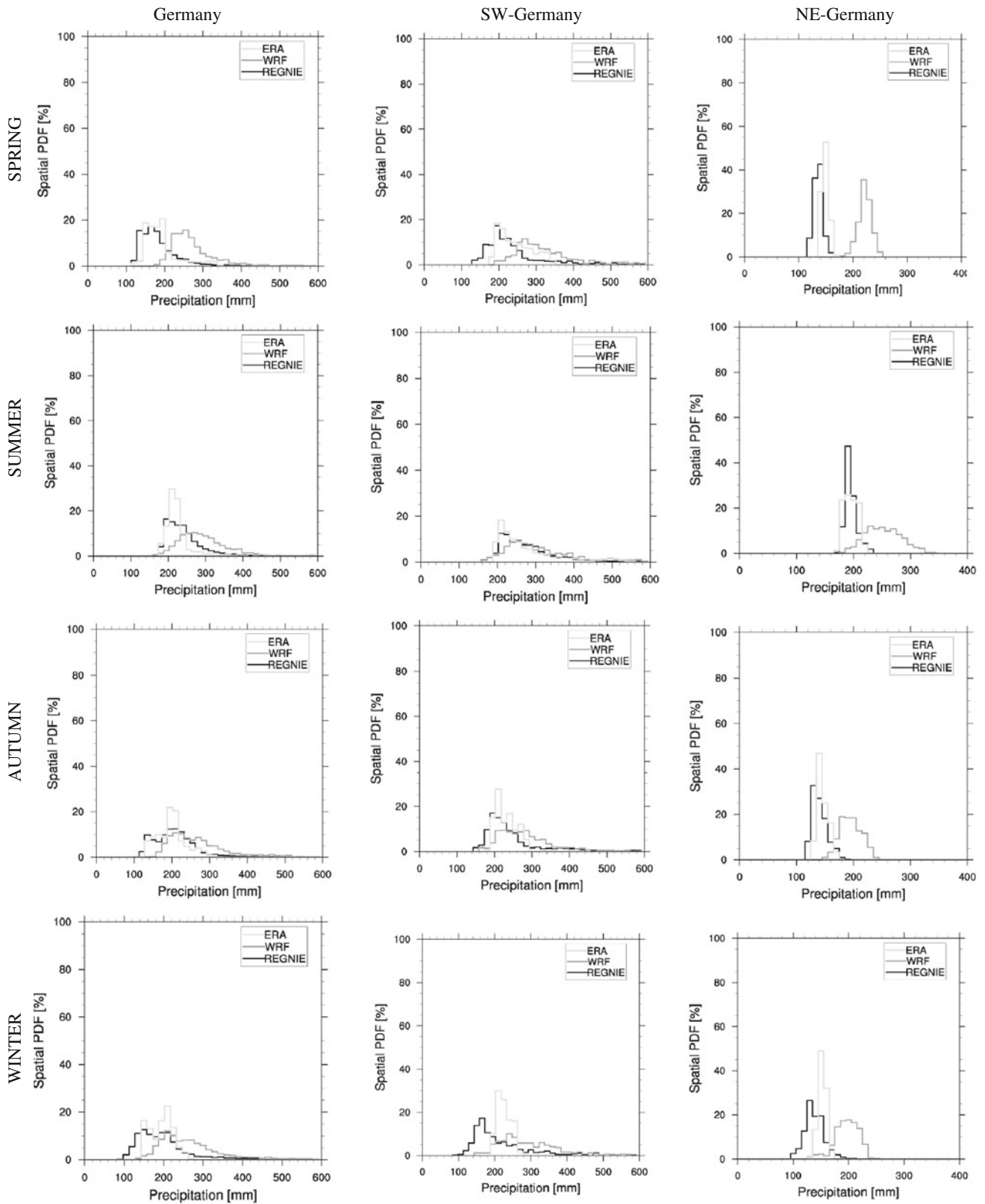
Fig. 4 The spatial probability density functions (pdf) of the mean seasonal precipitation (1990–2008) of REGNIE, WRF (0.11°) and ERA-interim as for the study regions (Germany, SW-Germany and NE-Germany) in spring, summer, autumn and winter

Fig. 5 The spatial distribution of the seasonal precipitation climatology of REGNIE (*blue*), WRF −0.11° (*black*) and ERA-interim (*red*) 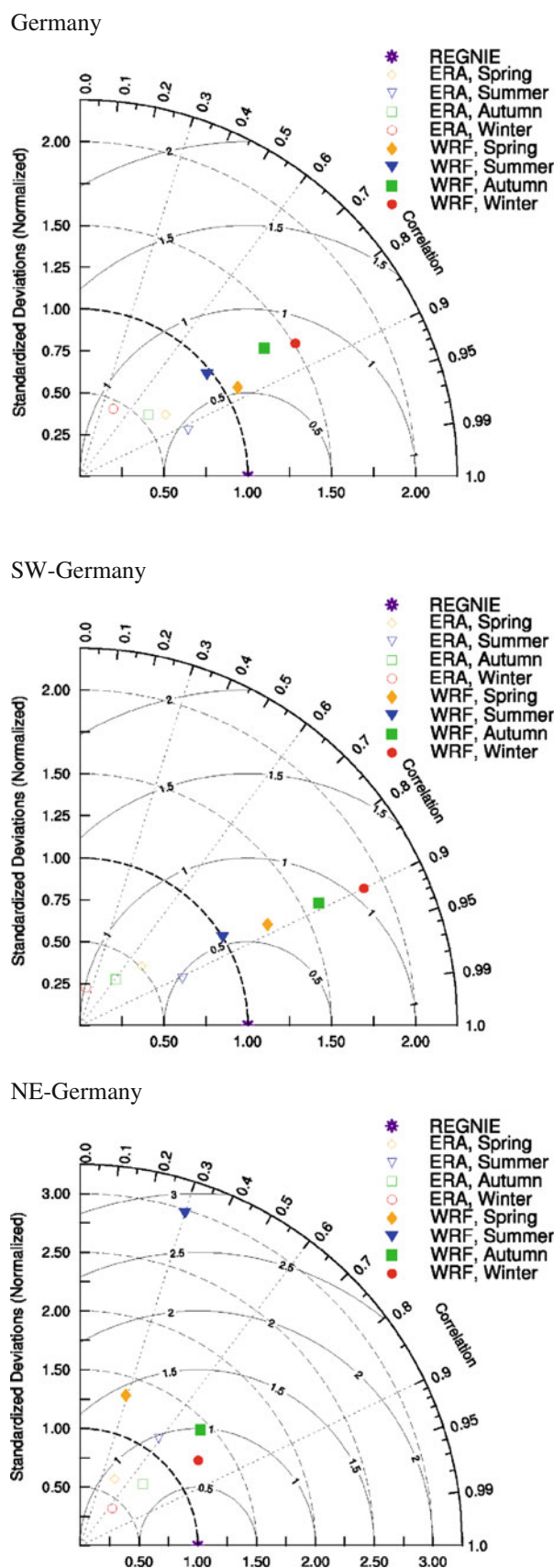as scatter plots with regression lines for the study regions (Germany, SW-Germany and NE-Germany) in spring, summer, autumn and winter. Note that the scaling is different for NE-Germany due to the low seasonal precipitation in this domain

Germany. The precipitation fields are more structured and show a strong relationship to the orography. Besides the Alps, the Black Forest is the highest mountain range in Germany and the Rhine valley has a distinct climate. The climate is more continental in southern Germany. In SW-Germany it is even more evident that, while WRF–NOAH-0.11° simulates more precipitation in all seasons than REGNIE and ERA-interim, it generally resolves the heterogeneous structures in the precipitation distribution whereas ERA-interim smoothes out most structures (Fig. 2).

WRF–NOAH's precipitation is overestimated almost everywhere in SW-Germany in spring and winter by 0.5–2 mm/day (Fig. 10) with the largest bias on the windward sides of the mountains. In autumn the wet bias is a lot lower in most regions and there is no bias in the lee of the northern Black Forest. In summer the precipitation pattern is especially affected by the orography, which cannot be resolved by ERA-interims coarse resolution. ERA-interim precipitation shows biases in the mountainous regions in spring, autumn and winter with biases of ±1.5 mm/day in most regions. In summer ERA-interim has a negative bias of 0.25–1.25 mm/day on the windward sides of the mountains. WRF–NOAH shows a similar shape of the spatial pdf of the mean seasonal precipitation to REGNIE in spring, summer and autumn but a bias towards stronger precipitation (Fig. 4). WRF–NOAH's distribution is always broader than REGNIE's indicating a larger variability. ERA-interim overestimates precipitation in summer and autumn in the 200 mm/season intensity class and underestimates stronger precipitation classes. However, ERA-interim's shape of the pdf agrees well with REGNIE's in the center of the pdf in summer. In spring and winter ERA-interim fails to meet the low intensity classes. In winter WRF–NOAH's distribution is broader and shows the wet bias, though the general observed shape is met. The scatter plots of simulated versus observed mean seasonal grid precipitation in Fig. 5 support the findings. In winter WRF–NOAH agrees well with REGNIE's distribution, in spring the precipitation shows the wet bias throughout the precipitation intensity classes. In autumn the regression line is too steep for WRF–NOAH and too flat for ERA-interim. In summer both simulations show a larger scatter.

Figure 6's normalized spatial Taylor diagram shows the improvements in the simulated seasonal precipitation climatology by downscaling with WRF–NOAH in SW-Germany. Except for summer, WRF–NOAH has a better correlation (0.86–0.9) than ERA interim (0.1–0.65). In

Fig. 6 Normalized spatial Taylor diagram of the seasonal precipitation (1990–2008) in Germany, SW-Germany and NE-Germany for WRF–NOAH (0.11°) and ERA-interim with respect to REGNIE as reference

summer, the correlation of ERA interim is slightly stronger (0.9 vs. 0.87) but has a worse normalized STD and a similar RMSE. For SW-Germany the normalized Taylor diagram reveals namely an improvement in the spatial correlation of seasonal precipitation through downscaling with WRF–NOAH.

For SW-Germany, the mean annual cycle of precipitation (Fig. 8) shows a similarly wet bias over the whole of Germany, with August being slightly drier in WRF–NOAH than in REGNIE. In general, the annual cycle is different in WRF–NOAH showing a relative minimum from February to April and in August and September while REGNIE has minima in January, February and April. However, this bimodal structure in the annual cycle of WRF–NOAH's precipitation is already observed by Feldmann et al. (2008) with REMO and COSMO–CLM for SW-Germany. They suggest the cause to be due to the coarser scale of the forcing model. The bias in SW-Germany's mean precipitation is largest in November and January. The bias reduces in June. From July to September, WRF–NOAH agrees well with REGNIE i.e., in a season when local conditions have a stronger impact on precipitation, namely in the structured terrain and continental climate of SW-Germany. The mean

annual cycle of ERA-interim's precipitation follows REGNIE's annual cycle. It agrees well with REGNIE from December to April and shows a dry bias of about 10 % from May to November.

4.4 NE-Germany

The NE-German study area is characterized by its flat terrain and sandy soils. The northern parts are close to the Baltic Sea coast. Precipitation fields are far more homogeneous than throughout Germany and SW-Germany. The precipitation is met well by ERA-interim with a maximum bias of ± 0.5 mm/day, but WRF–NOAH-0.11° overestimates the precipitation in all seasons by 0.5–2 mm/day in most regions (Fig. 11). This bias is especially strong in the spring season. The scatter plots of simulated versus observed mean seasonal grid precipitation in Fig. 5 show that in NE-Germany the main problem of WRF–NOAH is the wet bias.

Figure 6's normalized spatial Taylor diagram supports the findings, that for NE-Germany the WRF–NOAH downscaling is worsening the simulated precipitation with respect to the ERA-interim. This is especially obvious in
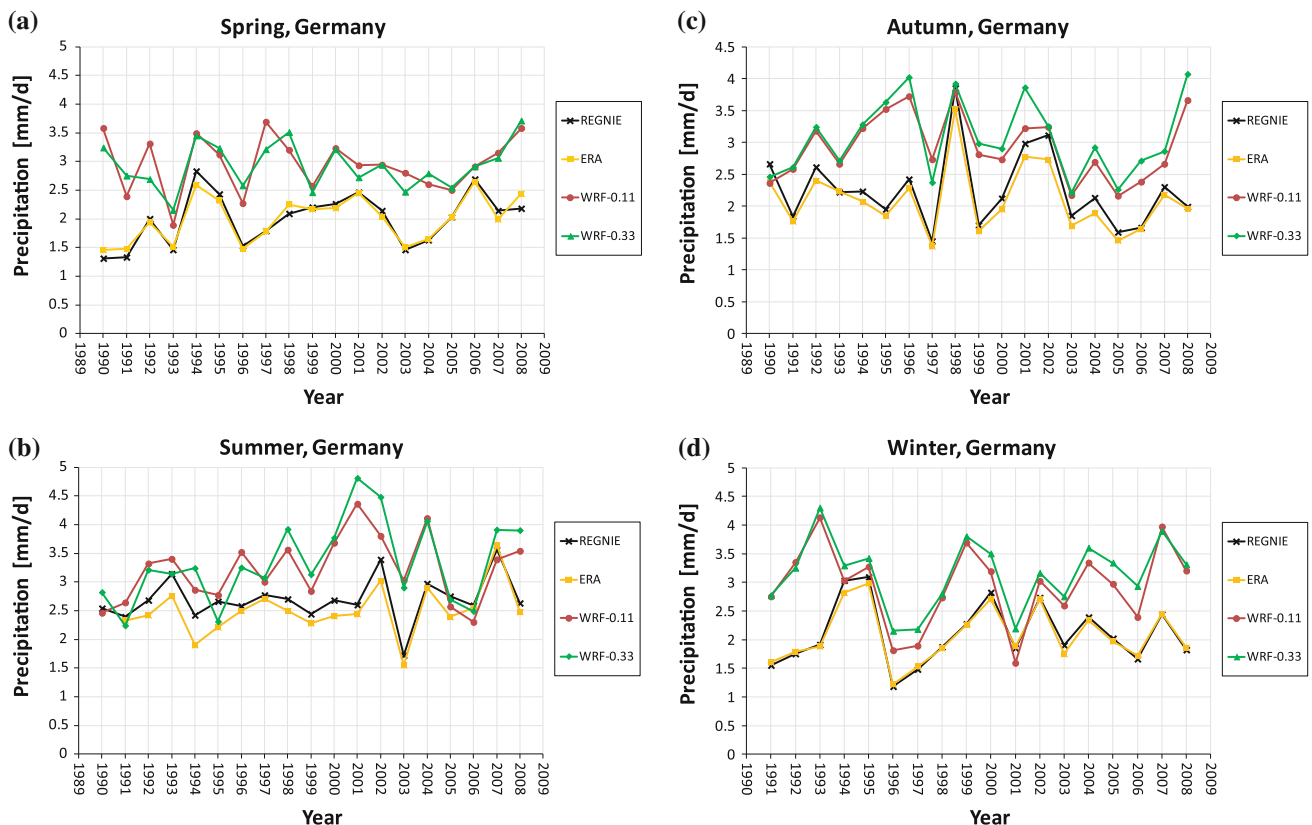
Fig. 7 Seasonal areal mean precipitation for Germany: **a** spring, **b** summer, **c** autumn, **d** winter for ERA-interim, REGNIE, WRF–NOAH at 0.11° and WRF–NOAH at 0.33°

Fig. 9 Annual cycle of daily precipitation statistics (1990–2008) ▶ averaged over Germany for the observation (REGNIE, *solid black*) and the simulations [WRF-0.11° (*solid gray*), WRF-0.33° (*dashed gray*) and ERA-interim (*dotted black*)]: **a** wet-day frequency, **b** precipitation intensity on wet days, **c** 90 % quantile of precipitation amounts

(a)

(a)

(b)
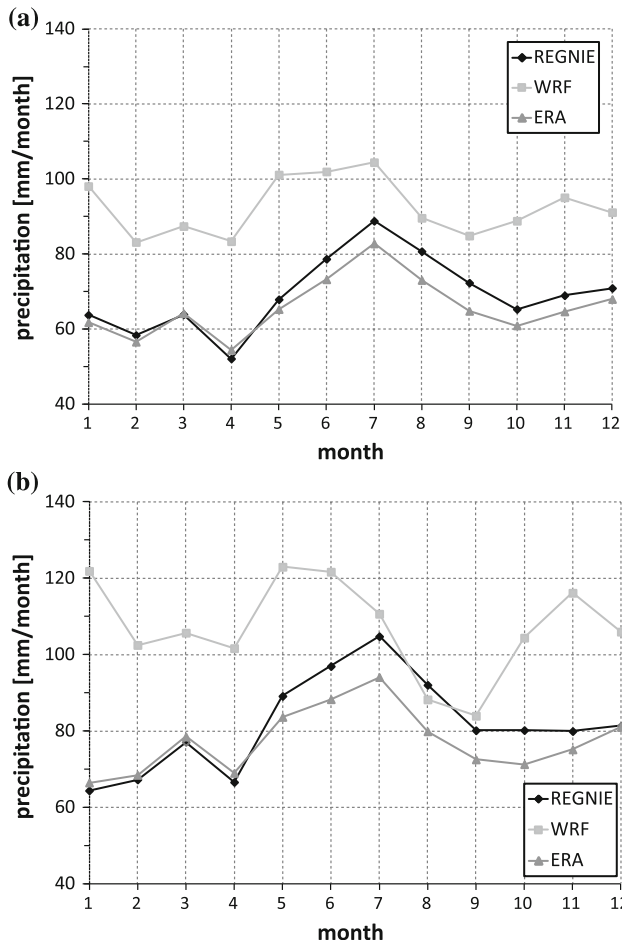
Fig. 8 Annual cycle of areal mean precipitation for WRF–NOAH (0.11°) and REGNIE the study period 1990–2008 for **a** Germany and **b** SW-Germany

(b)

(c)

summer, when ERA-interim shows a normalized correlation of 0.6, RMSE of 1 and STD of 1.2 while WRF–NOAH-0.11° shows a normalized correlation of 0.3, RSME of 2.8 and STD of 3 with respect to the REGNIE data. Only in winter does WRF–NOAH-0.11° slightly improve the precipitation pattern with a normalized correlation of 0.8 versus 0.6 in case of ERA-interim.

5 Discussion

Downscaling ERA-interim's atmospheric data with WRF–NOAH led to a systematic overestimation of mean precipitation in Germany and the wet day frequency.
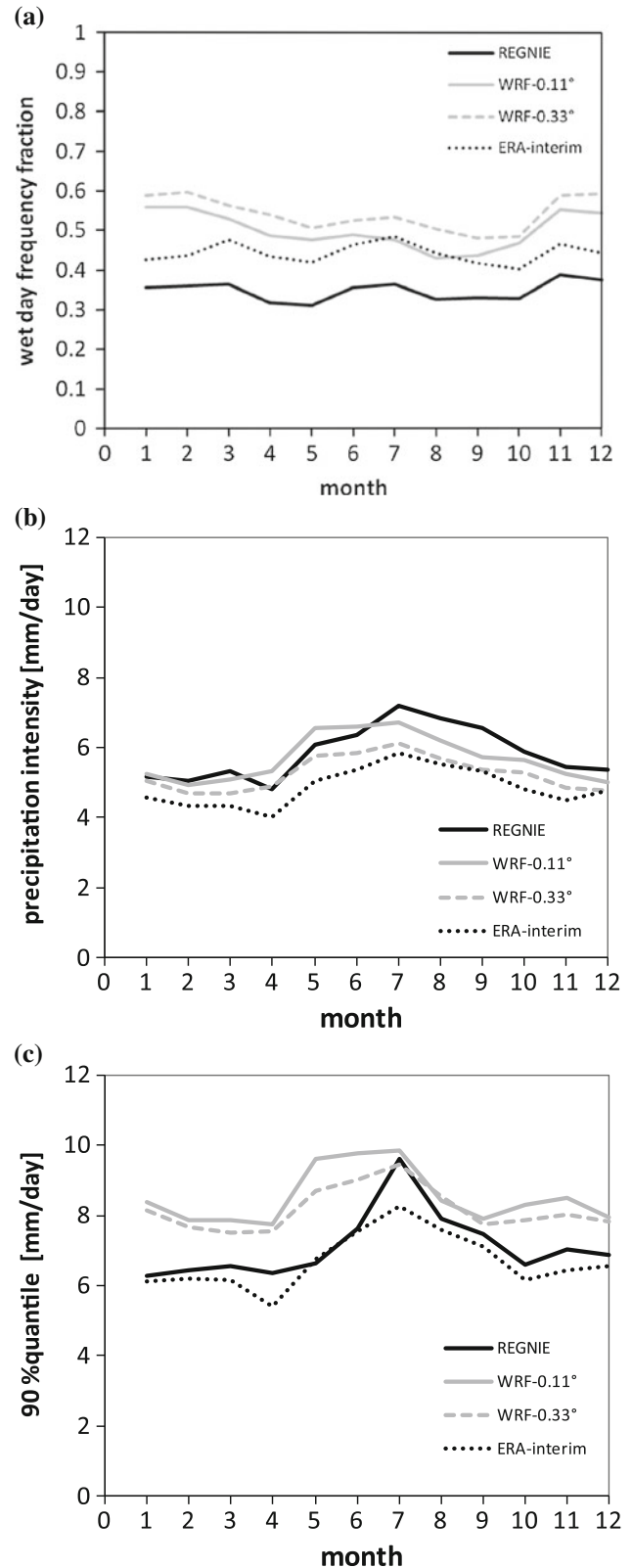
Nevertheless, the study revealed a gain from dynamic downscaling of ERA-interim's atmospheric data for Germany with respect to the representation of spatial

variability and precipitation intensity. The areal mean precipitation over Germany of ERA-interim compares well with the REGNIE data, i.e., ERA-interim has a dry bias in the order of the mean undercatch of 5.6–33.5 % of the German observational data. However, the spatial precipitation distribution is far too homogeneous. WRF–NOAH has a systematic wet bias in most regions. Its mean in all months is 10–30 % wetter than the (dry biased) observations. It is of concern, that some regions and months show a difference of more than 50 % between WRF–NOAH and REGNIE. The difference shows a strong interannual variability suggesting a strong connection to the large scale conditions of the specific season. ERA-interim's areal mean precipitation agrees well with the observational data, which is not surprising, as observations have been assimilated in the analysis, but the precipitation distribution is far too homogeneous.

Both, WRF–NOAH-0.33° and WRF–NOAH-0.11° show the positive precipitation bias but due to their higher resolution they are both able to show more structure than the 0.75° resolving ERA-interim data. However, at 0.33° the model has similar problems to resolve the finer observed precipitation patterns, namely around the low-mountain ranges like ERA-interim. These get better resolved by WRF–NOAH-0.11°. However, at 0.11° the windward–lee-effect in the precipitation simulation appears, namely in the Black Forest region. The two WRF simulations overestimate the annual cycle of mean areal wet day frequency, but at 0.11° this is closer to REGNIE than at 0.33°, namely in summer, when local scale forcing plays a larger role than in the other seasons. The downscaling experiment improved the annual cycle of the precipitation intensity, which is underestimated by ERA-interim. Here also 0.11° outperforms the 0.33° simulation.

The question arises what is the origin of the strong precipitation bias in the WRF simulations. This requires an analysis of the chain of parameterizations used in this simulation. Candidates of errors are the radiation scheme, soil texture, evapotranspiration, which is also influenced by the representation of vegetation, the turbulence parameterization, cloud microphysics, and the convection parameterization. In the following, we make the attempt to identify error sources based on the verification of our simulations and on previous regional climate simulations.

Former climate model simulations in Europe e.g., downcaling the ERA-40 re-analysis data in ENSEMBLES already revealed a wide spread in model results. Rauscher et al. (2010) compared the seasonal and annual precipitation simulated by 9 regional climate models from 1961 to 2000 at 25 km resolution with CRU observational precipitation data. For the ENSEMBLES region ME (most of Germany, Belgium, the Netherlands, Luxemburg and parts of northeastern France) they found an annual wet bias of

5–35 % depending on the model—one model has no bias, and one model a dry bias of 11 %. In winter the models have a wet bias of 22–61 %, with only 1 model showing a dry bias in winter of 18 %. In summer the bias ranged between −20 and +14 %. All in all, the bias of the WRF–NOAH-simulation of our study is of the same order of magnitude as of some models of the ENSEMBLES project.

Meissner et al. (2009) analyzed the precipitation in SW-Germany from simulations with the COSMO–CLM model at 7 and 14 km forced with ERA-40 and NCEP reanalysis data from 1991 to 2000. They found a wet bias between 15 and 60 % in most of the domain even at the 7 km simulation, depending on the area, the dynamic scheme and the convection parameterization chosen.

In NE-Germany, WRF–NOAH significantly overestimates precipitation. In this region, orography plays no significant role, but here there are large inconsistencies in soil data, in contrast to the rest of Germany. The FAO soil texture map contains loam over a large area, whereas the maps of the German authorities (Landesämter für Rohstoffe, Geologie und Bergbau) show that sandy soils dominate the area. The soil texture impacts the infiltration capacity and gravitational drainage, soil water availability and evapotranspiration. Sandy soils have a significantly lower field capacity and larger gravitational drainage than loamy soils, i.e., infiltrated water drains through the soil more quickly leading to less water availability for transpiration, a moisture supply source for the atmosphere. Exchanging the soil texture from loamy soils to sandy soils in offline simulations with the land surface model TERRA-ML (i.e., forced with observational meteorological data) by Warrach-Sagi et al. (2008) showed a significant difference in soil water content and runoff generation. Davin et al. (2011) implemented the Community Land Model (CLM) into COSMO–CLM (now called COSMO–CLM^2) and compared the results to COSMO–CLM with its standard land surface model TERRA-ML. However, exchanging the land surface model led to the application of a different soil texture data set. Davin et al. (2011) ran the simulations from 1986 to 2006 at 0.44° resolution for Europe. Compared with the CRU 3.0 data from 1986 to 1995 COSMO–CLM^2 reduces the wet bias of COSMO–CLM in most areas including NE-Germany. Note that for the COSMO–CLM and our WRF–NOAH simulation the soil texture map of the FAO is used. Acs et al. (2010) revealed an impact of different soil texture maps on the precipitation simulated with the limited area model MM5 in Hungary. The studies of Acs et al. (2010), Davin et al. (2011) and Warrach-Sagi et al. (2008) indicate that soil texture should receive more attention in climate modeling at high spatial resolution due to its large heterogeneity and importance on land-surface atmosphere feedback processes.
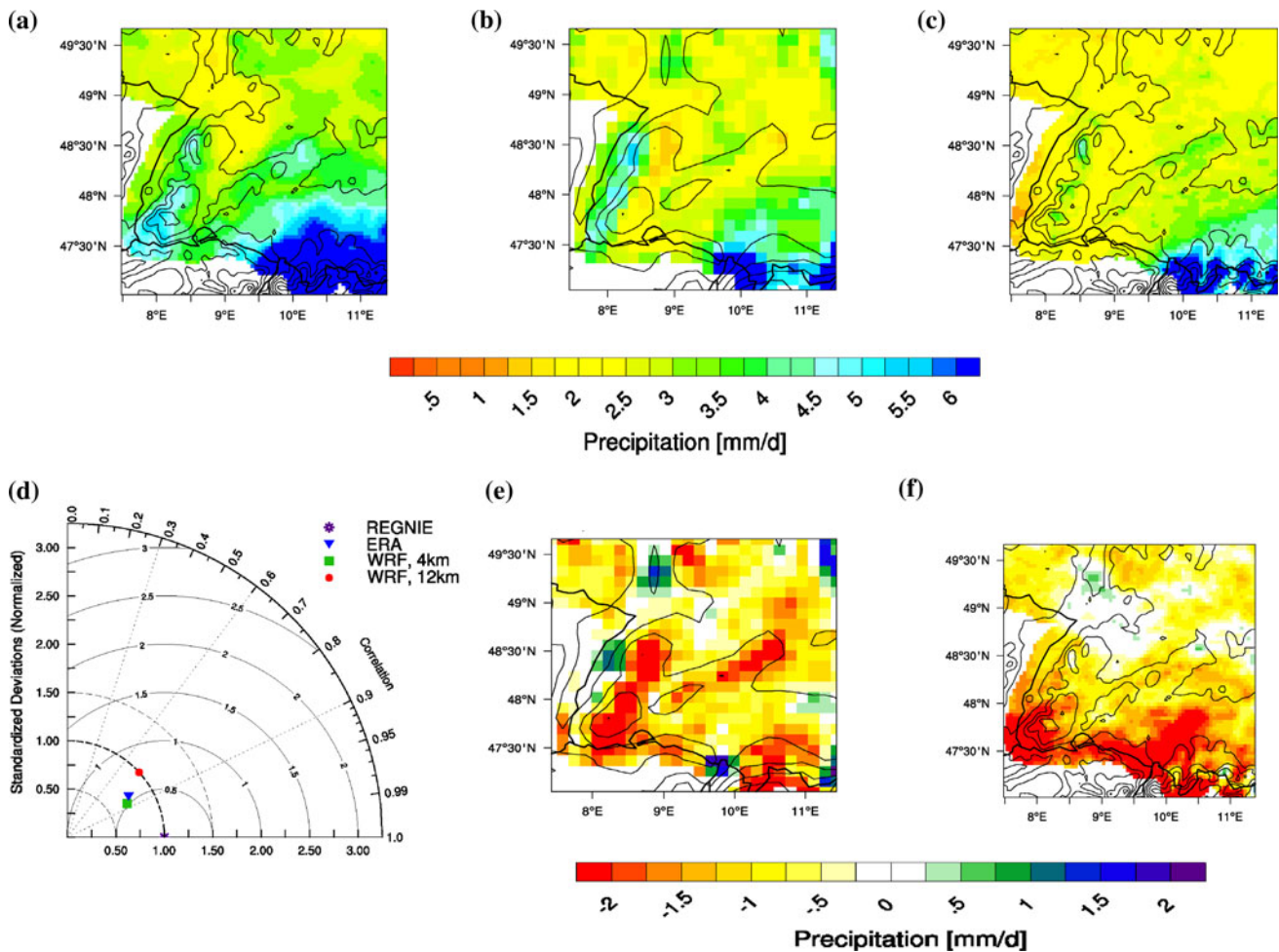
Fig. 10 As Fig. 3, but for SW-Germany

WRF -REGNIE

ERA-interim -REGNIE

SPRING

SUMMER

AUTUMN

WINTER
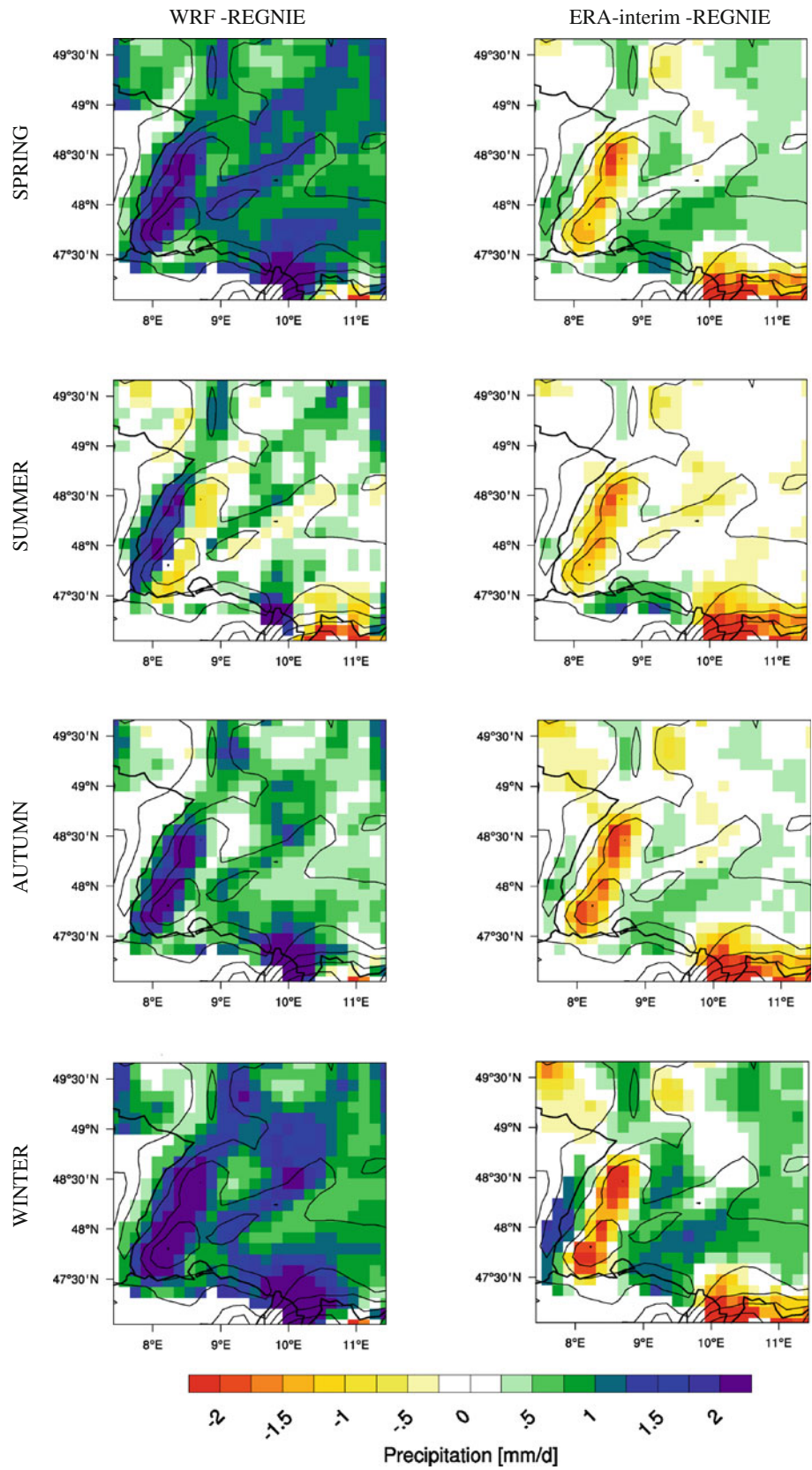
Precipitation [mm/d]

Fig. 11 As Fig. 3, but for NE-Germany
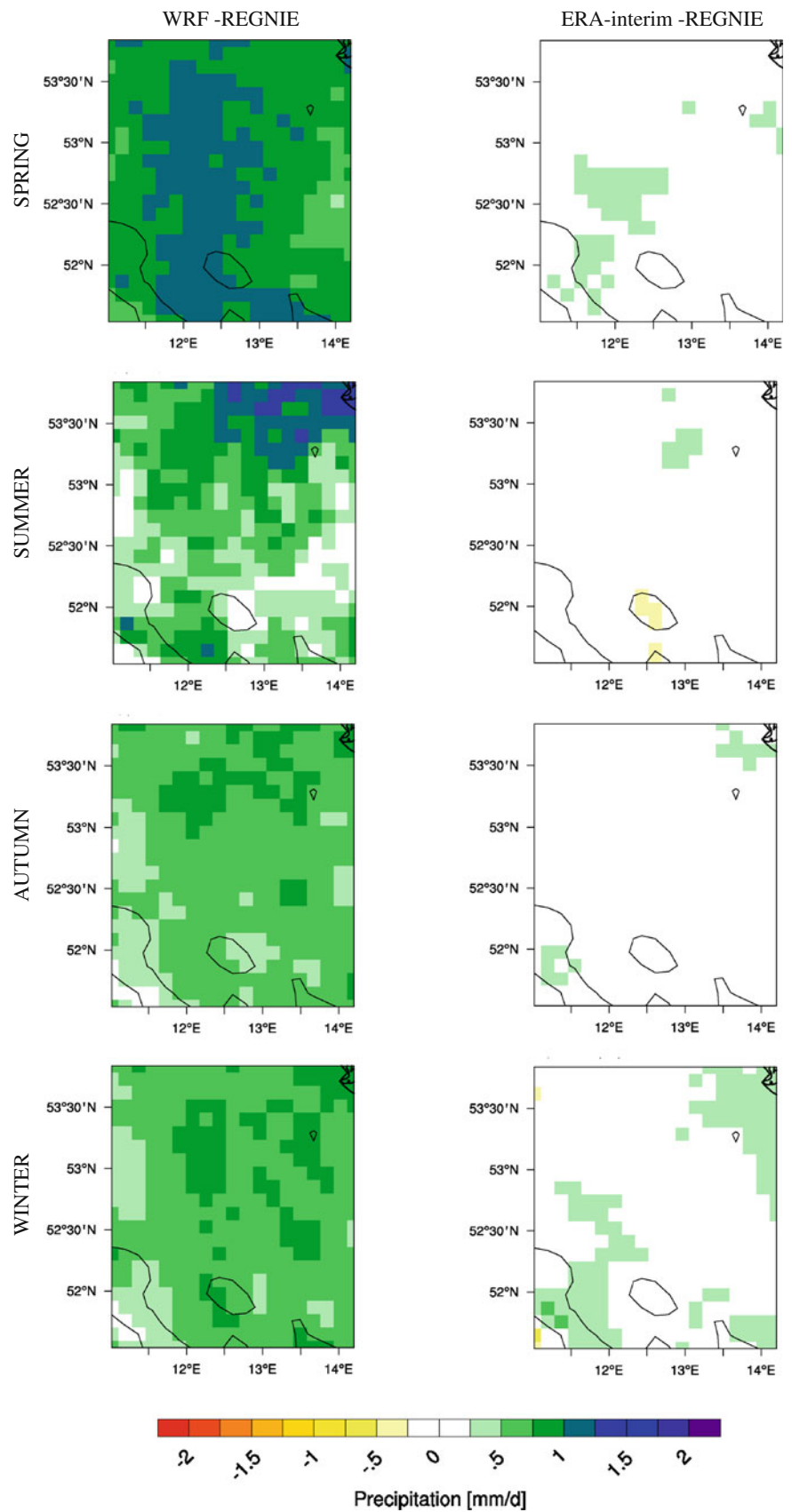
Fig. 12 Precipitation in summer (June–August) 2007 in SW-Germany: **a** REGNIE-0.0367°, **b** WRF–NOAH-0.11°, **c** WRF–NOAH-0.0367° and **d** normalized spatial Taylor diagram, **e** difference WRF–NOAH–REGNIE (0.11°), **f** WRF–NOAH–REGNIE (0.0367°). *Black thin contour lines* show the orography

Heikkilä et al. (2011) applied WRF 3.1.1 over northern Europe and the North Atlantic forced with ERA-40 reanalysis data from 1961 to 1990 at 10 km resolution to study the precipitation, temperature and wind fields in Norway. They found a mean bias of 33 % in comparison with precipitation observed at stations. Heikkilä et al. (2011) identify the still too coarse resolution in the steep orographic terrain of Norway as a source of the bias. The other problematic region they found is a specifically dry area in northern Norway. Both features compare well with our findings for Germany. The dry area of NE-Germany shows a strong wet bias and the mountainous regions show the windward–lee effect.

Bauer et al. (2011) evaluated a multi-model ensemble simulation of the WWRP Forecast Demonstration Project "Demonstration of the Probabilistic Hydrological and Atmospheric Simulation of Flood Events in the Alpine region" (Rotach et al. 2009). They clearly demonstrated superior performance of convection-permitting models

with respect to quantitative precipitation forecast. In order to investigate the dependence of the precipitation on the resolution of the orography and problems of the convection parameterization, we set up a case study for SW-Germany: a third domain with 0.0367° (∼4 km) resolution is nested into the 0.11° domain (white frame in Fig. 1) and a convection permitting simulation was performed for summer 2007, when the well studied Convective and Orographically-induced Precipitation Study (COPS) (Wulfmeyer et al. 2011) took place. Summer 2007 had a dry bias in both simulations, 0.0367° and 0.11° (Fig. 12e, f). The convection permitting case study shows a stronger dry bias in the Rhine valley and towards the Alps than the 0.11° simulation. A strong windward-lee effect could be seen in SW-Germany in the 0.11° simulation at the Black Forest and Swabian Jura (Fig. 12a, b). The precipitation simulation at convection permitting resolution (0.0367°) improved the location of precipitation maxima on the mountains, i.e., the simulation does not show the windward–lee effect (Fig. 12c).

The differences between WRF–NOAH and REGNIE (Fig. 12e, f) show an improvement of precipitation by the convection permitting simulation, namely in the northern Black Forest, Swabian Jura and Rhine Valley, but in the northern part of the region the spatial variability is worse in the convection permitting simulation than in the 0.11° run. WRF–NOAH-0.0367° has a better correlation and smaller RMSE (Fig. 12d). The correlation of the 12 km simulation is 0.75 and 0.88 in the 4 km simulation. RMSE is 0.5 in the 4 km simulation and 0.75 in the 12 km simulation. This is in agreement e.g., with Bauer et al. (2011), who systematically evaluated the models participating in D-PHASE with observations collected during COPS.

But also in WRF convection permitting resolution simulations, as demonstrated in Schwitalla et al. (2011), a strong precipitation bias can remain. The most important error source is the cloud microphysics, which has not been tuned to the conditions in Europe. If the resolution is reduced, the cloud microphysics couples with the convection parameterization increasing the sensitivity to model errors. In future model runs, ensembles will be produced in order to reveal the errors due to different combinations of parameterizations.

6 Conclusions

Forced with the currently best available re-analysis data (ERA-interim) and compared to a high resolution gridded precipitation data set (REGNIE) the evaluation results can be attributed to the model physics, parameterizations, resolution and static input data (soil, vegetation). Downscaling ERA-interim's atmospheric data with WRF–NOAH version 3.1.0 introduced a systematic overestimation of mean precipitation in Germany and the wet day frequency. The areal mean 90th % quantile of precipitation amount is overestimated in the downscaling experiment except for July. Nevertheless, the study shows also a benefit from dynamical downscaling with WRF–NOAH. The downscaling experiment improved the annual cycle of the precipitation intensity, which is underestimated by ERA-interim. Downscaling with WRF provides a more structured spatial distribution with better spatial correlation than the ERA interim precipitation analyses in southwestern Germany and most of the whole of Germany. Only in NE-Germany the dynamical downscaling introduces too much spatial variability.

It is essential to identify the reasons for the precipitation bias for simulations for future climate scenarios, namely since the validity of currently applied bias correction methods are questionable under changing climate conditions (Maraun 2011). The simulation shows some features that need more in depth investigation, e.g., in most of all cases the grid scale precipitation is very high, so an investigation of the microphysics scheme, wind field and the atmospheric boundary layer parameterization is suggested for this model set up.

The pattern of the strong precipitation bias in NE-Germany led to a closer look at the soil texture maps applied in WRF–NOAH. Warrach-Sagi et al. (2008) already identified the coarse FAO soil maps to be a problem in simulating the water fluxes at the land surface in the Enz river catchment in SW-Germany. Namely NE-Germany is dominated by large croplands. In summer in croplands the latent and sensible heat fluxes highly depend the ripening state of the crops, which means that this should be properly accounted for in the vegetation parameters (e.g., leaf area index, minimum stomata resistance) of the land surface scheme (Ingwersen et al. 2011). Currently weather and crop dependent dynamic formulations of these parameters are not implemented in WRF–NOAH.

The results show that the 0.11° resolution is introducing the windward-lee effect in the low mountain ranges in Germany. This is unfortunate for application where spatially accurate precipitation is requested, e.g., hydrological applications. The convection permitting case study set up with WRF–NOAH at a large domain in summer 2007 improved the precipitation simulations with respect to the location of precipitation maxima in the mountainous regions and the spatial correlation of precipitation. Though, a climate simulation for such a large model domain at this resolution is extremely expensive in computing time and storage space, this avoids the strong spatial and case dependent sensitivity and high systematic errors due to the parameterization of deep convection. Thus, in the future, we suggest the extensive performance of convection permitting resolution downscaling experiments to overcome the systematic error barrier set up by the convection parameterization and to realize a more accurate simulation of land-surface–atmosphere feedback.

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