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Mettools IX

Added value of high-resolution regional climate simulations for regional impact studies

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Abstract

We present a comparison of results from the regional climate model COSMO-CLM at a horizontal resolution of 2.8 km with observations and assess the added value of such higher resolution compared to a coarser resolution of 7 km. Such an added value is expected to result from a better resolution of orography and land use as well as from direct simulation of deep convection.

The simulations are driven by ERA40 reanalyses for the years 1971 to 2000 and cover southwestern Germany and parts of eastern France. We show that 2.8 km horizontal resolution simulations yield in many, but not all, cases a better agreement of temperature, precipitation, humidity, and global radiation with observation data than simulations with 7 km resolution, especially during the summer half year. At 2.8 km resolution, the model also is well able to capture the mechanisms generating small-scale features, e.g. wind systems. However, the added value is highly dependent on region and altitude. In general, we conclude that high-resolution climate modeling allows studying the impact of climatological parameters on regional scales. It produces encouraging results and has a high potential for applications and direct use in regional and local impact models and impact studies.

Keywords: regional climate modeling, COSMO-CLM, added value of high resolution, input data for regional impact studies

1 Introduction

For many purposes, climate data either as time series or as statistics are required to assess a present state or for future planning. Often, such applications use impact models which require input data on climatological timescales at spatial and temporal resolutions that are not readily available from current standard climate simulations. Most of these models do not only require one climate variable, but sets of them; hence, physical consistency of the data is crucial. For instance, hydrological models need near-surface temperature, humidity, long-wave and short-wave radiation, wind speed, precipitation, and air pressure as time series of data fields of catchment size with a horizontal resolution of several meters. For urban planning and energy-efficient design of buildings, at least temperature, radiation, and wind speed for the site considered are required on the meter scale. Regional climate models can provide consistent data sets, but at resolutions between 10 and 50 km (Feldmann et al., 2013; Christensen et al., 2007). However, they often suffer from biases (Kotlarski et al., 2014, Christensen et al., 2008). COSMO-CLM, the model used here, is known to have a cold and wet bias, i.e. a systematic difference between model results and observations over Central Europe (Keuler et al., 2012). In order to mitigate this problem, bias correction methods have been designed and applied (e.g. Gutjahr and Heinemann, 2013; Berg et al., 2012). Apart from being somewhat subjective, this approach also is unsatisfactory, because it creates inconsistency among variables and because high-quality observational data of all the variables mentioned above, which are necessary for a consistent correction, are not available. A resort is to only correct for the available data (mostly temperature and precipitation), which means sacrificing consistency with other variables.

For several reasons, simulation results are expected to be improved at resolutions in the order of one to five km. First, such resolution reduces the scale gap between climate models and impact models. The latter usually run on scales of tens to hundreds of meters. Second, a considerable reduction, if not an elimination of the model bias, is obtained. This can be expected due to a better representation of orography and land cover as well as an explicit calculation of deep convective precipitation instead of a parameterization. It is widely agreed that a horizontal grid spacing smaller than 4 km allows switching off convection parameterization (Weisman et al., 1997). Deep convection is the main process leading to heavy precipitation events. Convection-permitting models thereby reduce a major model error caused by parameterizations (e.g. Déqué et al., 2007).

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Fosser et al. (2015) found that this improves both the hourly intensity distribution and the diurnal cycle of precipitation intensity, which are insufficiently represented in simulations with convection parameterizations (Ban et al., 2014; Brockhaus et al., 2008). Third, a high spatial resolution induces a more realistic small-scale temporal and spatial variability of meteorological variables as a result of a better representation of the orography and land use patterns. This is especially the case in complex (Knote et al., 2010; Zängl 2007a, b) and in urban terrain (Trusilova et al., 2013). Small-scale variability is also important to capture weather extremes more realistically as well as for a better representation of persistent and, hence, climatically relevant small-scale features like local/regional wind, precipitation systems, and temperature regimes. These small-scale circulation systems can occur on scales of a few kilometers under suitable synoptic conditions (Schädler, 1990). Due to their regularity, they may affect local and regional climates.

Whereas the resolutions of the impact models mentioned above are still far beyond present capabilities of regional climate models, resolutions of the order of a few kilometers become feasible and can help reduce the existing scale gap between climate and impact models. Operational weather forecast models already operate at such high resolutions. The main obstacle for similar simulations on climatic time scales is the high computational costs and storage expenditure due to the high spatial resolution.

A number of studies have been conducted to investigate the improvement of meteorological simulations by an increased model resolution. The improvements in precipitation are found for extreme events and small-scale temporal and spatial variability of rainfall. A review of the characteristics of convection-permitting climate models can be found in Prein et al. (2015). There are several studies with COSMO-CLM based on simulations covering a wide span of time periods from single events to decades (e.g. Fosser et al., 2015; Panitz et al., 2015; Ban et al., 2014; Junk et al., 2014; Tölle et al., 2014; Prein et al., 2013; Knote et al., 2010).

Prein et al. (2013) study the added value of convection-permitting seasonal simulations in an Alpine region for a single winter and summer season using an ensemble of regional climate simulations at about 3 km resolution. Comparing these to simulations with 10 km resolution, they find added value in terms of better representation of the diurnal cycle of precipitation, extreme precipitation intensity during the summer season, and on short spatial and temporal scales, which they attribute to the direct simulation of deep convection. They also find improvements in global radiation due to better partitioning of cloudy and cloud-free areas. Ban et al. (2014) describe an improvement of representation of hourly events during summer as well as of the spatial distribution of precipitation for a single event. Fosser et al. (2015) also find an improvement of the diurnal cycle of precipitation. Knote et al. (2010) study temperature and precipitation extremes derived from high-resolution simulations and find added value by a better representation of variability. An application of high-resolution simulation data to heavy precipitation statistics in a river catchment can be found in Panitz et al. (2015). Simulations at 1.3 km horizontal resolution for two ten-year periods were made by Junk et al. (2014) in order to investigate thermal stress indices. Tölle et al. (2014) performed sensitivity studies on land use changes for five-year periods at 1 km model resolution.

This paper focuses on the added value of high-resolution modeling on a climate scale. For this purpose, we compare the results of climate simulations with the regional climate model COSMO-CLM at 2.8 km and at 7 km horizontal resolution for the period 1971–2000, on the one hand, and long-term observations, on the other hand. In contrast to most of the studies mentioned above, our simulations cover a period of 30 years and a relatively large region with different orographic characteristics. This allows for climatological analyses and comparisons with observations over the standard period of 30 years, and we can assess the interannual and interdecadal variability at high spatial resolution. In contrast to studies based on shorter simulation periods, our approach also permits a better estimation of the model error, since the statistical basis is considerably larger. The aim of our study is to examine how well COSMO-CLM at very high spatial resolution is able to reproduce climate characteristics on regional and local scales (e.g. on the scale of metropolitan areas, small river catchments) and whether sufficient added value is generated by the 2.8 km simulations compared to the 7 km simulations to justify the larger computational costs. We would expect added value in terms of a better representation of local processes, e.g convection and orographically/thermally induced wind systems and a more realistic spatial and temporal variability As a result, bias correction and the problems associated with it, namely availability of reliable reference data and lacking consistency between variables, would be avoided. We also anticipate that the improvement of near-surface temperatures will be larger than just by height correction due to a better representation of stability and small-scale horizontal and vertical gradients. We analyze how the added value varies for different variables. Since the focus is on validation, our simulations were driven by ERA 40 reanalyses (Uppala et al., 2005). As variables, near-surface temperature, precipitation, relative humidity, global radiation and wind speed/direction (important for small-scale circulation systems) are considered

We compare climate simulations at resolutions of 2.8 and 7 km with observations for the whole investigation area, i.e. southwestern Germany. The evaluated variables generally play an important role in applications like hydrology and urban climate. Local wind systems are useful for applications, such as the ventilation of built-up areas. At the end of the study, we will zoom in on a subregion of the investigation area (Stuttgart metropolitan area) to analyze differences in the local wind field in more detail.

Table 1: Model setup of CCLM2.8 and CCLM7.

	CCLM2.8	CCLM7
Model version	COSMO-CLM 4.8_clm7	COSMO-CLM 4.8_clm7
Horizontal resolution	0.025 °	0.0625 °
Temporal resolution of the output data	1 hour	1 hour
Simulation period	1968–2000, thereof 3 years spin-up	1968–2000, thereof 3 years spin-up
Number of horizontal grid points	140 × 150	165 × 200
Number of vertical layers	40	40
Time step	25 sec.	60 sec.
Time integration scheme	Runge-Kutta time integration scheme	Runge-Kutta time integration scheme
Driving data	ERA 40 reanalysis data (Uppala et al., 2005)	ERA 40 reanalysis data (Uppala et al., 2005)
Convection scheme	Parameterization of shallow convection, explicit calculation of deep convection	Parameterization of deep and shallow convection
Call of radiation scheme	every 15 min.	every 60 min.

The paper is structured as follows: Section 2 describes methods and data, Section 3 studies the added value of higher resolution. The results are discussed in Section 4, conclusions and an outlook are given in Section 5.

2 Methods and data

Model and setup

For our simulations, we used the regional climate model of the Consortium for Small-scale Modeling in Climate Mode, COSMO-CLM (hereinafter referred to as CCLM). It is based on the operational weather forecast model COSMO of the German Weather Service (hereinafter: DWD, Steppeler et al., 2003). COSMO is a non-hydrostatic model, which allows for a theoretically arbitrarily high resolution (Adrian and Frühwald, 2002). At higher resolutions, it allows for the explicit calculation of deep moist convection, which, in combination with a better resolution of orography, enables a better representation of orographically induced convection (Doms et al., 2011). It is formulated on a rotated grid with the equator and the prime meridian near the center of the modeling domain. In the vertical direction, a generalized terrain-following height coordinate is used. The model is based on the primitive thermo-hydrodynamic equations describing compressible flow in a moist atmosphere. Subgrid scale processes are described by various parameterization schemes (Doms et al., 2011). A more detailed description of CCLM can be found in Rockel et al. (2008). Recent studies by e.g. Fosser et al. (2015), Berg et al. (2013), Feldmann et al. (2013), and Meissner et al. (2009) present good examples of using CCLM for various scientific studies.

To proceed from the 1.25 ° resolution of the ERA40 reanalysis driving data (Uppala et al., 2005) to our final resolution of 0.025 ° (about 2.8 km), we use a cascade of three nests with resolutions of 0.44 °, 0.0625 °, and 0.025 °. The vertical grid consists of 40 non-equidistant layers with smaller spacing between the layers that are located closer to the surface to capture small-scale vertical processes induced by the earth's surface. After initializing the atmospheric and soil fields, only the atmospheric boundary conditions are updated every six hours. Standard settings for COSMO-CLM are used. For details on the model setup, see Table 1.

The regional simulations are driven by ERA40 reanalysis data (Uppala et al., 2005) produced by the European Centre for Medium-range Weather Forecast (ECMWF). ERA40 reanalysis provides assimilated initial and boundary conditions to reproduce the daily weather and climate conditions for the decades from 1957 to 2002. In this study, the two CCLM simulations at spatial resolutions of about 7 km (0.0625 °, hereinafter abbreviated by CCLM7) and 2.8 km (0.025 °, hereinafter CCLM2.8) are compared with observations.

Validation Data

For validation, the CCLM results are compared with gridded observation data and observations at selected meteorological stations of the German Weather Service (DWD).

The gridded data used are the HYRAS dataset with 5 km horizontal resolution for precipitation and relative humidity and 1 km horizontal resolution for temperature; an assessment of the HYRAS data quality can be found in Rauthe et al. (2013). The mean absolute error in precipitation is found to be less than 2 mm/day with high spatial and temporal variability. In addition, gridded data of global radiation and wind speed at 1 km horizontal resolution (Maier and Müller-Westermeier, 2010; Müller-Westermeier, 1995; Müller-Westermeier et al., 2005) are used, which are available from DWD (ftp://ftp-cdc.dwd.de/pub/CDC/). For comparison, all data sets are remapped with bilinear interpolation to the CCLM grid of the 2.8 km simulation run (CCLM2.8). In order to make sure that improvements in the representation of the temperature field are not only an effect of a better resolution of local orography, the CCLM7 temperature output is height-corrected in addition to the interpolation, assuming a vertical temperature gradient of 0.65 K/100 m. The correction is based

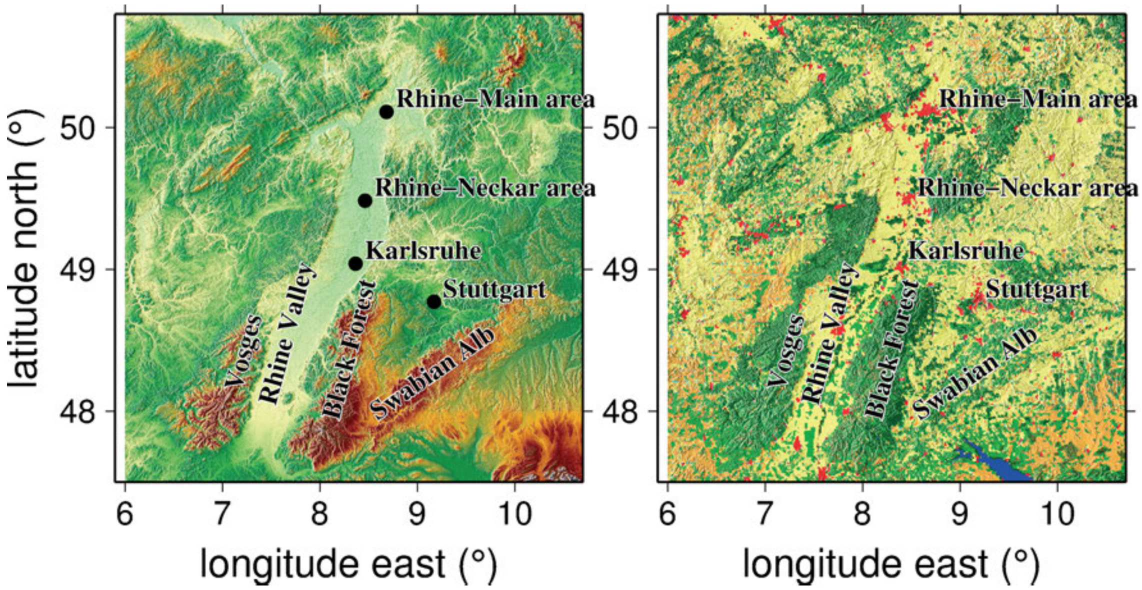

Figure 1: The investigation area in southwestern Germany. Left: Orography; right: Land use.

on the surface elevation difference between the CCLM7 orography interpolated to 2.8 km horizontal resolution and the CCLM2.8 orography. In this way, the potential added value by dynamical downscaling compared to simple spatial interpolation and linear height correction can be assessed. Only temperature is corrected in this way. Even though there also is an influence of orography on humidity and precipitation, no similar height correction exists for these quantities. For this reason, the original output of the humidity and precipitation fields as calculated in CCLM7 (bilinearly interpolated on the 2.8 km grid) and CCLM2.8 is used for comparison.

For a selected site, the model results are also compared with station data from DWD (ftp://ftp-cdc.dwd.de/pub/CDC/). The station is Stuttgart Schnarrenberg (9.2000 ° E, 48.8282 ° N, 314 m a.s.l, measurements 1971 to 2000 on a daily basis and 1977 to 2000 on an hourly basis).

Investigation Area

The investigation area is located between 47.5 ° N to 50.5 ° N and 6 ° E to 11 ° E and covers southwestern Germany with the state of Baden-Württemberg, parts of Rhineland-Palatinate and Bavaria as well as parts of eastern France (Fig. 1). It is an orographically complex terrain, including parts of the upper and middle Rhine valley (about 100 m a.s.l.), mid-range mountains, such as the Black Forest (Feldberg summit 1,493 m a.s.l.), the Swabian Alb (around 500 m a.s.l.), Hunsrück, Eifel, and the Vosges (Grand Ballon summit 1,424 m a.s.l.), the catchment of the Neckar river, and parts of the Rhine, Danube, and Moselle catchments and their tributaries. It also includes densely populated regions like the Rhine-Main area with Frankfurt, Mainz, and Wiesbaden, the Rhine-Neckar area with the cities of Ludwigshafen, Mannheim, and Heidelberg, and the Stuttgart metropolitan area in the Stuttgart basin with population densities above 500 inhabitants per km^2. Land cover is mainly forests, agriculture, and settlements. The study region includes some of the warmest, driest, and most humid regions in Germany. Annual average temperatures vary between more than 11 °C (Rhine valley) and less than 4 °C (Black Forest), annual precipitation sums are between less than 600 mm (Rhine valley) and more than 1,600 mm (Black Forest, Vosges). The number of hot days (maximum temperature not less than 30 °C) exceeds 30 in the Rhine-Neckar and Stuttgart areas (State Office for the Environment, Measurements and Nature Conservation of the Federal State of Baden-Württemberg, 2006). Climatic change in terms of temperature and precipitation extremes is evident in the region and is described in more detail e.g. in the KLIWA reports available under www.kliwa.de and in Feldmann et al. (2013).

Assessment of added value

A prerequisite for using climate model data for impact studies is to know how well the fields of different meteorological variables are represented by the climate model. Our hypothesis is that higher resolution improves this representation, i.e. generates added value. Below, we will compare the error of the 2.8 km simulations $\Delta 2.8$ (i.e. the grid point value at 2.8 km resolution minus the grid point value of HYRAS) with the error of the 7 km simulations $\Delta 7$ (i.e. the bilinear interpolated grid point value at 7 km resolution on the 2.8 km grid minus the grid point value of HYRAS) averaged over 30 summer (May to October) and winter (November to April) half years.

In order to assess the added value, three different approaches are applied. First, the significance of the difference between the absolute errors $|\Delta 2.8|$ and $|\Delta 7|$ is determined by means of the Wilcoxon rank sum test (confidence level = 0.95). To include altitude dependence of the variables, the test is performed for three different altitude ranges. The results are shown as box-whisker plots. Second, difference maps for Δ2.8 and Δ7 are shown. Third, the MSESS (Mean Squared Error Skill Score) is calculated for easy identification of the spatial improvement between both resolutions. The MSESS is defined as 1−MSE(2.8 km)/MSE(7 km) with the mean squared error MSE. MSESS is positive, if MSE(2.8 km) < MSE(7 km) and vice versa. Note the non-linear scale of the MSESS, which is defined for values between −∞ and +1. Depending on the variable, suitable approaches are applied.

3 Results for southwestern Germany

In this section, model results are compared with observations for temperature, precipitation, relative humidity, global radiation, and wind for the whole investigation area. For wind speed and direction, we focus on a single valley.

Temperature

Fig. 2 shows the distribution of the differences between CCLM and observations in the whole simulation area for mean temperatures in the winter half year and summer half year at the three altitude ranges. The CCLM7 simulations are generally too cold. In CCLM2.8, up to about 25 % of the grid points within some altitude ranges change from a cold bias to a warm bias. The reduction of the temperature error in CCLM2.8 in comparison to CCLM7 is significant for all altitude ranges and for both time periods of the winter half year and summer half year.

Looking more into detail, the improvements by CCLM2.8 in the summer half year are larger than in the winter half year. In the summer half year, the median difference over all grid points decreases from around −0.9 K (CCLM7) to −0.2 K (CCLM2.8). An interesting finding also valid for the other variables considered here is that the degree of improvement depends on the altitude, with largest improvements for grid points at altitudes below 400 m and smallest for grid points at altitudes above 800 m. This is in contrast to the 7 km simulations: While the CCLM7 error becomes smaller with altitude, the CLLM2.8 error increases with altitude. The differences between CCLM7 and CCLM2.8 are generally smaller in the winter half year. Here, the median difference over all grid points decreases from −0.5 K (CCLM7) to −0.4 K (CCLM2.8), with comparable improvements in the different altitude ranges.

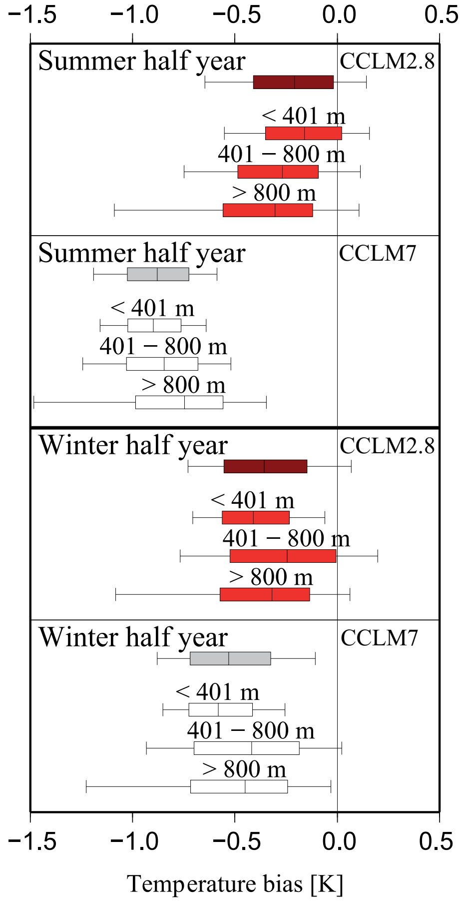

Figure 2: Distribution Δ2.8 and Δ7 for temperature means in the winter and summer half years (1971–2000). The box indicates the 25th and 75th percentiles, and is the median, the ends of the whiskers indicate the 10th and 90th percentiles. The distributions are shown for the whole simulation area (gray box; significant improvements by CCLM2.8: dark red box) and for three different altitude ranges (white box; significant improvements by CCLM2.8: red). Significance is assessed by a Wilcoxon rank sum test, confidence level = 0.95) for |Δ2.8| compared to |Δ7|.

Improvement due to higher spatial resolution cannot solely be explained by a better representation of orography, since the temperatures of CCLM7 are still too low after a height correction with reference to the surface elevations of CCLM2.8. In CCLM2.8, also the land use and soil type distribution is more differentiated. This larger variability affects atmospheric stability and produces larger horizontal and vertical gradients. These effects are neglected, if only a linear height correction is applied to model results of coarser resolution. Another point is that height correction only considers a mean vertical gradient of temperature, so that weather situations with higher or lower vertical gradients are not accounted for adequately by linear height correction of CCLM7.

Additionally, the temperature near the surface is strongly connected to the amount of incoming solar radiation. As there is an added value for global radiation (Fig. 9) in CCLM2.8, this also improves the temperature representation.

Looking at the spatial distributions of Δ2.8 and Δ7 for the summer half year (Fig. 3), a considerable added value is obtained by the CCLM2.8 simulation. The temperature mean in the summer half year is reproduced very well in CCLM2.8, 43 % of the grid points have an absolute difference of less than 0.2 K (white areas

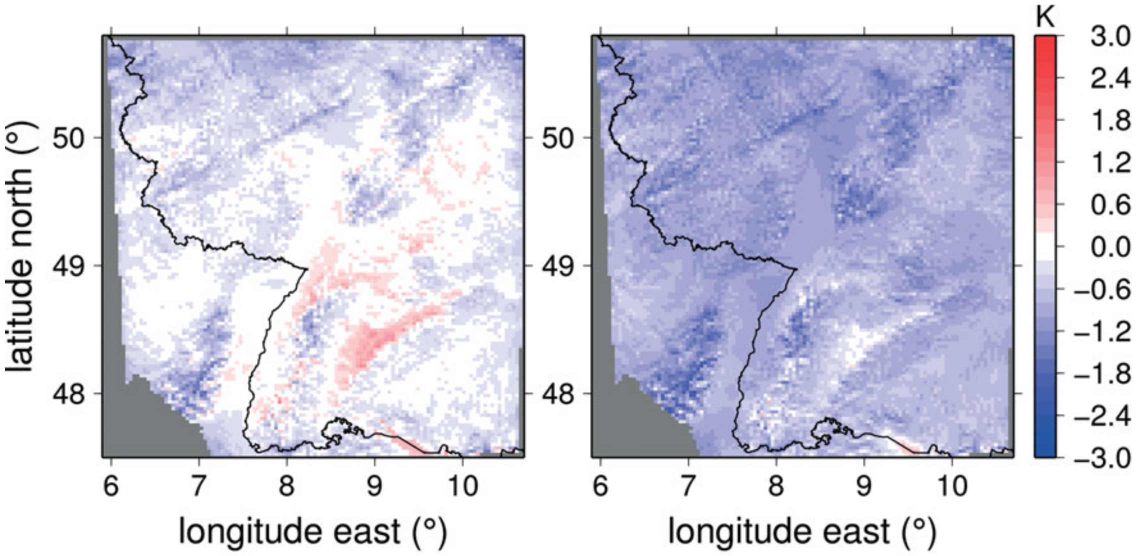

Figure 3: Difference maps for mean temperature in the summer half year for the time period 1971 to 2000. Left: Δ2.8; right: Δ7.

in Fig. 3, left). In contrast to this, the mean difference between CCLM7 and HYRAS is −0.9 K, with only 4 % of the grid points having an absolute difference of less than 0.2 K (white areas in Fig. 3, right). There also is an improvement in the winter half year, albeit less pronounced (not shown). There, the portion of grid points with an absolute difference of less than 0.2 K is 27 % for CCLM2.8 and 15 % for CCLM7. This improvement is also reflected by positive MSESS values in the whole area, except for the Swabian Alb, especially in the summer half year (not shown).

Our results suggest that there is a quite uniform warm offset between CCLM2.8 and CCLM7, as implied by a regression CCLM7 against CCLM2.8 (centered to the median value of CCLM7; intercept: 0.65 K, slope: 1.09). This reduces the cold bias in most parts of the area, but also produces a slight warm bias in those regions, where temperatures were adequately represented in CCLM7, e.g. the Swabian Alb.

Precipitation

Fig. 4 shows the distributions of Δ2.8 and Δ7 for mean precipitation sums in the winter half year and summer half year for the three altitude ranges and for the whole area. For the half-year precipitation sum, the median difference is almost 10 mm per month in the summer half year and roughly 24 mm per month in the winter half year in CCLM2.8 and 12 mm per month (summer half year) and 27 mm per month (winter half year) in CCLM7. While CCLM2.8 shows a significant improvement for both time periods and altitudes below 401 m, there even is a significant impairment for altitudes between 401 and 800 m and above 801 m. Again, a strong altitude dependence of the error is found. Especially in the winter half year, Δ2.8 is larger than Δ7 for altitudes above 801 m. Here, the spread is also large, which is possibly due to the small number of grid points at this altitude range.

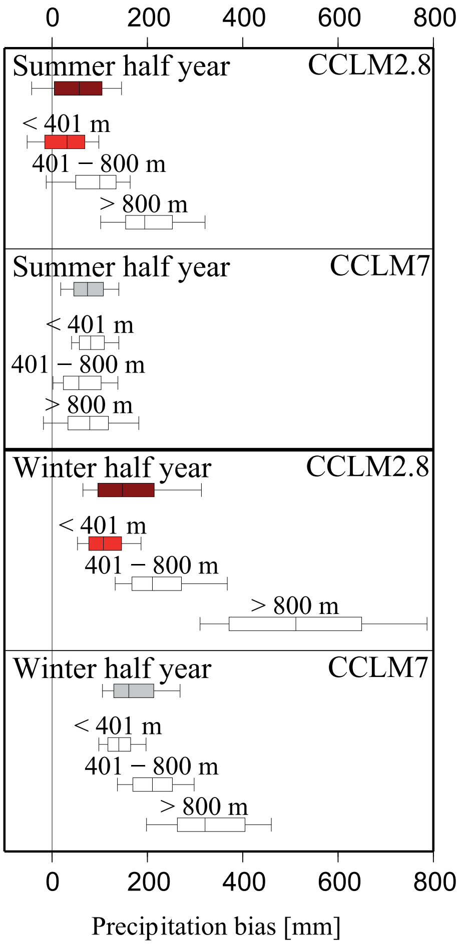

Figure 4: Distribution Δ2.8 and Δ7 for precipitation sums in the winter and summer half years (1971–2000). For details see Fig. 2.

Figs. 5 and 6 show the spatial distributions of Δ2.8 and Δ7 for the summer and winter half years, respectively. In the summer half year, 40 % and 29 % of the grid points in CCLM2.8 and CCLM7, respectively, have an absolute bias of less than 50 mm (Fig. 5). In the win-

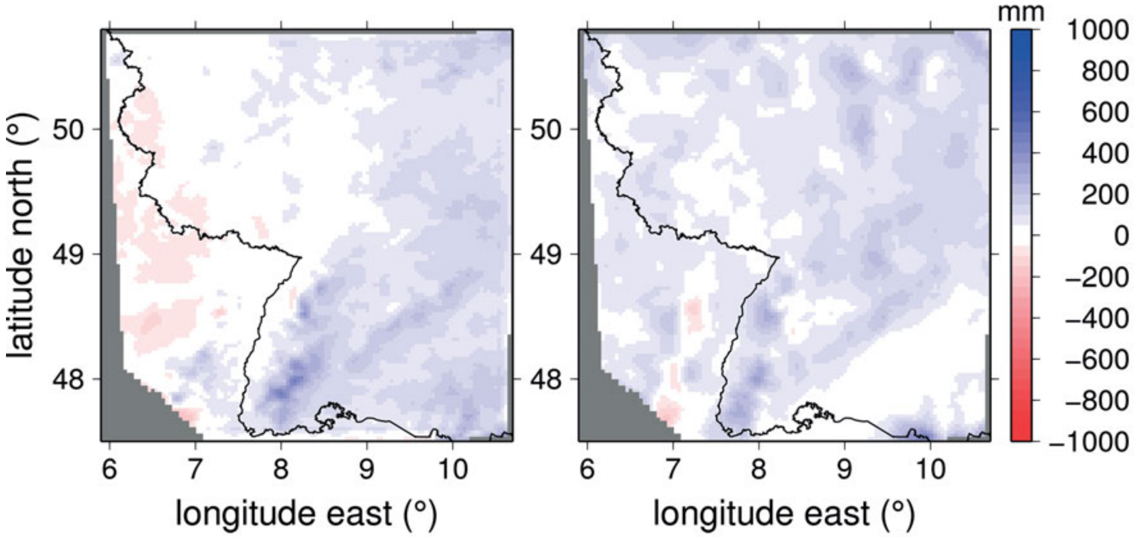

Figure 5: Difference maps for the precipitation amount in the summer half year for the time period 1971 to 2000. Left: Δ2.8; right: Δ7.

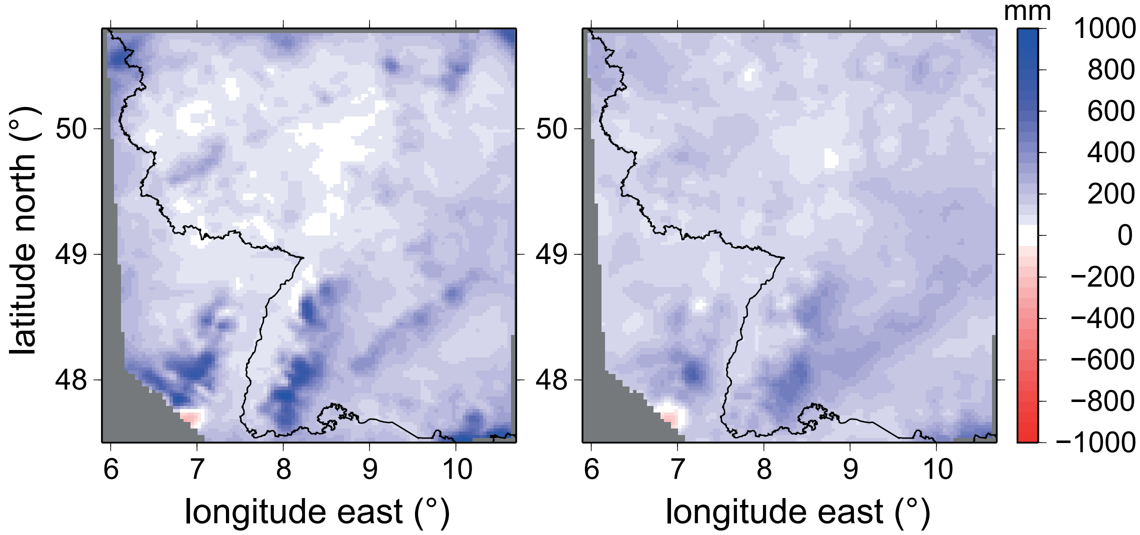

Figure 6: Difference maps for precipitation amount in the winter half year for the time period 1971 to 2000. Left: Δ2.8; right: Δ7.

ter half year, these numbers are 6 % and 2 %, respectively (Fig. 6). As already seen in Fig. 4, the relative error for the annual precipitation sum in both the winter half year and summer half year increases with altitude. Especially in winter, a strong overestimation of precipitation is observed in CCLM2.8 simulations in the mountainous regions of the Black Forest, the Vosges, the foothills of the Alps, and to a lesser extent in the Swabian Alb (Fig. 6, left). This overestimation increases almost linearly with altitude. The mean bias in the summer half year ranges between 5 % in the lowlands (0 to 200 m a.s.l., 12 % of the grid points) and 32 % in the mountainous regions (above 1,000 m a.s.l., 0.5 % of the grid points). In the winter half year, the bias is between 24 % and 88 %.

The reasons of this increasing difference between observed and simulated precipitation with altitude are not clear. Part of the difference may be explained by the uncertainty of the processed observations, which increases with terrain complexity, and by undercatchment of precipitation in measurements, which increases with wind speed and, hence, with altitude and can amount to 30 % and more.

For the model skill (MSESS) in the summer half year (Fig. 7, left), both negative and positive skills are obtained by CCLM2.8. No effects of the model domain boundaries are obvious, even though according to Brisson et al. (2016), a certain distance from the borders is necessary to allow for the development of convective events at higher resolution. This is supposed to be especially important in the summer half year when a large part of precipitation is due to convection. In the winter half year, small boundary effects can be seen at all borders of the model domain with a negative MSESS. In addition, the model skill score is very negative in the mountainous regions of the Black Forest and Swabian Alb due to the strong overestimation of precipitation in CCLM2.8 (not shown).

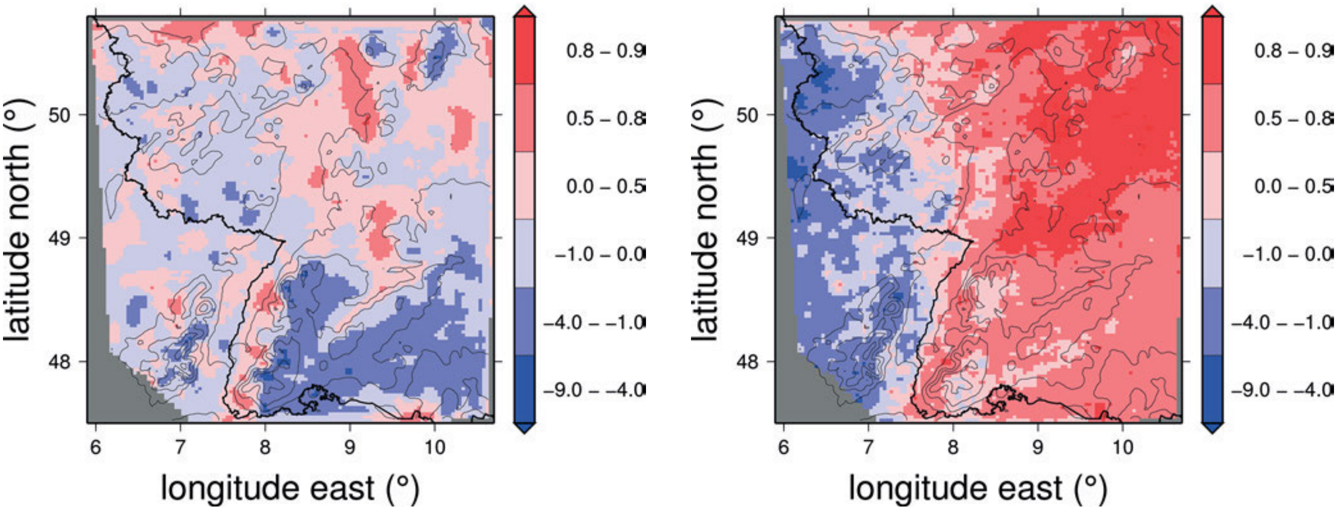

Figure 7: Left: Mean Squared Error Skill Score (MSESS) for precipitation summer half year sums. Right: Mean Squared Error Skill Score (MSESS) for summer half year number of wet days (daily precipitation sum at least 1 mm). Note the non-linear scale of the MSESS.

In order to assess the ratio between dry and wet days, the number of days per year with a daily precipitation sum of at least 1 mm is examined. In CCLM7 the number of such wet days is strongly overestimated in the winter half year in the whole investigation area and in the summer half year in most of the region. In CCLM2.8 the picture is more complex: In the winter half year, we see a more realistic number of wet days compared to observations. This holds for the whole investigation area. In the summer half year, the investigation area is divided into two parts: In the western part, there are too few days with precipitation, while the number is simulated correctly in the eastern part. Accordingly, the MSESS is positive throughout for the winter half year and positive for the eastern part in the summer half year. In the western part in the summer half year, by contrast, it is negative (Fig. 7, right).

Additionally, the error in the number of wet days does not exhibit any obvious dependence on the altitude range. This leads to the conclusion that the overestimation of precipitation half year sums at high altitudes is not due to too many precipitation events, but to too high a precipitation amount per event in mountainous regions. The number of days with precipitation sums above 30 mm in the mountainous regions is strongly overestimated (not shown).

Relative humidity

Fig. 8 shows the distribution of the differences between CCLM and observations in the whole simulation area for mean relative humidity in the winter half year and summer half year and at different altitude ranges.

A significant reduction of the model error can be seen for the summer and the winter half year and for all altitude ranges, with larger improvements in the summer half year. There, the median difference over all grid points decreases from 8 % in CCLM7 to 3 % in CCLM2.8 (winter half year: 6 % to 4 %).

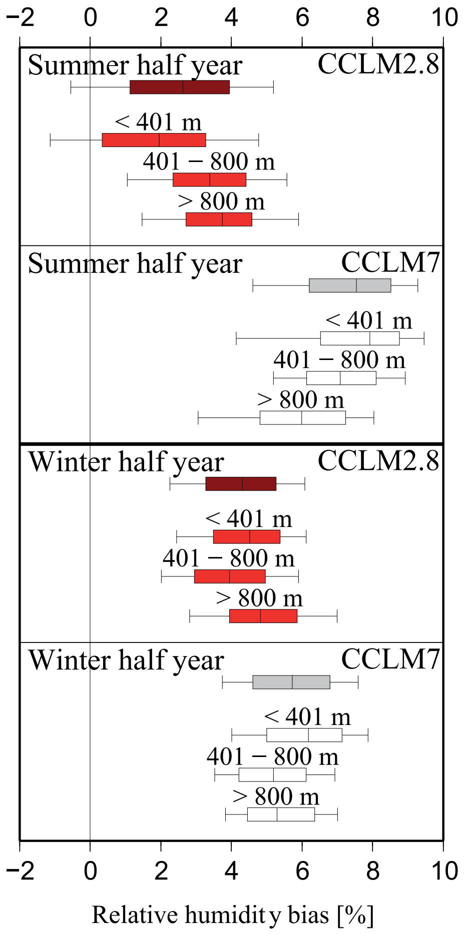

Figure 8: Distribution Δ2.8 and Δ7 for relative humidity means in the winter and summer half years (1971–2000). For details see Fig. 2.

Since relative humidity is closely connected to temperature, the spatial pattern in the summer half year is very similar to that of temperature: CCLM2.8 has an error that increases with altitude, the error of CCLM7

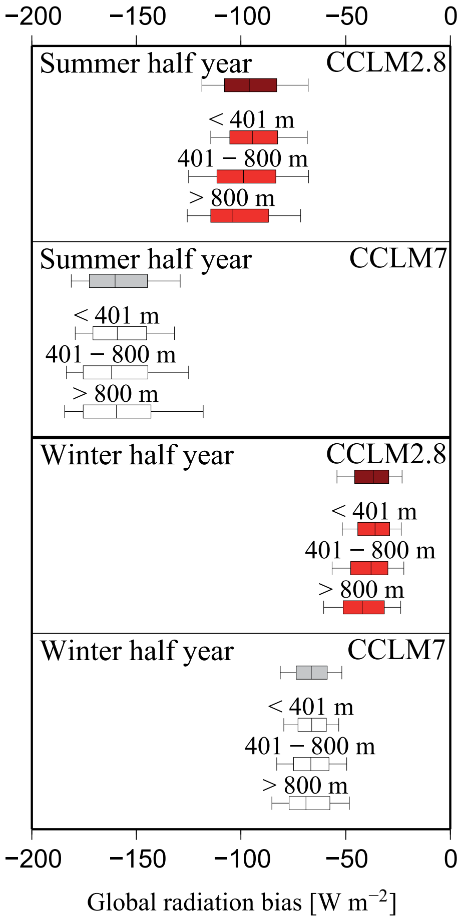

Figure 9: Distribution of CCLM2.8 and CCLM7 minus observations (DWD) global radiation sums in the winter and summer half years (1983–2000). For details see Fig. 2.

decreases with altitude. In the winter half year, the improvements are similar for all altitude ranges.

In the summer half year, CCLM2.8 is very close to observations, with 88 % of the grid points having an absolute difference of less than 5 %, compared to only 14 % of the grid points in CCLM7. For the winter half year, the added value is also pronounced, with 69 % (CCLM2.8) versus 35 % (CCLM7) of grid points with an absolute error of less than 5 %.

Global radiation

Global radiation, temperature, precipitation, and relative humidity are closely connected and influence each other. Looking at the half year mean sums of global radiation from 1983 to 2000, there is a significant improvement by CCLM2.8 (Fig. 9) in the summer and winter half years. The observation data (DWD), which are available for the period from 1983 to 2000 on a half-year basis, over the investigation area show sums between 723 and 850 kWh m^{-2} in the summer half year and between 314 and 427 kWh m^{-2} in the winter half year. CCLM7 underestimates the half year mean sum by 160 kWh m^{-2} on the average (summer half year) and 66 kWh m^{2} (winter half year), respectively. In the simulations of CCLM2.8, this considerable underestimation decreases significantly to a median difference of −96 kWh m^{-2} (summer half year) and −37 kWh m^{-2} (winter half year), respectively. In spite of this still existing underestimation, a better representation of global radiation by CCLM2.8 is evident.

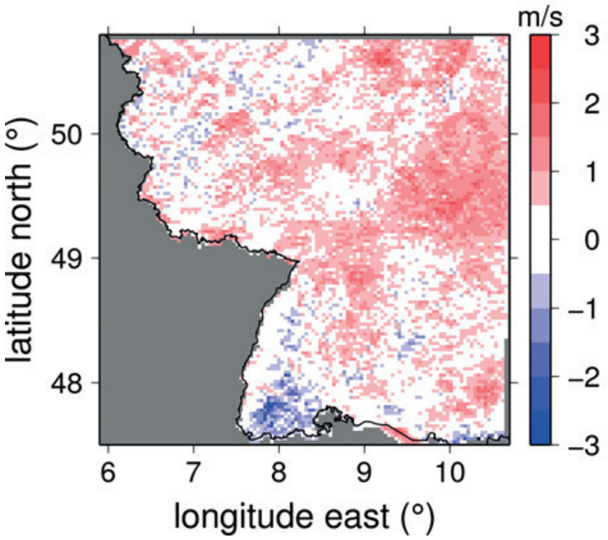

Figure 10: Difference map for the mean wind speed for CCLM2.8 (1971 to 2000) minus DWD raster data (1981 to 2010).

Wind

No added value is seen in the mean wind speed in the whole research area for CCLM2.8 (Fig. 10). At all altitude ranges, the median differences between CCLM2.8 and CCLM7 are nearly zero. At many grid points, the difference between the simulated and observed wind speed is smaller than 0.5 m s^{-1}. In some regions, the model slightly overestimates wind speed with values between 0.5 and 1 m s^{-1}. In mountainous regions, over- and underestimation by up to 3 m s^{-1} occur. However, marked improvements can be seen in smaller regions with small-scale complex orography.

Thanks to a more detailed representation of orography and land use in CCLM2.8, we expect a better representation of wind speed, wind direction, and regional wind systems. To illustrate this, we use the Stuttgart region with the Neckar valley, which is roughly orientated from southeast to northwest in the investigation area. It is a good example of a local wind system.

Local wind systems are initiated by orographic structures. For example, drainage flows during night and channeling are such local phenomena. Due to their persistence, they are of climatic importance and affect temperature, fog, and pollutant transport. Their reproduction by a climate model requires coverage of the valley by several grid points, together with a detailed resolution of orography.

For the Neckar valley, the wind roses for day hours (08:00 to 19:00 UTC) and night hours (20:00

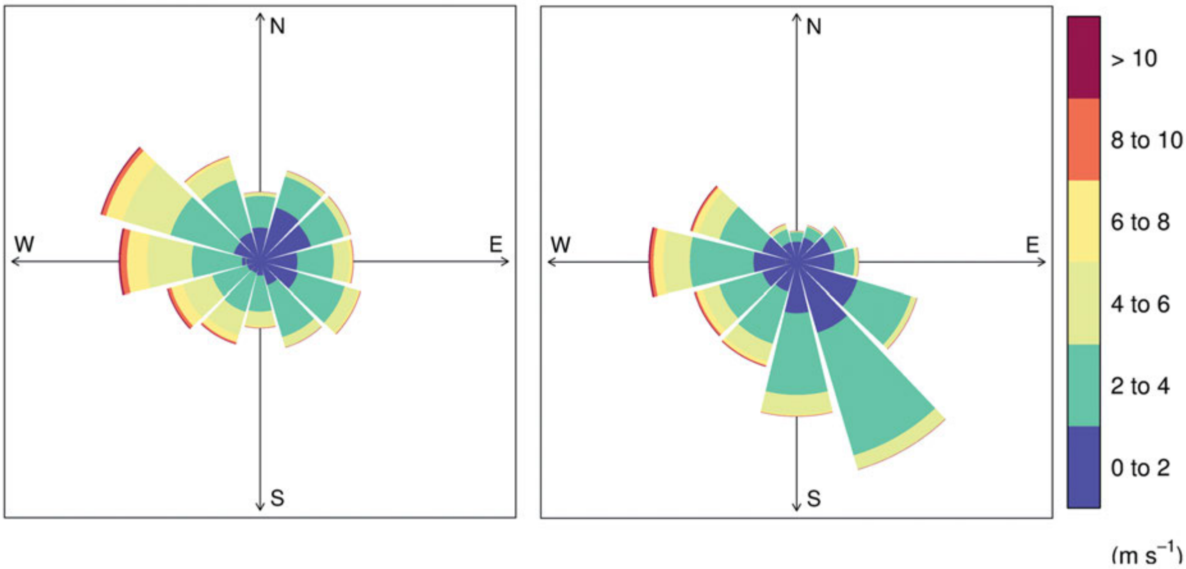

Figure 11: Wind roses for the station of Stuttgart Schnarrenberg (DWD) for the years 1971 to 2000. Left: Day hours (08:00 to 19:00 UTC); right: Night hours (20:00 pm to 07:00 am UTC).

to 07:00 UTC) and in CCLM2.8 are compared with hourly station data measured at Stuttgart Schnarrenberg (DWD).

The measurements at Stuttgart Schnarrenberg at the border of the Neckar valley show a very pronounced local feature (Fig. 11). During day hours (Fig. 11, left), the most frequent wind directions are between west and northwest (255 to 345 °). The next highest amount of wind directions is around southeast (105 to 165 °), especially during hours with low wind speeds between 2 and 4 m s^{-1}. During night hours (Fig. 11, right), the by far most frequent wind direction is around south-southeast (135 to 165 °). This direction prevails at low wind speeds (2 to 4 m s^{-1}). A second peak is seen in the western sector (255 to 285 °). This second peak is connected to higher wind speeds (6 to 8 m s^{-1}). These observations can be explained by a local wind system resulting from the interaction of large-scale flow, channeling, and stability effects: Large-scale flow, associated with higher wind speeds, is mainly westerly with some northerly and southerly components, explaining the westerly wind directions. The southeasterly peak during night is mainly due to channeling and nocturnal drainage flows downstream of the southeast-northwest oriented Neckar valley.

CCLM2.8 is able to reproduce these distributions of wind directions and wind speeds in the area around the Neckar valley and, thus, captures the spatial and temporal variation of this local wind system (Fig. 12). First, a turning of the main wind direction during night hours can be seen. Especially during nighttime, a clear distinction between the wind roses in the Neckar valley – with marked directions along the valley axis – and those on the surrounding heights are visible. During daytime, northwesterly directions appear. Secondly, the share of very low wind speeds between 0 and 2 m s^{-1} in the whole distribution is considerably higher in the low-lying Neckar valley than in higher elevated areas.

Altogether, the wind roses during day and night in the Neckar valley are very similar to the observations made at Stuttgart Schnarrenberg, indicating that the model at this resolution captures the mechanisms behind the observed behavior.

4 Discussion

For the variables considered here, namely, temperature, precipitation, relative humidity, global radiation, and wind, the CCLM2.8 results indeed are closer to observations than the CCLM7 ones. The degree of improvement depends on the variable under consideration, the season, region, and altitude. We also find a considerable spatial variability.

A clear improvement by CCLM2.8 can be seen for temperature. The absolute temperature difference is very small in most of the simulation area in the summer half year, whereas a large overall cold bias exists in the 7 km simulations. For the winter half year, the error is larger, but still significantly smaller than in CCLM7. Our results are in agreement with the study of Ban et al. (2014) in the alpine region for horizontal resolutions of 12 km and 2.2 km. They found a slightly cold bias in winter temperature and a slightly (12 km horizontal resolution) or enhanced (2 km horizontal resolution) warm bias in summer temperature, while diurnal variations in temperature were better resolved at higher resolution. Prein et al. (2013) found an improved representation of mean temperature for a single summer in mountainous regions due to increased spatial variability of the temperature field in simulations with 3 km horizontal resolution. A small or no effect was seen in winter. In contrast to their findings of similar improvements due to dynamical

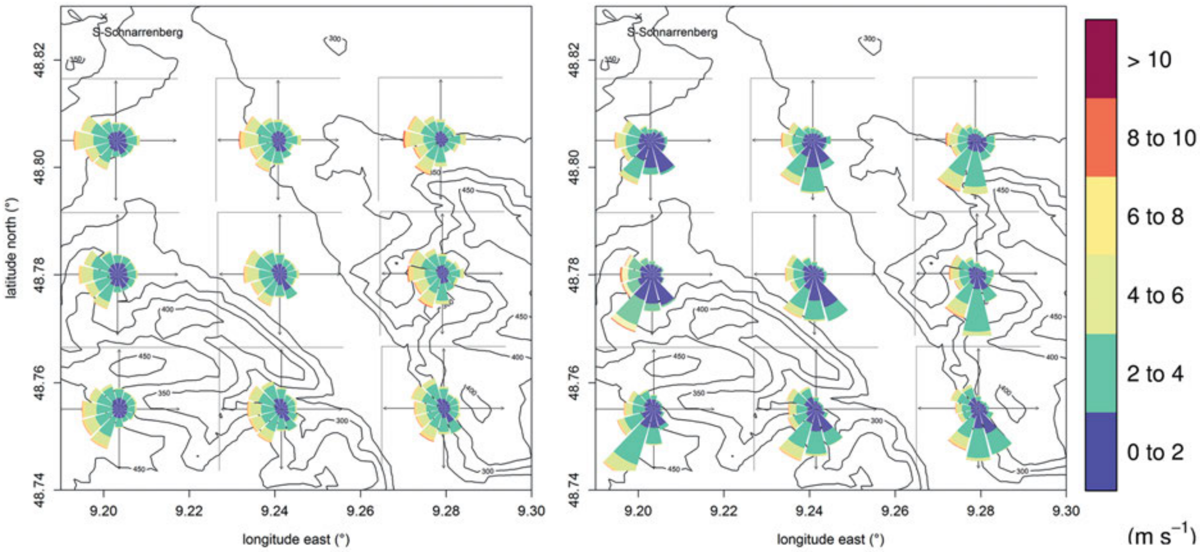

Figure 12: Wind roses of CCLM2.8 in the Neckar valley for the years 1971 to 2000. Left: Day hours (08:00 to 19:00 UTC); right: Night hours (20:00 pm to 07:00 am UTC). The black lines indicate the real orography.

downscaling and simple altitude correction, our results show that a better representation of orography height is only one of several reasons of improved temperature and that a simple correction with orography height (which is often applied to adjust the near-surface temperature) is not sufficient to produce realistic temperatures. This was found by studying the differences between the height-adjusted (using the high-resolution grid) CCLM7 temperatures and the CCLM2.8 temperatures. In the difference field, deviations on various spatial scales and at the same orography heights can be seen, indicating that apart from orography, factors like wind, precipitation, and soil moisture also affect the temperature field. This leads to a pronounced added value by CCLM2.8 compared to the height-corrected CCLM7 in the summer half year. Improvements in precipitation depend on region and season. There is a considerable overestimation of precipitation by CCLM2.8 in elevated regions in winter and in summer, much higher than in the 7 km simulations. We presently cannot offer a convincing explanation of this strong increase of error with altitude for precipitation. Clear reductions of the bias occur in the summer half year over low terrain and in the western part of the area. The latter could partly be due to advection of drier upper air over the western boundary and too much moistening within the simulation domain.

Hence, our 30-year climatic study confirms other studies for shorter time periods. For example, Langhans et al. (2013) found an overestimation of precipitation for an 18-day simulation in Switzerland with 2.2 km horizontal resolution. An overestimation of precipitation above 1000 m a.s.l. in the alpine region was also found by Ban et al. (2014), who performed a simulation with COSMO-CLM at 2.2 km horizontal resolution over a 10-year period. It should be noted that the order of magnitude of the errors is similar, relative to the time period considered.

Our climatological statistics, however, do not confirm the pronounced added value in complex terrain in summer for extreme precipitation intensities, which was found by Prein et al. (2013) and Zängl (2007a, b). From a study of two single events, Zängl (2007a, b) concludes that a higher model resolution leads to an increased model skill in the Alps, where orographic effects dominate precipitation on a small scale, whereas he sees no positive effect in the Alpine foreland. Our results reveal an error increasing with altitude above sea level.

We found that the number of wet days is represented better in the whole investigation area in CCLM2.8, while the half year precipitation sums are overestimated in mountainous regions. Our result of the precipitation amount per event being too high at higher altitude is supported by the findings of too high amounts of precipitation in the daily cycle in literature. An analysis of the diurnal cycle of precipitation for the same simulation data set we used can be found in Fosser et al. (2015). Using CCLM2.8, they found a similar shape of the diurnal cycle in summer as in observations, but a considerable overestimation of the mean hourly intensities in summer and winter. Similarly, an improvement of the mean diurnal cycle for certain summer periods is found by Ban et al. (2014), Langhans et al. (2013), Prein et al. (2013), and Kendon et al. (2012). Most studies also reveal a tendency towards too high precipitation amounts, especially the studies in alpine terrain show a strong overestimation of mean daily precipitation. Considering this overestimation in studies of similar horizontal resolution, undercatchment effects in the measurement of precipitation as well as a limited number of stations in mountainous regions have to be taken into account (Isotta et al., 2014; Frei and Schär, 1998).

The special pattern of MSESS on the number of wet days in the summer half year may be an effect of the simulation area boundaries, as for high-resolution climate simulations, domain size and vertical resolution are important factors. Suklitsch et al. (2008) made sensitivity studies in the Alps with different model settings and found that modifications of these two factors have the highest influence on temperature and precipitation representation. In a study on precipitation during a 4-month summer period, Brisson et al. (2016) recommend a distance of 150 km as "spatial spin-up" between the domain boundary and the area evaluated in order to allow for the development of convective precipitation events. In our study, the distance from the western boundaries might be too small in the western part of the investigation area, at least for the summer half year, when a large part of precipitation is convective.

To sum up, we see a pronounced cold and wet bias in summer as well as an underestimation of global radiation in CCLM7. Similar errors were also described by Jaeger et al. (2008) for simulations with an older version of COSMO-CLM (version 4.0) on a 0.22 ° and 0.44 ° grid. In our study, we see that, especially in the summer half year, the cold bias is reduced in CCLM2.8, together with a more realistic amount of global radiation for both half year sums. The wet bias is reduced in some areas. The degree of improvement for precipitation differs between winter and summer half year and is strongly related to the altitude of the region considered. For relative humidity, we found a significant added value in the spatial distribution for both the summer and winter half years.

For mean wind speed, no marked difference between CCLM2.8 and CCLM7 was found. However, the impact of orography and stability on the spatial and temporal variability of wind speed and wind direction was evident in several regions, as was shown for the Neckar valley.

The reasons of the differences in improvements from a coarser to a higher horizontal resolution are manifold. Better representations of orography, soil and land use, atmospheric stability, and larger local gradients certainly are important factors. The more frequent call of the radiation routine (every 15 minutes in CCLM2.8 instead of 1 hour in CCLM7) may also improve results, not only for global radiation, but also for temperature and the ratio of dry and wet days.

In the end, we see an added value for most parameters in the 30-year means as well as for daily and sub-daily statistics. This is partly in agreement with Prein et al. (2015), who conclude that the added value of convection-permitting models is largest for sub-daily statistics, for spatial scales below 100 km and steep orography, and for "higher-order statistics" like extreme values. At the same time, they suppose the added value to be reduced by smoothing out in climatological statistics, whereas we found an added value also in climatological statistics.

5 Conclusions and outlook

We found that 2.8 km resolution simulations with the regional climate model COSMO-CLM provide an added value for selected variables compared to coarser horizontal resolutions and that the additional computational effort, which is around 5 to 10 times that of the 7 km resolution, is therefore justified. The added value is obvious for temperature, precipitation, relative humidity, and global radiation as well as for regional wind systems, especially in the summer half year. The added value depends on the variable studied, region, altitude, season, and statistics (mean or extreme values). For precipitation, there still is a need for further research concerning the remaining overestimation of precipitation amounts in mountainous regions.

Hence, CCLM2.8 data may be used to derive climate parameters of practical relevance and for detailed regional impact studies, for example in cities or highly complex terrain or for hydrological modeling of river catchments or soil erosion. For impact studies in cities, the implementation of an urban scheme might lead to improved statements relating to e.g. heat events, which can defined by temperature thresholds like hot days or tropical nights or by percentage threshold exceedances. The health impacts due to heat stress can then be assessed by complex bioclimatic indices.

The results presented here reduce the still existing gap between the scientific climate community and the requirements of stakeholders. Based on results of high spatial resolution, interpretations on the regional and local scales may be possible. This is important, since local climate is very much affected by the surrounding regional to local conditions like orography and land use. Although simulations at a spatial resolution of 2.8 km cannot describe urban structures (buildings, urban canyons ...), the example of the agglomeration of Stuttgart shows that the large variability of e.g. temperature and wind fields induced by the complex terrain in and around Stuttgart is better captured with the CCLM2.8 simulations. A more detailed analysis reveals that the amplitude of daily temperature is too small and that maxima are underestimated. One reason may be the lack of a suitable urban parameterization, including better adapted urban land use classes and anthropogenic heat input. Recently, there are approaches to implement urban schemes in regional climate models for urban impact studies (e.g. Trusilova et al., 2013; Fallmann et al., 2013).

A number of open questions and problems on the climate simulation side still remain to be solved. More experience is needed in selecting the domain size, the position and influence of the lateral boundaries, the nesting strategy, and the transition zone between nests. Also, the exact reasons why higher resolution causes an improvement are not sufficiently clear. Higher resolution also poses questions in terms of how to adapt turbulence and other available subgrid parameterizations and parameter settings. There also is the difficulty of obtaining suitable validation data and how to perform the validation (double penalty problem, Anthes, 1983). Due to increasing variability, higher resolution may also tend to reduce the signal-to-noise ratio. In the future, an uncertainty assessment will be necessary, e.g. with ensemble simulations, which presently is too demanding in terms of computational costs. But higher resolution makes some model improvements feasible, which are relatively easy to implement, e.g. more realistic and detailed parameterization of urban areas.

Finally, it can be concluded that high-resolution climate simulation produces encouraging results and has a high potential for applications. Further research should be conducted to cope with typical end-user demands as well as to evaluate high-resolution climate simulations for practical parameters, since the data obtained will be important for regional impact studies and the coupling to impact models. Although resolutions higher than that of CCLM2.8 are required for many impact studies, the data presented here certainly have improved the basis considerably.

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