

# High Resolution Climate Projections Using the WRF Model on the HLRS

Viktoria Mohr, Thomas Schwitalla, Volker Wulfmeyer  
and Kirsten Warrach-Sagi

**Abstract** Considering the projections of different climate scenarios, global mean surface temperature is expected to rise over the 21st century accompanied by an increase of other weather extremes due to the past anthropogenic emissions of greenhouse gases. As the warming of many land areas is higher than on the global average, the impact of future climate conditions needs to be estimated rather on a regional scale. Thus, climate projections of spatially high resolution simulations are required in combination with their uncertainties and robustness. For a selected area, these simulations are being performed within the framework of EURO-CORDEX. ReKliEs-De (Regional Climate Ensembles Germany) is a Project which complements these simulations by providing projections of model ensembles about the development of future climate and climate extremes for Germany. With the Weather Research and Forecasting (WRF) model and its land surface model NOAH we are performing simulations from 1950 to 2100 with  $0.44^\circ$  ( $\sim 50$  km) and  $0.11^\circ$  ( $\sim 12$  km) resolution on the CRAY XC 40 at the High Performance Computing Center Stuttgart (HLRS). Results of the simulations on the  $0.44^\circ$  grid for a period from 1971–2000 and as comparison for two different future scenarios from 2071–2099 show an increase of the average temperature of up to 2–4 °C in Europe with respect to the chosen emission scenario. However, seasonally the changes are much more diverse.

## 1 Introduction

The expected climate change within the next decades is predicted to be caused by an increase of the emissions of anthropogenic CO<sub>2</sub> and other greenhouse gases. These processes will have a huge influence on the future climate and consequently on the society. Although climate change will be noticeable on the global scale, the effects will be much more diverse and extreme regarding the regional scale.

---

V. Mohr (✉) · T. Schwitalla · V. Wulfmeyer · K. Warrach-Sagi  
Institut für Physik und Meteorologie, Universität Hohenheim,  
70599 Garbenstrasse 30, Stuttgart, Germany  
e-mail: viktoria.mohr@uni-hohenheim.de

General circulation models (GCMs) currently are the most advanced tools for simulating the response of the global climate system to increasing greenhouse gas concentrations. They are able to numerically solve the equations of physics hence, GCMs have the ability of representing physical processes of the atmosphere, ocean, cryosphere and the land surface using a 3-D grid over the globe with a typical resolution. Nowadays, typically GCMs use a horizontal resolution of 100–200 km. However, to better understand also regional climate phenomena such as local extremes and in order to assess the effect of the expected climate change, scientists and end users like federal agencies and climate impact and adaptation researchers require projections on the regional scale with a higher horizontal resolution.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) [1] provides a framework for coordinated climate change experiments, where 20 different modelling groups carried out global climate projections with their GCMs, contributing to the latest assessment report of the Intergovernmental Panel on climate change (IPCC). Those projections are based on Representative Concentration Pathways (RCPs) [2], representing four different possible greenhouse gas (GHG) concentration scenarios of the future climate. Namely, these scenarios are the RCP8.5, RCP6, RCP4.5 and RCP2.6 scenario, indicating the possible range in the change of radiative forcing (in  $W/m^2$ ) by the year 2100 relative to pre-industrial values.

In 2009 the COordinated Regional climate Downscaling EXperiment (CORDEX, <http://wcrp-cordex.ipsl.jussieu.fr>) was established by the World Climate Research Programme (WCRP), in order to provide ensembles of regional climate simulations on a higher spatial resolution. The task within CORDEX is to apply the GCMs which contributed to the CMIP5 database for the boundary forcing of different regional climate models (RCMs). CORDEX is separated into different sub-groups, covering all continental regions of the globe, serving as input for climate change and adaptation studies. EURO-CORDEX, the european branch of the CORDEX initiative, is focusing on grid sizes of  $0.11^\circ$  ( $\sim 12$  km), but simulations using a resolution of  $0.44^\circ$  ( $\sim 50$  km) are carried out simultaneously.

The ReKliEs-De project funded by the Federal Ministry of Education and Research (BMBF), contributes to EURO-CORDEX by carrying out a certain number of regional climate projections. Several institutes in Germany are part of ReKliEs-De applying different downscaling techniques (dynamical and statistical downscaling), by forcing their RCMs with CMIP5 data. The goal of the ReKliEs-De project (<http://www.reklies.hlnug.de/>) is to provide robust informations about the future evolution of the climate in Germany based on regional climate projections using a high spatial resolution of  $0.11^\circ$ . Beside scientifically analysing the results of the simulations, the focus is also laid on producing user friendly data by providing special climate indices which can be applied easily by the end users. Today, the dynamical downscaling of GCM data is a well respected standard technique to produce high resolution climate projections.

An ensemble of RCMs participating in EURO-CORDEX, forced with ERA-Interim reanalyses data [3] were evaluated e.g. by [4]. Although model biases, predominantly cold and wet biases, emerged in the majority of the experiments, the

authors documented the general ability of the RCMs to represent the basic spatiotemporal patterns for the European climate.

The scope of this part of the WRFCLIM project at HLRS (see also [5]), is to produce high resolution regional climate projections in the framework of ReKliEs-De on  $0.11^\circ$ . We will carry out these long term simulations by dynamically downscaling different GCM model output from 1958 to 2100 with the Weather Research and Forecasting (WRF) [6] Model.

In the following chapter a technical description to the simulations within WRF-CLIM at HLRS is presented. A summary of the current analysis and some preliminary results of the simulations which were carried out from April 2015 to April 2016 are reported as well.

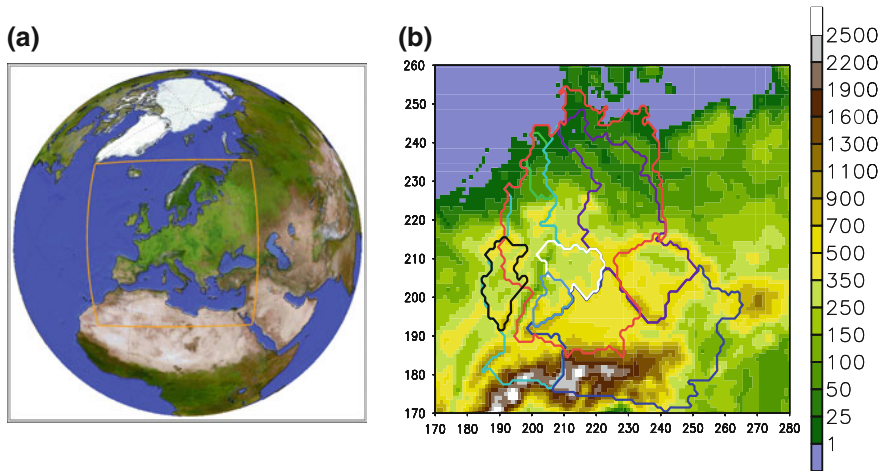
## 2 Simulation Setup with WRF and Forcing Data

The climate simulations are carried out on the CRAY XC40 System at the HLRS. The downscaling process of the coarse GCM output data to the required  $0.44^\circ$  and  $0.11^\circ$  grid resolution is performed by the WRF model version 3.6.1 with its coupled land surface model NOAH [7]. WRF uses the dynamical technique by numerically solving the governing equations of the atmosphere on a finer grid. The simulations are forced 6 hourly at the lateral boundaries with the sea surface temperature and the 3-D fields of temperature, horizontal winds and moisture from the forcing GCMs. We apply a one-way nesting approach via  $0.44^\circ$  to  $0.11^\circ$ . WRF was compiled at HLRS with PGI 14.7 and applied in a hybrid configuration using MPI and OpenMP to optimize the speed of the simulation. The model configuration was set to the same parameterizations like it was applied in [8]. Table 1 shows some technical details of the planned and the so far partly finalized simulations performed on hazelhen.

The WRF projections presented in this chapter are carried out within the frame of EURO-CORDEX to create climate projections. The simulation domains which were specified within CORDEX are displayed in Fig. 1 (left). The analysis focuses on Germany and its contributing river catchments area as shown in Fig. 1 (right). For the future climate projections, four different GCMs and two different RCP scenarios of the CMIP5 project, are applied as boundary forcing with the WRF model. The historical runs of the GCMs cover the period from 1850 to 2005. This period is forced by observed atmospheric composition changes of anthropogenic and natural sources. The RCP scenarios of the GCMs cover the period from 2006 to 2100. They represent mitigation scenarios that assume policy actions will be taken into account to achieve certain emission targets [1]. The numbers of the RCPs give a rough estimate of the range in the change of the radiative forcing by the year 2100 relative to the preindustrial values. The forcing data we applied, the resolution of the GCMs, its scenarios and the chosen simulation period is presented in Table 2.

**Table 1** Technical details of WRF simulations. Note: the raw model output size is minimized after simulation in the postprocessing process as the amount of the results cannot be stored in its raw output

| Simulation       | Nr. CPUs with openMPI | Simulation period     | Nr. of grid cells | $\Delta t$ (s) | Walltime (h) | Nr. of simulations | Raw output size |
|------------------|-----------------------|-----------------------|-------------------|----------------|--------------|--------------------|-----------------|
| 0.44° historical | 1536                  | 01.01.1958–31.12.2005 | 129 × 139 × 50    | 180            | 300          | 4                  | 42 TB           |
| 0.44° RCP8.5/2.6 | 1536                  | 01.01.2006–31.12.2100 | 129 × 139 × 50    | 180            | 570          | 5                  | 99 TB           |
| 0.11° historical | 5400                  | 01.01.1958–31.12.2005 | 452 × 460 × 50    | 60             | 1200         | 4                  | 700 TB          |
| 0.11° RCP8.5/2.6 | 5400                  | 01.01.2006–31.12.2100 | 452 × 460 × 50    | 60             | 2280         | 5                  | 1330 TB         |



**Fig. 1** Simulation domain as specified by CORDEX (a), and focal domain within ReKliEs-De with Germany (red) and the areas of its main river catchments (coloured) (b)

### 3 Results

Based on the WRF downscaling simulations to the 50 km grid, first results of the different forcing GCMs are presented (see GCM description in Table 2). Simulations were carried out for the EURO CORDEX domain with lateral boundaries from approximately 25°N to 75°N and 30°W to 50°E. Since our model simulations are still ongoing by this time (May 2016) exemplary results of the 2m temperature will

**Table 2** Applied GCM data for the WRF simulations

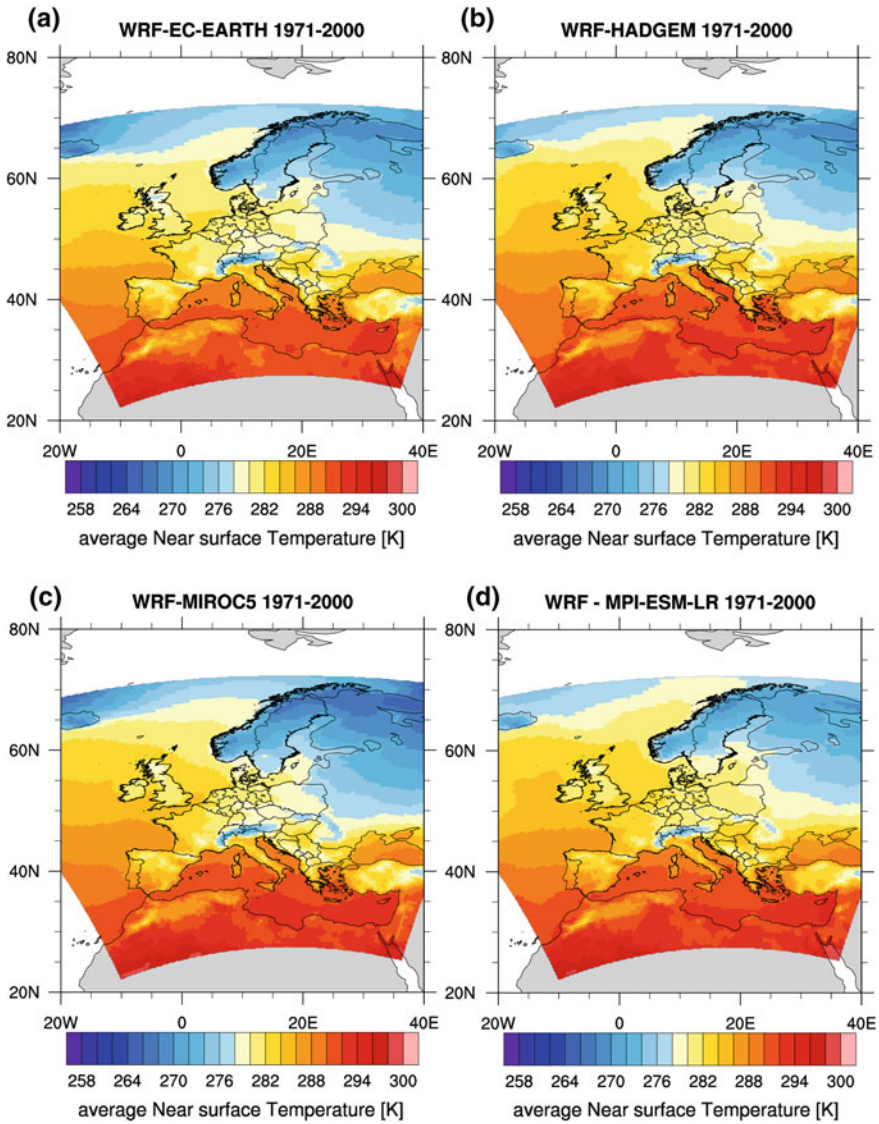
| GCM        | scenarios  | Simulation Period | GCM resolution     |
|------------|------------|-------------------|--------------------|
| MPI-ESM-LR | historical | 1958–2005         | 1.8653° × 1.875°   |
|            | RCP8.5     | 2006–2100         |                    |
|            | RCP2.6     | 2006–2100         |                    |
| MIROC5     | historical | 1958–2005         | 1.4008° × 1.40625° |
|            | RCP8.5     | 2006–2100         |                    |
| HadGEM2-ES | historical | 1958–2005         | 1.25° × 1.875°     |
|            | RCP8.5     | 2006–2100         |                    |
| EC-EARTH   | historical | 1958–2005         | 1.1215° × 1.125°   |
|            | RCP8.5     | 2006–2100         |                    |

be presented. In the first part the focus is based on a time period of the historical simulations from 1971–2000 represented by the four forcig GCMs which were applied in our study. The second part shows a time period of the projected simulations for the two future scenarios RCP2.6 and RCP8.5 represented by the MPI-ESM-LR model for the years 2071–2099. The average near surface temperature is presented in the following based on the annual and on the seasonal scale for the Northern Hemisphere (NH) summer and winter. It is emphasized that the results of this study are based on just one regional model and will need further analyses within the EURO-CORDEX ensemble and the ReKliEs-De project.

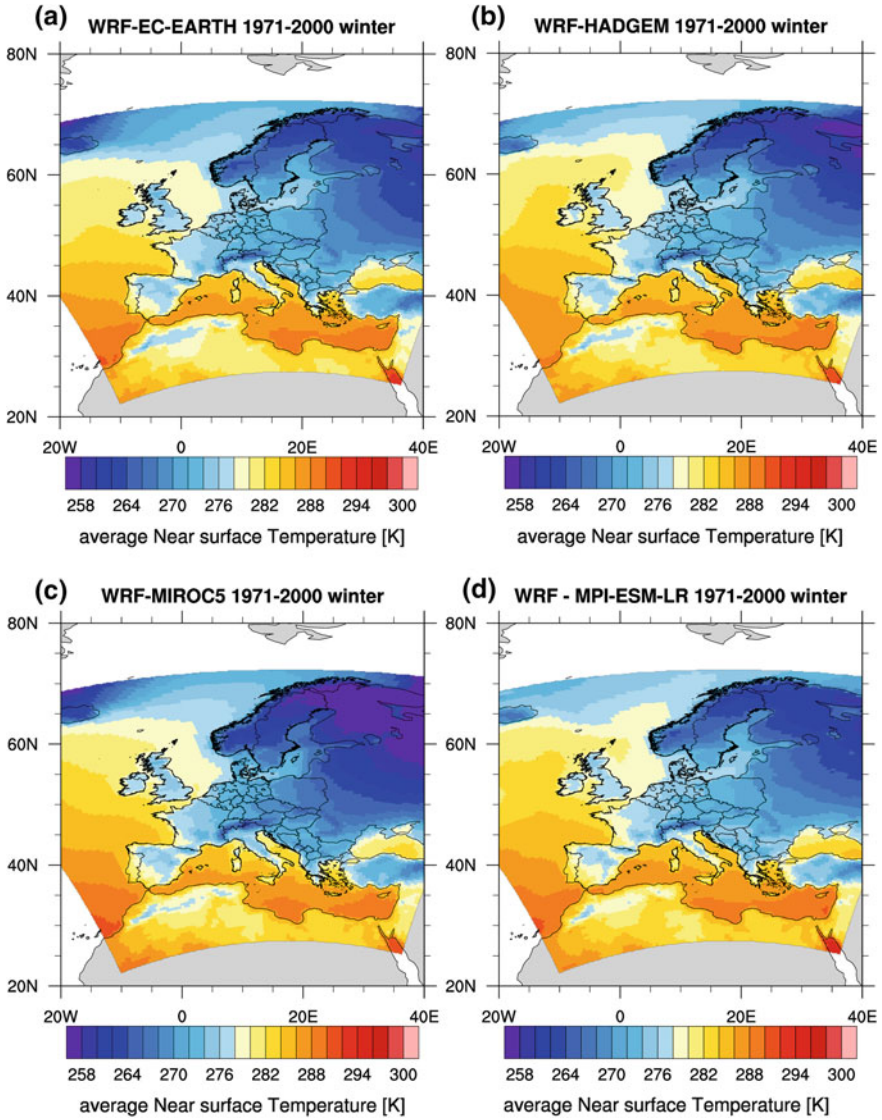
### 3.1 Historical Temperatures

The simulated annual average near surface temperature from 1971–2000 is given in Fig. 2. The four simulations show a common agreement of the average temperature pattern for Europe, which indicates a generally good performance of the models. The temperature ranges from around 264 K (−9 °C) in the North to 294 K (21 °C) in the Southern part of the simulation domain. However, some differences in the temperature range is apparent among the GCMs. Compared to HadGEM2-ESM Fig. 2b and MPI-ESM-LR Fig. 2d, lower temperatures are simulated by MIROC5 Fig. 2c and EC-EARTH Fig. 2a in the Northern and in the Eastern part of the CORDEX domain. Most of the GCMs show a cold bias. MIROC5 indicated to have the strongest bias compared to the other three which are presented here.

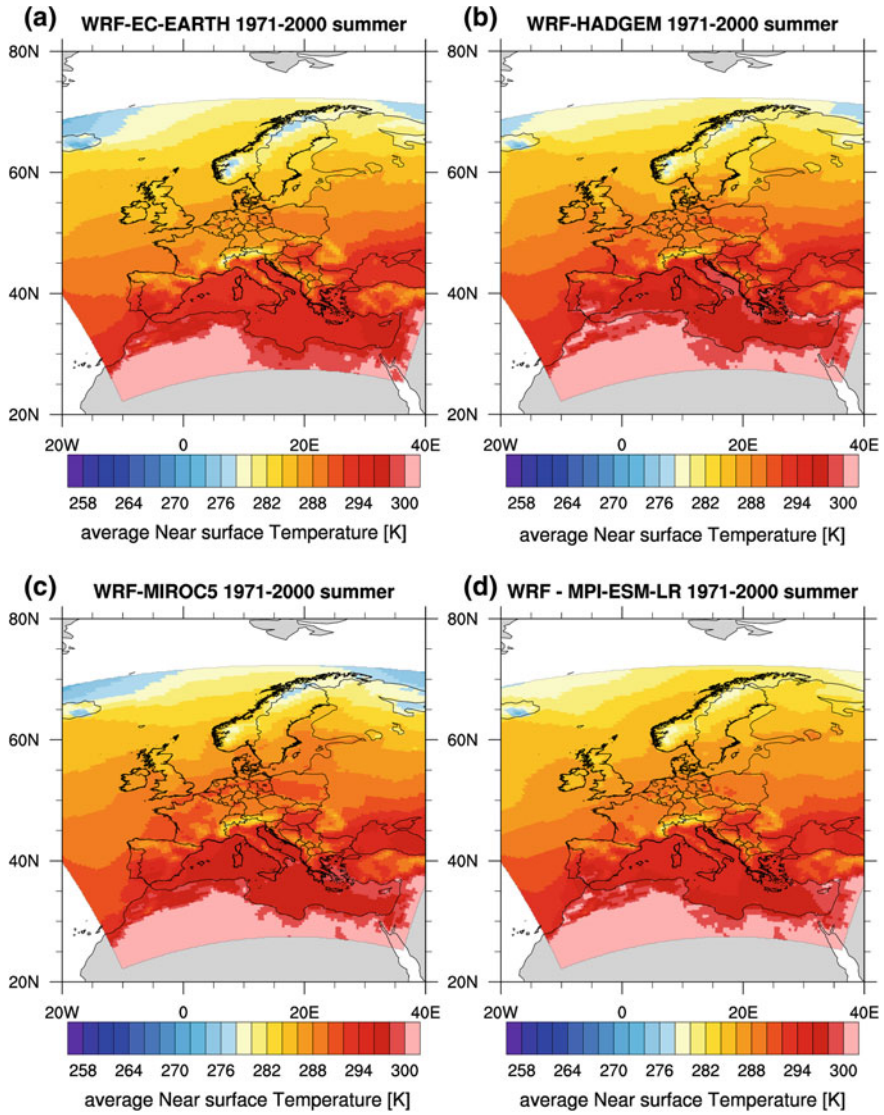
The average near surface temperature for the time period 1971–2000 as simulated by WRF with the four different forcing GCMs is given for the winter season (DJF) in Fig. 3 and for the summer season (JJA) in Fig. 4. The average temperatures during NH winter vary from around 258 K (−15 °C) in North-East to around 290 K (17 °C) over the atlantic ocean in the south-west of the domain. During NH summer the lowest temperatures occur over Iceland in the north-east and over the arctic ocean



**Fig. 2** Average near surface temperature on the 50 km resolution simulations from WRF. Boundary forcing with the different GCMs: EC-EARTH (a), HadGEM2-ESM (b), MIROC5 (c) and MPI-ESM-LR (d)



**Fig. 3** Average near surface temperature on the 50 km resolution simulations from WRF during winter. Boundary forcing with the different GCMs: EC-EARTH (a), HadGEM2-ESM (b), MIROC5 (c) and MPI-ESM-LR (d)



**Fig. 4** Average near surface temperature on the 50km resolution simulations from WRF during summer. Boundary forcing with the different GCMs: EC-EARTH (a), HadGEM2-ESM (b), MIROC5 (c) and MPI-ESM-LR (d)



with 276 K (3 °C). Highest temperatures in Europe aside from the Sahara desert are around 296 K (23 °C) over the mediteranean and the greek islands. Similar as for the annual average, EC-EARTH and MIROC5 indicate lower temperatures (Figs. 3a–c and 4a–c) in both presented seasons compared to the two GCMs HadGEM2-ESM and MPI-ESM-LR (Figs. 3b–d and 4b–d).

### 3.2 Projections for Temperature Changes

The future changes, based on the differences of the simulated average temperatures from 1971–2000 and 2071–2099, is shown in Fig. 5. Following the RCP2.6 scenario, the highest temperature increase reaches 2–2.4 °C above the Norwegian Sea and the Russian peninsula Kola. Following the RCP8.5 scenario, highest temperature changes are simulated above the Russian peninsula with an increase of around 5 °C.

The seasonal changes are displayed in Fig. 6 for the winter and for the summer averages. During winter the RCP2.6 scenario indicates a maximum increase of the temperatures over the peninsula of Russia with up to 4.5 °C (Fig. 6a). For the RCP8.5 scenario the temperature difference is even higher, revealing an increase of up to 6 °C (Fig. 6b). Beside Russia, also the eastern part of Turkey will experience as simulated for this high emission scenario a high temperature increase of around 5 °C compared to the historical period.

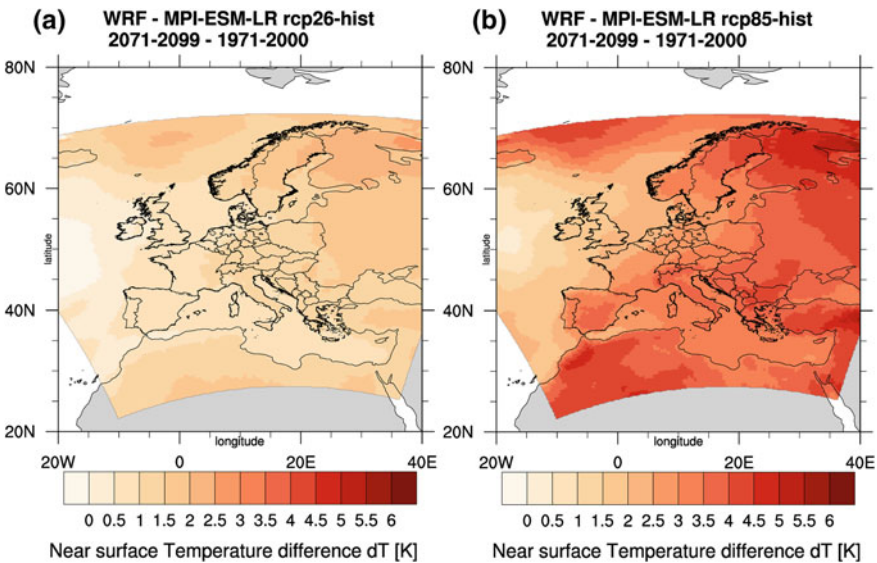
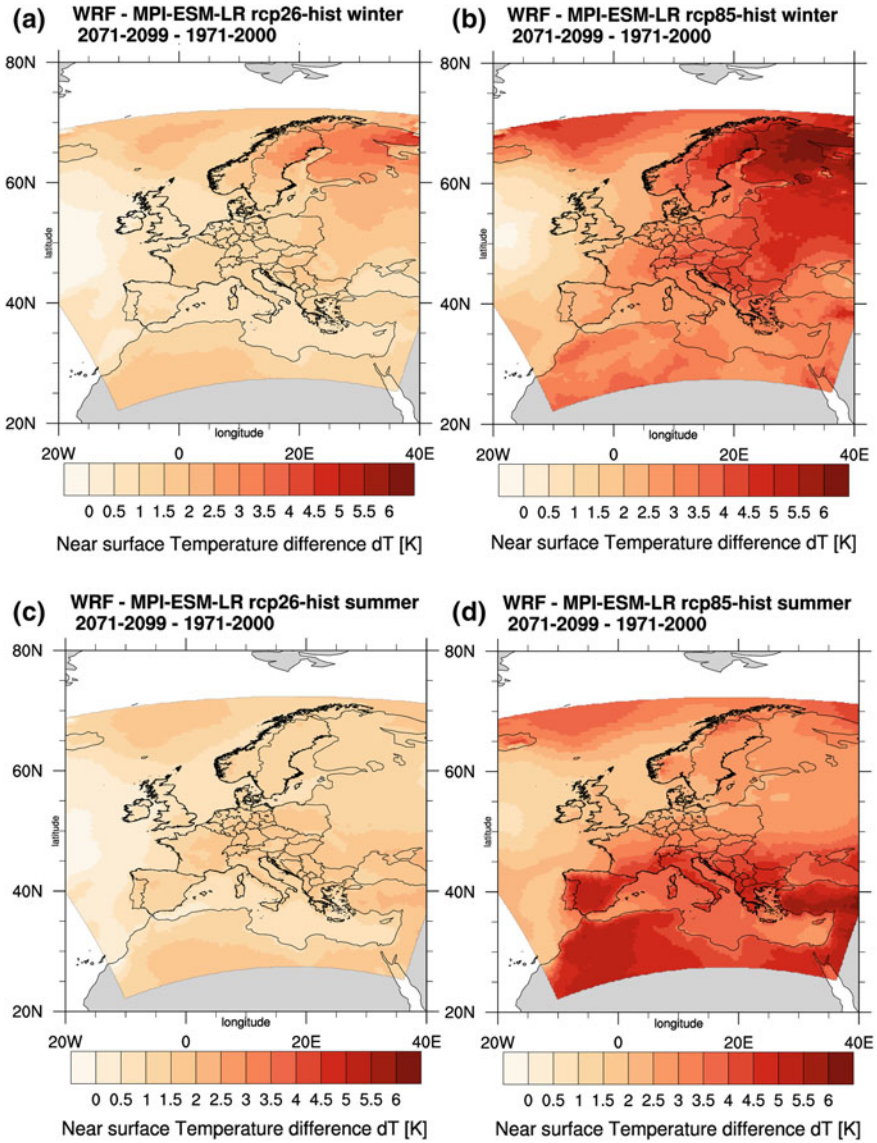


Fig. 5 Differences of the average near surface temperature on the 50km resolution simulations from WRF. Boundary forcing with MPI-ESM-LR for 1971–2100 RCP 26 (a) and RCP8.5 (b)



**Fig. 6** Differences of the average near surface temperature on the 50 km resolution simulations from WRF. Boundary forcing with MPI-ESM-LR for 1971–2100 for the winter season: RCP 26 (a) and RCP8.5 (b) and for the summer season RCP 26 (c) and RCP8.5 (d)

Compared to the temperature changes in winter, the increase of the average summer temperature is less intense for both scenarios. The increase in the temperature will reach around 1.5 °C in central Europe and in the southern part of the norwegian sea for the RCP2.6 scenario (Fig. 6a). For the RCP8.5 scenario the highest temperature increases are simulated over south and south eastern Europe and northern africa indicating a temperature increase of around 5 °C in Spain and up to 6 °C in Turkey.

## 4 Conclusion

The results shown in this chapter highlighted preliminary results based on the near surface temperature of the downscaling of four GCMs (EC-EARTH, HadGEM2-ESM, MIROC5 and MPI-ESM-LR) from the original model grid of around 150 km with WRF to a refined grid on 50 km resolution for the EURO-CORDEX domain. Further downscaling simulations to the 12 km grid for the historical and future time periods are still ongoing. It is expected to finalize the simulations as described in Table 1 by the end of this year (2016) accompanied with further improvements of the projection skills due to a better representation of the orographic effects.

The short insight of the seasonal differences which was shown in this chapter, pointed out the need of further analyses. In particular different variables and climate indices need to be investigated in more detail as the information about future changes of the climate is a major need for cultivators world wide. Precipitation is a parameter which needs to be pointed out and analysed carefully as it showed to be highly variable throughout the year in germany and also Europe.

We would like to point out the importance of analysing a model ensemble rather than choosing a single RCM when predictions of the evolution of climate parameters are being done. To achieve robust predictions, ReKliEs-De is an appropriate platform. Within this project a huge ensemble member of climate simulations can be realized with the contribution of several RCMs applying different techniques and GCMs.

**Acknowledgements** This work is part of the ReKliEs-De project funded by the BMBF (Federal Ministry for Education and Research) and the Research Unit 1695 funded by the DFG (Deutsche Forschungsgemeinschaft). We would like to thank the staff for the support of the DKRZ (Deutsches Klimarechenzentrum) to give access to the GCM data. Computational Resources for the model simulations on the HLRS CRAY XC40 within WRFCLIM were kindly provided by HLRS, we appreciate the great support.

## References

1. Karl, E.: Taylor, Ronald J Stouffer, and Gerald A Meehl. An overview of cmip5 and the experiment design. *Bulletin of the American Meteorological Society* **93**(4), 485–498 (2012)
2. Van Vuuren, Detlef P., Edmonds, Jae, Kainuma, Mikiko, Riahi, Keywan, Thomson, Allison, Hibbard, Kathy, Hurtt, George C., Kram, Tom, Krey, Volker, Lamarque, Jean-Francois, et al.: The representative concentration pathways: an overview. *Climatic change* **109**, 5–31 (2011)

3. Dee, D.P., Uppala, S.M., Simmons, A.J., Paul Berrisford, P., Poli, S., Kobayashi, Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., et al.: The era-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**(656), 553–597 (2011)
4. Kotlarski, Sven, Keuler, Klaus: Ole Bossing Christensen, Augustin Colette, Michel Déqué, Andreas Gobiet, Klaus Goergen, Daniela Jacob, Daniel Lüthi, Erik van Meijgaard, Gregory Nikulin, Christoph Schär, Class Teichmann, Robert Vautard, Kirsten Warrach-Sagi, and Volker Wulfmeyer. Regional climate modeling on european scales: a joint standard evaluation of the euro-cordex rcm ensemble. *Geoscientific Model. Development* **7**(4), 1297–1333 (2014)
5. Kirsten Warrach-Sagi, Thomas Schwitalla, Hans-Stefan Bauer, et al. A regional climate model simulation for euro-cordex with the wrf model. In *Sustained Simulation Performance 2013*, pages 147–157. Springer, 2013
6. William C Skamarock, Joseph B Klemp, Jimy Dudhia, David O Gill, Dale M Barker, Wei Wang, and Jordan G Powers. A description of the advanced research wrf version 2. Technical report, DTIC Document, 2005
7. Chen, Fei, Dudhia, Jimy: Coupling an advanced land surface-hydrology model with the penn state-ncar mm5 modeling system. part i: Model implementation and sensitivity. *Monthly Weather Review* **129**(4), 569–585 (2001)
8. Warrach-Sagi, Kirsten, Schwitalla, Thomas, Wulfmeyer, Volker, Bauer, Hans-Stefan: Evaluation of a climate simulation in europe based on the wrf-noah model system: precipitation in germany. *Climate Dynamics* **41**(3–4), 755–774 (2013)