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Evaluation of Agricultural Related Extreme Events in Hindcast COSMO-CLM Simulations over Central Europe

Huan Zhang * and Merja H. Tölle

Center for Environmental Systems Research (CESR), University of Kassel, Kassel, Germany; merja.toelle@uni-kassel.de

* Correspondence: huan.zhang@uni-kassel.de

Abstract: High horizontal resolution regional climate model simulations serve as forcing data for crop and dynamic vegetation models to generate possible scenarios for the future concerning effects of climate change on crop yields and pollinators. Here, we performed convection-permitting hindcast simulations with the regional climate model COSMO5.0-CLM15 (CCLM) from 1980 to 2015 with a spin-up starting at 1979. The model was driven with hourly ERA5 data, which is the latest climate reanalysis product by ECMWF, and directly downscaled to 3 km horizontal resolution over central Europe. The land-use classes are described by ECOCLIMAP, and the soil type and depth by HWSD. The evaluation is carried out in terms of temperature, precipitation, and extreme weather indices, comparing CCLM output with the gridded observational dataset HYRAS from the German Weather Service. While CCLM inherits a warm and dry summer bias found in its parent model, it reproduces the main features of the recent past climate of central Europe, including the seasonal mean climate patterns and probability density distributions. Furthermore, the model catches extreme weather events related to heat, drought, heavy rains, flooding, and spring frost events. The results highlight the possibility to directly downscale ERA5 data with regional climate models avoiding the multiple nesting approach and high computational costs. This study adds confidence to convection-permitting climate projections of future changes in agricultural extreme events.

Keywords: hindcast run; dynamical downscaling; model bias; agricultural related extreme events

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1. Introduction

Climate change is going on at a fast pace. Many sectors are affected by present and future global warming, which is projected by climate models. Climate change information is needed at regional and local scales for adaption and mitigation strategies. Furthermore, future scenarios concerning effects of climate change on crop yields and pollinators is still in its infant shoes. One reason among others is that the climate forcing data of a regional climate model to drive dynamic vegetation models are too coarse to generate local scale yield estimates, and a large precipitation bias compared to observational data of about 40% is inherent in the coarse climate model data (Ban et al. 2020). Statistical bias correction of the forcing data for impact models introduce another uncertainty into the local weather statistics.

The horizontal resolution of regional climate models decreased in the recent past decades in coordinated ensemble of climate simulations projects from 50 km (PRUDENCE project; Christensen et al. 2007) to 25 km (ENSEMBLES project) and to 12 km (PRINCIPLES and EURO-CORDEX project; Giorgi 2019). These projects assessed the uncertainty of RCM projections and of impact assessment studies by evaluating the systematic model behavior and biases. Kotlarski et al. 2014 found only small differences in seasonal mean quantities between 50 km and 12 km horizontal resolution simulations. At the same time convection-permitting simulations emerged at a kilometer-scale grid (Prein et al. 2015). These studies have been conducted for the recent past, as well as for projected future conditions and over different geographical regions at horizontal resolutions below 4 km, in which deep convection parameterization is switched off. Improvements were shown for land atmosphere couplings, temperature representation, in the timing and diurnal cycle of precipitation and the spatial structure of temperature and precipitation (Kendon et al. 2014, Ban et al. 2014, Tölle et al. 2014, Tölle et al. 2018).

Convection-permitting regional climate models at a few kilometer scale offer a tool to force dynamic vegetation models at local and regional scales on climate time scales without bias correction assuming that the bias is in the uncertainty range of observations. Such high horizontal resolution simulations realistically capture convection and snowfall in Europe (Leutwyler, Coppola et al. 2020; Ban et al. 2020) and over the Rocky Mountains in the U.S. (Rasmussen 2014, Liu et al. 2017). Investigations of climate and climate change impacts on yields and biodiversity would benefit of such high-resolution simulations at the climate time scale.

Inherent are the computational costs of such high horizontal resolution simulations. Multiple nesting steps are performed to reach the kilometer scale. A way around would be direct downscaling experiments. First results of direct downscaling simulations forced by ERA-Interim reanalysis generated realistically different convection events over an extended domain covering the Alps in Europe (Coppola et al. 2020). This is a promising way forward for reducing computational costs.

Multisectoral analysis of climate and land use change impacts on pollinators, plant diversity and crops yields (MAPPY) project combines for the first time diverse research sectors in a coordinated way using convection-permitting simulations for impact assessments on crop yields and pollinators. Central Europe and Spain has been defined as target areas for these experiment efforts.

In this manuscript, we present the first multi-decade climate evaluation simulations at convection-permitting resolution using ERA5 reanalysis as forcing. The main goal is to evaluate this multi decade long simulation against available high-resolution observations. Here we show the benefit of convection-permitting simulations from direction downscaling experiments for agricultural related extreme events over Central Europe. The objective is to investigate extreme weather events related to heat, drought, heavy rains, flooding, and spring frost events. ERA5 reanalysis data are directly downscaled with the regional climate model COSMO-CLM (Rockel et al. 2008) for the period 1980 to 2015.

Section 2 of this manuscript represents the regional climate model, data and methods used in this study. In section 3 results on the evaluation of precipitation and temperature and their agricultural related extremes are provided and discussed. A summary and conclusions are provided in section 4.

2. Methods

2.1. Model

Simulations are conducted as a direct downscaling experiment at convection-permitting horizontal resolution (about 3 km) over Central Europe within the frame of MAPPY. The region of the simulation domain is shown in Figure 1. The limited-area model used in this study is the COSMO model (Baldauf et al. 2011) in climate mode (Rockel et al. 2008) designed for applications for the meso-β to the meso-γ scales. The version used is COSMO-CLM v5.15. The selection of different dynamical and physical parameterization schemes allow the application of the model for a wide range of spatial and temporal scales. The model integrates the fully compressible, non-hydrostatic thermo-dynamical equations in a moist atmosphere. The equations are solved numerically on an Arakawa-C staggered grid (Arakawa and Lamb, 1977) in rotated coordinates with a Runge-Kutta time-stepping scheme (Wicker and Skamarock, 2002). The model uses a vertical terrain-following height coordinate (Doms and Baldauf, 2015). A one-moment micro-physics scheme including five categories of hydrometeors (cloud, rain, snow, ice, and graupel) is used for the parameterization of precipitation. Soil processes are presented by the multi-layer soil model TERRA-ML (Schrodin and Heise, 2002). The simulations used a modified Tiedtke parameterization of shallow convection. Deep convection is switched off allowing resolving convective processes. The radiative transfer scheme is based on Ritter and Geleyn (1992), and a turbulent kinetic energy-based surface transfer and planetary boundary layer parameterization (Raschendorfer, 2001) is applied. The land-use classes are described by ECOCLIMAP, and the soil type and depth by HWSD.

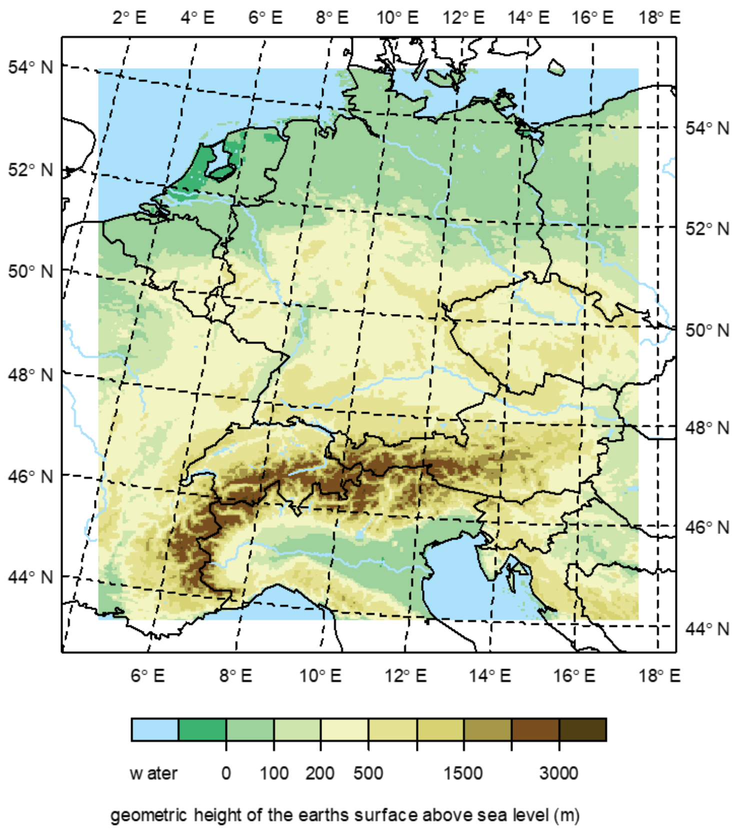


Figure 1. Orography of the model domain covering Central Europe without the sponge zone.

Simulation results are investigated for performance under present-day climate conditions. Thus, hourly ERA5 reanalysis (Hersbach et al, 2018) are downscaled for multiple decades from 1980 to 2015. ERA5 is the fifth generation model reanalysis of the global climate from the European Centre for Medium-range Weather Forecasts (ECMWF). A spin-up year 1979 is excluded from the analysis. A region of 23 grid points at each side are removed to exclude any lateral boundary artefacts.

2.2. Statistical analysis

High-resolution observational precipitation and temperature datasets are used for the evaluation analysis. The daily gridded datasets at five-kilometer horizontal resolution are from HYRAS (Razafimaharo et al. 2020) available over entire Germany and adjacent regions covering the period 1951-2015. It is generated using station data. Note that gridded observational data include a bias to real observations. Shortcomings, for example, could be associated with underestimation of precipitation or using interpolation methods.

Simulated temperature and precipitation are evaluated for absolute and relative biases, respectively, relative to the observations. The region selected depends on the coverage of the observational data of HYRAS. The absolute bias is the difference of model minus observations. The relative bias is the difference of model minus observations divided by observations. The simulation results are remapped to the observational grid prior to the analysis using bi-linear remapping. This ensures a grid-cell-by-grid-cell comparison between model and observations.

The analysis is done for the following indices listed in Table 1 regarding agricultural related extremes. These climate indices of temperature and precipitation extremes are related to droughts, floods, heat/cold waves and agriculture-specific events. We evaluate the CCLM simulation with respect to these indices. Often the RMSE (root-mean-square error) between the simulations and the observations is calculated to reflect the quality of simulations. As the selected indices have different units and ranges, here we calculate the standardized RMSE, which is adopted from Tschurr et al. (2020).

$$\frac{RMSE(I)}{SD(I)} = \frac{\sqrt{mean((sim(I)_g - obs(I)_g)^2}}{SD(I)} \quad (1)$$

where g indicates grid point; I indicates given index, *obs* are the observational data, and *sim* are the simulations data. The climate index is rated as well-performing when the standardized RMSE value is below 0.5, and as biased otherwise as suggested by Tschurr et al. (2020).

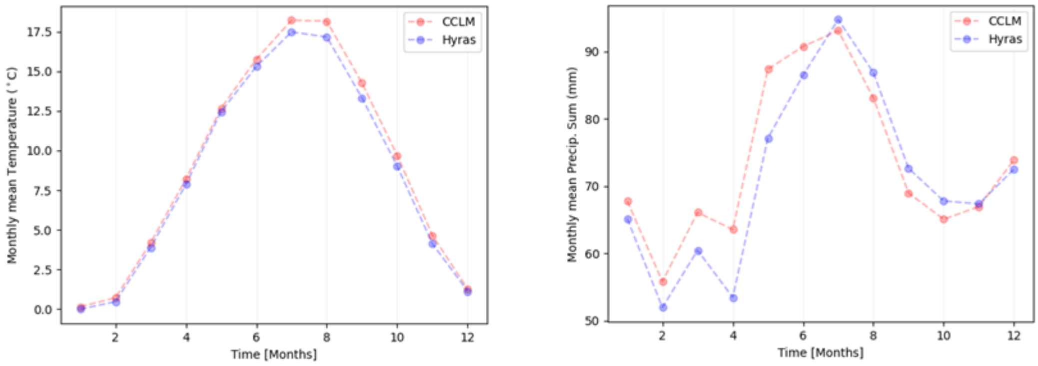
Table 1. Description and definition of the extreme indices used in this study.

CDD	Consecutive Dry Days	The number of dry periods of more than 5 days, PR<1mm
CWD	Consecutive Wet Days	The number of wet periods of more than 5 days, PR≥1mm
ID	Ice Days	The number of icy days with TX < 0°C
CFD	Consecutive Frost Days	The number of frost periods of more than 5 days, TN < 0°C
CSU	Consecutive Summer Days	The number of summer periods of more than 5 days, TX > 25°C
GSL	Growing Season Length	The number of days between: first occurrence of at least 6 consecutive days with TG > 5 °C, first occurrence of at least 6 consecutive days with TG < 5 °C within the last 6 months
GSL2	Growing Season Starting Day	The first occurrence of at least 6 consecutive days with TG > 5 °C

*PR: daily precipitation; TX: daily maximum temperature; TN: daily minimum temperature; TG: daily mean temperature.

3. Results and Discussion

Here we show the evaluation results between the simulated climate variables (temperature and precipitation) and the observed ones with respect to the annual cycle, spatial distribution, PDF (probability density function) and above mentioned extreme events.



(**a**) (**b**)

Figure 2. Annual cycle of temperature (°C) and precipitation (mm/month) for model simulations and observation data.

The observed annual cycle is well reproduced in the model with a small bias range (Figure 2). The temperature biases range between 0-1.0°C depending on the season and the precipitation biases range between -5% and 20%. In detail, the simulated summer tends to be 0.5-1.0°C warmer than the observed one, and the simulated winter is almost as cold as the observed one (biases below 0.3°C). For precipitation, the modeled spring season tends to be wetter (10-20%) and the autumn tends to be slightly drier (biases within -10%).

The spatial distribution of daily precipitation and temperature shows good agreement with model simulations (Figures 3 to 4). The results are presented for the winter and summer seasons. Most of the northern region tend to be colder in winter (biases within 1.0°C) and slightly warmer in summer (biases within 0.5°C). The northern part of the Alps is constantly warmer and the southern part of the Alps colder in the model (biases range between -2°C and 2°C). For precipitation, most western part of the domain tend to be drier and the eastern part wetter in model; and the Alps region shows the highest wet biases. The bias is higher in the winter season than summer. The winter season is dominated by mid-latitude storms, whereas isolated, convective events occur in the summer season. High precipitation in the model simulations occur in regions with high orography in both winter and summer. Some of these biases might by inherited by the driving model.

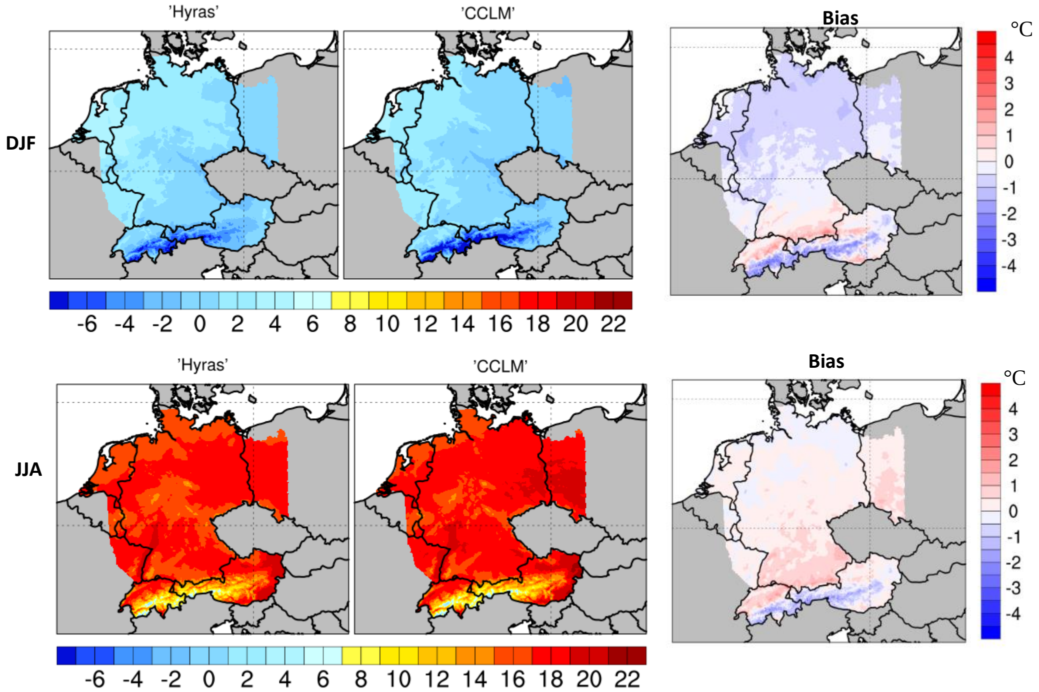


Figure 3. The spatial pattern of mean seasonal temperature for the observation and the simulation (left panel) and mean seasonal temperature bias (°C) for the period 1980–2015. Upper rows: winter (DJF), lower rows: summer (JJA).

Simulated precipitation amounts are higher over the Alps especially in winter compared to observations. Precipitation all-year round and snow in winter is difficult to measure in the Alps. Furthermore, wind introduces a systematic rain gauge under-catch. Most stations in mountainous regions are located in valleys, which increases the uncertainty estimates of mountain top and particularly mountain slopes. This may be the reason why the observations seem to be lower over the Alps compared to the 3 km simulation. Recent studies have shown that the 3 km model may estimate snowfall better than observations due to the ability to capture the main vertical motion associated with snow formation at these scales (Lundquist et al. 2020) and improvements in the microphysical parameterizations (Liu et al. 2011).

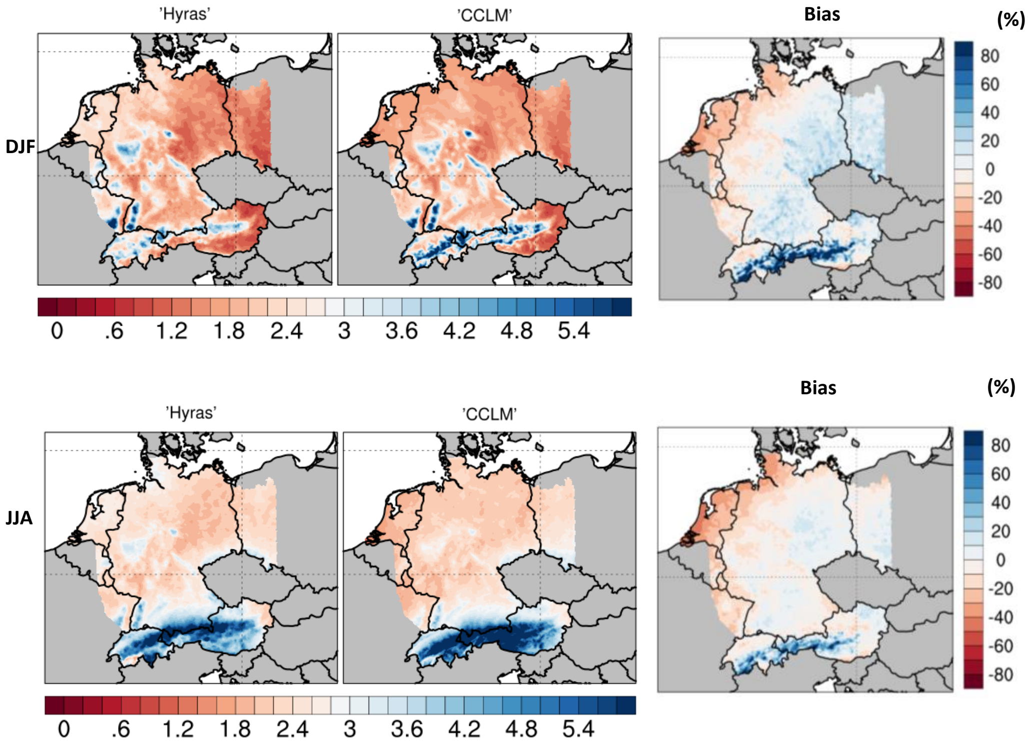


Figure 4. As Fig. 3 but for spatial pattern of daily precipitation and the mean relative seasonal precipitation bias (%).

Figures 5 and 6 show the PDF (probability density function) of averaged daily temperature and precipitation over the domain in the winter and summer season. The domain experiences slightly less warm events in the winter season, and less cold and more warm events in the summer season in the model. The simulation well reproduces the PDF of the observed precipitation events in the winter season. In the summer season, the model generates more extreme precipitation than the observations.

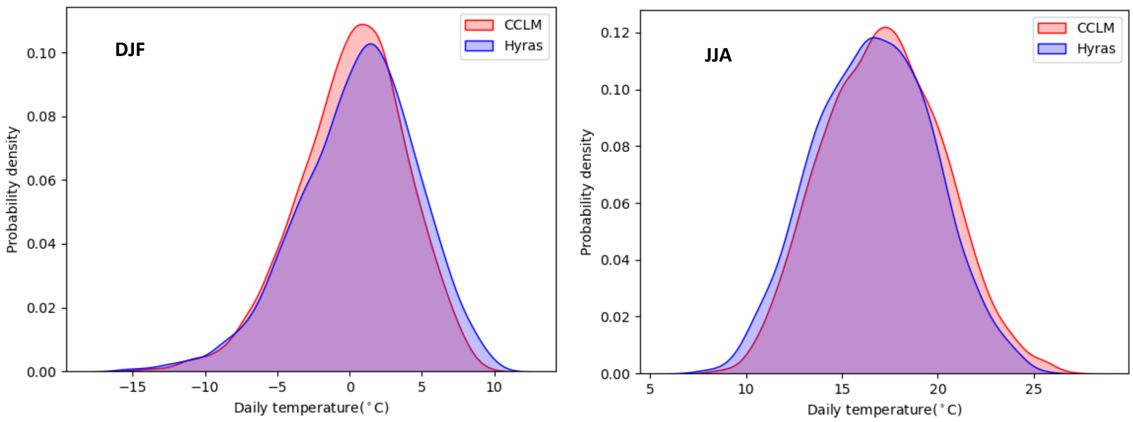


Figure 5. Probability density function of simulated (red) and observed (blue) daily mean temperature over the domain. Left: winter (DJF), right: summer (JJA).

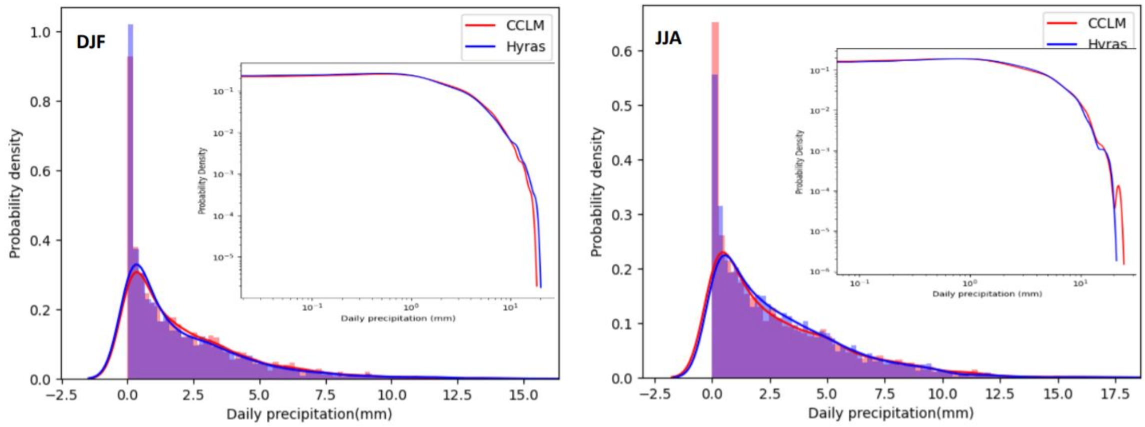


Figure 6. Probability density function of simulated (red) and observed (blue) daily precipitation over the domain. Left: winter (DJF), right: summer (JJA).

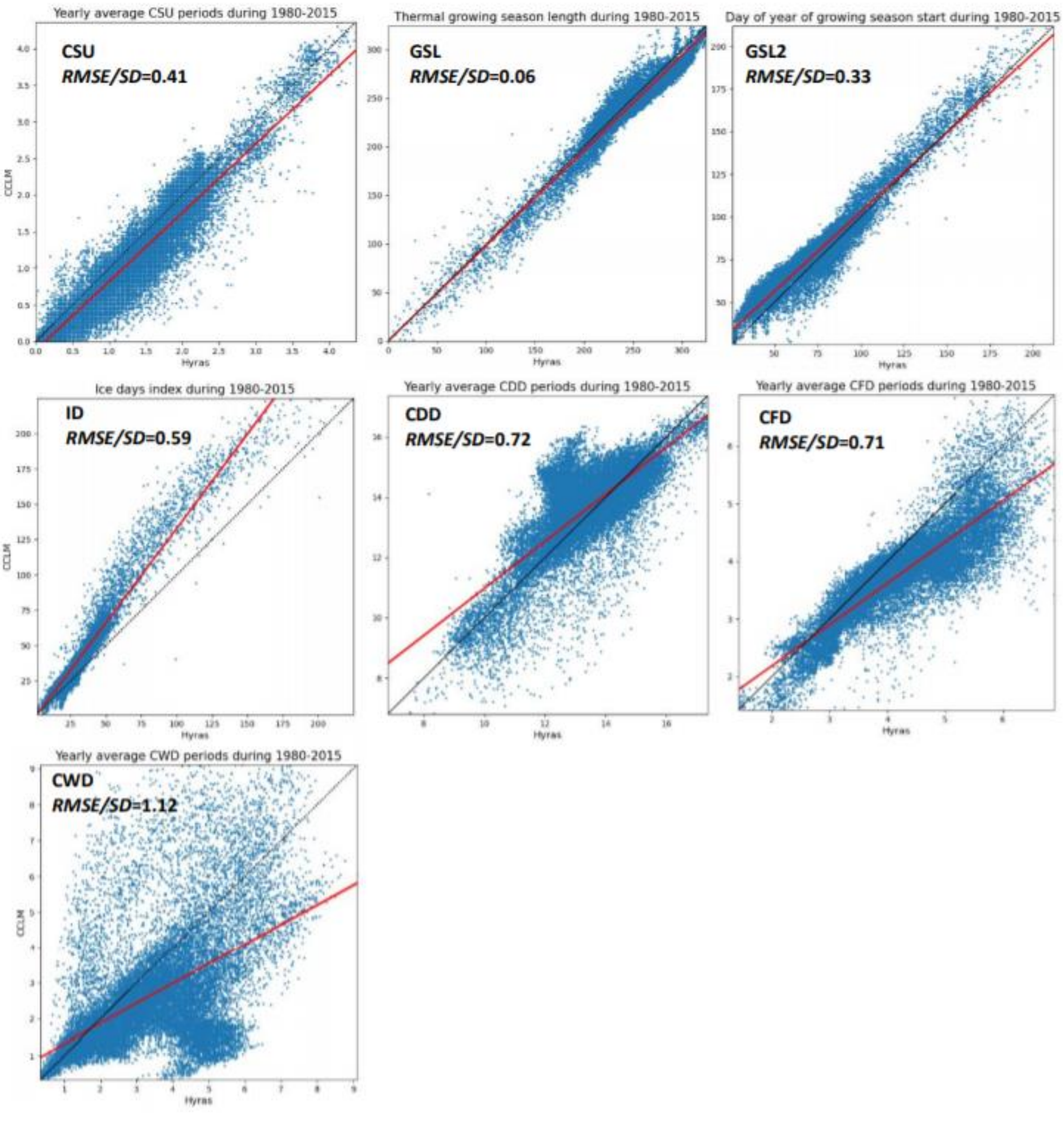


Figure 7. Validation of the extreme events indices, shown as scatter plots of observed (x-axis) and simulated (y-axis) values during 1980-2015. The indicated performance metric is defined as the standardized RMSE divided by the standard deviation of observed values across grid points (RMSE/SD < 0.5: well simulated; RMSE/SD > 0.5: relatively worse performance). Red line: the linear trend; the black dashed line: the perfect correlation between observed and simulated data.

Both the starting day of the growing season and the growing season length reveal a good performance with standardized RMSEs below 0.5, see Figure 7. Heat wave events (indicated by CSU) are well captured in the model with standardized RMSEs also below 0.5. Meanwhile, the model tends to generate less cold wave and droughts at most grid points (the simulated CDD and CFD values are smaller than the observed ones). The simulated ice days occur more frequently than in the observations. The model somehow failed to capture the floods, as the simulated CWD are different to the observed ones at many grid points.

Generally, the analysis shows that in all regions and for all indices the uncertainty ranges are small for convection-permitting simulations. The spatial representation of precipitation and temperature is very similar to observations.

4. Summary and Conclusions

Simulated precipitation and temperature were evaluated against observations in this study for their biases and agricultural related extremes of a new high-resolution climate simulation with a direct-downscaling approach at 3 km horizontal resolution. The simulation is driven by ERA5 reanalysis integrated over a 36-year long period. The model performance is analyzed by the absolute and relative biases and indices, which are important for agriculture. Generally, the spatial patterns and variability are well represented by the km-scale simulation on daily time scales. The uncertainty ranges are reduced by half with this high-resolution simulation compared to EURO-CORDEX simulations with coarser horizontal resolution, see Kotlarski et al. (2014). The benefit of convection-permitting simulations is that the model got rid of the uncertainty due to deep convection scheme since the deep convection parameterization is switched off. A more realistic orography and land use add further value to kilometer-scale simulations for providing local scale climate information.

The direct downscaling simulations perform in a realistic way and can be recommended without the intermediate nest. Downscaling directly from reanalysis without an intermediate nest has a high downscaling ratio, and can introduce significant lateral boundary artefacts. However, since the lateral boundaries are far away, and the simulation domain is big enough, it is not an issue.

Further simulations and analysis will be performed over Spain and the future period until 2070.

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