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Synthesis on the existing simulations at M25

D34b_Lot2.4.3.3

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1. Introduction

The goals of C3S_34b_Lot240 are to (i) monitor the advancement by regular verifications of the progressive fulfilment of the spread requirements defined in C3S_34b_Lot210; (ii) perform, over a few key metrics the evaluation of existing and new simulations allowing a scientific "health check" of all simulations as they are produced, and (iii) provide regular syntheses and demonstrations.

In this report we review the state of the EURO-CORDEX ensemble as of November 2019. We first describe the current status of the matrix and we perform an assessment of the simulations. These simulations are included in datasets that were produced outside of the project completed by the simulations produced in the project. All are now published on the Earth System Grid Federation.

For the assessment, a set of diagnostics and analyses is proposed. The set consists in a coordinated analysis of current biases and future trends over a number of indices in the form of maps and tables of numerical values for each PRUDENCE region, which are a number of European regions frequently used for climate model assessment. All these results are developed in two main articles (Vautard et al., 2019; Coppola et al., 2019), and we provide here only a short summary of these results. Other specific analyses are mentioned in a separate section.

After the key findings (Section 2), the coordinated evaluation design is described in Section 3 together with the model ensemble and the set of diagnostics. In Section 4 we present examples of the main results. Specific analyses are provided in Section 5.

2. Key findings

1.1 Concerning model biases

1. **As of 15 November 2019, 55 Euro-CORDEX climate projection simulations were available (vs. 34 in January 2019), using 8 Global climate models (GCMs) simulations downscaled by 11 regional climate models (RCMs), for the historical period and the RCP8.5. 29 of these 55 simulations have been produced within C3S_34b_Lot2. These climate projections allow a better understanding of the source of biases and drivers of trends of climate variables;**

2. **No GCM-RCM simulation analyzed model exhibit outlying temperature biases, despite some systematic biases across regions for a few models; GCMs and RCMs generally have a cold bias in North and Western Europe and a warm bias in South-Eastern Europe; This trend is similar for means and hot temperatures; biases in frost days have varying patterns;**

3. **RCMs do not improve GCM temperature biases; Maximum and mean temperature bias patterns depend mostly on the GCM, while minimum temperature bias patterns are rather driven by RCMs;**

4. **RCMs exhibit a systematic wet bias as compared to E-OBS observations; the biases appear to originate from both RCMs and GCMs; Models generally overestimate heavy precipitations as observed in E-OBS, especially in winter;**

5. **Wet RCM biases are also present in the water balance variables such as evaporation, runoff and soil moisture. Such variables show changes generally depending on the RCM to the largest extent;**

6. **Models generally reproduce observed dynamical patterns and surface winds well; A general underestimation of mean sea level pressure is found over North-Western Europe and the North-East Atlantic. A general overestimation of ERA5 surface winds is found in simulations but could not be explained here; part of the difference could come from a too low mean sea level pressure over North-Western Europe, but differences in parameterization of surface drag may also play a role. Part of the bias could potentially be due to a negative bias of the surface wind speed in ERA5;**

7. **RCM sea level pressure patterns are generally well correlated with driving GCM patterns, with pattern correlations of about 0.9 in winter and lower ones in summer (when the driving large-scale flow is weaker and other drivers such as soil moisture can be important);**

8. **Models surface radiation biases range from about -50 W/m² to about +50 W/m². Mean negative biases (10-20 W/m²) affect the Iberian Peninsula, and mean positive biases of the same amplitude affect Scandinavia. More analyses are needed to understand how these biases affected by clouds and aerosols uncertainties;**

9. **The biases for a number of sectoral impact-indices have been analyzed, including extremes such as extreme heat or heat stress. Extreme heat (resp. cold) indices generally show negative (resp. neutral to positive) biases; extreme precipitation and wind biases are positive; Drought index biases are more balanced; most biases of extreme indices are driven by the RCMs, except for drought;**

1.2 Concerning trends

1. **A combined analysis of GCMs and RCMs projections is conducted for Europe; projections are available from 11 RCM driven by 8 GCMs for two climate scenarios: RCP2.6 and RCP8.5. The regional RCM ensemble results are compared with two GCM ensembles: i) 12 simulations with the 8 driving CMIP5 global models and ii) an ensemble of 12 GCMs available from the most recent CMIP6 project;**

2. **Warming is largest for both the RCM ensemble and the two GCM ensembles over Northern Europe in winter, associated with maximum precipitation increase, and maximum over Mediterranean and Southern European regions in summer, associated with maximum precipitation decrease;**

3. **The available set of 12 CMIP6 projections indicate highest values of warming and highest precipitation changes while EURO-CORDEX warms the least and has lower precipitation changes but with increased spatial details on complex topography, along the coasts and islands and a more pronounced land-sea contrast;**

4. **An increase of warm extremes and decrease of cold extremes with the analogous behavior for the RCM ensemble and the two GCM ensembles are found, with a similar order in change magnitude as for temperature;**

5. **RCMs indicate important change details such as an increase of the number of high heat stress thresholds (eg. Wet bulb globe temperature above (WBGT)>35°C) in low-lying coastal areas of Southern Europe by the end of the century;**

1.3 Concerning specific studies

A comparison of PRIMAVERA global high-resolution (25-50 km) and EURO-CORDEX (12km and 50km) regional ensembles was carried out in terms of daily precipitation distribution; the results show very similar distribution between the two ensembles, with a clear improvement compared to CMIP5 GCMs. Differences are mainly for extreme precipitation over orography and coastal regions. This is the first comparison of an ensemble of high-resolution GCMs at the scale of the EURO-CORDEX models. An in-depth analysis and understanding of differences between models may improve coordination of GCM and RCM simulations for future model intercomparison projects.

3. Model ensemble and diagnostics

The ensemble of RCM-simulations available on the ESGF nodes on 15/11/2019 are considered, including different members of an ensemble using the same models (GCM, RCM), and different versions of the same model (for REMO). Two WRF versions were used but were considered as two different models due to a number of differences in parameterizations and implementation. Eleven RCMs and eight GCMs were used. For some GCMs three different ensemble members differing only in initial conditions at the start of the simulation in the 19th century were used. These three-member ensembles with three different realisations can be used to enable assessment of natural variability. In total there are 55 GCM-RCM simulations assessed. Table 1 lists the simulations that were analyzed. For some of the simulations, some dynamical fields were not available (see footnotes).

Table 1. Simulations analyzed in this study, which cover both historical and RCP8.5 periods. The name of GCM simulations is given as ”GCM (rR)” where ”R” is a number given by the institute running the GCMs denoting the model ensemble realization. Footnotes (blue numbers in the table): [1]: This simulation does not have sea-level pressure available; [2] This REMO version is REMO2009 while other versions are REMO2015; [3]: This simulation does not have daily surface wind available; [4] This simulation does not have daily maximum surface wind available; [5] This simulation does not have daily sea level pressure fields; [6] this simulation does not have surface solar downward radiation (rsds) field analyzed; [7] this simulation does not have WBGT index analyzed; [8] this simulation does not have total runoff; [9] this simulation does not have evaporation or total soil moisture content.

RCM-GCM	CNRM r1	ECEARTH r12, r1, r3	HADGEM r1	MPI r1, r2, r3	NORESM r1	IPSL r1	CANESM r1	MIROC r1
CCLM		r12	r1	r1			4	4
HIRHAM		r12,r1,r3						
RACMO		r12,r1,r3		r1				
RCA		r12,r1,r3		r1,r3				
REMO		r12		r1 2 ,r2 2 ,r3				
WRF361H		r12 4,5,6,7	4,5,6,7,8	r1 4,5,6,7				
WRF381P	9		9		9	6,9		
ALADIN53	3,4							
ALADIN63								
REGCM			1	r1 1				
COSMO -crCLIM		r12 6		r1,r2 6,r3				

Diagnostics

In the evaluation presented in Vautard et al. (2019), a number of variables and indices are analyzed. These are presented in Tables 2 and 3. The main variables (precipitation, temperature, wind, sea level pressure and radiation) are analyzed, with seasonal decomposition for temperature and precipitation only. Other indices include extreme indices and impact-oriented indices, for a few sectors. For instance the Heating Degree Day (HDD) index and Cooling Degree Day (CDD) indices are indicative for energy demand, while the Growing Degree Day (GDD) and the Length of Frost Free Period (LFFP) are indicative for agriculture. The simplified Wet Bulb Globe Temperature (WBGT) as well as the number of days above 35°C are indicative for health and labor productivity.

Similar indices are also used for the projections in Coppola et al. (2019).

Table 2. Variables used in this study with reference datasets and evaluation period. For details of the reference data sets see Vautard et al. (2020).

Variable	ECV involved CF variable name	Observation data set	Season
daily mean temperature	tas	E-OBSv17	Year, DJF and JJA
daily max temperature	tasmax	E-OBSv17	Year, DJF and JJA
daily min temperature	tasmin	E-OBSv17	Year, DJF and JJA
daily precipitation amount	pr	E-OBSv17	Year, DJF and JJA
daily mean surface wind	sfcWind	ERA5	Year
sea level pressure	psl	ERA5	Year
surface solar radiation	rsds	HELIOSAT	Year
evaporation	evspsbl	/	DJF and JJA
runoff	mrro	/	DJF and JJA
soil moisture	mrso	/	DJF and JJA

Table 3. Indices used in this study with reference datasets, evaluation period and concerned economic sectors. For details of indices and reference data sets see Vautard et al. (2020).

Index	ECV involved CF variable name	Observation dataset used for assessment	Link to sector	Category of extreme or impact-oriented index
Annual maximum temperature (TXx)	tasmax	E-OBSv17	all	Warm
Number of days year with maximum temperature above 35°C	tasmax	E-OBSv17	agriculture, health	Warm
Number of days per year with WBGT > 31°C	tasmax, huss, psl	ERA5	health	Warm
Length of frost-free period (LFFP)	tasmin	E-OBSv17	agriculture, ecosystems	Warm
Growing degree days (GDD) above 5°C	tas	E-OBSv17	agriculture, ecosystems	Warm
Cooling degree day (CDD) above 22°C	tas, tasmin, tasmax	E-OBSv17	energy	Warm
Yearly minimum temperature (TNn)	tasmin	E-OBSv17	all	Cold
Number of frost days per year	tasmin	E-OBSv17	agriculture, ecosystems	Cold
Heating degree day (HDD) below 15.5°C	tas, tasmin, tasmax	E-OBSv17	energy	Cold
The 99th percentile of daily precipitation amount for all days (R99a)	pr	E-OBSv17	flood	Wet
Annual maximum of daily precipitation amount (RX1d)	pr	E-OBSv17	flood	Wet
Number of drought spells per decade (DF6)	pr	E-OBSv17	agriculture	Dry
Annual maximum surface wind (SWXx)	sfcWindmax	ERA5	storm	Storm

Time periods

For the analysis of biases, we considered a single reference climate period which corresponds to the WMO period definition (1981-2010); since in CMIP5/CORDEX the historical period stops in 2005, we completed this period with RCP8.5 simulations until 2010. The choice of RCP8.5 was made as this is the scenario for which all RCM-GCM combinations exist. As differences between the RCPs are very small in the first decades this is not expected to have any impact on the analysis.

Time periods considered for the analysis of the climate change projections are; (i) the reference period as above, (ii) a mid-century period (2041-2070) and a far-future period (2071-2100).

Changes are calculated as differences in the climate between the future periods and the reference period. Indices are for means and extremes of temperature, precipitation, sea level pressure, surface winds and radiation.

4. Example of main results

We show here examples of our main results, and the reader is referred to the main articles by Vautard et al. (2019) and Coppola et al. (2019) for detailed results.

1.4 Model biases

Results include for instance maps of ensemble median bias and extreme biases taken as the 5% and 95% from the individual model simulations in the ensemble. Figure 1 shows for biases for temperature in winter and in summer as an example. In this case a general negative bias is found for the ensemble median.

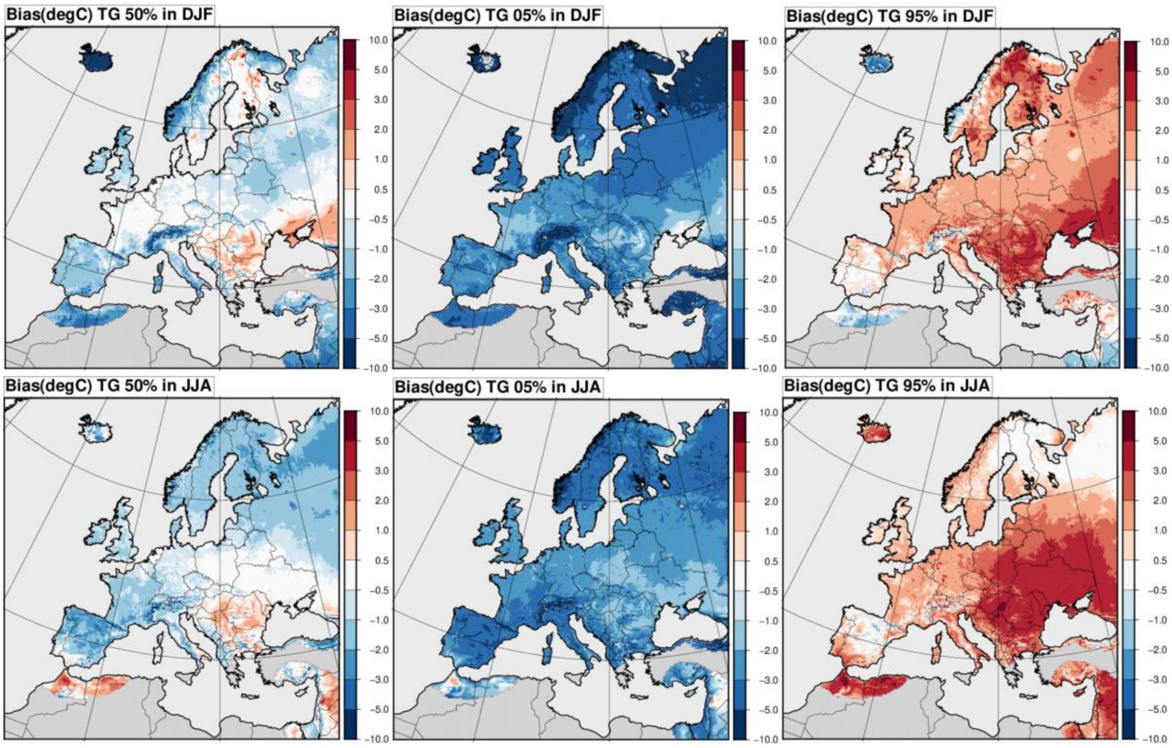

Figure 1 Median (left), 5% (middle) and 95% (right) biases of the EURO-CORDEX ensemble for temperature in winter (DJF, top) and summer (JJA, bottom).

The ensemble median indicates, generally, a positive bias for precipitation especially in winter. Also in summer positive biases are predominating, especially in Southern Europe (Figure 2).

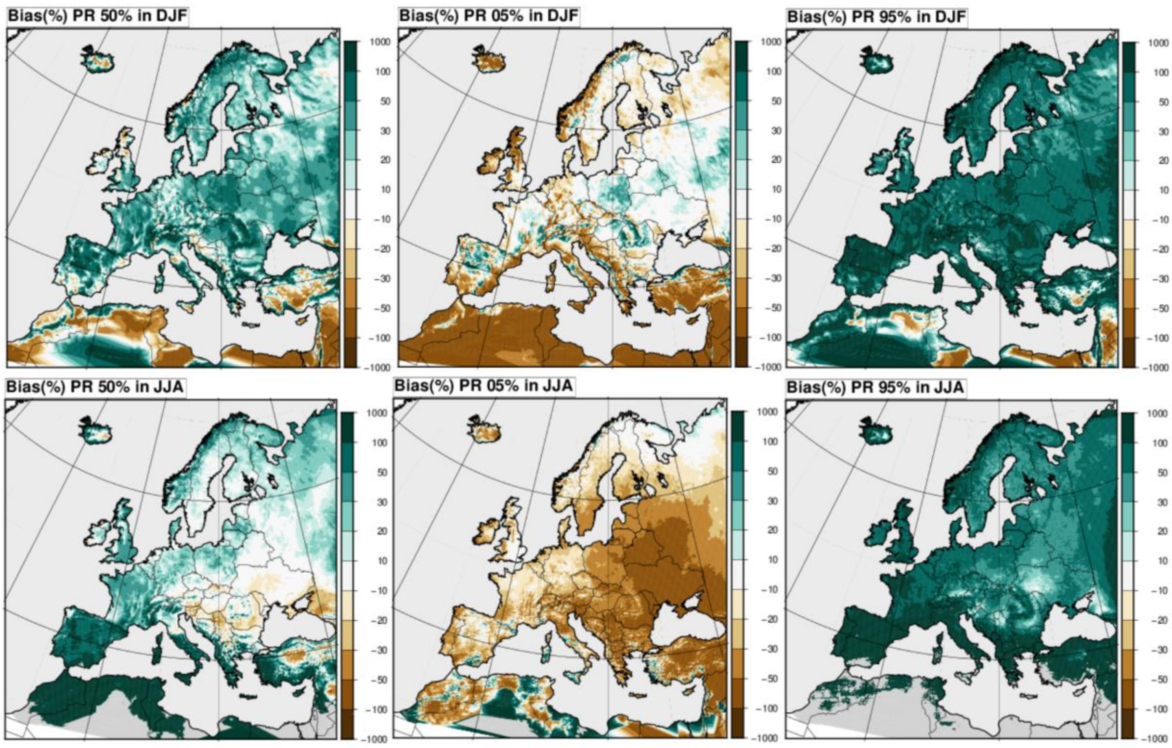

Figure 2. As Figure 1 but for precipitation biases.

The analysis also includes a decomposition of biases by PRUDENCE regions, and an analysis of variance to understand if bias variability is due to RCMs or GCMs. It includes also a proposition of methodology for model ranking, which can be based on user requirement, but kept generic here. For instance, Figure 3 shows the ranking of models based on individual ranking from each variable or index used and each region. In this case, the bias is first averaged over the region, then the absolute difference with respect to observations is calculated, and finally the ranking is made based on this absolute bias.

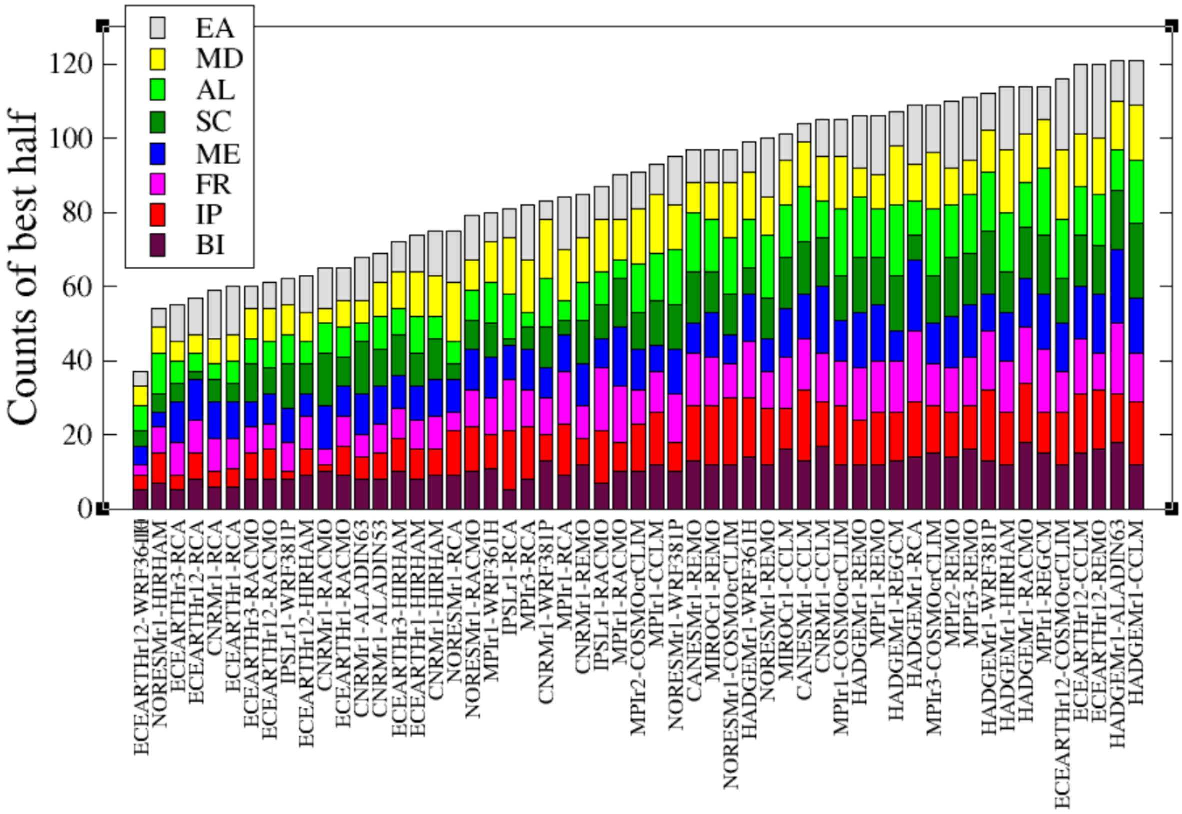

Figure 3. Counts of the number of times among 8 regions and 24 indices for which each model is ranked in the "best half", based on the absolute bias. The PRUDENCE regions are: Eastern Europe (EA), the Mediterranean region (MD), the Alps (AL), Scandinavia (SC), Middle Europe (ME), France (FR), the Iberian Peninsula (IP) and the British Isles (BI).

1.5 Future changes

Future changes as simulated by the EURO-CORDEX ensemble are assessed in depth in the article of Coppola et al. (2019). They are compared with CMIP5 simulations as well as with first CMIP6 simulations. This is the first model inter-comparison of this kind, which has been made possible thanks to the PRINCIPLES project. We note that there are issues of comparing the ensemble as they are based on different number of GCMs and that the GCMs in CMIP5 and CMIP6 are not the same. However CMIP6 models have a generally higher sensitivity to CO2, consistent with the results here. Also, the RCP and SSP scenarios may differ in terms of their impact on the results, as shown for the

EC-Earth model by Wyser et al. (2020). Here we show a few examples of projected changes of the EURO-CORDEX ensemble and compare them with the driving CMIP5 GCMs and the new CMIP6 ensemble.

Figure 4 shows DJF and JJA temperature changes for the EURO-CORDEX RCM-ensemble and the two GCM ensembles and for the mid-century and far-future for the RCP8.5 scenario. The warming is stronger in the northern European area in winter and in the Mediterranean in summer with the EURO-CORDEX ensemble showing a slightly lower intensity of change.

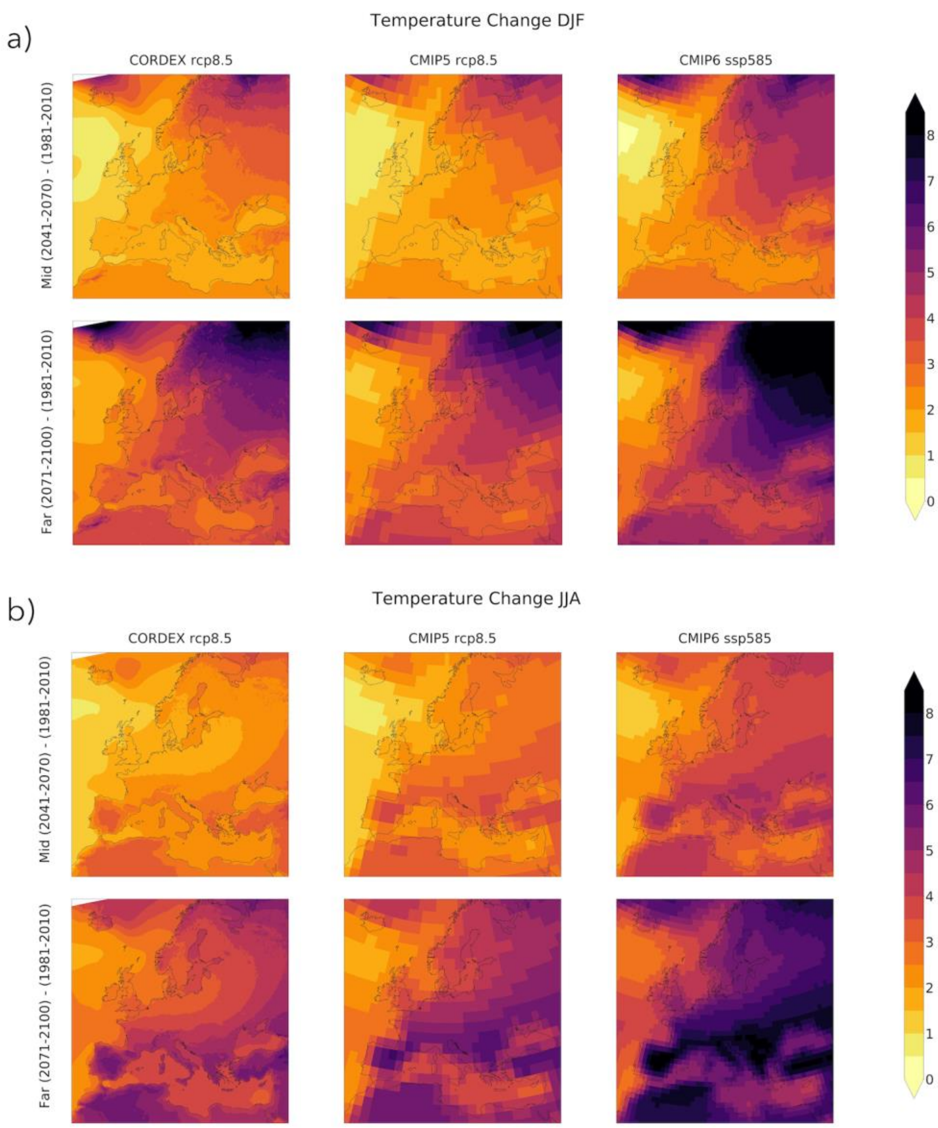

Figure 4. Seasonal mean temperature ensemble mean changes (DJF (a) and JJA (b)) for EURO-CORDEX, CMIP5 and CMIP6 for 2041-2070 (mid-century) and 2071-2100 (far-future) relative to 1981-2010 (Units: degrees) (after Coppola et al. 2019).

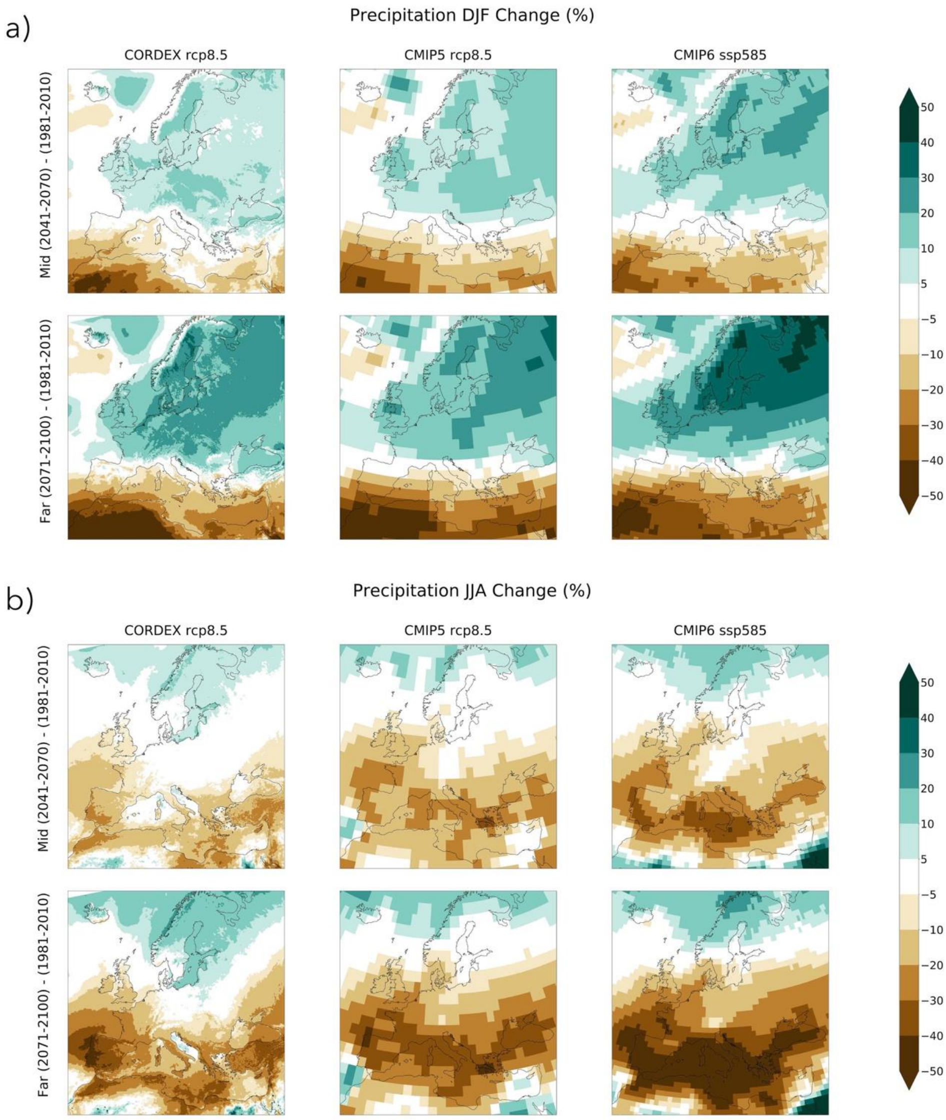

Figure 5. As Fig. 4 but for ensemble mean seasonal precipitation changes (DJF (a) and JJA (b)) (Units: percentage) (after Coppola et al 2019).

In Figure 5 the seasonal mean precipitation change is reported for two time slices and for the three ensembles. The increase of precipitation is maximum in winter in the north and the decrease is maximum in the south and in the Mediterranean basin for summer and the signal intensity is again slightly less for the EURO-CORDEX. The high resolution of the regional ensemble contributes to exhibit many spatial details of changes that are not possible to see in the change signal of global ensembles like for example over the Alpine region, the coastline and islands.

5. Specific analyses

1.6 Comparison between EURO-CORDEX and PRIMAVERA

It is interesting to compare the EURO-CORDEX ensemble with the ensemble of GCMs with highest resolution currently. The European project PRIMAVERA was designed to provide such an ensemble, with typical horizontal resolutions of 25-50 km. Demory et al. (2019) have performed an evaluation of six PRIMAVERA GCMs and nine EURO-CORDEX RCMs downscaling eight GCMs (12-50 km resolutions). The total number of RCM simulations are 32 for the 12 km resolution and 23 for 50. Although the PRIMAVERA and EURO-CORDEX ensembles are not based on an identical set of GCM simulations, the comparison can still inform about the added value of having climate models at the 12-50 km scale (PRIMAVERA GCMs and EURO-CORDEX RCMs) compared to the coarser scale CMIP5 GCMs used to drive the EURO-CORDEX RCMs. The study assesses the spread of regional climate information under current climate conditions in terms of daily precipitation distribution simulated by ensembles of GCMs and RCMs at similar horizontal resolutions. Both ensembles are evaluated against high quality national gridded observations in terms of resolution and station density. The PRIMAVERA GCMs simulate very similar distribution to EURO-CORDEX RCMs. This differs from the CMIP5 GCMs as a result of their coarser resolutions. The PRIMAVERA and EURO-CORDEX ensembles generally show similar strengths and weaknesses. They are of good quality in summer and autumn in most European regions, but tend to overestimate precipitation in winter and spring. PRIMAVERA show improvements in the latter bias by reducing mid-rain rate biases in Central and Eastern Europe. EURO-CORDEX models give less light rainfall compared to the PRIMAVERA GCMs in most regions and seasons, which improves this common bias of coarse-scale models. The PRIMAVERA models simulate less heavy precipitation than the EURO-CORDEX models in most regions and seasons, especially in summer (Fig. 6). The PRIMAVERA GCMs appear to be closer to observations. However, most national gridded datasets do not account for a precipitation undercatch error. When such a correction is applied (by adding 20% on average), EURO-CORDEX RCMs become closer to these synthetic datasets.

Considering 50 km resolution GCM or RCM datasets over Europe results in large benefits compared to CMIP5 models for impact studies at the regional scale. The effect of increasing resolution from 50 km to 12 km in EURO-CORDEX simulations is, in comparison, small in most regions and seasons outside mountainous regions (due to the importance of orography) and coastal regions (mostly depending on the resolution of the land-sea contrast).

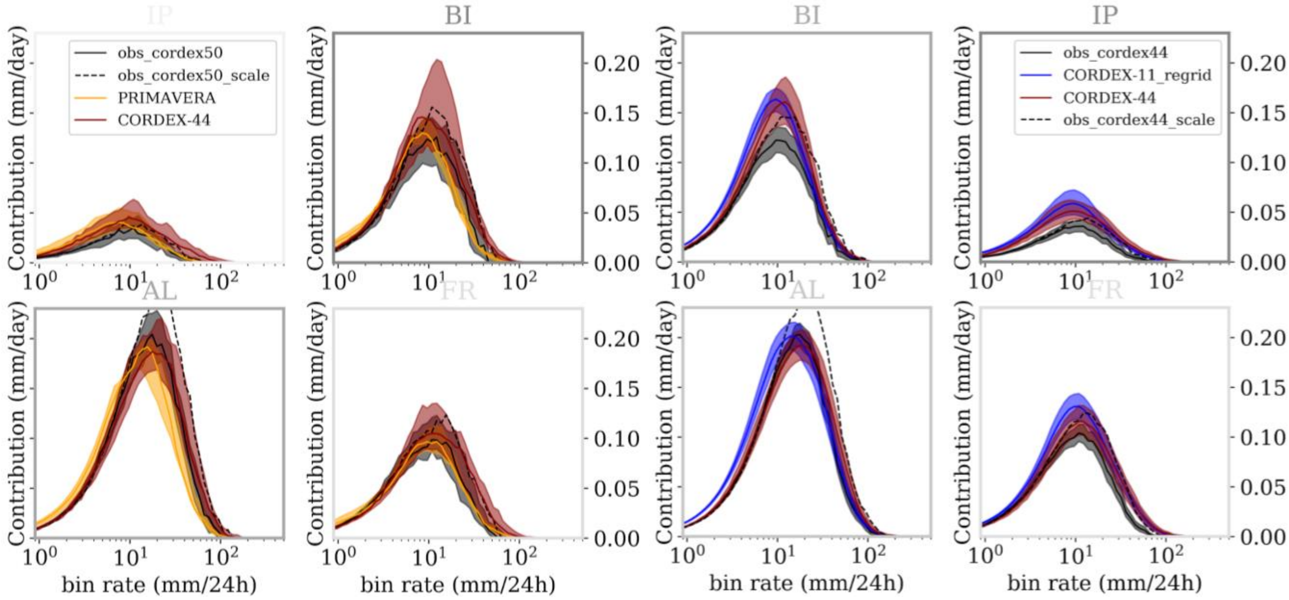

Figure 6: Precipitation contribution (frequency x bin rate) per rain rate in JJA over the Iberian Peninsula (IP), British Isles (BI), Alps (AL), France (FR) for EURO-CORDEX 50km RCMs (red), PRIMAVERA GCMs (orange, left panels), EURO-CORDEX 12.5km RCMs (blue, right panels), observations (black) and a synthetic observational dataset taking into account an additional 20% undercatch error (dashed line). All data are regridded on the EURO-CORDEX 50km grid.

Acknowledgements

E-OBS temperature and precipitation v17 were used: We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu)" (Haylock et al., 2008)

For the WRF381P simulations the TGCC supercomputer centre graciously provided the computer time required for the simulations of the PRINCIPLES project.

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