Clim Dyn
DOI 10.1007/s00382-016-3453-4

Assessment of multiple daily precipitation statistics in ERA-Interim driven Med-CORDEX and EURO-CORDEX experiments against high resolution observations

Adriano Fantini[1,2] · Francesca Raffaele[2] · Csaba Torma[2,3,4] · Sara Bacer[5] · Erika Coppola[2] · Filippo Giorgi[2] · Bodo Ahrens[6] · Clotilde Dubois[7,8] · Enrique Sanchez[9] · Marco Verdecchia[10]

Received: 21 September 2015 / Accepted: 13 November 2016

Abstract We assess the statistics of different daily precipitation indices in ensembles of Med-CORDEX and EURO-CORDEX experiments at high resolution (grid spacing of ~0.11°, or RCM11) and medium resolution (grid spacing of ~0.44°, or RCM44) with regional climate models (RCMs) driven by the ERA-Interim reanalysis of observations for the period 1989–2008. The assessment is carried out by comparison with a set of high resolution observation datasets for nine European subregions. The statistics analyzed include quantitative metrics for mean precipitation, daily precipitation probability density functions (PDFs), daily precipitation intensity, frequency, 95th percentile and 95th percentile of dry spell length. We assess an ensemble including all Med-CORDEX and EURO-CORDEX models together and others including the Med-CORDEX and EURO-CORDEX separately. For the All Models ensembles, the RCM11 one shows a remarkable performance in reproducing the spatial patterns and seasonal cycle of mean precipitation over all regions, with a consistent and marked improvement compared to the RCM44 ensemble and the ERA-Interim reanalysis. A good consistency with observations by the RCM11 ensemble (and a substantial improvement compared to RCM44 and ERA-Interim) is found also for the daily precipitation PDFs, mean intensity and, to a lesser extent, the 95th percentile. A general improvement by the RCM11 models is also found when the data are upscaled and intercompared at the 0.44° and 1.5° resolutions. For some regions the RCM11 ensemble overestimates the occurrence of very high intensity events while for one region the models underestimate the occurrence of the most intense extremes. The RCM11 ensemble still shows a general tendency to underestimate the dry day frequency and 95th percentile of dry spell length over wetter regions, with only a marginal improvement compared to the lower resolution models. This indicates that the problem of the excessive production of low precipitation events found in

This paper is a contribution to the special issue on Med-CORDEX, an international coordinated initiative dedicated to the multi-component regional climate modelling (atmosphere, ocean, land surface, river) of the Mediterranean under the umbrella of HyMeX, CORDEX, and Med-CLIVAR and coordinated by Samuel Somot, Paolo Ruti, Erika Coppola, Gianmaria Sannino, Bodo Ahrens, and Gabriel Jordà.

Electronic supplementary material The online version of this article (doi:10.1007/s00382-016-3453-4) contains supplementary material, which is available to authorized users.

✉ Adriano Fantini
afantini@ictp.it

1 Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy

2 Abdus Salam ICTP, Trieste, Italy

3 Department of Meteorology, Eötvös Loránd University, Budapest, Hungary

4 HAS Post-Doctoral Research Program, Budapest, Hungary

5 Atmospheric Chemistry Department, Max Planck Institute for Chemistry, Mainz, Germany

6 Goethe-Universitaet Frankfurt a.M., Frankfurt/Main, Germany

7 Météo-France, Toulouse, France

8 Mercator Océan, Ramonville-Saint-Agne, France

9 Universidad de Castilla-La Mancha, Toledo, Spain

10 Department of Physical and Chemical Sciences, University of L'Aquila, L'Aquila, Italy

many climate models persists also at relatively high resolutions, at least in wet climate regimes. Concerning the Med-CORDEX and EURO-CORDEX ensembles we find that their performance is of similar quality over the Mediterranean regions analyzed. Finally, we stress the need of consistent and quality checked fine scale observation datasets for the assessment of RCMs run at increasingly high horizontal resolutions.

Keywords Regional climate model · Daily precipitation · Med-CORDEX · EURO-CORDEX · Model validation · Extremes

1 Introduction

Med-CORDEX (Ruti et al. 2016) and EURO-CORDEX (Jacob et al. 2013) are initiatives under the framework of the COordinated Regional Downscaling EXperiment (CORDEX, Giorgi et al. 2009; Jones et al. 2011), whose mission is to advance and coordinate activities in regional climate downscaling science and application. The CORDEX framework envisions two experiment streams: the model assessment and the regional climate projection streams (Giorgi et al. 2009; Jones et al. 2011). Specifically, under the model assessment stream, regional climate models (RCMs) are driven by lateral boundary conditions (LBC) from the ERA-Interim reanalysis of observations (Dee et al. 2011), and are assessed against observations for the ERA-Interim simulation period. Then, in the regional projection stream the RCMs are driven by selected global climate models for late twentieth century climate simulations and twenty-first century climate projections aimed at providing information for use in impact and adaptation studies.

The model assessment stream has been completed by ensembles of both Med-CORDEX and EURO-CORDEX atmospheric RCMs over the respective Mediterranean and European domains. Two horizontal resolutions are used, roughly corresponding to grid intervals of ~0.44° (or ~50 km) and ~0.11° (or ~12 km), and for both sets (hereafter referred to as "RCM44" and "RCM11", respectively) the participating RCMs are driven by ERA-Interim LBC for the 20-year period 1989–2008. Some analyses of the EURO-CORDEX ERA-Interim driven ensemble are presented by Vautard et al. (2013), Kotlarski et al. (2014), Prein et al. (2015) and Casanueva et al. (2016). Specifically, Vautard et al. (2013) focused on the simulation of heat waves over the European region, Kotlarski et al. (2014) presented a basic evaluation of the precipitation and temperature climatologies of the models, Prein et al. (2015) examined extreme daily and sub-daily precipitation via a comparison with high resolution regional observation datasets, and Casanueva et al. (2016) analyzed different daily precipitation indices over the Iberian Peninsula and the Alpine region.

Besides the identification and quantification of model biases, these studies assessed the improvements in the model performance by increasing the horizontal resolution from 0.44° to 0.11° and found that such improvements depend on the variable under consideration. For example, while substantial improvements were found in the simulation of daily and sub-daily precipitation frequency, intensity and extremes (Prein et al. 2015; Casanueva et al. 2016), regional mean biases were not systematically reduced at the higher resolution (Kotlarski et al. 2014). In addition, the simulation of heat waves was not found to significantly depend on model resolution, being rather related to large scale processes (Vautard et al. 2013). These conclusions are also generally in line with analyses of RCM simulations over the whole European region conducted as part of previous projects (Jacob et al. 2007; Rauscher et al. 2010).

By comparison, to date no systematic assessments of the ERA-Interim driven Med-CORDEX RCM ensemble are available, although some individual simulations have been analyzed for specific purposes (e.g. Di Luca et al. 2014; Flaounas et al. 2013; Tramblay et al. 2013; Herrmann et al. 2011). In this paper we thus fill this gap by presenting an evaluation of the ERA-Interim driven Med-CORDEX ensemble. We assess this ensemble in conjunction with the corresponding EURO-CORDEX one, since a good portion of the Med-CORDEX domain is common to EURO-CORDEX, and in order to place the analysis in a broader context. We only analyze models for which simulations are available in the Med-CORDEX and EURO-CORDEX public archives at both the 0.44° and 0.11° resolutions, so as to assess the effect of resolution on the model performance. Our focus is on a range of precipitation metrics, and specifically mean model precipitation climatology, different daily precipitation indices of relevance for impact studies and daily precipitation probability density functions (PDFs). Towards the goal of investigating the role of resolution, we evaluate the models against high resolution gridded daily precipitation datasets assembled for different European sub-regions, as in Prein et al. (2015).

Our study extends previous work in several respects: it includes both Med-CORDEX and EURO-CORDEX ERA-Interim driven ensembles; it includes a larger set of regional observation datasets, compared for example to Prein et al. (2015) (we also include datasets for the UK and Central-Southern Italy); and it considers a larger set of daily precipitation indices and statistics. Note that in regions common to the Med-CORDEX and EURO-CORDEX domains, the ensembles are analyzed both together and separately (i.e. Med-CORDEX and EURO-CORDEX only) in order to investigate whether there are systematic

Table 1 List of the models analyzed in this work

Models	Institute	References
CCLM4-8-17	CLMcom	Rockel et al. (2008)
HIRHAM5	DMI	Christensen et al. (2006)
INERIS-WRF331F	IPSL	Vautard et al. (2013)
RACMO22E	KNMI	van Meijgaard et al. (2012)
RCA4	SMHI	Kupiainen et al. (2011)
ALADIN5.2*	CNRM	Colin et al. (2010)
RegCM4.3*	ICTP	Giorgi et al. (2012)
CCLM4-8-18*	GUF	Rockel et al. (2008)
PROMES*	UCLM	Castro et al. (1993)

Med-CORDEX models are those with the asterisk

differences between the two sets of models. The models, data and analysis measures are described in the next section, while in Sect. 3 we discuss the model results and in Sect. 4 we present our main conclusions.

2 Models, observations and performance metrics

2.1 Model ensembles

The Med-CORDEX and EURO-CORDEX ensembles of RCMs analyzed here are reported in Table 1. The Med-CORDEX ensemble includes four atmosphere only models (ALADIN, PROMES, RegCM4 and GUF-CCLM),

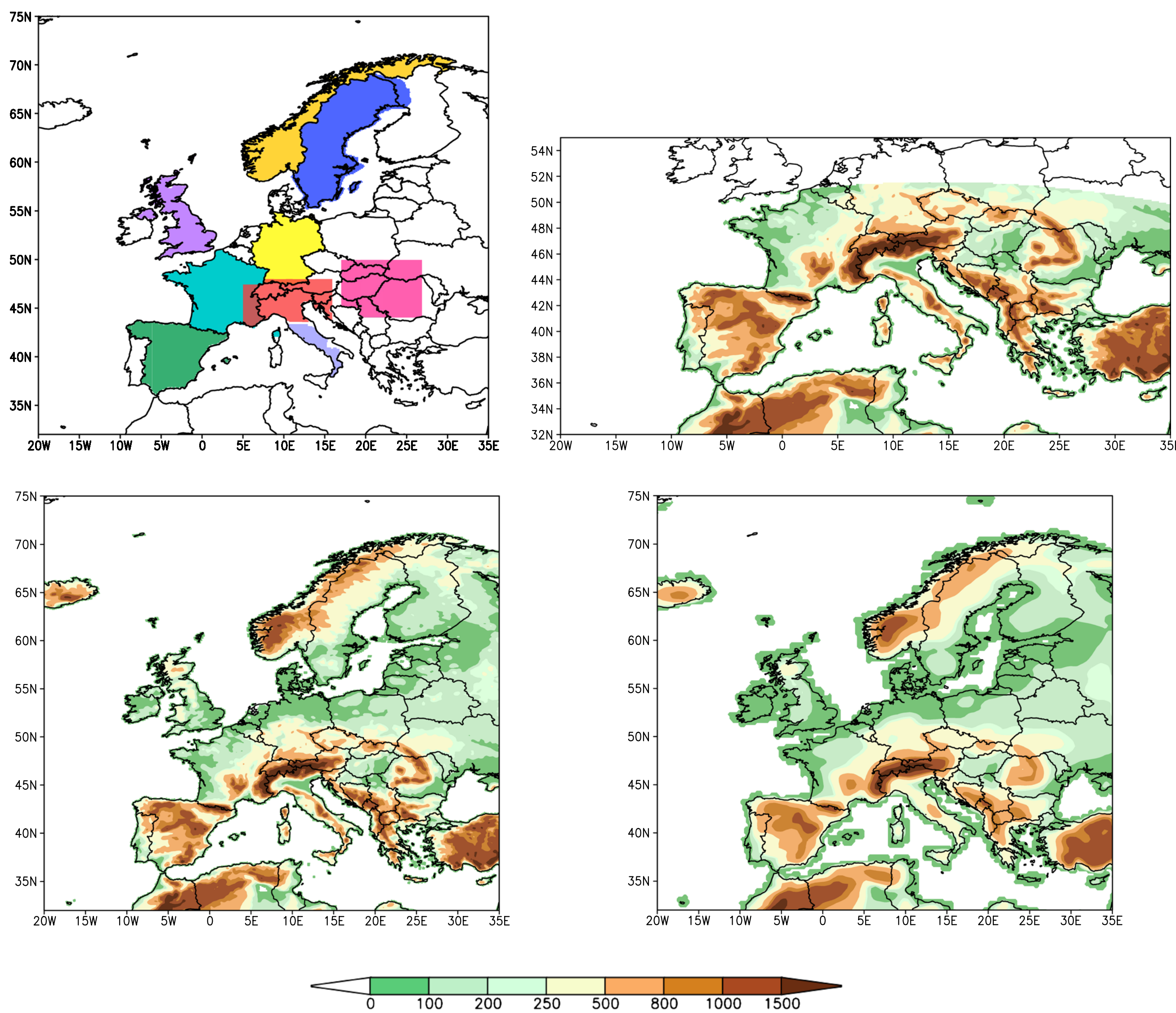


Fig. 1 *Upper panels* Analysis regions as defined by the availability of high resolution observation datasets (on the *left*) and the Med-CORDEX domain (on the *right*). *Lower panels* European topography at 0.11° resolution (on the *left*) and at 0.44° resolution (on the *right*)

while the EURO-CORDEX ensemble includes five RCMs (CCLM, HIRHAM, RACMO22E, RCA4, WRF331F). Note that the EURO-CORDEX ensemble is smaller than that used by Prein et al. (2015) since these were the only data available in the public archive. Figure 1 shows the Med-CORDEX and EURO-CORDEX domains, along with the sub-regions selected for analysis based on the availability of high resolution observation datasets (see Sect. 2.2). Some of the regions lie within both the Med-CORDEX and EURO-CORDEX domains (France, Alps, Spain, Italy, Carpathians), while others (Germany, UK, Norway, Sweden) only lie entirely within the EURO-CORDEX domain. For the southern European regions included in both ensembles we analyze the full Med-CORDEX + EURO-CORDEX ensemble (referred to as the "All Models" ensemble) along with the two ensembles separately. All the simulations cover the period 1989–2008 with LBC from the ERA-interim reanalysis (Dee et al. 2011) and use model horizontal grid spacings of 0.44° and 0.11°. We hereafter refer to these two ensembles as RCM44 and RCM11, respectively.

In order to facilitate the intercomparison of models and observations, the output of all the experiments is interpolated onto three common grids of 0.11°, 0.44° and 1.5° (i.e. characteristic of the RCM simulations and a large scale GCM resolution) using a distance-weighted method, as in Torma et al. (2015), who showed that this method provides a good conservation of the total field while not degrading its spatial structure. The data are then intercompared across all resolution grids to measure the downscaling performance as well as the performance of the RCMs when upscaled at the 1.5° grid resolution. The ERA-interim precipitation dataset is taken at its original resolution (0.8°) and interpolated onto the three common grids for the comparison with the RCM models.

2.2 High resolution observation datasets

The assessment of RCMs in reproducing extreme indices and fine scale spatial and temporal precipitation patterns requires the use of high quality observation datasets of comparable fine resolution. For this reason, we assembled a set of observational datasets consisting of gridded regional high resolution observations available from different European institutions (see also Prein et al. 2015). Figure 1 shows the location and area coverage of each dataset. Previous studies have also employed the European-wide 25 km resolution dataset E-OBS (Haylock et al., 2008), however the resolution of this data is too coarse to evaluate the fine scale structure produced by the RCM11 models (e.g. Prein et al. 2015). Table 2 lists the observation datasets used here and describes some of their characteristics. They cover the Alpine region, Spain, France, UK, Norway, Sweden, the Carpathian region, Germany and central/southern Italy (hereafter referred to as "Italy"). All datasets are station-based except for France, which is a high resolution regional reanalysis. It should also be noted that the datasets are characterized by different station densities (and thus effective resolutions), highest in the Alps and UK and lowest in the Carpathian and Swedish datasets (see corresponding references in Table 2).

For consistent comparison with the models, the observed data are also regridded on the common 0.11°, 0.44° and 1.5° grids of the model data by using the same distance weighted method. All the observation datasets cover the simulation period 1989–2008, with the exception of the UK dataset (1990–2008) and the Italian dataset (2000–2010). For these two regions the analysis is carried out including only the years of available observations. Also, the Italian data were gridded onto the 0.11° grid from about 1500 stations via the distance weighted approach using all stations lying within the surrounding grid boxes. Data were not available for the Marche and Puglia regions and thus gridding was not carried out there. Although we carefully checked the Italian dataset for internal consistency, we do stress the preliminary nature of its use.

Finally, due to the well known problem of precipitation under-catch, especially under cold season snow-blowing conditions (Adam and Lettenmaier 2003; Adam et al. 2006), we added a gauge correction for the datasets that do not include it, i.e. the Alps, Spain, Germany, Italy, UK and the Carpathians. A location-dependent monthly gauge under-catch correction was estimated from the data of Matsuura and Willmott (2010) (UDEL, version 3.01) following Torma et al. (2015). Since the correction is estimated at the climatological monthly scale, it was applied only in the validation of the precipitation means (i.e. not when calculating daily precipitation statistics). For the other regional datasets, a similar correction was already included or was implicit in the use of a reanalysis, as reported in the literature. Throughout the paper we will explicitly mention when the under-catch gauge correction is used.

2.3 Performance metrics

Besides standard metrics of performance such as the mean bias or the root mean square error (RMSE), we use additional targeted metrics to evaluate different aspects of model performance. Spatial patterns are assessed through the use of Taylor Diagrams (Taylor 2001), which include multiple metrics consisting of spatial correlation, spatial standard deviation and centered (or bias removed) RMSE. The model skill in reproducing observed daily precipitation PDFs is measured via the Kullback–Leibler divergence (KL, Kullback and Leibler 1951), which measures the departure

Table 2 List of regional observational datasets used inthis work

Dataset	Institution	Region	Period	Resolution	Approximate maximum number of stations per 1000 km^2	References
EURO4 M-APGD	MeteoSwiss	Alps	1971–2008	5 km	18	Isotta et al. (2014)
Spain02	Santander meteorology group	Spain	1971–2010	0.11°	6	Herrera et al. (2015)
SAFRAN	Meteo-France	France	1958–2013	8 km	7	Vidal et al. (2010)
UK gridded dataset	Met office	UK	1990–2010	0.11°	20	Perry et al. (2009)
KLIMAGRID	METNO	Norway	1957–2013	1 km	1 km	Mohr (2009)
PTHBV	SMHI	Sweden and part of Finland	1961–2010	4 km	4	Johansson (2002)
CARPATCLIM	Hungarian Meteorological Service	Carpathians	1961–2010	0.10°	2	Szalai et al. (2013)
REGNIE	DWD	Germany	1961–2009	1 km	11	Rauthe et al. (2013)
CETEMPS gridded dataset	CETEMPS, University of L'Aquila	Italy	2000–2014	0.11°	8	

between two PDFs accounting for the whole range of the distributions. In other words, the KL divergence is a metric of the mean difference between distributions, as opposed to the Kolmogorov–Smirnov distance (used for example by Torma et al. 2015) which measures the maximum distance between two cumulative distributions.

For two random variables $p(x)$ and $q(x)$, the symmetrized KL divergence was defined as follows:

$$_{symm}KL = \frac{1}{2}\left(\int_{-\infty}^{\infty} p(x)\log\frac{p(x)}{q(x)}dx + \int_{-\infty}^{\infty} q(x)\log\frac{q(x)}{p(x)}dx\right)$$

In order to assess the model performance in simulating different characteristics of daily precipitation, we consider four hydroclimatic indices (or suitable variations of them) widely used in previous studies (e.g. Sillmann et al. 2013; Giorgi et al. 2014) and relevant for impact applications:

SDII Mean wet daily precipitation intensity (mm/day)
DDF Mean frequency of dry days (%)
CDD95 95th percentile of dry spell length (No. days)
$P_{sum} > R95_{obs}$ Total precipitation above the reference 95th percentile of observed daily precipitation

In the calculation of these indices we assume that a day is rainy when the daily precipitation is greater than or equal to 1 mm/day, as for example in Sillmann et al. (2013) and Giorgi et al. (2014). Note that we adopt two modified indices compared to their standard meaning, CDD95 and $P_{sum} > R95_{obs}$. CDD95 is used instead of the more common CDD, the maximum dry spell length, in order to avoid the possible dominant role of anomalous individual dry spells within the relatively short simulation period. In the calculation of CDD95 we use the entire time sequence of events within the full analysis periods. $P_{sum} > R95_{obs}$ replaces the commonly used R95p (fraction of precipitation above the 95th percentile of the respective distribution). In this index definition, the 95th percentile of precipitation is first calculated from the observation data on the proper resolution grid and is then used as a common reference threshold to calculate the cumulative observed and simulated precipitation deriving from events of higher intensity. Therefore, if the observed 95th percentile defines a threshold for extremes, the index measures the amount of precipitation accounted for by extreme events (i.e. events above this threshold) in either observations or simulations. By using a common threshold, this definition allows a more consistent intercomparison of extreme precipitation amounts across models and observations.

3 Assessment of the Med-CORDEX and EURO-CORDEX precipitation statistics

3.1 Mean precipitation

Prior to the evaluation of daily precipitation statistics, it is important to provide an assessment of the model simulation of mean precipitation. Figure 2 compares the ERA-Interim and observed (gauge corrected) mean precipitation in December–January–February (DJF) and June–July–August (JJA) with the ensemble average results at all three resolutions (All Models ensembles). To complement this information, Fig. 3 shows the Taylor diagrams of mean precipitation for all seasons, the Med-CORDEX and EURO-CORDEX ensembles, while Fig. 4 presents the mean bias (simulated minus observed seasonal precipitation) and RMSE for the different regions for the different ensembles.

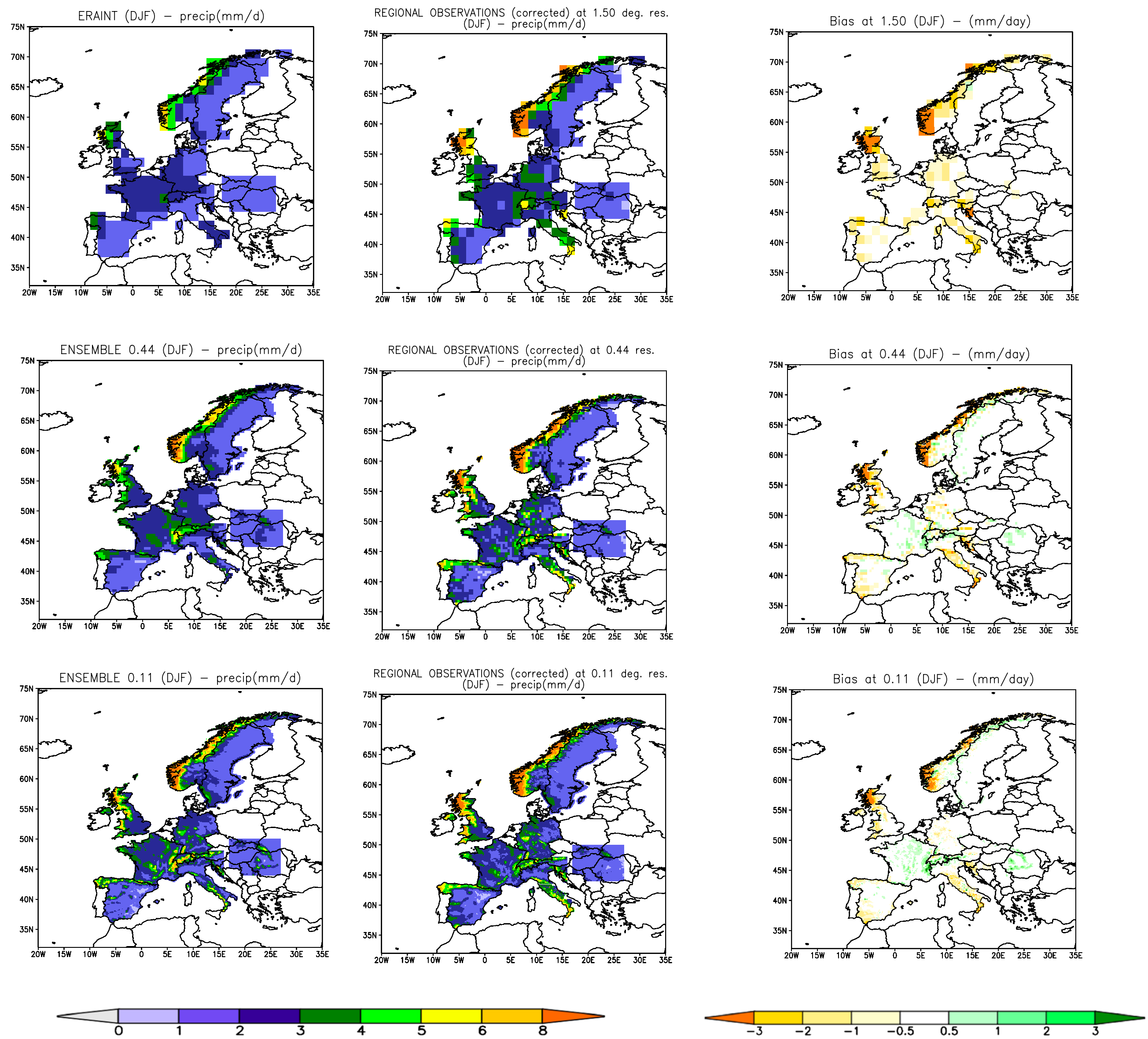


Fig. 2 Ensemble mean precipitation over the analysis regions for the ERA-Interim reanalysis, RCM44 and RCM11 All-Model ensembles (only EURO-CORDEX over regions outside the Med-CORDEX domain) and regional observations on the 0.11°, 0.44° and 1.5° resolution grids. *Upper panels* December–January–February (DJF); *lower panels* June–July–August (JJA). The *last column* on the *right* shows the precipitation bias at each resolution. Units are mm/day and the mean is taken over the different regional analysis periods (see Sect. 2)

It is clear from Fig. 2 that the high resolution ensemble captures the fine scale detail of the precipitation patterns exhibited by the high resolution observations. This detail is mostly driven by the topographical and coastline features of the different regions, most noticeably the Alps, Pyrenees, Carpathians and Apennines. Also captured are the precipitation gradients in flatter regions, e.g. over France, the central Iberian Peninsula, southern England, Germany and Sweden. In addition, the improved representation of spatial detail at the finest scale by the RCM11 ensemble compared to the RCM44 and especially the ERA-Interim reanalysis is visually evident, although it is important to notice that the ERA-Interim captures quite well the observed broad spatial precipitation gradients at the 1.5° scale. Also, the RCM44 models appear to somewhat underestimate the spatial variability shown by the observations on the 0.44° grid.

The Taylor diagrams of Fig. 3 provide a quantitative measure of the models' ability to capture the observed spatial patterns on the 0.11° and 1.5° grids (Supplementary Figure S1 shows the corresponding Taylor diagrams for the 0.44° grid). Overall, at the 0.11° resolution (Fig. 3a), the RCM11 ensemble exhibits the highest pattern correlations (~0.7–0.95 in DJF, MAM and SON, ~0.8–0.95 in JJA), while the ERA-Interim reanalysis mostly the lowest, with

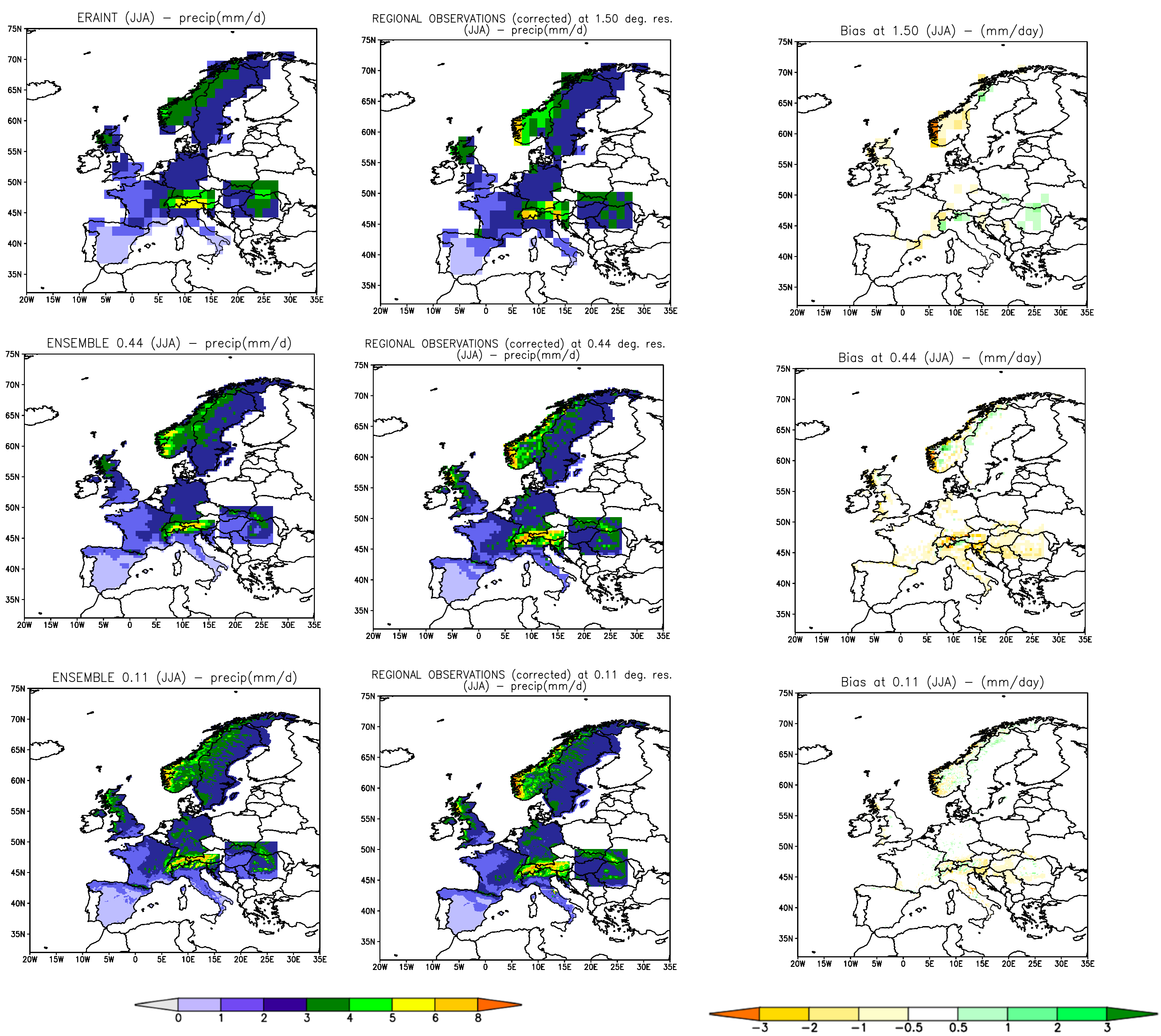
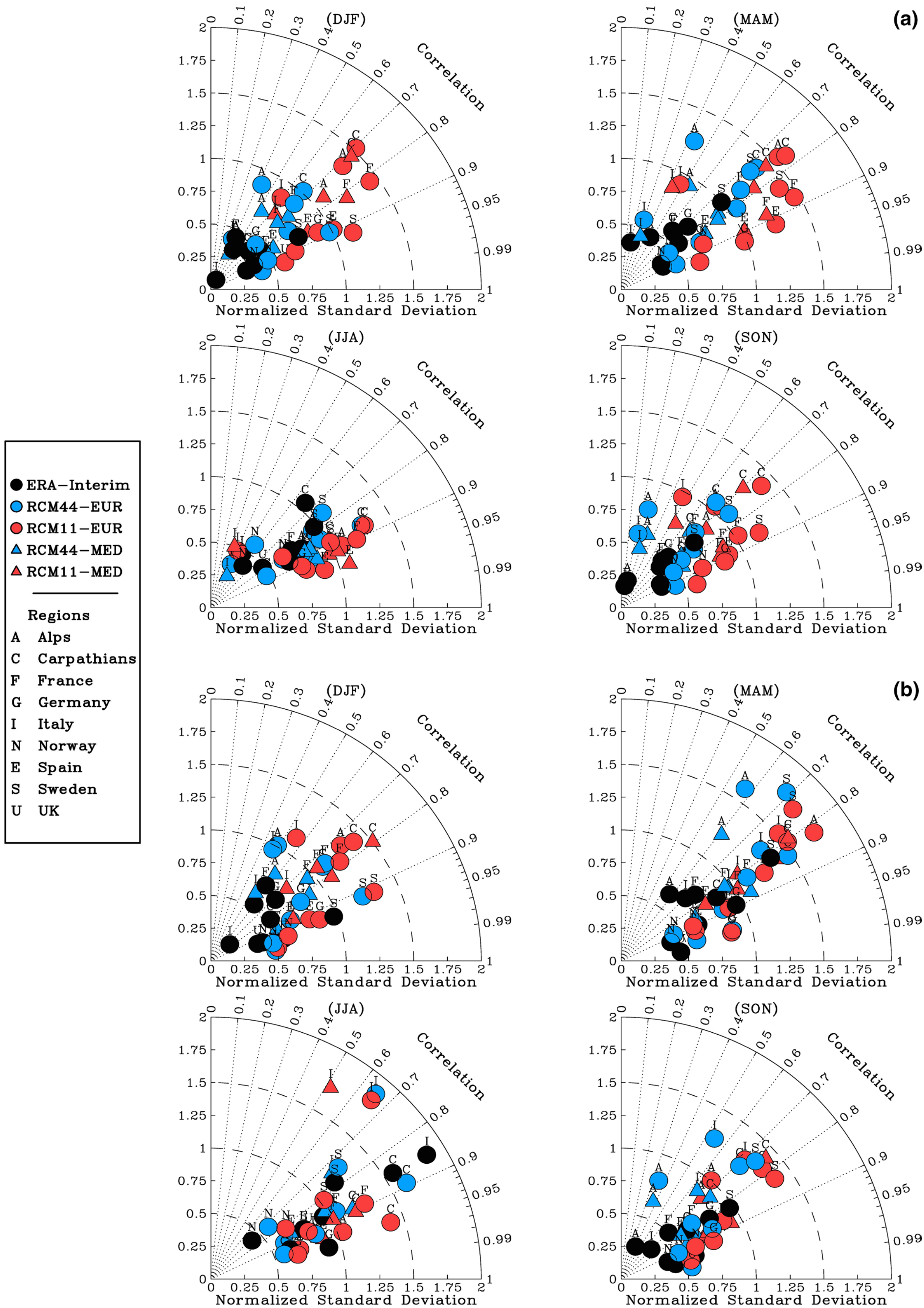


Fig. 2 continued

the RCM44 models showing intermediate results. Only over the Italy region the correlations are relatively low, although still better in RCM11 than RCM44 and ERA-Interim, probably due to the sparse station coverage of the Italian territory. Overall, the RCM11 models also exhibit the best skill in reproducing the normalized spatial standard deviation as well as the centered RMSE. Figures 2 and 3 thus clearly illustrate the fine scale (downscaling) added value provided by the high resolution in simulating the European mean precipitation spatial patterns. In addition, Fig. 3b shows that, overall, the RCM11 models exhibit a somewhat (but not ubiquitous) better performance also when upscaled on the 1.5° grid, confirming the conclusion by Torma et al. (2015) that the added value of downscaling is not simply due to a disaggregation of coarse scale data, but to a better simulation of relevant processes (e.g. topographic forcing). Finally, Fig. 3 indicates that the Med-CORDEX and EURO-CORDEX ensembles exhibit similar performances over the regions common to both sets of models. For reference, supplementary figures S6 shows the DJF and JJA mean precipitation over the Mediterranean analysis regions in the Med-CORDEX ensembles and supplementary figures S7 the same as S6 but for the EURO-CORDEX ensembles.

When looking at regional mean biases and RMSE, the results are more mixed in terms of improvements associated to increased resolution. Figure 4 presents mean biases and RMSE over the different regions for DJF and JJA


(a)
(DJF)
(MAM)
(JJA)
(SON)
(b)
Correlation
Normalized Standard Deviation
ERA−Interim
RCM44−EUR
RCM11−EUR
RCM44−MED
RCM11−MED
Regions
A Alps
C Carpathians
F France
G Germany
I Italy
N Norway
E Spain
S Sweden
U UK

◂**Fig. 3** Taylor diagrams of the ensemble mean seasonal precipitation in the different analysis regions for the ERA-Interim, RCM44 and RCM11 (both EURO-CORDEX and Med-CORDEX models) ensembles with respect to the corresponding regional observation datasets, at 0.11° (**a**) and 1.5° resolution (**b**). The distance from the point 1 measures the centered (bias removed) RMSE and the mean is taken over the different regional analysis periods (see Sect. 2)

precipitation with respect to gauge corrected values. The same metrics are shown in Figure S2 for uncorrected values. Both figures show that these metrics do not indicate a systematic reduction of biases and RMSE for the high resolution model configurations, although a slight tendency for lower biases is found in the RCM11. This is mostly due to the fact that the RCM11 ensemble produces generally higher precipitation amounts than the ERA-Interim and RCM44, and this can lead to both a decrease or increase in the biases and RMSE for the different regions. An increase in simulated precipitation with resolution over Europe was also found by Rauscher et al. (2010) in a previous generation of models.

Figures 4 and S2 show that the ensemble mean regional biases are mostly lower than 25%, therefore generally in line with, or better than, the performance expected from RCMs over Europe (Jacob et al. 2007; Rauscher et al. 2010). Instances of biases larger than 25% are found in the UK (DJF) and Carpathians (DJF uncorrected) for the RCM11, Italy (DJF and JJA), Norway (DJF) and Carpathians (DJF uncorrected) for RCM44, Spain (DJF, corrected), Germany (DJF, corrected), Norway (DJF) and Italy (DJF) for ERA-Interim. Finally, the biases and RMSE for the Med-CORDEX ensemble are generally similar to those found for the EURO-CORDEX ensemble.

Figure 5 shows the annual precipitation cycle in the models (Med-CORDEX and EURO-CORDEX ensembles, mean and inter-model standard deviation), the ERA-Interim reanalysis and the regional datasets. The models capture the seasonal precipitation cycle in all sub-regions, with two rainy seasons in spring and late fall over the Mediterranean regions (Spain, France and the Alps), a summer maximum over the continental regions (Carpathians, Germany and Sweden), and a winter precipitation maximum over England, Norway and Italy. Thus the models (as well as the ERA-Interim) are able to describe the various precipitation regimes characterizing different European climates. Some noticeable shortcomings in Fig. 5 are a shift of about one month in the precipitation maximum over the Carpathians (not present in ERA-Interim) and an underestimate of early fall precipitation over the Alps and winter precipitation over Norway and Italy. By and large, however, the observed precipitation amounts are within the range of the model data, and the higher RCM11 precipitation totals may be closer or farther away from the corresponding observed values than the RCM44 depending on region and season. In fact, the annual precipitation means are closer to observations in the RCM11 than the RCM44 in seven out of nine regions.

The results found in this Section are generally in line with previous analyses (e.g. Jacob et al. 2007; Rauscher et al. 2010; Kotlarski et al. 2014; Prein et al. 2015). We also note that the ERA-Interim reanalysis consistently underestimates precipitation, yielding the largest errors in most regions and that the Med-CORDEX and EURO-CORDEX ensembles show a comparable level of performance.

3.2 Daily precipitation intensity PDFs

Figure 6 shows daily precipitation intensity PDFs over all regions at the 0.11° resolution, for the ERA-Interim, RCM11 and RCM44 ensembles, and the regional observation datasets. The PDFs are calculated on an annual basis, i.e. they include all days in the respective records, and are presented for all individual models (circles) as well as the multi-model mean (i.e. for each bin the value in the continuous line represents the average of the corresponding circles). Based on observations, the Alps, France, Spain, Italy, Germany and Norway show the longest tails, with events exceeding 250 mm/day. Over the other regions, the PDFs drop sharply to events of maximum intensity lower than 200 mm/day. In all regions, except the Carpathians, the RCM11 models show PDFs closest to observations. The ERA-Interim cannot capture the high intensity event tails in all cases, a result evidently due to the relatively coarse resolution of this data. The RCM44 models improve upon the ERA-Interim, but still fall short of representing the observed high intensity events.

The agreement between the RCM11 and observed PDFs is remarkably good over the Alps, England, France and Germany, although in these cases the models produce occasional events of higher intensity than the observed maximum. This could be due to the occurrence of numerical point storms (Giorgi 1991) or more simply to the larger ensemble size in the models. Over Norway the RCM11 models tend to underestimate the frequency of medium intensity events and overestimate the occurrence of extreme events, while over Spain, Sweden and especially the Carpathians, the high resolution models appear to overestimate the occurrence of medium to high events, and in fact in the latter two regions the RCM44 runs are closer to observations. In this regard, it is likely that for the Carpathians region the station density (Table 2) is too low to accurately represent the 0.11° resolution.

Figures S3 and S4 show corresponding PDFs at the 0.44° and 1.5° resolution grids. As expected, the tails of the distributions become shorter, but we still find, in agreement with Torma et al. (2015) that over most regions the RCM11 PDFs are closest to the observations even when the data

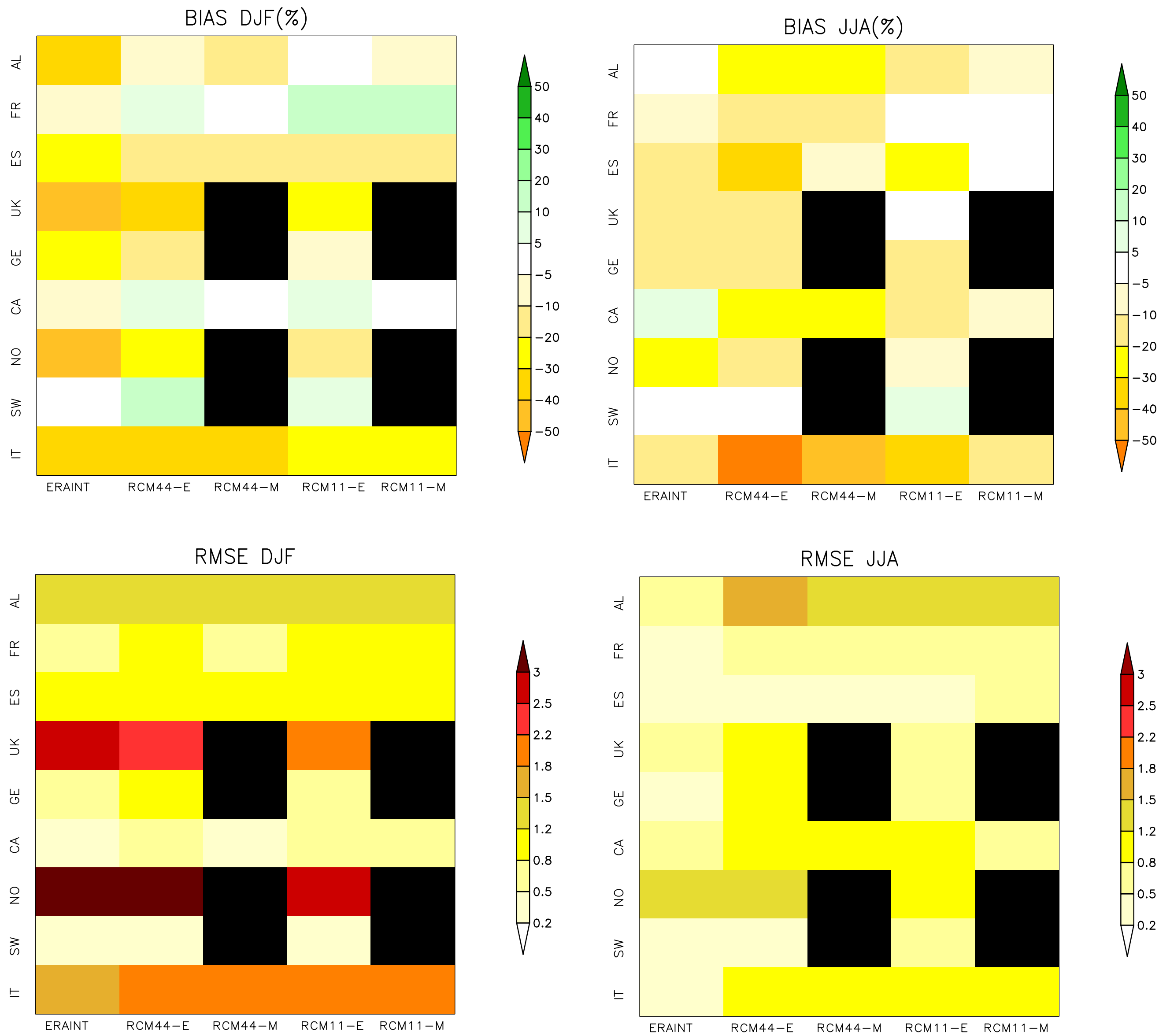


Fig. 4 Mean precipitation Bias (model minus observations, % of observed values, *upper panels*) and RMSE (mm/day, *lower panels*) for December–January–February (DJF, on the *left*) and June–July–August (JJA, on the *right*) for the different analysis regions, the ERA-Interim, and the RCM44 and RCM11 ensemble average (EURO-CORDEX Models and Med-CORDEX models). The observations include the under-catch gauge correction (see text)

are upscaled at the coarser resolution grids, i.e. that some added value by the high resolution is also transferred to the coarser scales.

Noticeably different from the other regional cases is that of Italy, in which the models underestimate the frequency of occurrence of the most intense extremes, especially at the 0.11° scale. These extremes are often produced in the southern Italian regions, especially Calabria, and can lead to devastating floods such as that of Soverato in September 2000 (Montani et al. 2003). Sometimes they are associated with intense tropical-like cyclones, often referred to as "medicanes" (Lagouvardos et al. 1999; Pytharoulis et al. 2000; Fita et al. 2007; Tous and Romero 2013), for which air–sea interactions are a key factor. Although previous studies have shown that RCMs can produce medicane-like cyclones (Gaertner et al. 2007, 2011; Lionello et al. 2008; Walsh et al. 2014; Akhtar et al. 2014), our results suggest that their intensity is still underestimated even at the high resolution of the RCM11 ensemble.

A quantitative measure of the model skill in reproducing observed PDFs is the KL divergence described in Sect. 2. Figure 7 shows the KL divergence for each region and all the three resolutions for the ERA-Interim reanalysis and the Med-CORDEX and EURO-CORDEX ensembles. It clearly

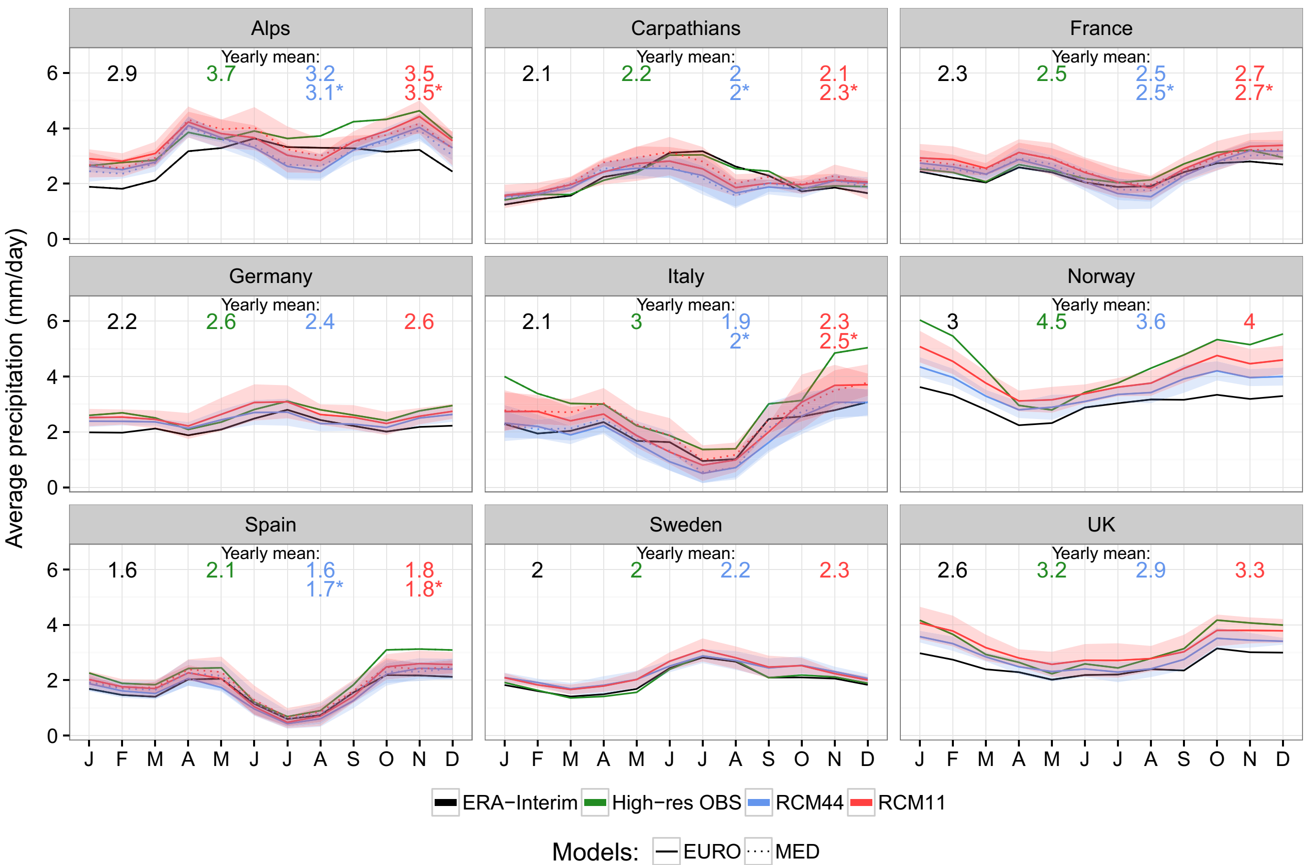


Fig. 5 Annual cycle of ensemble mean precipitation over the different analysis regions for the RCM44 and RCM11 ensembles (EURO-CORDEX and Med-CORDEX models), along with the ERA-Interim and observed precipitation. For the models ensembles, both the mean (*thick line*) and intermodel standard deviations range (*shaded area*) are shown. Units are mm/day and the mean is taken over the different regional analysis periods (see Sect. 2)

illustrates the consistent improvement (smaller KL divergence) obtained by the RCM11 runs compared to RCM44 and ERA-Interim, especially over Norway, UK, Italy, the Alps and France, an improvement that is retained also at the lower resolutions. In particular, in all cases and resolutions both RCM ensembles show better performance than the ERA-Interim, whose KL divergence is mostly outside the inter-model standard deviation range. Some overlap between the inter-model ranges of the RCM44 and RCM11 ensembles is instead found for most regions (except Norway and UK). For the Alps and Italy region we notice that the Med-CORDEX ensemble has slightly higher values of KL divergence and intermodel standard deviation, compared to the EURO-CORDEX one.

In summary, the analysis presented in this Section clearly shows the substantial improvement deriving from the high resolution RCMs in the simulation of daily precipitation PDFs, an improvement that is found across all scales analyzed here.

3.3 Daily precipitation indices

Figure 8 shows examples of model performance for the four precipitation indices described in Sect. 2 over selected regions and all the three resolutions. For a given region and index, the figure compares ERA-Interim, RCM44 and RCM11 data (ALL, Med-CORDEX and EURO-CORDEX ensembles) with the corresponding regional observations. Examples are selected in Fig. 8 which are illustrative of the general behavior of the models. We recall that all the indices are calculated on an annual basis.

Looking at the indices of precipitation amount, the strong signature of the morphology of the Alpine and Italian region on the Intensity index (SDII) is evident from Fig. 8a. Main centers of high intensity precipitation are found in the northern and southern flanks of the Alpine chain, the upwind side of the Jura mountains, the coastal mountainous regions of Croatia and along the Gulf of Genoa and southern Italian Tyrrhenian coasts, which

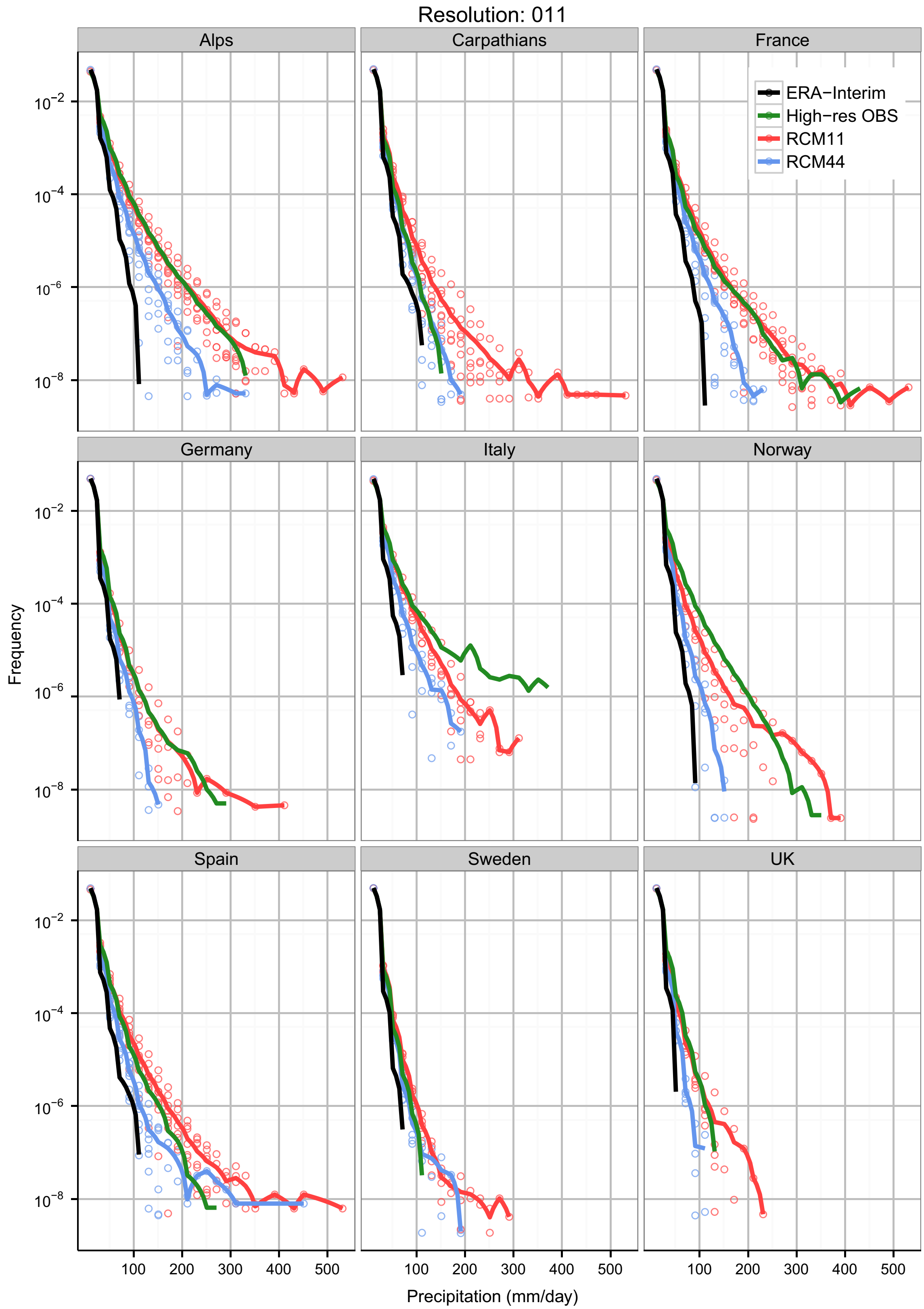


Fig. 6 Probability density function (PDF) of daily precipitation intensity (mm/day) over the different analysis regions in the ERA-Interim reanalysis, regional observation datasets, RCM44 and RCM11 ensembles (All Models). For the RCM44 and RCM11 ensembles both the individual model values (*circles*) and their ensemble mean (*continuous line*) are shown. The PDFs include daily data for the different regional analysis periods (see Sect. 2)

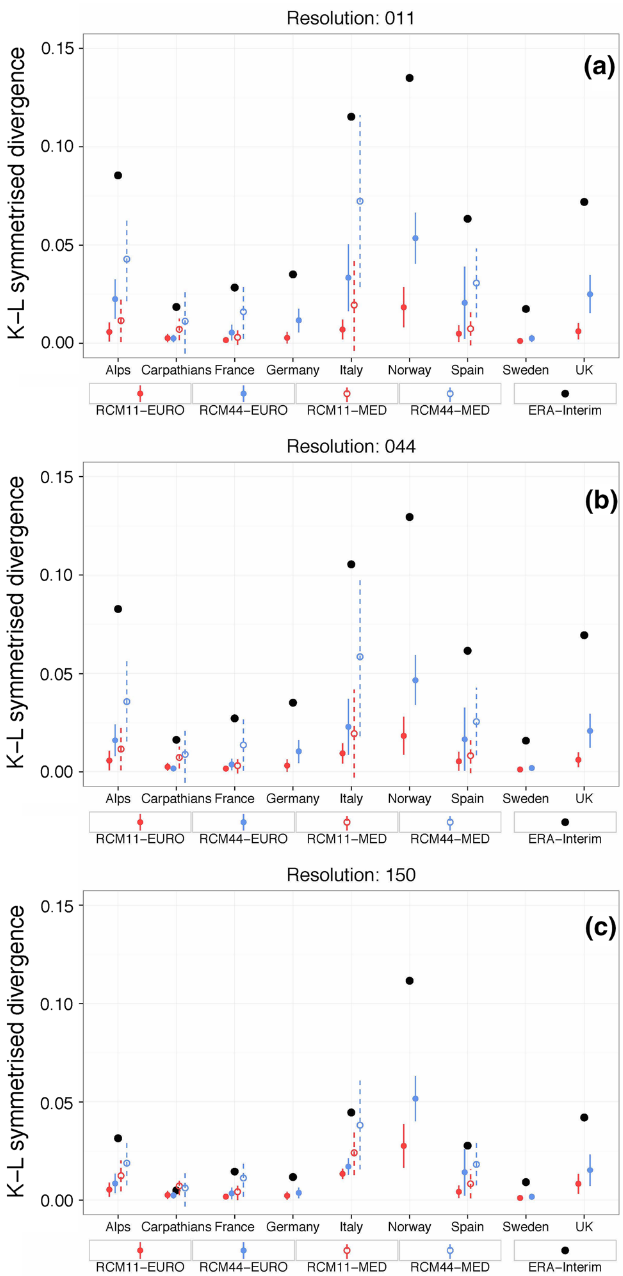
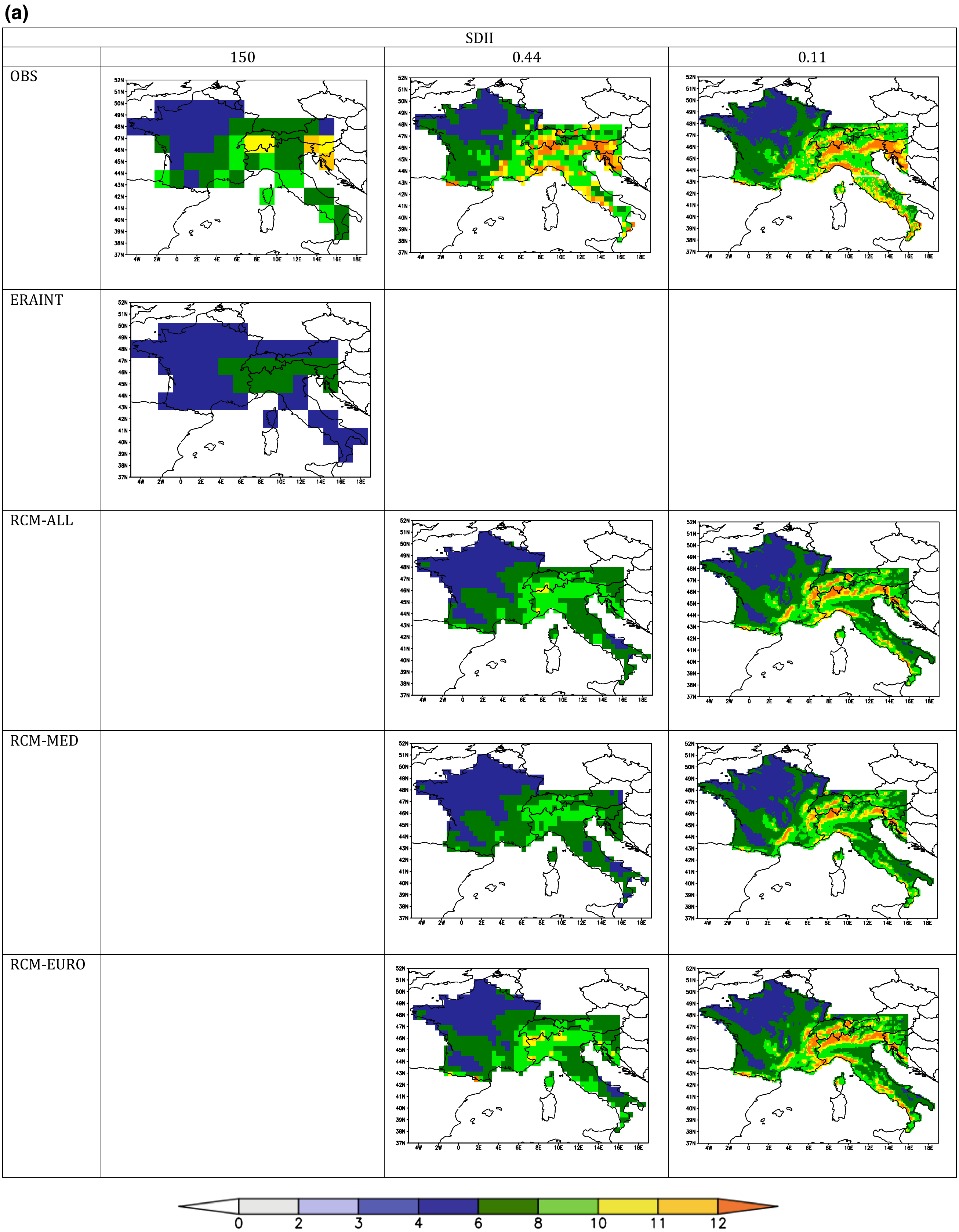


Fig. 7 Kullback–Leibler (KL) divergence (see Sect. 2) between simulated and observed regional daily precipitation PDFs for the ERA-Interim, RCM44 and RCM11 (both EURO-CORDEX and Med-CORDEX ensembles) at 0.11° (**a**), 0.44° (**b**) and 1.5° resolution (**c**). For the models, both the ensemble mean (*continuous line*) and inter-model standard deviation (*vertical bars*) of the KL divergence are shown. Lower KL values indicate closer agreement with observations

are well known areas of strong cyclogenesis (Porcú et al. 2003). The high resolution model ensemble captures these patterns remarkably well, while both the ERA-Interim and RCM44 models miss them. Similar considerations are valid for France (Fig. 8a). The Taylor diagrams of Fig. 9 confirm these conclusions, showing that the high resolution models of both Med-CORDEX and EURO-CORDEX ensembles are predominantly characterized by smaller centered RMSE for the SDII index compared to the corresponding ERA-Interim and RCM44 experiments on the 0.11° grid (panel a). Also note that the correlations between RCM11 and observed SDII are high, mostly between 0.7 and 0.9. The exception is the Carpathian region, for which the models produce substantially higher SDII than observed, again probably as a result of the low station density there. For the Italian peninsula, due to the model underestimation of the observed SDII along all the Tyrrhenian coast and Calabria region the correlation is not higher than 0.5. On the coarser resolution grids, the models (and ERA-Interim) appear to underestimate the areas of largest SDII values, and Fig. 9 indicates that a slight improvement in the RCM11 ensemble is found also in this metric.

Moving to the extreme index $P_{sum} > R95_{Obs}$, the illustrative example of Fig. 8b (UK) indicates a similar improvement induced by the fine scale representation of the morphological features of the regions. The improvement in the simulation of the spatial patterns in $P_{sum} > R95_{Obs}$ at high resolution is also clear from the Taylor diagram of Fig. 9. Although in this case the correlations are lower than for SDII, mostly between 0.3 and 0.6 for the RCM11 on the 0.11° grid (panel a) they are overall higher than for ERA-Interim and the RCM44 ensemble, which show many instances of even negative spatial correlations. In fact, Fig. 8b shows that both the ERA-Interim and RCM44 models underestimate the peak values of $P_{sum} > R95_{Obs}$ at the respective resolution grids much more than the RCM11 ensemble. In summary, both the precipitation intensity and extreme indices analyzed here show clear added value by the high resolution of the RCM11 ensemble, with the Med-CORDEX models being generally in line with the EURO-CORDEX models.

The conclusions are somewhat different for the dry day indices DDF and CDD95 as seen in Fig. 8c, d. For these statistics the improvement achieved by the high resolution runs, compared to both ERA-Interim and RCM44, is not as marked, or is even negligible, for most regions. All the model ensembles tend to underestimate the number of dry days over regions characterized by wet climates, such as UK, Germany, the Alps, northern France and Scandinavia (see Fig. 8d). As a consequence, the length of severe dry spells, as measured by the CDD95, is also underestimated over these regions. This is a well known deficiency in climate models, known as the “drizzle” problem (Sun et al. 2006), which has been attributed to the coarse model resolution or to limitations in the precipitation parameterizations. The important message deriving from Fig. 8d is that increasing resolution does not improve substantially this systematic error, implying that the error is not to be reconducted to a simple spatial scaling issue, but needs to


(a)
SDII
150
0.44
0.11
OBS
ERAINT
RCM-ALL
RCM-MED
RCM-EURO
0
2
3
4
6
8
10
11
12

◂**Fig. 8** **a** SDII mean regional patterns over the Alps, Italy and France in ERA-Interim, Ensemble mean RCM-ALL, EURO-CORDEX (RCM-EURO) and Med-CORDEX ensemble (RCM-MED) at 0.11° and 0.44° resolution. Regional observations at all the resolutions are shown. Units are mm/day. **b** Same as **a** but for the index $P_{sum} > R95_{Obs}$ over UK. Units are mm/year. **c** Same as **a** but for DDF (% days/year) over Spain. **d** Same as **a** but for CDD95 (No days) over the Scandinavian region

be improved by enhancing the model representation of the precipitation process. By contrast, the models exhibit a better performance in dry environments, such as Spain and southern France (Fig. 8c).

It should be noted that, when the mean bias is removed (Taylor diagrams of Figs. 9 and S5) the improvement associated with the high resolution becomes more evident, as in most regional cases the correlations are higher, and the centered RMSE lower, for the RCM11 ensemble than the RCM44 and ERA-Interim. Therefore, also for the dry day statistics the high resolution improves the simulation of fine scale spatial patterns, this is less the case for the coarser resolution grids.

In Fig. 10 the ratio between the 0.11° and 0.44° resolution bias and RMSE is reported for each model and for each region for all the four indices. As a general tendency the single model behaviors are in line with the results

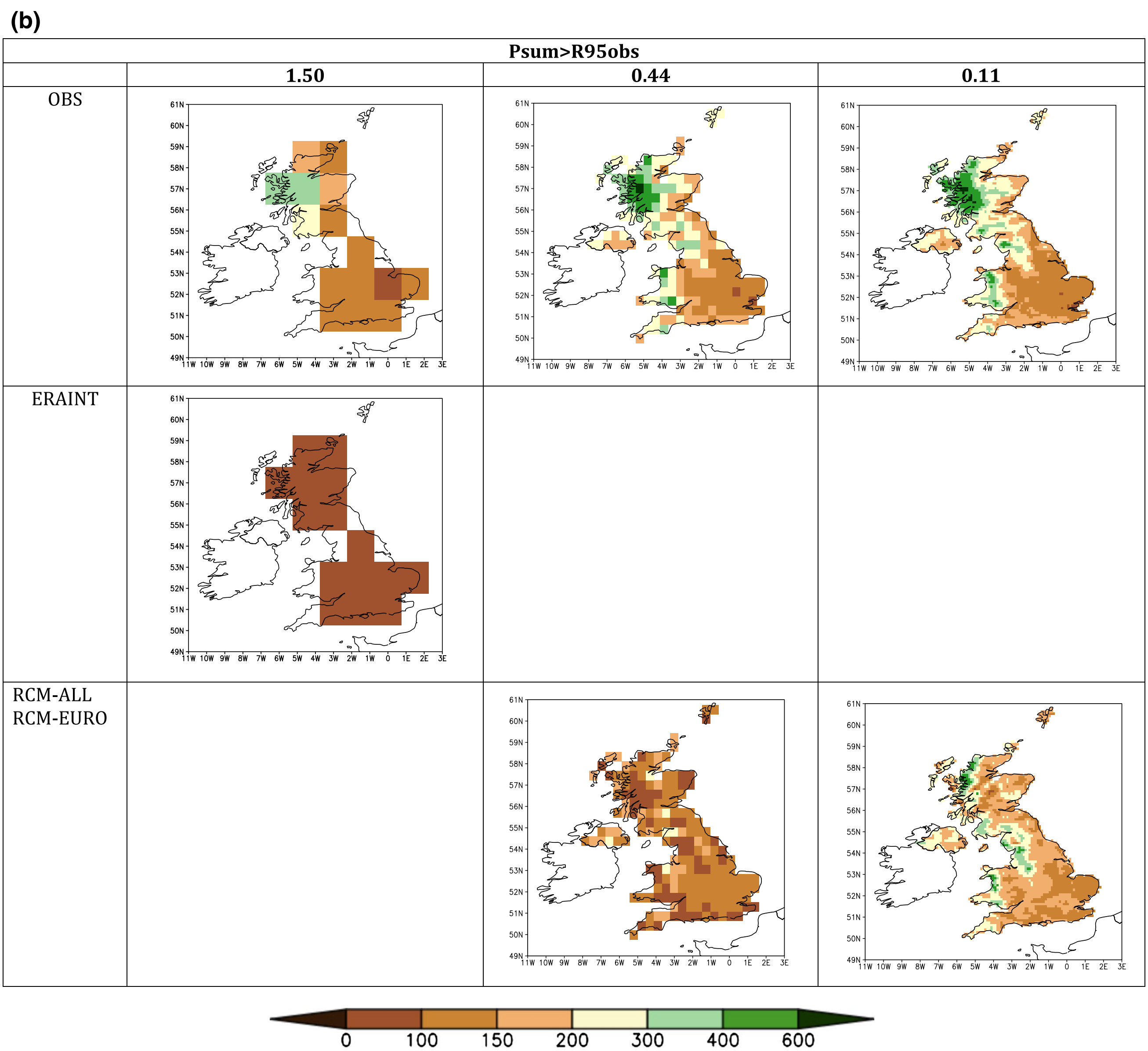


Fig. 8 continued

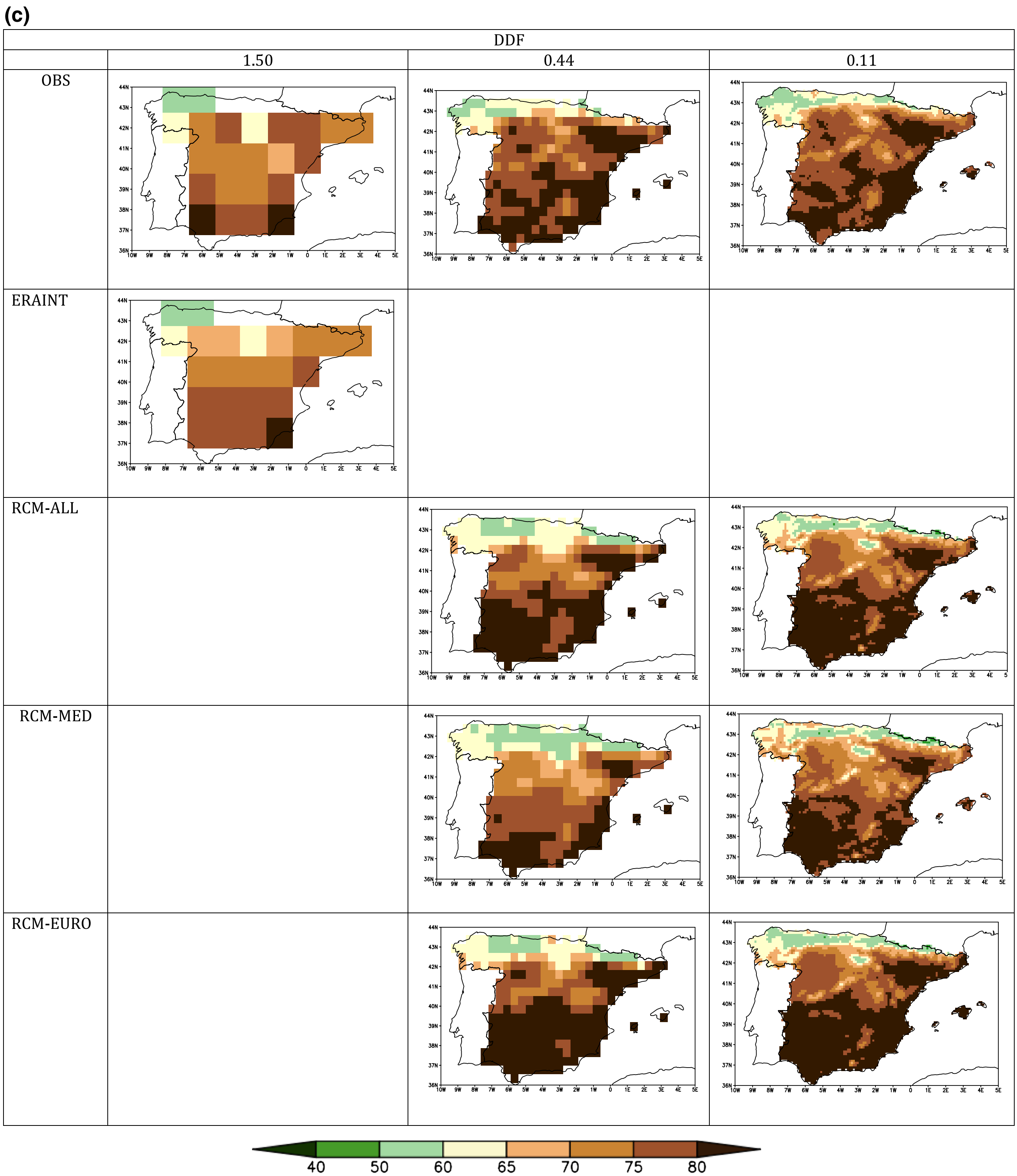


Fig. 8 continued

shown in Figs. 8 and 9. Most of the models have a lower bias and RMSE at 0.11° resolution and this is more evident for the wet indices (R95 and SDII) and less for the dry indices bias. Also in this case the region that shows the worst performance is the Carpathians for both bias and RMSE. The Italian region is not scoring well only for the RMSE of the R95 index (but not for bias) and this is again due probably to the underestimation of extreme events in the region

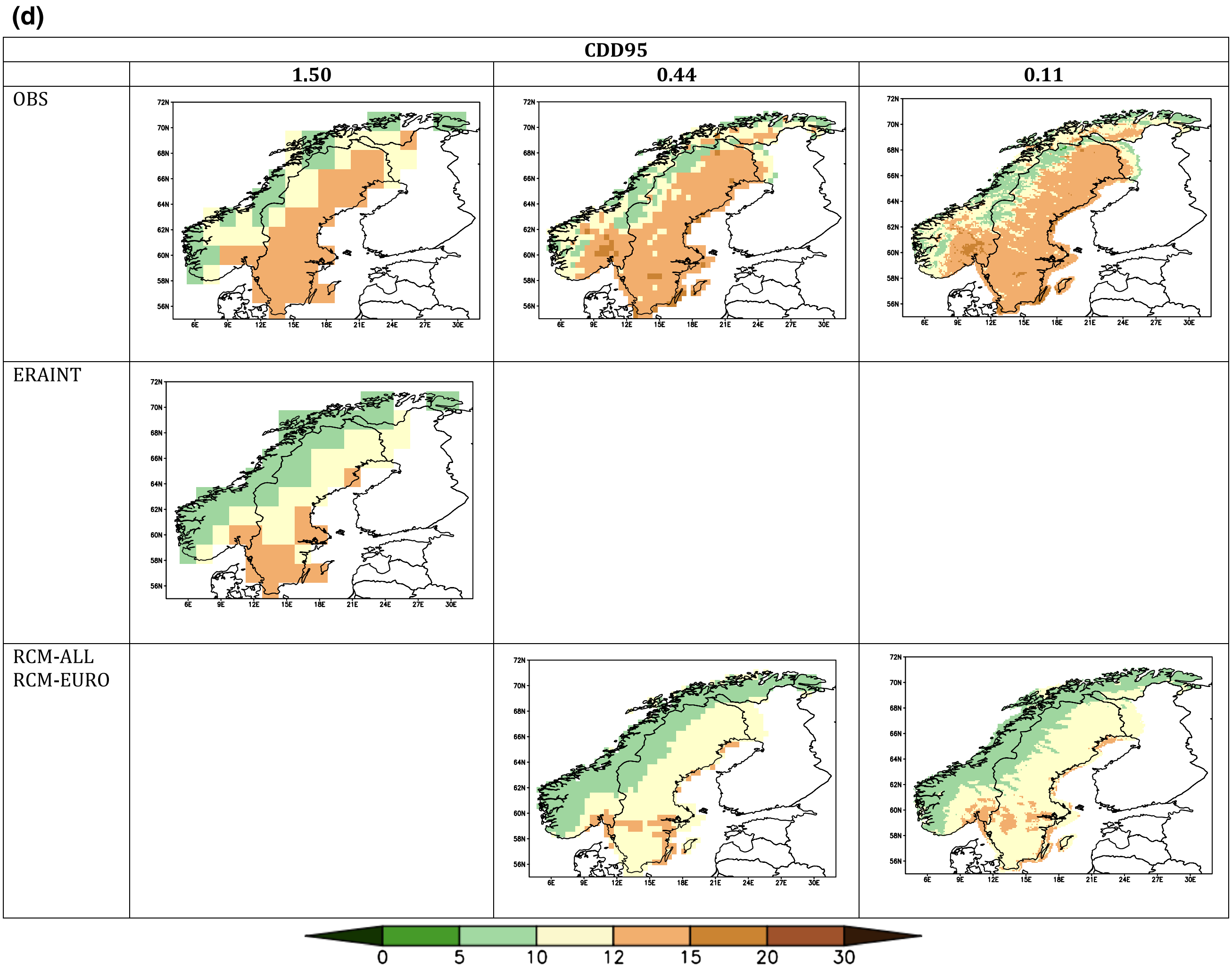


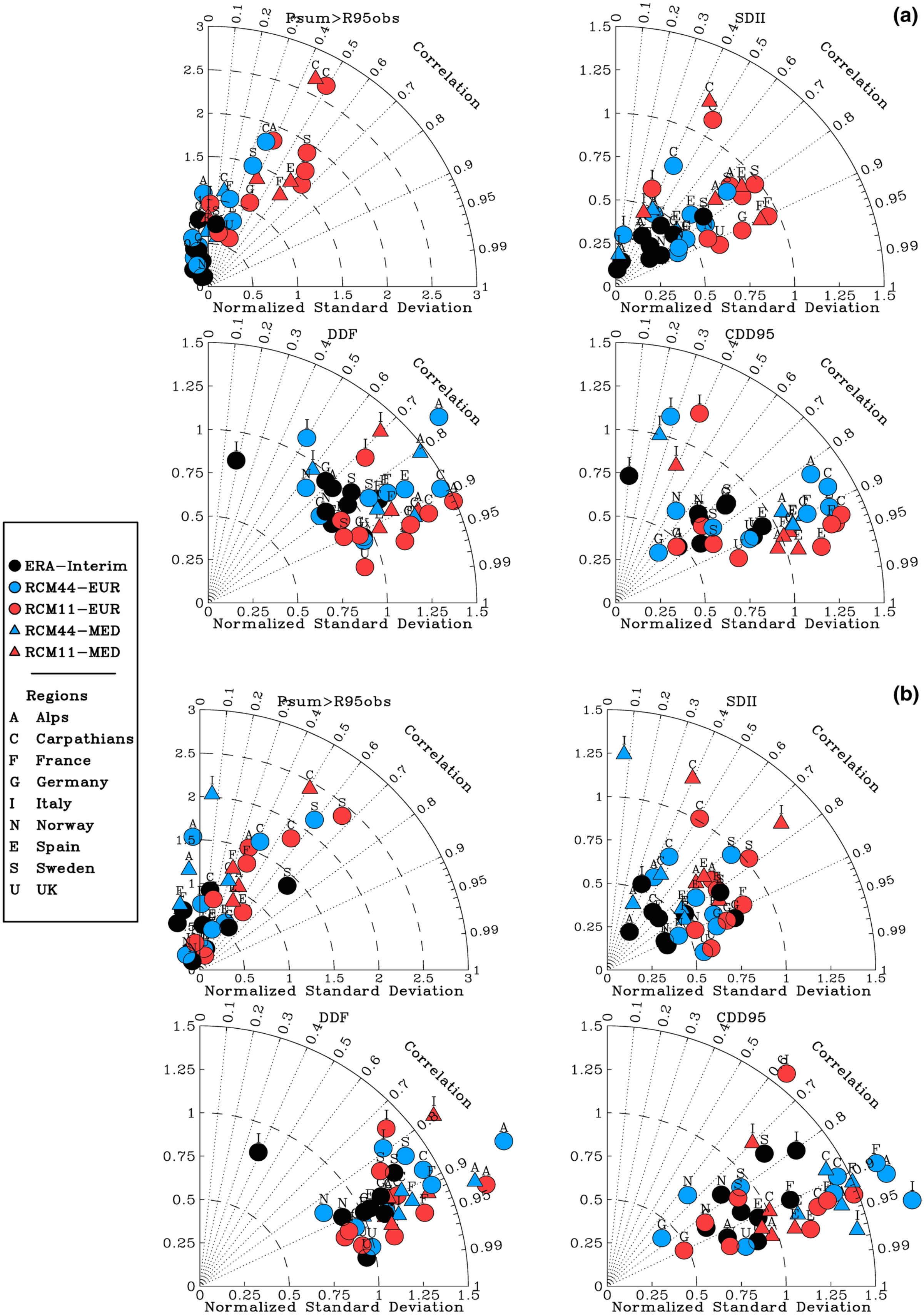
Fig. 8 continued

as explained before. Some problems are shown also for the bias and RMSE of the dry CDD95 index.

Figures 11, 12 and 13 show the annual cycle over the different regions for three indices, SDII, DDF and $P_{sum} > R95_{Obs}$ (CDD95 cannot be calculated for individual months because it requires use of the entire continuous time series of events), for both the Med-CORDEX and EURO-CORDEX ensembles on the 0.11° grid (both mean and inter-model standard deviation range are shown). SDII and $P_{sum} > R95_{Obs}$ are maximum in the fall over the Mediterranean regions (Spain, Italy, Alps and France), where, as mentioned, strong events in the fall are associated with local cyclogenetic processes induced by the Mediterranean waters and the Alpine topography (Porcú et al. 2003). Conversely, they peak in the summer over the more continental regions (Carpathians, Germany and Sweden), where summer convection dominates, and in the winter over the regions most affected by cold season Atlantic storms (UK and Norway). Despite the presence of regional biases in different months, by and large the model ensembles reproduce this seasonality, indicating that they can successfully simulate these underlying dominant precipitation regimes.

Despite the general underestimate, the models also reproduce well the seasonal cycle of dry day frequency over the different regions, with summer maxima in the Mediterranean regions (France, Italy, Spain) along with England and the Alps, a spring minimum and spring maximum over the Carpathian and Norway, respectively, and a double peaked seasonal structure over Germany and Sweden. Again, this is an indication of a good simulation of underlying circulations and processes.

A comparison across different ensembles shows that, for SDII and $P_{sum} > R95_{Obs}$ (Figs. 11, 12), ERA-Interim produces the lowest values with the greatest systematic error compared to observations, while the RCM11 shows the highest values and closest to observations. In fact, in


(a)
Psum>R95obs
SDII
DDF
CDD95
(b)
Correlation
Normalized Standard Deviation
ERA−Interim
RCM44−EUR
RCM11−EUR
RCM44−MED
RCM11−MED
Regions
A Alps
C Carpathians
F France
G Germany
I Italy
N Norway
E Spain
S Sweden
U UK

◂**Fig. 9** Taylor diagrams of the ensemble mean values of the four indices described in Sect. 2 in the different analysis regions for the ERA-Interim, RCM44 and RCM11 (both EURO-CORDEX and Med-CORDEX models) ensembles with respect to the corresponding regional observation datasets, at the 0.11° (**a**) and 1.5° (**b**) resolution. The distance from the point 1 measures the centered (bias removed) RMSE, the indices are calculated on an annual basis, and the mean is taken over the different regional analysis periods (see Sect. 2)

all regions (except the Carpathians) the higher resolution of the RCM11 ensemble leads to an improvement of SDII and $P_{sum} > R95_{Obs}$ compared to the RCM44, and although there is still a tendency to underestimate the observed values, in almost all cases the observations are within the inter-model standard deviation range of the RCM11 ensemble. The most noticeable exceptions are Norway, where both

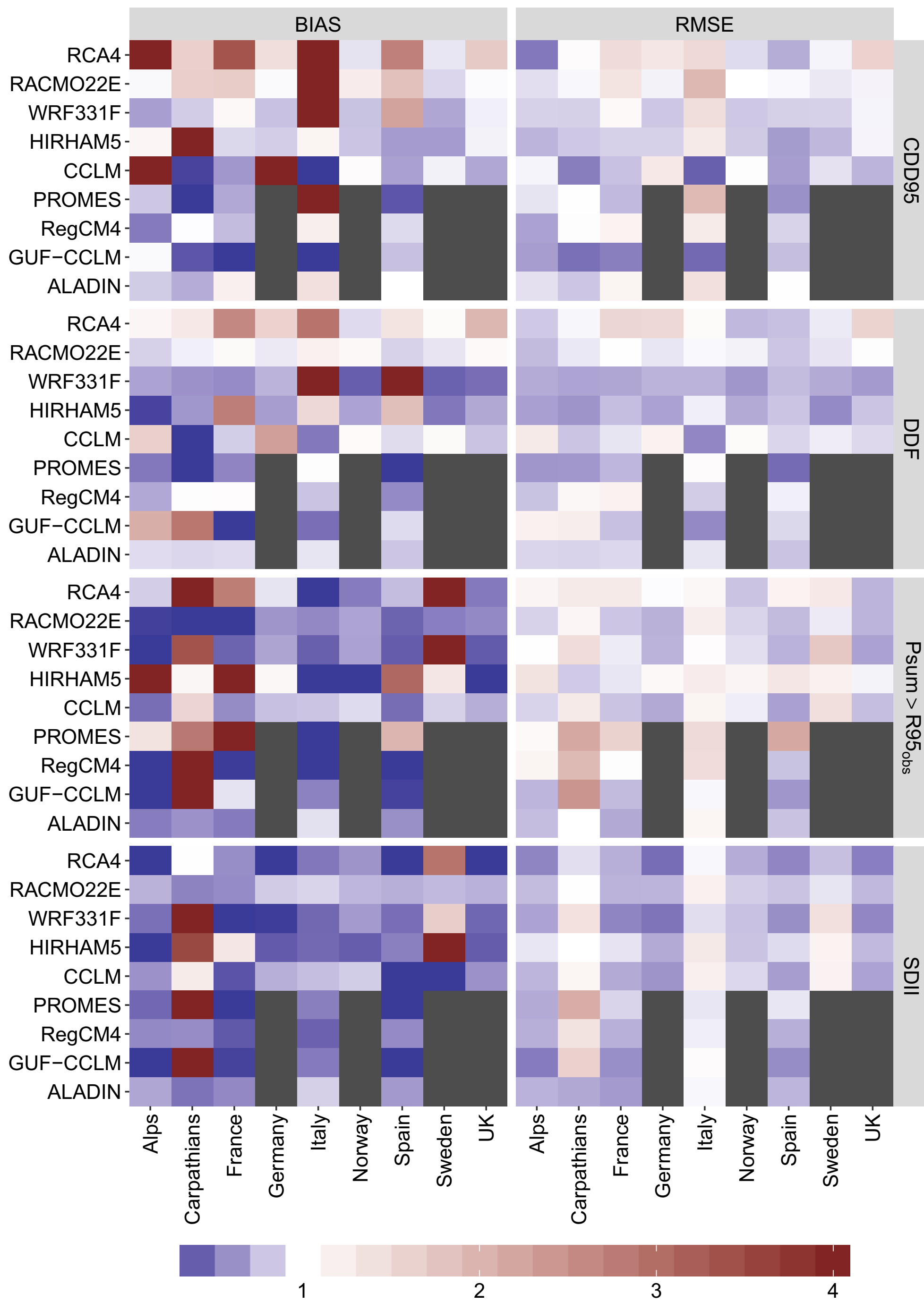


Fig. 10 The ratio between the 0.11° and 0.44° resolution BIAS and RMSE, for each model and for each region for all the four indices. *Red* indicates that BIAS or RMSE increased in the 0.11° simulations; *blue* on the contrary indicates an improvement in the 0.11° simulations. *Grey* areas indicate missing data due to the smaller domain of Med-CORDEX models, which does not fully cover all regions

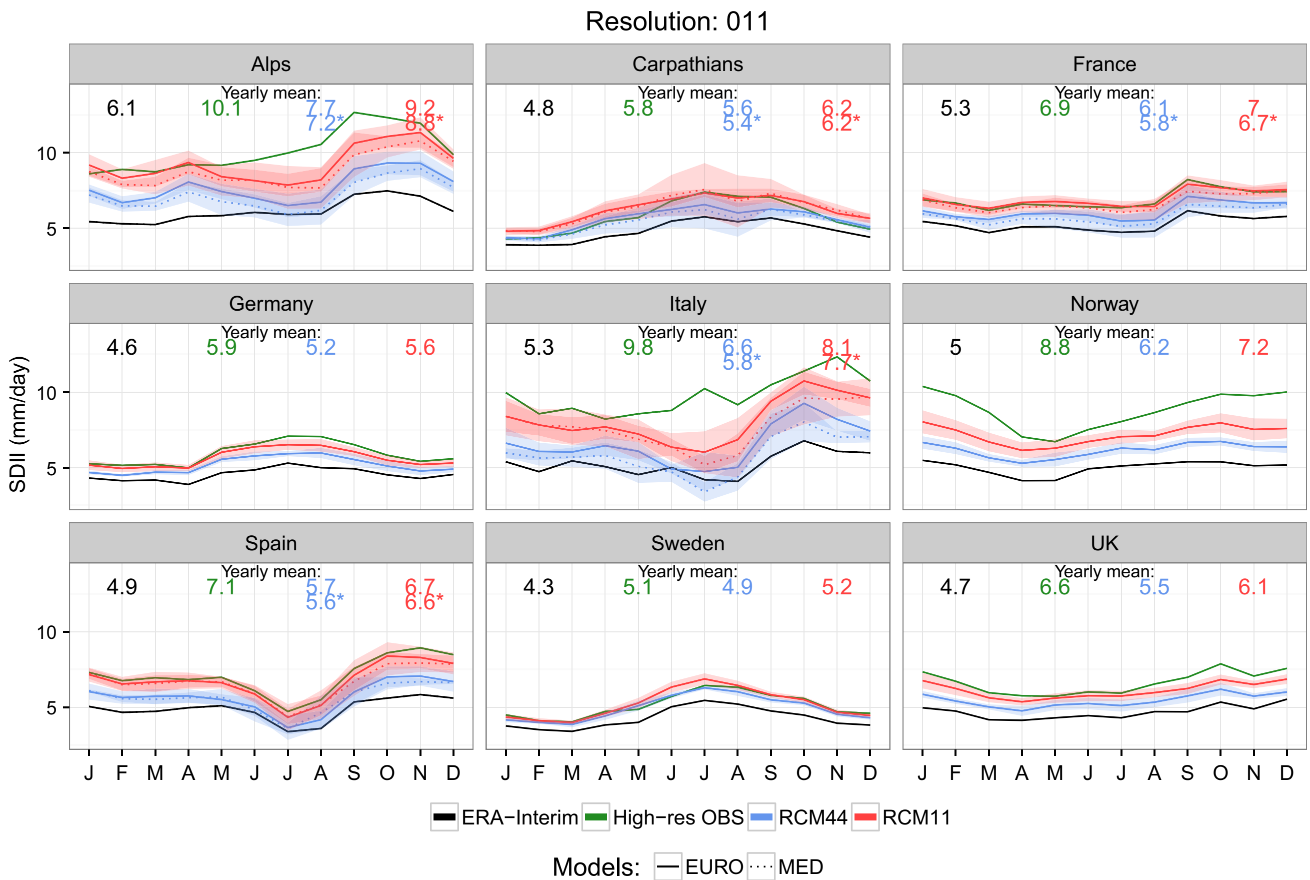


Fig. 11 Annual cycle of ensemble mean value of the SDII index over the different analysis regions for the RCM44 and RCM11 ensembles (EURO-CORDEX and Med-CORDEX models), along with the ERA-Interim and observed SDII, at the 0.11° resolution. For the model ensembles, both the mean (*thick line*) and intermodel standard deviations range (*shaded area*) are shown. Units are mm/day and the mean is taken over the different analysis periods (see Sect. 2)

SDII and $P_{sum} > R95_{Obs}$ are substantially underestimated in the cold months, and Italy, where SDII is underestimated throughout the year. On the other hand, the models overestimate the $P_{sum} > R95_{Obs}$ over the Carpathians, Alps in the cold season and France. Concerning the dry day frequency, the general underestimation by the models, along with the low sensitivity to resolution, are evident from Fig. 13. Again, the models mostly produce higher values than the ERA-Interim, which places them closer to observations. The largest underestimation of dry day frequency occurs over the wetter regions, Alps, Norway and Germany.

The results are similar also at the 0.44° (not shown because very similar to the 0.11° ones) and 1.5° resolution as shown in Figs S8–S10 where the annual cycles of the three indices are reported.

Summarizing the results of this section, the high resolution RCM11 ensemble shows an excellent performance in reproducing daily precipitation intensity, both in terms of spatial patterns and seasonal cycle. For this precipitation statistics the higher resolution of the RCM11 models yields a substantial improvement compared to the RCM44 and the ERA-Interim and this is also evident at lower resolution grids. A similar, albeit less marked, improvement is found for the related statistics of $P_{sum} > R95_{Obs}$, where in some cases the models show a tendency for overestimation with respect to observations. Different indications are found for the dry day statistics (DDF and CDD95), for which the models capture the seasonal cycle but over wet regions show a systematic tendency to underestimate the number of dry days and little sensitivity to model resolution. This is because the models, even at the highest resolution analyzed, tend to produce too many small intensity events that do not contribute much to the mean precipitation (which does not show a systematic bias) but are sufficient to cause a systematic bias in dry day occurrence. When this bias is removed, the high resolution still yields an improvement in the simulation of the spatial patterns of dry day statistics.

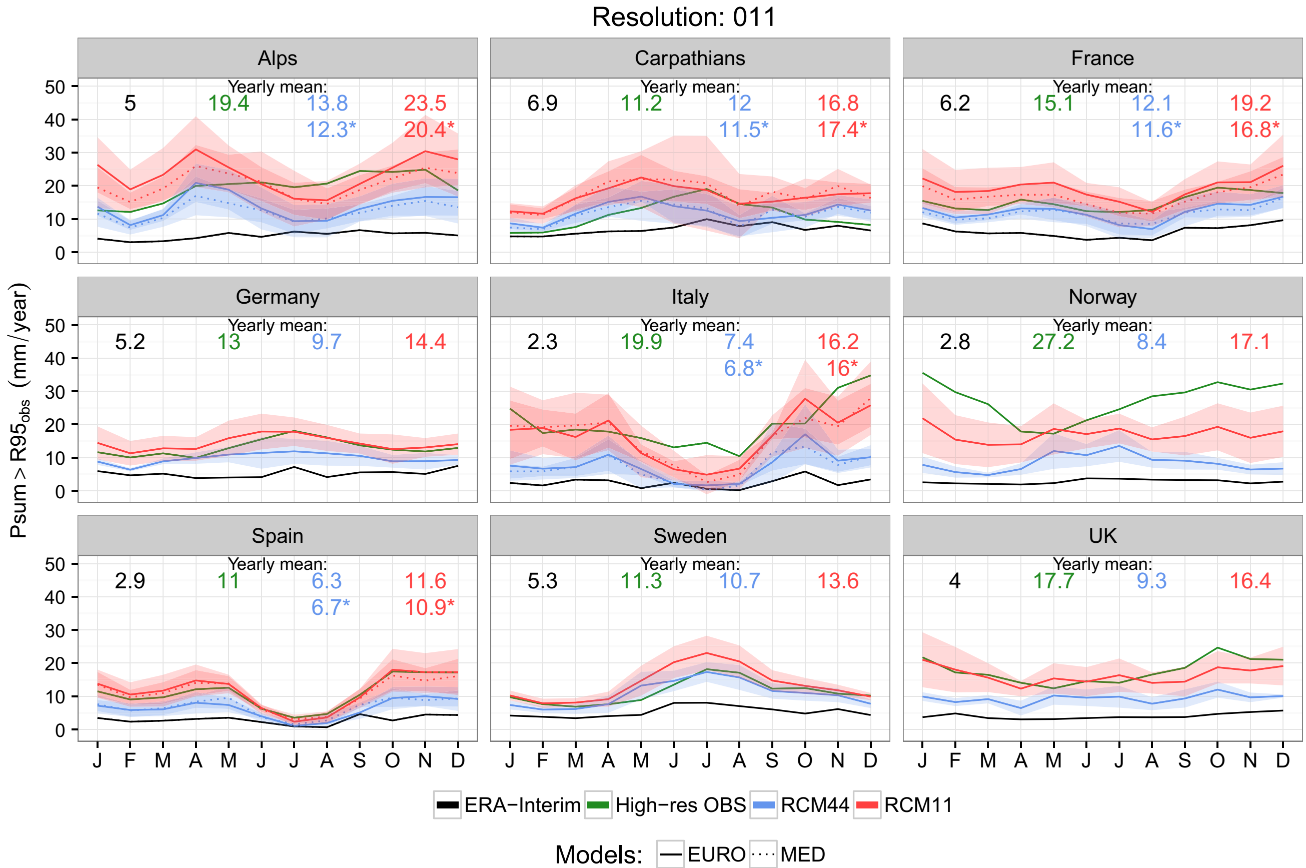


Fig. 12 Same as Fig. 11, but for the index $P_{sum} > R95_{Obs}$. Units are mm/year

4 Summary and discussion

In this paper we analyze different daily precipitation statistics in medium (RCM44) and high-resolution (RCM11) ensembles of Med-CORDEX and EURO-CORDEX experiments driven by the ERA-Interim reanalysis of observations. The model data are assessed against gridded high resolution observation datasets assembled for different European subregions. Quantitative performance metrics are used to validate statistics ranging from multi-decadal means to daily precipitation intensity PDFs and different daily precipitation indices.

Overall, the model ensembles show a remarkable performance in simulating the spatial patterns and annual cycle of all metrics analyzed, with a substantial improvement going from the low resolution of the ERA-interim data to the medium resolution RCM44 ensemble and the high resolution RCM11. This improvement is generally found not only at the finest 0.11° scale but also when the data are upscaled at the 0.44° and 1.5° scales, which adds robustness to the information provided by the fine resolution models. The performance of the models appears improved compared to previous generation RCMs (Jacob et al. 2007; Rauscher et al. 2010), at least for the daily precipitation indices considered here and for the high resolution configurations. The only metrics for which a marked improvement with resolution is not found are related to the frequency of dry days in wet climate regimes, which is generally underestimated even in the RCM11 models. This points towards the key role of the model's description of the precipitation process in determining an excessive number of small precipitation events. Experiments with very high resolution models, down to the cloud-permitting scale, provide indications that this problem might be ameliorated when moving to the sub-10 km scale in which cloud and convection processes are explicitly described (Kendon et al. 2012; Prein et al. 2013; Ban et al. 2014), but further work with larger ensembles is needed to confirm this conclusion.

Comparison between the Med-CORDEX and EURO-CORDEX ensembles over common sub-regions indicates that the two ensembles are characterized by similar performances and resolution-dependent behavior, despite the differences in domain size. Our results thus indicate that, at least in terms of daily precipitation statistics and

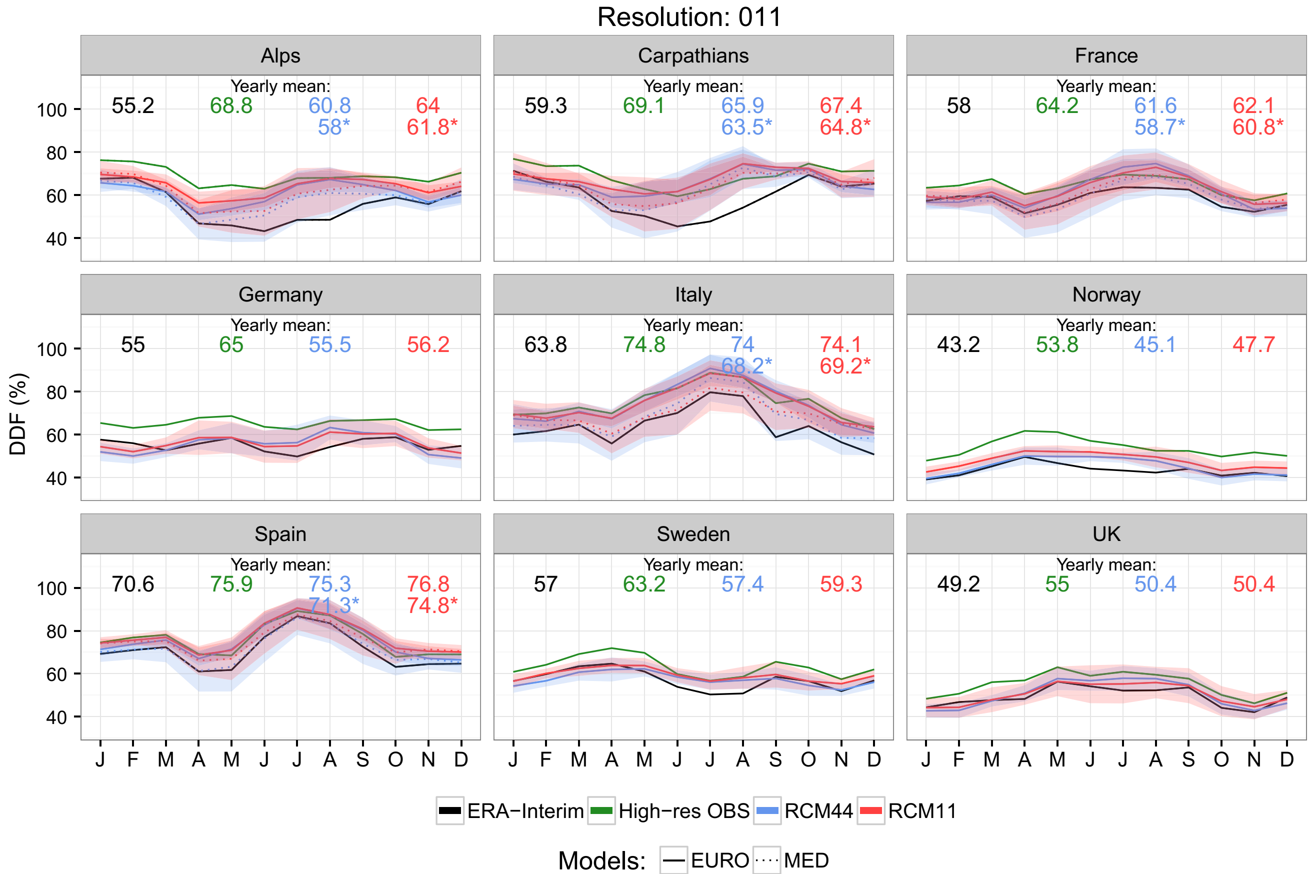


Fig. 13 Same as Fig. 11, but for the index DDF. Units are % days/year

climatologies, both the Med-CORDEX and EURO-CORDEX ensembles are of sufficient quality to be applied in climate projections, as done in the respective CORDEX frameworks. Also, our conclusions are mostly consistent with those of Kotlarski et al. (2014) and Prein et al. (2015), albeit some differences are found. For example, while Prein et al. (2015) report an improvement of dry day statistics at high resolution, we find this improvement to be only marginal, as shown also in Sanchez et al. (2011). Prein et al. (2015) also report a decrease of the model bias over large portions of the domain. This improvement in bias, however, depends on whether the models tend to underestimate or overestimate precipitation in a given region, since a consistent effect of increased resolution is the increase of precipitation amounts (as also found by Rauscher et al. 2010). We thus cannot conclude that increased resolution yields a systematic improvement of regional mean biases and RMSE.

A final consideration concerns the issue of observations. Clearly, the ever increasing resolution reached by RCMs will require the availability of high quality, high resolution observations for the assessment of the models. In this work we have assembled a set of gridded observations datasets which we used for model validation. However, this set only partially covers Europe, and it is characterized by products derived from widely different station densities (and thus effective resolution) and methodological approaches (some are purely based on station data while some make use of high resolution reanalysis). For example, the station density of the Alpine region is much larger than that of the Carpathians, and over central-southern Italy only a partial cover of the region was available. In fact, in some instances the results for the Carpathians and Italy were diverging from those in other regions. This diversity in the quality of observed data makes a rigorous and consistent model assessment rather difficult. While some European-wide datasets, such as E-Obs (Haylock et al. 2008), CRU (Mitchell and Jones 2005) and UDEL (Matsuura and Willmott 2010) are available, they are still based on relatively sparse station networks and coarse effective resolution. Our study thus calls for the need to develop a homogeneous and internally consistent high resolution, quality checked, observation dataset for the entire European territory which can be used for future development of very high resolution, European-wide models.

Acknowledgements We thank all the institutions in Table 2 for providing the observations and the Med-CORDEX and EURO-CORDEX groups. In particular, we thank the CETEMPS, University of L'Aquila for providing the Italian gridded data. We thank Fabio Di Sante and Graziano Giuliani, for helping in troubleshooting with the station data and other datasets. Bodo Ahrens acknowledges support by Senckenberg BiK-F, Germany. UCLM contribution has been partially funded by the Spanish Government and the European Regional Development Fund, through Grants CGL2007-66440-C04-02, CGL2010-18013 and CGL2013-47261-R.

References

Adam JC, Lettenmaier DP (2003) Adjustment of global gridded precipitation for systematic bias. J Geophys Res 108:4257. doi:10.1029/2002JD002499

Adam JC, Clark EA, Lettenmaier DP, Wood EF (2006) Correction of global precipitation products for orographic effects. J Clim 19:15–38

Akhtar N, Brauch J, Dobler A, Berenger K, Ahrens B (2014) Medicanes in an ocean–atmosphere coupled regional climate model. Nat Hazards Earth Syst Sci 14:2189–2201. doi:10.5194/nhess-14-2189-2014

Ban N, Schmidli J, Schar C (2014) Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. J Geophys Res 119:7889–7907. doi:10.1002/2014JD021478

Casanueva A, Kotlarski S, Herrera S, Fernández J, Gutiérrez JM, Boberg F, Colette A, Christensen OB, Goergen K, Jacob D, Keuler K, Nikulin G, Teichmann C, Vautard R (2016) Daily precipitation statistics in a EURO-CORDEX RCM ensemble: added value of raw and bias-corrected high-resolution simulations. Clim Dyn 47:719–737. doi:10.1007/s00382-015-2865-x

Castro M, Fernández C, Gaertner MA (1993) Description of a mesoscale atmospheric numerical model. In: Díaz JI, Lions JL (eds) Mathematics, climate and environment. Recherches en Mathematics Appliques Series Mason, pp 230–253

Christensen OB, Drews M, Christensen JH, Dethloff K, Ketelsen K, Hebestadt I, Rinke A (2006) The HIRHAM regional climate model, version 5, Tech. Rep. Dan. Meteorol. Inst, Copenhagen, pp 06–17

Colin J, Deque M, Radu R, Somot S (2010) Sensitivity study of heavy precipitation in limited area model climate simulations: influence of the size of the domain and the use of the spectral nudging technique. Tellus A 62:591–604

Dee DP et al (2011) The ERA Interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 137:553–597

Di Luca A, Flaounas E, Drobinski P, Brossier CL (2014) The atmospheric component of the Mediterranean Sea water budget in a WRF multi-physics ensemble and observations. Clim Dyn 43:2349–2375

Fita L, Romero R, Luque A, Emanuel K, Ramis C (2007) Analysis of the environments of seven Mediterranean storms using an axisymmetric, nonhydrostatic cloud model. Nat Hazards Earth Syst Sci 7:41–56

Flaounas E, Drobinski P, Vrac M, bastin S, Lebeaupin Brossier C et al (2013) Precipitation and temperature space-time variability and extremes in the Mediterranean region: evaluation of dynamical and statistical downscaling methods. Clim Dyn 40:2687–2705

Gaertner MA, Jacob D, Gil V, Domınguez M, Padorno E, Sanchez E, Castro M (2007) Tropical cyclones over the Mediterranean Sea in climate change simulations. Geophys Res Lett. doi:10.1029/2007GL029977

Gaertner MA, Gil V, Romera R, Domınguez M, Sanchez E, Gallardo C (2011) Climate change scenarios and risk of tropical cyclones over the Mediterranean Sea: analysis with ENSEMBLES data. Presented at the 3rd international summit on hurricanes and climate change. Rhodes

Giorgi F (1991) Sensitivity of summertime precipitation over the western United States to model physics parameterizations. Mon Weather Rev 119:2870–2888

Giorgi F, Jones C, Asrar G (2009) Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull 58:175–183

Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla MB, Bi X, Elguindi N, Diro GT, Nair V, Giuliani G, Turuncoglu UU, Cozzini S, Güttler I, O'Brien TA, Tawfik AB, Shalaby A, Zakey AS, Steiner AL, Stordal F, Sloan LC, Branković C (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29. doi:10.3354/cr01018

Giorgi F, Coppola E, Raffaele F, Diro GT, Fuentes-Franco R et al (2014) Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections. Clim Change 125:39–51

Haylock MR, Hofstra N, Tank AMGK, Klok EJ, Jones PD et al (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J Geophys Res 113:D20119

Herrera S, Fernández J, Gutiérrez JM (2015) Update of the Spain02 gridded observational dataset for Euro-CORDEX evaluation: assessing the effect of the interpolation methodology. Int J Climatol. doi:10.1002/joc.4391

Herrmann M, Somot S, Calmanti S, Dubois C, Sevault F (2011) Representation of daily wind speed spatial and temporal variability and intense wind events over the Mediterranean Sea using dynamical downscaling: impact of the regional climate model configuration. Nat. Hazards Earth Sys Sci 11:1983–2001

Isotta FA et al (2014) The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine raingauge data. Int J Climatol 34:1657–1675

Jacob D, Barring L, Christensen OB, Christensen JH, de Castro M et al (2007) An intercomparison of regional climate models for Europe: design of the experiments and model performance. Clim Change 81:31–52

Jacob D, Petersen J, Eggert B, Alias A, Christensen JH et al (2013) EURO-CORDEX: new high resolution climate change projections for European impact research. Reg Environ Change 14:563–578

Johansson B (2002) Estimation of areal precipitation for hydrological modelling, Ph.D. Thesis. Earth Sciences Centre, Göteborg University, Report nr. A76

Jones C, Giorgi F, Asrar G (2011) The coordinated regional downscaling experiment: CORDEX. An international downscaling link to CMIP5. CLIVAR Exch 16:34–40

Kendon EJ, Roberts NM, Senior CA, Roberts mJ (2012) Realism of rainfall in a very-high resolution regional climate model. J Clim 25:5791–5806

Kotlarski S, Keuler K, Christensen OB, Colette A, Deque M et al (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci Model Dev 7:1297–1333

Kullback S, Leibler RA (1951) On information and sufficiency. Ann Math Stat 22:79–86

Kupiainen M, Samuelsson P, Jones C, Jansson C, Willén U, Hansson U, Ullerstig A, Wang S, Döscher R (2011) rossby centre regional atmospheric model, RCA4, Rossby Centre Newsletter

Lagouvardos K, Kotroni V, Nickovic S, Jovic D, Kallos G, Tremback CJ (1999) Observations and model simulations of a winter subsynoptic vortex over the central Mediterranean. Meteorol Appl 6:371–383

Lionello P, Boldrin U, Giorgi F (2008) Future changes in cyclone climatology over Europe as inferred from a regional climate simulation. Clim Dyn 30:657–671

Matsuura K, Willmott C (2010) Terrestrial air temperature and precipitation: 1900–2008 gridded monthly time series (V 2.01). University of Delaware Department of Geography Center for Climatic Research. http://climate.geog.udel.edu/~climate/html_pages/archive.html

Mitchell T, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Mohr M (2009) Comparison of versions 1.1 and 1.0 of gridded temperature and precipitation data for Norway. Technical report Met. no note 19

Montani A, Marsigli C, Nerozzi F, Paccagnella T, Tibaldi S, Buizza R (2003) The Soverato flood in Southern Italy: performance of global and limited-area ensemble forecasts. Nonlinear Process Geophys 10:261–274

Perry M, Hollis D, Elms M (2009) The generation of daily gridded datasets of temperature and rainfall for the UK. Met Office Climate Memorandum No. 24

Porcú F, Caracciolo C, Prodi f (2003) Cloud systems leading to flood events in Europe: an overview and classification. Meteorol Appl 10:217–227. doi:10.1017/S1350482703003025

Prein AF, Gobiet A, Suklitsch M, Truhetz H, Awan NK et al (2013) Added value of convection permitting seasonal simulations. Clim Dyn 41:2577–2655

Prein AF, Gobiet A, Truhetz H, keuler K, Goergen K et al (2015) Precipitation in the EUOR-CORDEX 0.11° and 0.44° simulations: high resolution, high benefits? Clim Dyn. doi:10.1007/s00382-015-2589-y

Pytharoulis I, Craig GC, Ballard SP (2000) The hurricane-like Mediterranean cyclone of January 1995. Meteorol Appl 7:261–279

Rauscher SA, Coppola E, Piani C, Giorgi F (2010) Resolution effect of regional climate model simulation of precipitation over Europe part I: seasonal. Clim Dyn 35:685–711

Rauthe M, Steiner H, Riediger U, Mazurkiewicz A, Gratzki A (2013) A Central European precipitation climatology—part I: generation and validation of a high-resolution gridded daily data set (HYRAS). Meteorol Z 22:235–256. doi:10.1127/0941-2948/2013/0436

Rockel B, Castro CL, Pielke RA Sr, von Storch H, Lencini G (2008) Special issue regional climate modelling with COSMO-CLM (CCLM). Meteorol Z 17:347–348

Ruti P, Somot S, Giorgi F, Dubois C, Calmanti S, Ahrens B et al (2016) The MED-CORDEX initiative for Mediterranean climate studies. Bull Am Meteorol Soc. doi:10.1175/BAMS-D-14-00176.1

Sanchez E, Dominguez M, Romera R, Lopez de la Franca N, Gaertner MA, Gallardo C, Castro M (2011) Regional modeling of dry spells over the Iberian Peninsula for present climate and climate change conditions. Clim Change 107:625–634. doi:10.1007/s10584-011-0114-9

Sillmann J, Kharin VV, Zwiers FW, Zhang X, Bronaugh D (2013) Climate extreme indices in the CMIP5 multimodel ensemble: part 2. Future climate projections. J Geophys Res Atmos 118:2473–2493

Sun Y, Solomon S, Dai A, Portmann RW (2006) How often does it rain? J Clim 19:916–934

Szalai S et al (2013) Climate of the greater Carpathian region. Final Technical Report. www.carpatclim-eu.org

Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. J Geophys Res 106:7183–7192

Torma C, Giorgi F, Coppola E (2015) Added value of regional climate modeling over areas characterized by complex terrain—precipitation over the Alps. J Geophys Res 120:3957–3972

Tous M, Romero R (2013) Meteorological environments associated with medicane development. Int J Climatol 33:1–14

Tramblay Y, Ruelland D, Somot S, Bouaicha R, Servat E (2013) High resolution Med-CORDEX regional climate model simulations for hydrological impact studies: a first evaluation of the ALADIN-climate model in Morocco. Hydrol Earth Syst Sci 17:3721–3739

Meijgaard E van, Van Ulft LH, Lenderink G, de Roode SR, Wipfler L, Boers R, Timmermans RMA (2012) Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe. Climate Changes Spatial Planning Publications: KvR 054/12, p 44

Vautard R, Gobiet A, Jacob D, Belda M, Colette A et al (2013) The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. Clim Dyn 41:1–21

Vidal JP, Martin E, Franchistéguy L, Baillonb M, Soubeyroux JM (2010) A 50-year high-resolution atmospheric reanalysis over France with the Safran system. Int J Climatol 30:1627–1644. doi:10.1002/joc.2003

Walsh K, Giorgi F, Coppola E (2014) Mediterranean warm-core cyclones in a warmer world. Clim Dyn 42(3–4):1053–1066