



HAL
open science

Mediterranean extreme precipitation: a multi-model assessment

Leone Cavicchia, Enrico Scoccimarro, Silvio Gualdi, Paola Marson, Bodo Ahrens, Ségolène Berthou, Dario Conte, Alessandro Dell'Aquila, Philippe Drobinski, Vladimir Djurdjevic, et al.

► **To cite this version:**

Leone Cavicchia, Enrico Scoccimarro, Silvio Gualdi, Paola Marson, Bodo Ahrens, et al.. Mediterranean extreme precipitation: a multi-model assessment. *Climate Dynamics*, 2018, 51, pp.901-913. 10.1007/s00382-016-3245-x . hal-03658670

HAL Id: hal-03658670

<https://hal.science/hal-03658670v1>

Submitted on 7 Jun 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Mediterranean extreme precipitation: a multi-model assessment

Leone Cavicchia, Enrico Scoccimarro, Silvio Gualdi, Paola Marson, Bodo Ahrens, Ségolène Berthou, Dario Conte, Alessandro Dell' Aquila, Philippe Drobinski, Vladimir Djurdjevic, Clotilde Dubois, Clemente Gallardo, Laurent Li, Paolo Oddo, Antonella Sanna, Csaba Torma

L. Cavicchia
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy
E-mail: leone.cavicchia@cmcc.it

E. Scoccimarro · S. Gualdi · P. Marson · A. Sanna
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy

P. Marson
Ca' Foscari University, Venice, Italy

E. Scoccimarro · S. Gualdi · Paolo Oddo
Istituto Nazionale di Geofisica e Vulcanologia (INGV), Bologna, Italy

Paolo Oddo
Present address: Centre for Maritime Research and Experimentation STO NATO (CMRE), La Spezia, Italy

Bodo Ahrens
Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt am Main, Germany

Ségolène Berthou · Philippe Drobinski · Laurent Li
IPSL/Laboratoire de Meteorologie Dynamique, Ecole Polytechnique, ENS, UPMC, ENPC, CNRS, Palaiseau, France

Dario Conte
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Lecce, Italy

Alessandro Dell'Aquila
ENEA Climate Modeling and Impacts, Rome, Italy

Vladimir Djurdjevic
Institute of Meteorology, Faculty of Physics, University of Belgrade, Serbia

Clotilde Dubois
Météo France, Toulouse, France

Clemente Gallardo
Departamento de Ciencias Ambientales Universidad de Castilla-La Mancha, Toledo, Spain

Csaba Torma
Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

Abstract Exploiting the added value of the ensemble of high-resolution model simulations provided by the Med-CORDEX coordinated initiative, an updated assessment of Mediterranean extreme precipitation events as represented in different observational, reanalysis and modelling datasets is presented. A spatiotemporal characterisation of the long-term statistics of extreme precipitation is performed, using a number of different diagnostic indices. Employing a novel approach based on the timing of extreme precipitation events a number of physically consistent subregions are defined. The comparison of different diagnostics over the Mediterranean domain and physically homogeneous sub-domains is presented and discussed, focussing on the relative impact of several model configuration features (resolution, coupling, physical parameterisations) on the performance in reproducing extreme precipitation events. It is found that the agreement between the observed and modelled long-term statistics of extreme precipitation is more sensitive to the model physics, in particular convective parameterisation, than to other model configurations such as resolution and coupling.

Keywords Extreme precipitation · Mediterranean climate · Regional climate modelling

1 Introduction

Hazards due to heavy precipitation play a major role in the socio-economic impacts of extreme meteorological events (Easterling et al, 2000). A precise estimate of the risks associated with extreme precipitation is thus a scientific issue of high relevance for society. Furthermore, it has been shown that, due to changes in the hydrologic cycle (Trenberth, 1999), the incidence of extreme precipitation in a warmer climate can possibly

increase even in areas where mean precipitation is projected to decrease (Allan and Soden, 2008; Trenberth et al, 2003). It is thus crucial to estimate the performance of state-of-the-art climate models in reproducing the observed statistics of extreme precipitation events. The performance of models in reproducing precipitation has seen a steady improvement in the last decades following the increase of spatial resolution (Giorgi and Marinucci, 1996). On the other hand a number of issues remain, concerning both mean seasonal precipitation, like the excessive contribution from drizzles to the total precipitation amount (Dai, 2006), and the demanding challenge to reproduce precipitation extremes correctly (Meehl et al, 2000; Li et al, 2011). Reasons responsible for the difficulties encountered by climate models in reproducing the tail of daily precipitation intensity distribution, including the role of resolution and sub-grid physics parameterisations, have been extensively discussed in the literature (see e.g. Gordon et al (1992) and Iorio et al (2004), and references therein).

The Mediterranean region, due to the complex topography and land-ocean interactions, is known to be an area severely affected by extreme precipitation events (Alpert et al, 2002; Lionello et al, 2012). A number of recent works investigated different aspects of heavy precipitation in the Mediterranean area. Scoccimarro et al (2014) used the CMIP5 models to investigate how climate change might influence the characteristics of extreme events in the region. Their results show that extreme precipitation events might increase in terms of intensity as a response to global warming. Flaounas et al (2013) evaluated the skill of a regional climate model at different resolutions in reproducing heavy precipitation events in the region, finding a weak sensitivity on the horizontal resolution in term of spatial correlation with observations. Evaluation of RCMs capability in reproducing precipitation in the Euro-Mediterranean area in multi-model ensembles from the PRUDENCE (Jacob et al, 2007), ENSEMBLES (Lenderink, 2010) and EURO-CORDEX (Jacob et al, 2014) projects has pointed out on the other hand the role of horizontal resolution in improving the model skills (Rauscher et al, 2010). A number of works (Mariotti et al, 2008; Giorgi and Lionello, 2008; Marcos and Tsimplis, 2008), however, showed that studying the features of the Mediterranean Sea by means of global ocean-atmosphere coupled climate models (AOGCMs) or on atmosphere or ocean-only regional models presents some weaknesses. A shortcoming common to the global coupled and regional atmosphere only models is their limited capability to include a realistic representation of the processes associated with the presence of the Mediterranean Sea into the climate of the region. The global AOGCMs

used so far, in fact, have spatial resolutions generally not sufficient to resolve the small-scale features and processes that characterise the Mediterranean basin and its climate. Atmosphere only regional models, on the other hand, are forced with prescribed lower boundary conditions (sea-surface temperatures, SSTs) and thus they do not take into account any air-sea feedbacks. Furthermore, the Mediterranean SST used to force the models over the basin are produced with low-resolution AOGCMs. Assessing to what extent the improved representation of physical processes in a regional coupled system has an impact on the modelled precipitation extremes is one of the aims of the present work. The effort to attempt a realistic representation of the Mediterranean climate, including air-sea feedback, was initiated in Somot et al (2008) and carried on in the framework of the CIRCE project (Gualdi et al, 2013). The modelling data used in the present study are provided by the Med-CORDEX coordinated modelling initiative (Ruti et al, 2015), which activities are common with the HyMeX regional climate modelling activities (Drobinski et al, 2014). Conceived as the Mediterranean area contribution to the coordinated regional climate downscaling experiment CORDEX, Med-CORDEX produced a large number of long-term RCM simulations over the area (www.medcordex.eu). Given its importance for reproducing the region's climate features, a particular focus has been devoted within Med-CORDEX to the coupling of atmosphere and ocean RCMs.

The scope of the present work is twofold. On the one hand, we seek to provide an updated spatio-temporal characterisation of the long-term statistics of extreme precipitation events, exploiting the added value of state-of-the-art regional climate models in a multi-model approach. On the other hand we aim to evaluate the respective impact of a number of model features on the models skill in reproducing the observed statistics of Mediterranean extreme precipitation events, including: a very high resolution of the atmosphere, different physical parameterisations employed in atmospheric RCMs, and the coupling with high resolution models of the Mediterranean sea ocean circulation.

The paper is organised as follows. In Sec. 2 the features of the different datasets (observations, reanalysis, and models) used in the study are described, and the diagnostics quantities (the daily precipitation 99th percentile, and the timing of the extremes) that we use to characterise the long-term statistics of extreme precipitation events are presented and discussed, along with the method used to compare the tails of the precipitation intensity probability distribution. Sec. 3 is devoted to illustrate the inter-comparison between the different datasets of the aforementioned statistical properties of

extreme precipitation. In Sec. 4 the interpretation of the main results from such inter-comparison is discussed.

2 Data and methods

2.1 Model, observation and reanalysis datasets

Modeling data used in the present study is provided by the simulations performed in the coordinated Med-CORDEX initiative (Ruti et al, 2015). We use data from several different simulations performed with both atmosphere-only regional models and coupled atmosphere-ocean regional models at different resolutions. All the simulations are driven from the same lateral boundary conditions derived from the ERA-Interim reanalysis¹ (Dee et al, 2011). For the uncoupled simulations, the lower boundary conditions (sea surface temperature) are also taken from ERA-Interim. The horizontal resolution of the atmospheric model of the analysed simulations ranges between 50 km and 10 km. A summary of the main features of the different model simulations included in the study is provided in Table 1.

In addition to modelling data, the analysis of Mediterranean extreme precipitation events includes three reanalysis datasets: the ERA-Interim reanalysis, also used as a forcing for the Med-CORDEX regional climate models, and two additional recent reanalysis products, NASA’s MERRA reanalysis (Rienecker et al, 2011) and the Japan Meteorological Agency JRA-55 reanalysis (Kobayashi et al, 2015), both featuring a horizontal resolution comparable to the one of the Med-CORDEX simulations with coarser resolution.

The observational reference dataset is the ECA&D E-OBS gridded dataset, version 11.0 (Haylock et al, 2008). The E-OBS dataset is a gridded product providing daily precipitation data obtained interpolating station observations on a regular 25 km resolution grid. The choice of E-OBS as a reference dataset over other products with similar spatial resolution depends on its temporal coverage, extending for the whole time period spanned by the model simulations. The errors and uncertainties of such dataset, arising from many sources (e.g. changes in station locations, measurement errors, interpolation uncertainties) have been comprehensively evaluated in the literature (Hofstra et al, 2009, 2010). Regarding the Mediterranean region, Flaounas et al (2012) have compared E-OBS with HyMeX stations in three different zones in the Mediterranean region. The day to day biases were small for semi-arid and coastal stations, while a strong cold bias was obtained for the

low elevation stations and high elevation station located in Italy. Although the regions were different, their results show that E-OBS was in better accordance with the observations than for aforementioned studies, probably resulting from the use of an updated version of E-OBS, which contains more station data.

As a reference for the analysis of extreme precipitation, a comparison of the skill of the different datasets in reproducing the mean (Supplementary Fig. S1) and the standard deviation (Supplementary Fig. S2) of seasonally averaged observed precipitation is performed. The two variables, after having been evaluated on the native grids for each dataset, are interpolated on a common grid (E-OBS) performing a bi-linear interpolation; the inter-comparison is then shown by means of Taylor diagrams (Taylor, 2001). As a brief reminder, Taylor diagrams allow to show three different statistical properties of a given physical variable on a bi-dimensional diagram: the spatial variance in the selected domain normalised to the reference dataset (represented on both the x and y axes), the spatial correlation between the selected and reference dataset (represented by the angle with respect to the y axis), and the centered root mean square error (RMSE) versus the reference dataset (represented by the circles centered at unity on the x axis). The patterns of precipitation from reanalysis and models, considering both the mean precipitation intensity and its variability, show a good agreement with the one of observed precipitation during summer (correlation > 0.8), while the correlation is decreased to ~ 0.7 in spring and autumn and ~ 0.6 during winter. Reanalysis datasets tend to be closer to observations in terms of root mean square error with respect to models. Comparing different model simulations, the ones with higher resolution exhibit generally a higher spatial variance with respect to observations, compared to low resolution simulations, but comparable correlations. Finally, paired coupled-uncoupled simulations using the same model and resolution of the atmosphere show almost identical skills. This is consistent with a realistic representation of the SST in the coupled simulations. This is also consistent with Brossier et al (2015) who showed that the response of precipitation to variations in sea surface temperature affects mainly precipitation over the Mediterranean Sea, and especially their location and not their intensity. The onshore influence of ocean-atmosphere coupling is felt over a horizontal range limited by the surrounding mountain ranges, therefore leaving the major parts of the European and North African countries insensitive to ocean-atmosphere coupled processes.

¹ Most simulations are performed for the period 1979-2011, with the exception of few models as indicated in table 1.

Table 1 List of datasets used, and their main properties. For each dataset whose name is defined in the second column the following information is reported. First column: numerical code used to identify the dataset in Taylor plots. Third column: horizontal resolution of the atmospheric fields (in km). Fourth column: whether the data is from a coupled (C) or atmosphere-only (A) model, reanalysis (R) or observations (O). Fifth column: time period included in the dataset.)

N.	NAME	RES. (km)	C.	PERIOD	REF.
-	E-OBS	25	O	1979-2011	Haylock et al (2008)
1	ERA-Interim	75	R	1979-2011	Dee et al (2011)
2	MERRA	50	R	1979-2011	Rienecker et al (2011)
3	JRA-55	50	R	1979-2011	Kobayashi et al (2015)
4	CMCC	50	A	1979-2011	Cavicchia et al (2015)
5	CNRM	50	A	1980-2011	Colin et al (2010)
6	ENEA	50	A	1982-2011	Artale et al (2010)
7	GUF	50	A	1979-2011	Akhtar et al (2014)
8	ICTP	50	A	1979-2011	Giorgi et al (2012)
9	IPSL	50	A	1989-2011	Drobinski et al (2012)
10	LMD	50	A	1979-2011	Li (1999)
11	UBEL	50	A	1989-2008	Djurdjevic and Rajkovic (2008)
12	UCLM	50	A	1989-2011	Gallardo et al (2001)
13	CMCC_HI	12	A	1979-2011	Cavicchia et al (2015)
14	CNRM_HI	12	A	1980-2011	Colin et al (2010)
15	GUF_HI	10	A	1979-2011	Akhtar et al (2014)
16	ICTP_HI	12	A	1979-2011	Giorgi et al (2012)
17	IPSL_HI	20	A	1989-2011	Drobinski et al (2012)
18	UCLM_HI	12	A	1989-2011	Gallardo et al (2001)
19	CMCC_C	50	C	1979-2011	Cavicchia et al (2015)
20	CNRM_C	50	C	1979-2011	Sevault et al (2014)
21	ENEA_C	50	C	1982-2011	Artale et al (2010)
22	IPSL_HI_C	20	C	1989-2011	Drobinski et al (2012)
23	LMD_C	50	C	1979-2011	L'Hévéder et al (2013)
24	UBEL_C	50	C	1989-2008	Djurdjevic and Rajkovic (2008)

2.2 Extreme events characterisation

A number of methods to characterise extreme precip⁻²⁶³itation events have been used in the literature, based on different indices (Alexander et al, 2006), underlying properties of the intensity probability distribution function (Becker et al, 2009), or extreme value theory (Toreti et al, 2013). In the present work the following quantities are used: the 99th percentile of daily precipitation intensity (P99) and the timing of extreme precipitation events (T_P). Moreover the tail of the precipitation distribution from the different datasets are compared with observations adopting the non-parametric approach of Toreti and Naveau (2015).

The parameter P99, computed from the time series of daily precipitation for every grid point, considering only wet days ($P > 1 \text{ mm day}^{-1}$), provides an immediate information about the strength of extreme precipitation in different areas.

The timing parameter T_P is defined, for every grid point, as the bin with the maximum value in the twelve months histogram obtained including for the whole simulation period the precipitation events such that $P > P99$. The timing parameter is computed only if there is a well

defined peak in the histogram of the frequency of heavy precipitation days, thus the further condition $M_{max} - M_{min} > n/12$ is imposed (where M_{max} and M_{min} are respectively the largest and smallest bin counts, and n is the number of values in the histogram).

In the following, we illustrate the outlined diagnostic quantities for the reference observational dataset, E-OBS.

The precipitation 99th percentile (Fig. 1) shows the largest values along the Alps (in particular in the western and eastern sides of the chain) and in the north-western Italian coast (Liguria region). Other areas characterised by large values of P99 include the north-western part of the Iberian peninsula, and coastal areas on the northern shore of the basin, in particular the Aegean coast of Anatolia, the Mediterranean coast of Catalonia and southern France.

Concerning the timing of extreme precipitation events (Fig. 2), different regimes emerge. In the south-western part of the northern Mediterranean region (including the Iberian peninsula, southern France, the central and southern Italian peninsula and the western Balkans) the majority of extreme precipitation events occur during late summer and autumn months (September, October

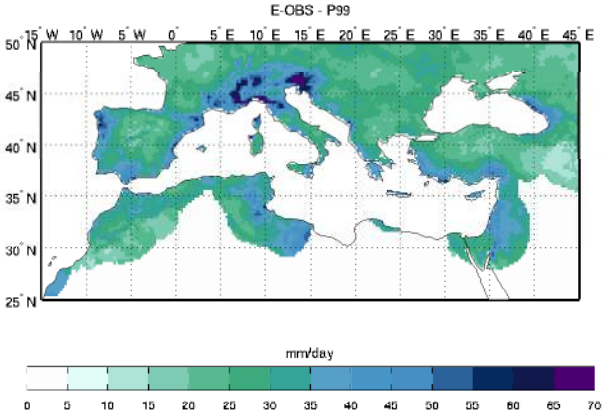


Fig. 1 Wet days 99th percentile of daily precipitation in the E-OBS dataset. Areas where E-OBS has no data are represented as white.

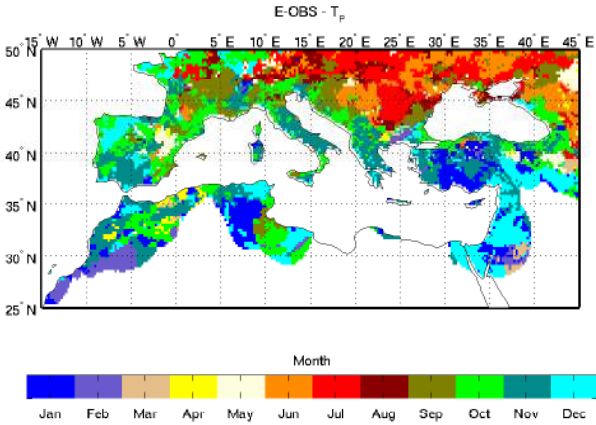


Fig. 2 Timing of extreme precipitation events in E-OBS dataset. Areas where E-OBS has no data are represented as white.

and November). On the other hand, the north-eastern part of the domain (eastern Balkans and eastern central Europe) shows a regime dominated by summer precipitation. Northern France and the Alpine region show a mixture of the two aforementioned regimes. Finally, the areas facing the southern and eastern shores of Mediterranean (Anatolia, middle east and northwestern Africa) show extreme precipitation activity in both autumn and early winter (December-January).

Few studies on extreme precipitation have dealt with the comparison of tails of the precipitation intensity distribution, based on both parametric (Chan et al, 2014) and non-parametric approaches (Toreti and Naveau, 2015). In the present work we follow the approach of Toreti and Naveau (2015). A modified two-sample Anderson-Darling statistic is used to compare the tails of the precipitation intensity distribution from models and ob-

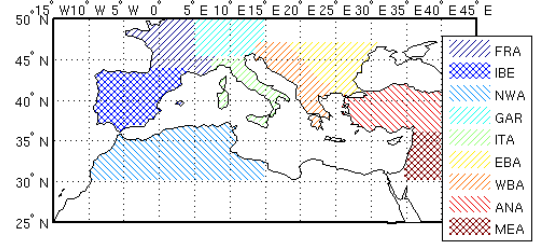


Fig. 3 Sub-regions used in the analysis: France (FRA), Iberia (IBE), north-west Africa (NWA), great Alpine region (GAR), Italy (ITA), eastern Balkans (EBA), western Balkans (WBA), Anatolia (ANA), Middle East (MEA).

303
 servation. Given two random samples X_1, \dots, X_n and Y_1, \dots, Y_m the test statistics is defined (Pettitt, 1976; Sinclair et al, 1990) as:

$$A = \frac{mn}{N} \int_{-\infty}^{\infty} \frac{(F_n(x) - G_m(x))^2}{H_N(x)} dH_N(x)$$

$$H_N(x) = \frac{nF_n(x) + mG_m(x)}{N} \quad (1)$$

where $N = n + m$, while $F_n(x)$ and $G_m(x)$ are the survival distribution functions respectively of the X and Y samples. Following Toreti and Naveau (2015), to which the reader is referred for further details on the method, the samples X and Y are the tails of the observed and modelled precipitation distributions P^O and P^M rescaled by the mean value of the tail:

$$X = \frac{P^O(x)}{\langle P^O(x) \rangle} \Big|_{x > x_{90}^O}, \quad Y = \frac{P^M(x)}{\langle P^M(x) \rangle} \Big|_{x > x_{90}^M}, \quad (2)$$

where $x_{90}^{M,O}$ is the value corresponding to the 90th percentile of $P^{M,O}$.

In order to compare the performance of different model and reanalysis datasets in reproducing the statistics of observed extreme precipitation events, the Mediterranean domain has been divided into a number of sub-regions. It is desirable that such division in sub-regions is representative of physical properties of severe precipitation rather than being only based on geography or political borders. The partitioning of the domain relies on the visual inspection of timing maps of extreme precipitation events. Coherent seasonality clusters of extreme events are assigned to the same sub-region, provided the areas are large enough so that there is a reasonable agreement within the majority of models. As an example, the geographic area of Balkans is divided in two different sub-regions, since in the eastern part of the region extremes are dominated by summer precipitation, while in the western part autumn heavy precipitation prevails. Proceeding as described, nine sub-regions are defined (shown in the map in Fig. 3): Iberia

(IBE), north-west Africa (NWA), France (FRA), great Alpine region (GAR), Italian peninsula (ITA), eastern Balkans (EBA), western Balkans (WBA), Anatolia (ANA), Middle East (MEA).

In order to compare the performance of the different models and reanalysis datasets in reproducing the observed patterns of P99, the variable, after having been evaluated on the native grids for each dataset, is interpolated on a common grid (E-OBS); the inter-comparison is then shown by means of Taylor diagrams for the different subregions.

3 Results

The timing of extreme precipitation events as represented by the different reanalysis and model simulation datasets is shown in Fig. 4 and supplementary Fig. S2. Difference maps are obtained comparing all the datasets on a common grid through a nearest neighbour interpolation. All the datasets reproduce the main dipole feature of timing, i.e. the transition from the area dominated by autumn/early winter events in the southwestern part of the domain to a summer precipitation area in central Europe (Fig. S1). On a finer scale, some differences are visible between the different datasets, with lags in the peak of extreme precipitation events timing in particular in areas characterised by a mixed regime (e.g. Anatolia, northwest Africa, the southern part of east Balkans). Considering the whole domain, for all the datasets the majority of grid points have a lag in the timing of less than two months (Fig. 4 a). Considering the ensemble mean of the timing lag (Fig. 4 b), a limited number of systematic effects emerge (e.g. a positive lag in the Middle East and a negative lag in the northwestern sector of the Balkans).

Model inter-comparison for the variable P99 is shown in Fig. 5. Considering the correlation with observations, a number of regions emerges, where most of the datasets appear to be more skilled in reproducing the observed patterns: Iberia, France, the great Alpine region and Anatolia. The largest deviations from observation are found, on the other hand, in the eastern Balkans and north-west Africa regions². Moreover, within the same region, the different types of dataset analysed (reanalysis, high/low resolution coupled/uncoupled models) exhibit generally a correlation with observations comparable to each other, independently on the overall performance in the specific region. In other words, it is found that the skill in reproducing observation exhibits

² It has to be noticed, however, that in such regions the density of stations is lower, possibly influencing the reliability³⁸⁴ of the observational reference dataset. Further discussion of this aspect is presented in Section 4.

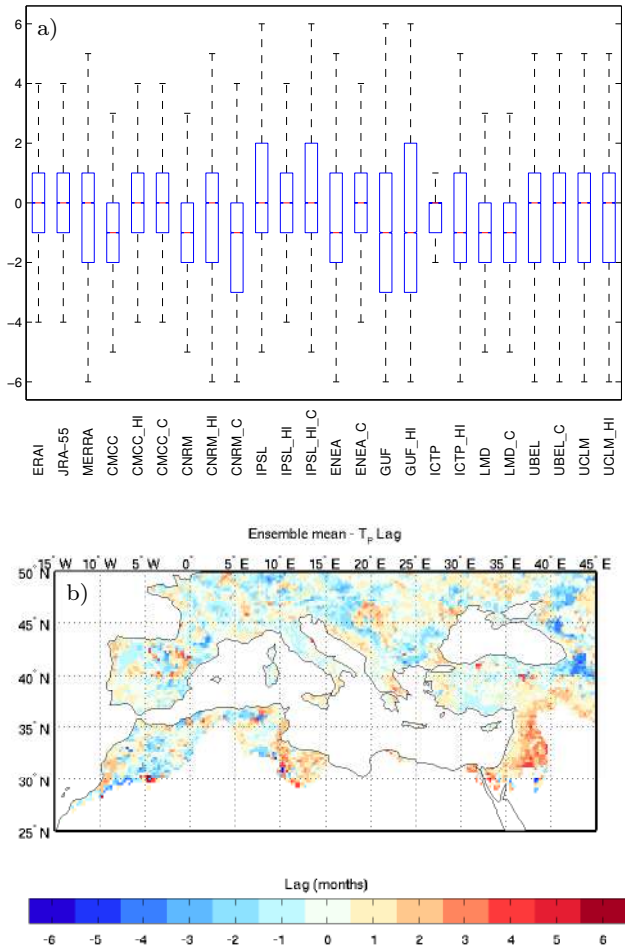


Fig. 4 Timing of extreme precipitation events, time lag between models and observation. Top panel: box plot of timing difference with respect to E-OBS for the different models as indicated in the x axis. For each model the following statistical properties of the set of timing values computed for all the grid points in the domain are represented: median value (red line), interquartile range (blue bar), 1st and 99th percentile (extremities of dashed lines). Bottom panel: ensemble mean of timing difference with respect to E-OBS.

a larger spread between different regions, than between different datasets. Such important point will be further discussed in Sec. 4 below.

On the other hand, focusing on spatial variability, reanalyses tend on average to show a smaller standard deviation compared to observations, while high-resolution models show standard deviation generally larger than observations. The spatial variability values found in low resolution models are equally distributed below and above the one of reference observation dataset. Such behaviour can be explained in part as an effect of varying resolution of different datasets (interpolation and averaging process). However, reanalysis datasets even though they have comparable resolution with the coarser

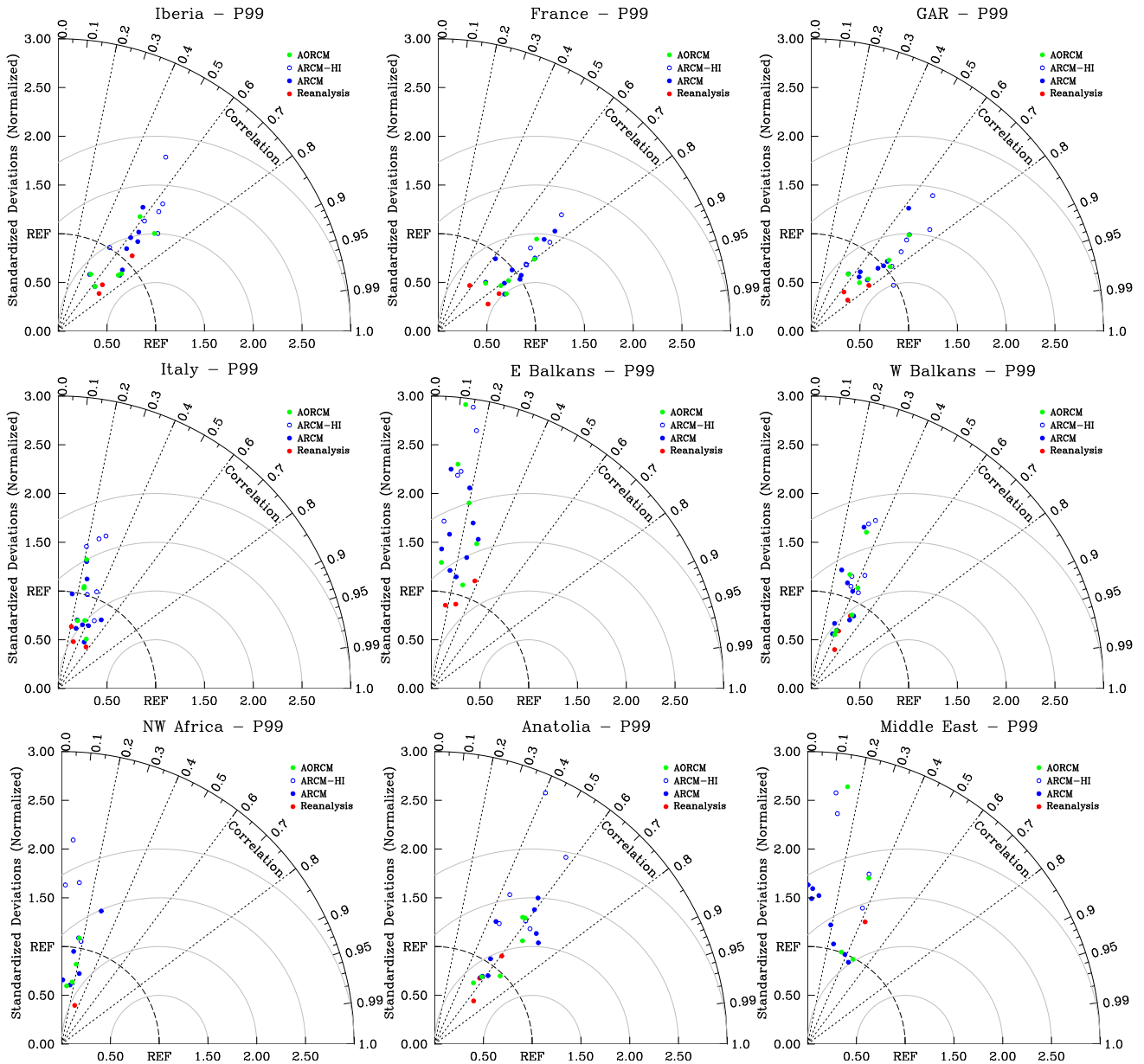


Fig. 5 Taylor plots of 99th percentile of daily precipitation in different datasets, for the nine sub-regions as indicated in the title bar of each panel. Red dots: reanalysis datasets; blue dots: atmosphere-only RCMs; blue circles: high resolution atmosphere-only RCMs; green dots: coupled ocean-atmosphere RCMs. Numerical labels identifying different datasets are defined in Table 1. The label REF indicates the reference dataset (E-OBS).

resolution models, tend to exhibit smaller values of spatial variability.

Concerning the root mean square error, in regions where the patterns are better reproduced (France, Iberia, great Alpine region) most of the models show a comparable error, while the RMSE range spanned by different models increases proportionally to the decrease in spatial correlation.

Finally, we find that, for models for which paired coupled-uncoupled runs are available, the two simula-

tions produce generally values of both correlation and spatial variability very close to each other.

Concerning the statistical comparison of the tail of modelled precipitation distribution, the main results are summarised in Fig. 6. A large spread is found in the agreement of different models with the observations (Fig. 6 a). Considering the ensemble mean of the test statistics, a number of areas emerge where the agreement between the observed and modelled precipitation distribution tails is lower: the Alps, the Balkans,

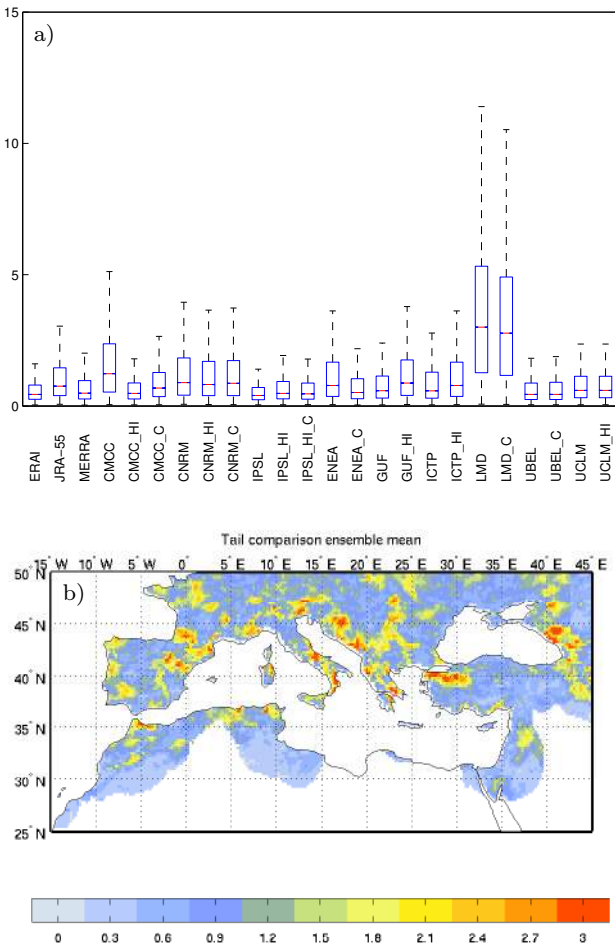


Fig. 6 Test statistics (as described in Eq. 1) for the precipitation intensity tail comparison. Values closer to zero indicate a better match between the two datasets. Top panel: box plot of the test statistics A for the different models compared with E-OBS, as indicated in the x axis. For each model the following properties of the set of the values of the test statistics A computed for all the grid points in the domain are represented: median value (red line), interquartile range (blue bar), 1st and 99th percentile (extremities of dashed lines). Bottom panel: ensemble mean of the test statistics A .

northwestern Anatolia and the northeastern part of the Iberian peninsula (Fig. 6 b). Maps of tail comparison for the different models and reanalysis datasets are shown in supplementary Figure S3.

4 Discussion

The rest of the paper is devoted to provide some interpretation of the results shown in Section 3. Namely, two main aspects are addressed: the first issue tackled is the coherent dependence on the subregion of the performance in reproducing extreme precipitation events exhibited by all the analysed datasets; the second is-

sue is the sensitivity of modelled extreme precipitation on different model configurations, including resolution, coupling and physical parameterisations.

Before discussing the models performance, the quality of observation has to be taken into account. It has been shown in previous works (Lenderink, 2010) that the used reference dataset is prone to underestimating precipitation extremes in some areas, due to the scarcity of stations in such areas and to the fact that the interpolation scheme adopted is not specifically designed for extremes. Fig. 7 shows the relation between the mean models bias and the station density in the different subregions considered in the present study. Some of the regions where the agreement between models and observation is lower (Middle East, Northwest Africa) are characterised by a very low number of stations in E-OBS, while the mean model bias tends to decrease in areas where underlying observations are more dense. There are however some exceptions to this general behaviour (Italy and west Balkans), showing a larger bias with respect to regions with less stations. This reflects the fact that the spatial complexity of a region is expected to play a role, in addition to station density. Ensemble mean bias has also been computed using a different observational dataset available for Iberia, IB02 (Herrera et al, 2012; Belo-Pereira et al, 2011), based on a much larger number of stations. The amplitude of the bias averaged over the region is comparable using the two datasets; however, differences in the bias pattern emerge, in particular in areas characterised by a complex orography (not shown).

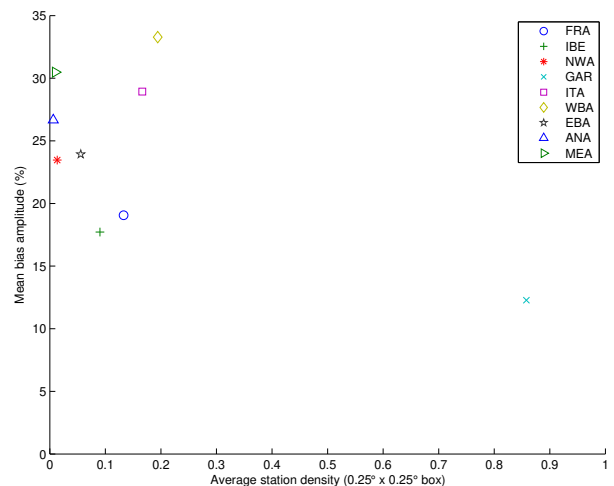


Fig. 7 Average model relative bias (ensemble mean with respect to observation) as a function of the underlying stations number in the E-OBS dataset, in the different sub-regions considered.

In order to investigate the dependence on the analysed subregion of the skill in reproducing the observed statistics of extreme precipitation events exhibited by the different datasets in a coherent way, we take into account the contributions to the extreme precipitation events from large scale and convective precipitation. In Fig. 8 is shown the ratio of large scale to total precipitation for the extreme precipitation events in the ERA-Interim dataset. As Fig. 8 shows, the regions where the modelled extreme precipitation is in better agreement with the observations (Iberia, great Alpine region, Anatolia, France see Fig. 5) are the ones where large scale precipitation gives a significant contribution to extreme precipitation. Similar results are found for the CMCC model (not shown). Such behaviour has been observed also in previous studies based on global models (Iorio et al, 2004; Kopparla et al, 2013).

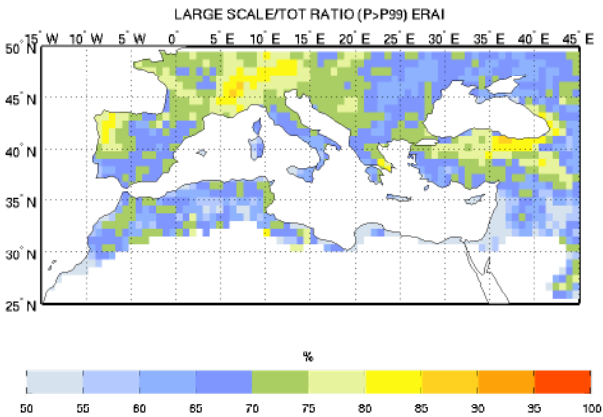


Fig. 8 Ratio of large scale to total precipitation for extreme events (daily precipitation $> P99$) in ERA-Interim. Areas where the average daily precipitation amount in ERA-Interim is less than 0.2 mm are represented as white.

In order to shed light on the possible dependence on model configurations of the skill in reproducing the observed statistics of extreme precipitation events, we focus in the following on one particular model (the CMCC model), of which several realisations of the hindcast simulation are available. The main features of the different model configurations analysed is reported in Table 2. Beyond horizontal resolution and coupling, the difference between the model versions lies in the change of two different parameterisations. As Table 2 shows, the different simulations use for the parameterisation of atmospheric aerosols either the Tanré parameterisation (Tanre et al, 1984), prescribing a fixed aerosol concentration, or the Tegen parameterisation (Tegen et al, 1997), that introduces a seasonal cycle for the different aerosol components. Concerning the convective scheme,

the difference is between the Tiedtke scheme (Tiedtke, 1989) and the scheme from the ECMWF IFS cycle 33r1 (Bechtold et al, 2008). The main differences between the two convective schemes are in the closure and criterium for deep convection and in precipitation microphysics (for further details see Lange et al (2014)).

In Fig. 9 the Taylor plots for P99 as represented in ERA-Interim and different simulations using the CMCC model are reported. As the figure shows, in areas where extreme precipitation is reasonably well represented (Iberia, France, great Alpine region, and Anatolia) the different model simulations give similar results in terms of spatial correlation and RMSE. Neither switching on the coupling nor increasing the horizontal resolution seems to improve the spatial correlation with respect to the driving ERA-Interim reanalysis, coherently with the findings presented in Fig. 5. In some areas (eastern Balkans and Middle East), where extreme precipitation is poorly represented, changing the convective parameterisation results instead in a larger impact, on the increase of correlation, and on the reduction of root mean square error between modelled and observed extreme events. Such behaviour is coherent with the interpretation outlined above, relating the poor model performance to a large contribution of convective precipitation to extreme events in the analysed areas.

Analysing in more detail the bias of precipitation P99 exhibited by the different model versions (Fig. 10), we find that indeed both switching on the coupling and increasing the horizontal resolution of the atmospheric model, lead to very limited changes in the pattern and magnitude of bias. Model versions with a different convective parameterisation on the other hand show biases with different patterns. Investigating in detail the physical processes involved in extreme precipitation, and how they are represented in the different model parameterisations, is beyond the scope of the present work. The results shown, however, give an indication that in areas where extreme precipitation events are driven by large scale precipitation processes the current generation of regional climate models reproduces the observed statistics with reasonable accuracy. On the other hand, in areas dominated by local precipitation processes a better understanding of the representation of convection is desirable in order to increase the agreement between simulated and observed extreme events (Emori et al, 2005; Boyle and Klein, 2010).

Table 2 List of CMCC model configurations, and their main properties. For each dataset whose name is defined in the second column the following information is reported. First column: numerical code used to identify the dataset in Taylor plots. Third column: horizontal resolution of the atmospheric fields (in km). Fourth column: whether the data is from a coupled (C) or atmosphere-only (A) model or reanalysis (R). Fifth column: parameterisation scheme for aerosols. Sixth column: parameterisation scheme for convection.

N.	NAME	RES (Km)	CLASS	AEROSOL	CONVECTION
1	ERA-Interim	75	R	Tegen	IFS
2	CMCC	50	A	Tanré	Tiedtke
3	CMCC_HI	12	A	Tanré	Tiedtke
4	CMCC_C_V1	50	C	Tanré	Tiedtke
5	CMCC_C_V2	50	C	Tegen	Tiedtke
6	CMCC_C_V3	50	C	Tegen	IFS
7	CMCC_C_V4	50	C	Tanré	IFS

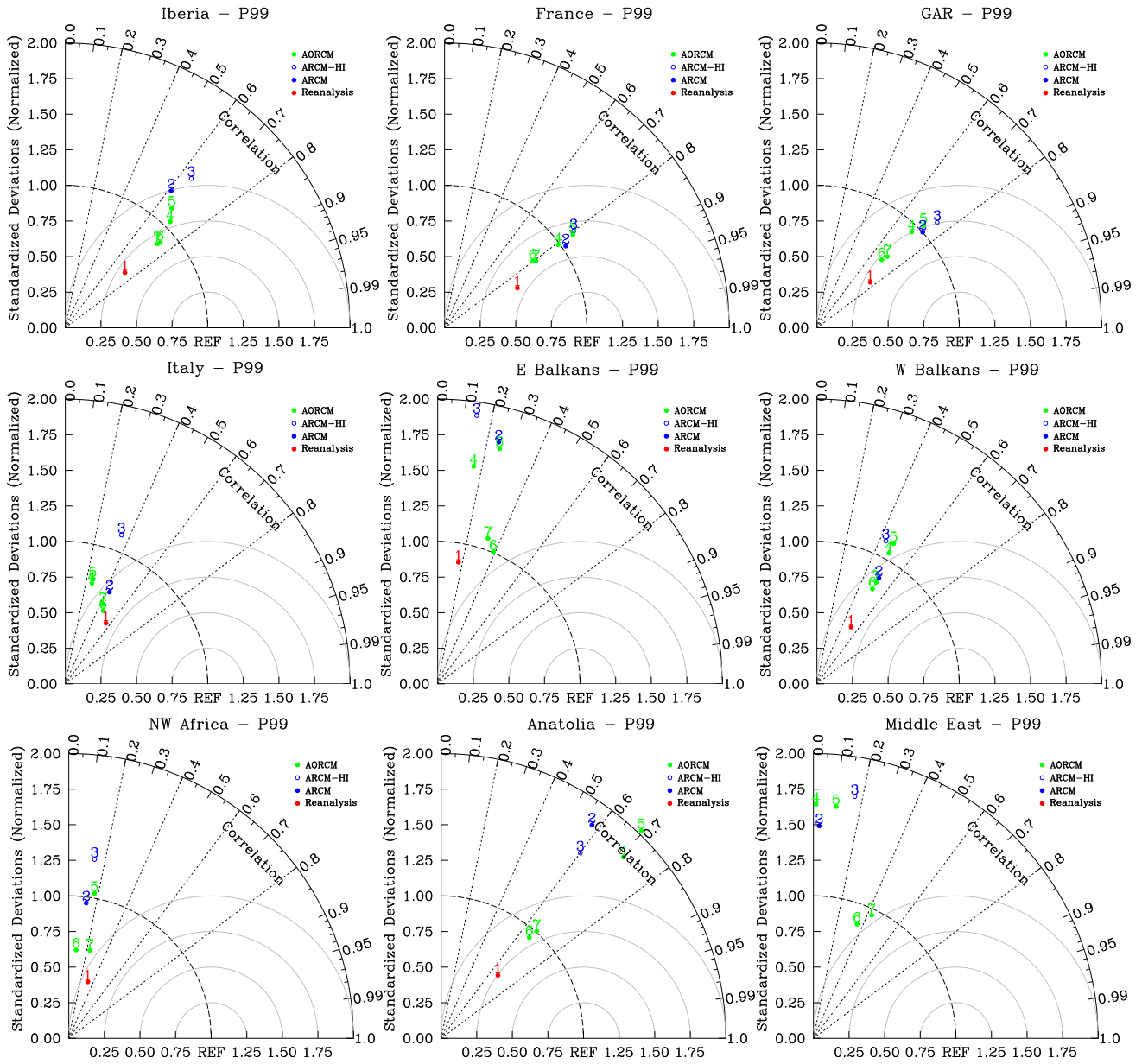


Fig. 9 Taylor plots of 99th percentile of daily precipitation in ERA-Interim and different versions of CMCC model, for the nine sub-regions as indicated in the title bar of each panel. Numerical labels identifying different datasets are defined in Table 2. The label REF indicates the reference dataset (E-OBS).

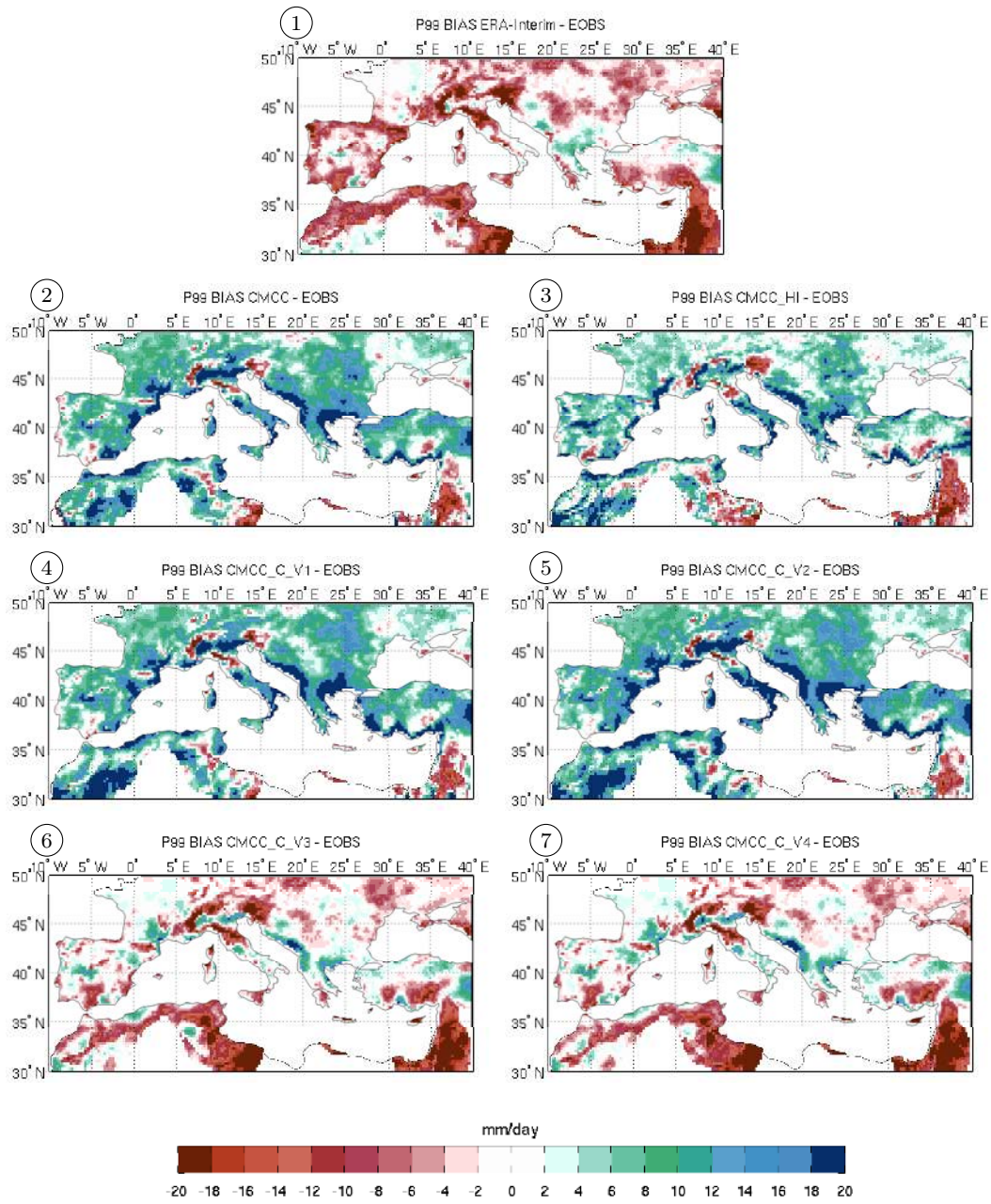


Fig. 10 Bias of daily precipitation P99 with respect to E-OBS in: ERA-Interim (first panel), and different versions of the CMCC model defined in Table 2, as indicated by the title bar of each subplot. Areas where E-OBS has no data are represented as white.

5 Conclusions

Exploiting the added value of the Med-CORDEX models ensemble, including several very high resolution and/or coupled simulations, a comparison of the skill of different reanalysis and modelling datasets in reproducing the observed features of Mediterranean extreme precipitation events has been presented and discussed. The characterisation of extreme precipitation statistics is based on the 99th percentile of the wet days precipitation intensity probability distribution function. Moreover, the agreement between observed and modelled extreme precipitation is assessed by performing a statistical test taking into account the tails of the precipitation intensity distributions. As the models resolution keeps increasing, along with their ability in representing heavy precipitation processes, the necessity of observational datasets of high quality and comparable resolution emerges.

The present analysis effort provides two main achievements. First, a novel approach for the subsetting of the domain based on the timing of precipitation (i.e. the maximum in the twelve months histogram of events exceeding the precipitation 99th percentile) is provided. Such approach allows to divide the domain in several subregions by clustering areas characterised by coherent timing behaviours; the resulting areas are thus defined in a way that relies on the physical properties of precipitation rather than on merely geographical criteria, providing a more meaningful insight on the typical variability patterns of the considered diagnostics. Furthermore, it was shown that increasing resolution and switching on the coupling has a mild impact on the long-term statistics of extreme precipitation. Changes of the convective parameterisation on the other hand, turn out to have a relatively larger impact on the correlation of the analysed diagnostics quantities with observations. The effect of physical parameterisations is particularly relevant in areas where extreme precipita-

tion events are dominated by convective rather than large-scale precipitation, consistently with the subsetting described above.

More detailed investigation on the different precipitation parameterisations, and their performance in realistically representing the physical mechanisms that lead to extreme precipitation events will be the subject of further work.

Acknowledgements The present work has been funded by 576 the Italian Ministry of Education, University and Research 577 and the Italian Ministry of Environment, Land and Sea under 578 the GEMINA and NEXTDATA projects. This work has been 579 partially funded by the Spanish Government and the Euro580 pean Regional Development Fund, through grants CGL2007-581 66440-C04-02, CGL2010-18013 and CGL2013-47261-R.

References

- Akhtar N, Brauch J, Dobler A, Béranger K, Ahrens B (2014) Medicanes in an ocean-atmosphere coupled regional climate model. *Nat Hazards Earth Syst Sci* 14:2189–2201
- Alexander L, Zhang X, Peterson T, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F, et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres* (1984–2012) 111(D5)
- Allan RP, Soden BJ (2008) Atmospheric warming and the amplification of precipitation extremes. *Science* 321(5895):1481–1484
- Alpert P, Ben-Gai T, Baharad A, Benjamini Y, Yekutieli D, Colacino M, Diodato L, Ramis C, Homar V, Romero R, et al (2002) The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophysical Research Letters* 29(11):31–1
- Artale V, Calmanti S, Carillo A, Dell’Aquila A, Herrmann M, Pisacane G, Ruti PM, Sannino G, Struglia MV, Giorgi F, et al (2010) An atmosphere-ocean regional climate model for the Mediterranean area: assessment of a present climate simulation. *Climate Dynamics* 35(5):721–740
- Bechtold P, Köhler M, Jung T, Doblas-Reyes F, Leutbecher M, Rodwell MJ, Vitart F, Balsamo G (2008) Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales. *Quarterly Journal of the Royal Meteorological Society* 134(634):1337–1351
- Becker EJ, Berbery EH, Higgins RW (2009) Understanding the characteristics of daily precipitation over the United States using the North American Re-

- gional Reanalysis. *Journal of Climate* 22(23):6268–6286
- Belo-Pereira M, Dutra E, Viterbo P (2011) Evaluation of global precipitation data sets over the Iberian peninsula. *Journal of Geophysical Research: Atmospheres* 116(D20)
- Boyle J, Klein SA (2010) Impact of horizontal resolution on climate model forecasts of tropical precipitation and diabatic heating for the TWP-ICE period. *Journal of Geophysical Research: Atmospheres* (1984–2012) 115(D23)
- Brossier CL, Bastin S, Béranger K, Drobinski P (2015) Regional mesoscale air–sea coupling impacts and extreme meteorological events role on the Mediterranean Sea water budget. *Climate Dynamics* 44(3–4):1029–1051
- Cavicchia L, Gualdi S, Sanna A, Oddo P, et al (2015) The regional ocean-atmosphere coupled model COSMO-NEMO_MFS. CMCC Research Paper (RP0254)
- Chan SC, Kendon EJ, Fowler HJ, Blenkinsop S, Roberts NM, Ferro CA (2014) The value of high-resolution Met Office regional climate models in the simulation of multihourly precipitation extremes. *Journal of Climate* 27(16):6155–6174
- Colin J, Déqué 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(5):591–604
- Dai A (2006) Precipitation characteristics in eighteen coupled climate models. *Journal of Climate* 19(18):4605–4630
- Dee D, Uppala S, Simmons A, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda M, Balsamo G, Bauer P, et al (2011) The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* 137(656):553–597
- Djordjevic V, Rajkovic B (2008) Verification of a coupled atmosphere-ocean model using satellite observations over the Adriatic Sea. *Annales Geophysicae* 26(7):1935–1954
- Drobinski P, Anav A, Brossier CL, Samson G, Stéfanon M, Bastin S, Baklouti M, Béranger K, Beuvier J, Bourdallé-Badie R, et al (2012) Model of the Regional Coupled Earth system (MORCE): application to process and climate studies in vulnerable regions. *Environmental Modelling & Software* 35:1–18
- Drobinski P, Ducrocq V, Alpert P, Anagnostou E, Béranger K, Borga M, Braud I, Chanzy A, Davolio S, Delrieu G, Estournel C, Filali Boubrahmi N, Font J, Grubisic V, Gualdi S, Homar V, Ivancan-Picek B, Kottmeier C, Kotroni V, Lagouvardos K, Lionello P, Llasat M, Ludwig W, Lutoff C, Mariotti A, Richard E, Romero R, Rotunno R, Roussot O, Ruin I, Somot S, Taupier-Letage I, Tintore J, Uijlenhoet R, Wernli H (2014) HyMeX: a 10-year multidisciplinary program on the Mediterranean water cycle. *Bulletin of the American Meteorological Society* 95(7):1063–1082
- Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. *Science* 289(5487):2068–2074
- Emori S, Hasegawa A, Suzuki T, Dairaku K (2005) Validation, parameterization dependence, and future projection of daily precipitation simulated with a high-resolution atmospheric GCM. *Geophysical research letters* 32(6)
- Flaounas E, Drobinski P, Borga M, Calvet JC, Delrieu G, Morin E, Tartari G, Toffolon R (2012) Assessment of gridded observations used for climate model validation in the Mediterranean region: the HyMeX and MED-CORDEX framework. *Environmental Research Letters* 7(2):024,017
- Flaounas E, Drobinski P, Vrac M, Bastin S, Lebeaupin-Brossier C, Stéfanon M, Borga M, Calvet JC (2013) Precipitation and temperature space–time variability and extremes in the Mediterranean region: evaluation of dynamical and statistical downscaling methods. *Climate dynamics* 40(11–12):2687–2705
- Gallardo C, Arribas A, Prego JA, Gaertner MA, De Castro M (2001) Multi-year simulations using a regional-climate model over the Iberian Peninsula: Current climate and doubled CO₂ scenario. *Quarterly Journal of the Royal Meteorological Society* 127(575):1659–1681
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Global and Planetary Change* 63(2):90–104
- Giorgi F, Marinucci MR (1996) A investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies. *Monthly Weather Review* 124(1):148–166
- Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla M, Bi X, Elguindi N, Diro G, Nair V, Giuliani G, et al (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research* 2(7)
- Gordon H, Whetton P, Pittock A, Fowler A, Haylock M (1992) Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. *Climate Dynamics* 8(2):83–102

- Gualdi S, Somot S, Li L, Artale V, Adani M, Bellucci A, Braun A, Calmanti S, Carillo A, Dell’Aquila A, et al (2013) The CIRCE simulations: regional climate change projections with realistic representation of the Mediterranean Sea. *Bulletin of the American Meteorological Society* 94(1):65–81
- Haylock M, Hofstra N, Klein Tank A, Klok E, Jones P, New M (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *Journal of Geophysical Research: Atmospheres* (1984–2012) 113(D20)
- Herrera S, Gutiérrez JM, Ancell R, Pons M, Frías M, Fernández J (2012) Development and analysis of a 50-year high-resolution daily gridded precipitation dataset over Spain (Spain02). *International Journal of Climatology* 32(1):74–85
- Hofstra N, Haylock M, New M, Jones PD (2009) Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature. *Journal of Geophysical Research: Atmospheres* (1984–2012) 114(D21)
- Hofstra N, New M, McSweeney C (2010) The influence of interpolation and station network density on the distributions and trends of climate variables in gridded daily data. *Climate dynamics* 35(5):841–858
- Iorio J, Duffy P, Govindasamy B, Thompson S, Khairoutdinov M, Randall D (2004) Effects of model resolution and subgrid-scale physics on the simulation of precipitation in the continental United States. *Climate Dynamics* 23(3–4):243–258
- Jacob D, Barring L, Christensen OB, Christensen JH, de Castro M, Deque M, Giorgi F, Hagemann S, Hirschi M, Jones R, et al (2007) An inter-comparison of regional climate models for Europe: model performance in present-day climate. *Climatic Change* 81(1):31–52
- Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, et al (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change* 14(2):563–578
- Kobayashi S, Ota Y, Harada Y, Ebata A, Moriya M, Onoda H, Onogi K, Kamahori H, Kobayashi C, Endo H, et al (2015) The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan* DOI 10.2151/jmsj.2015-001
- Kopparla P, Fischer EM, Hannay C, Knutti R (2013) Improved simulation of extreme precipitation in a high-resolution atmosphere model. *Geophysical Research Letters* 40(21):5803–5808
- Lange S, Rockel B, Volkholz J, Bookhagen B (2014) Regional climate model sensitivities to parametrizations of convection and non-precipitating subgrid-scale clouds over South America. *Climate Dynamics* pp 1–19
- Lenderink G (2010) Exploring metrics of extreme daily precipitation in a large ensemble of regional climate model simulations. *Climate Research* 44(2/3):151–166
- L’Hévéder B, Li L, Sevault F, Somot S (2013) Inter-annual variability of deep convection in the Northwestern Mediterranean simulated with a coupled AORCM. *Climate dynamics* 41(3–4):937–960
- Li F, Collins WD, Wehner MF, Williamson DL, Olson JG, Algieri C (2011) Impact of horizontal resolution on simulation of precipitation extremes in an aqua-planet version of Community Atmospheric Model (CAM3). *Tellus A* 63(5):884–892
- Li ZX (1999) Ensemble atmospheric GCM simulation of climate interannual variability from 1979 to 1994. *Journal of Climate* 12(4):986–1001
- Lionello P, Abrantes F, Congedi L, Dulac F, Gacic M, Gomis D, Goodess C, Hoff H, Kutiel H, Luterbacher J, Planton S, Reale M, Schröder K, Struglia VM, Toreti A, Tsimplis M, Ulbrich U, Xoplaki E (2012) Mediterranean Climate - Background Information. In: Lionello P (ed) *The climate of the Mediterranean region: from the past to the future*, Elsevier, pp 266–290
- Marcos M, Tsimplis MN (2008) Comparison of results of AOGCMs in the Mediterranean Sea during the 21st century. *Journal of Geophysical Research: Oceans* (1978–2012) 113(C12)
- Mariotti A, Zeng N, Yoon JH, Artale V, Navarra A, Alpert P, Li LZ (2008) Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations. *Environmental Research Letters* 3(4):044,001
- Meehl GA, Zwiers F, Evans J, Knutson T, Mearns L, Whetton P (2000) Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change. *Bulletin of the American Meteorological Society* 81(3):427–436
- Pettitt AN (1976) A two-sample anderson-darling rank statistic. *Biometrika* 63(1):161–168
- Rauscher SA, Coppola E, Piani C, Giorgi F (2010) Resolution effects on regional climate model simulations of seasonal precipitation over Europe. *Climate Dynamics* 35(4):685–711
- Rienecker MM, Suarez MJ, Gelaro R, Todling R, Bacmeister J, Liu E, Bosilovich MG, Schubert SD, Takacs L, Kim GK, et al (2011) MERRA: NASA’s modern-era retrospective analysis for research and

- applications. *Journal of Climate* 24(14):3624–3648
- Ruti P, Somot S, Giorgi F, Dubois C, Flaounas E, Obermann A, Dell’Aquila A, Pisacane G, Harzallah A, Lombardi E, Ahrens B, Akhtar N, Alias A, Arsouze T, Aznar R, Bastin S, Bartholy J, Béranger K, Beuvier J, Bouffies-Cloch e S, Brauch J, Cabos W, Calmanti S, Calvet JC, Carillo A, Conte D, Coppola E, Djurdjevic V, Drobinski P, Elizalde-Arellano A, Gaertner M, Gal n P, Gallardo C, Gualdi S, Goncalves M, Jorba O, Jord  G, L’Heveder B, Lebeaupin-Brossier C, Li L, Liguori G, Lionello P, Maci s D, Nabat P, Onol B, Raikovic B, Ramage K, Sevault F, Sannino G, Struglia M, Sanna A, Torma C, Vervatis V (2015) MED-CORDEX initiative for Mediterranean climate studies. *Bulletin of the American Meteorological Society*
- Scoccimarro E, Gualdi S, Bellucci A, Zampieri M, Navarra A (2014) Heavy precipitation events over the Euro-Mediterranean region in a warmer climate: results from CMIP5 models. *Regional Environmental Change* pp 1–8
- Sevault F, Somot S, Alias A, Dubois C, Lebeaupin-Brossier C, Nabat P, Adloff F, D qu  M, Decharme B (2014) A fully coupled Mediterranean regional climate system model: design and evaluation of the ocean component for the 1980-2012 period. *Tellus A* 66
- Sinclair C, Spurr B, Ahmad M (1990) Modified Anderson-Darling test. *Communications in Statistics-Theory and Methods* 19(10):3677–3686
- Somot S, Sevault F, D qu  M, Cr pon M (2008) 21st century climate change scenario for the Mediterranean using a coupled atmosphere–ocean regional climate model. *Global and Planetary Change* 63(2):112–126
- Tanre D, Geleyn J, Slingo J (1984) First results of the introduction of an advanced aerosol-radiation interaction in the ECMWF low resolution global model. *Aerosols and their climatic effects* pp 133–177
- Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research: Atmospheres* (1984–2012) 106(D7):7183–7192
- Tegen I, Hollrig P, Chin M, Fung I, Jacob D, Penner J (1997) Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results. *Journal of Geophysical Research: Atmospheres* (1984–2012) 102(D20):23,895–23,915
- Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Monthly Weather Review* 117(8):1779–1800
- Toreti A, Naveau P (2015) On the evaluation of climate model simulated precipitation extremes. *Environmental Research Letters* 10(1):014,012
- Toreti A, Naveau P, Zampieri M, Schindler A, Scoccimarro E, Xoplaki E, Dijkstra HA, Gualdi S, Luterbacher J (2013) Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. *Geophysical Research Letters* 40(18):4887–4892
- Trenberth KE (1999) Conceptual framework for changes of extremes of the hydrological cycle with climate change. In: *Weather and Climate Extremes*, Springer, pp 327–339
- Trenberth KE, Dai A, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. *Bulletin of the American Meteorological Society* 84(9):1205–1217