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Future evolution of extreme precipitation in the Mediterranean

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Abstract
Mediterranean basins can be impacted by severe floods caused by extreme rainfall, and there is a growing awareness about the possible increase in these heavy rainfall events due to climate change. In this study, the climate change impacts on extreme daily precipitation in 102 catchments covering the whole Mediterranean basin are investigated using nonstationary extreme value model applied to annual maximum precipitation in an ensemble of high-resolution regional climate model (RCM) simulations from the Euro-CORDEX experiment. Results indicate contrasted trends, with significant increasing trends in Northern catchments and conversely decreasing trends in Southern catchments. For most cases, the time of signal emergence for these trends is before the year 2000. The same spatial pattern is obtained under the two climate scenarios considered (RCP4.5 and RCP8.5) and in most RCM simulations, suggesting a robust climate change signal. The strongest multi-model agreement concerns the positive trends, which can exceed + 20% by the end of the twenty-first century in some simulations, impacting South France, North Italy, and the Balkans. For these areas, society-relevant strong impacts of such Mediterranean extreme precipitation changes could be expected in particular concerning flood-related damages.

1 Introduction

Heavy rainfall events have strong human and economic impacts in the Mediterranean region where flood is the main natural hazard (Llasat et al. 2013). There is a growing concern about the potential climate change impacts on extreme events in the region, in particular for developing countries highly vulnerable to these events (Di Baldassarre et al. 2010). Indeed, the Mediterranean has been

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identified as one of the most responsive region (a "hot-spot") to climate change (Giorgi 2006), where future scenarios indicate an increase of temperature associated with a decrease of precipitation. However, previous multi-model studies on extreme precipitation were not focused on Mediterranean basins but Europe, yet not providing future projections for the whole extent of the Mediterranean domain at the basin scale (e.g., Sillmann et al. 2013; Rajczak and Schär 2017).

Many studies reported a global increase of precipitation extremes associated with the temperature increase, in historical records as well as in future climate projections (Donat et al. 2016; Min et al. 2009; Kharin et al. 2013; Toreti et al. 2013; Maraun 2013; King et al. 2015). For the Mediterranean region, several studies suggest an increasing trend in past observations (Alpert et al. 2002; Vautard et al. 2015; Blanchet et al. 2016; Ribes et al. 2018) and also an increase in extreme precipitation under different future scenarios, with different changes for different parts of the Mediterranean basin (Beaulant et al. 2011; Planton et al. 2012; Kyselý et al. 2012; Tramblay et al. 2012a; Jacob et al. 2014; Hertig et al. 2014; Paxian et al. 2015; Drobinski et al. 2016; Rajczak and Schär 2017; Polade et al. 2017; Colmet-Daage et al. 2018). The Mediterranean extreme precipitation changes would result from the competition between an overall drying linked with a poleward shift of the circulation (Pfahl et al. 2017) and a thermodynamic effect leading to an increase of precipitable water content in the atmosphere (Drobinski et al. 2016; Pfahl et al. 2017). One of the main drivers of extreme precipitation in the Mediterranean region is the instability at low levels, the differential heating between the sea surface and the low troposphere that affects the potential instability. The Mediterranean cyclogenesis is another main factor responsible of heavy precipitations in the region (Jansà et al. 2014). Several studies observed an increase in the number of dry days associated with increased precipitation intensities, suggesting that dry spells in these regions are become longer, but that precipitation may be more extreme when it occurs (Sillmann et al. 2013; Hertig et al. 2014; Paxian et al. 2015). The increase in extreme rainfall will not compensate the decrease of precipitation totals, since the losses from decreasing frequency of low-medium-intensity precipitation are projected to dominate gains from more extreme precipitation events (Polade et al. 2017). Furthermore, Kyselý et al. (2012) found that the projected increases in short-term extremes may exceed those of daily and multi-day extremes. However, there are still strong uncertainties in hourly precipitation extreme changes since the current generation of climate models is only capable of reproducing convection through parametrization, which differs between models (Rajczak and Schär 2017; Zhang et al. 2017).

The detection of change in extreme precipitation is often based on climate indices (Sillmann et al. 2013; Donat et al. 2016; King et al. 2015; Filahi et al. 2017) that provide a worldwide consistent approach to compare between regions. However, Zhang et al. (2004) demonstrated by Monte Carlo simulations that the explicit consideration of the extreme value distributions (Coles 2001) when computing trends on extremes outperforms classical approaches such as the nonparametric Mann-Kendall test for trends. Several studies have proposed a parametric framework based on extreme value distributions to compare extreme quantiles computed on different time slices in historical and future periods (Kharin et al. 2013; Hertig et al. 2014; Paxian et al. 2015; Toreti et al. 2013; Rajczak and Schär 2017). Yet, strong uncertainties could arise from this type of approach due to short record lengths reducing the robustness of model inference. Indeed, the time intervals used to compute extreme quantiles (typically 30 years) are usually too short to identify climate changes against the background of high-frequency components of climate variability (Paeth et al. 2017). This is particularly true in the case of semiarid areas where the inter-annual variability of extreme precipitation can be very strong

(Nasri et al. 2016). An alternative to this approach is to use nonstationary extreme value models with parameters dependent on time (Min et al. 2009; Fowler et al. 2010; Tramblay et al. 2012b; Aalbers et al. 2017) or a covariate (Tramblay et al. 2012a; Nasri et al. 2016). By doing so, the models are fitted on much longer time periods, reducing the uncertainties on extreme quantiles (Aalbers et al. 2017). Moreover, considering in this framework, the starting date of the trend (e.g., Min et al. 2009; Fowler et al. 2010; Maraun 2013; Blanchet et al. 2016) could help to answer the question of when the precipitation change signal would emerge from the underlying variability (Giorgi and Bi 2009; King et al. 2015).

The objective of this study is to quantify the future evolution of extreme precipitation for all Mediterranean basins using nonstationary extreme value models. The future projections are provided by a multi-model ensemble of high-resolution regional climate model (RCM) simulations from the Euro-CORDEX experiment. In this study, both the time of signal emergence and the magnitude of the detected trends are analyzed for Mediterranean catchments, using extreme value models with time-dependent parameters. The datasets and methods considered are presented in Section 2, and the results of the detected trends are presented in Section 3.

2 Data and methods

2.1 Euro-CORDEX regional climate simulations

An ensemble of regional climate simulations of daily precipitation from the Euro-CORDEX experiment (Jacob et al. 2014) with a 12-km horizontal resolution is considered (Table 1). Déqué and Somot (2008), Tramblay et al. (2013), Prein et al. (2015), Ruti et al. (2016), and Fantini et al. (2016) observed an improved representation of precipitation and in particular extremes in these 12-km-resolution RCM simulations over the Euro-Mediterranean area, compared to previous simulations at 25- or 50-km resolutions. Since the precipitation projections are strongly impacted by inter-model spread and internal noise, there is a need for large model ensemble to assess uncertainties (Paeth et al. 2017). As noted by Pierce et al. (2009), it is better to use large model ensembles rather than best-performing simulations with respect to observed climate, since there is little agreement on metrics used to select or weight the individual model projections (Knutti et al. 2010; Tramblay et al. 2012b).

The selected model runs allow considering all general circulation models (GCMs) included in the Euro-CORDEX experiment. Each GCMs is driving two different RCMs (except for NorESM1) to assess the uncertainties in terms of GCM/RCM combinations. The six GCMs

Table 1 Matrix of the 11 RCM/GCM simulations

Institute	RCM/GCM	CNRM-CM5	ICHEC-EC-EARTH	IPSL-CM5	HADGEM2	MPI-ESM	NorESM1
SMHI	RCA4	x	x	x	x	x	
CLM	CCLM4.8.17				x		
CNRM	ALADIN5.3	x					
DMI	HIRHAM5.1						x
KNMI	RACMO2.2		x				
IPSL	WRF3.3.1			x			
MPI	REMO2009					x	

included in the present study (Table 1) were found to be adequate over Europe by McSweeney et al. (2015). Despite lower performance for the IPSL-CM5 model, we choose to keep it in the ensemble to sample the full range of uncertainties present in Euro-CORDEX simulations (Jacob et al. 2014). Two future scenarios are considered: the Representative Concentration Pathways (RCP)4.5, with greenhouse gas emissions peaking around 2040 then declining, and the RCP8.5 considering a continuing rise of greenhouse gas emissions during the twenty-first century. Note that a mistake has been recently detected in the CNRM-CM5 files used as lateral boundary conditions in CORDEX. More specifically, CNRM-CM5 data for the historical period consists of data from the same model but from different ensemble members: the 2D surface fields come from one member (r1i1p1), whereas the 3D atmospheric fields come from a different member (unpublished). The two ensemble members have the same long-term climate statistics, but show different variability. For the current study, we have decided to keep RCMs driven by CNRM-CM5 in the analysis as we do consider that the mistake has little impact on our results. It is also worth noting that HIRHAM and WRF have no GHG forcing evolution along the simulation and that only ALADIN and RACMO have aerosol forcing evolution along the simulation. The potential impacts of such differences in the RCM experimental protocol are currently unclear.

2.2 Delineation of Mediterranean catchments

The HydroShed (http://hydrosheds.cr.usgs.gov) database, which contains flow direction, flow accumulation maps, and a digital elevation model at a 300-m spatial resolution, has been considered to delineate Mediterranean catchments where intense precipitation may induce floods (Nile excluded, since its floods are caused by Tropical influences). A minimum catchment size of 200 km^2 has been retained to be consistent with the RCM resolution (12 km). Using a geographic information system (GIS) processing, 102 catchments bordering the Mediterranean Sea have been delineated. In regions with several small coastal rivers, such as South France, Italy, or the Balkans, the catchments have been aggregated into homogeneous spatial units. For each catchment, the corresponding model grid cells are extracted from the Euro-CORDEX simulations.

2.3 Nonstationary extreme value modeling

The generalized extreme value distribution (GEV) is used to model annual maximum daily-mean precipitation for each model grid cell (Jenkinson 1955):

$$\begin{aligned} F(x) &= \exp\left[-\left(1-\frac{-\kappa}{\alpha}(x-\mu)\right)^{1/-\kappa}\right] \quad && \kappa\neq 0 \\ F(x) &= \exp\left[-\exp\left(-\left(\frac{x-\mu}{\alpha}\right)\right)\right] \quad && \kappa = 0 \end{aligned} \tag{1}$$

where μ is the location parameter, α the scale parameter, and κ the shape parameter. The GEV parameters are estimated with the generalized maximum likelihood (GML) method (Martins and Stedinger 2000; El Adlouni et al. 2007). The GML method is based on the same principle as the ML method but with a constraint on the shape parameter. Martins and Stedinger (2000) introduced a prior distribution of κ adapted to hydro-meteorological series, based on a beta distribution with a mode at -0.1 and shape parameter values limited to the interval $[-0.5, +0.5]$. El Adlouni et al. (2007) adapted this approach for the nonstationary context, and Tramblay et al. (2012b) or Rajczak and Schär (2017) applied it to assess the climate change impacts on extreme precipitation.

To detect the starting date of a possible trend and its magnitude, the GEV0 model with stationary parameters (Eq. 1) is compared with the GEV1 model allowing a linear trend for its location parameter starting in year t_0:

$$\mu(t) = \mu_0 t \le t_0 \\ \mu_0 + \mu_1 (t - t_0) t \ge t_0 \tag{2}$$

From Eq. 2, the location parameter of the GEV1 model is constant before the year t_0 and is linearly dependent on time after t_0. Every possible t_0 is considered between the year 1970 and 2080, and the model with the highest log-likelihood is retained, using a similar approach as Fowler et al. (2010) or Blanchet et al. (2016). Then, the nonstationary GEV1 model is compared with the stationary GEV0 model with a deviance test based on a likelihood ratio (El Adlouni et al. 2007; Coles 2001):

$$D = 2\{\log(ML_0) - \log(ML_1)\} \tag{3}$$

With ML_0 being the likelihood of the GEV0 model and ML_1 the likelihood of the GEV1 model. The D-statistic is distributed according to a chi-square distribution, with υ degrees of freedom. If D is larger than the critical value, the model M_1 is deemed more adequate at representing the data than the model M_0.

2.4 Regional significance

The false discovery rate (FDR) procedure (Benjamini and Hochberg 1995) provides a computationally straightforward approach to identify a set of at-site significant tests, by controlling the expected proportion of falsely rejected null hypotheses when multiple tests are conducted (Renard et al. 2008; Wilks 2016). Several studies have shown that the FDR procedure is robust if dependency exists between sites, suggesting it could be applied for correlated datasets such as climate data that often exhibit spatial correlation (Wilks 2006, 2016; Renard et al. 2008). In the present study, the field significance is computed for the deviance test results for all grid cells located in a given catchment, to identify regionally significant results. Field significance is declared for a catchment if at least one local deviance test has a p value smaller than the global significance level, indicating regionally significant trends in the catchment considered. The global significance level considered in the present work is 0.1.

Finally, the results are presented in terms of the proportion of RCM simulations, for each catchment, with a significant increase or decrease in extreme precipitation. For a given catchment u, a multi-model index of agreement MIA_u is introduced:

$$\mathrm{MIA}_u = \frac{1}{n}\left(\sum_{n=1}^{n} i_m\right) \tag{4}$$

Where for a given model m, $i_m = 1$ for regionally significant positive trends, $i_m = -1$ for regionally significant negative trends, $i_m = 0$ in case of no significant trends, and n is the number of climate simulations. The index is equal to 1 (− 1) if all model projects an increasing (decreasing) trend. This index allows quantifying the robustness of the different climate model projections. Since it scales between − 1 and 1, the results between different catchments are comparable.

3 Results

3.1 Time of emergence of trends

The detection of the starting dates of trends involves the fitting of GEV distributions with different starting dates for t_0 (Eq. 2) between 1970 and 2080. No starting dates after 2080 are allowed to avoid fitting nonstationary GEV distributions on less than 20 data points. The starting dates for positive or negative trends detected in the different RCM simulations are shown on Fig. 1 for the scenario RCP4.5 and on Fig. 2 for the scenario RCP8.5. The global spatial pattern is very coherent among models; only the starting dates of trends seem to depend on the different RCM/GCM combinations. Increasing trends are found in South France, Northern Italy, Greece, and Western Turkey, while decreasing trends are mainly found in North Africa. Similar spatial patterns have been previously identified by Maraun (2013) in ENSEMBLES RCM simulations. On average, significant trends (positive or negative) are detected in 40% of the model grid cells covering Mediterranean basins under the RCP4.5, and in 52% under RCP8.5 (if considering a smaller significance level such as 0.05, the proportions are reduced to 28% and 41% for RCP4.5 and RCP8.5, respectively). However, there is a strong spatial variability in the detected trends among the different models. As seen in Fig. 1, the same grid cells do not necessarily show the same trends with the different models, thus calling the need for spatial aggregation of the results.

It can be noticed that most often, when a trend is detected, it is almost on the whole record (i.e., starting between 1980 and 2000). However, for the negative trends mostly detected in North Africa, in several areas, the decreasing trends are detected later (by 2050) overall with a larger variability compared to the trends detected in Northern basins. For some models under RCP4.5, in particular RACMO2.2 driven by EC-Earth, trends are detected in several locations after 2060. The largest number of trends is detected with RCMs driven by the IPSL-CM5 GCM in particular under the RCP8.5 scenario: the RCA4 (SMHI) run has 76% grid cells with significant trends and 67% for the WRF3.3.1 run (IPSL).

3.2 Trend magnitude

Following the detection of starting dates for significant trends, the trend magnitude has been quantified by comparing the 20-year return period of extreme precipitation (i.e., extreme precipitation that is likely to occur on average once every 20 years) computed before the beginning of the trend and at the end of the time period considered (2100). This 20-year quantile has been chosen to be consistent with several other studies using this quantile (e.g., Kharin et al. 2013), as a compromise between the rareness of the event and the uncertainty in the estimated return levels. Figure 3 shows the relative changes on the 20-year quantiles for RCP4.5 and RCP8.5. The relative mean changes between the different RCMs are spanning between − 20% and + 20% on average, depending on the locations. Increasing trends are observed in North Spain, South France, Northern Italy, Greece, and the Adriatic, whereas decreasing trends are found in North African basins. The negative trends found in North Africa are lower in intensity and less pronounced under the scenario RCP4.5 than with the scenario RCP8.5, which also indicates a strong reduction of total precipitation in these regions (Tramblay et al. 2018). If considering seasonal changes, with a winter season between October and March and a summer season between April and September as in Toreti et al. (2010), similar patterns are found except

Fig. 1 Starting years of significant trends in RCP4.5 detected with the nonstationary GEV model

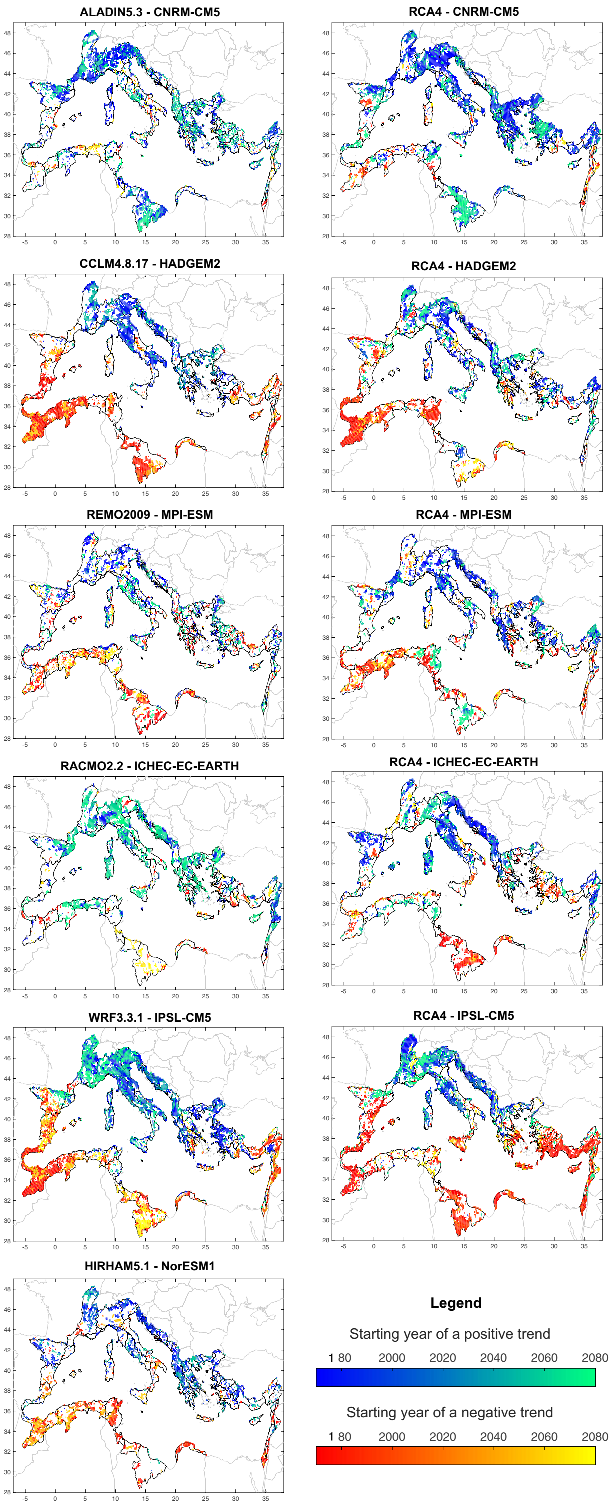
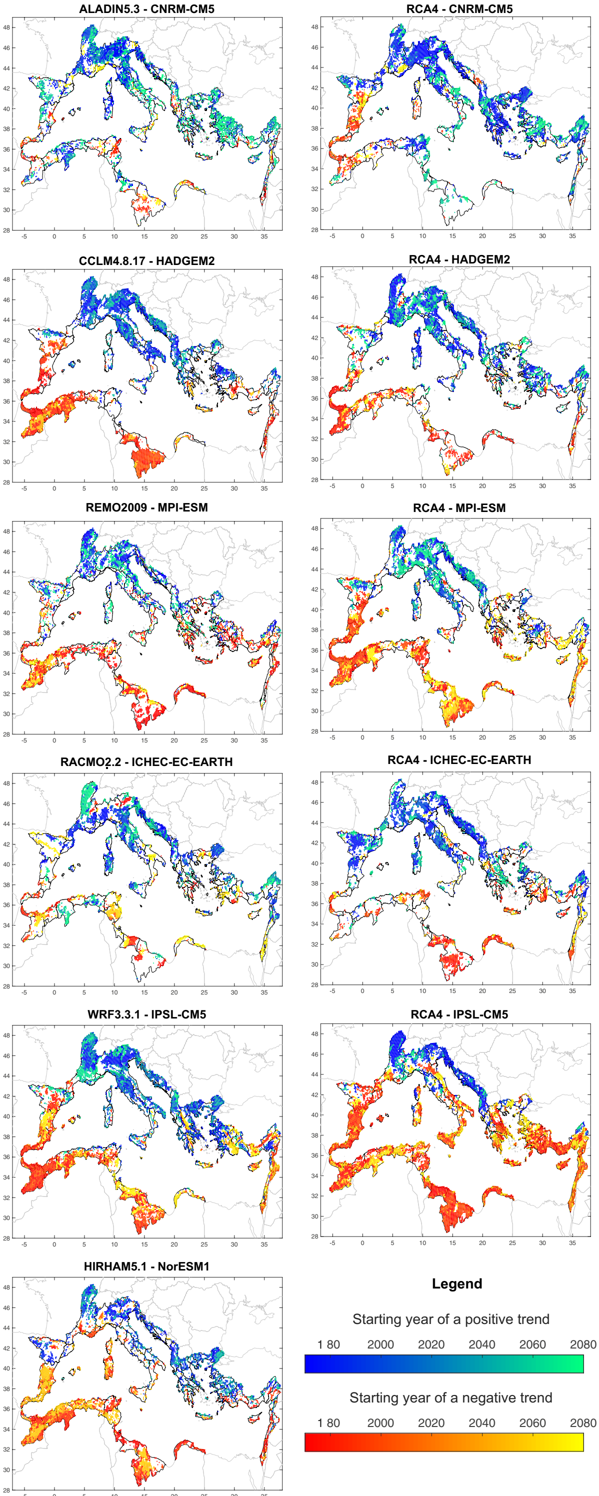


Fig. 2 Starting years of significant trends in RCP8.5 detected with the nonstationary GEV model



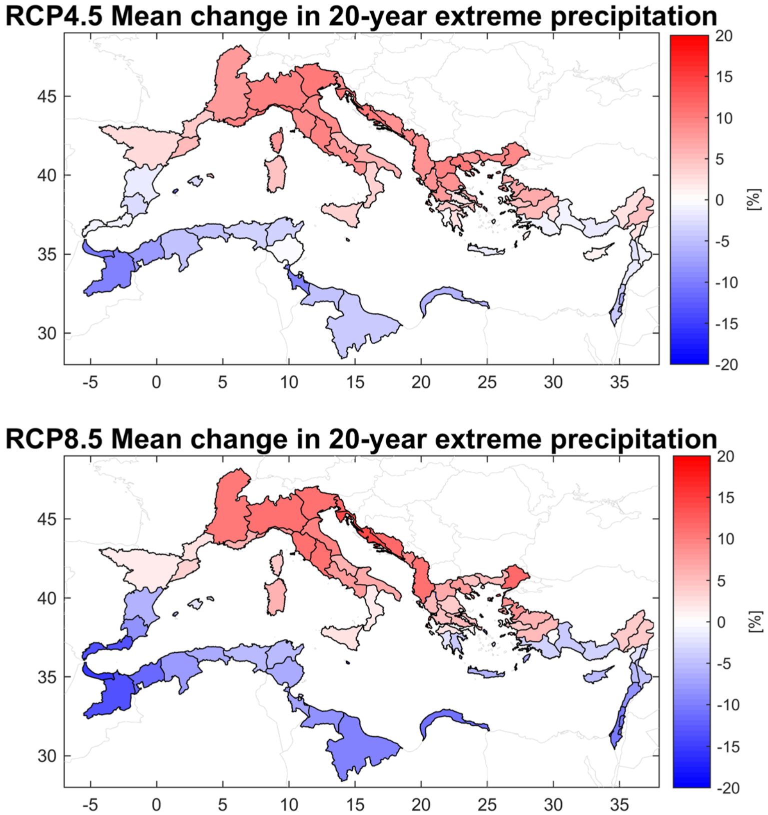


Fig. 3 Mean relative changes towards the year 2100 in the 20-year return period of extreme precipitation for each of the 102 Mediterranean basins under scenario RCP4.5 and RCP8.5

for smaller increasing trends in the summer (Fig. S1 in supplementary materials). However, this result should be interpreted with care since there are fewer heavy precipitation events during summer that could reduce the robustness of model inference.

The changes in all basins, towards an increase or a decrease, are generally intensified under the RCP8.5, and they affect larger areas. Yet, there is a strong variability on the trend magnitude in the different models; the trends locally could exceed + 60% for some grid cells. The simulations projecting the largest increase in the 20-year quantiles of extreme precipitations are the CCLM4.8.17 and RCA4 models driven by HADGEM2, as well as the WRF3.3.1 model driven by IPSL-CM5. The fact that the RCA4 model driven by the same IPSL-CM5 GCM simulates a quite lower increase is exemplifying that the GCM signal can be modulated by the RCM.

3.3 Regional significance at the basin scale

Many studies based on statistical test repeated many times, as it is the case of the present study, encounter the risk of overstated conclusions (Wilks 2016). This is the reason why we adopted the FDR procedure to adapt the p values of the multiple deviance tests used to detect significant trends. To present the number of RCM simulations for each catchment where regionally significant positive or negative trends are found, a multi-

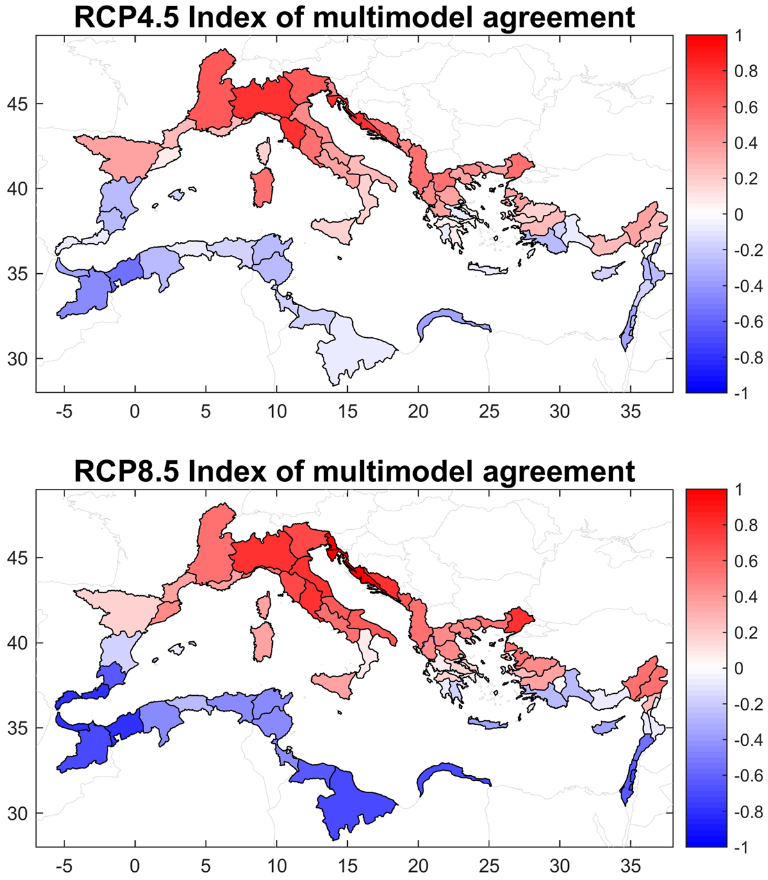


Fig. 4 Multi-model index of agreement for RCP4.5 and RCP8.5

model index of agreement (MIA; Eq. 4) is presented in Fig. 4. This index is defined for each basin as the difference between the number of RCM simulations with regionally significant positive and negative trends, normalized by the number of model simulations. For the RCP4.5, there is not a strong multi-model agreement on the projected changes except for Northern Italy with most models projecting a significant increase. For negative trends, there is much less model convergence in North African basins. Conversely, under RCP8.5, the RCM simulations are projecting a regional significant increase in the Po and Veneto basins in Italy, the Rhône in France, and the basins covering Slovenia and Croatia. More than half of the models are also projecting an increase in extreme precipitation in South France, most of Italy except Calabria, the Adriatic region, and West Turkey regions. For negative trends, there is on average less convergence between the models. Nonetheless, for South Spain, western North Africa, Lebanon, West Bank and Israel basins, most models project a significant decrease in extreme precipitation. At the seasonal scale (Fig. S2 in supplementary materials), there is a stronger multi-model agreement towards an increase during winter in northern basins than at the annual scale. On the contrary, during summer, there is little agreement between models except for negative trends in southern basins.

4 Conclusions and perspectives

This study provided a regional assessment of future trends in extreme precipitation in Mediterranean basins. An ensemble of RCM simulations with a 12-km horizontal resolution and a parametric method based on extreme value models was considered to investigate the time of emergence of trends as well as their magnitude. The results show contrasted trends, with an increase in extreme rainfall in Northern basins with a strong convergence between the different models, and conversely a decline in Southern and Southeastern basins but with a greater uncertainty. The order of magnitude of the projected changes in extreme precipitation at the end of the twenty-first century, with a mean change within the interval +20% to −20% depending on the basin, is consistent with previous studies (Rajczak and Schär 2017). The time of emergence of the trends is detected before the year 2000 in most cases, in accordance with observational studies in the same regions (Alpert et al. 2002; Blanchet et al. 2016; Ribes et al. 2018). However, the time of emergence of extreme precipitation changes is detected earlier than that of mean precipitation changes, which occur in the first decades of the twenty-first century depending on the scenario (Giorgi and Bi 2009). In the present study, similar spatial patterns of changes in extreme precipitation are obtained under the two climate scenarios considered (RCP4.5 and RCP8.5) and in all RCM simulations, suggesting a robust climate change signal. Yet, the climate change signal is much stronger under RCP8.5 with a better multi-model agreement on projected changes. Under RCP8.5, most RCM simulations are projecting a regional significant increase, which could exceed +20% locally in the Po and Veneto basins in Italy, the Rhône in France, Northern Greece, and the basins covering Slovenia and Croatia in the Adriatic.

For a better knowledge of future changes in extreme precipitation and their impacts, two research questions should be further addressed: First, this study only focuses on daily extremes, while several studies pointed the possible large changes in sub-daily extremes. The analysis of sub-daily extremes would require convection-permitting regional climate models, since the current generation of climate models cannot explicit resolve convection and the parameterized schemes that are used to represent convection can induce potentially large uncertainties (Beranová et al. 2017). Second, an increase in precipitation intensity does not necessarily imply an increase in flood risk (Ivancic and Shaw 2015). There are complex interplays between precipitation and loss processes at the surface that may strongly modulate flood magnitudes (Wasko and Sharma 2017). For some Mediterranean basins, increased heavy precipitation associated with less wet days may decrease the soil water content and consequently increase infiltration capacity, hence reducing runoff. On the opposite, more intense rain on urbanized areas or bare soils subject to crusting may increase runoff. Therefore, it is necessary to use hydrological or land surface models that are able to represent these processes.

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