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Evaluation of convection-permitting extreme precipitation simulations for the south of France

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Abstract. In the autumn, the French Mediterranean area is frequently exposed to heavy precipitation events whose daily accumulation can exceed 300 mm. One of the key processes contributing to these precipitation amounts is the deep convection, which can be resolved explicitly by state-or-the-art convection-permitting model to reproduce heavy rainfall events that are comparable to observations. However, this approach has never been used in climate simulation for the Mediterranean coastal region. In this research, we investigate the added values of using three ensembles of climate simulations at convection-permitting resolution (approx. 3 km) in replicating extreme precipitation events in both daily and shorter time scale over the South of France. These three convection-permitting simulations are performed with the Weather Research and Forecasting Model (WRF). They are forced by three EURO-CORDEX simulations, which are also downscaled with WRF at the resolution of 0.11° (approx. 12 km). We found that a convection-permitting approach provides a more realistic representation of extreme daily and 3-hourly rainfall simulations in comparison with EURO-CORDEX simulations. Their similarity with observations allows a use for climate change studies and its impacts.

1 Introduction

Deep convection is a key atmospheric process leading to heavy rainfall in short duration that can generate floods and infrastructure destruction with large impact on societies. This process has close interactions with other physical and micro-physical processes, large-scale and local dynamics of the atmosphere. However, because of the limitation in computer resources, deep convection processes have rarely been solved explicitly in long climate simulations. Parameterization schemes that are based on statistical properties of convection process within a grid box and their interactions with prognostic variables have been designed to represent this process at local scale (Kendon et al., 2012). This procedure brings large uncertainty to the results of climate models, including biases of rainfall characteristics such as the underestimation of short-duration extreme rainfall (Lenderink and Van Meijgaard, 2008; Hohenegger et al., 2008; Prein et al., 2013; Fosser et al., 2015; Kendon et al., 2019). A prominent way that has been used in the recent two decades to resolve explicitly deep convection and avoid the application of convective parameterization schemes is to increase horizontal resolution to convection-permitting (or cloud-resolving) resolution (i.e. less than 4 km). Convection-permitting models hold promises of representing central processes in the climate system, and could

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make a step change in the climate projections as they better represent impactful precipitation extremes. There also is a hope that they could remove important biases if employed at global scale (Palmer and Stevens, 2019). However, this approach requires solving a trade-off between conducting a long run with a sufficient resolution (e.g. for impact of extreme event or attribution studies) and saving the expense of computing resource (Giorgi and Mearns, 1999; Trenberth, 2008).

Several simulations at convection-permitting resolutions were conducted for different regions and periods of time to examine the added value of this approach in reproducing precipitation (Prein et al., 2015). Regional models have been used to dynamically downscale the output of global models (e.g. CMIP5 (Taylor et al., 2012)) or reanalysis data (e.g. ERA-Interim (Dee et al., 2011)) to these convection-permitting resolutions. Generally, the simulated rainfall from those models have a better agreement with observations compared to those using convective parameterization schemes, especially in terms of temporal and spatial distributions of extreme rainfall event from sub-daily to daily time scales (Kendon et al., 2012; Prein et al., 2013; Chan et al., 2013, 2014; Ban et al., 2014; Fosser et al., 2015; Ban et al., 2018; Knist et al., 2018; Hodnebrog et al., 2019). Additionally, the diurnal cycle of precipitation is also better represented in this cloud-resolving model (Prein et al., 2013; Langhans et al., 2013; Ban et al., 2014; Fosser et al., 2015; Knist et al., 2018; Scaff et al., 2019). The increase of extreme hourly rainfall at super adiabatic rate (e.g. around 14%/°C) when scaling with temperature in observations analyses is also reproduced in convection-permitting simulations for a few areas (Ban et al., 2014; Knist et al., 2018). Kendon et al. (2012) found that cloud-resolving model can reduce the "drizzle problem" found in many lower-resolution simulations, which is characterized by frequent and persistent light rainfall events. Scaff et al. (2019) additionally showed that the timing of the peak of convection was better performed by such very high resolutions. Given these added values of convection-permitting model in reproducing extreme precipitation events, a large number of studies used this approach for a robust future projection of this variable with more confidence, especially in short duration events (Kendon et al., 2017, 2019; Hodnebrog et al., 2019; Vanden Broucke et al., 2019).

The improvement in reproducing heavy precipitation events of the convection-permitting approach over parameterization methods comes from the higher resolution itself, the better representation of surface field and complex topography (e.g. steep mountainous region), the explicit-solving of convection processes at local scale and its interaction with large-scale circulation and better solving of atmospheric dynamics (Feng et al., 2018; Prein et al., 2013, 2015). Despite those enhancements, the systematic errors in the simulation results are inevitable because of the use of other parameterization schemes and discrete numerical methods and the fact that convection (both deep and shallow) is not completely resolved at the grid spacing of 1 to 3 km (Vanden Broucke et al., 2019). For instance, a convection-permitting model could overestimate or underestimate heavy rainfall, prolong the duration of light rainfall, provide more extreme precipitation events than observations and fail in simulating the location of the heaviest rainfall events (Chan et al., 2013, 2014; Fosser et al., 2015; Armon et al., 2019; Fumière et al., 2019; Vanden Broucke et al., 2019).

The coastal region along the Mediterranean has received an increasing scientific interest, for example under the framework of the HyMex[1] project (Drobinski et al., 2014; Ducrocq et al., 2014). The convection-permitting approach has been recently used to reproduce and obtain insights of extreme precipitation events in this area. Armon et al. (2019) showed that convection-

[1]Hydrological cycle in the Mediterranean eXperiment

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permitting model can reproduce the structure and location of 95% of 41 observed heavy precipitations events in the eastern Mediterranean and consequently suggested to use this approach for a long simulation. Zittis et al. (2017) found that convection-permitting model outperformed the convection parameterization approach for extreme rainfall events over the eastern Mediterranean. Fumière et al. (2019) used convection-permitting model to downscale the ERA-Interim reanalysis and proved that this high resolution improved the simulations of intensity and location of daily and sub-daily extreme precipitation. Coppola et al. (2018) used a multi-model approach with convection-permitting resolution to simulate a few case studies of heavy rainfall events over the European Mediterranean areas. They showed that each convection-permitting model can reproduce the case studies. However, the results among models spread when the event was convective and less constrained by the large-scale dynamics. These results highlighted the importance of using a multi-model approach to investigate convective precipitation events

The assessment of convection-permitting simulations over long simulations requires further attention, in particular for the dynamical downscaling of global climate models used for projections of future scenarios. However, such long simulations, to the best of our knowledge, have never been done for coastal area in the Mediterranean region. This article is designed to evaluate the skills of a unique regional climate model (WRF) with a convection permitting set-up to simulate extreme hourly and daily precipitations in a region prone to such convective event in the Mediterranean area (Nuissier et al., 2008). The analysis made here is at a climate scale and is done by downscaling the existing results of EURO-CORDEX simulations (Jacob et al., 2014; Kotlarski et al., 2014; Coppola et al., 2020; Vautard et al., 2020). The assessment is not made at the event or process levels but uses long simulations to evaluate whether the statistical properties (intensity, duration) of events are comparable to observations. The area under consideration in this article is the Cévennes mountain range where extreme precipitations are most intense in France (Vautard et al., 2015). The experimental design of these runs, reference datasets and evaluation methods are presented in Section 2. The evaluation and discussion are given in Section 3. The last section presents the conclusion.

2 Experimental design, data and methods

2.1 Experimental design

In this study, the Weather Research and Forecasting Model (WRF-ARW) version 3.8.1 is used to conduct several long simulations at convection-permitting resolution (approx. 3 km) for the French Mediterranean region. These simulations are forced by the three different EURO-CORDEX (0.11°, approx. 12 km, hereafter mentioned as EUR-11) simulations without nudging, for which outputs are available every 3 hours. These EUR-11 simulations were downscaled from General Circulation Models (GCMs) also with WRF-ARW version 3.8.1 and driven by three GCMs including the IPSL-CM5A-MR, the HADGEM2-ES and the NORESM1-M (see Vautard et al. (2020) for details about the new EURO-CORDEX ensemble). Each convection-permitting simulation (hereafter mentioned as CPS) is conducted for two different periods including 1951-1980 and 2001-2030 with the RCP8.5 scenario for the year after 2005. These two periods are chosen with a gap period (1981-2000) rather than a seamless one in order to perform a climate change impact study which will be presented in another article.

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The seasonal target of these downscaling experiments is the autumn when heavy rainfall events occur frequently over the Cévennes in the south of France. Hence, we initialize each autumn on August 26th and end the season on the 1st of December, as Mediterranean events do not generally occur outside of this period and years can be considered independent from each other. Only a few days at the end of August are spent as spin-up time for the model to obtain the physical consistency among prognosis variables after being interpolated from 12 km to 3 km in the preparation step, given that EUR-11 and CPS share the same regional model (i.e. WRF). Another factor that could take a long spin-up time (up to 10 years) in climate simulation is the soil moisture, especially the deep layer (Yang et al., 2011). Here, we facilitate our downscaling strategy (i.e. re-initializing the model every August) by interpolating the span-up soil moisture (and temperature) in EUR-11 results for the initialization of each season run of the CPS. Even though the imbalance of soil moisture is inevitable by doing so, this procedure is expected to minimize, to some extent, the perturbation in the land surface model of WRF.

The spatial configuration contains 301×301 grid points covering the Cevennes mountain range, a large part of the French Mediterranean Sea including Corsica (Figure 1). This size and position of CPS domain are selected after evaluating four different configurations for simulations of the autumn 2014 (see the Supplementary section). We use the same number of hybrid sigma vertical levels of 32 as the EUR-11 boundary conditions. The time step of our simulations is 15 seconds, which is a fourth of the time step used in the EUR-11 (i.e. similar ratio as for resolutions). We adapt the same rotated map projection of EUR-11 simulations to these CPS experiments. Similar set of physics schemes as in EUR-11 simulations is used for these downscaling experiments. Those parameterization schemes incorporate the Thompson microphysics scheme (Thompson et al., 2008), the Rapid Radiative Transfer Model for GCMs (RRTMG) for long and short waves radiation (Iacono et al., 2008), the Monin-Obukhov (Janjic eta) surface layer scheme (Janjic, 1996), the Unified Noah land-surface model and the MYNN scheme for boundary layer (Nakanishi and Niino, 2006). We also update the sea surface temperature every 6 hours.

2.2 Evaluation methods and reference datasets

We use four indices to investigate the skills of CPS and EUR-11 simulations in reproducing extreme rainfall over the Cévennes mountain range. These indices consist of: i) comparing the autumn maximum rainfall (Rx); ii) comparing the distribution of wet events; iii) comparing the scaling of extreme precipitation and temperature at 2-meter height; iv) determining the total moisture source from the surface to 700 mb (i.e. water vapour is mainly concentrated this low level of the atmosphere) that transports from the Mediterranean to the Cévennes.

The first index takes the average of autumn maxima rainfall values for the considering period. The second index compares the cumulative distributions of all rainfall values that are greater or equal to 0.1 mm (defined as wet events) in the considered period. The third index determines the non-parametric scaling of extreme precipitation with the increasing in surface temperature proposed by Lenderink and Van Meijgaard (2008). In particular, we pair the rainfall (daily or hourly) dataset with their corresponding daily mean 2m temperature over the Cévennes. This pairing dataset is then sorted in the ascending order of temperature. Next, we divide this dataset into several bins whose width is 2°C with 1°C overlapping between the two consecutive bins and calculate the 99th percentile for rainfall and the mean temperature for each bin. For making inference for each bin, we use a non-parametric bootstrap by picking 1000 samples of pairing temperature and rainfall with replacement from that

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original bin. Each sample size is similar to that of the sample of the original bin. We repeat calculating the statistics for each bin and then estimate the 90% confidence interval of each bin based on those 1000 samples. The first three comparisons are applied to both daily rainfall events and daily maximum of 3-hour rainfall events which create six indices.

An important ingredient facilitating the mechanism of the severe precipitation events over the Cévennes is the abundance of moisture source conveyed from the Mediterranean by an unstable low-level flow. This massive moisture is forced to lift up by high and steep orography of the Cévennes that triggers the quasi-stationary mesoscale convective system over the area. The updraft in this system is frequently strengthened at the same location as long as the low-level moist flows are persistent and intensified (Ducrocq et al., 2008, 2014; Nuissier et al., 2008, 2011; Lee et al., 2018). We propose here the fourth index to investigate the model ability in producing this low-level moisture transport impinging on the Cévennes mountain range using the method in Lélé et al. (2015):

$$\overrightarrow{Q} = -\frac{1}{g}\int_{ps}^{pu} q\overrightarrow{U}\,dp \quad (1)$$

In this equation, $\overrightarrow{Q}$ is the zonal and meridional moisture transport vector (kg.m^{-1}.s^{-1}), g denotes the standard gravitational acceleration at mean sea level (9.81 m.s^{-1}), q is water vapour content (kg/kg), $\overrightarrow{U}$ is zonal and meridional wind vector (m.s^{-1}), ps and pu are surface and upper pressure level, in this case, 1000 mb and 700 mb, respectively. This equation is used to estimate the moisture transport for the 12 heaviest daily rainfall events occurring over the Cévennes mountain range in 30 years of each simulation and observations. Before selecting the events in each dataset, we first define the Cévennes box by deriving the maxima and minima of the latitudes and longitudes of the 14 stations along the Cévennes used in Vautard et al. (2015). This box is roughly limited from 2.6°E to 5°E and from 43.3°N to 45.1°N. Next, we determine the 12 maxima rainfall values and their date of occurrence at any station within the box. We extract the maxima from all stations (i.e. not only considering the 14 stations) we have as long as those stations are located within the box. We eliminate a less heavy event between the two events occurring within 7 days that are both ranked on the top 12 heaviest events, so that we can avoid considering twice the same large-scale dynamic and moisture characteristics leading to those heavy rainfall events. For each determined event, we take the average of a few time steps from 18 UTC of the previous day to 21 UTC of the day that event happened. Finally, we compute the mean moisture transport of those mean values of the 12 heaviest rainfall events over the Cévennes box.

In this study, we use four reference datasets to evaluate the CPS and EUR-11 simulations. The first dataset includes in situ observations of daily and daily maximum of 3-hour rainfall. The daily rainfall data spans 1961 to 2014. The sub-daily dataset is available from 1982 (a few stations start only from 1998) to 2018. The second reference dataset is the SAFRAN reanalysis (Quintana-Seguí et al., 2008; Vidal et al., 2010). SAFRAN is provided in hourly interval with the horizontal resolution of 8 km and start from 1958. We only use this dataset to evaluate the daily precipitation event because the hourly rainfall was interpolated from daily data that made its quality insufficient (Vidal et al., 2010). The third reference dataset is the COmbinaison en vue de la Meilleure Estimation de la Précipitation HOraiRE (COMEPHORE), which is a combined product of rain gauge and radar observations (Tabary et al., 2012). This dataset has high temporal (1 hour) and spatial (1 km) resolutions and higher quality than any other gridded observations in France, especially over the complex terrain regions (e.g. the Cévennes) (Fumière

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et al., 2019). However, this dataset only covers 11 years, from 1997 to 2007. The last dataset used for the evaluation is the ERA5 atmospheric reanalysis, which is a new-released dataset to replace the ERA-Interim operationally stopped in 2019. The ERA5 has a higher horizontal resolution (approx. 38 km) compared to its predecessor ERA-Interim and starts from 1979. We collect a few variables in pressure level such as the horizontal winds and specific humidity to serve the moisture transport investigation. Given that the time span of these reference datasets is different, we select different periods of simulations to be evaluated using different indices proposed in the beginning of this section. The selection of periods of simulations and reference datasets corresponding to each index is described in Table 1 below.

3 Evaluation results and discussion

In this section, we analyse and discuss the performance of EUR-11 and CPS simulations following the indices proposed in Section 2.2. Given the fact that EUR-11 and CPS simulations share the same regional model (i.e. WRF-ARW version 3.8.1) and physics, we mention each simulation shortly by its resolution combining with the driving GCMs (e.g. EUR-11-IPSL-CM5A-MR).

3.1 Autumn maximum daily rainfall (Rx1day)

We first look at the spatial distribution of mean of autumn maxima daily rainfall (Rx1day) from all simulations and observations (Figure 2). The results from the two reference datasets including the SAFRAN (Figure 2-g) and the in situ observations (Figure 2-h) show that daily rainfall events occur along the Cévennes mountain range (i.e. the diagonal of the Cévennes box), especially over its northern part (i.e. above the latitude of 44°N). The maximum and mean of 14 stations (as used in Vautard et al. (2015)) from the SAFRAN and observations are close to each other, 98 mm and 77 mm, respectively for SAFRAN versus 97 mm and 81 mm for observations. This coherence comes from the fact that SAFRAN is an interpolation product from in situ observations. Generally, we observe an agreement between all simulations and reference datasets that rainfall patterns are heavier along the Cévennes. However, the intensity of Rx1day from the CPSs and their driving EUR-11 are very different. The three EUR-11 simulations (Figure 2-a-c) show large dry biases over the Cévennes box. The mean dry bias from those simulations range from 33% (EUR-11-HadGEM2-ES) to 47% (EUR-11-NorESM1-M). Similarly, the three CPSs (Figure 2-d-f) slightly underestimate Rx1day over the Cévennes box with a dry bias ranging from 12% (CPS-HadGEM2-ES) to 28% (CPS-NorESM1-M). In contrast, all simulations tend to show a wet bias in Rx1day over the French Alps. The wet biases in this area are more intensified by the CPSs. We find that the behaviour of CPSs depends on their driving EUR-11 simulations. The EUR-11-HadGEM2-ES or CPS- HadGEM2-ES show the best agreement with observations.

3.2 Autumn maximum of daily maximum 3-hours rainfall (Rx3hour)

The convection-permitting model is expected to improve the representation of deep convection process that leads to heavy precipitation at local scale in a short period of time (e.g. sub-daily time scale). In this section, we investigate the autumn maximum 3-hour rainfall (Rx3hour) to clarify how much the CPSs could improve the short-duration rainfall in comparison

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with their driving EUR-11 simulations for the period of 2001–2030. We use the COMEPHORE (1997–2007) and rain gauge measurement (1998-2018) for this evaluation. We skip the SAFRAN dataset due to its insufficient quality of hourly rainfall, which was obtained by interpolation process from daily data in combination with analysed hourly specific humidity and other factors (Vidal et al., 2010).

The spatial distributions of Rx3hour from simulations and observations are shown in Figure 3. We find that heavier rainfall events are still observed along a northeast-southwest axis, as for Rx1day. In addition, this pattern is expanded to the plain area on the south-east of the Cévennes range in the 11-years mean of COMEPHORE (Figure 3-g) and the 11-years and 21-years means of in situ observations (Figure 3-h-j). The spatial max/mean of Rx3hour of all 23 stations located within the Cévennes box from COMEPHORE are 81mm/45mm. This mean value is consistent with the two mean values from two different period of in-situ observations, but the maximum value is almost 30% larger compared to those from rain gauge data. This discrepancy could be explained by either the method applied to combining radar and in situ observations or the uncertainty in radar information over a complex topography area despite the good coverage of radar system.

All simulations reproduce well this pattern, despite the fact that their magnitudes of the event vary compared to the observations. This is consistent with what was found by those analyses of Fumière et al. (2019) who estimated the extreme tail percentile, rather than the mean, of daily and hourly rainfall from convection-permitting driven by reanalysis ERA-Interim data. As expected, the EUR-11 simulations underestimate 3-hour rainfall over the Cévennes. The mean dry biases of Rx3hour over 23 stations inside the Cévennes box from EUR-11-IPSL-CM5A-MR, EUR-11-HadGEM2-ES and EUR-11-NorESM1-M are -64%, -57% and -66%, respectively (Figure 3-a-c). The results from CPSs also underestimate the in situ observations. The spatial mean precipitation biases of 23 stations within the Cévennes box compared to observations range from -28% (CPS-NorESM1-M) to -6% (CPS-HadGEM2-ES). These CPSs perform better than EUR-11 in reproducing heavy rainfall over the plain and coastal area to the east of the Cévennes mountain range and over the Alps. However, the behaviour among CPSs varies for those areas. The CPS-IPSL-CM5A-MR shows a wet bias ranging from 20% to 60%. The CPS-HadGEM2-ES keeps showing the best performance with its bias ranging from -20% to 20%. The CPS-NorESM1-M shows a dry bias at most of the stations ranging from 10% to 40%. In summary, the convection-permitting model show consistent skills in reproducing spatial distribution of heavy rainfall from daily to sub-daily time scale. We also find the coherence in the results in CPS and its driving EUR-11 simulation.

3.3 Scaling extreme rainfall with surface temperature

From the Clausius-Clapeyron relation, we can infer that when the atmospheric temperature increases by 1 K (or °C), the capacity of the atmosphere in holding water vapour accordingly increases by approximately 7%. This means that given the absence of significant changes in relative humidity, the water vapour supplied for the convection may increase following the Clausius-Clapeyron relation when the atmospheric temperature increases (Lenderink and Attema, 2015). This relationship links the increase in extreme daily and sub-daily time scale to reginal and global warming (Pall et al., 2007; Westra et al., 2014; Lenderink et al., 2017). In this section, we model the Clausius-Clapeyron relation by a simple non-parametric scaling method described in section 2.2. We apply this method to EUR-11 and CPS simulations and then compare to the result obtained on in

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situ observations. We use 14 stations as in Vautard et al. (2015) and Luu et al. (2018) for the scaling of daily rainfall and 23 stations within the Cévennes box for the scaling of 3-hourly rainfall.

Figure 4-a compares the scaling model of extreme daily precipitation (99^{th} percentile) with daily mean surface temperature from all simulations against in situ observations. The analysis of observations (black line) over the Cévennes shows that the dependence of extreme rainfall on the increasing in surface temperature closely follows the Clausius-Clapeyron relation for the temperature above 3°C and breaks once exceeding 18°C. The three CPS simulations reproduce this behaviour, yet in different temperature ranges. Specifically, the CPS-IPSL-CM5A-MR, CPS-HadGEM2-ES and CPS-NorESM1-M follows this thermodynamic relation roughly for temperature ranging from 4° to 16°C, from 4° to 18°C and from 5° to 15°C, respectively. The results of EUR-11 simulations show almost similar behaviour to their corresponding CPSs, but the rainfall intensity is lower.

The analysis for scaling of extreme 3-hourly rainfall with daily mean surface temperature is presented in Figure 4-b. We show that the observations analysis follows the double (or super) Clausius-Clapeyron relation for the temperature range of 5°C to 20°C. This super relation can be directly explained that the latent heat released during the condensation period of water vapor can enhances the moisture convergence in lower level and the cloud dynamics (Trenberth et al., 2003; Lenderink et al., 2017). However, this result is different from what was found in (Drobinski et al., 2016). Their analysis showed that this scaling follows the Clausius-Clapeyron relation rather than the super Clausius-Clapeyron relation. This difference could come from the fact that Drobinski et al. (2016) used more than 200 stations which cover a large area in the South of France (i.e. not only restricted to the Cévennes) and they did not focus only on the autumn. This leads to the mixture of different patterns of rainfall in different seasons and areas.

For the simulations, we find that CPSs can reproduce the double (or super) Clausius-Clapeyron relation similarly to observations (Figure 4-b). These simulations have a better agreement with observations in terms of intensity. In contrast, the three EUR-11 simulations are unsuccessful in approximating the super scaling behaviour as well as the rainfall intensity. We could explain this underestimation by the fact that the convection scheme used in EUR-11 over-simplified the cloud process (Lenderink and Attema, 2015). In addition, we find the decreasing trend (i.e. the hook shape) of this scaling model in high temperature ranges for both daily and sub-daily precipitation. Because we use surface temperature as a proxy of condensation temperature (i.e. dew point), we overestimate the real saturation temperature (Drobinski et al., 2016). In other word, this hook shape results from the lack of sufficient water vapour in the atmosphere, therefore the condition of saturation is broken.

3.4 Distribution of wet events

In this section, we compare the station-pooling distributions of wet events and the biases of the right tail (10%) of those distributions from all simulations against the in situ observations (Figure 5 for daily wet events and Figure 6 for 3-hourly wet events). We find the advantage of CPSs in simulating the extreme rainfall events in either daily or 3-hourly time scales compared to the EUR-11 simulations. The analysis for daily rainfall is shown in Figure 5. The tail of daily rainfall events in CPSs and EUR-11 is underestimated (Figure 5-b). However, the CPSs show better agreement with in situ observations. Their mean biases in the 10% tail range from -40% to -20%. The dry mean biases of EUR-11 simulations range from -60% to -50%

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for the 10% right tail of the distributions. The improvement in reproducing extreme event of CPSs compared to EUR-11s is more obvious in the analysis of 3-hourly event (Figure 6). The distributions of 3-hourly wet events from CPSs are close to in situ observations (Figure 6-a). The mean biases in the right tail of these simulations range from −20% to 5%. The dry mean biases of EUR-11 simulations remain similar to their analysis of daily wet events (approx. −60%) (Figure 6-b). For either daily or sub-daily wet events, we find that the downscaling experiments from the HadGEM2-ES achieve the best skills in reproducing extreme rainfall events in comparison with other simulations with corresponding resolutions.

3.5 Moisture sources

In this section, we investigate the ability of simulations in reproducing the mean moisture source brought by the south-eastern flow impinging on the Cévennes. We use the method described in Section 2.2 to compare the mean moisture transport of the 12 heaviest Cévennes events in each simulation against the ERA5 reanalysis.

The comparison of the mean moisture transport of the 12 heaviest Cévennes rainfall events occurring over the Cévennes box is shown in Figure 7. Because the size of CPS domain is insufficient for this large-scale analysis, we visually embed each CPS domain inside its driving EUR-11 domain in each panel showing the results from CPSs (Figure 7-d-f). This means that we estimate the mean moisture transport of the 12 heaviest Cévennes events from each CPS simulation and the corresponding information from its driving EUR-11 to perform those plots. Therefore, the information from EUR-11 simulations in those cases (Figure 7-d-f) may differ from those mean moisture transport investigations for the 12 heavy Cévennes events determined from EUR-11s themselves (Figure 7-a-c). The result from the ERA5 reanalysis indicates a low-pressure system locating around 50N and 9W in the north Atlantic with its trough expanding to the south (Figure 7-g). This large-scale system produces southerly to easterly flows that transport the moisture from the warm Mediterranean hitting the Cévennes. The mean moisture flux covering the Cévennes box in this case is 265 $kg.m^{-1}.s^{-1}$ and larger than surrounding areas. All EUR-11 simulations (i.e. either analysis of themselves in Figure 7-a-c or complement large-scale dynamics information for the CPS analyses in Figure 7-d-f) can reproduce well these synoptic features. The low-pressure systems are generally located between 45°N to 50°N and 5°W to 10°W. These systems enable the low-level flows bringing larger water vapour content into the Cévennes box compared to nearby areas in all simulations in a way that is coherent with ERA-5 analysis. The bias of mean moisture source on the Cévennes box from EUR-11 simulations is roughly 25% lower than in ERA5. The CPS simulations can reproduce better agreement of moisture source over the Cévennes box with ERA5, in spite of their restriction in domain size. The mean moisture of the 12 heaviest rainfall events over the Cévennes box from CPSs are approximately underestimated by 17% compared to the ERA5. In summary, all simulations can reproduce the moisture source hitting the Cévennes, with a slightly better performance from CPSs. However, the CPSs show more added values in reproducing more realistic extreme precipitation events. This suggests that the explicitly-resolving convection, finer resolution and more elaborated topography all play a role in this improvement.

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4 Conclusions

In this study, we conducted three dynamical downscaling experiments from 12 km to 3 km using the WRF-ARW version 3.8.1 for two different periods including 1951-1980 and 2001-2030. These simulations are driven by the three EURO-CORDEX simulations using the same WRF-ARW version which downscaled three GCMs from CMIP5 including IPSL-CM5A-MR, HADGEM2-ES and NORESM1-M. We simulate precipitation only for the autumn over the French Mediterranean with focusing on the South of France. This downscaling strategy benefits from time and energy efficiency we can run simulations for different autumns and experiments at the same time.

We find that convection-permitting simulations (CPS(s)) can reproduce more realistic heavy precipitation events in terms of magnitude, spatial coverage and statistical properties than EURO-CORDEX simulations. This improvement is more pronounced in 3-hourly rainfall analysis than in the daily one. In particular, the CPSs can reproduce double rate of the Clausius-Clapeyron relation for the scaling of 3-hourly rainfall to surface temperature that is completely absent in the EUR-11 simulations with convection parameterized method and reproduce the high extremes in plain areas. These findings are coherent with other studies with convection-permitting approach forced by reanalysis data for other areas (Kendon et al., 2012; Armon et al., 2019; Ban et al., 2018; Knist et al., 2018; Fumière et al., 2019). We also find that the behaviour of CPS simulations is modulated by their driving GCM simulations given that they share the same regional climate model. For example, the downscaling experiment of the HadGEM2-ES show the best performance compared to others at the same resolution.

Both EUR-11 and CPS simulations can reproduce the moisture transport hitting the Cévennes with slightly better agreement of CPS with ERA5 in terms of mean amount of moisture on the Cévennes box. Even though the moisture source is well presented in all simulations, with a slight enhancement in CPS simulations, only three CPS simulations are able to reproduce realistic sub-daily extreme precipitation over the Cévennes. It can be deduced that cloud-solving feature, higher resolution, better representation of complex orography and a better supply of moisture source can all play a role in the added values of convection – permitting simulations.

One of the remaining inherent problems in evaluating long simulations at hourly time scale is the uncertainty in observations (as mentioned in Ban et al. (2014). The 3-hourly observational dataset used in this research started at different times among stations. In addition, the coverage of stations, especially inside the Cévennes box, is limited only to the south-eastern part of the area. A large part in the north of Cévennes range where a lot of heavy rainfall value happened is missing (as shown by COMEPHORE data). The COMEPHORE data, which is the combination of radar measurement and in situ observations, provides a better representation of the spatial distribution of heavy rainfall. Even though this data also contains a lot of uncertainty which comes from poor observations and radar information over the complex topography, its quality over the Cévennes is sufficient (as discussed in Fumière et al. (2019)). However, the length of this dataset is quite short and its observation period is different from the simulations in this research.

We conclude that a convection-permitting approach appears to provide a fairly realistic representation of extreme daily and 3-hourly rainfall simulations. Their similarity with observations allows for a use for climate change studies and their impacts. They should provide more reliable simulations than GCMs or even the high-resolution EURO-CORDEX simulations. However,

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we suggest to use multi-model approach have a better consideration in the sensitivity of this variable on different model dynamics or micro-physic schemes.

Data availability. The ERA5 reanalysis data can be found at Copernicus Climate Data Store (https://cds.climate.copernicus.eu) and the EURO-CORDEX simulations can be found at https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/

Author contributions. LL set up and ran the convection-permitting simulations, designed the article, produced all figured and wrote the main text. J-MS provided the 3-hourly in situ observations. All authors contribute to the review and writing.

Competing interests. We declare that there is no competing interest.

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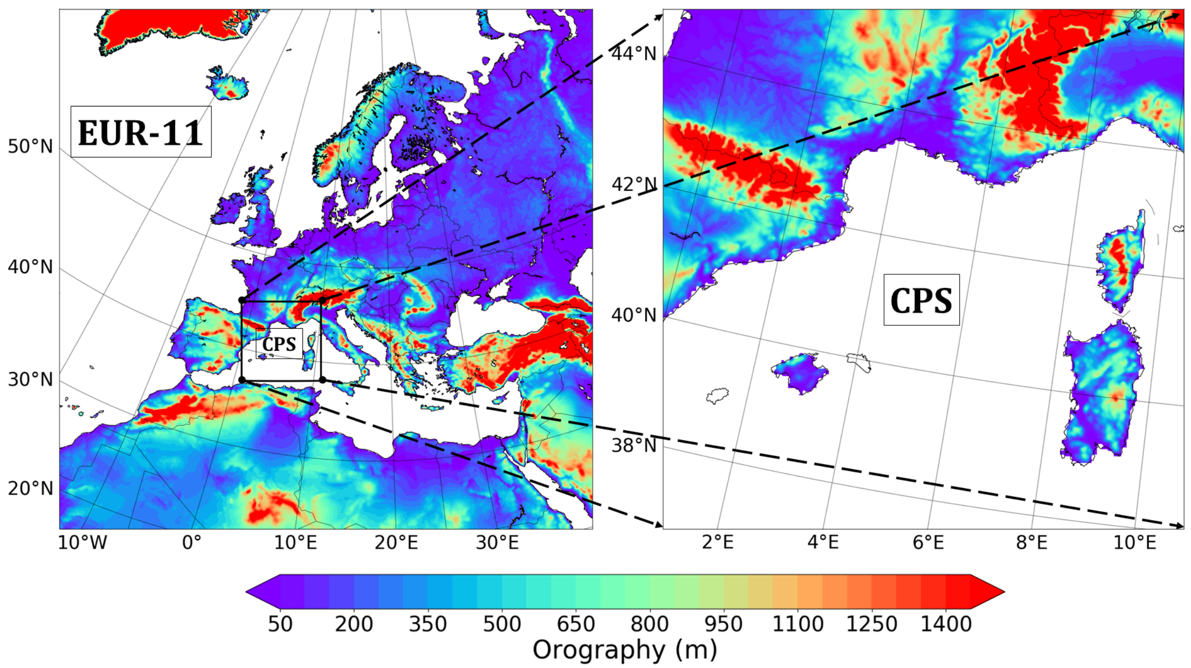

Figure 1. The domains of EURO-CORDEX and convection-permitting simulations. The shading colours denote the surface height above mean sea level from WRF.

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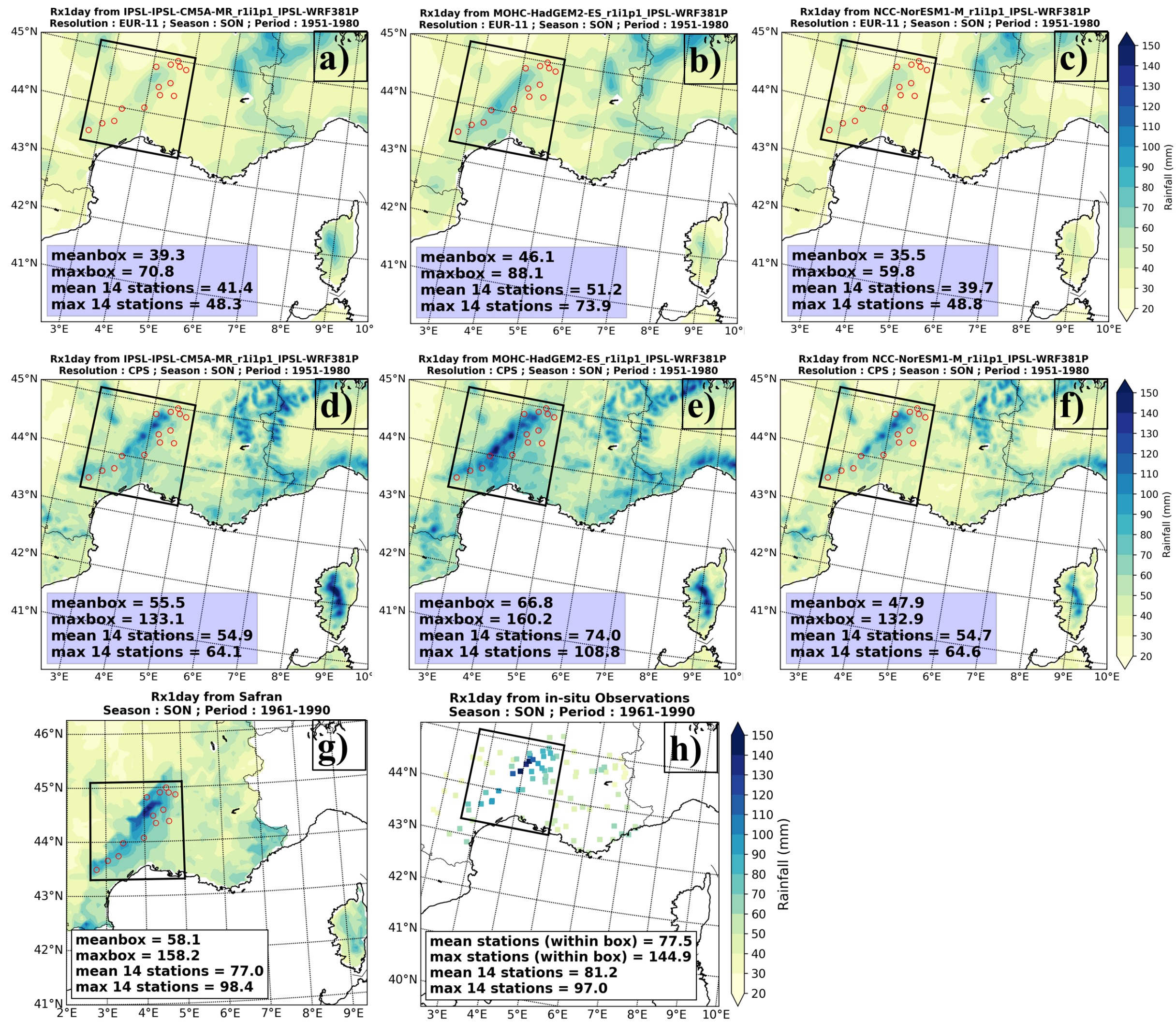

Figure 2. The Autumn maximum daily rainfall (Rx1day) from EUR-11 (a-c) simulations (1951–1980), CPS (d-f) simulations (1951-1980), SAFRAN (g) (1961-1990) and in situ observations (h) (1961-1990) data; The red empty circles inside the Cévennes box from panel a to g denote 14 stations used in Vautard et al. (2015)

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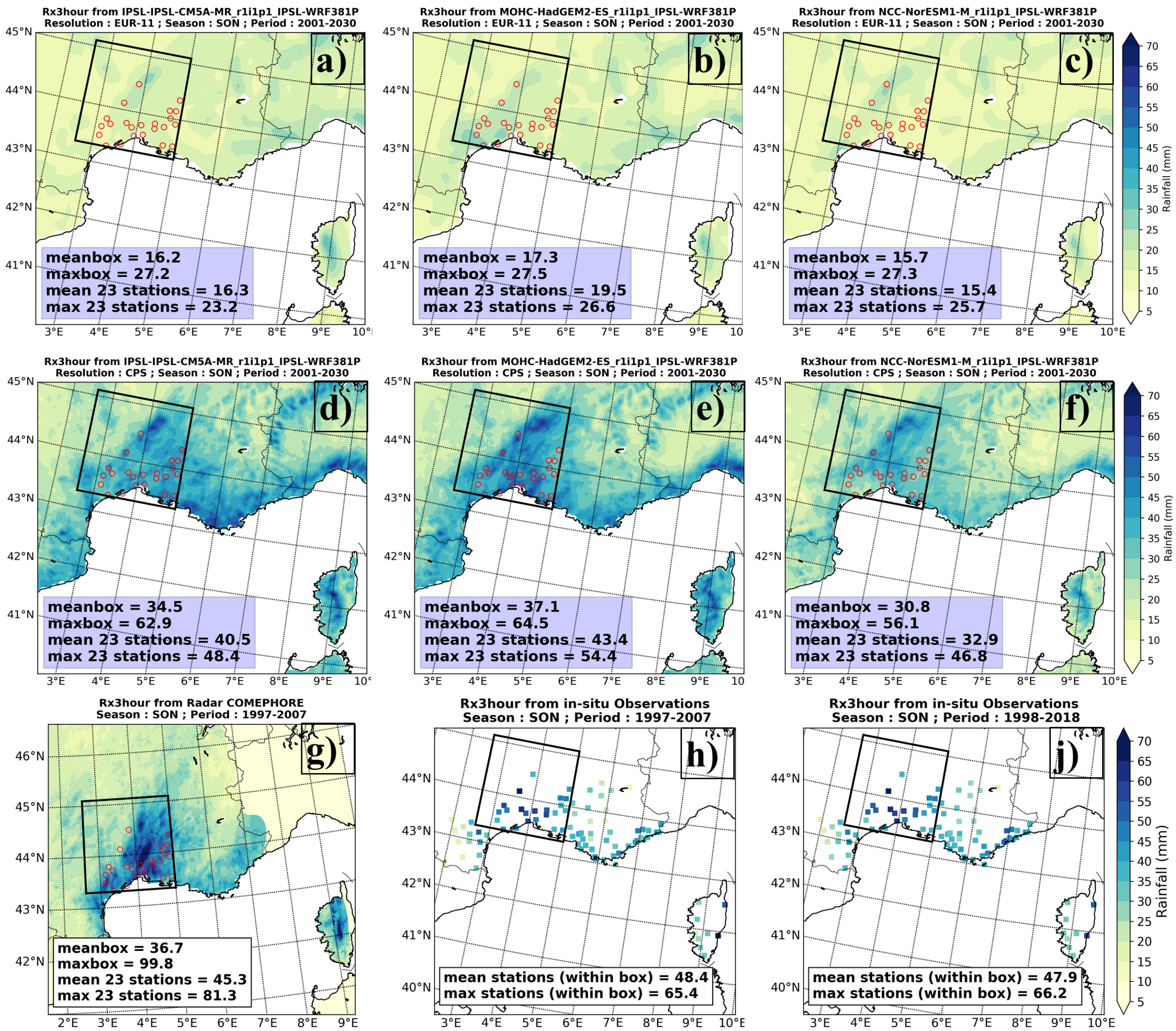

Figure 3. The Autumn maximum 3-hour rainfall (Rx3hour) from EUR-11 (a-c) simulations (2001-2030), CPS (d-f) simulations (2001-2030), COMEPHORE (g) dataset (1997-2007) and in situ observations (h-j) datasets (1997-2007 and 1998-2018, respectively); The red empty circles inside the Cévennes box from panel a to g denote 23 stations that 3-hourly data is available.

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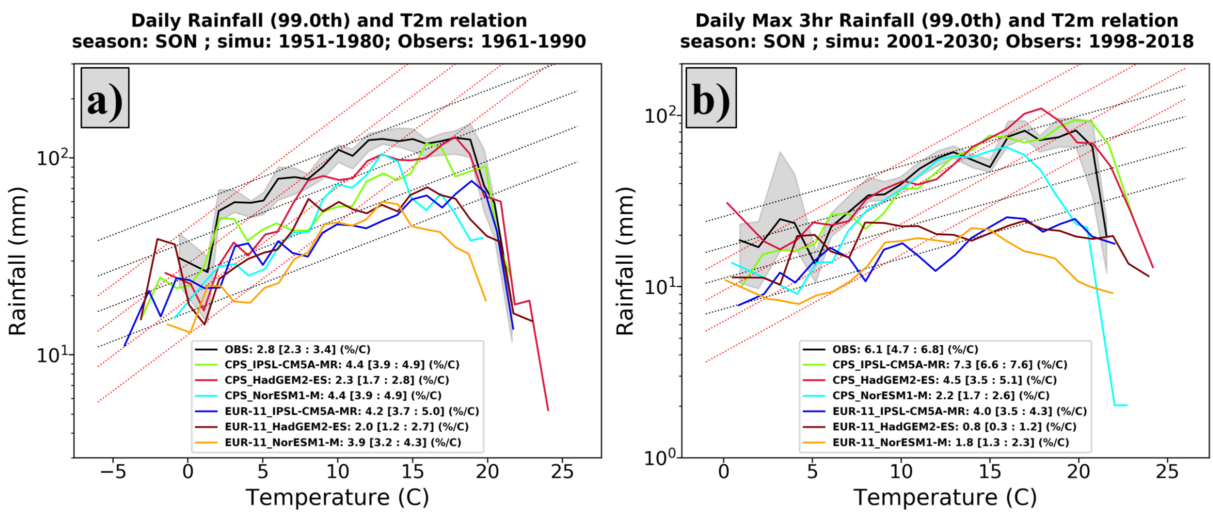

Figure 4. Extreme (99th percentile) daily precipitation (a) and daily maximum of 3-hourly rainfall (b) in scaling with daily temperature at 2m from simulations (1951-1980 for daily rainfall and 2001-2030 for 3-hourly rainfall) and in situ observations (1961-1990 for daily rainfall and 1998-2018 for 3-hourly rainfall); the black dot lines show Clausius-Clapeyron relation and the red dot lines show the super Clausius-Clapeyron relation; the grey band denotes 90% confident interval of observational scaling.

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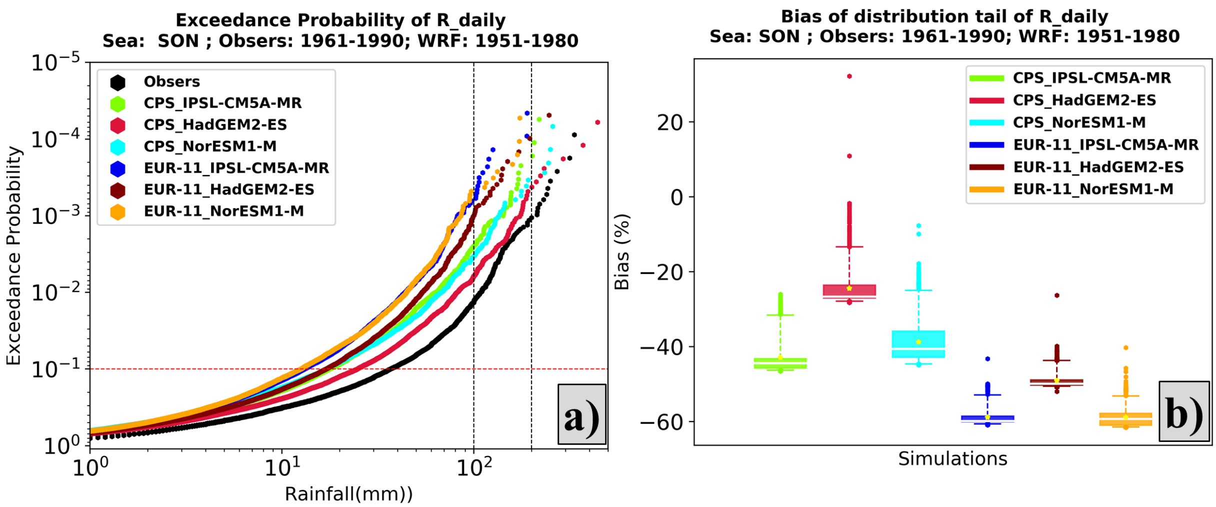

Figure 5. Exceedance probability distribution (a) for daily rainfall in the autumn from in situ observations (1961-1990) and all simulations (1951-1980) and the bias (b) of 10% in the tail of the distribution from each simulation against in situ observations. The red dotted line on panel a denotes the exceedance probability of 0.1 above which the simulated rainfall values are used to estimate the bias of the distribution tail on panel b.

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Earth System Dynamics
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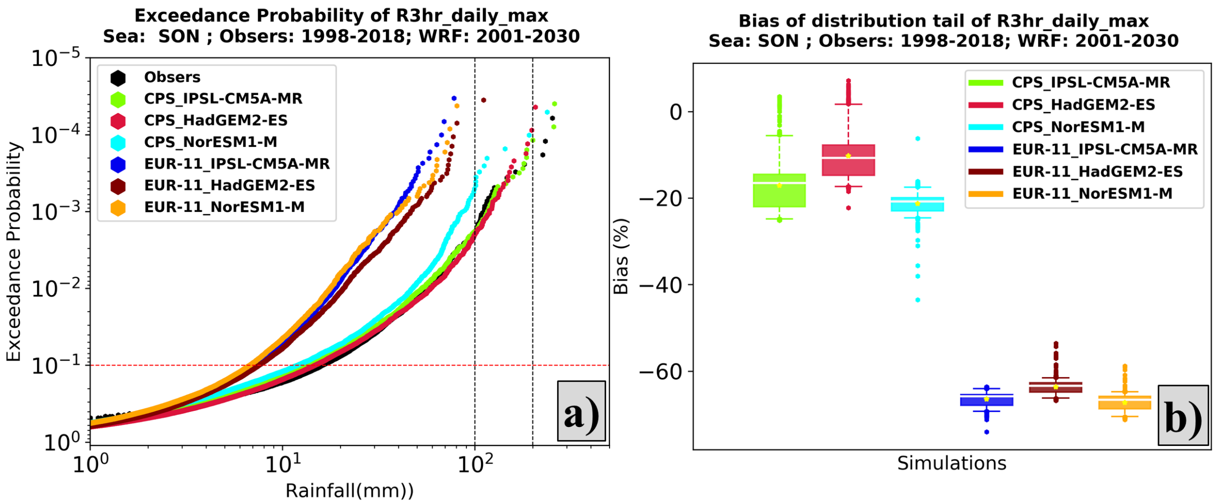

Figure 6. Exceedance probability distribution (a) for daily maximum of 3-hour rainfall in the autumn from in situ observations (1998-2018) and all simulations (2001-2030) and the bias (b) of 10% in the tail of the distribution from each simulation against in situ observations. The red dotted line on panel a denotes the exceedance probability of 0.1 above which the simulated rainfall values are used to estimate the bias of the distribution tail on panel b.

Earth System Dynamics
Discussions

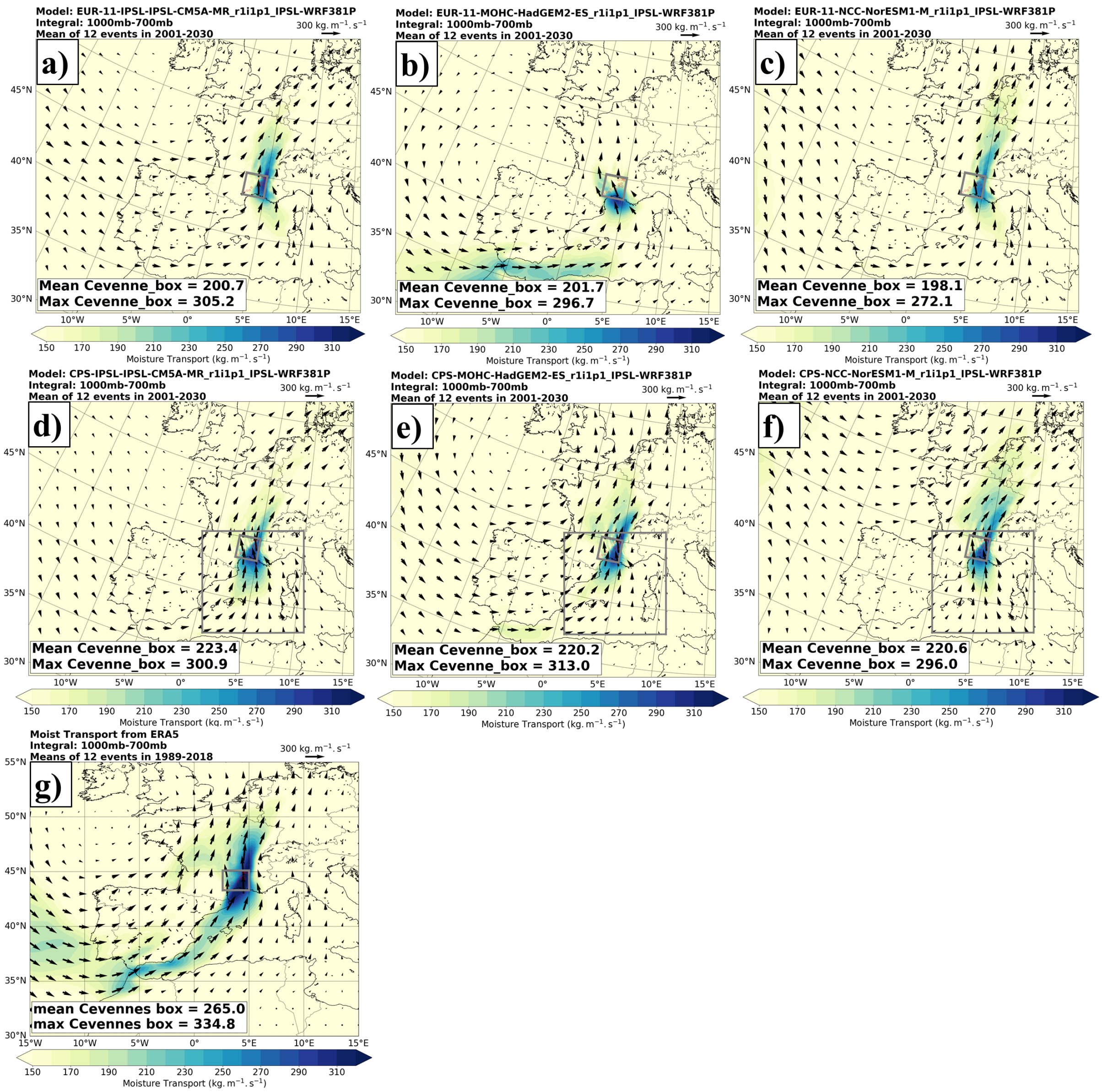

Figure 7. Mean moisture transport of the 12 heaviest daily rainfall events from all simulations (2001-2030) and ERA5 (1989-2018).

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Table 1. The selection of periods of simulations and reference datasets for evaluation of each index.

No.	Indices	Period for each Dataset				
		OBS	WRF	COMEPHORE	SAFRAN	ERA5
1	Rx1day	1961-1990	1951-1980	-	1961-1990	-
2	R-T Scaling (daily rainfall)			-	-	-
3	Distribution of wet events (daily rainfall)			-	-	-
4	Rx3hour	1998-2018	2001-2030	1997-2007	-	-
5	R-T Scaling (daily maximum 3-hour rainfall)			-	-	-
6	Distribution of wet events (daily maximum 3-hour rainfall)			-	-	-
7	Moisture source	1989-2018	2001-2030	-	-	1989-2018