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Key Points:

- High-resolution ensemble and object-oriented approach offer a unique opportunity to study changes in Mediterranean extreme precipitation
- Robust agreement is found for an increase in intensity, volume and severity for future French Mediterranean Heavy Precipitation Events
- Even at convection-permitting scale, considerable uncertainty remains regarding the degree of intensification of the most extreme events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Northwestern Mediterranean Heavy Precipitation Events in a Warmer Climate: Robust Versus Uncertain Changes With a Large Convection-Permitting Model Ensemble

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Abstract Taking advantage of a large ensemble of Convection Permitting-Regional Climate Models on a pan-Alpine domain and of an object-oriented dedicated analysis, this study aims to investigate future changes in high-impact fall Mediterranean Heavy Precipitation Events at high warming levels. We identify a robust multi-model agreement for an increased frequency from central Italy to the northern Balkans combined with a substantial extension of the affected areas, for a dominant influence of the driving Global Climate Models for projecting changes in the frequency, and for an increase in intensity, area, volume and severity over the French Mediterranean. However, large quantitative uncertainties persist despite the use of convection-permitting models, with no clear agreement in frequency changes over southeastern France and a large range of plausible changes in events' properties, including for the most intense events. Model diversity and international coordination are still needed to provide policy-relevant climate information regarding precipitation extremes.

Plain Language Summary Despite growing computational resources and multiple model developments, projecting future changes in the high-impact Mediterranean Heavy Precipitation Events remains both a numerical and scientific challenge. The present study takes advantage of the recent availability of a relatively large ensemble of high resolution Regional Climate Models (2–3 km), which represent a step change in the simulation of precipitation extremes, and of an object-oriented approach, allowing us to track the convective precipitating systems on an hourly basis. Looking at future changes in fall Mediterranean Heavy Precipitation Events at high warming levels, we identify a robust multi-model agreement for an increased frequency from central Italy to the northern Balkans combined with a substantial expansion of the affected areas, and an increase in intensity, area, volume and severity over the French Mediterranean. However, considerable uncertainties remain in terms of frequency over parts of the domain arising from uncertainty in changes in large scale weather patterns, and in terms of degree of intensification for the most intense events. It suggests the need for model diversity and for more coordinated high resolution climate projections with careful selection of different driving global models in order to provide policy-relevant climate information regarding precipitation extremes.

1. Introduction

In a context of climate change, future changes in the intensity and frequency of High Impact Weather Events (HIWEs) raise large societal concerns at global and regional levels alike. The northwestern Mediterranean is particularly affected by a typical example of convection-driven HIWEs called Heavy Precipitation Events (HPEs) (Ducrocq et al., 2008; Khodayar et al., 2021; Nuissier et al., 2008, 2011): mainly during the fall season, rainfall amounts greater than 100 mm are recorded in less than a day and often within just a few hours and lead to devastating flash flooding causing many fatalities and economic damage. The occurrence of these extreme events can be explained by favorable meteorological conditions, including synoptic and mesoscale weather features, topography and the proximity of the Mediterranean Sea. The combination of these ingredients leads to the formation of slowly moving or quasi-stationary Mesoscale Convective Systems (MCSs), which explains the exceptional hourly rainfall records.

Concerning observed changes, there is still low confidence in heavy precipitation changes and their attribution over the whole Mediterranean region (Seneviratne et al., 2021). Yet, several studies (Blanchet & Creutin, 2022; Blanchet et al., 2018; Ribes et al., 2019; Vautard et al., 2015) focusing on the French Mediterranean domain showed an observed and potentially human-induced increase in the HPEs intensity and frequency since the middle of the 20th century. The overall trend is consistent with the observed concomitant regional warming and a super Clausius-Clapeyron (CC) scaling of precipitation extremes.

Regarding future changes, the latest IPCC AR6 WP1 report indicates that, at the global scale, extreme daily precipitation events are projected to intensify by about 7% per degree of global warming close to the CC rate (Seneviratne et al., 2021). Yet, when focusing on the Mediterranean region, large uncertainties remain with important discrepancies in the response of Global Climate Models (GCMs, 150 km resolution, e.g. John et al. (2022)) that could be explained by dynamical rather than thermodynamical processes (Pfahl et al., 2017). Multi-model ensembles based on Regional Climate Models (RCMs, 12 km resolution, EURO-CORDEX) still show large uncertainties over this region (Rajczak & Schär, 2017; Tramblay & Somot, 2018; Zittis et al., 2021), with, for example, RX1 day changes ranging from −7 to +17% in Coppola et al. (2021). Part of these regional uncertainties may come from a possible but GCM-dependant decrease in the frequency of favorable weather conditions which could offset thermodynamic increases related to increased humidity as a result of warming and thus make unclear the global intensification of the water cycle.

Moreover, those studies do not provide any information about the response of subdaily precipitation. Yet, short duration rainfall extremes are typical manifestations of Mediterranean HPEs produced through small-scale convective motions. Despite sub-grid parametrizations, state-of-the-art GCMs or RCMs typically used in CMIP or CORDEX are not able to account for this mesoscale dynamical response and the resulting extremes (Ban et al., 2021; Caillaud et al., 2021; Pichelli et al., 2021).

It was only recently that high resolution (typically 2–3 km) Convection-Permitting RCMs (CP-RCMs) could be run in climate mode (Kendon et al., 2021; Lucas-Picher et al., 2021; Prein et al., 2020). This new generation of RCMs allows a step change in the representation of the convective phenomena with a clear added-value compared to lower resolution climate models with parametrized convection to simulate daily and mostly subdaily precipitation extremes. The benefit is particularly evident for Mediterranean HPEs given their typical spatial and time scales (Berthou et al., 2020; Caillaud et al., 2021; Fumière et al., 2020; Pichelli et al., 2021). Moreover, CP-RCMs allow us to go beyond the basic Eulerian approach and to set up an object-oriented Lagrangian tracking to study the propagation and intrinsic characteristics of the extreme convective events. This approach was first applied over North America (Li et al., 2020; Prein et al., 2017, 2020) but has also been used to study European HPEs (Chan et al., 2023; Kahraman et al., 2021), German convective cells (Brisson et al., 2018; Purr et al., 2019, 2021, 2022), as well as Alpine and Northwestern Mediterranean HPEs (Caillaud et al., 2021; Müller et al., 2022, 2023). Thanks to the CORDEX Flagship Pilot Study (FPS) on Convection (Coppola et al., 2020), a first ensemble of kilometer-scale 10-year-timeslice CP-RCM simulations is now available on a common pan-Alpine domain. The extreme precipitation of the hindcast simulations driven by atmospheric reanalyzes has already been evaluated with both Eulerian statistics (Ban et al., 2021) and a Lagrangian approach (Müller et al., 2022). The first Eulerian study focusing on late-century changes (Pichelli et al., 2021), extending the results found by Fumière (2019), foresees a stronger intensification of extreme precipitation at hourly rather than daily timescale, but still with large uncertainties, ranging from about no change to +34% over South-East of France.

In this context, our work aims at providing a more comprehensive and physically oriented study of future changes in the frequency and properties, including intensity, of the Mediterranean HPEs by taking advantage of:

- the recent availability of appropriate modeling and diagnostic tools to study northwestern Mediterranean HPEs under climate change, that is, high resolution CP-RCMs and an object-oriented approach that allows the separation between the frequency and the intrinsic characteristics of convective systems,
- the first-of-its-kind large CP-RCMs ensemble available over the common pan-Alpine domain for strong warming levels.

2. Methods

2.1. Models and Simulations

We use a large ensemble of fourteen CP-RCMs simulations performed within the CORDEX FPS on Convection program and protocol, that means high resolution (2–3 km) non-hydrostatic climate simulations, with explicitly resolved deep convection. Six families of CP-RCM models are included in this study, derived from CPM originally developed for National Weather Prediction purposes for AROME, COSMO-CLM or CCLM, UM, and WRF, or newly developed non-hydrostatic high resolution models based on existing RCM (RegCM, REMO).

All the CP-RCM simulations are performed over domains that encompass the common CORDEX FPS pan-Alpine domain called ALP-3 (cf. Figure S1 in Supporting Information S1). Only UM-UKMO covers a large pan-European domain (Berthou et al., 2020).

Due to computational limitations, 10-year only periods are simulated for 3 time slices: 1996–2005, 2041–2050, 2090–2099 (i.e., historical, mid-century and end-century, respectively). The RCP8.5 high-emission scenario (Meinshausen et al., 2011) is chosen for all the future simulations in order to increase the signal-to-noise ratio and highlight projected changes in heavy precipitation despite a background of strong natural variability. Thirteen simulations are available for the mid-century period (all except WRF-FZJ-IDL), as well as for the end-century period (all except REMO-GERICS).

The FPS protocol sets a CP-RCM resolution range, common domain and periods but each institute made its own choice for the simulation setup and the driving RCM and GCM according to their needs and constraints. Most of the simulations are based on a two-tier modeling chain (cf. Figure S1 in Supporting Information S1) with CP-RCMs driven by GCM projections (typically at 150 km resolution) with an intermediate RCM step (12–15 km resolution) to limit the resolution jump.

Further details and references can be found in Table S1 and Figure S2 in Supporting Information S1.

2.2. Mediterranean HPEs Detection and Tracking

To identify and characterize the northwestern Mediterranean heavy precipitating systems in the CP-RCM simulations, we apply a specific detection and tracking algorithm (Caillaud et al., 2021; Morel & Senesi, 2002) onto successive 1-hr accumulated precipitation fields. This method (summarized in Text S1 in Supporting Information S1) has already been used for high-frequency precipitation evaluation in single-model (Caillaud et al., 2021) and multi-model (Müller et al., 2022) studies.

To select French Mediterranean HPEs following Caillaud et al. (2021), a spatial criteria is applied: only the tracks crossing the French Mediterranean area (cf. Figure S1 in Supporting Information S1) are taken into account. Moreover, in addition to the 10 mm/hr intensity threshold set in order to select convective heavy precipitation, only tracks occurring during 24-hr sliding windows with accumulated precipitation exceeding the 100 mm threshold at least over one grid point of the French Mediterranean area are selected. One Mediterranean HPE can thus correspond to a combination of several convective systems (Duffourg et al., 2016), and therefore to several tracks.

All CP-RCMs simulations are firstly interpolated using conservative remapping to the common regular 3 km resolution ALP-3i grid. Then, the tracking algorithm and Mediterranean HPE detection are applied. In order to evaluate the historical simulations, the same methodology is applied to the available kilometric and hourly observations (COMEPHORE over France and GRIPHO over Italy).

The focus is on an extended fall season (from September to December), when most of the HPEs occur in the northwestern Mediterranean region (Ricard et al., 2012). The changes of seasonality of Mediterranean HPEs (studied in Chan et al. (2020)) are not part of this study.

3. Results

3.1. Evaluation of the Historical Simulations

The preliminary step before studying future changes is to check the ability of the 14 CP-RCMs historical simulations to reproduce the main characteristics of fall northwestern Mediterranean HPEs, with a focus on the French Mediterranean area with reliable observations. The detailed evaluation can be found in Text S2 in Supporting Information S1.

The main results are the following:

- good spatial representation of the areas known to be affected by fall HPEs in terms of number and positioning, even if there are differences among simulations that cannot be explained by the CP-RCM family or the driving GCM;
- overestimated numbers of HPEs over mountainous regions and Italy that can partly arise from a possible observational rainfall deficit;
- lower numbers of HPEs in the Cevennes foothills with respect to the observations, though to a lesser extent with the AROME simulations. The limitations of CP-RCM in capturing mesoscale convection, such as cold pools (Hirt et al., 2020), may be responsible for this underestimation, which was also found in Müller et al. (2022);
- in the French Mediterranean area, overall good representation of the main characteristics of fall HPEs in terms of intensity, area, volume and severity as defined in Text S1 in Supporting Information S1. Duration and propagation speed are overestimated by almost all the simulations. For AROME and RegCM simulations and even more for REMO, a significant overestimation of rain volumes is found, related to long-lasting and oversized systems. RegCM-ICTP simulates too high maximum intensities (Stocchi et al., 2022), whereas AROME-CNRM underestimates them (Caillaud et al., 2021).

Therefore, this evaluation allows us to conclude that all our historical timeslice simulations reasonably represent the main present-day characteristics of Mediterranean HPEs, so that it was decided to keep all available GCM/CP-RCM combinations to study their response in a warmer climate.

3.2. Future Changes Under RCP8.5 Scenario

We present here the results for the last decade of the 21st century using an ensemble of 13 CP-RCM simulations. The focus is here mostly on the ensemble-mean response and on the qualitative multi-model agreement (i.e., the number of models that agree about the sign of the anomalies and the statistical significance of sign change at the 90% confidence level using a bootstrapping method described in Text S1 in Supporting Information S1). The results of individual models are presented in Supporting Information S1 (Figures S11–S16).

3.2.1. Changes in Frequency Over the Pan Alpine Domain

Figure 1 presents the ensemble-mean spatial density of precipitating systems above 10 mm/hr and focuses on the fall season over (a) the historical period, (b) the end-century period and (c) the differences between the two periods. An increased frequency is simulated in the major part of the pan-Alpine domain and most strongly in its eastern part, from central Italy to the northern Balkans. If the multi-model ensemble mean does not show any negative anomaly, no change is expected in the south-west and north-east parts of the domain. Moreover, the 10-cell contour isoline of the historical simulation, well representative of the present-day areas known to be affected by Mediterranean HPEs, was superimposed on the projected anomalies and thus highlights a substantial extension of the affected areas. At the end of 21st century, the pre-Alps, the interior of Italy, Slovenia or Croatia, the south of Austria or Switzerland may be affected by intense convective systems during the fall, whereas they are hardly impacted nowadays. The land area with densities above 10 cells per year is expected to almost double by the end of the century, from 214002 to 411,867 km^2, that is, +92%.

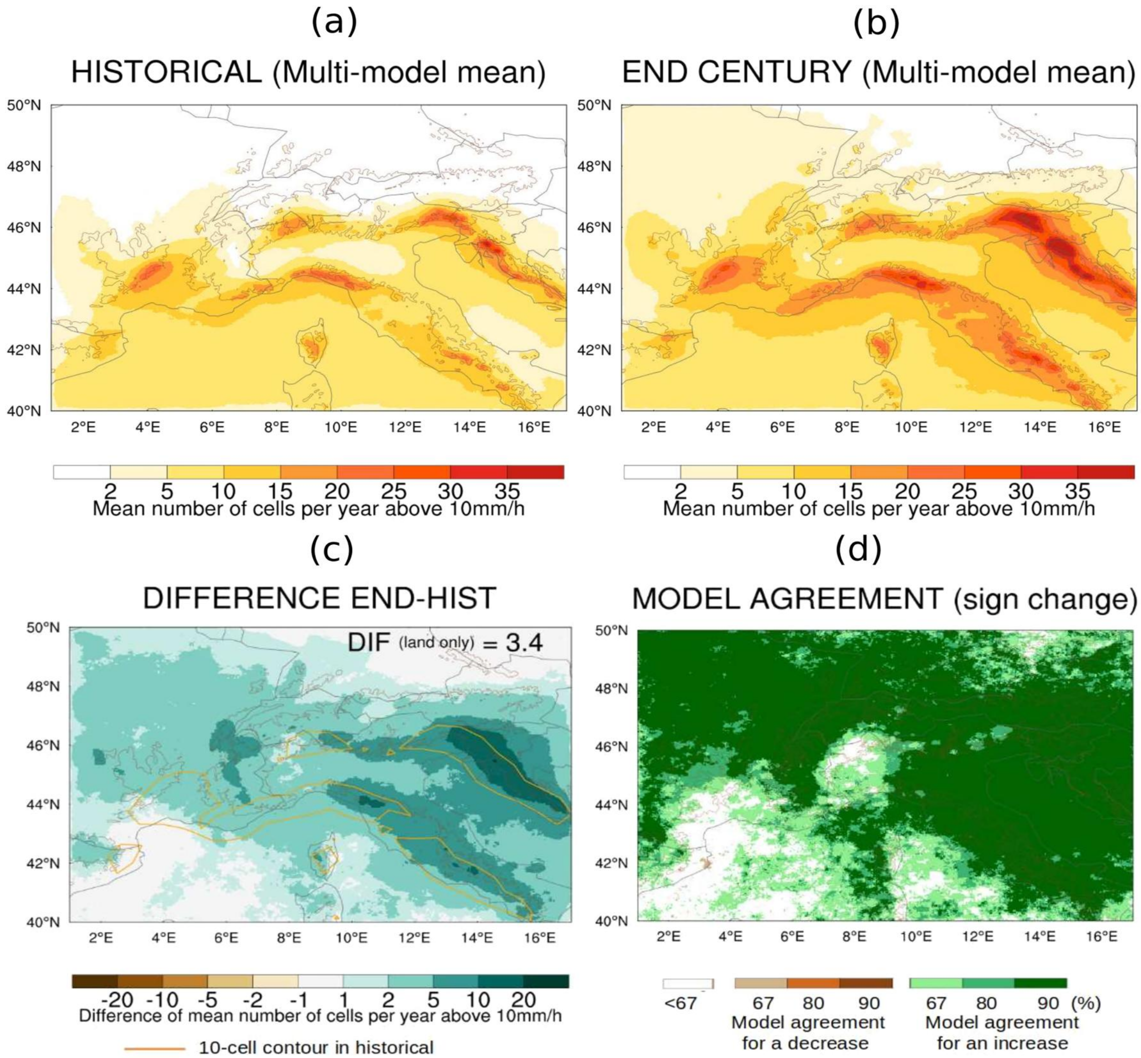

Figure 1. Spatial density of cells above 10 mm/hr during SOND for the multi-model mean for the historical (a) and the end-century (b) periods. Raw differences (c) with difference of number of cells per year over land indicated at the top right and in orange, the 10-cell contour isolines for the historical period. Model agreement (d) for the sign changes in %. On all figures, orography (750 m) plotted in brown lines.

Figure 1d highlights the good agreement among the different simulations. About 95%, 83% and 71% of the land domain exhibit a model agreement above 67%, 80%, and 90% respectively. However, there is no clear model agreement over the Southeast of France, the Northwest of Italy and a large portion of the Mediterranean sea. Looking at individual model changes (cf. Figure S11 in Supporting Information S1), the large increase in the frequency of heavy precipitation is also found over central Italy to the northern Balkans for all simulations. If we classify the simulations according to the driving GCM, we find some common behaviors: for example, the three simulations driven by EC-Earth r12 present lower changes, with differences of annual number of cells above 10 mm/hr over land between +1.7 and +1.9 to be compared to the +3.4 of the ensemble mean. In contrast, no common behavior can be easily identified among the CP-RCM families. Such results highlight a dominant influence of the driving GCM for predicting changes in the number of HPEs, pointing the dominant role of the change in large scale dynamics and natural variability in setting the frequency change of the Mediterranean HPEs.

The lack of consensus on frequency changes over parts of the ALP-3 domain leads us to investigate whether consensus can be found for the other characteristics of Mediterranean HPEs. The French Mediterranean area, where a reliable evaluation of the simulations has been carried out, provides an appropriate study area.

3.2.2. Focus on the French Mediterranean

Figure 2a shows the multi-model ensemble changes of French Mediterranean HPEs' characteristics projected at the end of the century and spatially averaged over the area. For the change in the number of tracks ("Number"), the lack of consensus is confirmed: the ensemble-mean increase in the number of tracks (+19%) hides indeed a large range of anomalies across the individual simulations between −12% and +125%. Moreover, a majority of simulations shows a limited and no significant sign change (between −12% and +8%). Three simulations anticipate larger and significant increases of which the two driven by HadGEM2-ES and the UM-UKMO simulation driven by HadGEM3-GC with an outstanding increase of +125%. These changes can be linked with the changes in the number of days exceeding 100 mm/d ("Nb100"), a proxy of the number of days with favorable large-scale conditions for HPEs. This highlights again a dominant influence of the driving GCM for predicting changes in the number of HPEs.

A full model agreement, which is also highly statistically significant, is found for an increase in mean and maximum precipitation intensities, ranging from +0% to +11% and from +3% to +20%, respectively. For changes in mean and maximum area, there is more inter-model spread in the magnitude, but a good agreement (12/13 simulations) for an increase (ranging from −23% to +28% and from −24% to +20% respectively). In line with the projected increase in intensities and areas, 12 out of 13 simulations show an increase in volume and severity (with a large range of values among simulations, from −9% to +87% and from −2% to +56%, respectively). A good model agreement is also found for little and no significant change in duration and in propagation speed. Future increases in areas are also found in Müller et al. (2023) for all-year Mediterranean HPEs, in Purr et al. (2021) for convective cells over Germany and in Prein et al. (2017) for intense summertime MCSs over North-America.

Yet, the UM-UKMO behaves differently for most characteristics: in addition to the highest number of tracks, the simulation shows a larger decrease in duration and is the only one to propose a decrease in areas (around −25%). On the other hand, it presents the highest increase in mean and maximum intensity (+11% and +20% respectively). These contrasting and significant changes explain non-significant changes in volume and severity. This simulation thus projects different changes in convection over the French Mediterranean, in line with the changes in European storms found by Chan et al. (2023) comparing the same UM-UKMO simulation to a CCLM-ETHZ simulation over a pan-European domain, with the latter using a pseudo-global warming approach: more frequent, smaller storms with UM-UKMO contrast with fewer, larger ones with CCLM-ETHZ. In this case, differences in changes in the large scale dynamics are identified as being responsible for the differences in changes in storm characteristics.

In order to combine different tracks characteristics, we also present IDH plots (maximum Intensity Duration Histogram, cf. Figures 2b–2d) and IAH plots (maximum Intensity maximum Area Histogram, cf. Figures 2e–2g) which present the distribution of tracks' frequency defined as the combined occurrence of maximum intensity and duration or area values in chosen bins, normalized by the total number of tracks. The IDH and IAH plots for the multi-model frequency ensemble mean confirm the increase of intensity expected at the end of the century for HPEs. For intensities below 30 mm/hr, the frequency of short and small events increases. Above 30 mm/hr, an increase of the frequencies of heavy precipitating systems whatever the duration and the area is expected. The individual changes in IDH distributions (cf. Figure S12 in Supporting Information S1) are rather patchy. For the simulations driven by MPI-ESM-LR or EC-Earth r14, it is difficult to find a clear signal. For the others, the pattern is close to the multi-model mean's one, in particular those driven by HadGEM2-ES and for the UM-UKMO simulation, which shows the clearest increase in frequency of short duration events. The panel for IAH changes (cf. Figure S13 in Supporting Information S1) displays a little more dispersion, but still with a clearer signal of increased frequency of small-sized events for UM-UKMO.

Understanding these differences deserves further investigation which is however beyond the scope of the present study. Multiple differences in the model set-up may contribute to such differences and suggest the need for even more coordinated and comprehensive intercomparisons or additional sensitivity tests to allow a better interpretation of the results.

The full agreement for an increase in intensity of the future fall French Mediterranean convective systems is however noteworthy when compared to other past studies such as Tramblay and Somot (2018) on French Mediterranean catchment basins at daily scale, but the values are relatively low, ranging from +3% to +20%. Normalizing these values by the corresponding fall (SOND) changes in mean 2 m temperature averaged over the

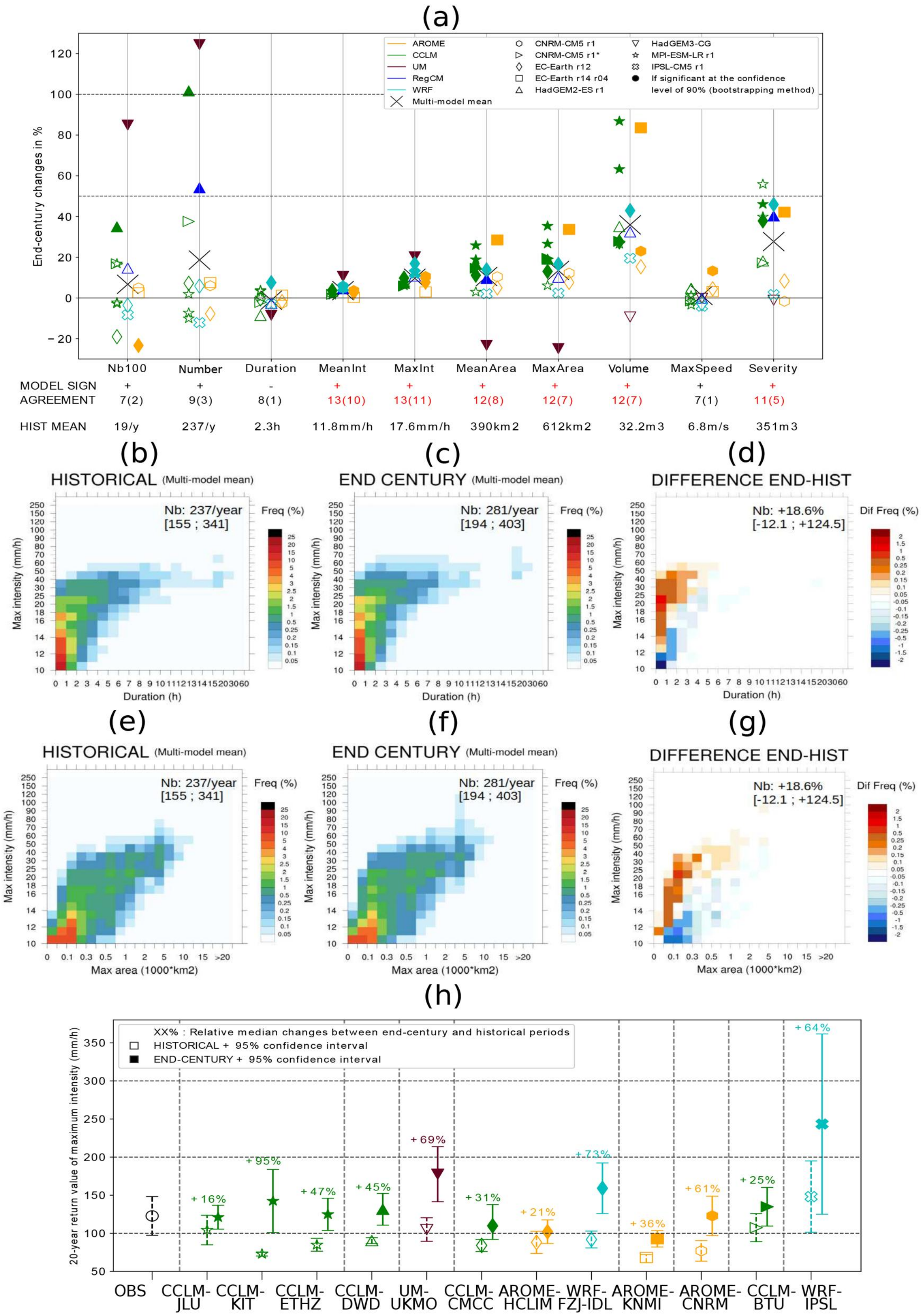
(a)
AROME
CCLM
UM
RegCM
WRF
Multi-model mean
CNRM-CM5 r1
CNRM-CM5 r1*
EC-Earth r12
EC-Earth r14 r04
HadGEM2-ES r1
HadGEM3-CG
MPI-ESM-LR r1
IPSL-CM5 r1
If significant at the confidence level of 90% (bootstrapping method)
End-century changes in %
Nb100
Number
Duration
MeanInt
MaxInt
MeanArea
MaxArea
Volume
MaxSpeed
Severity
MODEL SIGN AGREEMENT
+ 7(2)
+ 9(3)
- 8(1)
+ 13(10)
+ 13(11)
+ 12(8)
+ 12(7)
+ 12(7)
+ 7(1)
+ 11(5)
HIST MEAN
19/y
237/y
2.3h
11.8mm/h
17.6mm/h
390km2
612km2
32.2m3
6.8m/s
351m3
(b)
HISTORICAL (Multi-model mean)
Nb: 237/year
[155 ; 341]
Freq (%)
Max intensity (mm/h)
Duration (h)
(c)
END CENTURY (Multi-model mean)
Nb: 281/year
[194 ; 403]
(d)
DIFFERENCE END-HIST
Nb: +18.6%
[-12.1 ; +124.5]
Dif Freq (%)
(e)
HISTORICAL (Multi-model mean)
Nb: 237/year
[155 ; 341]
Max area (1000*km2)
(f)
END CENTURY (Multi-model mean)
Nb: 281/year
[194 ; 403]
(g)
DIFFERENCE END-HIST
Nb: +18.6%
[-12.1 ; +124.5]
(h)
XX% : Relative median changes between end-century and historical periods
HISTORICAL + 95% confidence interval
END-CENTURY + 95% confidence interval
20-year return value of maximum intensity (mm/h)
+16%
+95%
+47%
+45%
+69%
+31%
+21%
+73%
+36%
+61%
+25%
+64%
OBS
CCLM-JLU
CCLM-KIT
CCLM-ETHZ
CCLM-DWD
UM-UKMO
CCLM-CMCC
AROME-HCLIM
WRF-FZJ-IDL
AROME-KNMI
AROME-CNRM
CCLM-BTU
WRF-IPSL

Figure 2.

whole ALP-3 domain (see Table S2 in Supporting Information S1) leads to a range from +1 to +5%/°C, below the expected +7%/°C CC rate (Vergara-Temprado et al., 2021) and therefore well below the super-CC rate that has been reported for extreme hourly precipitation in previous studies (Kendon et al., 2014; Lenderink et al., 2011, 2017, 2019). Although our study is not aligned with these previous studies, a stronger intensification could be found for the most extreme precipitation events (Purr et al., 2021), which leads us to look at the tail distribution of the events.

Therefore, we focus now on the most intense tracks, that is, those with maximum intensities above each simulation's historical 97th percentile of maximum intensities. This fixed value is chosen to be consistent in the observations with the thresholds used in the operational weather warning system of Météo-France for heavy precipitation in southeastern France, but also to have a sufficient number of convective systems.

Changes in the main characteristics of the most intense tracks (cf. Figure S14 in Supporting Information S1) show now a full model agreement for a strong increase in frequency, ranging from +38% to +326%, still large model agreement for the increase in intensity but larger spread for changes in spatial extent, and hence volume and severity of HPEs. The individual distributions of the maximum intensities (cf. Figure S15 in Supporting Information S1) illustrate the difference of behavior among simulations. Most of the historical simulations underestimate the observed highest values but reach very different maximum values. The differences are even larger for end-century simulations, with, for example, much higher values for UM-UKMO or WRF-IPSL. RegCM-ICTP behaves differently with very high values, some of them exceeding 300 m/hr, in both historical and end-century simulations.

Despite the limited length of the simulations, our tracking methodology allows to identify a large number of tracks (at least 155/year) and therefore to use a Generalized Pareto Distribution (GPD, presented in Text S1 in Supporting Information S1) for modeling the tails of the distribution of the tracks' maximum intensities. In particular, this method allows us to infer intensity changes of events with return periods exceeding 10 years. Individual return period plots are presented in Figure S16 in Supporting Information S1. Figure 2h focuses on the 20-year return values and mean relative changes between historical and end-century periods for each simulation, except RegCM-ICTP which is the only one to project a decrease associated with much higher values and very large confidence intervals (see Table S2 in Supporting Information S1 for details). Most historical simulations show lower than observed values. For the end-century period, increases in 20-year return values are higher than when looking at changes in intensity for all tracks, still with a large range among simulations, from +16% to +95%. Based on the value calculated from observations, this range of increase would correspond to 20-year return values between 142 and 239 mm/hr at the end of the century. These very high values must be set against the record values already measured: world record of 305 mm/hr (June 1947, Missouri, USA), southeastern France record of 160 mm/hr (October 1986, Pyrénées-Orientales). When compared to the average temperature increase (see Table S2 in Supporting Information S1), we also find very large differences, with values (+4 to +27%/°C) ranging from below the CC rate up to 4 times the CC rate. Again, it is not possible to find common behavior within CP-RCM family or according to the driving GCM. For instance, two CP-RCMs of the same family driven by the same GCM show the smallest and largest increase respectively. Likewise, there is no direct relationship between the increase in intensity for 20-year return periods and the increase in frequency and neither when comparing to the increase in regional near-surface temperature, highlighting that the HPE future evolution can deviate substantially from the assessed global picture of an increase at the CC rate (Seneviratne et al., 2021).

For the mid-century period (see Text S3 in Supporting Information S1 for details), the conclusions are close to those given for the end-of-century period; although with lower values and less statistical significance for the changes of the main characteristics, and a stronger impact of the climate natural variability on the frequency change.

Figure 2. For the selection of tracks over the French Mediterranean area during SOND: main characteristics' differences (a) between the end-century and the historical periods for the multi-model mean and the 13 CP-RCMs (one color per family of CP-RCM and one symbol per driving GCM). Model agreement on the sign change in color if higher than 80%, otherwise in black and the number of simulations with significant sign changes in brackets. Multi-model mean for IDH and IAH plots for the historical (b, e) and the end-century (c, f) periods, and the differences (d, g). Individual values of maximum intensity (h) for 20-year return periods given by a GPD fit for the most intense tracks (except RegCM) with the same colors and symbols as (a).

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4. Conclusions

Taking advantage of the unprecedented large ensemble of Convection Permitting-Regional Climate Models (CP-RCMs) deployed in the CORDEX Flagship Pilot Study (FPS) on Convection on a common pan-Alpine domain and combining it with an object-oriented approach, this study aims to investigate the future changes in fall Mediterranean Heavy Precipitation Events (HPEs) at high warming levels. A convective-cell detection and tracking algorithm is applied to 1-hr accumulated precipitation fields of fourteen CP-RCM simulations: the 10-year historical simulations are first evaluated with regards to the observations, then compared to mid-century and end-century timeslices to assess future changes. This Lagrangian approach is used to analyze both the frequency and the intrinsic characteristics of either all or the most extreme convective systems. The multi-model approach allows us to quantify model uncertainties, assess the qualitative agreement among the available simulations, and thus identify the most robust changes.

The following robust results were identified:

- All CP-RCM historical simulations reasonably represent the main present-day characteristics of Mediterranean HPEs.
- At high warming levels, an increased frequency is simulated in the greater part of the pan-Alpine domain and most strongly in its eastern part where there is full agreement among simulations. This increase in frequency is combined with a substantial extension, that is, a doubling of the affected areas.
- The study highlights a dominant influence of the driving GCM for projecting changes in the frequency of HPEs. Hence, the choice of the driving GCM is essential and should be done through studies on GCM simulations focusing on favorable weather regimes such as Nuissier et al. (2011) or Brigode et al. (2018) using a storyline perspective (Shepherd, 2019; Zappa & Shepherd, 2017).
- Over the French Mediterranean, a full model agreement is found for an increase in mean and maximum intensities (ranging from +0% to +11% and from +3% to +20% respectively) for all tracks. Large agreement is also outlined for an increase in mean and maximum areas and therefore in volume and severity. A relatively good agreement is also found for little change in duration and propagation speed.

However, large quantitative uncertainties persist despite the use of CP-RCMs:

- Even with high-resolution modeling and explicitly resolved deep convection, significant biases in present-day precipitation extremes still remain, as also highlighted in the DYAMOND global CPM simulations (Feng et al., 2023).
- No clear model agreement is found in frequency changes over part of the pan-Alpine domain including southeastern France, probably linked to differences in large-scale synoptic conditions imposed by the driving GCMs.
- A large range of plausible changes in HPE properties is simulated across the ensemble of GCM/CP-RCM combinations, including for the scaling of increased intensity with the corresponding regional warming.
- One simulation, with a distinctive set-up, projects different, yet plausible, changes in convection with more intermittent but more intense convective systems with shorter lifetime and smaller size.
- Regarding the most intense HPEs over the French Mediterranean, the large range of projected changes in frequency and in 20-year return maximum intensity values (up to +95%) cannot be easily related to the choice of the CP-RCM or driving GCM, or to the projected regional warming.

Various limitations of the present study provide some lessons for future studies:

- 10-year simulations are not long enough to assess accurately changes in extremes such as Mediterranean HPEs which show a high interannual variability, as confirmed by the mid-century study. Similarly, simulations over larger domains would allow CP-RCMs to express their own internal variability and their intrinsic sensitivity, potentially leading to a different signal to noise ratio.
- 2 to 3-km convection-permitting models allow us to switch off the parametrization of deep convection, but still need some parametrization such as turbulence or micro-physical processes, which may also contribute to model uncertainties and also need specific assessments. Therefore, increasing model resolution will not necessarily lead to a reduction of uncertainty and should not lead to decreasing model diversity and/or the size of multi-model ensembles.
- Although the CORDEX FPS on Convection has made possible this first CP-RCM intercomparison, it remains an ensemble of opportunity with limited coordination regarding the driving method and GCM strategy. Larger

and better designed ensembles are thus needed, possibly combined with a new hybrid downscaling technique such as a RCM emulator (Doury et al., 2022).

- Additional impact variables (hail, wind gusts) or process-oriented diagnostics (composites of environmental variables such as the vertical profile of temperature and humidity) are needed to better document and understand future changes in Mediterranean HPEs.

Our final message is thus that efforts to provide policy-relevant climate information regarding future changes in precipitation extremes using ensembles of high-resolution regional models should be continued and will need enhanced coordination, at least at the European level as a follow-up to the CORDEX FPS on Convection.

Data Availability Statement

The hourly precipitation data of the CORDEX-FPS on Convection CP-RCMs ensemble are or will soon become available on the ESGF archive. COMEPHORE data set is available through AERIS platform (https://radarsmf.aeris-data.fr/en/home-page/). The archiving of the tracking data over the whole ALP-3 domain and the selection of tracks over the French Mediterranean for all simulations (historical, mid-century and end-century periods) and observation is available on Zenodo (Caillaud, 2023). Codes for data visualization are based on the NCL language (NCAR, 2019) and the Python library (Hunter, 2007).

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