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Extreme rainfall in Mediterranean France during the fall: added value of the CNRM-AROME Convection-Permitting Regional Climate Model

Quentin Fumière¹ · Michel Déqué¹ · Olivier Nuisser¹ · Samuel Somot¹ · Antoinette Alias¹ · Cécile Caillaud¹ · Olivier Laurantin² · Yann Seity¹

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Abstract

South-East France is a region often affected by heavy precipitating events the characteristics of which are likely to be significantly impacted in the future climate. In this study, CNRM-AROME, a Convection-Permitting Regional Climate Model with a 2.5 km horizontal resolution is compared to its forcing model, the Regional Climate Model ALADIN-climate at a horizontal resolution of 12.5 km, self-driven by the ERA-interim reanalysis. An hourly observation dataset with a resolution of 1 km, COMEPHORE, is used in order to assess simulated surface precipitation from a seasonal to hourly scale. The representation of the spatial pattern of fall precipitation climatology is improved by CNRM-AROME. It also shows a clear added value with respect to ALADIN-climate through the improvement of the localization and intensity of extreme rainfall on a daily and hourly time scale on both fine and coarse spatial scales (2.5, 12.5 and 50 km). CNRM-AROME in particular is able to simulate intense rainfall on lowlands and makes sub-daily rainfall events more intense than ALADIN-climate. CNRM-AROME still underestimates very extreme precipitation from above 30 mm/h or 230 mm/day.

Keywords Convection-Permitting Regional Climate Model · Heavy precipitating events · Added value · CNRM-AROME · ALADIN-climate · COMEPHORE

1 Introduction

The Mediterranean region is emerging as one of the primary hot-spots in future climate change projections (Giorgi 2006). On one hand, this region is prone to water shortages in summer, and on the other, it is often affected by High Precipitation Events (HPES, Nuisser et al. 2011), which can lead to highly destructive flash floods especially during the fall. These events generally occur around Mediterranean coastal regions, in particular in the south of France in the extended fall season typically from September to December (SOND in the following). More specifically for Mediterranean France, HPES often lead to surface precipitation amounts which sometimes exceed 200 mm in just a few hours (Ducrocq et al. 2008; Nuisser et al. 2008). Mediterranean HPES have been

studied in particular in recent years, especially in the framework of HyMeX (Hydrological cycle in the Mediterranean eXperiment, Drobinski et al. 2014; Ducrocq et al. 2014). These HPES are usually produced by intense deep convection generally associated with quasi-stationary convective systems (Nuisser et al. 2008). It has been shown that a typical synoptic-scale pattern with an upper-level flow centered just west of Western Europe, favors a warm and moist southerly low level flow over the north-western part of the Mediterranean Sea (Nuisser et al. 2011; Ricard et al. 2012).

Recent studies have shown an increasing trend in HPE intensity and frequency at the end of the twentieth century in South-Eastern France (Vautard et al. 2015; Blanchet et al. 2018; Ribes et al. 2019). Using rain gauge observations, Ribes et al. (2019) showed that the mean intensity increase of the annual maximum rainfall is significant and estimated at + 22% (+ 7% to + 39% at a 90% confidence level) over the 1961–2015 period in South-Eastern France. Changes in frequency for events exceeding high thresholds are found to be significant, typically approaching the double of the initial frequency in agreement with twice the Clausius–Clapeyron expected value. The area affected by HPES and the

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precipitated water volume during these events also exhibits increasing trends.

Studies based on climate change projections showed that HPE intensity is expected to increase due to climate change, despite an overall Mediterranean climate drying (Beaulant et al. 2011; Planton et al. 2016; Jacob et al. 2014; Drobinski et al. 2018; Colmet-Daage et al. 2017; Trambly and Somot 2018). RCMS used in these studies have a typical resolution of 50–12.5 km with parameterized deep convection. Their ability to represent correctly HPES and the associated small-scale processes is therefore questionable as is their ability to provide robust estimates of the future evolution of HPES.

Concerning the role of model resolution in regards to the representation of HPES, studies by Déqué and Somot (2008), Torma et al. (2015), Fantini et al. (2018), Ruti et al. (2016) and Prein et al. (2016) proved the added value of a horizontal resolution of 12.5 km RCMS (Regional Climate Model) with respect to a horizontal resolution of 50 km RCMS. In Richard et al. (2007) and Khodayar et al. (2016), the authors showed that by using a set of explicit convection models at a horizontal resolution of 2 km, the simulated extreme precipitation for some HPE cases was closer to the observations than were the hydrostatic models with a coarser resolution. Berthou et al. (2018) showed that when it came to daily precipitation, at a resolution of 12.5 km, two RCMS behaved differently concerning the representation of high precipitation events in the Gard in September 2002 whereas their Convective Permitting Regional Climate Model (CPRCMS) counterpart converged for a better representation. In addition, Ducrocq et al. (2002) and Nuissier et al. (2008) showed, using twin simulations, the added value of a model with explicit convection (a resolution of 2.5 km) regarding a model with a parameterized convection (of 10 km resolution) for typical HPES. The multi-model study of Coppola et al. (2019) proves the ability of high-resolution models to reproduce three cases of heavy rainfall in Europe in climate mode (a summer time extreme precipitation event over Austria, a fall Foehn event over the Swiss Alps and an intensively documented fall event along the Mediterranean coast). This proves motivational to the current study which proposes the testing of a model with explicit convection on a multi-annual scale in order to assess its statistical representation of HPES.

Due to increased computer capacity, running CPRCMS on a climate scale is now affordable. Prein et al. (2017) demonstrates the ability of CPRCM to simulate meso-scale circulations with a convection-permitting model. Kendon et al. (2014) showed a more realistic representation of convection which is poorly represented in coarser RCMS in the summer in England. Later, Ban et al. (2015) and Kendon et al. (2017), using CPRCM showed that an increase in the intensity of hourly heavy precipitating events in a warmer climate should be expected over different climate zones in Europe. The study of Leutwyler et al. (2017) showed that in general,

precipitation amounts are greater with CPRCM. They highlighted an added value by using CPRCM even if a verification of hourly precipitation with high-resolution data sets over Switzerland and Germany suggests that, over a flat terrain, precipitation frequency is underestimated whilst the 99th percentile of precipitation is overestimated. Across areas with strong topographic forcing, both the hourly frequency and the all-hour 99th percentile is overestimated. Moreover, Berthou et al. (2018) also showed the added value in climate mode of two different CPRCMS with respect to their associated RCMS on the simulation of hourly rainfall by CPRCM over the United Kingdom, Switzerland and Germany.

To the authors' knowledge however the added value of CPRCM to better represent the specific Mediterranean HPES has not yet been studied statistically in particular in the fall and on an hourly time scale. This is the major goal of this study in which a parameterized convection RCM at 12.5 km (ALADIN-Climate) is compared with a CPRCM at a resolution of 2.5 km (CNRM-AROME38t1, referred to as AROME in the following) in 10-year long simulations, so as to assess the statistical robustness of the results.

As highlighted by Kendon et al. (2014), Fosser et al. (2015) and Ban et al. (2015), a high quality reference observation dataset is of primary importance in order to establish the added value of CPRCM. For this reason, for the first time, a new reference dataset available over France at a 1 km and 1 h resolution, COMEPHORE is employed. Intense rain events generally occur for a few hours, so the use of an hourly observations dataset with such a high resolution is therefore a very useful and robust way in which to evaluate the climate models on an hourly scale. This dataset is only available in France so we chose to focus on the Mediterranean France (South-Eastern France) where HPES are most intense. COMEPHORE will be compared with SAFRAN the amount reference dataset for the study of precipitation from models in France (Déqué and Somot 2008; Fantini et al. 2018; Prein et al. 2016; Berthou et al. 2018). In the study, Sect. 2 presents the models used for the comparison and the reference datasets. Section 3 shows the results of the comparison between the two models and observations and assesses the added value of AROME with respect to ALADIN-Climate. Section 4 presents a discussion of the results, and, finally, a conclusion is provided in Sect. 5.

2 Methodology

2.1 SAFRAN observations

SAFRAN (Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige) is a precipitation analysis for France and Corsica which uses an optimal interpolation method (Durand et al. 1993; Quintana-Segui et al. 2008;

Vidal et al. 2011). It has a 8 km spatial resolution grid with an effective resolution of around 30 km. Analyses are performed over climatically homogeneous areas where the horizontal climatic gradients are weak. The precipitation analysis is performed daily at 0600 UTC, in order to include in the analysis the numerous rain gauges which measure precipitation on a daily basis (approximately 4200 rain gauges. The first guess is in this case deduced from climatological fields). An hourly separation based on a climatological profile is then performed. For this reason, an hourly precipitation study using SAFRAN as a reference makes no sense. Consequently these SAFRAN data will be used only as a reference for daily rainfall.

So far, SAFRAN has been the reference for evaluating extreme precipitation in RCMs across France (Déqué and Somot 2008; Ruti et al. 2016; Prein et al. 2016; Fantini et al. 2018; Berthou et al. 2018). HPES are very localized and short phenomena which an analysis at 8 km with an effective resolution of 30 km cannot represent correctly. We therefore believe that a higher horizontal and temporal resolution dataset than that of SAFRAN is required for the improvement of the robustness of HPES studies. In the following, SAFRAN is shown for comparison with previous studies but we consider COMEPHORE as the reference product.

2.2 COMEPHORE observations

COMEPHORE (COmbinaison en vue de la Meilleure Estimation de la Précipitation HOraire), the second observation dataset (Tabary et al. 2012), is used as a reference for precipitation estimates in this study. COMEPHORE provides a synthesis of different sources of information available in Météo-France's operational archives, in order to obtain the best representation of surface precipitation accumulation over metropolitan France, at an hourly frequency and a kilometric resolution, with no temporal or spatial gap. The initial project provided a 10-year (1997–2006) reference observational dataset based on radar and rain gauge data (approximately 4200 rain gauges with a daily timestep including approximately 1200 rain gauges with an hourly timestep). A specific processing chain has been implemented and is explained in Tabary et al. (2012), notably in order to address the various sources of error affecting radar data.

The beginning of the period was constrained by the consistency of available archived radar data. The French operational network consisted of only 13 radars in 1997, and this number was raised to 24 in 2006, approaching the present configuration. This variation in the radar coverage directly impacts the quality of COMEPHORE, which has improved over time. Moreover, radar data are of low quality in high altitude mountainous areas like in the Alps, in Corsica and in the Pyrenees because some areas are hidden by the mountains. The Fig. 1 shows that mountainous areas does not have a

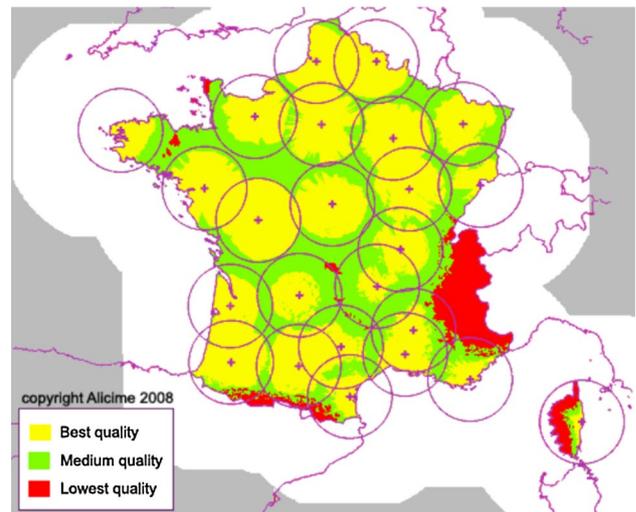


Fig. 1 Map of the quality of the radar rainfall measurement with the French radar network in 2006 (24 radars)

good radar coverage like in the Alps, in Corsica and in the Pyrenees (areas with the lowest quality of the radar data are in red on Fig. 1). However, in the Cevennes, the quality of the rainfall measurement is good.

Besides, COMEPHORE benefits from rain gauge data collected by the French electricity company which owns various hydroelectric power plants to increase the quality of the dataset in some regions such as Brittany, Normandy, and central France. Even if the quality of rain gauges is not very good in mountainous areas (Isotta et al. 2014), the combination of radar and rainfall data makes it possible to obtain an observation database on the Alps, Corsica and the Pyrenees that is of lower quality than the data on the rest of France but that remains of higher quality than the other observation databases currently available on these mountainous regions. The ground elevation is not taken into account in the interpolation method as it is not straight forward enough to do so at an hourly time step. COMEPHORE is the first rainfall observational dataset with hourly and kilometric resolution over the entire French metropolitan territory. The dataset which has recently been extended to 2015 covers land points as well as sea points along the shoreline thanks to radars. This product allows sub-daily and small scale phenomena evaluations such as Mediterranean HPES for climatological purposes across France.

2.3 Model setups

In this study, we compare a RCM at a resolution of 12.5 km, based on hydrostatic equations and with parameterized convection (ALADIN-climate), to a non-hydrostatic CPRCM at a resolution of 2.5 km and with an explicit representation of deep convection (AROME). Both models are compared across the

COMEPHORE 1997–2006 period for the extended fall season (SOND for September, October, November and December).

2.3.1 ALADIN-climate

ALADIN-climate is the RCM used by the climate group at Météo-France since the early 2000s (Spiridonov et al. 2005). In this study, ALADIN-climate is used with a horizontal grid spacing of 12.5 km, the current highest resolution in international inter-comparison projects such as Euro-CORDEX (Jacob et al. 2014) or Med-CORDEX (Ruti et al. 2016). ALADIN-climate is a numerical model with a bi-spectral Fourier truncation and a semi-implicit semi-lagrangian advection scheme. This model uses the hydrostatic approximation and therefore a parameterized deep convection (Bougeault 1985). The ALADIN-climate version used is the version 5.3 with 31 vertical levels and no spectral nudging. The original version 5 is described in Colin et al. (2010) and in Herrmann et al. (2011) (more details can be found at <http://www.cnrm.meteo.fr/gmgec/arpege-climat/ARPCLI-V5.1/index.html>). Version 5.3 is the ALADIN-climate version used for Euro-CORDEX (Bador et al. 2017; Colmet-Daage et al. 2017). The version of the physical parametrizations used in this study is very similar to the version described in Voltaire et al. (2013), for the CNRM-CM5 CMIP5 model. Major physical differences between V5 and V5.3 are:

- RRTM (Rapid Radiation Transfer Model, Mlawer et al. 1997) for long wave radiation;
- FB (Fouquart and Bonnel 1980; Termonia et al. 2018), the spectrum for short wave radiation is divided into six bands;
- ECUME (Exchange Coefficients from Unified Multi-campaign Estimates) for air-sea turbulent fluxes;
- a mixing-length parameterization described in Lenderink and Holtslag (2004).

In this study, ALADIN-climate simulation is carried out over a domain centred across France (Fig. 2), a domain which enables the encompassing of most cases of intense precipitation over France (Colin et al. 2010).

Limited Area Models need lateral boundary conditions which are usually provided by global models. RCMs strongly depend on the information given at the boundaries by their driving model. In this study, ALADIN-climate is driven by ERA-interim, a global atmospheric reanalysis with a horizontal resolution of about 77 km (Berrisford et al. 2011). Sea Surface Temperatures (SST) used in the simulation are those of ERA-interim interpolated at 12.5 km while aerosols are those of Nabat et al. (2013) and the greenhouse gases are those of CMIP5. This ALADIN-climate simulation covers the COMEPHORE 1997–2006 period after a 9-year spin-up.

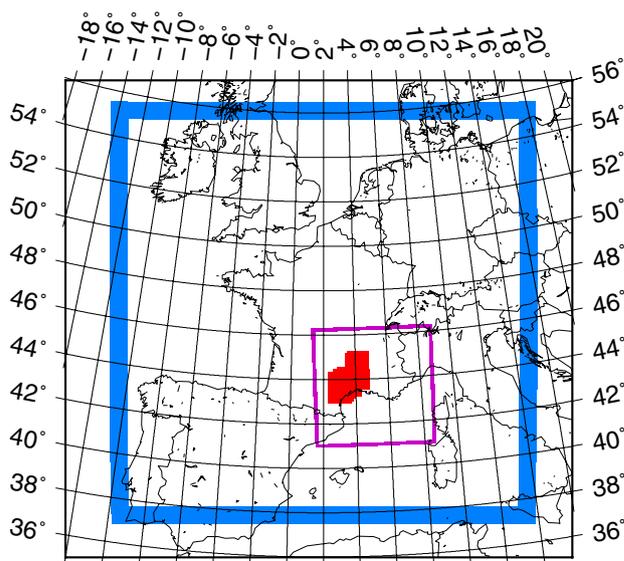


Fig. 2 Computational domains used for ALADIN-climate (driving model in blue) and for AROME (driven model in purple). The color bands show the relaxation zone. The red zone corresponds to the Extreme Precipitation Area (EPA, see text for definition, Sect. 2.3.1)

2.3.2 AROME

CNRM-AROME38t1 is a high resolution CPRCM recently developed at CNRM with a horizontal resolution of 2.5 km. It is derived from the operational short range numerical weather prediction model AROME (Seity et al. 2011; Termonia et al. 2018), in operation at Météo-France since 2008. Pioneer works using AROME in climate mode can be found in Déqué et al. (2016) and in Lind et al. (2016). The model name is divided into several parts, CNRM for “Centre National de Recherches Météorologiques”, AROME for “Applications de la Recherche à l’Opérationnel à Méso-Echelle” and “38” for the cycle inherited from the numerical weather forecast. The “t1” signifies “Toulouse 1” because the cycle 38 is shared with the ECMWF (European Centre for Medium-range Weather Forecasts) and the cycle 38t1 corresponds to the cycle 38 with improvements made by Météo-France.

The dynamical core is that of the spectral non-hydrostatic version of the limited-area ALADIN model (Bénaud et al. 2010) with a two-time level semi-lagrangian, semi-explicit scheme. Its prognostic variables are the same as those of ALADIN-climate except for the three-dimensional fields: “f” the pressure departure, the vertical divergence of the wind and the solid and liquid phases of water. Deep convection is assumed to be resolved explicitly by the dynamics of the model at a 2.5 km resolution, whilst ALADIN-climate used at a coarse resolution needs deep convection parameterization (Bougeault 1985).

Thanks to the SURFEX soil-atmosphere interface (Masson et al. 2013), AROME inherits a detailed description of

continental surfaces with a high resolution physiographic database and each model grid box is made of four tiles of adjacent surfaces: land, urban, sea and inland waters. Most physical parameterizations of AROME are inherited from Meso-NH model (Lac et al. 2018), including a bulk one-moment microphysics scheme which represents five water species (ICE3 scheme, Pinty and Jabouille 1998), a PDF-based sedimentation scheme (Bouteloup et al. 2011; Caniaux et al. 1994). The turbulence in the planetary boundary layer is represented by a prognostic Turbulent Kinetic Energy (TKE) equation combined with a diagnostic mixing length (Bougeault and Lacarrere 1989). The TKE scheme used in AROME is derived from the full set of equations for the second-order moment. It was developed by Cuxart et al. (2000).

For shallow convection, a parametrization of sub-grid effects is used (Pergaud et al. 2009). It is a mass-flux scheme based on the eddy-diffusivity mass-flux scheme (Soares et al. 2004). A statistical cloud scheme is used in AROME (Bechtold et al. 1995; Bougeault 1982). A version of the ECMWF radiation parameterization is implemented (Iacono et al. 2008; Mlawer et al. 1997; Fouquart and Bonnel 1980; Morcrette 2001).

AROME is used for this study with a 2.5 km spectral resolution, 60 vertical levels and a 60 s time-step. A relaxation toward ALADIN-Climate is applied at the top of the model for wind divergence, wind vorticity and temperature with a weak coefficient (0.01 s^{-1}). It is applied to the highest model levels for wave numbers inferior to 20 km. This nudging can be considered as the upper boundary condition allowing to compensate for a poor representation of the upper stratosphere in AROME. With regards to the other model forcings, Sea Surface Temperatures (SST) used in the simulation are those of ERA-Interim interpolated at 2.5 km whilst aerosols are those of Tegen et al. (1997) and the greenhouse gases come from CMIP5.

The AROME domain (Fig. 2) covers South-East France and the neighbouring mountains (the Pyrenees, the Cevennes and the Alps), as well as the upstream flow over the Mediterranean Sea favoring HPES. AROME is driven every hour by the ALADIN-Climate which is self-driven every 6 h by ERA-Interim. If we go from ERA-Interim at a resolution of 77 km to AROME at 2.5 km, the resolution jump is too important. It is necessary to pass by an intermediary model at 12.5 km. That model is ALADIN-Climate. ALADIN-Climate is therefore used as an intermediate driving model for AROME in order to avoid the possible detrimental effects caused by a too important resolution jump, given the small size of the AROME domain (Laprise et al. 2008). We assume that the two-tier modelling strategy allows the limiting of the spatial spin-up zone within the AROME domain.

The AROME simulation starts in January 1997 after a 9 year spin-up and finishes in December 2006 as in ALADIN-Climate. In order to evaluate the added value of AROME, with respect

to ALADIN-Climate, both models will be compared over the AROME domain. According to Matte et al. (2017), the borders of the domain might be affected by boundaries effects, we decided to take off a spatial spin-up zone of 30 points as suggested by the authors.

2.4 Extreme Precipitation Area (EPA)

In order to obtain robust statistics for the most extreme part of the precipitation distribution, we decided to define an Extreme Precipitation Area (EPA), so as to pool a large group of grid points. This EPA has been defined to focus on the rainiest area of Mediterranean France and to be relatively homogeneous from a climatological point of view.

To define the EPA, a method of sliding box to discriminate the HPE area is applied to the COMEPHORE observation dataset. For each box, the number of grid points above a specific threshold is calculated for every day within the period. The box is selected as an extreme box, when the number of points is greater than a given value at least once during the period. All selected boxes define the EPA. The smaller the boxes, the more the EPA is representative of the area prone to heavy rainfall.

We chose $50 \text{ km} \times 50 \text{ km}$ boxes so that the boxes would contain enough points of the coarsest model grid (12.5 km resolution) and were large enough to capture HPES. Each box contains 2500 grid points at a resolution of 1 km. Boxes are moved 10 km by 10 km in the x- and y-directions, so that they overlap. To be selected for the EPA, the box has to contain at least 10 grid points with an observed precipitation value over the threshold of 250 mm/day for at least one day during the period. This method allows the defining of an EPA of 28,672 points (red area in Fig. 2). It corresponds to a surface of $28,672 \text{ km}^2$ representing most accurately the area in which the strongest precipitation occurs (Colmet-Daage et al. 2017; Ribes et al. 2019).

The strongest HPES in South-Eastern France occurs in the extended fall season (Nuissier et al. 2008; Ribes et al. 2019). Thereby, data for this EPA between September and December (SOND) over the available COMEPHORE period 1997–2006 will be considered in Sects. 3.3 and 3.4.

2.5 Interpolation methods

In order to perform fair comparisons between the four datasets and to determine the CPRCM added value if there is one, we first interpolate all the datasets on common grids. Three grids have been defined so as to assess the model quality at the resolution of the CPRCM (2.5 km), at the resolution of the RCM (12.5 km) and also at a coarser resolution (50 km) typical of the current highest General Climate Model (GCM) resolution.

In this study, for interpolation on higher resolution grids, the algorithm used is based on triangulation with linear combination. This approach has three advantages:

- no artificial smoothing of input data (which could hide problems in the data);
- no overshoot (a positive field remains positive);
- a clean approach for masked interpolation (target grid land values come only from land points).

At any point M , the barycentric algorithm is based on:

$$OM = \alpha OA + \beta OB + \gamma OC$$

with α , β and γ being the barycentric coordinates of the triangle ABC and A , B and C points of the coarse source grid. The sum of the barycentric coordinates of the triangle ABC is 1 and these do not depend on O . If the point M of the high resolution grid is inside the triangle, the coefficients stay between 0 and 1, so that no overshoot can occur. If a point moves from one triangle to a neighboring one, there is no jump, because along a triangle side, the result depends only on the values at the two vertices.

For interpolation onto a coarser grid, the method used is “dual interpolation”. This method uses the neighbors and weights constructed for the barycentric interpolation from the target grid (the coarser grid) to the source grid (the fine grid). The interpolation is therefore an average of all source points inside a polygon centered at the target point. This polygon is based on the triangulation constructed when preparing the target-to-source interpolation.

3 Overall performance of both climate models

This section presents different comparisons between simulations of both models and reference observational datasets focusing on spatial pattern and Probability Distribution Function (PDF) over the EPA from on a seasonal to sub-daily scale.

3.1 Seasonal mean precipitation

During the fall, mean precipitation is strongly influenced by extremes in the region. Spatial distribution of the seasonal mean precipitation over an extended fall (SOND) is presented in Fig. 3 at three different resolutions (2.5, 12.5 and 50 km). Figure 3 shows a common high-precipitation pattern oriented South-West to North-East which corresponds to the South-Eastern slopes of Massif Central mountains where heavy precipitation occurs preferentially (Nuissier et al. 2011). This common pattern is also visible in SAFRAN (Fig. 3a, b), COMEPHORE (Fig. 3d, e), AROME (Fig. 3j, k) and

ALADIN-climate (Fig. 3g, h) at a resolution of 2.5 km and 12.5 km. At 50 km, this pattern is still discernible although attenuated due to the smoothed resolution. It does however correctly represent the area where HPES occur (Fig. 3c, f, i, l).

The comparison between both observational datasets shows that COMEPHORE and SAFRAN have very similar results except for the Cevennes mountain range, where the area corresponding to the highest average rainfall is larger in COMEPHORE than in SAFRAN. It is probably one of the consequences of the coarse resolution of SAFRAN and the inclusion of radar data into the COMEPHORE dataset.

Following on from this we calculate the spatial average of those values over the EPA domain (Fig. 2, land points only, Table 1). COMEPHORE and SAFRAN depict on average more precipitation than the two models. It is important to note that precipitation on mountainous areas with high altitude are underestimated in observation datasets as mentioned in the Sect. 2.2, due to the low quality of the radar data on high altitude, the kick off station measurements because some radar was installed during the period, and rain gauges data are also underestimated because of precipitation undercatch. These uncertainties in mountainous regions generally give reduced quality to observational data (Isotta et al. 2014; Prein et al. 2016).

Mean surface rainfall amounts of both models are weaker over plains than on the Massif Central slopes on every figure, in agreement with the observations. At 2.5 km, AROME shows in addition the four local precipitation peaks (in red on Fig. 3d, j) visible on the COMEPHORE map (Fig. 3d). These correspond to areas where rainfall is highest due to orographic forcing and appears to be realistic. On the spatial maps and using COMEPHORE as reference, AROME shows a clear added value with respect to the ALADIN-climate. This is the case for the three grid resolution showing in particular that CPRCM can add value not only on a small scale but also on the GCM scale. This added value is particularly clear over the Cevennes area. For the spatial maximum values of mean rainfall over the whole period, AROME is more realistic than ALADIN-climate (Table 1).

In conclusion, despite a mean value underestimation for models over the Massif Central mountain slopes in the Cevennes mountains, AROME shows an added value compared to the ALADIN-climate for seasonal mean precipitation. This added value can be considered as an up-scaled added value as AROME improves the spatial pattern of the long-term precipitation climatology (Berthou et al. 2018).

3.2 Daily extreme precipitation

Figures 4 and 5 show maps of daily quantiles of heavy (95th percentile) and extreme (99th percentile) precipitation for an extended fall (SOND) between 1997 and 2006 for the observation and model datasets.

Fig. 3 Spatial distribution of the seasonal-mean precipitation (mm/day) at three different resolutions (2.5 km, 12.5 km and 50 km) for SAFRAN (a–c), COMEPHORE (d–f), ALADIN-climate (g–i) and AROME (j–l) during an extended fall (SOND) between 1997 and 2006

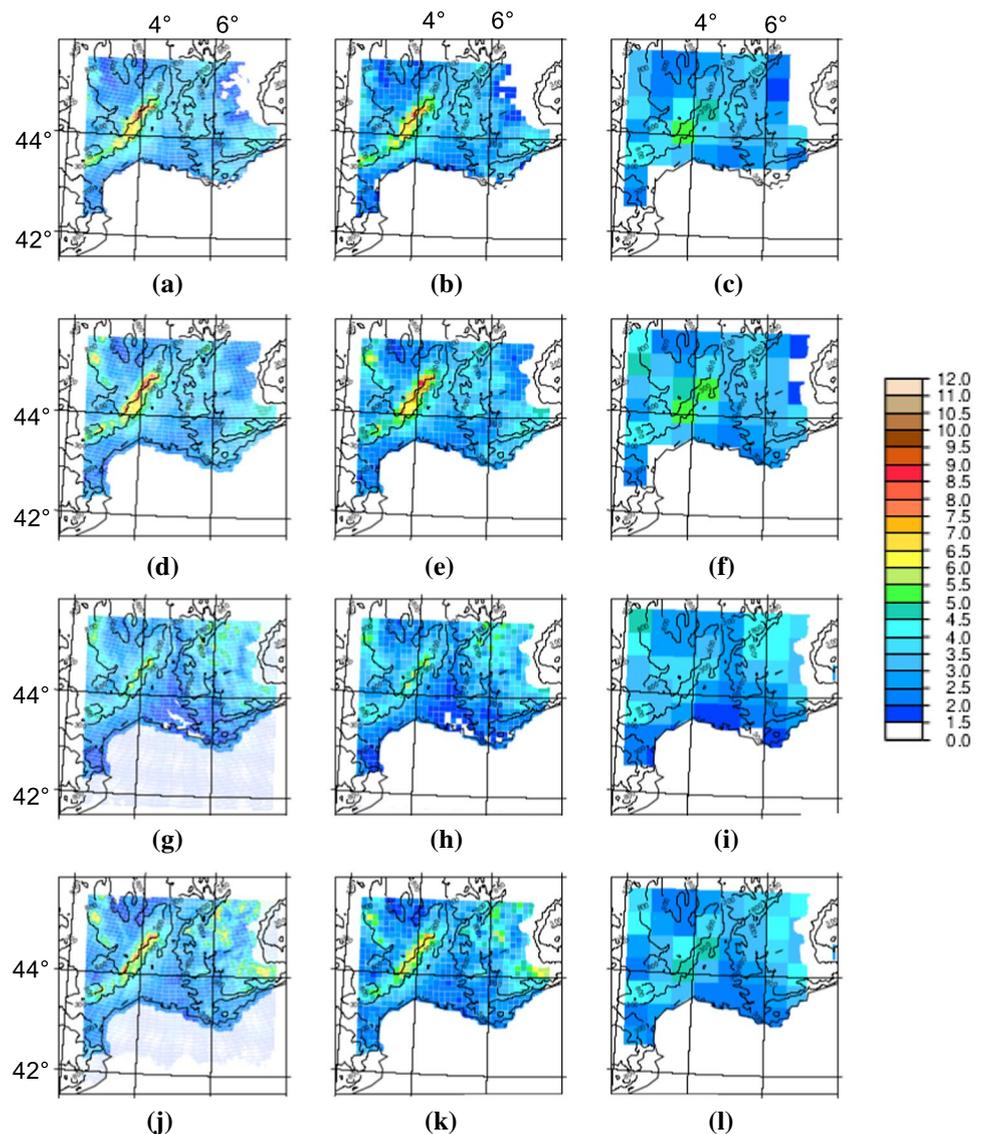


Table 1 Spatial mean and maximum values over the EPA of mean seasonal precipitation, 95th, 99th quantiles precipitation in mm/day for SAFRAN, COMEPHORE, ALADIN-climate and AROME at a 12.5 km resolution during an extended fall (SOND) between 1997 and 2006

	SAFRAN	COMEPHORE	ALADIN-climate	AROME
Mean of means	5.3	5.6	3.1	4.6
Max of means	9.1	10.3	6.5	8.4
Mean of Q95	21.7	23.7	16.8	20.1
Max of Q95	51.3	64.2	37.0	48.7
Mean of Q99	62.0	71.3	44.0	61.8
Max of Q99	137.9	172.5	89.3	130.6

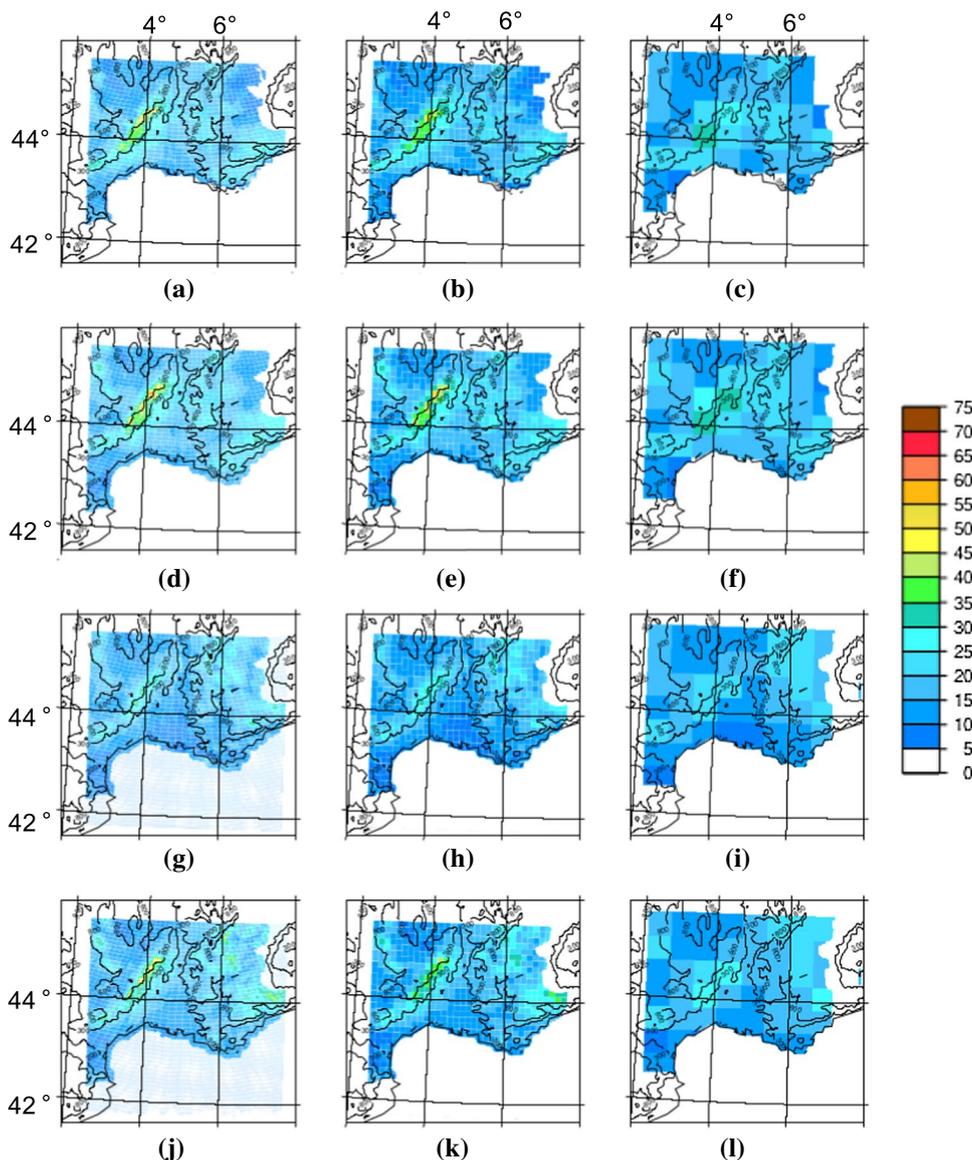
The same pattern oriented South-West to North-East is also observed with extreme daily precipitation. It is visible at the three resolutions and for the four datasets for

the 95th and the 99th quantile even if this pattern is more pronounced for very extreme daily rainfall.

Figures 4a–f and 5a–f show that both observation datasets present different values for the 95th and the 99th quantiles. Values are higher for the 99th quantiles. In fact, for the four datasets, there is more than two times more rainfall on average for the 99th quantile (Table 1). Moreover, for the maximum values of all datasets for the 95th and the 99th quantile, AROME simulates almost as much rainfall as SAFRAN (respectively 48.7 mm/day and 51.3 mm/day for the 95th and 130.6 mm/day and 137.9 mm/day for the 99th) while the values for COMEPHORE are higher (64.2 mm/day for the 95th and 172.5 mm/day for the 99th) and ALADIN-climate does not simulate enough rainfall (37 mm/day for the 95th and 89.3 mm/day for the 99th).

This is probably a consequence of the reanalysis processing of SAFRAN which may smooth the extreme values.

Fig. 4 Spatial distribution of the 95th quantile for daily precipitation (mm/d) at three different resolutions (2.5 km, 12.5 km and 50 km) for SAFRAN (a–c), COMEPHORE (d–f), ALADIN-climate (g–i) and AROME (j–l) during an extended fall (SOND) between 1997 and 2006



Moreover, SAFRAN and COMEPHORE have the same number of rain gauges for daily, but COMEPHORE also use hourly rainfall readings for a quarter of the rain gauges. This shows that it is more relevant to use COMEPHORE for the study of intense rainfall phenomena in France. Figures 4 and 5 also show that AROME is closer to COMEPHORE than ALADIN-climate for the representation of heavy and extreme daily precipitation. This added value is effective whatever the study grid.

3.3 Hourly extreme precipitation

During Mediterranean HPES, a substantial accumulation of surface precipitation can occur in a few hours and over very localized areas. COMEPHORE has an effective hourly temporal resolution allowing a better spatio-temporal representation of HPES compared to SAFRAN from which hourly precipitation

come from daily rainfall with a separation based on a climatological profile. The COMEPHORE observation database will therefore be the only one used for the study of sub-daily extreme rainfall.

We have seen previously that the study of precipitation at 50 km does not represent the fine scale location of HPES, so in the following, the study will focus on precipitation at 12.5 km and 2.5 km. For the sake of clarity, we have also decided that these data from both models will be compared at a resolution of 12.5 km (Fig. 6) whilst AROME will be also compared to COMEPHORE at a resolution of 2.5 km (Fig. 7) in order to take advantage of the high resolution of AROME and COMEPHORE.

The same pattern oriented South-West to North-East is once again observed with extreme hourly precipitation. This pattern is extended however to the southern plains of

Fig. 5 Spatial distribution of the 95th quantile for daily precipitation (mm/day) at three different resolutions (2.5 km, 12.5 km and 50 km) for SAFRAN (a–c), COMEPHORE (d–f), ALADIN-climate (g–i) and AROME (j–l) during an extended fall (SOND) between 1997 and 2006

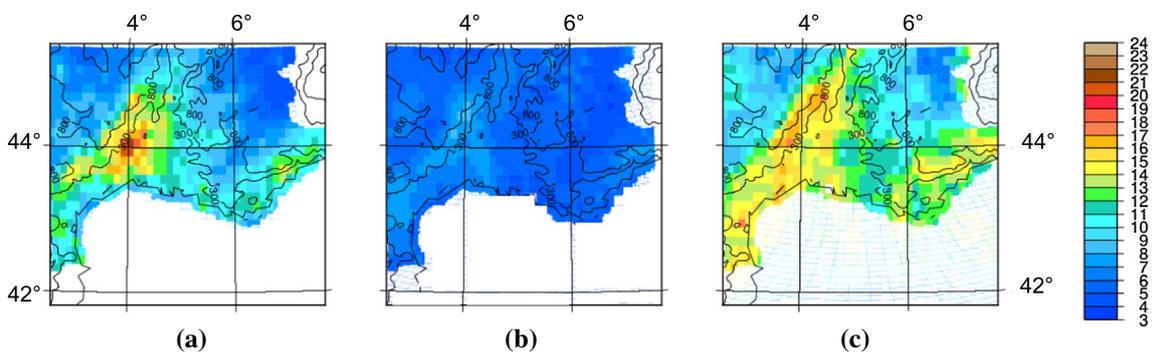
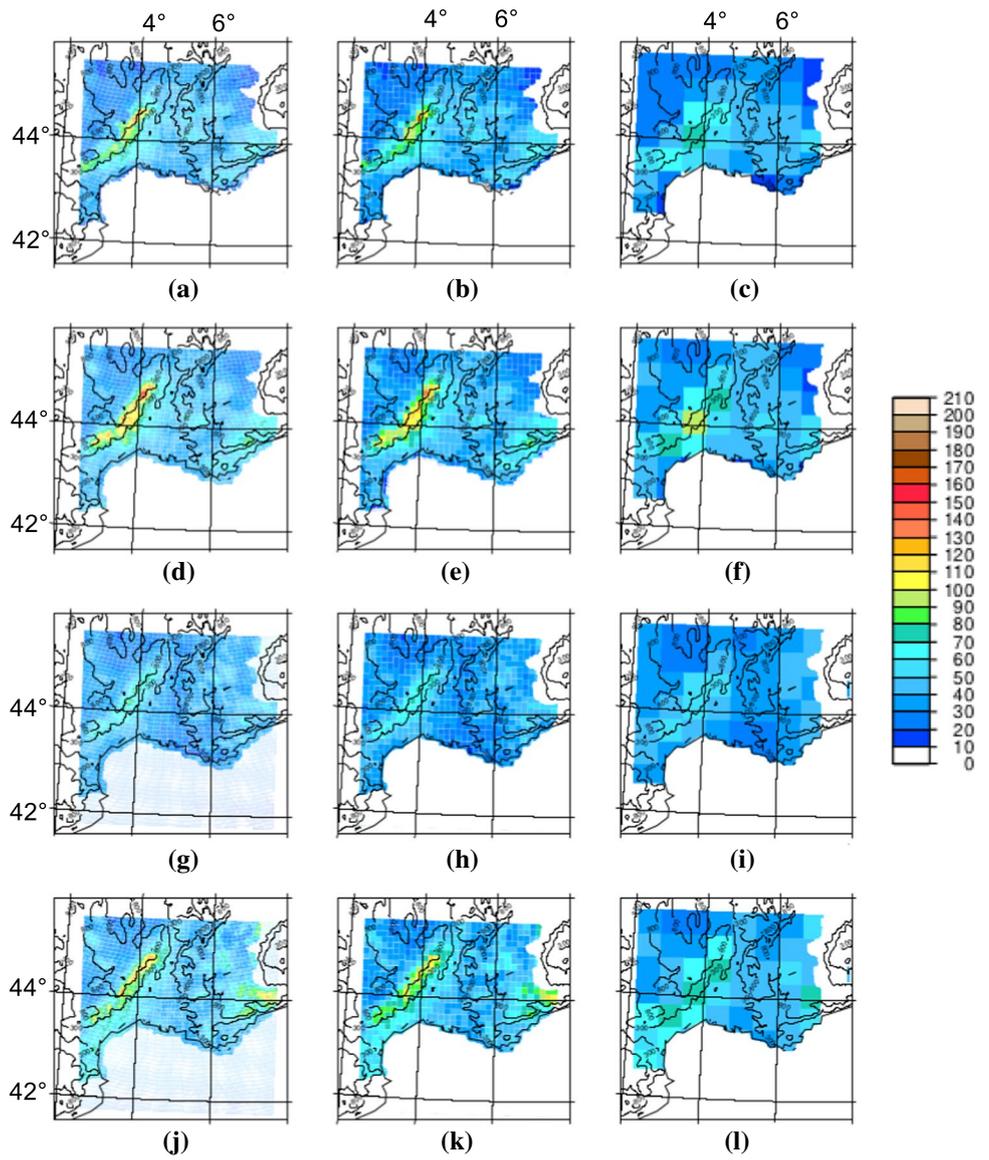


Fig. 6 Spatial distribution of the 99.9th quantile for hourly precipitation (mm/h) at 12.5 km for COMEPHORE (a), ALADIN-climate (b) and AROME (c) during an extended fall (SOND) between 1997 and 2006

Fig. 7 Spatial distribution of the 99.9th quantile for hourly precipitation (mm/day) at 2.5 km for COMEPHORE (a) and AROME (b) during an extended fall (SOND) between 1997 and 2006

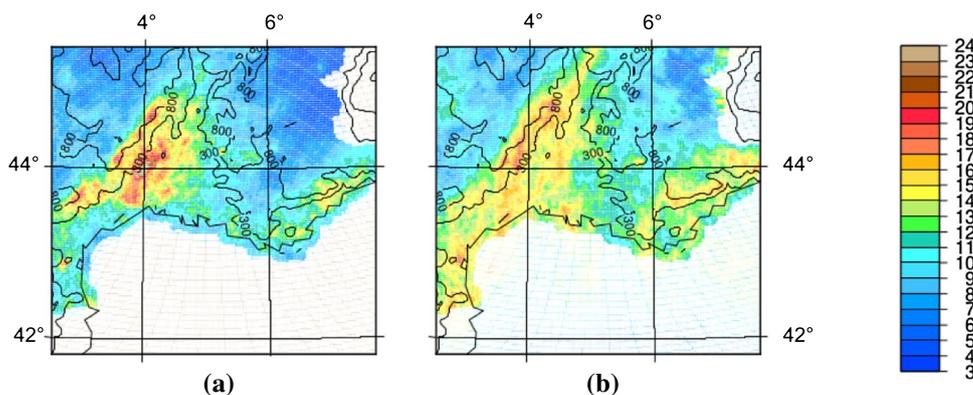


Table 2 Spatial mean and maximum values of the 99.9th quantiles of hourly precipitation and the absolute spatio-temporal maximum hourly values (mm/h) for COMEPHORE, ALADIN-Climate and AROME at a resolution of 12.5 km during an extended fall (SOND) between 1997 and 2006 across the EPA

	COMEPHORE	ALADIN-Climate	AROME
Mean of 99.9th quantiles	15.5	6.7	13.9
Max of 99.9th quantiles	22.9	10.9	20.3
Max	78.8	22.3	63.0

the Cevennes. In Figs. 6a and 7a, the maximum hourly precipitation is located on plains. This extension of the pattern is visible with AROME but not with the ALADIN-Climate. AROME simulates intense rainfall on plains but its hourly maximum is still located on the Cevennes mountains contrary to observations.

The study of hourly precipitation shows a clear added value on extreme hourly rainfall at 12.5 km (Fig. 6) with ALADIN-Climate strongly underestimating intense hourly rainfall. Table 2 shows the added value of AROME compared to ALADIN-Climate for the 99.9th quantile over the EPA. For the 99.9th quantile, mean and max precipitation of AROME over the EPA are twice as important as the precipitation of ALADIN-Climate. It is worth noting however that AROME extreme hourly precipitations are slightly underestimated.

The comparison between the 99.9th quantile of hourly precipitation simulated by AROME and observations shows new information in Figs. 6 and 7. Indeed, precipitation corresponding to the 99.9th quantile is not only localized on topography but also over low lands with AROME (Fig. 7a) as expected from COMEPHORE. This probably means that the mechanism of the low level cold pool resulting from the evaporation of precipitation falling under storms is fairly reproduced. However, AROME simulates too much rainfall on the Eastern Pyrenees and over the Southern Alps. AROME overestimates intense precipitation on low lands and this point will be addressed in the discussion section.

3.4 Cumulative Density Function (CDF)

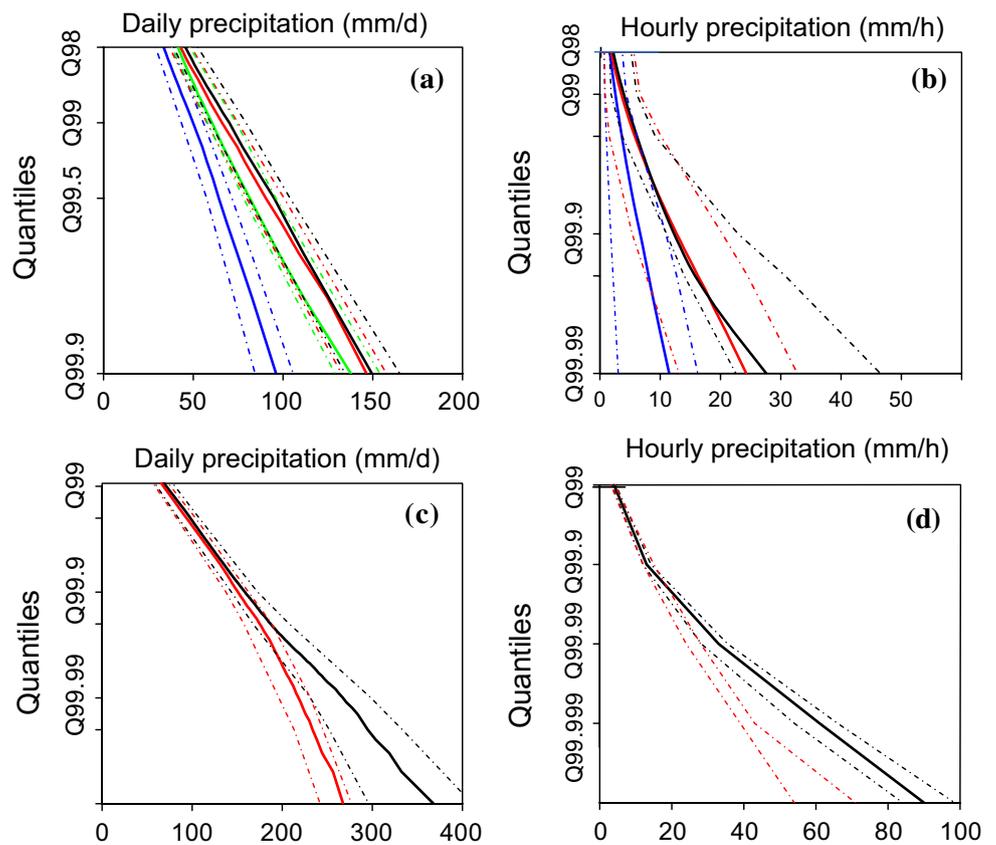
In order to focus on the greatest amount of precipitation, CDF of all datasets over the EPA during the same period of time (SOND, 1997–2006) will be analyzed forthwith. See Sect. 2.3.1 for a description of the EPA.

We use the bootstrapping technique to estimate a 90% uncertainty range around every quantile value (Efron and Tibshirani 1994). This consists of a random draw, 10 times, year by year during the 1997–2006 period with replacement. This 10-year draw is repeated 1000 times. The 5th and 95th percentile values of the distribution are calculated for each 10-year series in order to obtain a 90% confidence interval for each dataset. The bootstrapping technique is computed on both study grids (12.5 km and 2.5 km), so as to achieve a fair comparison between models and observations after the dataset interpolation step. The four datasets (COMEPHORE—1 km, SAFRAN—8 km, ALADIN-Climate—12.5 km and AROME—2.5 km) are first studied on the grid of ALADIN-Climate at 12.5 km (Fig. 8a, b). To assess thereafter the differences between AROME and COMEPHORE without losing the high resolution information, datasets are examined on the grid of AROME at a resolution of 2.5 km (Fig. 8c, d).

For daily precipitation on the 12.5 km grid (Fig. 8a), the CDFs of AROME and COMEPHORE match each other very well for every calculated quantile from the 98th quantile to the 99.9th quantile. On the contrary, ALADIN-Climate shows an underestimation from the 98th quantile (around 40 mm/day) that increases for higher quantiles.

The interpolation at 12.5 km of AROME and COMEPHORE leads however to a loss of information for the most extreme values in these datasets. If a 2.5 km comparison were therefore to be inaccurate for ALADIN-Climate, the comparison between AROME and COMEPHORE on the 2.5 km grid is relevant (Fig. 8c). Moreover, at this resolution, the EPA contains more points. This makes the study of more intense events possible with a lower probability proving rare at coarser resolutions. Precipitation in AROME and COMEPHORE is significantly different only for events with

Fig. 8 Tail of the Cumulative Density Functions (1-CDF) of daily rainfall **a, c** in mm/day and of hourly rainfall **(b, d)** in mm/h from all the grid points of the EPA during 10 extended fall (SOND) between 1997 and 2006; COMEPHORE (black), SAFRAN (green), ALADIN-Climate (blue) and AROME (red) (dotdashed lines correspond to the 90% confidence interval according to the bootstrapping method). Figures **a** and **b** represent the datasets at a resolution of 12.5 km (ALADIN-Climate grid) whilst figures **c** and **d** represent COMEPHORE and AROME datasets at a resolution of 2.5 km (AROME grid)



daily rainfall higher than 230 mm/day. This corresponds to an occurring probability of 0.0002 (4 events per year).

To conclude on the subject of daily precipitation, CDF resolution at 12.5 km shows a clear added value of AROME with respect to the ALADIN-Climate on daily upper quantiles, the more intense the HPES, the greater the difference between ALADIN-Climate and AROME. At 12.5 km, AROME is not significantly different from the observations. At 2.5 km, AROME is comparable to observations up to the 230 mm/day threshold.

For hourly precipitation on the 12.5 km grid (Fig. 8b), ALADIN-Climate is significantly different from COMEPHORE for values higher than 5 mm/h. At this resolution, differences between AROME and observations are not significant up to the 99.99th quantile (around 25 mm/h). At a resolution of 2.5 km (Fig. 8d), hourly precipitation of AROME are significantly different from the observations for events with hourly rainfall over 30 mm/h (5 events per year) but not significantly different below this threshold.

In addition to the added value of AROME for representation of daily rainfall with respect to ALADIN-Climate, we therefore confirm here its added value for the representation of very extreme and rare hourly rainfall events in the South-Eastern part of France.

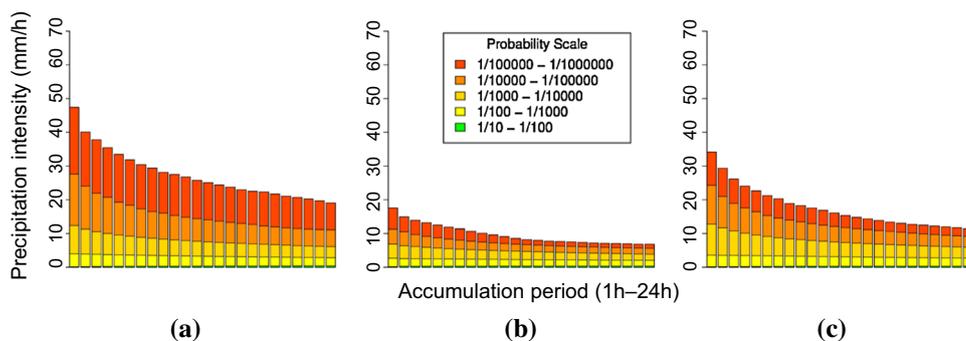
3.5 Relationship between duration and intensity

Probability Density Duration (PDD) histograms can be used to address relationships between the probability of occurrence and precipitation intensity for various accumulation periods (Kendon et al. 2014).

Here, PDD histograms (Fig. 9), in which all accumulations periods between 1 and 24 h can be seen as a generalization of the CDFs shown in Sect. 3.4. PDDs are based on hourly rainfall data from the three datasets (COMEPHORE, AROME and ALADIN-Climate) for the period between September and December 1997 to 2006, after interpolation on the 12.5 km grid. Each bar of the histograms has an hourly accumulation time ranging from 1 to 24 h and is divided into intervals of probability of the occurrence of the events. All values are expressed in mm/h.

The COMEPHORE histogram shows a precipitation peak for the shortest events. This indicates that intense precipitation usually occurs on a sub-daily scale. The AROME histogram reproduces this overall shape with underestimated precipitation values whatever the accumulation period. ALADIN-Climate shows the same behaviour as in AROME but with a larger underestimation during every accumulation period.

Fig. 9 Histograms of the relationship between the duration (in h) and intensity (in mm/h) of an event for COMEPHORE (a), ALADIN-Climate (b) and AROME (c) on the grid of the 12.5 km grid over the EPA, for an extended fall (SOND) between 1997 and 2006



During every accumulation period, AROME produces twice the amount of precipitation as ALADIN-Climate during heavy precipitating events and about 70% of observed precipitation. The analysis of the PDD confirms the added value of the AROME model compared with ALADIN-Climate in the simulation of heavy rains.

4 Discussion

The HPE in South-Eastern France are very localized and intense phenomena lasting a few hours. For the first time in this study, the hourly aspect of these phenomena is studied in a climate mode. We have shown that the hourly and daily precipitation of the AROME model is closer to the observations than the precipitation simulated by ALADIN-Climate. On one hand, this illustrates the added value of CPRCMS for phenomena never investigated before (Mediterranean HPES, fall season). On the other hand, it confirms the added value of CPRCMS in simulating hourly precipitation compared to the parameterized convection RCMS already obtained in other European regions such as Switzerland, Germany and the United Kingdom (Kendon et al. 2017; Fosser et al. 2015; Leutwyler et al. 2017; Berthou et al. 2018). It is beyond the scope of the current study to determine the reasons explaining this added value. Indeed, this would require climate scale sensitivity tests which are currently unaffordable from a computer cost point of view. We can however claim that the increase in resolution, the physical parameterizations of AROME and its explicit representation of deep convection probably play a role together in explaining this added value. Ducrocq et al. (2002) showed the added value resulting from an explicit convection and an increase in resolution. They reproduced a few cases of HPES with the same non-hydrostatic model (MESO-NH) at two different resolution, 2.5 km with an explicit convection and 10 km without a parameterized convection. The simulations with the highest resolution and the explicit convection simulated better HPES. Nevertheless, Vié et al. (2011) showed that the added value may also depend on how key processes (especially microphysics) are

parameterized in the model and it depends strongly on the meteorological conditions.

Our study shows that long-term high spatio-temporal resolution and high quality observation datasets are mandatory in order to prove the added value of CPRCMS. Such datasets, like COMEPHORE, are still rare even in Europe, one of the best observed areas in the world and it is worth noting that they can also suffer from deficiencies. In particular, there are two limits when it comes to the use of COMEPHORE. Precipitation in the Comephore database is of poorer quality at altitude. Precipitation in the high Alps are likely overestimated due to observations uncertainty. In the Alps, the overestimation is probably due to uncertainties of station measurements, precipitation undercatch and unreliable radar data in mountainous regions (Tabary et al. 2012; Prein et al. 2016). Then, radar coverage is not uniform on French territory during the 10-year period. Some radars have been functional after 1997 (Tabary et al. 2012), the Opoul radar in the Eastern-Pyrenees was installed during the study period, so observations on the extreme South-Western part of the study area are poorer in quality in the beginning of the period study. For the Cevennes mountain, the quality of COMEPHORE's radar data is good so we can say that the results on the Cevennes are robust.

In this study, AROME simulation is carried out over a relatively small domain but it covers the South-Eastern France and the neighbouring mountains as well as the upstream flow over the Mediterranean Sea regions triggering HPES. We focused on the center of the domain by excluding 30 points on each side in order to remove any potential boundary effect as suggested in Matte et al. (2017). In addition, an ongoing study (not shown) performed with AROME over the larger CORDEX-FPS convection domain (Coppola et al. 2019) shows that the size of the domain does not impact the results obtained above.

In Sect. 3.3, we showed that AROME overestimates intense precipitation over low lands. The version of AROME is the 38t1 described in Seity et al. (2011). This version of the model is known to simulate too much precipitation in convective systems (Malardel and Ricard 2015) which probably explains in part the overestimation of precipitation over

plains. A correction has been recently made to the AROME code to correct these phenomena in cycle 41 (Termonia et al. 2018), currently in use at CNRM in the CORDEX-FPS convection (Coppola et al. 2019).

5 Conclusion

10-year continuous simulations in climate mode are performed with two models, the parameterized convection Regional Climate Model (RCM) ALADIN-climate at a resolution of 12.5 km and the Convection-Permitting Regional Climate Model (CPRCM) CNRM-AROME at 2.5 km. These simulations are compared to a new reference dataset, COMEPHORE, blending station and radar data and available at 1 km and 1 h spatial and temporal resolution, respectively, for a 10-year period (1997–2006) over France. This new dataset has been compared to SAFRAN, the current reference observations dataset for France. SAFRAN and COMEPHORE show similar patterns for mean and extreme precipitation with significantly higher precipitation amounts however for daily extreme rainfall in the latter. Moreover COMEPHORE allows the studies of HPES on the hourly scale. The objective is to evaluate the distribution of daily and hourly precipitation and to show the added value of a CPRCM at 2.5 km resolution compared to a RCM at 12.5 km resolution. This study focuses in the Mediterranean France during the 4 fall months (SOND)

Mean rainfall are better represented with AROME. For precipitation with a threshold below 5 mm/h and 40 mm/day respectively, precipitation of AROME and ALADIN-climate approach the observations. Above those values, ALADIN-climate is unable to simulate the observed precipitation whereas AROME precipitation is still close to observations. This is verified with daily and hourly extreme precipitation. The study shows that AROME has a better ability to represent HPES with respect to ALADIN-climate in terms of frequency, intensity and also the location of extreme rainfall. Finally, for the rarest events with the highest cumulative precipitation in the COMEPHORE reference, AROME simulates high precipitation but is still somewhat underestimated (values above 230 mm/day and 30 mm/h).

This study shows the added value of the AROME CPRCM for extreme precipitation simulation compared with the ALADIN-climate parameterized convection RCM. In a completely new framework [new CPRCM and new RCM, new reference dataset, Mediterranean High Precipitation Events (HPES), fall season], this study confirms the results obtained in other contexts by UKMO and COSMO-CLM CPRCMS over other European regions. In particular, our study reinforces the proof of the added value of CPRCM with respect to 12.5 km RCMS used currently in CORDEX for extreme precipitation representation on daily and hourly scales (Leutwyler et al. 2017; Berthou et al. 2018).

The present study is the first step to proving the ability of AROME to properly simulate Mediterranean HPES in a climate mode. The issue of the evolution of Mediterranean HPES in future climate is currently being investigated in the framework of the FPS on convection and EUCP projects. The results will be reported in forthcoming publications.

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