Convective-scale and short-range predictability of high-impact weather events

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1 Introduction

The Western Europe is very prone to high-impact weather events such severe cyclogenesis during winter. Recently, this region was concerned by two extreme windstorm cases, Klaus and Xynthia, which occurred in Jan. 2009 and Feb. 2010, respectively. The western Mediterranean area is also frequently affected by disastrous flash-flood events generated by Heavy Precipitation Events (HPEs), particularly during autumn. In past decades, devastating flash floods have been responsible for many human casualties, and heavy damages. All of the coastal areas of the western Mediterranean region are concerned in particular the southeastern part of France (Fig. 1).

The ability to predict such dramatic events remains weak because of the contribution of very fine-scale processes and their non-linear interactions with the larger scale processes. Furthermore, for operational purpose, new generation of non-hydrostatic high-resolution numerical atmospheric models have been developed in the past years. Therefore, the realism of the precipitating systems has been significantly improved with these new-generation models due to a better representation of the water cycle processes and resolved deep convection. Moreover, the success of high-resolution models may however strongly depends on initial conditions. A large part of the uncertainties comes from the lack of assimilation of observations within the cloudy and precipitation areas. Data assimilation systems are currently biased towards observations in cloud-void areas. Development of mesoscale data assimilation, with emphasis put on assimilation of observations within cloudy and precipitating systems, is a promising lead of improvement. However, more faithful forecasts do not imply systematic improvement of deterministic quantitative precipitation forecasts. Atmosphere predictability is intrinsically limited by non-linearities and instabilities [*Lorenz*(1963)]. The loss of skill is caused by the rapid growth of small-amplitude perturbations, due to the lack of a precise knowledge of the atmospheric state at any time and location and model errors. Ensemble forecasting or ensemble simulations approaches are well known tools to estimate predictability. For a global medium-range EPS, methods to create perturbed initial states are well established and include singular vectors [1], breeding modes [*Toth and Kalnay*(1997)], and the use of randomly perturbed observations in the assimilation cycle [*Houtekamer et al.*(1996)].

However, methods for generating ensembles used for estimating synoptic- and sub-synoptic-scale predictability are not fully relevant for short-range forecasts at convective-scale using non-hydrostatic high-resolution models. Strong non-linear physics at smaller-scale, different behaviours in sensitivity to initial conditions and a substantial computing time cost for the model forecast call for development of dedicated ensemble generation methods. The goal of this research topic is to quantify and rate the different uncertainty sources and assess the meteorological processes that govern convective-scale predictability of intense events. For that purpose, methods using data assimilation techniques and approach of generation of ensembles are designed and evaluated.

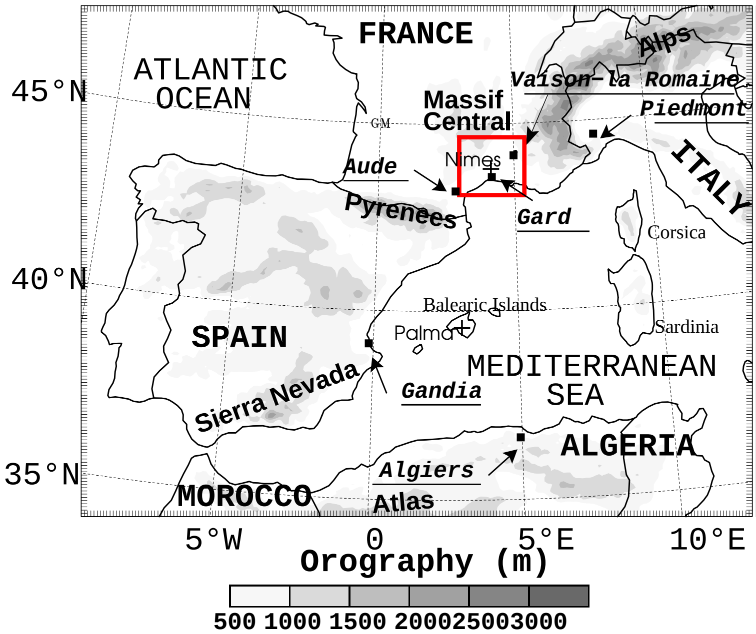

FIG. 1: *Topography (10 km resolution) of the western Mediterranean region (from [Nuissier et al.(2008)].*

2 Impact of model parameterizations and physical processes

In this section the impact of model parameterizations and physical processes are illustatred through the case of a windstorm (Xynthia) and a case of HPE in Sept. 2002 over Southern France.
Xynthia was a severe windstorm which crossed Western Europe between 27 Feb. and 1 Mar. 2010. It reached a minimum pressure of 967 mb on 27 Feb. Xynthia caused numerous damages and killed at least 60 people, with the hardest hit in France. Xynthia entered in France through the Pyrenees on 27 Feb 2010 in a general southerly flow (Fig. 2), inducing very strong winds over the Pyrénées-Atlantiques, the Hautes-Pyrénées and the Haute-Garonne. The strong winds were located not only on the peaks (238 km/h at Pic du Midi), but also in the valleys, as in Luchon where a human death occurred.
The non-hydrostatic numerical atmospheric AROME model predicted the event with a good accuracy in terms of location and gust intensities, reproducing a band of strong winds along Pyrenees downstream on the northern side, up to Pyrenees foothills. The model clearly shows trapped orographic waves (Fig. 3a), and their presence is confirmed by the Lannemezan lidar. These trapped waves, characterized by an energy propagating vertically and horizontally downstream, contribute to enhance the low level winds (Fig. 3b), and are associated with non hydrostatic processes. Indeed, the AROME simulation in the hydrostatic version does not reproduce the trapped waves guide (Fig. 3c), and therefore the downstream low level winds are reduced (Fig. 3d), and the storm winds are underestimated.

Other convective-scale physical processes can be very crucial and have a strong impact on high-resolution forecasts, especially for heavy precipitation. On 8-9 Sept. 2002, a major Mesoscale Convective System (MCS) affected the southeastern region of Massif Central in France named Cévennes-Vivarais (the Gard region). 24 people were killed during this event and the economic damage was estimated at 1.2 billion euros. The Gard precipitation event was an exceptional one due to many factors. Firstly, the intensity of the event was extreme with more than 600 mm in 24 hours and a large area was affected by precipita-

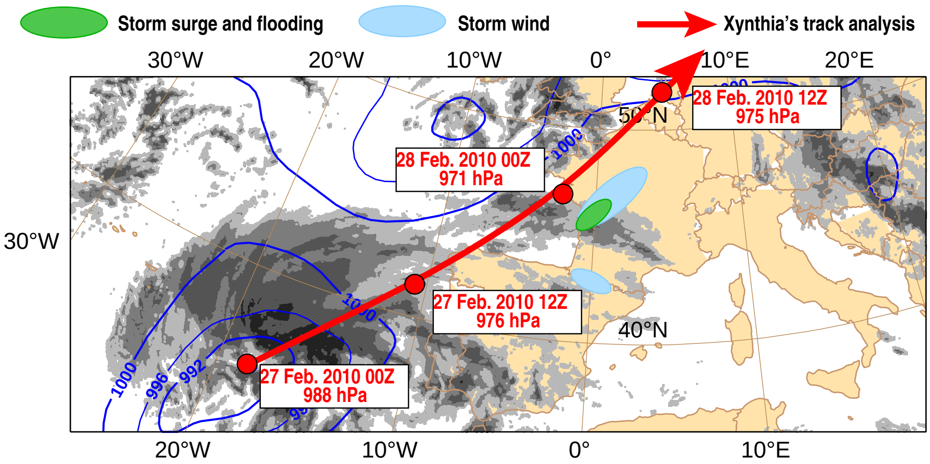

FIG. 2: *METEOSAT infrared brightness temperatures and ARPEGE analysis in terms of mean sea level pressure (blue) 27 Feb. 2010 at 00 UTC*

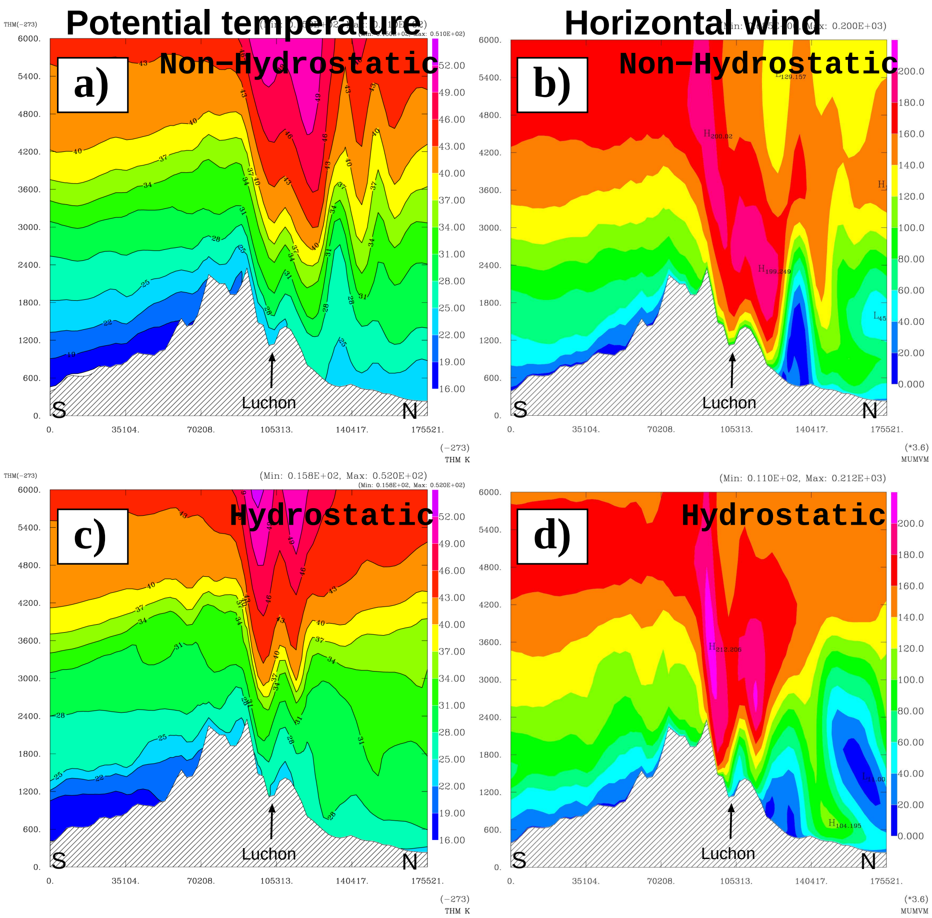

FIG. 3: *Vertical cross section along the South-North axis on 27 Feb. 2010 at 21 UTC of :* **a)** *potential temperature simulated by AROME in the Non Hydrostatic version,* **b)** *horizontal wind magnitude simulated by AROME in the Non Hydrostatic version,* **c)** *potential temperature simulated by AROME in the Hydrostatic version and* **d)** *horizontal wind magnitude simulated by AROME in the Hydrostatic version, respectively (Courtesy of C. Lac).*

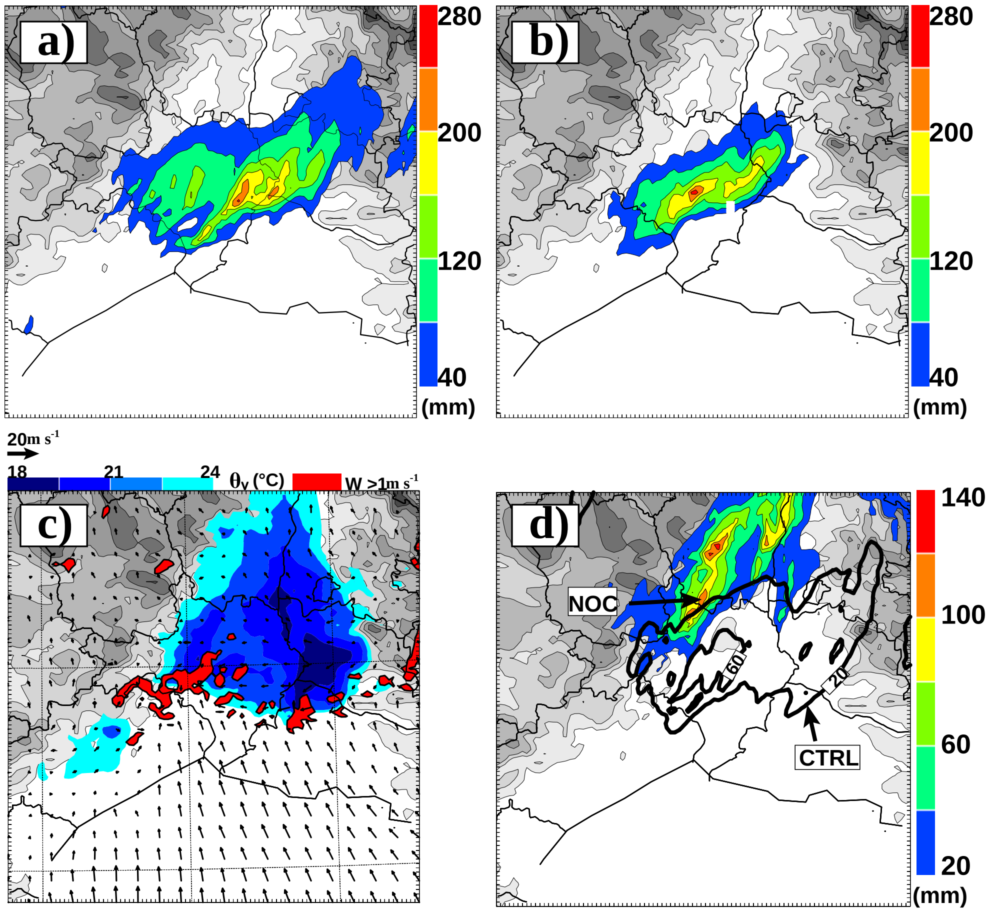

FIG. 4: **a)** *Simulated accumulated rainfall from 12 to 22 UTC, 8 Sept. 2002.* **b)** *Rainfall observation for the same period. Panel* **c)** *shows the virtual potential temperature at 30 m AGL (colour) and 10 m AGL wind (arrows). Finally, panel* **d)** *displays NOC (without evaporative cooling of liquid water, colour) and CTRL (bold contours) experiments, respectively. The area shown here is the same than the red box represented in Fig. 1.*

tion exceeding 200 mm over the same period. Secondly, the heaviest precipitation was located upstream over the plains just north of the city of Nîmes (see also Fig. 1 for location), i.e. a rather unusual location according to climatology. Convective-scale numerical experiments performed with a mesoscale data analysis show that the Meso-NH model can reproduce and forecast significant rainfall amounts associated with a convective system with a quasi-stationary behaviour, in good agreement with observations (Fig. 4a and b). A Low-Level Cold Pool (LLCP) is analysed forming just under the simulated MCS and is clearly visible through the low values of virtual potential temperature θ_v (about 4-5 ˚C lower than the environment). This LLCP is the result of evaporation of precipitation falling in the lower troposphere and it blocks the warm and moist low-level jet and pushes the deep convection upstream (Fig. 4c). In order to assess the role of this LLCP on the MCS stationarity, a sensitivity experiment has been performed in which diabatic effect (evaporative cooling of liquid water) is removed (NOC experiment). Figure 4d shows the simulated MCS in NOC to lose its stationarity over the Gard plains and the resulting precipitation pattern is significantly shifted northwestwards over the Massif central foothills.

3 Impact of meso-scale initial conditions

The success of high-resolution models strongly depends on mesoscale initial conditions. A large part of the uncertainties comes from the lack of assimilation of observations within the cloudy and precipitation areas. Data assimilation systems are currently biased towards observations in cloud-void areas. Development of mesoscale data assimilation, with emphasis put on assimilation of observations within cloudy and precipitating systems, is a promising lead of improvement.
Since December 2008, a new-generation of Numerical Weather Prediction (NWP) system at convective scale is operationally running at Météo-France. This system, called AROME, covers the French territory with a 2.5-km horizontal resolution ([*Seity et al.*(2010)]). Its main goals are to improve the local meteorological forecast of potentially dangerous convective events (storms, unexpected floods, wind bursts, etc.) and of low-level tropospheric meteorological parameters (wind, temperature, turbulence, visibility, etc.). AROME is a Cloud Resolving Model (CRM) which uses the physical parameterizations from the non-hydrostatic Meso-NH model [*Lafore et al.*(1998)] that allows in particular to resolve deep convection and a representation of the microphysical processes within clouds thanks to a 6-water species microphysical parameterization. The AROME data assimilation system uses a rapid forward intermittent assimilation cycle with a 3-hourly data analysis frequency, using a three dimensional variational data assimilation (3Dvar) system at 2.5-km resolution. Among many other observation types (from ground based measurements to satellite radiances), AROME assimilates radial velocities and reflectivities coming from observations of the ARAMIS radar network over a wide part France [*Montmerle and Faccani*(2009)] ; [*Caumont et al*(2010)].
Figure 5 shows an example of the good impact of the assimilation of radar reflectivity on a 3-hour forecast of a squall line on the South East of France on 8 Oct. 2008. The experiment assimilating radar reflectivities displays an increased positive specific humidity increment (more moisture) where the convective system is actually observed and strong negative increment (drying) in front of the deep convection (fig. 5b and c). The benefit of radar reflectivity assimilation for this case is a better handle of the intensity and eastward propagation of the convective line (Fig. 5e and f).
Despite the fact that cloud-resolving non-hydrostatic models are able to simulate very realistic features of heavy precipitation events (improvement of mesoscale initial conditions), there are still uncertainties of which it is necessary to assess the impact. Ensemble forecasts are one approach to quantify the uncertainties of such hydrometeorological forecasts.

4 EPS approach for hydrometeorological forecasts

The aim of this part of this study is to develop dedicated methods of generation of ensembles to quantify the convective-scale predictability of AROME forecasts. For that purpose the study first examines in a quite separated way the uncertainty at synoptic-scale on both initial and lateral boundary conditions and on the other hand the uncertainty on mesoscale initial conditions. Both approaches are presented in Fig. 6. To take into consideration the sources of uncertainty impacting high-resolution forecasts, ensemble simulations are performed using the AROME model. The uncertainty at synoptic-scale on both initial and lateral boundary conditions is given by the Météo-France's large-scale ensemble forecasting system PEARP (*AROME-PEARP*). Error on mesoscale initial state is represented from experiments assimilating randomly perturbed observations (*AROME-PERTOBS*). An other ensemble combines both previous sources of uncertainty (*AROME-COMB*).

Ensembles are evaluated over a one month- period encompassing HPEs. Calculated probabilistic scores (ROC) show a fair resolution and the ability of these forecast systems to discriminate between precipitation event occurrences and non-occurrences (Fig. 7a and b). Moreover, the mesoscale perturbations have their maximum impact at very short-range, whereas the influence of synoptic-scale uncertainty becomes significant beyond 12h (Fig. 7c and f). More details on these results can be found in [*Vi et al*(2010)].

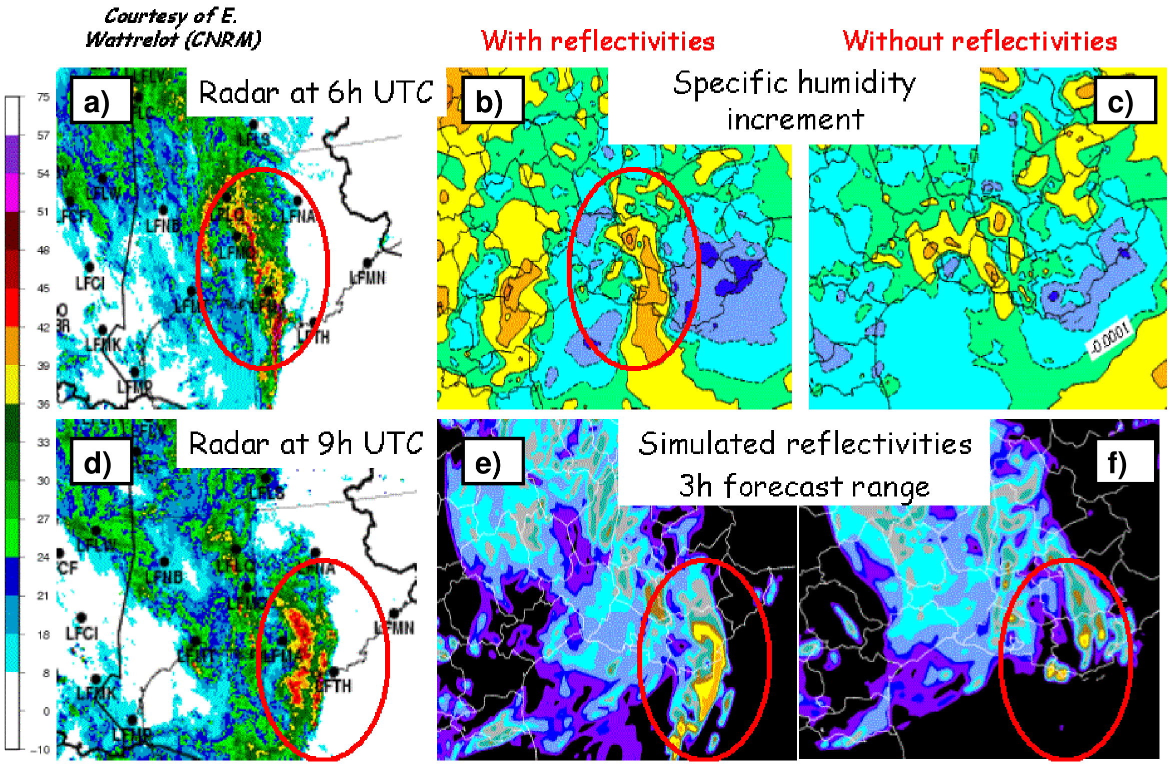

FIG. 5: *a) and d) Observed radar reflectivities on 8 Oct. 2008 at 06 UTC and 09 UTC, respectively.* **b)** *and* **c)** *Specific humidity increment for analysis with reflectivities and without reflectivities, respectively.* **e)** *and* **f)** *Simulated radar reflectivities from AROME valid for 8 Oct. 2008 at 09 UTC (Courtesy of E. Wattrelot).*

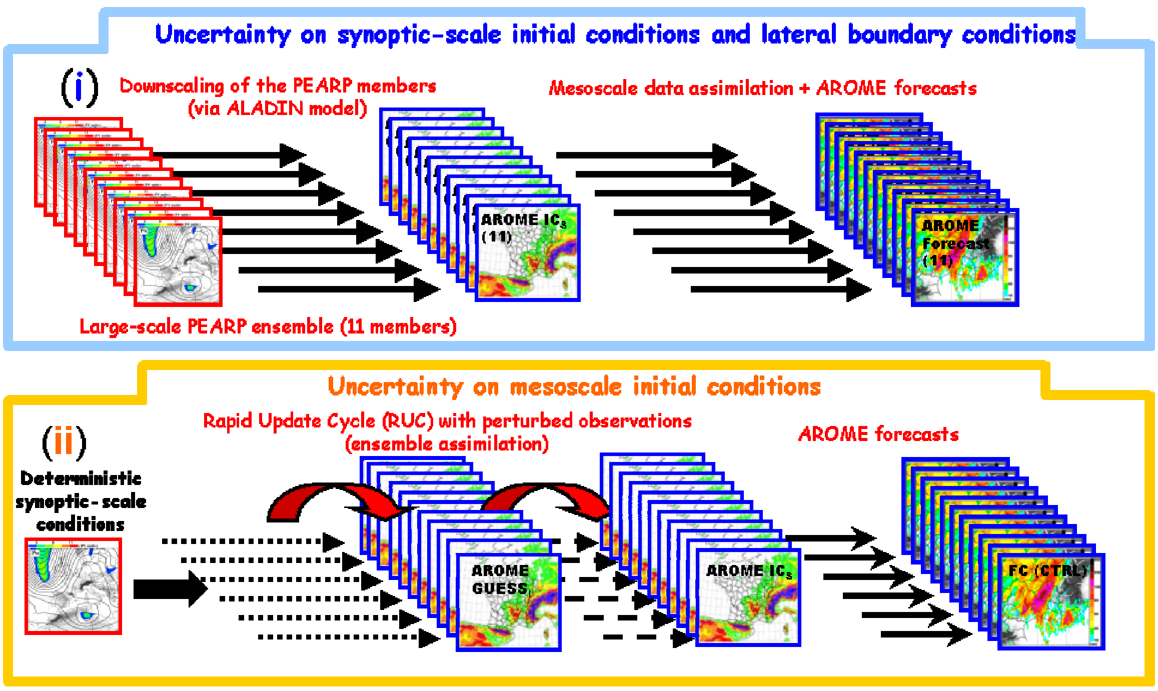

FIG. 6: *General overview of the approach to take into account the uncertainty on synoptic-scale initial conditions and lateral boundary conditions in a first hand, and the uncertainty on meso-scale initial conditions in a second one.*

In order to further investigate the propagation of rainfall forecast uncertainties in the hydrological model, the quantitative precipitation forecasts from the atmospheric ensemble are used to drive the ISBA-TOPMODEL. Figure 8l shows the discharges simulated by ISBA-TOPMODEL using *AROME-PEARP* hourly rainfall ensemble members on 1 Nov. 2008 at 12 UTC (Fig. 8a to k). The ensemble spread between quantiles $q_0.25$ and $q_0.75$ of the members is also represented in Fig. 8l.

For the case of Boucoiran watershed presented here, the median of the members is generally closer to the observations than the simulation driven by the AROME deterministic operational forecast. Both the median and the ensemble spread simulate a flood peak, and this shows that this probabilistic approach introduces a valuable information compared to the deterministic one [*Vincendon et al*(2010)].

An other alternative method is also designed and evaluated directly introducing some perturbations in the AROME rainfall fields to obtain relevant ensemble spread (not shown here). Further verification on a larger size sample of flash-flood cases is needed to confirm these promising results. The observing periods of the HyMeX field experiment (http ://www.hymex.org) will be also a test-bed for evaluating these methods in a real-time framework.

5 Synthesis

The are several benefits of using non-hydrostatic mesoscale numerical models to simulate and forecast intense events. For instance, the fine-scale AROME model was able to reproduce the strong winds associated with the windstorm Xynthia. A non-hydrostatic numerical tool such AROME was crucial to better forecast Xynthia, since there were important non-hydrostatic processes through trapped gravity waves which contributed to enhance the low-level wind. For heavy precipitation, high-resolution and sometimes explicit parameterization of microphysical processes (evaporative cooling under storms) are crucial for better forecasts.
Convective-scale assimilation of non-conventional data (Doppler velocities and reflectivities) is useful to improve mesoscale initial conditions for heavy precipitation. The general benefit of the analysis appears during the first 12-h forecast ranges, then lateral conditions mostly take over the model solution. However, despite realistic and improved high-resolution forecasts, convective-scale ensemble forecasts are needed to assess predictability.
An ensemble simulation approach can be used to assess and quantify the uncertainty on synoptic-scale initial conditions and lateral boundary conditions in a first hand, and mesoscale initial conditions in the other one. Convective-scale ensemble experiments have been performed, either coupling AROME with global PEARP ensemble, or doing convective-scale assimilation cycles of perturbed observations in AROME 3D-Var. It has been shown that the meso-scale perturbations have their maximum impact at very short-range, whereas the influence of synoptic-scale uncertainty becomes significant beyond 12h.

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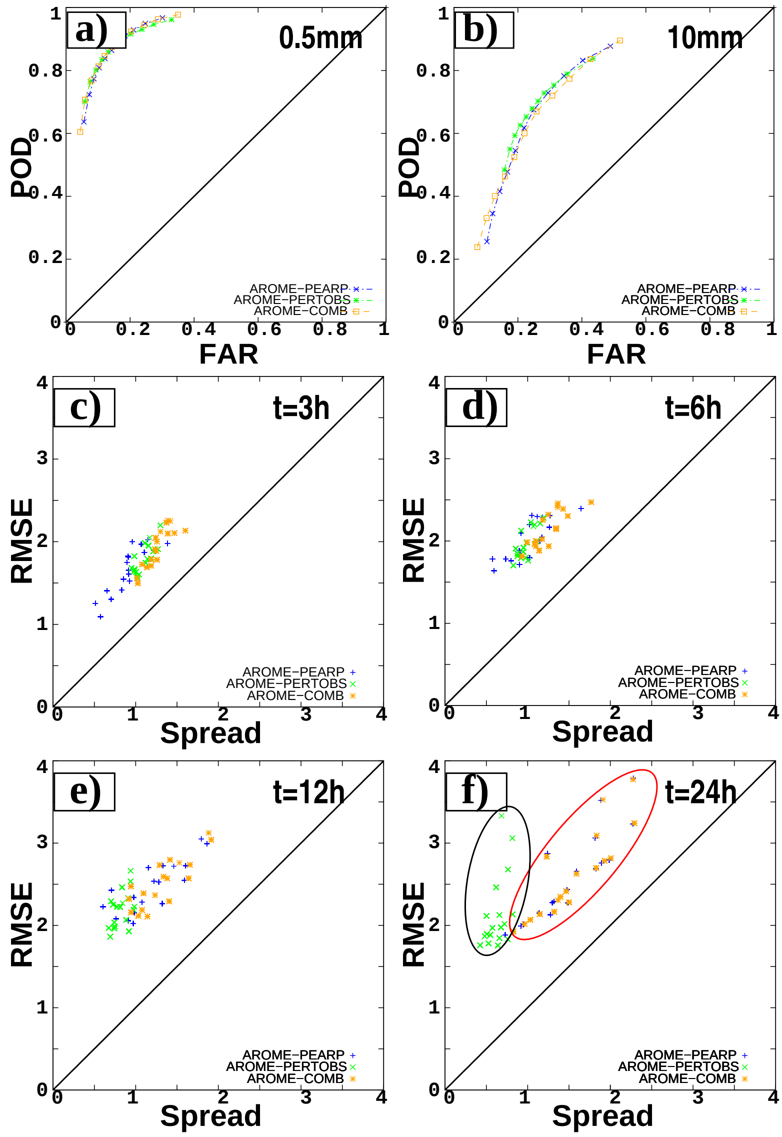

FIG. 7: *ROC (Relative Operating Characteristics) scores calculated for the 24h-accumulated rainfall and for thresholds of :* **a)** *rain- no rain 0.5 mm and* **b)** *10 mm. Panels* **c)**, **d)**, **e)** *et* **f)** *stand for the root mean squared error as a function of the mean ensemble spread for wind at 925 hPa. The quality of a forecast system is estimated by the area under the ROC curve, the larger the area the better the quality (or resolution). Each symbol represents one day in the period.*

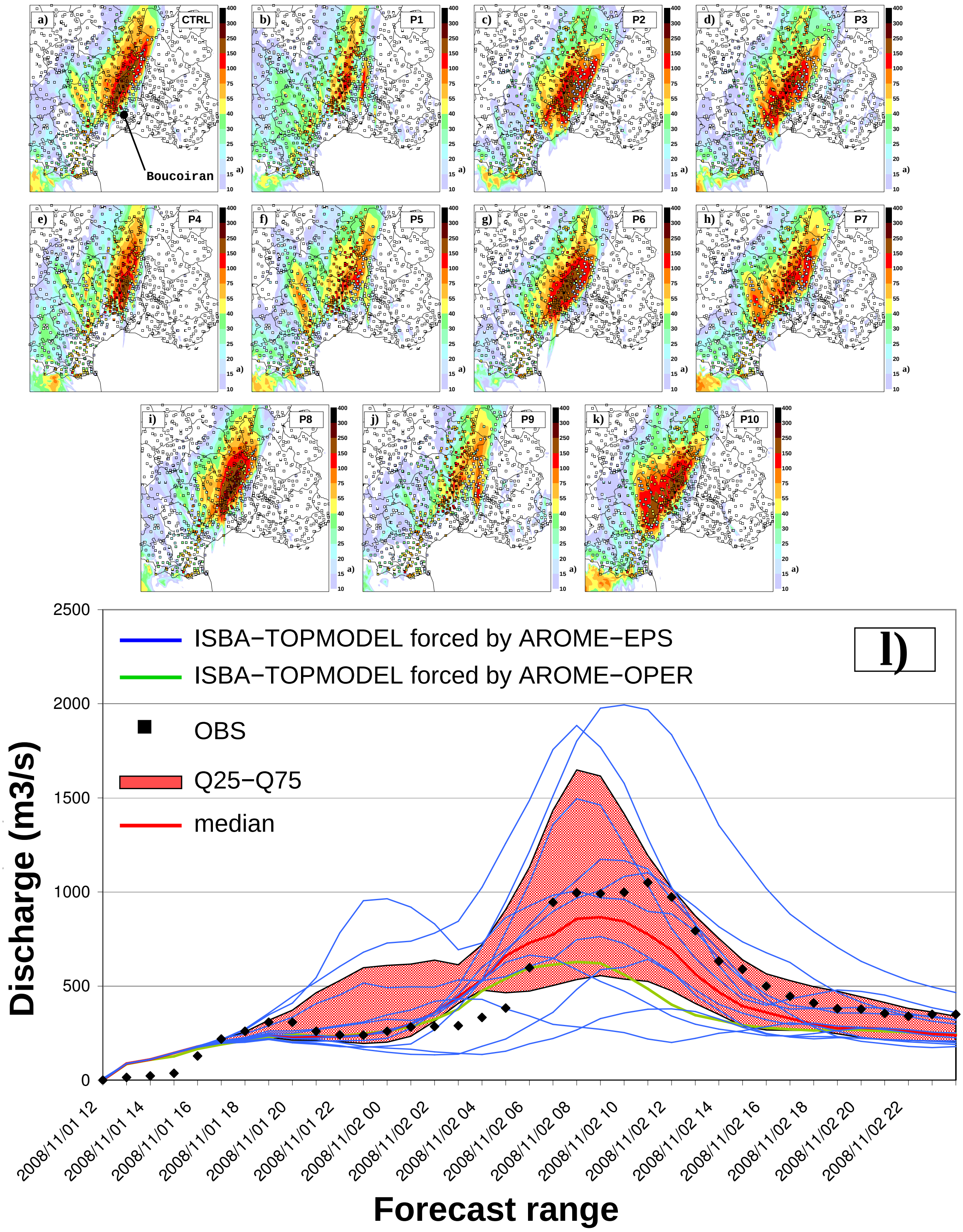

FIG. 8: *24-h simulated accumulated rainfall from AROME-PEARP ensemble (panels* **a)**, **b)**, **c)**, **d)**, **e)**, **f)**, **g)**, **h)**, **i)**, **j)** *and* **k)**. *Panel* **l)** *shows the streamflow ensemble forecasts obtained coupling the AROME ensemble with ISBA-TOPMODEL. The simulated discharges (m^3/s) are estimated at the outlet of Boucoiran watershed. The deterministic AROME forecast is the green line wheras observations are represented with squares (Courtesy of V. Vincendon for* **l)**.

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