Hydrology and Earth System Sciences Discussions

A flood episode in Northern Italy: multi-model and single-model mesoscale meteorological ensembles for hydrological predictions

S. Davolio[1], M. M. Miglietta[2], T. Diomede[3], C. Marsigli[3], and A. Montani[3]

[1]Institute of Atmospheric Sciences and Climate, National Research Council, Bologna, Italy
[2]Institute of Atmospheric Sciences and Climate, National Research Council, Lecce, Italy
[3]HydroMeteoClimate Regional Service of ARPA Emilia Romagna, Bologna, Italy

Correspondence to: S. Davolio (s.davolio@isac.cnr.it)

Abstract

Numerical weather prediction models can be coupled with hydrological models to generate streamflow forecasts. Several ensemble approaches have been recently developed in order to take into account the different sources of errors and provide probabilistic forecasts feeding a flood forecasting system. Within this framework, the present study aims at comparing two high-resolution limited-area meteorological ensembles, covering short and medium range, obtained via different methodologies, but implemented with similar number of members, horizontal resolution (about 7 km), and driving global ensemble prediction system. The former is a multi-model ensemble, based on three mesoscale models (BOLAM, COSMO, and WRF), while the latter, following a single-model approach, is the operational ensemble forecasting system developed within the COSMO consortium, COSMO-LEPS (Limited-area Ensemble Prediction System).

The meteorological models are coupled with a distributed rainfall-runoff model (TOPKAPI) to simulate the discharge of the Reno River (Northern Italy), for a recent severe weather episode affecting Northern Apennines. The evaluation of the ensemble systems is performed both from a meteorological perspective over the entire Northern Italy and in terms of discharge prediction over the Reno River basin during two periods of heavy precipitation between 29 November and 2 December 2008. For each period, ensemble performance has been compared at two different forecast ranges.

It is found that both mesoscale model ensembles remarkably outperform the global ensemble for application at basin scale as the horizontal resolution plays a relevant role in modulating the precipitation distribution. Moreover, the multi-model ensemble provides more informative probabilistic predictions with respect to COSMO-LEPS, since it is characterized by a larger spread especially at short lead times. A thorough analysis of the multi-model results shows that this behaviour is due to the different characteristics of the involved meteorological models and represents the added value of the multi-model approach.

Finally, a different behaviour comes out at different forecast ranges. For short ranges, the impact of boundary conditions is weaker and the spread can be mainly attributed to the different characteristics of the models. At longer forecast ranges, the similar behaviour of the multi-model members, forced by the same large scale conditions, indicates that the systems are governed mainly by the large scale boundary conditions.

1 Introduction

Coupling Numerical Weather Prediction (NWP) and hydrological models is an essential practise in order to generate short- to medium-range hydrological forecasts. Moreover, it is certainly a necessary step for implementing an early warning system suitable for a medium-sized catchment (1000–10 000 km^2): prediction of the hydrological response of these river basins, characterized by complex orography and short response times, aims at providing timely forecasts and adequate emergency planning, thus can not rely on observed precipitation, but needs an alternative forcing function available at earlier times (Melone et al., 2005), that is meteorological forecast fields.

The provision of accurate streamflow forecasts, especially in case of flood events, represents a major research and operational challenge (Rotach et al., 2012). In such an effort, early warning systems have been developed, based on coupled state-of-the-art meteorological and hydrological models. When data from different model simulations are combined, such systems provide different scenarios and valuable probabilistic information that acknowledges the different sources of errors affecting the meteo-hydrological forecasting chains.

Although each component of the system is affected by its source of error, the available literature (Krzysztofowicz, 1999; Hapuarachchi et al., 2011; Zappa et al., 2011) seems inclined to indicate that the uncertainty affecting Quantitative Precipitation Forecasting (QPF) is dominant. Recently, the hydrological model uncertainty was estimated to be ten times less pronounced than the uncertainty from rainfall forecasts (Zappa et al., 2011). Errors in QPF arise from uncertainties in the initial (and
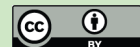
boundary) conditions and in the models formulation, growing during the forecasting process and propagating from atmospheric (rainfall) to hydrological (runoff) predictions (Zappa et al., 2010).

Considering such problems, the main efforts for the improvement of discharge pre-
5   diction have been devoted to: (i) development of NWP models, i.e. increasing their resolution and improving the representation of the relevant physical processes in order to attain better rainfall forecast skill (Weusthoff et al., 2010; Bauer et al., 2011), especially at the small scales that are particularly relevant for hydrological applications; (ii) development of meteorological ensemble prediction systems, which represent a suitable
10 way to cope and deal with uncertainties, as they provide probabilistic forecasts that represent an attractive product to be used for flood predictions. Cuo et al. (2011) provide an overarching review of this topic and an up-to-date description of the main open issues related to integrated meteo-hydrological forecasting systems.

Ensemble prediction is a well-established practise for global meteorological models,
15 initiated in the 90's, since it proved to provide greater forecast skill than any single deterministic prediction (Buizza, 2008). Perturbed initial conditions, generated using either singular vectors (Palmer et al., 1997), bred vectors (Toth and Kalnay, 1997), perturbed observations in multiple data assimilation cycles (Houtekamer et al., 1996), or Ensemble Transform Kalman Filter (Wei et al., 2006), were employed to initialize a number of
20 different forecasts, which form all together an ensemble prediction system (EPS). More recently, multi-analysis and multi-model procedures, obtained by combining different ensemble systems, each based on a different NWP model, proved to be even more skilful (Mylne et al., 2002; Bowler et al., 2008), thus leading to the implementation of super-ensembles (Krishnamurti et al., 1999; Park et al., 2008) and to specific inter-
25 national initiatives, such as TIGGE (THORPEX Interactive Grand Global Ensemble; Bougeault et al., 2010) programme.

EPS forecasts have been used as an input for hydrological models (Gouweleeuw et al., 2005; Hamil et al., 2005; Hou et al., 2007; Thielen et al., 2009; Rotach et al., 2012), thus propagating the meteorological uncertainty along the flood forecasting

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

| ◄◄ | ►► |
| ◄ | ► |

| Back | Close |

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

system (Pappenberger et al., 2005) in order to provide a probabilistic and more informative hydrological prediction. Recently, there is a general agreement on the benefit of using ensemble forecasting for early flood warning applications. However, although representing a progress with respect to a deterministic approach, EPSs based on global models suffer from their coarse spatial resolution and often turned out to be not accurate enough for basin-scale applications, especially in areas characterized by complex orography. In response to such a limitation, during the last decade different ensemble approaches based on limited area models (LAMs) have been developed (Marsigli, 2009; Garcia-Moya et al., 2011; Iversen et al., 2011; Montani et al., 2011) sometimes involving convection-permitting models (Davolio et al., 2008; Gebhardt et al., 2011). This kind of limited-area ensemble prediction systems (LEPSs), that have recently become operational in several centres, basically perform a dynamical downscaling of global EPSs and represent the state-of-the-art for meteo-hydrological forecasting applications (Cloke and Pappenberger, 2009; Adams and Ostrowsky, 2010; Addor et al., 2011), suitable especially for risk-related events. During MAP-DPHASE (Rotach et al., 2009), the forecasters appreciated the availability of ensemble information much more than being provided with a plethora of different models. Apparently, the usual probabilistic output (probability maps, etc.), as provided by ensemble modelling systems, meets their needs (Rotach et al., 2012).

However, the accurate description of analysis and model uncertainties at the mesoscale is still an open issue and the research is still far from assessing an optimal way for providing perturbed initial and boundary conditions to LAM ensembles (Marsigli et al., 2012). New methods of combining different LEPSs in a multi-model system are being developed; in particular, multi-analysis multi-model approaches seem able to provide a suitable way to describe the uncertainties affecting the forecasting system. Considering the entire meteo-hydrological chain, the lack of theoretical development supporting strategies for flood forecasting leaves room for testing ad hoc methodologies on a case by case basis (Cloke and Pappenberger, 2009).

Within this framework, in the present study two different multi-analysis ensemble approaches, both focused on the short-to-medium range, are compared: a multi-model ensemble, based on three LAMs developed independently, and a single-model ensemble. Both ensembles receive initial and boundary conditions from a limited number of members selected among the whole European Centre for Medium-range Weather Forecasts (ECMWF) global EPS through a clustering analysis. In order to allow a fair comparison, the two ensembles were implemented with a similar set up. The ensemble implementation is described in detail in Sect. 2, together with models and clustering procedure description. Both the ensembles have been used to generate probabilistic precipitation maps, analysed in Sect. 3, and to provide the input fields to the same hydrological model. The results, in terms of discharge prediction, are presented in Sect. 4 and allow to evaluate the ensembles performance in a recent severe weather episode affecting the Reno River basin, located in Northern Italy (Fig. 1) in the Apennines. The multi-model ensemble is further analysed in Sect. 5, while Sect. 6 is devoted to concluding remarks.

2 Numerical models and ensembles generation

The poor man's multi-model ensemble implemented here is based on three mesoscale models, BOLAM, COSMO and WRF, briefly described in the following, while the single-model approach is based on the COSMO model only (COSMO-LEPS ensemble). The two ensembles have been implemented with almost the same characteristics, such as the number of members, the model horizontal resolution (about 7–8 km), the driving global EPS (Table 1). Also, the integration domains (Fig. 1) are very similar, although the grid points are not exactly coincident. In the present section, a short description of the numerical models and of the ensembles is provided.

2.1 BOLAM

BOLAM (BOlogna Limited Area Model; Davolio et al., 2008) is a hydrostatic, primitive equation meteorological model with prognostic variables distributed on a non-uniformly spaced Lorenz grid. The horizontal discretization uses geographical coordinates, with latitudinal rotation on the Arakawa C-grid. BOLAM uses a hybrid vertical coordinate system, in which the terrain-following sigma coordinate gradually tends to a pressure coordinate with increasing height above the ground, and with the relaxing factor prescribed as a function of the maximum orographic height present in the domain. The model implements a Weighted Average Flux scheme for the three dimensional advection. The temporal integration scheme is split-explicit, forward-backward for the gravity modes. The lateral boundary conditions are imposed using a relaxation scheme that minimises wave energy reflection. The water cycle for stratiform precipitation is described by means of five additional prognostic variables: cloud ice, cloud water, rain, snow, graupel. Deep convection is parameterized using the Kain-Fritsch (Kain, 2004) convective scheme. The surface and boundary layer parameterization is based on the E-l approximation, in which turbulent kinetic energy is predicted explicitly (Zampieri et al., 2005). A four-layer soil scheme is implemented for the computation of surface balances, heat and water vertical transfer, vegetation effects at the surface and in the soil, taking into account different soil types and physical parameters. The radiation is computed with a combined application of the Geleyn's scheme (Ritter and Geleyn, 1992) and the ECMWF scheme.

2.2 COSMO

COSMO model (http://www.cosmo-model.org/; Steppeler et al., 2003) is the non-hydrostatic limited-area model of the COSMO Consortium, designed for both operational NWP and various scientific applications on the meso-β and meso-γ scale. COSMO is based on the primitive thermo-hydrodynamical equations describing compressible flow in a moist atmosphere without any scale approximation. The basic

equations are written in advection form and the continuity equation is replaced by a prognostic equation for the perturbation pressure. The model equations are solved numerically using the traditional finite difference method. A basic state, represented by a time-independent dry atmosphere at rest, is subtracted from the equations to re-duce numerical errors associated with the calculation of the pressure gradient force in case of sloping coordinate surfaces. The model equations are formulated in rotated geographical coordinates and a generalized terrain following height coordinate.

The parameterization schemes used operationally are: δ-two stream radiation scheme of Ritter and Geleyn (1992) for short- and long-wave fluxes, with full cloud-radiation feedback; Tiedtke (1989) mass-flux convection scheme with equilibrium clo-sure based on moisture convergence; precipitation formation with a bulk microphysics parameterization including water vapour, cloud water, cloud ice, rain and snow with 3-D transport for the precipitating phases; prognostic turbulent kinetic energy closure at level 2.5; multi-layer version of the Jacobsen and Heise soil model.

2.3 WRF

The Weather Research and Forecasting (WRF) model (see http://www.wrf-model.org; Skamarock et al., 2008) is a numerical weather prediction system that solves the fully compressible, nonhydrostatic Euler equations. The model uses the terrain-following, hydrostatic-pressure vertical coordinate with vertical grid stretching. The prognostic equations are cast in conservative (flux-) form for conserved variables, while non-conserved variables like pressure and temperature are diagnosed from prognostic con-served variables. The horizontal grid is Arakawa-C.

WRF offers multiple options for physics parameterization schemes that can be se-lected based on the specific problem that is investigated. In the present model con-figuration (version ARW-3.1), the following schemes have been chosen: Thompson et al. (2004) microphysics, which includes six classes of moisture species plus num-ber concentration for ice as prognostic variables; Kain (2004) cumulus parameteriza-tion; Rapid Radiative Transfer Model for longwave radiation and Dudhia (1989) scheme

A flood episode in Northern Italy

S. Davolio et al.

for shortwave radiation; a turbulent kinetic energy closure, the Mellor–Yamada–Janjíc scheme, for the boundary layer; the Noah land-surface model.

2.4 Ensemble systems: COSMO-LEPS and multi-model

COSMO-LEPS is the mesoscale limited-area ensemble developed and implemented by ARPA-SIMC in the framework of the COSMO Consortium and running operationally at ECMWF since November 2002 (Montani et al., 2011). The ensemble is based on 16 runs of the COSMO model and was designed for high-resolution probabilistic forecasts in the short and medium range (up to day 5). The ensemble is generated from the global ECMWF EPS (Molteni et al., 2001) and combines the forecast potential of a high-resolution non-hydrostatic limited-area model with the probabilistic information of the ensemble approach. Due to the constraints on the computational resources, the COSMO-LEPS methodology reduces the number of global-ensemble elements driving the limited-area runs, but still keeps a large fraction of the driving-ensemble information. Specifically, the cluster analysis is performed on 102 members of two successive ECMWF EPS runs (00:00 and 12:00 UTC of day d), since each EPS consists of one control run plus 50 perturbed members. Then, EPS members are grouped into 16 clusters, following a cluster analysis (see Montani et al., 2011, for details). Cluster analysis is performed over the area shown in Fig. 1. From each cluster, a representative member (RM) is selected, which provides initial and boundary conditions to each COSMO model run. Moreover, for each COSMO-LEPS run the procedure chooses randomly either Kain-Fritsch or Tiedtke convection scheme, and perturbs turbulence schemes and other physics parameterization schemes randomly.

The same clustering procedure described above is applied again for selecting 5 RMs in order to drive the multi-model forecasting system. Since the results of the cluster analysis are different from that for COSMO-LEPS, different initial/boundary conditions may force the two ensembles. For each initialization time, the multi-model is therefore based on 5 forecasts issued by each implemented LAM, producing 15 forecasts overall.

Summarizing, the main difference between the two ensembles resides mainly in the relative importance which has been attributed to the representation of the boundary condition error with respect to that of the LAM error. For the single-model ensemble, the same LAM has been run 16 times receiving initial and boundary conditions from 16 selected members of the ECMWF EPS, while for the multi-model ensemble, only 5 EPS members have been selected out of the EPS, but 3 different LAMs have been run on each EPS member. Both ensemble systems are integrated in time for 132 h, and three initialization times 24 h apart have been selected: 12:00 UTC of three consecutive days, 26, 27 and 28 November 2008. Hourly rainfall fields produced by the two ensemble systems are provided to the same hydrological model TOPKAPI in order to produce ensemble discharge forecasts.

2.5 Hydrological model: TOPKAPI

The streamflow predictions are provided by TOPKAPI (TOPographic Kinematic AP-proximation and Integration) (Todini and Ciarapica, 2002), a distributed rainfall-runoff model. TOPKAPI couples the kinematic approach with the topography of the catch-ment and transfers the rainfall-runoff processes into three "structurally-similar" zero-dimensional non-linear reservoir equations. Three equations, which derive from the in-tegration in space of the non-linear kinematic wave model describe the drainage in the soil, the overland flow on saturated or impervious soils and the channel flow, respec-tively. The parameters of the model are shown to be scale independent and obtainable from digital elevation maps (DEM), soil maps and vegetation or land-use maps in terms of slopes, soil permeabilities, topology and surface roughness. Land cover, soil proper-ties and channel characteristics are assigned to each grid cell that represents a com-putational node for the mass and the momentum balances. The flow paths and slopes are defined starting from the DEM, according to a neighbourhood relationship based on the principle of minimum energy. The evapo-transpiration is taken into account as water loss, subtracted from the soil water balance. This loss can be a known quan-tity, if available, or it can be calculated using temperature data and other topographic,

geographic and climatic information. The snow accumulation and melting component is driven by a radiation estimate based upon air temperature measurements. A detailed description can be found in Liu and Todini (2002).

The calibration and validation procedures of TOPKAPI over the Reno River basin are based on an hourly meteo-hydrological dataset available from 1990 to 2000. TOPKAPI is currently used for the real-time flood forecasting system operational at ARPA-SIMC.

3 Meteorological analysis

3.1 Case study

The severe weather period between 29 November and 2 December 2008 was characterized by the presence of a deep cold trough over the Western Mediterranean Sea (Fig. 2) in the middle troposphere. This synoptic configuration was associated with a cyclonic circulation affecting all Western and Northern Europe, driving several frontal systems towards the Italian Peninsula. The presence of a blocking anticyclone located over Eastern Europe, together with the highly meridional flow along the western side of the trough, maintained the synoptic situation nearly unchanged for several days. Intense warm and moist south-westerly flow on the eastern side of the trough, impinging on the Northern Apennines, was responsible for severe weather and heavy precipitation in the area. In particular, two periods of intense precipitation (Fig. 3), during the nights of 29 November and in a 24 h period between 30 November and 1 December produced two relevant discharge peaks of the Reno River, a medium-sized catchment (total dimension about 5000 km^2), whose upstream portion (about 1000 km^2) belongs to the north-eastern slopes of the Northern Apennines. The Reno River basin has been studied in the past (Davolio et al., 2008; Diomede et al., 2008) and was the subject of investigation in several European research projects in relation to the application of real time flood forecasting systems. In both periods of heavy rainfall analysed in the present study, the warning threshold was exceeded at the closure section of the mountain

portion of the Reno catchment, Casalecchio Chiusa, characterized by a concentration time of about 10–12 h. In the operational practice, a flood event at such river section is defined when the water level, recorded by the gauge station, reaches or overcomes the value of 1.6 m (corresponding to a discharge value of about 630 $m^3 s^{-1}$). This value represents the warning threshold, while the alarm level is set to 2.5 m (corresponding to a discharge value of about 1480 $m^3 s^{-1}$).

3.2 Ensemble results: probability of precipitation

The evaluation of the ensemble systems is firstly performed from a meteorological perspective over an area larger than the single catchment (e.g. entire Northern Italy). The attention is focused on the two periods of intense precipitation: 6 h between 29 November, 18:00 UTC and 30 November, 00:00 UTC, and 24 h between 30 November, 12:00 UTC and 1 December, 12:00 UTC. Moreover, for sake of brevity, only the simulations starting on 26 and 28 November are thoroughly analysed and discussed: thus, for each period, ensemble performance will be compared at two different forecast ranges. For reference, global EPS results are also shown. They refer to the operational ECMWF ensemble, composed of 51 members, run at a horizontal spectral resolution T_L 399 (about 50 km).

During the 29 November, intense precipitation in excess of 20 mm/6 h (Fig. 3) affected the whole Northern Apennines (with peaks close to 100 mm/6 h, locally) and also some Alpine areas. Results of the two LEPSs and the global EPS, in terms of probability maps of occurrence of precipitation exceeding 20 mm/6 h, are shown in Fig. 4, for two different forecast lead times. At longer range (78–84 h; initialization time 12:00 UTC, 26 November), the global EPS does not provide any indication of intense precipitation over the Reno basin, but only over Western Apennines (probability up to 60 %). On the other hand, both LEPSs forecast some probability of rainfall (up to 60 % for the multi-model, 30 % for COSMO-LEPS) over the Reno River basin. Moreover, only the multi-model provides a signal also over the Central Alps, where precipitation did occur. Similarly, for shorter forecast range (30–36 h; initialization time 12:00 UTC,

28 November), only the two LEPSs are able to forecast the possible occurrence of intense precipitation (up to 90 %) over the target basin. Very high probability is assigned to intense rainfall over Western Apennines and the Alpine chain by all the prediction systems, with a progressively increasing probability with shorter lead times, thus im-
5 proving the confidence in the prediction as the event approaches. It is worth noting that, in the multi-model forecasts, broader areas are indicated as possibly affected by heavy precipitation, showing more uncertainty in the forecast. In this case, the greater degree of diversity among the multi-model members represents an additional value, since the estimated uncertainty turns out to be more able to include the observed sce-
10 narios, especially at longer forecast ranges. If such a diversity is representative of the meteorological (and hence discharge) uncertainty, it provides a useful information to support civil protection authorities in their decisions.

Similar results have been obtained for the second period of intense precipitation. However, in this case, a longer interval of time has been considered, 24 h instead
15 of 6 h. This was chosen since the observed rainfall lasts for a longer period, and for accounting some timing errors that were evident in the precipitation forecasts, due to the much longer forecast ranges. The threshold has been increased accordingly from 20 mm/6h to 50 mm/24 h. Rainfall exceeding this threshold (Fig. 3) affected both the Apennines and the Alps. A probability, although quite low, of intense precipitation is
20 forecast by both the ensembles, five days in advance (Fig. 5). However, only the multi-model and, only partially, COSMO-LEPS are able to provide a warning for possible intense precipitation over the Reno River basin. Approaching the event, the pattern of rainfall probability does not change significantly and still the multi-model forecasts intense rainfall over the Reno basin, with a probability ranging between 30 and 60 %.
25 While the multi-model identifies the Reno River basin as an area likely to be affected by intense precipitation more than three days in advance, the global EPS probability maps provide no evidence of heavy rainfall there, even at short forecast range. This result confirms that structural global model deficiencies, that is the low resolution and consequently the coarse orography representation, pose a limit to this kind

of ensemble approach at such scales. Higher resolution models are needed at basin scale for medium-sized watershed, thus explaining the remarkable added value of LAM ensembles with respect to global ensembles for hydrological applications.

4 Hydrological predictions

The two intense precipitation events generated two relevant and distinct discharge peaks in the Reno basin (Fig. 6 top), both exceeding the warning threshold, but not reaching the alarm level. The river discharge started to increase rapidly during the night of 29 November, reaching a maximum of almost $900\,\mathrm{m^3\,s^{-1}}$ at 06:00 UTC, 30 November. A second peak, of the same magnitude but characterized by a less steep increase of water level, occurred in the morning of 1 December. The discharge computed using raingauges data, spatially distributed using the Thiessen Polygons method (Diomede et al., 2008), is in good agreement with the observation at the basin closure, thus indicating that the error ascribable to the hydrological model is reasonably limited.

The ensemble discharge forecasts are strongly related to the results shown in the maps of probability of precipitation. Indeed, at longer forecast range (forecasts initialized on 26 November), discharge predictions driven by the global EPS fails to generate any relevant peak, while those driven by both LEPSs are remarkably better (Fig. 6, top panels). Although underestimated in magnitude, the possible occurrence of high discharge peaks is forecast respectively four and five days ahead by both LEPSs, thus their operational use would have provided a useful indication of the potential severity of the events to the civil protection authorities. In particular, at these long forecast ranges, some members of the multi-model exceed the warning threshold, thus providing a correct warning and an informative prediction to the forecaster. Furthermore, a reasonable reproduction of the two-peak structure is provided by some members. Also COSMO-LEPS displays some relevant peaks, although the warning level is not reached and the timing is affected by larger uncertainty.

A flood episode in Northern Italy

S. Davolio et al.

Even at shorter forecast ranges (initialization date 28 November), up to respectively two and three days in advance, LEPSs remarkably outperform the global EPS (Fig. 6, bottom panels). With respect to the long forecast range results, the intensity and the timing of the two events predicted by LEPSs at short range are generally better repro-
5 duced. Among the ensemble systems, the discharges obtained with the multi-model display a larger spread among the members and a more accurate prediction, especially concerning the second peak. Also, the hydrological predictions driven by COSMO LEPS provide some hints of the occurrence of two peaks, although underestimating their magnitude. On the other hand, the flood event is still missed using the global
10 EPS.

Although improving the hydrological forecasts with respect to the system driven by the global ensemble, in general both LEPSs underestimate the discharge peaks, which is particularly evident if some parameters of the ensemble distribution, such as the mean and 90-percentile, are considered (Fig. 6, magenta and green curves). However,
15 these curves do not account for the whole information conveyed by the ensemble and the forecaster should look also at the "spaghetti plot" of the LEPS. The discharge forecasts producing the highest discharge peaks permit to take into account also the most dangerous, although less probable, scenarios.

By analysing each curve of the multi-model ensemble forecasts at long range (Fig. 7),
20 it is possible to recognize that the highest peaks are associated with mesoscale forecasts driven by the same global ensemble representative members (namely, members 3, 35 and 36 of the EPS). It means that for longer lead times (more than 3 days) the behaviour of the different members of the multi-model is dominated by the boundary condition forcing (although the intensity of the peak is significantly different among the
25 models). This is not true for shorter forecast ranges (not shown), where it is not possible to identify the same clear correspondence between discharge forecasts and driving representative members. In this case, the impact of boundary conditions is weaker and the spread is reasonably ascribable to the characteristics of the single models of the ensemble.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

5   Further considerations on multi-model performance

In the present specific application, the multi-model ensemble performs better than the other systems, since it is characterized by a larger spread at short-range with respect to COSMO LEPS, i.e. it provides a more reliable estimation of the meteorological uncertainty, and the predicted precipitation produces more accurate hydrological forecasts. However, to provide some support to these conclusions and to investigate in more detail the behaviour of the multi-model ensemble, a further meteorological analysis is performed. In the following, the attention is thus focused on the multi-model results, and the precipitation fields forecast by its single members are shown for different lead times. Only the first period of intense precipitation (night of 29 November, Fig. 3) is considered, since it allows to analyse the forecasts behaviour at both short- (+36 h) and long-range (+84 h).

At longer forecast range (simulations initialized at 12:00 UTC, 26 November), the rainfall fields (Fig. 8) show a pretty large variability among the five forecasts issued by the same model. At the same time, switching from a model to the other, the precipitation patterns remain similar among the forecasts driven by the same global representative member. In particular, although in a qualitatively way, it is quite simple to identify that the worst forecast for each of the three LAMs is always the forecast driven by the same global representative member (m12) (Fig. 8, second panel of each row). The three mesoscale predictions that use the initial and boundary conditions provided by this representative member are affected by a remarkable underestimation of the precipitation all over the displayed domain, both over the Apennines and over the Alps, missing completely the heavy precipitation over Northern Italy and the Reno basin.

A straightforward explanation of the LAM forecast failure may be found comparing the large scale fields of the m12 forecast (that drives the LAM predictions) with the ECMWF analysis, both at 18:00 UTC, 29 November 2008, corresponding to the beginning of the heavy rainfall period (Fig. 9). Indeed, the geopotential field at 500 hPa of the m12 simulation presents a remarkable and evident error, displaying a westerly

and slightly anti-cyclonic mid-tropospheric flow over Northern Italy and in particular over the Apennines, instead of the observed south-westerly flow, typically harbinger of heavy precipitation in the target area. Also the forecast temperature field in the lower layer does not agree with the analysis. Being driven by a forecast characterized by

5   such a large error, at long forecast range (more than three days in advance) all the corresponding LAM forecasts are consequently affected by a similar and remarkable error too. It is worth noting that an error of the same magnitude is not present in the forecasts provided by any other representative members. Moreover, it is possible to assess that mesoscale forecasts driven by representative member m36 display a pretty

10 good forecast.

Therefore it seems reasonable to conclude that at long forecast range (day 3–5) the behaviour of the multi-model ensemble members is dominated more by the boundary conditions than by the model used for the integration. Nonetheless, model characteristics may impact the forecast, although at a less extent. Indeed, BOLAM generally fore-

15 casts more intense precipitation with respect to the other two models of the ensemble. Also, small qualitative differences among the model precipitation fields are amplified in terms of hydrological response, so that pretty similar rainfall patterns, produced by the three LAMs forced by the same representative member (Fig. 8), generate significantly different discharge predictions (Fig. 7). This sensitivity of the hydrological response to

20 small-scale rainfall pattern is a clear indication that coupled atmospheric-hydrological simulations may serve as an effective validation tool for atmospheric models at regional (or sub-regional) scale (Jasper and Kaufmann, 2003).

Repeating the analysis of the multi-model results for shorter forecast range (36 h) during the same period of heavy rainfall (Fig. 10), the five forecasts issued by the

25 same mesoscale model present much less variability than that observed before for long forecast range. In this case, the different forecast "trajectories", due to different initial conditions, have not fully diverged yet, since the initial perturbations have not grown enough during such a short forecast range. Also, the large scale fields driving the multi-model (not shown) as boundary conditions are quite close each other and

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

in good agreement with the global analysis, and have not fully entered the integration domain from the boundaries. At short forecast ranges, the strong similarities between the LAM forecasts driven by the same representative member (as seen for long lead times) are not present any longer and it is not easy anymore to recognize the worst or the best representative member. However, moving from one model to the other, large differences among the precipitation fields are evident. Therefore it is reasonable to speculate that the variability among the LAM forecasts is dominated by the model characteristics. This is one of the positive aspects of the multi-model which allows a quite large spread among the forecasts also at short ranges. Similar considerations can be drawn from the second period of intense precipitation.

6 Conclusions and future plans

In the present work, two different meteorological limited-area multi-analysis ensemble approaches to quantitative precipitation forecasting, both focused on the short to medium range, have been implemented in order to provide a range of possible meteorological inputs to the same hydrological rainfall-runoff model: a multi-model ensemble based on three mesoscale models, BOLAM, COSMO and WRF, and a single-model approach, the COSMO-LEPS ensemble. In order to allow a fair comparison, the two ensembles have been implemented with almost the same characteristics; also, both ensembles are driven by a limited number of members taken from a large scale EPS, to which the two limited-area ensembles have also been compared. The implementation of the proposed systems is presented for a case study characterized by two periods of intense precipitation over Northern Apennines, whose ground effects are evaluated over the Reno River basin, a medium-sized catchment in Northern Italy.

Although limited to a single event, the comparison among EPSs provided some interesting results. In particular, it highlights the added value of mesoscale models for ensemble forecasting with respect to the global ensemble. At variance with LEPS, the global EPS forecasts do not provide evidence of any relevant probability of intense

precipitation over the Reno River basin, even at short forecast ranges. This points out that structural large scale model deficiencies (i.e. low resolution, coarse orography representation) negatively affect the rainfall prediction at the scales typical of hydrological applications. Instead, higher resolution models are needed: both LEPSs remarkably improve the forecast quality with respect to the "driving" global model ensemble for this case study, in terms of both probability of precipitation over the area affected by intense rainfall and discharge prediction over the Reno River basin.

Looking in more detail at the multi-model results, the system seems able to identify the Reno River basin as an area likely to be affected by intense precipitation almost four days in advance, with a progressively increasing probability with shorter lead times, thus improving the confidence in the prediction as the event approaches. The multi-model ensemble provides better results with respect to COSMO-LEPS, being characterized by a larger spread at short range due to the different model characteristics. In fact, the multi-model approach takes into account both the uncertainty associated with the model error and that related to the initial and boundary conditions. The latter is accounted for by COSMO-LEPS too, but the former, namely the model error, is addressed only in a simplified manner, via perturbations of few parameters of the model physics scheme. The mesoscale model diversity implemented in the multi-model approach permits to account for a larger fraction of the model error. In the multi-model forecasts, the areas with high probability of heavy precipitation are generally broader, and the differences in the forecast members are larger. In the present case study, the greater degree of diversity of the multi-model ensemble members permits to forecast correctly the Reno River basin as an area likely affected by heavy precipitation and represents the added value of the multi-model approach with respect to single-model COSMO-LEPS. The spread of the discharge ensemble forced by the multi-model system seems adequate to convey a quantification of the discharge forecast uncertainty, useful to support civil protection authorities in their decisions. Indeed, the possible flood occurrence would have been predicted with a sufficient lead time, and the magnitude

of the event could have been properly estimated by the decision makers considering the extreme members of the ensemble.

Still focusing on the multi-model ensemble, a different behaviour can be identified considering short and long forecast ranges. For short forecast ranges, the large scale conditions are similar and have not affected the integration domain yet, thus the impact of boundary conditions is weaker and the spread can be mainly attributed to the different characteristics of the models. At longer forecast ranges, the similar behaviour of the corresponding multi-model members indicates that they are governed mainly by the large scale boundary conditions.

However, the considerations of the present study are confined to just one case study. Further events, associated with different synoptic conditions, need to be analysed in order to support these conclusions. Also, the present paper is limited to ensembles based on convection-parameterized models. The horizontal resolution adopted here (7–8 km) is close to the "no man's land" (Weisman et al., 2008) separating classical convective parameterization schemes from explicitly convection-resolving models. As a result, the ability of mesoscale models to accurately reproduce atmospheric phenomena on such fine spatial scales can be questionable. Further simulations using short-range ensembles employing convection-resolving models at higher resolution, which should be able to better represent the small scales and to better simulate convective rainfall, will be analysed in a future study.

References

Adams, T. and Ostrowski, J.: Short lead-time hydrologic ensemble forecasts from numerical weather prediction model ensembles, Proc. World Environment and Water Resources Congress, 16–20 May 2010, Providence, RI, American Society of Civil Engineers, 2294–2304, 2010.

Addor, N., Jaun, S., Fundel, F., and Zappa, M.: An operational hydrological ensemble prediction system for the city of Zurich (Switzerland): skill, case studies and scenarios, Hydrol. Earth Syst. Sci., 15, 2327–2347, doi:10.5194/hess-15-2327-2011, 2011.

Bauer, H.-S., Weusthoff, T., Dorninger, M., Wulfmeyer, V., Schwitalla, T., Gorgas, T., Arpagaus, M., and Warrach-Sagi, K.: Predictive skill of a subset of the D-PHASE multi-model ensemble in the COPS region, Q. J. Roy. Meteor. Soc., 137, 287–305, 2011.

Bougeault, P., Toth, Z., Bishop, C., Brown, B., Burridge, D., Chen, D. H., Ebert, B., Fuentes, M., Hamill, T. M., Mylne, K., Nicolau, J., Paccagnella, T., Park, Y. Y., Parsons, D., Raoult, B., Schuster, D., Dias, P. S., Swinbank, R., Takeuchi, Y., Tennant, W., Wilson, L., and Worley, S.: The THORPEX interactive grand global ensemble, B. Am. Meteorol. Soc., 91, 1059–1072, 2010.

Bowler, N. E., Arribas, A., and Mylne, K. R.: The benefits of multianalysis and poor man's ensembles, Mon. Weather Rev., 136, 4113–4129, 2008.

Buizza, R.: The value of probabilistic prediction, Atmos. Sci. Lett., 9, 36–42, 2008.

Cloke, H. L. and Pappenberger, F.: Ensemble flood forecasting: a review, J. Hydrol., 375, 613–626, 2009.

Cuo, L., Pagano, T. C., and Wang, Q. J.: A review of quantitative precipitation forecasts and their use in short- to medium-range streamflow forecasting, J. Hydrometeorol., 12, 713–728, 2011.

Davolio, S., Miglietta, M. M., Diomede, T., Marsigli, C., Morgillo, A., and Moscatello, A.: A meteo-hydrological prediction system based on a multi-model approach for precipitation forecasting, Nat. Hazards Earth Syst. Sci., 8, 143–159, doi:10.5194/nhess-8-143-2008, 2008.

Diomede, T., Davolio, S., Marsigli, C., Miglietta, M. M., Moscatello, A., Papetti, P., Paccagnella, T., Buzzi, A., and Malguzzi, P.: Discharge prediction based on multi-model precipitation forecasts, Meteorol. Atmos. Phys., 101, 245–265, 2008.

Dudhia, J.: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, J. Atmos. Sci., 46, 3077–3107, 1989.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Garcia-Moya, J. A., Callado, A., Escribà, P., Santos, C., Santos-Muñoz, D., and Simarro, J.: Predictability of short-range forecasting: a multimodel approach, Tellus A, 63, 550–563, 2011.

Gebhardt, C., Theis, S. E., Paulat, M., and Ben Bouallègue, Z.: Uncertainties in COSMO-DE precipitation forecasts introduced by model perturbations and variation of lateral boundaries, Atmos. Res., 100, 168–177, 2011.

Gouweleeuw, B. T., Thielen, J., Franchello, G., De Roo, A. P. J., and Buizza, R.: Flood forecasting using medium-range probabilistic weather prediction, Hydrol. Earth Syst. Sci., 9, 365–380, doi:10.5194/hess-9-365-2005, 2005.

Hamill, T., Clark, M., Schaake, J., and Buizza, R.: Second HEPEX Workshop Summary Report, Boulder, Colorado, available at: http://hepex.nmpi.net/files/download/workshops/2nd/HEPEX05-Summary.pdf (last access: 3 December 2012), 2005.

Hapuarachchi, H. A. P., Wang, Q. J., and Pagano, T. C.: A review of advances in flash flood forecasting, Hydrol. Process., 25, 2771–2784, 2011.

Hou, D., Mitchell, K., Toth, Z., Lohmann, D., and Wei, H.: Ensemble streamflow forecasting with the coupled GFS-NOAH modelling system, 3rd HEPEX workshop, Book of Abstracts, European Commission EUR22861EN, edited by: Thielen, J., Bartholmes, J., and Schaake, J., 65–68, 2007.

Houtekamer, P. L., Derome, J., Ritchie, H., and Mitchell, H. L: A system simulation approach to ensemble prediction, Mon. Weather Rev., 124, 1225–1242, 1996.

Iversen, T., Deckmyn, A., Santos, A., Sattler, K., Bremnes, J. B., Feddersen, H., and Frogner, L. L.: Evaluation of GLAMEPS – a proposed multimodel EPS for short range forecasting, Tellus A, 63, 513–530, 2011.

Jasper, K. and Kaufmann, P.: Coupled runoff simulations as validation tools for atmospheric models at the regional scale, Q. J. Roy. Meteor. Soc., 129, 673–93, 2003.

Kain, J. S.: The Kain-Fritsch convective parameterization: an update, J. Appl. Meteorol., 43, 170–181, 2004.

Krishnamurti, T. N., Kistawal, C. M., LaRow, T. E., Bachiochi, D. R., Zhang, Z., Williford, C. E., Gadgil, S., and Surendran, S: Improved weather and seasonal climate forecasts from multimodel superensemble, Science, 285, 1548–1550, 1999.

Krzysztofowicz, R.: Bayesian theory of probabilistic forecasting via deterministic hydrologic model, Water Resour. Res., 35, 2739–2750, 1999.

Liu, Z. and Todini, E.: Towards a comprehensive physically-based rainfall-runoff model, Hydrol. Earth Syst. Sci., 6, 859–881, doi:10.5194/hess-6-859-2002, 2002.

A flood episode in Northern Italy

S. Davolio et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Marsigli, C.: COSMO-SREPS Priority Project "Short Range Ensemble Prediction System" (SREPS): final report, COSMO Technical report, 13, available at: http://www.cosmo-model.org/content/model/documentation/techReports/default.htm (last access: 3 December 2012), 2009.

5   Marsigli, C., Montani, A., and Paccagnella, T.: Perturbation of initial and boundary conditions for limited-area ensemble: multi-model versus single-model approach, Q. J. Roy. Meteor. Soc., in review, 2012.

Melone, F., Barbetta, S., Diomede, T., Perucacci, S., Rossi, M., Tessarollo, A., and Verdecchia, M.: Review and selection of hydrological models – integration of hydrological models

10   and meteorological inputs, Resulting from WP1, Action 13, RISK AWARE – INTERREG III B – CADSES, 34 pp., 2005.

Molteni, F., Buizza, R., Marsigli, C., Montani, A., Nerozzi, F., and Paccagnella, T.: A strategy for high-resolution ensemble prediction: Part I. Definition of representative members and global-model experiments, Q. J. Roy. Meteor. Soc., 127, 2069–2094, 2001.

15   Montani, A., Cesari, D., Marsigli, C., and Paccagnella, T.: Seven years of activity in the field of mesoscale ensemble forecasting by the COSMO-LEPS system: main achievements and open challenges, Tellus A, 63, 605–624, 2011.

Mylne, K. R., Evans, R. E., and Clark, R. T.: Multi-model multi-analysis ensemble in quesi-operational medium-range forecasting, Q. J. Roy. Meteor. Soc., 128, 361–384, 2002.

20   Palmer, T. N., Barkmeijer, J., Buizza, R., and Petroliagis, T.: The ECMWF ensemble prediction system, Meteorol. Appl., 4, 301–304, 1997.

Park, Y. Y., Buizza, R., and Leutbecher, M.: TIGGE: preliminary results on comparing and combining ensembles, Q. J. Roy. Meteor. Soc., 134, 2029–2050, 2008.

Pappenberger, F., Beven, K. J., Hunter, N. M., Bates, P. D., Gouweleeuw, B. T., Thielen, J.,

25   and de Roo, A. P. J.: Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European Flood Forecasting System (EFFS), Hydrol. Earth Syst. Sci., 9, 381–393, doi:10.5194/hess-9-381-2005, 2005.

Ritter, B. and Geleyn, J. F.: A comprehensive radiation scheme for numerical weather prediction

30   models with potential applications in climate simulations, Mon. Weather Rev., 120, 303–325, 1992.

Rotach, M. W., Ambrosetti, P., Ament, F., Appenzeller, C., Arpagaus, M., Bauer, M. S., Behrendt, A., Bouttier, F., Buzzi, A., Corazza, M., Davolio, S., Denhard, M., Dorninger, M.,

Fontannaz, L., Frick, J., Fundel, F., Germann, U., Gorgas, T., Hegg, C., Hering, A., Keil, C., Liniger, M. A., Marsigli, C., McTaggart-Cowan, R., Montani, A., Mylne, K., Ranzi, R., Richard, E., Rossa, A., Santos-Muñoz, D., Schär, C., Seity, Y., Staudinger, M., Stoll, M., Volkert, H., Walser, A., Wang, Y., Werhahn, J., Wulfmeyer, V., and Zappa, M.: MAP D-PHASE: real-time demonstration of weather forecast quality in the Alpine region, B. Am. Meteorol. Soc., 90, 1321–1336, 2009.

Rotach, M. W., Arpagaus, M., Dorninger, M., Hegg, C., Montani, A., and Ranzi, R.: Uncertainty propagation for flood forecasting in the Alps: different views and impacts from MAP D-PHASE, Nat. Hazards Earth Syst. Sci., 12, 2439–2448, doi:10.5194/nhess-12-2439-2012, 2012.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X.-Y., Wang, W., and Powers, J. G.: A Description of the Advanced Research WRF Version 3, NCAR Technical note NCAR/TN-475 + STR, 2008.

Steppeler, J., Doms, G., Schättler, U., Bitzer, H. W., Gassmann, A., Damrath, U., and Gregoric, G.: Meso-gamma scale forecasts using the nonhydrostatic model LM, Meteorol. Atmos. Phys., 82, 75–96, 2003.

Thielen, J., Bartholmes, J., Ramos, M.-H., and de Roo, A.: The European Flood Alert System – Part 1: Concept and development, Hydrol. Earth Syst. Sci., 13, 125–140, doi:10.5194/hess-13-125-2009, 2009.

Thompson, G., Rasmussen, R. M., and Manning, K.: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis, Mon. Weather Rev., 132, 519–542, 2004.

Tiedtke, M.: A comprehensive mass flux scheme for cumulus parameterization in large-scale models, Mon. Weather Rev., 117, 1779–1800, 1989.

Todini, E. and Ciarapica, L.: The TOPKAPI model, in: Mathematical Models of Large Watershed Hydrology, edited by: Singh, V. P. and Frevert, D. K., Water Resources Publications, Littleton, Colorado, USA, 914 pp., 2002.

Toth, Z. and Kalnay, E.: Ensemble forecasting at NCEP and the breeding method, Mon. Weather Rev., 125, 3297–3319, 1997.

Wei, M. Z., Toth, Z., Wobus, R., Zhu, Y. J., Bishop, C. H., and Wang, X. G.: Ensemble transform Kalman filter-based ensemble perturbations in an operational global prediction system at NCEP, Tellus A, 58, 28–44, 2006.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Weisman, M. L., Davies, C., Wang, W., Manning, K. W., and Klemp, J. B.: Experiences with 0–36-h explicit convective forecasts with the WRF-ARW model, Weather Forecast., 23, 407–437, 2008.

Weusthoff, T., Ament, F., Arpagaus, M., and Rotach, M. W.: Assessing the benefits of convection permitting models by neighborhood verification – examples from MAP D-PHASE, Mon. Weather Rev., 138, 3418–3433, 2010.

Zampieri, M., Malguzzi, P., and Buzzi, A.: Sensitivity of quantitative precipitation forecasts to boundary layer parameterization: a flash flood case study in the Western Mediterranean, Nat. Hazards Earth Syst. Sci., 5, 603–612, doi:10.5194/nhess-5-603-2005, 2005.

Zappa, M., Beven, K. J., Bruen, M., Cofino, A. S., Kok, K., Martin, E., Nurmi, P., Orfila, B., Roulin, E., Schröter, K., Seed, A., Szturc, J., Vehviläinen, B., Germann, U., and Rossa, A.: Propagation of uncertainty from observing systems and NWP into hydrological models: COST-731 working group 2, Atmos. Sci. Lett., 11, 83–91, 2010.

Zappa, M., Jaun, S., Germann, U., Walser, A., and Fundel, F.: Superposition of three sources of uncertainties in operational flood forecasting chains, Atmos. Res., 100, 246–262, 2011.

Table 1. Model set up: horizontal and vertical resolution, grid characteristic and initial/boundary conditions.

Model	Horizontal resolution	Number of grid points	Number of vertical levels	Initial/boundary conditions
BOLAM	8 km	426 × 354	50	EPS (5 members)
COSMO	7 km	511 × 415	40	EPS (5 members)
WRF	7.5 km	460 × 380	40	EPS (5 members)
COSMO-LEPS	7 km	511 × 415	40	EPS (16 members)
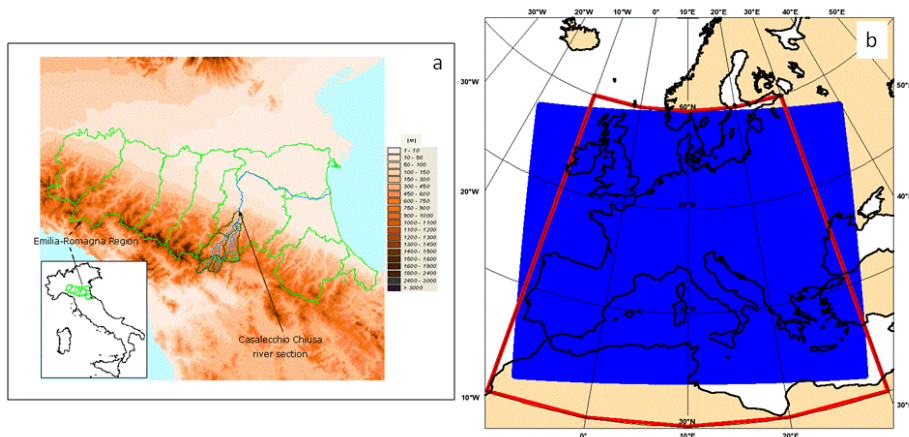
Fig. 1. (a) Localisation of the Reno River basin in the Emilia-Romagna Region, Northern Italy. The upper basin closure at Casalecchio Chiusa river section is indicated. **(b)** Model integration domains (blue area), and domain employed for the cluster analysis (red line).
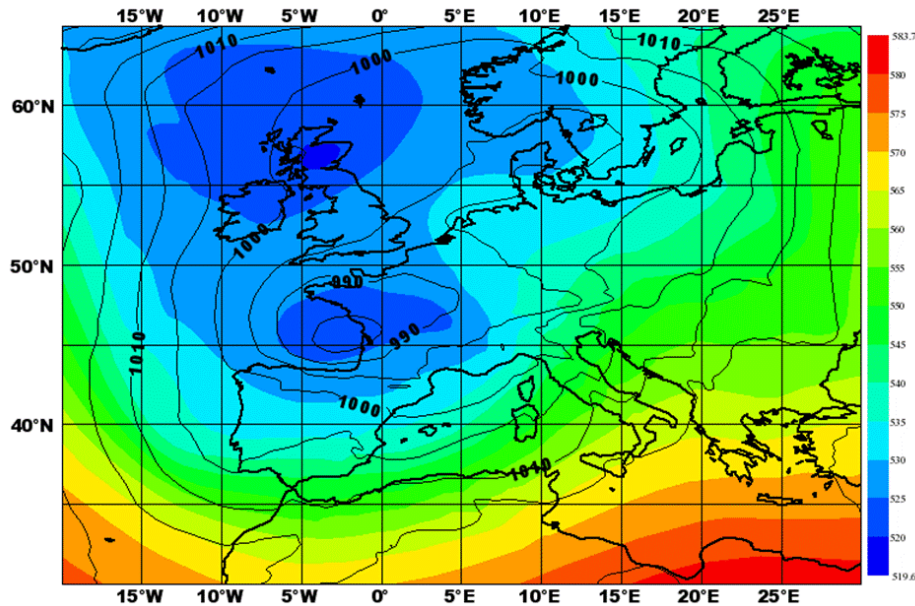
Fig. 2. ECMWF analysis at 00:00 UTC, 30 November 2008. Geopotential height at 500 hPa (gpm, colour shading) and mean sea level pressure (hPa, contour).
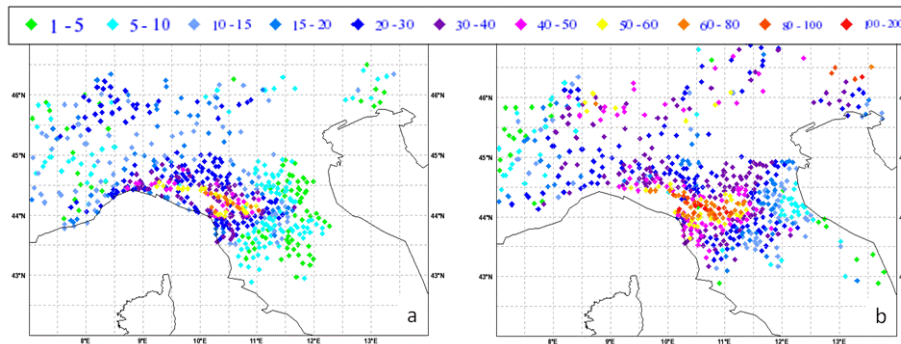
Fig. 3. Observed precipitation (mm) for the two period of most intense rainfall: **(a)** 6-h accumulated rainfall at 00:00 UTC, 30 November 2008; **(b)** 24-h accumulated rainfall at 12:00 UTC, 1 December 2008.
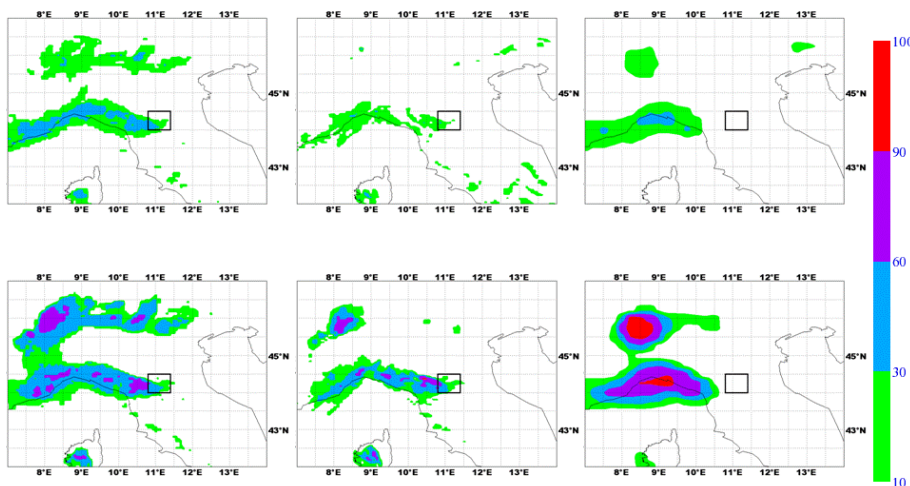
Fig. 4. Maps of probability of precipitation exceeding 20 mm in 6 h obtained at long (+84 h, top panels) and short (+36 h, bottom panels) forecast ranges: multi-model (left), COSMO-LEPS (middle) and ECMWF global EPS (right) forecasts valid at 00:00 UTC, 30 November 2008. Reno River basin is also indicated by the black rectangle.
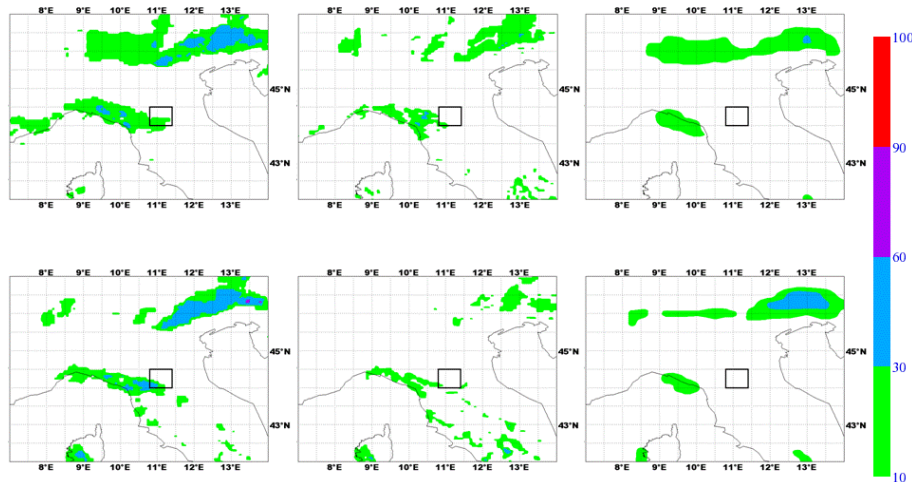
Fig. 5. Maps of probability of precipitation exceeding 50 mm in 24 h obtained at +120 h (top panels) and +72 h (bottom panels) forecast range: multi-model (left), COSMO-LEPS (middle) and ECMWF global EPS (right) forecasts at 12:00 UTC, 1 December 2008.
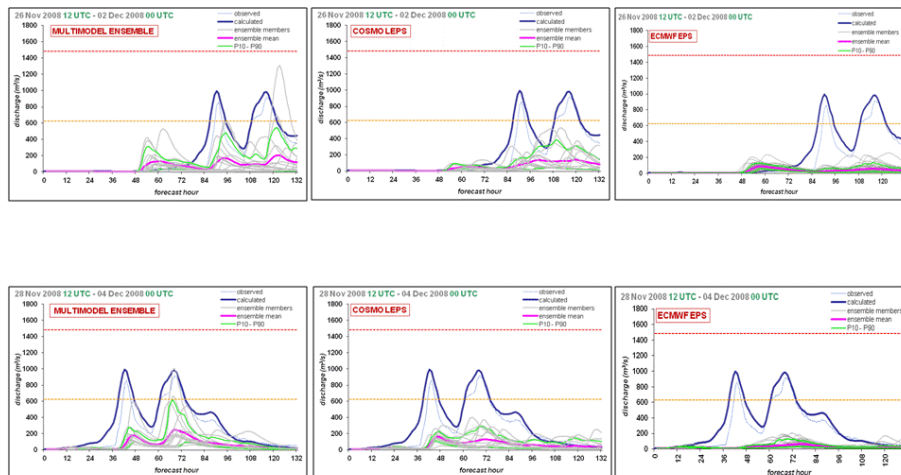
Fig. 6. Discharge forecasts ($m^3 s^{-1}$) as a function of the forecast range (h). The different (grey) curves have been obtained by feeding the TOPKAPI hydrological model with the precipitation forecast by the ensemble members: multi-model (left), COSMO-LEPS (middle) and ECMWF global EPS (right). The raingauge-driven (thick blue line) and the observed (blue dashed line) discharges are also plotted for reference. The pink line represents the ensemble mean, while the two green lines represent the 10th and the 90th percentile curves. Top panels refer to forecasts initialized at 12:00 UTC, 26 November 2008 (short-range in the text); bottom panels to those initialized at 12:00 UTC, 28 November 2008 (long-range in the text). Orange (red) horizontal line indicates warning (alarm) level.
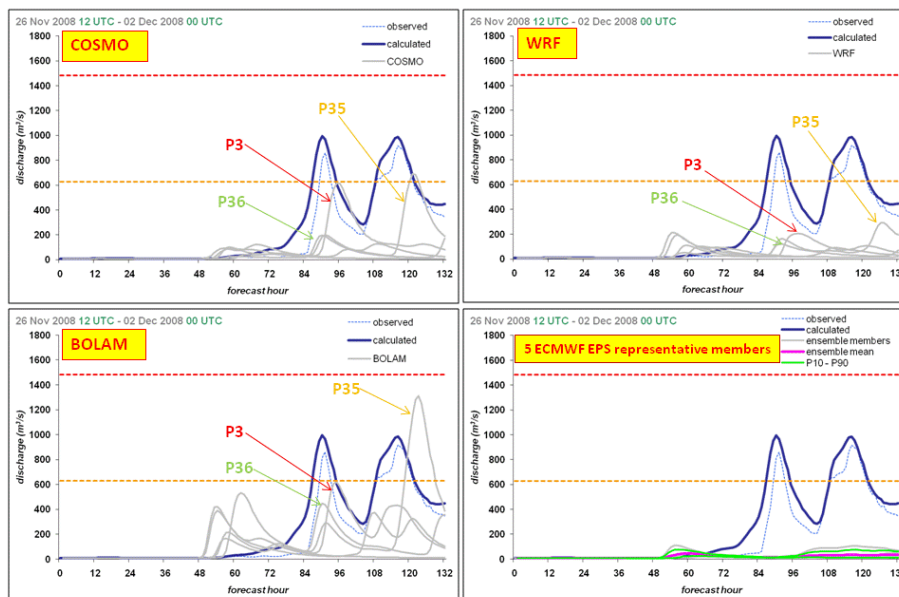
Fig. 7. Discharge forecasts (m^3 s^{-1}) as a function of the forecast range (h) obtained by feeding the TOPKAPI with the rainfall predicted by the five members of each model of the multi-model ensemble system and for the five representative members of the ECMWF global EPS. Forecasts are initialized at 12:00 UTC, 26 November 2008 (long-range, see text). The raingauge-driven (thick blue line) and the observed (blue dashed line) discharges are also plotted for reference. The forecasts driven by a particular representative member of the global ensemble are indicated with arrows and with the member number. Orange (red) horizontal line indicates warning (alarm) level.
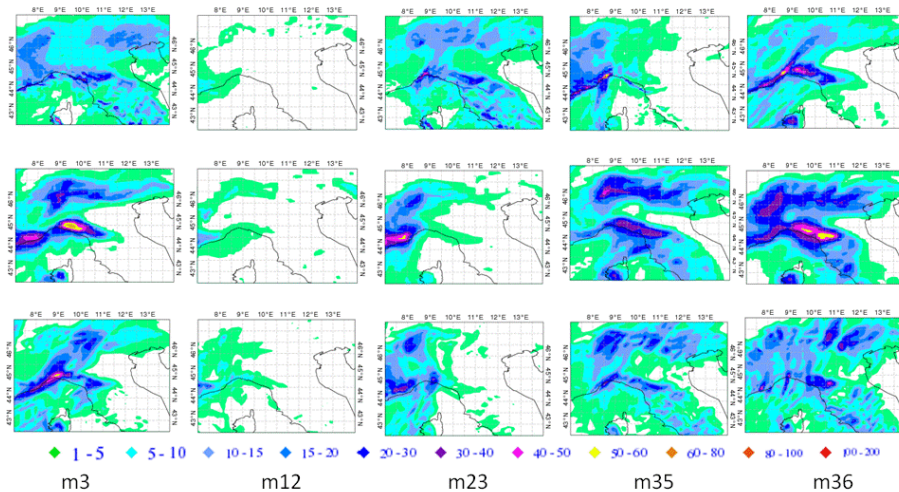
Fig. 8. 6 h accumulated precipitation (mm) at 00:00 UTC, 30 November 2008 forecast by the different members of the multi-model ensemble at long-range (+84 h, see text). Five forecasts for each model: COSMO (top), BOLAM (middle) and WRF (bottom). Models are initialized at 12:00 UTC, 26 November 2008. The driving global representative member (m) is indicated below each column of panels.
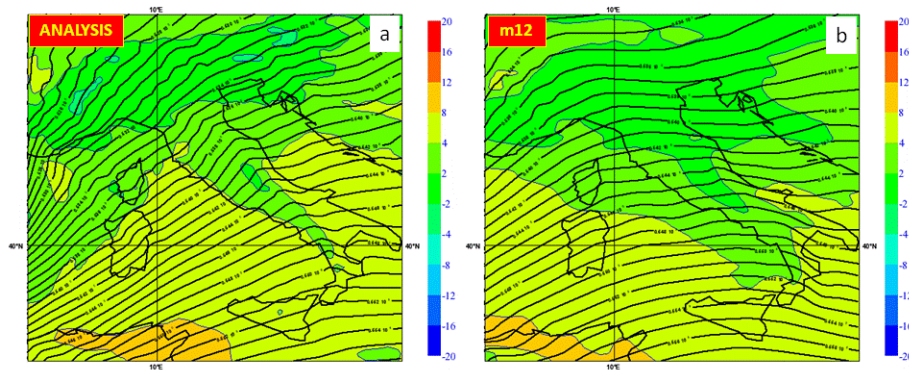
Fig. 9. Geopotential height at 500 hPa (gpm, contour lines) and temperature at 850 hPa (colour shading) at 18:00 UTC, 29 November 2008. **(a)** ECMWF analysis. **(b)** Forecast fields issued by the ECMWF representative member number 12 (m12).
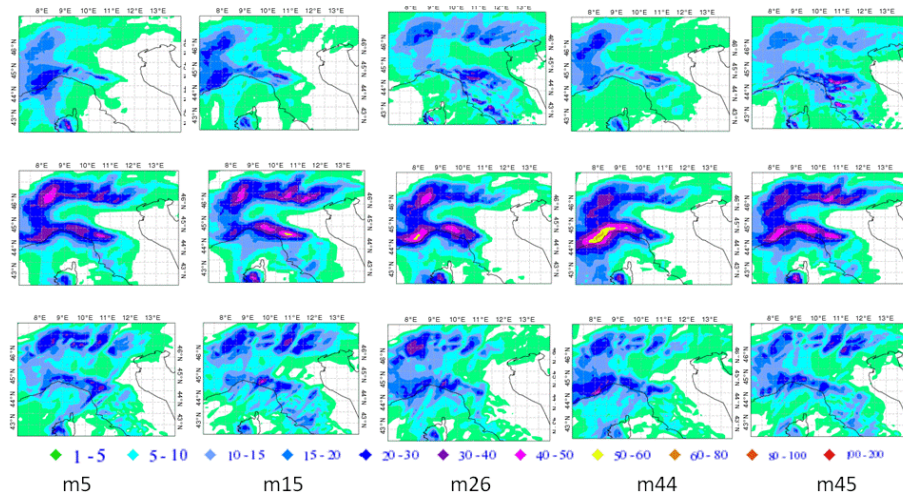
Fig. 10. As in Fig. 8, but for the forecasts initialized at 12:00 UTC, 28 November 2008 (short-range, +36 h, see text).