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Comparing different meteorological ensemble approaches: hydrological predictions for a flood episode in Northern Italy

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Abstract. Within the framework of coupled meteorological-hydrological predictions, this study aims at comparing two high-resolution meteorological ensembles, covering short and medium range. The two modelling systems have similar characteristics, as almost the same number of members, the model resolution (about 7 km), the driving ECMWF global ensemble prediction system, but are obtained through different methodologies: the former is a multi-model ensemble, based on three mesoscale models (BOLAM, COSMO, and WRF), while the latter follows a single-model approach, based on COSMO-LEPS (Limited-area Ensemble Prediction System), the operational ensemble forecasting system developed within the COSMO consortium.

Precipitation forecasts are evaluated in terms of hydrological response, after coupling the meteorological models with a distributed rainfall-runoff model (TOPKAPI) to simulate the discharge of the Reno river (Northern Italy), for a severe weather episode.

Although a single case study does not allow for robust and definite conclusions, the comparison among different predictions points out a remarkably better performance of mesoscale model ensemble forecasts compared to global ones. Moreover, the multi-model ensemble outperforms the single model approach.

1 Introduction

Prediction of the hydrological response of a watershed to rainfall can be handled by coupling meteorological and hydrological numerical weather prediction (NWP) models. This is especially true for small and medium-sized catchments (smaller than 10 000 km^2), characterized by complex orography and short response times, where the sole observed precipitation is not suitable to drive hydrological models for timely forecasts and adequate emergency planning. The reliability and the practical use of a coupled discharge forecasting system are tightly dependent on the accuracy of the forecast precipitation data. However, increased NWP model resolution and improved rainfall forecast skill do not ensure a positive impact on hydrological predictions, since quantitative precipitation forecasts (QPFs) issued by meteorological models are still affected by errors at the small scales that are particularly relevant for hydrological applications.

In the forecasting process, it is therefore necessary to acknowledge the different sources of errors affecting QPF (initial condition, model structure), which represent the largest source of uncertainty in discharge prediction. An ensemble prediction system (EPS) can quantify at least part of these uncertainties by producing probabilistic forecasts, thus representing an attractive product to be used for flood predictions (for a review, see Cloke and Pappenberger, 2009). Probabilistic forecasts are considered much more valuable than a single deterministic forecast for weather prediction (Buizza, 2008); recently there is a general agreement on the usefulness of ensemble forecasting for early flood warning application

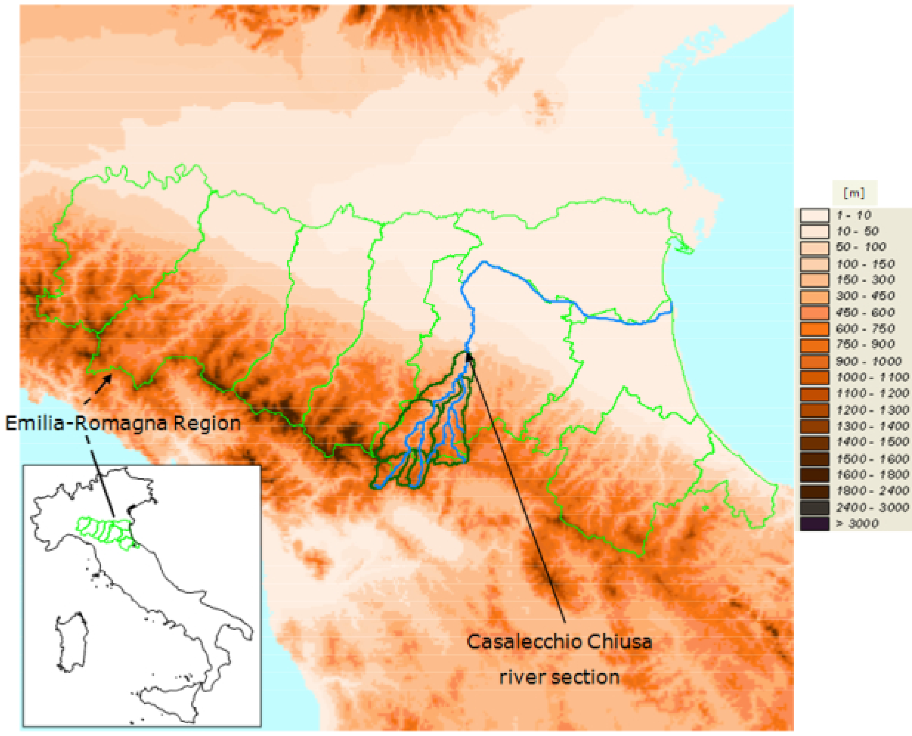

Figure 1. Localisation of the Reno river basin. The main river is showed in cyan. The upper part of the basin, closed at Casalecchio Chiusa, is evidenced with dark green lines.

too. EPS forecasts can be used as an input for hydrological models, thus propagating the uncertainty along the flood forecasting system, in order to provide a probabilistic and hopefully more informative hydrological prediction.

Although providing positive results, global model ensemble predictions suffer from their coarse resolution and often proved not to be accurate enough for application at basin scale, especially in region with complex orography. Thus, during the last decade, different ensemble approaches based on limited area models (LAMs) have been developed (e.g. Montani et al., 2011). These local ensemble prediction systems (LEPSs) basically perform a dynamical downscaling of global EPS and represent the state-of-the-art in meteo-hydrological forecasting (Cuo et al., 2011).

In this study, two different ensemble approaches, both focused on the short/medium range, are compared. In order to allow a fair comparison, the two ensembles have been implemented using almost the same set up in terms of integration domain, horizontal resolution, number of members. The difference resides 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, thus yielding a 15 member ensemble. Both the ensembles have been used to generate probabilistic precipitation maps and to provide the input fields to the same hydrological model. The results, in terms of discharge prediction, allow to evaluate the ensembles performance in a recent severe weather episode affecting the Reno river basin, located in Northern Italy (Fig. 1).

2 Case study and ensemble generation

The analysed severe weather period, between 29 November and 2 December 2008, was characterized by the presence of a deep trough over the Mediterranean Sea, driving several frontal systems towards the Italian peninsula. Persistent and intense moist south-westerly flow impinging on the northern Apennines (where the Reno river basin is located) was responsible for severe weather. Two period of intense precipitation, during the nights of 29 November (Fig. 2) and between 30 November and 1 December, respectively, produced two relevant discharge peaks, both exceeding the warning threshold at the closure section of the mountain portion of the Reno catchment.

Discharge forecasts for this event were produced by the distributed rainfall-runoff model TOPKAPI (Todini and Ciarapica, 2002), whose input rainfall fields have been provided by the following EPSs:

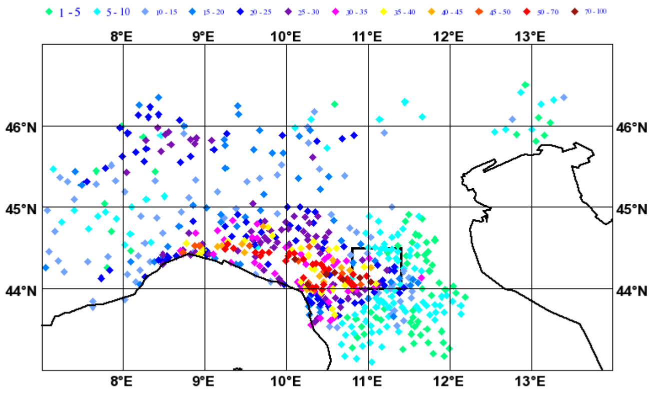

Figure 2. Observed 6-h accumulated precipitation at 00:00 UTC, 30 November 2008. Dark blue diamonds correspond to 20–25 mm/6 h. Black rectangle indicates approximately the Reno river basin.

1. A 15-member multi-model ensemble, based on three mesoscale models, each of them initialized by 5 representative members of ECMWF EPS: BOLAM (Malguzzi et al., 2006) has been developed and implemented by the Institute of Atmospheric Sciences and Climate (ISAC); COSMO (Steppeler et al., 2003) has been developed within the COSMO consortium and implemented by ARPA-SIMC; WRF (Skamarock et al., 2005) is the USA community model and it is implemented at ISAC.

2. A single-model approach, based on COSMO-LEPS (COSMO Limited-area Ensemble Prediction System), the operational forecasting system of the COSMO Consortium, driven by 16 representative members of the ECMWF EPS.

The same cluster analysis (Montani et al., 2011) has been used in both EPSs for selecting the representative members within the 102-members generated by the ECMWF EPS initialized both at 00:00 and 12:00 UTC. The two EPSs have been initialized at three different instants 24-h apart, starting from 26 November at 12:00 UTC, in order to evaluate the forecasting system at different lead times.

In order to have a reference prediction, forecasts provided by ECMWF EPS (51 members), initialized at 12:00 UTC on the same days, were also used as input for the TOPKAPI model.

3 Results: meteorological perspective

The evaluation of the ensemble systems is first performed from a meteorological perspective over a larger area than the single catchment (e.g. entire Northern Italy). For sake of brevity, only the first period of intense precipitation, shown in Fig. 2, will be presented. Intense precipitation affected the

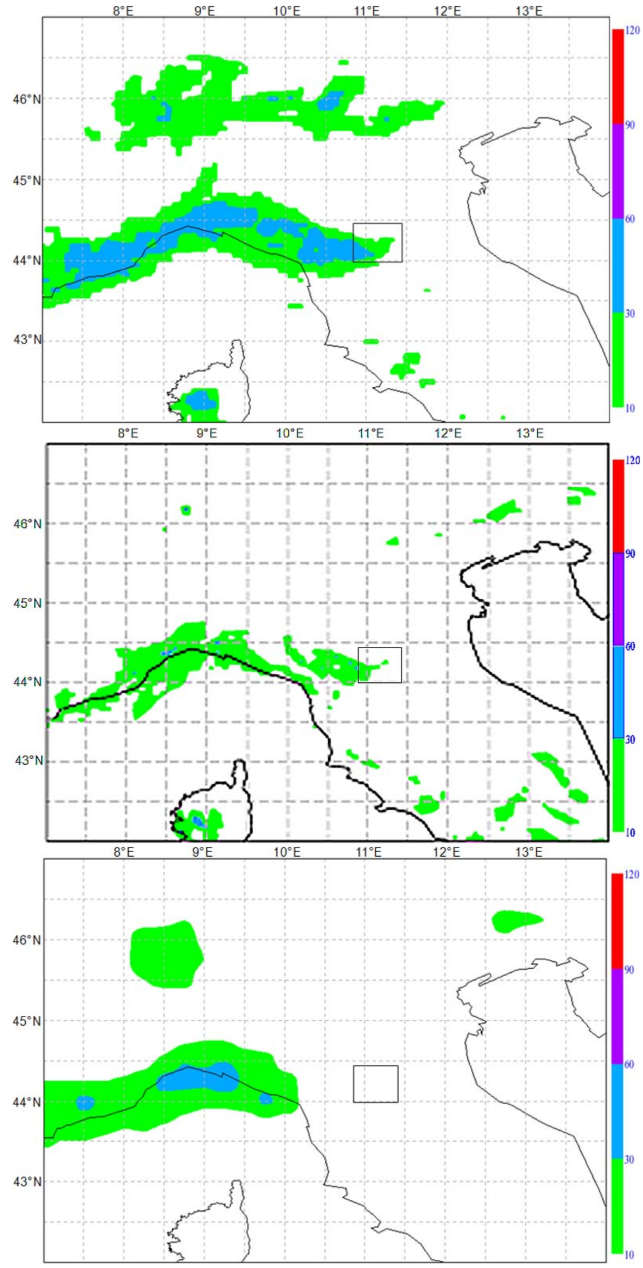

Figure 3. Probability of precipitation exceeding 20 mm/6 h forecast by (from top to bottom) multi-model, COSMO-LEPS and ECMWF EPS, at 00:00 UTC, 30 November 2008. Simulations are initialized at 12:00 UTC, 26 November 2008.

whole northern Apennines and also some Alpine areas. Results of the two LEPSs and of the global EPS are compared for two different forecast lead times, in terms of probability maps of occurrence of precipitation exceeding 20 mm/6 h. At 78–84 h range (Fig. 3, 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) over the Reno river basin. Moreover, the multi-model provides a signal also over the central Alps, where precipitation did occur.

Similarly, for a shorter forecast range (not shown, initialization time 12:00 UTC, 28 November), only the two LEPSs are able to forecast the possible occurrence of precipitation over the target basin. Very high probability is assigned to rainfall over western Apennines and the Alpine chain by all the systems, with a progressively increasing probability for shorter lead times, thus improving the confidence in the prediction as the event approaches.

Similar results have been obtained for the second period of intense precipitation (not shown).

4 Results: hydrological perspective

The two intense precipitation events generated two relevant discharge peaks in the Reno basin (Fig. 4). The ensemble discharge forecasts are the expected consequence of the result shown by the maps of probability of precipitation. Indeed, while the discharge prediction driven by the global EPS fails to generate any relevant peak, the discharge predictions driven by both LEPSs are remarkably better. Although underestimated in intensity, the possible occurrence of high discharge peaks is forecast almost 4 day ahead by both LEPSs, thus providing a useful indication of the event for the civil protection authorities. In particular, at this long forecast range, some members of the multi-model exceed the warning threshold. At a less extent, also the COSMO-LEPS displays some relevant peaks, although the timing is affected by large uncertainty.

Even at shorter forecast ranges, up to 2 days in advance, LEPSs outperform the global EPS (not shown). The multi-model ensemble displays a large spread among the members and a more accurate discharge prediction, especially concerning the second peak.

Looking into detail at the discharge forecasts generated by every single model of the multi-model ensemble, it is possible to recognize that for longer lead times (more than 3 days) the behaviour of the different members is dominated by the boundary conditions effect, since the higher discharge peaks are associated with mesoscale forecasts driven by the same global ensemble members. This is not true for short forecast ranges, where the impact of boundary conditions is weaker and the spread is reasonably ascribable to the characteristics of the models.

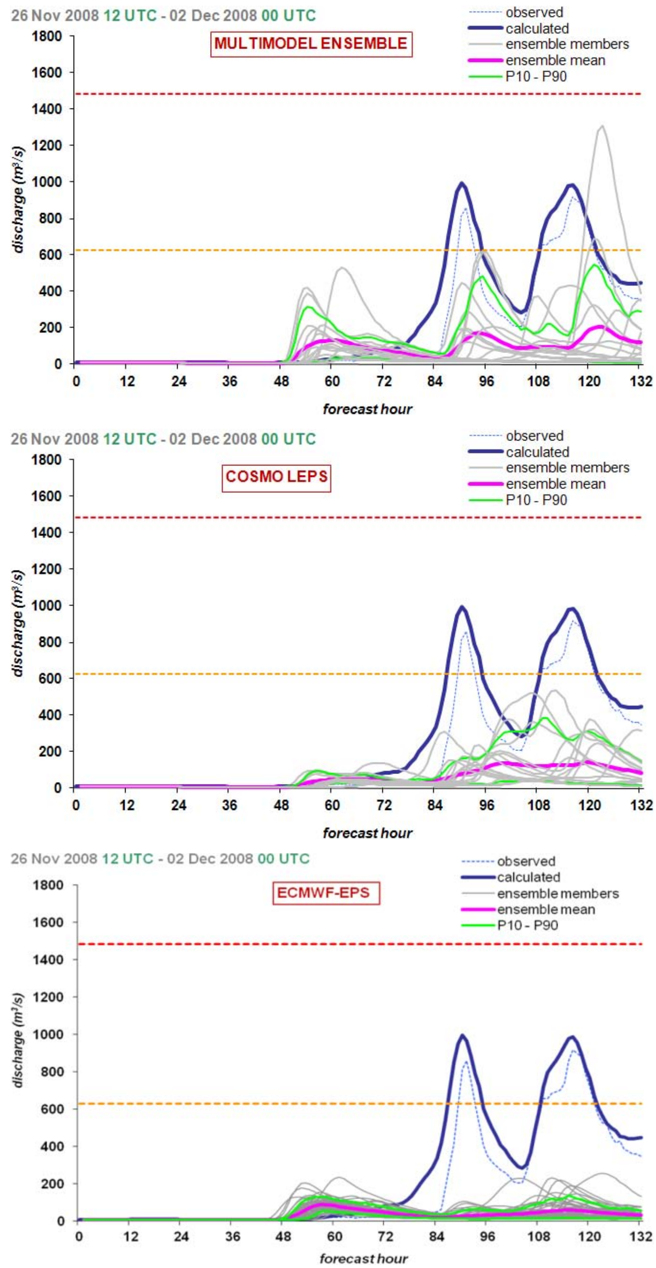

Figure 4. Discharge forecast ($m^3\,s^{-1}$) vs. forecast range (hours) for multi-model, COSMO-LEPS and ECMWF EPS (51 members), respectively, initialized at 12:00 UTC, 26 November 2008. Each grey line corresponds to an ensemble member. For reference, the observed discharge (dotted blue) and the discharge computed using rainfall observations are provided. Ensemble mean (pink) and the P10-P90 curves (green) are also plotted. Horizontal dashed orange and red lines indicate warning and alarm thresholds, respectively.

5 Conclusions

Although limited to a single event, the comparison among EPSs provided some interesting results, in particular highlighting the added value of mesoscale models for ensemble forecasting with respect to a 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 model deficiencies (i.e. low resolution, coarse orography representation) cannot be accounted for by this kind of ensemble approach. Instead, higher resolution models are needed. LAMs are indeed able to improve remarkably the forecast quality, also in terms of hydrological response of the basin. Looking in more detail at the multi-model LEPS, the system seems able to identify the Reno river basin as an area likely to be affected by intense precipitation almost 4 days in advance. The multi-model LEPS provides better results with respect to COSMO-LEPS, being characterized by a larger spread at short range due to different model characteristics. At longer forecast ranges, the similar behaviour of the multi-model LEPS members indicates the relevant impact of the boundary conditions. The greater degree of diversity of the multi-model LEPS members seems to be the added value of the multi-model approach with respect to single-model COSMO-LEPS. Such conclusions require to be verified in additional case studies.

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