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Regional ensemble forecast for early warning system over small Apennine catchments on Central Italy

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Abstract. The weather forecasts for precipitation have considerably improved in recent years thanks to the increase of computational power. This allows to use both a higher spatial resolutions and the newly developed parameterization schemes for representing sub-grid scale physical processes. However, precipitation estimation is still affected by errors that can impact on the response of hydrological models. To the aim of considering the uncertainties in the precipitation forecast and how they propagate in the hydrological model, an ensemble approach is investigated. A meteo-hydro ensemble system is built to forecast events in a complex orography terrain where catchments of different size are present. In this context, the meteo-hydrological forecast system is implemented and tested for a severe hydrological event occurred over Central Italy on November 15, 2017. During this period, a flash flood hit the Abruzzo region causing precipitation up to 200mm/24hours and producing damages with a high impact on social and economic activities.The newly developed meteo-hydro ensemble system is compared with a high resolution deterministic forecast and with the observations over the same area, showing a very good response. In addition, the ensemble allows for an estimation of the predictability of the event a few days in advance and of the uncertainty of this flood. Although the modelling framework is implemented on the basins of Abruzzo region, it is portable and applicable to other areas.

1 Introduction

Floods and extreme rainfall are one of the major natural hazards in Europe with over 1000 fatalities and an estimate cost of about 5.000 billion of Euros in damages, between 1998-2009 only (European Environment Agency , 2010). Italy is one of the countries more exposed to hydrogeological risk in the Mediterranean basin, with more than 90% of municipalities affected by flood and landslide risk (ISPRA , 2018). From 2013 to 2017, 67 casualties due to floods have been reported, with 26 casualties in 2018 only (IRPI-CNR , 2019). The Mediterranean basin is characterized by a highly urbanized coast and mountain ridges close to the coast. During the autumn season, when large gradients are occurring because of the cooler atmosphere and the warmer sea favoring heat and moisture fluxes, there is an increase of the energy available for storms (Duffourg and Ducrocq , 2011). That is why most of the heavy rainfall and floods are occurring in autumn in the Mediterranean area (Ferretti et al. , 2014; Rebora et al. , 2013; Rotunno and Houze , 2007; Rotunno and Ferretti , 2003) causing natural disasters in the region. Recent decades observations and modelling experiments highlighted the changes of precipitation distribution, frequency and intensity (Van den Besselaar et al. , 2011; Scoccimarro et al. , 2015), and how those changes affected the hydrological cycle in terms of increasing frequency of flash flood events (Drobinski et al. , 2018; Marchi et al. , 2010). Specifically, a warmer atmosphere and a greater amount of water vapor may lead to an increment of intense to extreme precipitation events (Trenberth et al. , 2003; Willet et al. , 2008; Giorgi et al. , 2011). In a context of increasing likelihood for future weather extremes, the availability of an accurate meteorological and hydrological forecast system is essential for improving civil protection early warning systems, to which community safety and impacts reduction directly depend (Penning-Rowsell et al. , 2009). Moreover, because of the complex orography of the Italian regions with many small - to medium-sized steep and densely urbanized coastal catchments, a further reduction of the hydrological response time and an increase of flood risks occur. Indeed, in the framework of the EU Directive 2007/60/CE (EU Flood Directive , 2007) these regions are mainly classified as P3 (highly dangerous) zones. Recent studies are focused on the coupling between meteorological and hydrological models in order to improve the quantitative precipitation forecast (QPF) and to predict the floods with a sufficient lead time. The coupling of the meteo and hydrological models requires meteorological observed or simulated variables (mainly, but not only, precipitation and temperature) used as forcing fields in hydrological models (Cloke and Pappenberger , 2009; Alfieri et al. , 2013; Abaza et al. , 2017; Wanders and Wood , 2016; Fan et al. , 2015). Assuming an appropriate hydrological model formulation, the quality of hydrological forecasts is indeed determined by the quality of atmospheric input (Pappenberger et al. , 2005). Temporal and spatial scale of the atmospheric forcing have to be calibrated according to the catchment features. In case of small-sized and mountainous catchments, because of a more responsive hydrology to the precipitation events, the discharge predictions require a very accurate precipitation forecast. An accurate, in space and time, precipitation prediction represents one of the most difficult tasks in Numerical Weather Prediction (NWP), as resulting from complex processes ranging from large-scale atmospheric dynamics to clouds microphysics. The use of meteorological models with high spatial resolution improves the QPF, but the estimation of the exact location and space-time evolution is still a challenge. In addition, their high computational cost limits the length of the forecast time which is often not enough to ensure sufficient lead time for actions. A potential solution consists on Ensemble Prediction Systems (EPS) which represent one of the areas from which the largest benefits in predictive skill have been obtained in the context of NWP (Buizza et al. , 2005; Bauer et al. , 2015). Even though EPS are characterized by a lower resolution respect to deterministic forecasting, their added value belong mainly to two aspects: 1) providing information about forecast uncertainty; 2) severe-to-extreme events occurrence likelihood. More in detail, the analysis of ensemble members distribution allows to provide the most likely events magnitude coupled to an estimation of all potential outcomes which characterizes forecast uncertainty (ensemble members standard deviation or spread). On the other hand, the portion (i.e., frequency) of ensemble members predicting values exceeding arbitrary thresholds corresponding to extreme events can be derived.

As already discussed in previous studies, ensemble weather prediction systems at different spatial scales and using different approaches (Marsigli et al. , 2005; Vie et al. , 2011) hold a large potential for hydrological forecasting (Demargne et al. , 2014; Cloke and Pappenberger , 2009; Schaake et al. , 2007; HEPEX , 2004). In the last decade, the scientific community paid an increasing attention to study the EPS coupled to hydrological models aiming at improving early warning systems on different spatial scale ranging from global to regional (Addor et al. , 2011; McCollor and Stull , 2007; Davolio et al. , 2008; Calvetti and Filho , 2014; Hally et al., 2015; Saleh et al., , 2016).

In this context, the possibility to quantify and estimate forecast uncertainties allows the end users of hydrological models to manage the risk and to decide the actions to be taken with the aim of reducing the possible damages (Hamill et al. , 2005; Schaake et al. , 2007). Although the main uncertainty characterizing hydrological forecast results from the precipitation input, uncertainty characterizing the hydrological sphere represents another point to be carefully considered. Traditionally, only uncertainty pertaining the weather forecast sphere is accounted (Cloke and Pappenberger , 2009). In fact, being forced by individual ensemble members, the same probabilistic approach previously discussed could be applied to the hydrological model as well. This would allow to characterize the range for all potential hydrological scenarios and also to assess how weather prediction uncertainty propagates into the hydrological model. This coupled probabilistic approach could further fostering the level of confidence that may be placed in the forecasts. In this work the traditional approach is followed; based on Cloke and Pappenberger (2009), the total uncertainty is probably underestimated because of the lack of the hydrological model uncertainty which can be obtained by perturbing, for example, the geometry of the system, the model parameters, etc..

In this paper a preliminary evaluation of a meteo-hydro ensemble forecast chain, developed at the Center of Excellence in Telesensing of Environment and Model Prediction of Severe events (CETEMPS) is carried out. The meteo-hydrological modeling chain consists on connecting, dynamically downscaled at regional scale, the Weather Research and Forecasting model (WRF-ARW) simulations initialized by 20 members and the control of GFS forecast to the CETEMPS Hydrological Model (CHyM, Tomassetti et al. (2005); Coppola et al. (2007); Verdecchia et al. (2008)). To the purpose of assessing the reliability of an operational regional ensemble, a preliminary study of a heavy precipitation event is used as test case for the above mentioned meteo-hydro ensemble chain. The CHyM hydrological model is forced by two different initializations: the WRF-ensemble mean and the 21 WRF members. The results of the ensemble chains will be compared to the results of both: i) a deterministic high resolution (HR) chain initialized using the best GFS Initial Conditions (IC) , where HR is used as benchmark; ii) a CHyM simulation initialized using the observation (precipitation and temperature). The results of the chains will be discussed in terms of the hydrological stress index the Best Discharge-based Drainage (BDD), maps and time series, devoted to detect catchment segments that are most likely to be stressed by weather extreme events. In this work we assumed that the 20 GFS members are sufficient to represent the meteorological uncertainty as it has been discussed by previous studies (Cloke and Pappenberger , 2009; Marsigli et al. , 2005). Jaun et al., (2008) showed that using 10 members only can be sufficient for having benefits from an ensemble approach for flood forecasting.

The novelty of this work consists in applying a coupled probabilistic approach to both the weather and the hydrological ensemble forecasts, for a small catchments in complex orography. Two different ensemble meteo-hydro configurations are proposed: 1) a pseudo-hydro ensemble forecast where the hydrological model is forced by the mean precipitation produced by the WRF 21-member ensemble; 2) a CHyM ensemble composed by 21 members initialized using the 21 WRF members. The uncertainty (i.e., ensemble members spread) and probability of extreme events (e.g., frequency of ensemble members predicting values beyond defined threshold) will be provided for both ensemble configurations by WRF regional ensemble, but for the second configuration a contribution by the hydrological component may occur. The analysis of these two configurations

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will help understanding how weather forecast uncertainty propagates into the hydrological modeling outputs, representing an added value in the hazardous weather-related events prediction.

2 Case study

During November 13, 2017 a deep upper level trough associated with an intrusion of cold air from the Arctic region, entered the Mediterranean area and advected south-westerly flow over western central Italian regions. The surface depression was located over central Italy, advecting easterly flow over the Adriatic regions (Fig. 1a), and the thermal front was extending from north Africa to the southern Abruzzo region. In the following 48 hours the upper level trough developed into a cut-off low (Fig. 1b) over the central Mediterranean Sea and the axis of the surface depression tilted (becoming in phase with the upper level one) advecting north-eastern flow over Abruzzo region. The thermal advection at this time over the Adriatic sea was warm at low levels and cold at the upper ones, producing a highly unstable environment. Hence the event was characterized by two phases: during the first phase 13 November 2017 the thermal front produced rainfall over southern Marche and northern Abruzzo regions (not shown). During the second phase, the one related to the tilted axis, the precipitation moved southward (Fig. 2, b) and was characterized by cold air producing also snowfall on the east side of the mountain ridges of Abruzzo region.

Figure 2 shows the accumulated precipitation on 24 hours (from 12 UTC of 14 November) over Italy; heavy precipitation is found only along the Adriatic regions, with maximum peaks of 200mm/24h (Fig. 2a,b) recorded along the Apennine ridges. The long lasting rainfall produced effects at the ground over the Adriatic regions, particularly on Abruzzo region (Fig. 2 b) as the alert called by the Civil Protection Agency (CPA) in the morning of 15 November shows (Fig. 9). This figure shows both the forecast for the alert area and the observation of flooded area because of the symbols (triangle on the figure) added by CPA as the event develops.

3 WRF Ensemble set up and precipitation forecast

The Advanced Weather Research and Forecasting (WRF-ARW) model is used to build the regional ensemble. WRF-ARW is a non-hydrostatic model with terrain-following vertical coordinates and multiple-nesting capabilities (Skamarock et al. , 2008). The configuration for the regional ensemble is the following: one domain covering Italy (Fig. 3) with a horizontal resolution of 9 km and 40 unequally spaced vertical levels up to 100 hPa, with higher resolution in the planetary boundary layer. The ensemble is built using 20 members and the control forecast (CNTR) from GFS Ensemble. The horizontal resolution of GFS ensemble system is 1^o; these analysis and forecast are used to produce a dynamically downscaled ensemble forecast at 9km. Similarly to the CETEMPS operational forecast, the WRF parameterizations used for this study, are the following:

- *Radiation:* Rapid Radiative Transfer Model (RRTM, Mlawer et al. (1997)) for long-wave, Dudhia scheme (Dudhia , 1989) for short-wave radiative processes;
- *Cumulus:* Kain-Fritsch (Kain , 2004) ;

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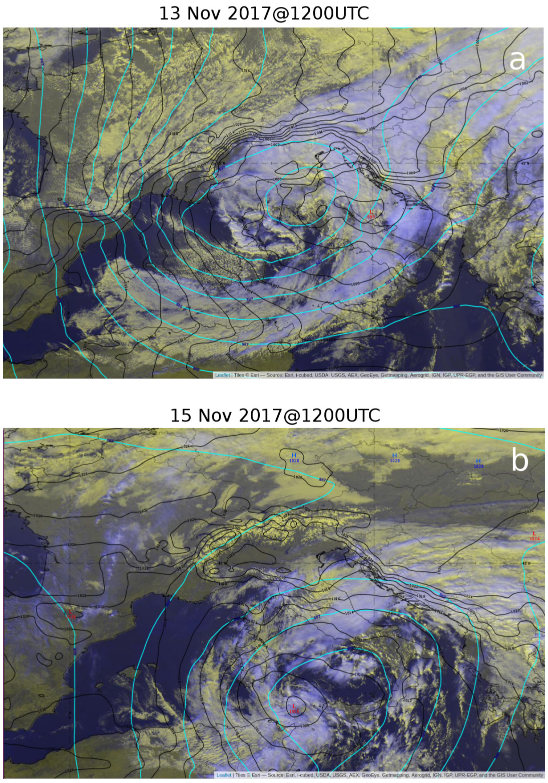

Figure 1. ECMWF analysis, Geopotential height at 500 hPa (cyan lines) and mslp (black lines labelled in hPa) and satellite WV (a) 13 Nov. 2017, 12UTC ; (b) 15 Nov. 2017, 12UTC . The maps have been retrieved from EUMeTrain/ePort archive (http://eumetrain.org/eport.html).

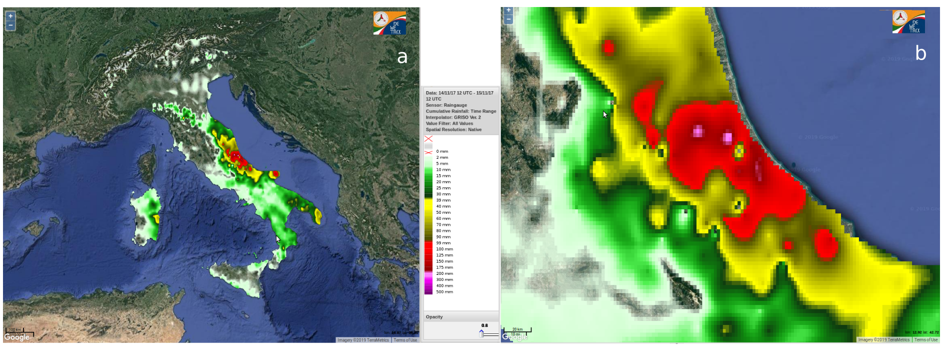

Figure 2. Observed accumulated precipitation over 24hours on 15 November 2017:a) over Italy; b) over Abruzzo region. The daily rainfall maps are provided by the DEWETRA Platform (Italian Civil Protection Department).

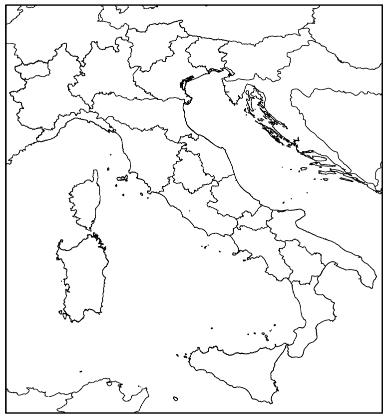

Figure 3. Domain for the WRF regional ensemble at 9km.

- *Microphysics:* Hong and Lim (2006) single-moment bulk scheme, 6 class hydrometeors;
- *Boundary-layer and turbulence:* Mellor-Yamada-Janjic (Janjic , 1994) One-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing;
- *Surface:* Monin-Obukhov-Janjic surface scheme with the Noah land-surface scheme (Niu et al. , 2011);

Moreover, based on the high resolution (1km) WRF deterministic forecast (HR) operational over the Abruzzo region at CETEMPS since 2016 (Pichelli et al. , 2017), a simulation initialized using the best GFS high resolution analysis and forecast at 0.25 ^{o}, update every 6 hours, is performed for this event and it is used as benchmark .

All simulations start at 12UTC on Nov 13, 2017 and they end at 12UTC on Nov 16, 2017 and the boundary conditions are updated every 6 hours with the GFS members forecasts, for the ensemble.

3.0.1 Ensemble members precipitation forecast

The accumulated precipitation and the associated weather characteristics produced by the 21 WRF members are quite different. An example of the variability obtained forcing WRF regional ensemble using the 20 GFS members is discussed by analyzing a few of the WRF members (01, 14, 19, 20 and CNTR). Similarly to most of the members, member 01 (Fig. 4b) clearly shows a large area of precipitation over central Tyrrhenian sea produced by the surface depression, whereas the area of heavy precipitation at the border between Marche and Abruzzo regions, reaching 100mm/12h (red area), is clearly driven by an orographic forcing. Member 14 shows (Fig. 4c) a similar pattern but the area covered by the highest values of accumulated precipitation (red area) is increased (Fig. 4b) and a second maximum in the south Abruzzo is found.

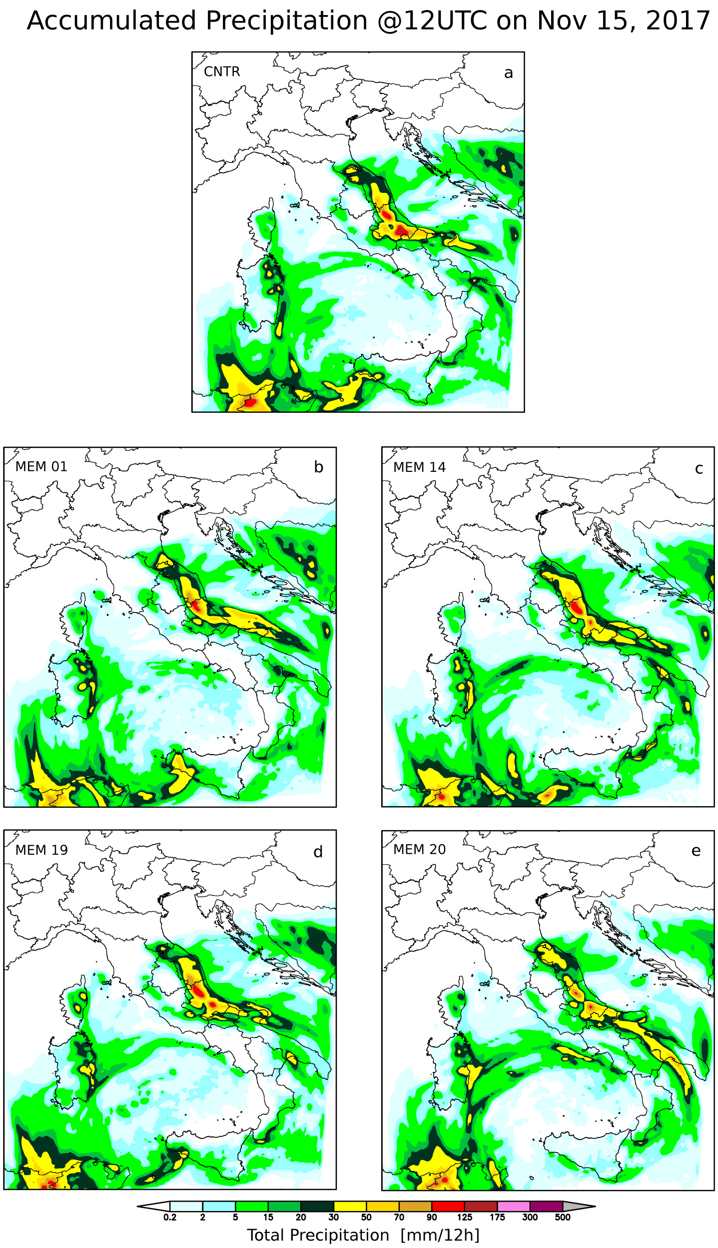

Figure 4. WRF accumulated precipitation over 12hours produced by GFS initial conditions for : a) control (CNTR), and members b) 01; c)14; d) 19; e) 20.

Similarly, member 19 produces a smaller area of high precipitation along the Apennine ridge in the southern Abruzzo (Fig. 4,d) and a larger cell in the north side with a higher maximum of precipitation (dark red area) than member 14. Member

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20 strongly reduces the precipitation for both cells with respect to member 19 showing peaks no higher than 100mm/12h (Fig. 4,e red-brown area). The accumulated precipitation for CNTR is the one producing the largest amount of precipitation for the southern cell showing maximum values of 200mm/12h and the largest cell (Fig. 4,a). The cell in the north side is comparable with the one produced by most of the members. A qualitative comparison between the WRF members forecast and the observed accumulated precipitation (Fig.2b) suggests a good agreement with the control simulation and with member 19 for the precipitation in the south side of Abruzzo, and a good agreement with most of the members for the north side. In addition, both the members and the control forecasts underestimate the observed heavy rainfall along the Abruzzo coast if compared with the observations (Fig.2b).

3.1 Ensemble precipitation statistics

The information provided by the EPS relies on the analysis of three different statistics derived from the ensemble members distribution:

- ensemble mean from the 20 ensemble members and the control run;
- mean-related spread, which is the standard deviation (variability of the event representation) of the members respect to the ensemble mean. This provides an estimation of the reliability or uncertainty which characterizes the ensemble mean forecast;
- probability of the rainfall (or any other meteorological variables) exceeding a given threshold. This statistical analysis is derived mapping the ensemble members distribution respect to the threshold.

To avoid the linear dependency between standard deviation value and mean ensemble precipitation, a normalized ensemble spread is computed, where the value of the ensemble standard deviation is normalized to the corresponding ensemble mean. This allows to assess the precipitation uncertainty independently from the amount of rainfall. For what concerns the threshold in figure 5c has been arbitrarily defined and it can be adjusted in function of regional/local features, season and length of the forecast period; at each time step and for each grid point the following is computed (Eq. 1):

$$if \qquad var(i) > threshold \qquad then \qquad freq = \frac{\sum_{i=1}^{t_{mem+1}} i}{t_{mem+1}} \tag{1}$$

where var(i) is any meteorological variable of the i-member ; t_{mem} is the total number of the members.

The comparison between the 12h accumulated ensemble mean precipitation at 12 UTC on November 15, 2017 computed using all members (Fig.5a) and the control simulation clearly shows a reduction of the precipitation on the southern Abruzzo region with respect to the control run (Fig. 4a). This is an expected result confirming the dampening effect of the ensemble mean if compared to the deterministic simulation at the same resolution. For this event, even though this latter takes advantage of best GFS forecast IC, it produces a forecast poorer than the one using all members. In fact, unlike the control simulation, the ensemble mean partially reduces the underestimation of precipitation along the coast of Abruzzo region and reduces the

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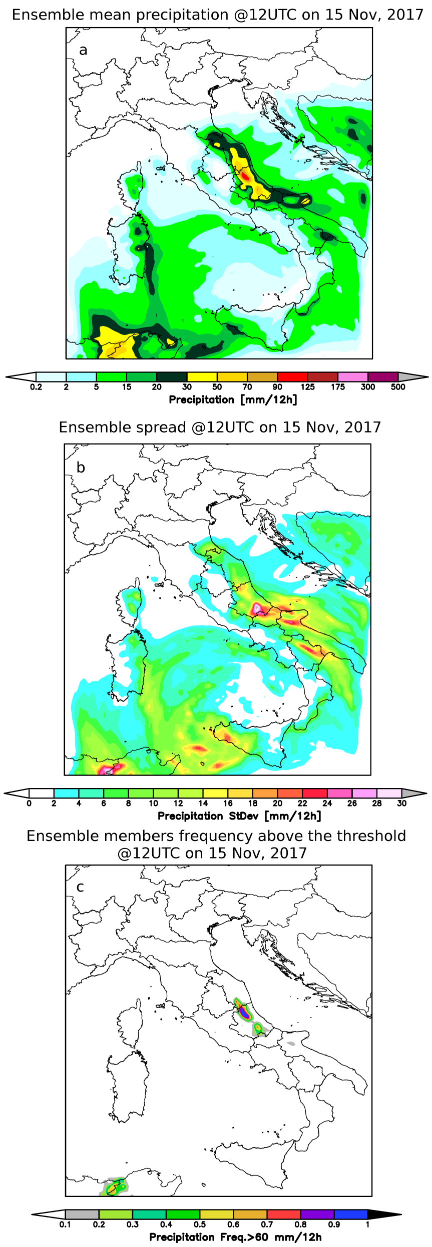

Figure 5. 12hours accumulated precipitation at 12UTC on Nov, 15 2017: a) Ensemble Mean precipitation, b) Ensemble spread, c) Ensemble probability of precipitation above 60mm/12h produced by the members

overestimation in the southern Abruzzo. However, it is noteworthy how the cell located in south Abruzzo shows higher values of the spread (Fig. 5b) even if characterized by less accumulated precipitation, suggesting a larger uncertainty in the southern

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Abruzzo area, for this event. Moreover, in correspondence of the most intense northern Abruzzo cell, there is a small ensemble spread. In fact the ratio between the standard deviation and the mean is close to zero. This gives good confidence to the precipitation predicted by the ensemble mean. Beside ensemble mean value and related uncertainty, the characterization of severe-to-extreme events represents a focal point yet. At this regard, the probability of accumulated precipitation above 60mm in 12 hours is shown (Fig. 5c) where almost the whole ensemble (more than 90% of the members) agrees on predicting precipitation equal or beyond such a threshold, suggesting a quite confident forecast.

3.2 Ensemble precipitation time series

Finally, an analysis of the EPS precipitation time series at a few stations located at the foothills of the Apennine (Tossicia, Arsita, and Villa Santa Lucia,Fig. 6a) and along the coast (Giulianova, Pescara and Chieti, Fig. 6a) is presented. A comparison is performed among the ensemble members (blue lines), the ensemble mean (cyan line), the deterministic high resolution (HR, red line) forecast and the observation (black line). The two stations along the coast (Pescara and Giulianova) show the maximum rainfall in the very early Nov 15, 2017 (Fig. 6 b, c, black line) starting from Giulianova. Both the ensemble mean and the HR simulations show a good agreement with the observation in the onset of the rainfall at Giulianova and Pescara, but a large underestimation is found at Giulianova for both simulations (Fig. 6,b red and cyan lines). On the other hand a very good agreement is produced by the ensemble mean at Pescara (Fig. 6, c cyan line) for both timing and amount of precipitation for the first peak in the early morning of Nov 15, 2017, but the largest peak of precipitation at the end of the event is misrepresented by both ensemble mean and HR. At both stations the HR produces a second peak which was not observed. At Chieti station a fairly good timing is found for both ensemble mean and HR simulations, but an underestimation of the amount of precipitation is found (Fig. 6, d red and cyan lines). For what concerns the stations at the foothills (Tossicia, Arsita and Villa Santa Lucia) still a timing disagreement is found but the amount of rainfall is better reproduced by both HR and ensemble mean (Fig. 6, e, f, g, black, red and cyan lines) suggesting a more accurate forecast if the orographic forcing is playing a key role.

4 Hydrological model

The CHyM hydrological model was developed at CETEMPS by the hydrological group since 2005 and since then it runs operationally (Tomassetti et al. , 2005; Coppola et al. , 2007; Verdecchia et al. , 2008) producing alert mapping service to support Abruzzo Regional Functional Centre decisions. The model is based on the kinematic wave approximation (Lighthil and Whitam , 1955) of the shallow water wave and the continuity and momentum conservation equations are used to simulate the surface routing overland and the channel flow. The CHyM model is a distributed grid-based hydrological model reaching a spatial resolution of 300m; it includes an explicit parameterization of different physical processes contributing to the hydrological cycle. CHyM is initialized using different sets of precipitation data which are assimilated and merged in a hierarchical way at each time step. The model can be used for any geographical domain up to the Digital Elevation Model (DEM) resolution and the drainage network is extracted by a sequence of native algorithm. The interpolation methods for DEM smoothing and meteorological variables spatialization are based on Cellular Automata-based algorithm (Wolfram , 2002; Coppola et al. , 2007).

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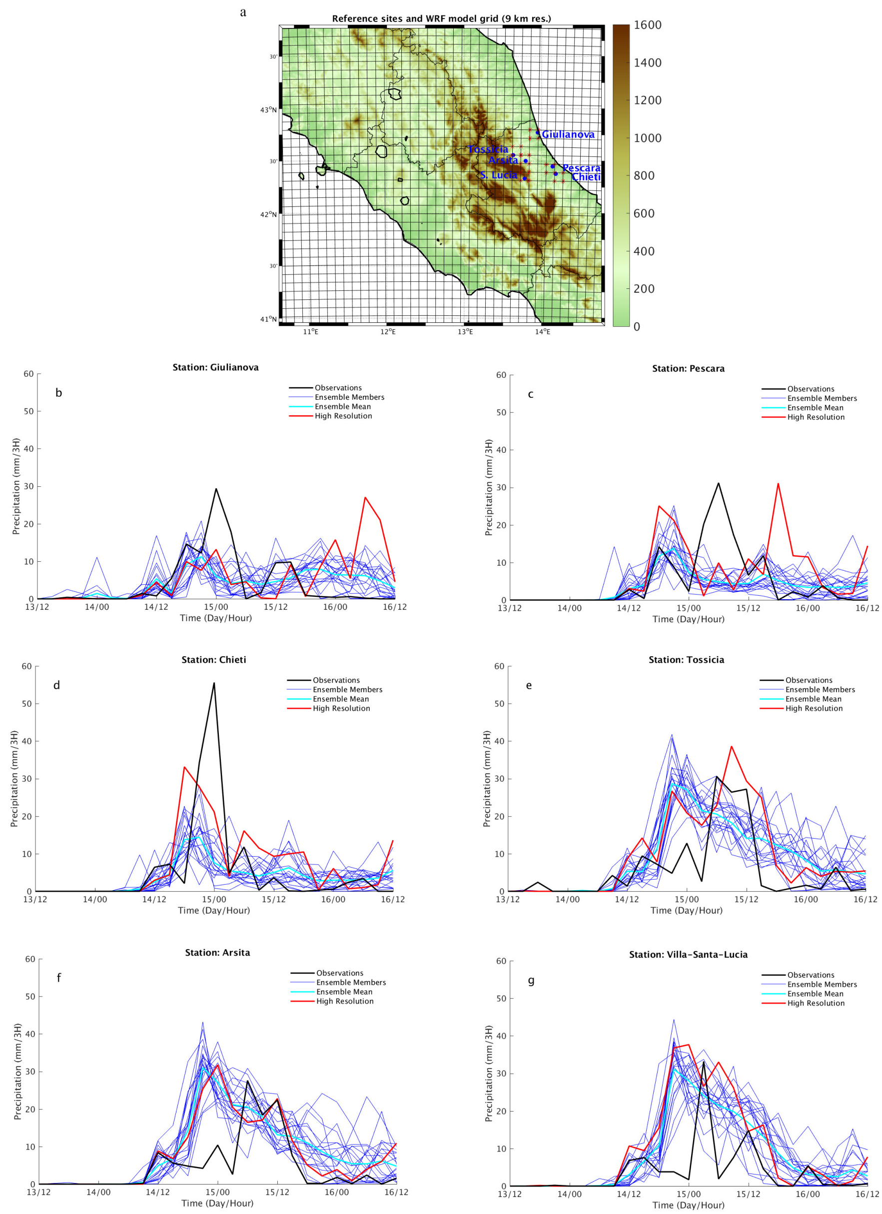

Figure 6. a) Location of the reference stations. Time series of precipitation at a few stations: b) Giulianova, c) Pescara , d) Chieti, e) Tossicia, f) Arsita, g) Villa-Santa Lucia for the ensemble mean (cyan line), ensemble members (blue lines), HR (red line) and observation (black line).

For the Abruzzo Region operational activity, CHyM runs at a spatial resolution of 300m and it is initialized using observed precipitation and temperature data for a spin-up time of 120 hours. The following 48 hours forecast is produced using the

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meteorological model forecast. For this case study, the same operational configuration is used: CHyM is forced with observed meteorological data until 23 UTC of 13 November 2017 and with WRF data for the following 48 hours. The control simulation is carried out forcing CHyM with observed data only.

4.1 BDD index

The analysis of the hydrological forecast is presented in terms of the hydrological stress index the Best Discharge-based Drainage (BDD, mm/h) which is able to detect catchment segments that are most likely to be stressed by severe weather. The use of a hydrological stress index is necessary because of the lack of discharge measurements over the considered basins.The BDD index is computed at each grid point at two different time steps as the ratio between the flow discharge and the squared hydraulic radius that is function of the drained area, following Eq. 2:

$$BDD_{(i,j)} = \frac{max_{t_1 \to t_2} Q(i,j)}{R(i,j)^2} \tag{2}$$

where Q is the discharge, R is the hydraulic radius and t_1 and t_2 are two time steps used for the computation and i and j are the grid points.

Two warning thresholds are defined for the BDD index: a medium (orange) and a high warning (red), with a similar meaning to those defined by the Civil Protection authorities for the hydrometric height (Thielen et al. (2009), Fig. 7). Moreover, as the

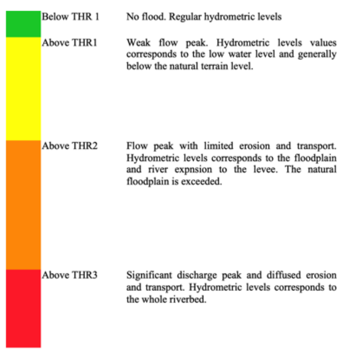

Figure 7. Hydrometric level warning thresholds and their significance.

BDD index is based on the relationship between the computed discharge and the river geometry at each grid-point, the defined thresholds are general and applicable over the whole drainage network. These characteristics makes the index a strong user-oriented instrument. To assess the flood event occurrences, the hydrometric level threshold exceedances or not-exceedances for the official station network belonging to the Abruzzo Functional Centre (CFA) is detected for this case study at the station level. A more complete geolocation of registered flood events, outside instrumented fluvial segments, is also inferred from local authorities reports (fire fighters, civil protection volunteers, police) as shown in figures 8 and 9.

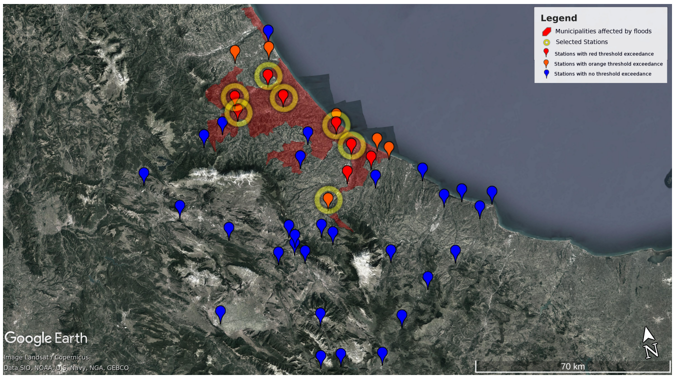

Figure 8. A map on Google Earth showing the geolocation of the hydrometric sensors over the Abruzzo Region (pinpoints) color code based on the warning threshold exceeded during the event. Yellow-circled sensors represents the subgroup where the analysis at station level is presented. The red areas correspond to the municipalities affected by flood.

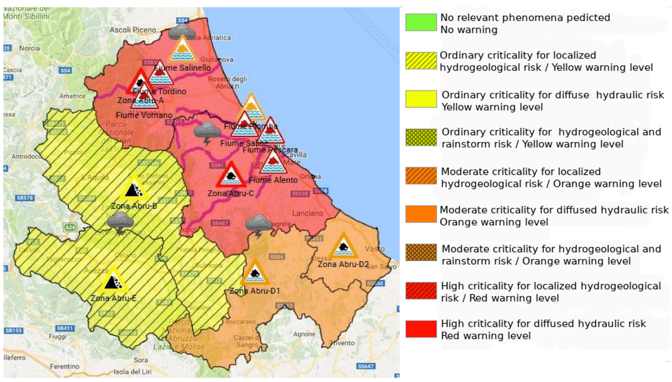

Figure 9. Hydrogeological Criticality Bullettin issued by the Civil Protection in the morning of 15 November 2017, where the Abruzzo region territory is divided into six warning areas (indicated with the prefix 'Zona Abru'), coloured according to the legend included. Triangle-shaped, thin-bounded signs are geolocated over relevant hydrometers and coloured according to the colour-code explained in figure 7, resulting from observed data. Triangle-shaped, thick-bounded signs indicates the forecasted warning level in the reference warning area. Yellow triangle indicates landslide risk at warning area level, while, thunderstorm risk is assigned through figurative icon. Purple lines on the coastal warning areas highlight river segments where the red threshold has been overpassed.

A preliminary evaluation of the BDD index is now presented. Figure 10 shows a comparison, between two different, even though related, physical quantities: the recorded water level time series (hourly data in m) and the corresponding BDD time series obtained from the CHyM control simulation, for 7 relevant stations highlighted (yellow circle) in figure 8. The CHyM control run is here assumed as the reference for the BDD threshold definition.To this aim the two quantities (BDD index and water level) are normalized to their maxima. It has to be pointed out that the BDD index obtained from the CHyM control simulation will be used in what follows as reference product for the BDD index itself and the meteo-hydro ensemble chain because of the lack of discharge observations. The comparison is qualitative and mostly focused on the threshold exceedance and maximum timing accordance between the index and the hydrometric level curves. From north to south the following rivers are accounted: Vomano, Tordino, Saline and Pescara (Fig. 9). The BBD index correctly reproduces the timing and the hydrometric level peak (Fig. 10, red and blue lines respectively) for the Vomano, Tordino, Saline and Pescara (Fig. 10 a,b,c,d,e, f and g, respectively). On the other hands, at the Alanno hydrometric station (Pescara river, Fig. 10g), both the BDD index and water level do not exceed their own high warning threshold. A further confirmation of the goodness of this result is obtained by analyzing the Hydrogeological Criticality Bullettin issued by the Civil Protection in the morning of 15 November 2017, for these rivers. The alert map (Fig. 9) shows all these rivers in red color clearly suggesting a risk for flood. On the other hand, for the Pescara river at both Alanno and Santa Teresa stations (Fig. 10, f and g) a few disagreement are found: besides the maximum, the hydrometric level peak is overestimated. Note also that Vomano, Tordino and Pescara rivers are heavily impacted from water uptake for hydropower production and hydrometric level peak time can be affected by human management which is not considered in the hydrological simulations. Therefore, the good performance of the BDD index for this event for the Abruzzo rivers allows to use it for the following analysis.

5 Hydrological model results

To the aim of highlighting differences resulting in the hydrological forecasts a few experiments are performed (Table1) using the WRF-CHyM chain with different initializations. An experiment is performed by using the WRF ensemble mean, a second one by using the deterministic high-resolution simulation and, finally, a hydrological ensemble is built. Hence two different ensemble meteo-hydro configurations are tested:

- a pseudo-hydro ensemble forecast where the hydrological model is forced by the mean precipitation produced by the WRF 21-member ensemble (Fig. 11,a);
- a CHyM ensemble composed by 21 members initialized using the 21 WRF members (Fig. 11,b) which will be presented in the next paragraphs.

For what concerns the hydro-ensemble, the uncertainty (i.e., ensemble members spread) is provided by WRF regional ensemble in the first case, whereas a contribution by the hydrological model is expected in the second one.

5.1 Pseudo hydro-ensemble versus hydro-deterministic

At first, a CHyM simulation using WRF temperature and precipitation ensemble mean is performed. By means of quantifying reliability of ensemble mean driven hydrological forecast, 24 hours BDD stress index maps obtained considering ensemble mean driven CHyM simulation and observed values (Fig.12, b,c) are compared, for 15 November 2017. High values (warmer

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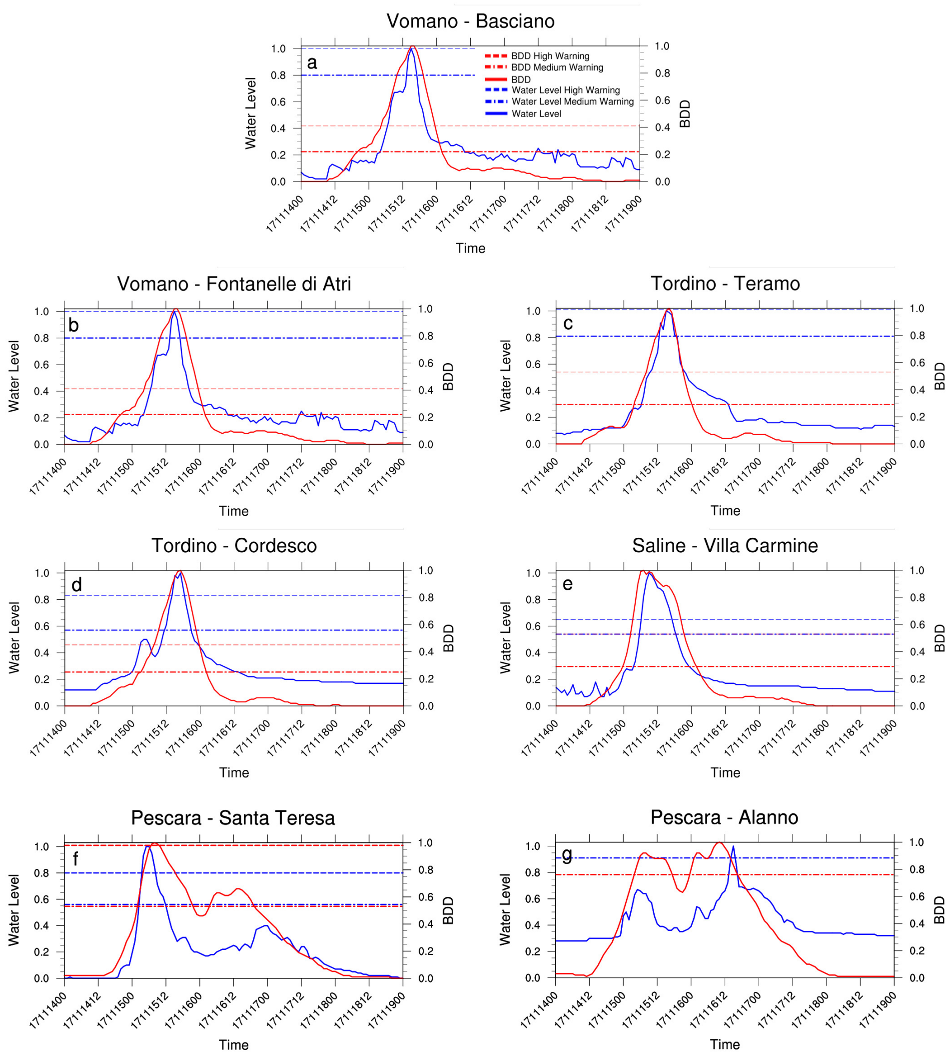

Figure 10. Normalized BDD time series and water level for catchments Vomano, Tordino, Saline and Pescara at stations: a) Basciano(Vomano); b) Fontanelle di Atri (Vomano); c) Teramo (Tordino); d) Cordesco (Tordino); e) Villa Carmine (Saline); f) Santa Teresa (Pescara) ; g) Alanno (Pescara); BDD index red lines, observed water level blue lines

colors) of BDD highlight fluvial segments characterized by a high level of hydrological stress, where flooding are most likely to occur. The map is obtained by assigning to each grid cell of the drainage network the maximum hourly BDD index obtained from 00 UTC to 23 UTC of the 15 November 2017, according to Eq. 3. This map (Fig.12, a) represents the worst situation expected during the day over the regional hydrography. The comparison between the BDD observed map (Fig.12, a) and the figures 8 and 9, where actual flooded areas are highlighted along the central and northern Abruzzo drainage network, along the main river channels, as well as smallest ones, shows a good spatial coherence. Southern rivers are partially involved in the

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Model	*Input*	*Output*	*BDD*
CHyM	mean from all WRF members	CHyM output	BDD mean
CHyM	each WRF member	20 members CHyM output	BDD probability
CHyM	WRF CNTR	CHyM output	BDD
CHyM	HR WRF forecast	CHyM output	BDD (from HR)
CHyM	Observation	CHyM output	BDD observation

Table 1. CHyM simulations

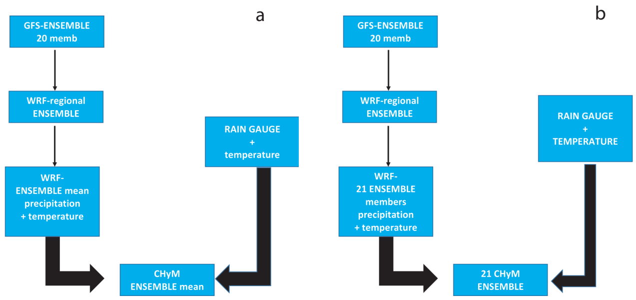

Figure 11. Outline of the two proposed ensemble forecast chains: a) the hydrological model is forced with ensemble mean precipitation and temperature (one hydrological simulation); b) the hydrological model is forced with every member of the meteorological ensemble, included the control run (21 hydrological simulations). In both cases, the CHyM model has been forced with observed meteorological data for 120 hours before the event (until 23 UTC of 13 November 2017).

event, being affected by a moderate overflow and BDD index slight overestimates the hydrological stress over these areas. The BDD map obtained using the 21 members averaged precipitation (Fig.12, b) shows a good agreement with the hydrological control run (Fig.12, a), for the main catchments over central-northern Abruzzo on the Adriatic side. However, an overestimation along the coast in the south side of Abruzzo region and an underestimation in the north side is found for the small catchments for the ensemble mean driven CHyM simulation. This is caused by an underestimation of the rainfall along the coast (Fig. 5,a) by WRF as well. In this condition, the main contribution to the hydrological stress (i.e. BDD index) is given by the heavy rainfall produced on the mountains which is able to charge the longest rivers, whereas the shortest streams nearby the coast do not receive enough precipitation to turn on (warm color) the BDD index. Furthermore, the hydrological stress is overestimated in the southern part of the domain (Fig.12, b). To further verify the CHyM forecast driven by the WRF regional ensemble mean a comparison with the deterministic high resolution forecast (HR) is performed. This output is used for forcing CHyM producing a BDD index (Fig.12, c) very similar to the index map resulting from the hydrological control run (Fig.12, a). In this configuration, the CHyM model is able to capture a higher hydrological stress over the small catchments in the northern coastal area of Abruzzo (Fig.12, c, red color), that are missed in the CHyM simulation forced by the WRF ensemble mean precipitation

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(Fig.12, b, light blue). On the contrary, the smallest flooded fluvial segment along the coast, as the Calvano stream (in the north side of Abruzzo but southern of the previous one), are not flooded by the deterministic run even if heavy precipitation was recorded. This is caused by precipitation not catched by the meteorological model because occurring only on a very small area. The stress index over the southern catchments is overestimated, as well. A further verification of the goodness of these results is obtained by comparing the BDD index maps with the alert map issued by the Department of Civil Protection of Abruzzo for these rivers (Fig. 9) where a risk of flood was issued. Hence, these results would suggest an overall good performance of both the CHyM driven by the deterministic high resolution forecast and the one driven by the WRF regional ensemble forecast.

5.2 CHyM Ensemble

Finally, a CHyM hydrological ensemble forecast is built by performing 21 simulations using the 20 members and the control forecast produced by the WRF-ensemble as initial conditions (Fig. 11,b). The output of the 21 CHyM members is used to build a probability BDD$_{prob}$ index (Fig.13) which is computed by the following equation:

$$BDD_{prob} = \frac{N_{BDD}}{N_{ens}} \quad (3)$$

where N_{BDD} is the number of members for 24h BDD above the high warning threshold and N_{ens} the total ensemble members (20, excluding the WRF control run).

To verify this BDD$_{prob}$ index, a comparison with the alert map issued by the Civil protection agency during the event (Fig.8 and 9) is presented. Maximum flood probability is found over the northern Adriatic-side catchments (Fig. 13a), where almost all members simulates precipitation peaks, according to the observations and according to the deterministic WRF-HR set-up (Fig.12, c). Small catchments stress is not simulated over this area, because of a general underestimation of the precipitation amount in the costal area, probably caused by to the lower horizontal resolution used in the meteorological ensemble. An improvement by the CHyM ensemble is clearly obtained as it is shown by the BDD$_{prob}$ index over the southern part of the region (Fig. 13a) , where the overestimation of the stress condition detected by forcing CHyM using the WRF mean average (Fig.12, b) is not found, coherently with the real hydrological effect caused by the event in that area. The CHyM ensemble spread is also computed (Fig. 13b), in order to give a complementary information to the BDD$_{prob}$ map. The large value for the spread of the precipitation in the southern Apennine's ridge produced by WRF regional ensemble (Fig. 5c) has implications on the largest catchment of southern Abruzzo: the maximum BDD spread is here obtained for the main catchment, corresponding to the Sangro river, whereas in the northern part of the domain the spread is smaller confirming the reliability of the flood forecast. These results suggest a linear relation between the WRF variability and the CHyM one.

5.3 CHyM time-series

To the aim of further evaluating the ability of the hydrological ensemble to correctly reproduce the stress distribution, an analysis of the BDD index time series at a few stations is also presented. The CHyM control run using meteorological observations as input is compared with: the one produced by the pseudo-hydro ensemble forecast where the hydrological model is forced by

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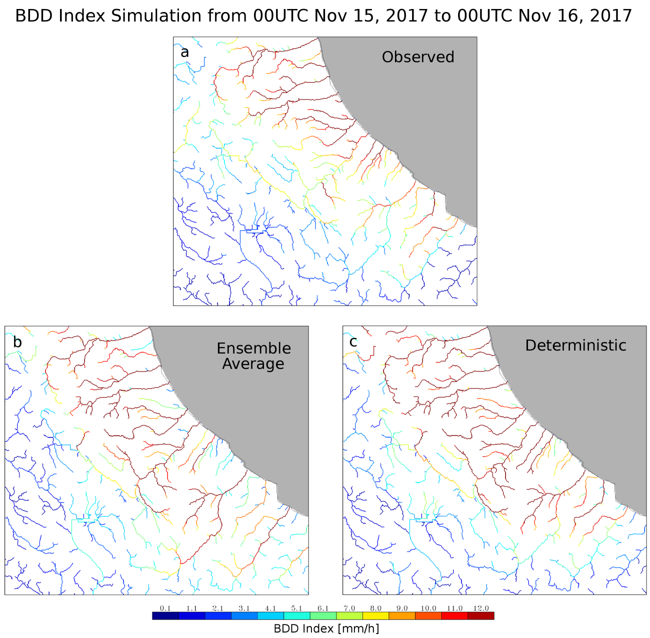

Figure 12. BDD index computed by CHyM using: a) the observed accumulated precipitation; b) the mean precipitation produced by the WRF ensemble; c) the precipitation produced by the deterministic wrf @ 1km (HR)

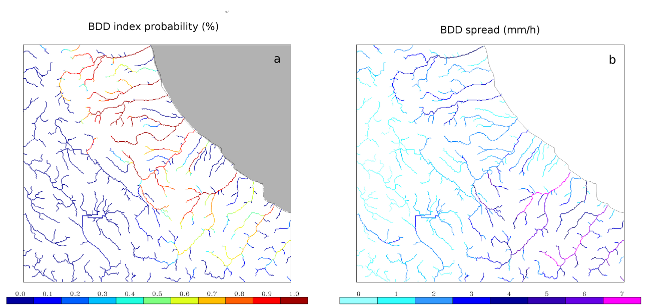

Figure 13. a) BDD probability index computed forcing CHyM with the 21 WRF members; b) CHyM ensemble spread.

the mean precipitation produced by the WRF 21-member ensemble; the CHyM ensemble composed by 21 members initialized using the 21 WRF members; CHyM simulation forced using the HR deterministic forecast. In what follows the BDD index time series are presented for all the CHyM simulations except for the 21 CHyM ensemble mean because it is similar to the one produced by the CHyM forced by the WRF ensemble mean precipitation. This would suggest a variability of the ensemble produced by the meteorological input only and that there is no contribution on the variability coming from the hydrological model. This result agrees with what found for the CHyM ensemble spread. Both the mean and spread similarity between WRF and CHyM strongly suggest that the uncertainty in this study is underestimated; to increase it, a contribution by the hydrological model should be accounted by perturbing the geometry of the system and other model parameters. The BDD index time series for the stations along the rivers Vomano, Tordino, Saline and Pescara (from north to south) shows (Fig. 14) a BDD spread between 10 and 20 mm/h around the peak. The CHyM simulation forced using the ensemble mean precipitation (Fig. 14, green line) is overestimated at the Pescara river stations, if compared with the BDD time series obtained using the hydrological control run (black line). Moreover, it results in a red BDD threshold exceedance at the Pescara Alanno station, that was actually affected by an orange threshold exceedance, only. As for the timing, there is a different behavior between the northern basins and the central ones. For the northward catchments (Vomano and Tordino), the ensembles-modeled peak timing is progressively simulated up to 6 hours in advance (Fig. 14, a , b, c and d respectively green and black lines), respect to the control hydrological simulation. At the Saline-Villa Carmine station, in the central area, the maximum of the BDD index is reproduced with high timing accuracy (Fig. 14, e, black and green lines), whereas an approximately 12 hours of delay at the Pescara river station (south area) is found (Fig. 14, f and g respectively; black and violet lines). The hydrological simulation using the HR WRF input seems to be not affected by the aforementioned time shift. These results would suggest a contribution from the WRF error in the timing of the maximum peak as it is found at several stations (Fig. 6) propagating in the CHyM forecasts.

6 Conclusions

On November 15, 2017 a severe hydrological event hit the Abruzzo region, causing damages with a high social and economic impact on human activities. This event is used to investigate the reliability of a meteo-hydrological ensemble chain. An operational and portable meteo-hydrological forecast system is implemented and tested at CETEMPS over the Abruzzo Region basins. The results of both the meteorological regional ensemble and the coupled meteo-hydrological ensemble chain are discussed and compared with the observations and the results of a deterministic meteorological model. The meteorological ensemble well reproduces the event in terms of heavy precipitation area identification, as well as its onset and length. A further comparison with the observed precipitation and the deterministic, high-resolution meteorological model precipitation time-series at station level supports this conclusion. The meteo-hydrological ensemble chain results are discussed in terms of the hydrological BDD stress index able to identify catchment segments that are most likely to be stressed by weather extremes. The evaluation of the BDD index, as a user-oriented instrument to assess the flood risk over the Abruzzo Region drainage network, is carried out by comparing the occurrence of the index thresholds exceedance in the control hydrological simulation and the corresponding water level thresholds exceedance, at station level: they show a good agreement. At this regard, it should be taken into account that the BDD index obtained from the CHyM control simulation is used as reference product for the BDD index itself and the meteo-hydro ensemble chain, because of the lack of discharge estimations and of updated rating curves. Moreover, the BDD thresholds are extendible to each grid-point of the drainage network and are used to produce a hydrological stress map over the whole spatial domain. The BDD maps are also compared with the hydrogeological criticality bulletin released during the event, in order to emphasize and confirm the spatial coherence between hydrological control simulation and detection of actual flooded areas. Moreover, a very good performance of the BDD index (for both maps and time series) is found using the HR forecast. Besides the BDD index, a BDD probability index and the associated spread are built using the 21 members of the CHyM ensemble. The index allows for estimating the probability of a flooding events, which is not possible to estimate by both the deterministic forecast and the CHyM forecast forced using the ensemble mean. The comparison of the BDD_{prob} map with the BDD map produced with the hydrological control simulation points out a good reliability of this index for this event by both correctly identify flooded river segments and producing a small spread in these areas.

Hence we can summarize the major findings as follows:

- the pseudo-hydro ensemble forecast, that is the hydrological model forced by the mean precipitation produced by the WRF 21-member ensemble, well reproduces the alert map issued by the Civil protection agency during the event, conferring reliability to this tool;

- the CHyM ensemble composed by 21 members initialize using the 21 WRF members, produces the BBD probability maps which well agrees with the alert map issued by the Civil protection agency during the event slightly reducing the overestimation produced by the pseudo-ensemble especially in the south side of the Abruzzo region;

- the CHyM simulation forced using the HR deterministic forecast further reduces the over/underestimations produced by the ensemble mean forecast, especially over the smallest basins.

An advantage in using an ensemble prediction chain, in terms of Decision Support System efficiency, is the low computational cost if compared with a HR deterministic modeling chain. Even though high resolution meteorological model are useful to detect hydrological stress over the smallest basins, the EPS is found to be useful for an early identification of flood risk at warning area level. Hence, HR-deterministic and probabilistic-ensemble-based approaches should be considered as a complementary tools by using both. Indeed, the computationally cheaper ensemble approach allows for longer forecast periods, identifying days ahead potential damaging events, but HR still provides the best information in the very short term, thanks to its improved representation of regional to local scale dynamics.

An attempt is made to estimate the uncertainties in the precipitation forecast and how their errors propagate in the hydrological model if an ensemble approach is adopted. To this purpose a comparison is made between the BBD index time series extracted at station level, computed using CHyM forced by the WRF ensemble mean precipitation and temperature, and computed using the discharge field average calculated downline from 21 WRF members meteorological input. The results do not show differences and the CHyM ensemble spread reproduces a distribution similar to the WRF one. Hence no informations are obtained on how the weather prediction uncertainty propagates into the hydrological model. This result suggests that only uncertainty pertaining to the weather forecast is accounted, as it is traditionally done. To avoid the lack of uncertainty by the hydrological model the same probabilistic approach used for the meteorological model should be applied to the hydrological one. In a forthcoming work a sensitivity study to the hydrological model uncertainty that can be obtained by perturbing, for example, the geometry of the system, the model factors etc. will be performed.

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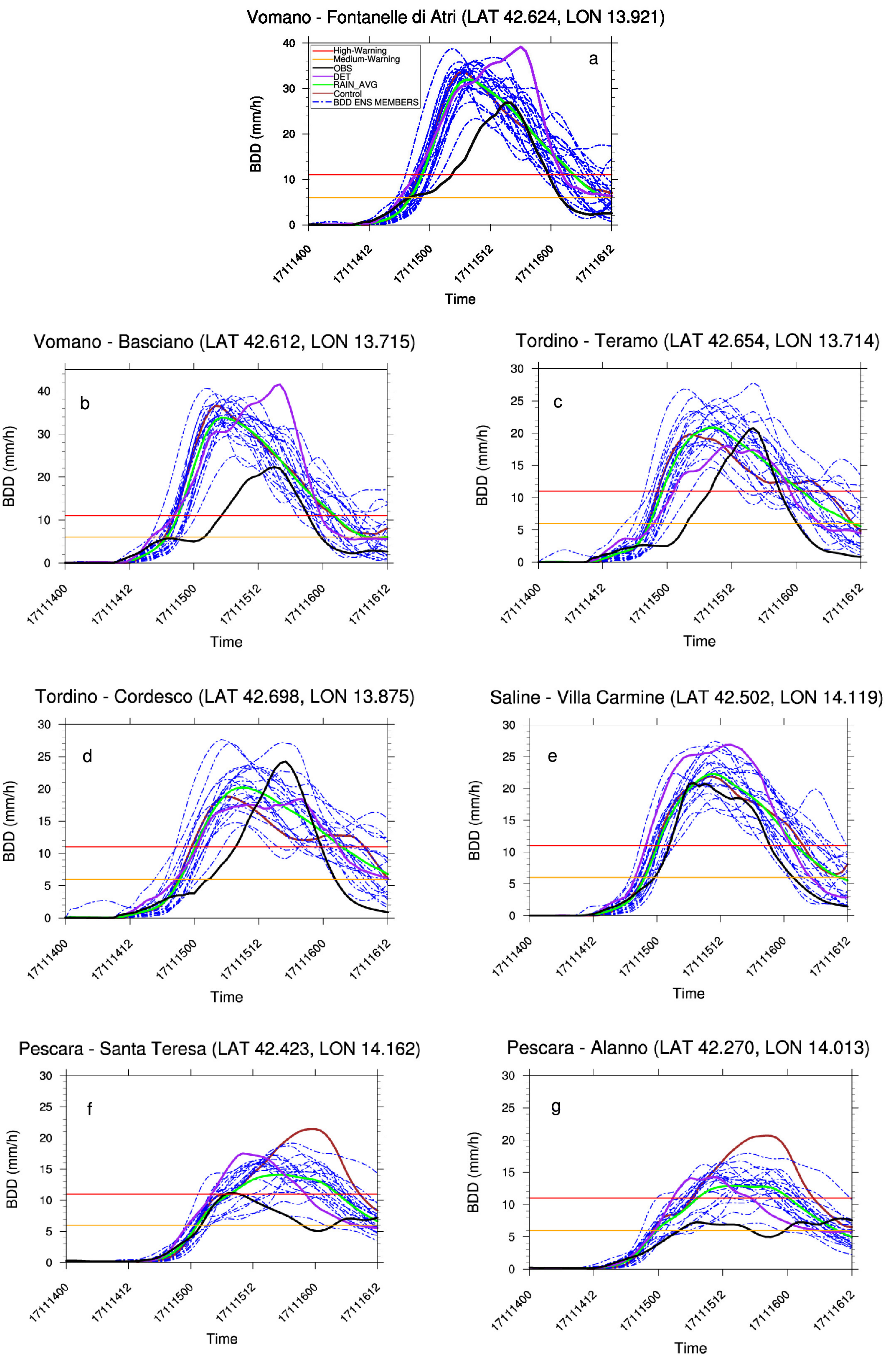

Figure 14. BDD time series for catchments Vomano, Tordino, Saline and Pescara at stations: a) Fontanelli di Atri (Vomano); b) Basciano (Vomano); c) Teramo (Tordino); d) Cordesco (Tordino); e) Villa Carmine (Saline); f) Santa Teresa (Pescara); g) Alanno (Pescara)

Competing interests. The authors declare that they have no conflict of interest.

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