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Potentialities of ensemble strategies for flood forecasting over the Milano urban area

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SUMMARY

Analysis of ensemble forecasting strategies, which can provide a tangible backing for flood early warning procedures and mitigation measures over the Mediterranean region, is one of the fundamental motivations of the international HyMeX programme. Here, we examine two severe hydrometeorological episodes that affected the Milano urban area and for which the complex flood protection system of the city did not completely succeed. Indeed, flood damage have exponentially increased during the last 60 years, due to industrial and urban developments. Thus, the improvement of the Milano flood control system needs a synergism between structural and non-structural approaches. First, we examine how land-use changes due to urban development have altered the hydrological response to intense rainfalls. Second, we test a flood forecasting system which comprises the Flash-flood Event-based Spatially distributed rainfall–runoff Transformation, including Water Balance (FEST-WB) and the Weather Research and Forecasting (WRF) models. Accurate forecasts of deep moist convection and extreme precipitation are difficult to be predicted due to uncertainties arising from the numeric weather prediction (NWP) physical parameterizations and high sensitivity to misrepresentation of the atmospheric state; however, two hydrological ensemble prediction systems (HEPS) have been designed to explicitly cope with uncertainties in the initial and lateral boundary conditions (IC/LBCs) and physical parameterizations of the NWP model. No substantial differences in skill have been found between both ensemble strategies when considering an enhanced diversity of IC/LBCs for the perturbed initial conditions ensemble. Furthermore, no additional benefits have been found by considering more frequent LBCs in a mixed physics ensemble, as ensemble spread seems to be reduced. These findings could help to design the most appropriate ensemble strategies before these hydrometeorological extremes, given the computational cost of running such advanced HEPSs for operational purposes.

1. Introduction

The number of great natural catastrophes is increasing worldwide. Among these, flood is the worst hazard causing thousands losses of life and damage to property (Munich Re, 2014). The HyMeX (HYdrological cycle in the Mediterranean EXperiment, http://www.hymex.org) program is an international effort aimed at advancing in the scientific knowledge of the water cycle variability from a seamless approach. A better understanding, modelling and forecasting of hydrometeorological extremes over the flood-prone Western Mediterranean region is one of the milestones of HyMeX (Drobinski et al., 2014). To reduce flood losses, real-time flood forecasting systems based on coupling meteorological and hydrological models are synergic to structural measures by issuing warnings in advance (Amengual et al., 2007, 2015; Rabuffetti et al., 2008; Ceppi et al., 2013). Despite the widespread use of real-time flood forecasting systems and the great steps that have been taken by hydrometeorologists, many open issues still remain when dealing with flash floods affecting urban areas and catchments of small dimensions (Silvestro et al., 2015).

One major issue concerns the land-use change due to urban developments that alters the basin response to intense precipitation. With less storage capacity and more rapid runoff, urban river basins rise more quickly during storms and have higher peak discharge rates than rural catchments. In addition, developments along stream channels and floodplains can alter the capacity of a

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canal to convey water and can increase the height of water surface corresponding to a given discharge.

A further issue when dealing with urban flash floods is the accuracy of Quantitative Precipitation Forecasts (QPFs). Major floods at small drainage areas are mostly generated by convective systems characterized by heavy precipitation and short duration. The use of high-resolution Numerical Weather Prediction (NWP) models is effective to capture the triggering and subsequent evolution of the convectively-driven precipitation systems that are directly linked to small-scale dynamics and are highly sensitive to local topographic features (Leoncini et al., 2013; Fiori et al., 2014). Nowadays, convection-permitting models are suitable for the spatial and temporal scales of small- and medium-size flood-prone basins. QPFs can be directly used to drive rainfall–runoff models without the need of implementing additional downscaling procedures (Amengual et al., 2008; Addor et al., 2011; Vincendon et al., 2011).

Nevertheless, accurate numerical simulation of deep moist convection and extreme precipitation is difficult owing to: (i) complexity, uncertain definition and highly nonlinear character (also affecting their interrelations) of the physical parameterization schemes used in NWP models; and (ii) its sensitivity to any misrepresentation of the initial atmospheric state or boundary forcing across the relevant convective and meso-scales. Indeed, these errors can grow rapidly during the forecast horizon, strongly penalizing the quality of the nonlinear system forecast (Mullen and Baumhefner, 1988; Toth and Kalnay, 1993; Houtekamer and Derome, 1995; Du et al., 1997). Thus, QPFs uncertainties arise from both the initial and lateral boundary conditions (IC/LBCs) and from physical parameterizations of the NWP model. When dealing with flood risk in small-size catchments, the provision of correct spatial and temporal QPF distributions is paramount, as small errors can relatively result in misleading Quantitative Discharge Forecasts (QDFs), preventing the issuance of precise and dependable early flood warnings (Le Lay and Saulnier, 2007; Amengual et al., 2007, 2009; Bartholmes et al., 2009; Cloke et al., 2013).

Ensemble prediction systems (EPSs) aim at forecasting the set of plausible outcomes and accounting for the most relevant uncertainties in the forecasting system. Uncertainties in the initial and boundary fields can be encompassed by conveniently perturbing IC/LBCs (Buizza, 2003; Grimit and Mass, 2007; Hsiao et al., 2013). NWP model errors for QPFs arise mainly from the imperfect representation of convection, planetary boundary layer (PBL) processes, land physics and moist microphysical processes (Stensrud et al., 2000; Jankov et al., 2005; Tapiador et al., 2012). Uncertainties in model parameterizations are coped by populating the ensemble with multiple combinations of equally-skillful physical schemes.

When driving hydrological models for flood forecasting purposes, EPSs can be used to convey these external-scale uncertainties and to construct hydrological ensemble prediction systems (HEPSs). The inclusion of these external-scale uncertainties aims at improving the skill and spread of the HEPSs by introducing independent information of all plausible atmospheric states. However, the most suitable methods for generating HEPSs and the quantification of their added value are still under investigation (Cloke and Pappenberger, 2009; Cloke et al., 2013).

Alternative statistical methods to explore meteorological forecast uncertainty require numerous samples that satisfy the assumption of historic precipitation events sharing the same statistical characteristics with the precipitation event being forecast (Lee et al., 2013). In the current paper, we decide to explore the predictive skill of a perturbed IC/LBCs scheme (PIBL) and a multiple physical scheme (MPS) as ensemble strategies for short-range flood forecasting. To this end, we examine separately the impact of the IC/LBCs and NWP model errors into the skill of QPFs and QDFs for two of the most critical events of the last 20 years affecting the Milano urban area, northern Italy. We assess the skill of each ensemble strategy to predict the exceeding of a given threshold through the physically-based distributed hydrological FEST-WB model (Rabuffetti et al., 2008). Performance of physically-based distributed approach is generally shown superior than a lumped one in the case of extreme flood events (Carpenter and Georgakakos, 2006; Moore et al., 2006) and can be suitable to issue public warnings with a threshold based methodology (Reed et al., 2007).

An understanding of how these distinct EPS strategies perform and how the external-scale uncertainties propagate into the HEPSs is crucial for an optimal design of an operational hydro-meteorological forecasting system in the area. The rest of the paper is structured as follows: Section 2 consists of a brief description of the study area, land use change, and study cases; Sections 3 and 4 describe the hydrological and meteorological tools; Section 5 discusses the results; and Section 6 provides an assessment of the methods used, including further remarks.

2. Data and case studies

2.1. Study area

Milano is one of the most populous cities in Italy (1,316,000 inhabitants live in 182 km^2), and is also one of its most important economic areas. A large region from the Italian PreAlps drains to Milano (Fig. 1). The main rivers are the Lambro (area of 500 km^2), Seveso (area of 207 km^2), and Olona (area of 208 km^2), plus a number of minor tributaries for a total drainage surface of about 1300 km^2.

In the past, the Milano urban area has been subjected to a high flood hazard and, in fact, during the 1970s a series of risk mitigation works were carried out with the aim of reducing the exceeding discharges flowing through the urban areas. The main work consisted in the construction of a bypass channel (CSNO, acronym from Italian "Canale Scolmatore di Nord Ovest") with a maximum capacity of 30 m^3/s, which collects the excess of discharge from the Seveso River, preventing their entry into the city. In the upper Lambro River Basin, the regulated Pusiano Lake acts as a storage basin with respect to flood events, while more recently, in 2010 an on-stream detention basin (Ponte Gurone dam) was built on the Olona River near Varese city, just upstream the hydrometric station (Section 1 in Fig. 1). The maximum storage capacity of this reservoir is 1,520,000 m^3 accounting for a total drainage area of 3.83 km^2. The Ponte Gurone dam is regulated through three automatic gates to keep a released rate below 36 m^3/s, which is considered as the maximum allowable discharge for downstream locations. The complex existing structural engineering works alter the natural response of river basins and make calibration of hydrological models more difficult.

The complex flood protection system of the city did not completely succeed in the recent years; hence, the implementation of a hydro-meteorological chain can provide an additional support as a non-structural method for early warning systems. In fact, since lag times of these basins are a few hours (Table 1), alerts with sufficient lead time permit civil protection authorities and the public to exercise caution and take preventive measures to mitigate the impacts of flooding (Yang et al., 2015). In this study, we analyse 48 h forecasts initialized one day before the observed peak flood, as this lead time is considered sufficient and adequate by local authorities.

Available meteorological data are: precipitation and temperature, collected hourly by the telemetric monitoring system managed by the ARPA (Regional Agency for Environmental Protection) of the Lombardy region since 2003 and the