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Impact of improved meteorological forcing, profile of soil hydraulic conductivity and data assimilation on an operational Hydrological Ensemble Forecast System over France

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SUMMARY

A Hydrological Ensemble Forecasting System (HEFS) known as SIMPE has been run over France in real time by Météo-France since 2004. The system combines the 51-member, 10-day ECMWF EPS atmospheric forcing at a 1.5° resolution with the ISBA-MODCOU physically-based distributed hydrological model to provide streamflow forecasts over France. The initial conditions for all the HEFS runs are provided by SIM; i.e., the ISBA-MODCOU model forced by the outputs of the mesoscale meteorological analysis system SAFRAN. A previous study introduced and tested two improvements of this system over a past period. These modifications consisted of an improved representation of the profile of hydraulic conductivity and the implementation of a data assimilation subsystem. The purpose of the present study was to test the HEFS and its two modifications in operational mode, with the new higher-resolution ECMWF EPS atmospheric forcing at 0.25° resolution, available in real time on the Météo-France database, and with less observed discharge available for the data assimilation subsystem. The new ISBA physics scheme led to a notable improvement in the discharge simulation in western and northeastern France, where no aquifers were simulated by the MODCOU model. This improvement was not impacted by real-time conditions. Likewise, the improvement resulting from the data assimilation system applied over France was not significantly affected by real-time conditions. The propagation of the data assimilation correction to gauging stations located upstream or downstream of the assimilated stations limited the deterioration of forecasted streamflow due to real-time conditions. Finally, the ECMWF EPS high-resolution atmospheric forcing had a significant impact on the streamflow forecasts for small catchments, which increased with lead time.

1. Introduction

Over the last few decades, ensemble prediction systems (EPSs) have greatly contributed to the improvement of meteorological forecasts (Toth and Kalnay, 1993; Molteni et al., 1996; Buizza et al., 1999). These systems account for the uncertainty in the initial conditions and the representation of processes in numerical weather prediction (NWP) models. They include several members, representing an ensemble of possible atmospheric conditions. As opposed to deterministic weather forecasts, EPSs increase the lead time of high-quality forecasts beyond several days (Cuo et al., 2011). For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) has been providing 10-day ensemble weather forecasts since 1992 and 15-day ensemble forecasts since 2006 (Palmer et al., 2007). The use of EPSs is now common among operational meteorological centres (Park et al., 2008).

The availability of high-quality meteorological EPSs has led to the development of Hydrological Ensemble Forecast Systems (HEFSs). In these systems, meteorological forecasts from EPSs are used to force a hydrological model, which produces an ensemble of discharges or water levels. The uncertainty in the hydrological forecast may help end users to make better decisions (Boucher

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et al., 2012; Ramos et al., 2013). Therefore, many projects have been launched to examine this topic, such as the Hydrological Ensemble Prediction Experiment (HEPEX) (Schaake et al., 2006), which addresses the issue of hydrological forecast uncertainty, including uncertainty in meteorological forcing, hydrological modelling and final user needs. HEFSs have been used at the national scale since the 2000s (see Zappa et al., 2008 or Cloke and Pappenberger, 2009 for a more complete review of these systems in real-time conditions). HEFSs have also been developed at the European scale with the European Flood Forecasting System (De Roo et al., 2003), which subsequently led to the European Flood Alert System (EFAS) (Thielen et al., 2009a,b) and more recently, at the global scale, the Global Flood Awareness System (GloFAS), which provides forecasts for very large river basins (Alfieri et al., 2013). HEFSs now cover a large range of lead times from short-range (1–2 days) (Alfieri and Thielen, 2012; Marty et al., 2013; Vincendon et al., 2011) to medium-range (3–10 days) (Thirel et al., 2010a,b; Addor et al., 2011) to longer range, with monthly or seasonal water resources management (Yuan et al., 2013; Singla et al., 2012).

The improvement of HEFSs represents an important field of research. First, some works aim to improve the EPSs' performances. For example, Pappenberger et al. (2011) used a finer spatial resolution for the EPSs to improve their HEFS. Davolio et al. (2012) used many EPSs combined as input to their HEFS, such as TIGGE (THORPEX Interactive Grand Global Ensemble) (Bao and Zhao, 2012; Park et al., 2008). Another method is to improve the physics of the EPS (Tobin et al., 2012). Improvements can also focus on the hydrological model and its uncertainties: Nicolle et al. (2012) added a snow model to the hydrological model GR3P in order to improve forecasts in mountain watersheds, while Duan et al. (2007) used a multi-model approach to improve the representation of uncertainties related to hydrological processes. Some studies have added a data assimilation system to their hydrological model (Thirel et al., 2010a,b; Liu et al., 2012; MacMillan et al., 2012). Finally, a quantile–quantile correction can be applied to correct the distribution of ensemble forecasts (Verkade et al., 2013).

In France, a HEFS has been operational since 2004 over the entire country (Rousset-Régimbeau et al., 2007). The HEFS is based on the SAFRAN-ISBA-MODCOU (SIM) chain (Habets et al., 2008) of Météo-France and the ECMWF EPS, available at 1.5° resolution in the Météo-France operational database. Thirel et al. (2010a,b) developed and tested two modifications of this HEFS – an improved representation of the profile of hydraulic conductivity and the implementation of a data assimilation subsystem – in research mode. The objective of this work is to test the HEFS and its two modifications in operational mode, namely with the new higher-resolution ECMWF EPS atmospheric forcing at 0.25° resolution available in real time in the Météo-France database and with less observed discharge available for the data assimilation subsystem. Section 2 describes the original ensemble forecast system and the modifications applied. Then, Section 3 presents the data used for this study and the experiments carried out. The results are shown in Section 4. The discussion and the main conclusions of this work are presented in Section 6.

2. Description of the HEFS and its modifications

2.1. The SIMPE initial chain

The Hydrological Ensemble Forecast System used in operational mode at Météo-France is based on the hydrometeorological chain SAFRAN-ISBA-MODCOU (SIM). SIM consists of the meteorological analysis model SAFRAN (Durand et al., 1993, 1999; Quintana-Seguí, 2008), the land surface model ISBA (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) and the distributed hydrogeological model MODCOU (Ledoux et al., 1989). This chain was validated using discharge at around 500 gauges over France by Habets et al. (2008) and is used for operational soil wetness monitoring. SAFRAN provides the meteorological forcing to ISBA on an 8×8 km grid. ISBA simulates the water and energy fluxes between the atmosphere, the vegetation (interception, evapotranspiration), the soil moisture evolution and the runoff and infiltration fluxes. The soil contains three layers, characterized by their moisture: w1 for the superficial layer, w2 for the root layer and w3 for the deep layer. Finally, MODCOU transfers the runoff and infiltration produced by ISBA to aquifers and through the river network. Only two large aquifers are simulated in this version: the Seine (North of France) and the Rhone (East of France). The discharges, calculated at a 3 h time step, are averaged at a daily time step. This chain is called SIM-analysis.

The operational HEFS is based on the SIM system and is called SIMPE (for SIM-"prévision d'ensemble" in French). It is run daily and produces 10-day forecasts. The SIM-analysis chain provides the ISBA and MODCOU initial states. In forecast mode, the SAFRAN forcing is replaced by the 51-member meteorological ensemble forecast of the ECMWF. These forecasts are available at a resolution of 1.5° in the Météo-France operational database. In order to reduce computation costs, only precipitation and temperature are used; other atmospheric variables necessary for the ISBA model are assigned to the climatological means from the SAFRAN analysis between 1995 and 2003 (preliminary tests showed that the effect is negligible for 10-day hydrological forecasts). The rainfall and temperature values are interpolated over the SAFRAN grid, which is composed of 615 climatically homogeneous zones, by an inverse distance method. Then, the difference in elevation between the ECMWF and ISBA grids is taken into account by applying a vertical gradient of 0.65 °C/100 m for temperature and a gradient of +2 mm d^{-1} m^{-1} below 800 m and +0.7 mm d^{-1} m^{-1} above 800 m for precipitation (Rousset-Régimbeau et al., 2007). With the exception of these temperature and rainfall elevation corrections, the SIMPE chain does not have pre or post-processors. The SIMPE discharge ensemble forecast system described above has been used operationally since September 4th, 2004 and was validated over the period from September 4th, 2004 to July 31st, 2005 (Rousset-Régimbeau et al., 2007).

2.2. Modifications applied to the SIMPE initial chain

The three changes described below were introduced and evaluated: the use of an EPS at a finer spatial resolution, the improved representation of the profile of soil hydraulic conductivity and the implementation of a data assimilation system.

Since the operational implementation of SIMPE, several changes have been applied to the ECMWF EPSs, notably concerning its resolution and its physics. The resolution of the EPSs decreased from 120 km (1.125°) with 40 vertical levels to 80 km (0.7°) with 40 vertical levels, then to 50 km (0.45°) with 62 vertical levels in 2006 (Pappenberger et al., 2011) and finally to 30 km (0.25°) with 62 vertical levels in 2010. These increases in the model resolution were considered to have an important impact on the NWP quality (Buizza et al., 2008; Buizza, 2009). Changes in the convection scheme were also implemented in January 2003 and November 2007, with a large impact on the quality of the precipitation forecasts (Bechtold et al., 2004, 2008; Tompkins et al., 2004 in Pappenberger et al., 2011). All these improvements clearly contributed to the improvement in the EFAS hydrological forecasts (Pappenberger et al., 2011). The EPS time series at 0.25°, with 51 members and a 10-day lead time going back to January 2010, have been available in the Météo-France operational database since 2012. The replacement of the 1.5° EPS previously available at