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Integrating remotely sensed surface water extent into continental scale hydrology

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ABSTRACT

In hydrological forecasting, data assimilation techniques are employed to improve estimates of initial conditions to update incorrect model states with observational data. However, the limited availability of continuous and up-to-date ground streamflow data is one of the main constraints for large-scale flood forecasting models. This is the first study that assess the impact of assimilating daily remotely sensed surface water extent at a $0.1° \times 0.1°$ spatial resolution derived from the Global Flood Detection System (GFDS) into a global rainfall-runoff including large ungauged areas at the continental spatial scale in Africa and South America. Surface water extent is observed using a range of passive microwave remote sensors. The methodology uses the brightness temperature as water bodies have a lower emissivity. In a time series, the satellite signal is expected to vary with changes in water surface, and anomalies can be correlated with flood events. The Ensemble Kalman Filter (EnKF) is a Monte-Carlo implementation of data assimilation and used here by applying random sampling perturbations to the precipitation inputs to account for uncertainty obtaining ensemble streamflow simulations from the LISFLOOD model. Results of the updated streamflow simulation are compared to baseline simulations, without assimilation of the satellite-derived surface water extent. Validation is done in over 100 *in situ* river gauges using daily streamflow observations in the African and South American continent over a one year period. Some of the more commonly used metrics in hydrology were calculated: KGE', NSE, PBIAS%, R^2, RMSE, and VE. Results show that, for example, NSE score improved on 61 out of 101 stations obtaining significant improvements in both the timing and volume of the flow peaks. Whereas the validation at gauges located in lowland jungle obtained poorest performance mainly due to the closed forest influence on the satellite signal retrieval. The conclusion is that remotely sensed surface water extent holds potential for improving rainfall-runoff streamflow simulations, potentially leading to a better forecast of the peak flow.

1. Introduction

Flood forecasting systems are based on rainfall-runoff, channel flow routing, or snow-melt models, at times coupled with land surface models. These models or systems aim at simulating streamflow as close as possible to reality, and *in situ* streamflow time series typically used as a reference ground "truth". However, the use of *in situ* observational data in near real-time flood forecasting systems is constrained due to its public unavailability at near real-time in many regions of the globe. In addition, for many large rivers, even if gauge data are available, the network might be very sparse (e.g., at Niger River). As complementary data, remotely-sensed products have been recognised as very valuable (van Dijk and Renzullo, 2011), having particular potential for use within sparsely equipped and ungauged regions where these remotely-sensed products are the only observations available. Further, remote sensing data are very useful as they provide routinely collected data with a wide spatial extent and available for scientific research and applications, and their use in hydrologic forecasting needs to be fully explored. Both *in situ* and satellite-derived data are used for calibration and validation of hydrological models (e.g., Di Baldassarre et al., 2009; Gupta et al., 1998; Madsen, 2000; Wanders et al., 2014a). Other methodologies used to enhance the skill of the simulated streamflow are (a) data assimilation of observations into a model (e.g., Clark et al., 2008; Seo

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et al., 2009), and (b) post-processing of the hydrological ensemble predictions (e.g., Bogner and Kalas, 2008; van Andel et al., 2013). Both methodologies have diverse strengths and, up to a certain point, are complementary. Therefore, the use of both is highly recommended (Bourgin et al., 2014), if we aim to improve forecast reliability and accuracy.

Data assimilation schemes are expected to reduce hydrological uncertainty of hydrological models (Bates, 2012; Bourgin et al., 2014), especially at shorter lead times. Despite constant development in the use of data assimilation technics in operational hydrological forecasting and Earth science in general (Reichle, 2008; Seo et al., 2014), the theoretical frameworks and the adequate characterisation of uncertainties still provides important options for both challenges and opportunities alike (see Liu et al., 2012 for a review). Another research field which requires exploration is the assimilation of observations, with emphasis on those not use in developing the model. Assimilation of state variables such as streamflow (Rafieeinasab et al., 2014; Randrianasolo et al., 2014; Sun et al., 2015) and remotely-sensed soil moisture (see Kornelsen and Coulibaly, 2013; Ni-Meister, 2008 for a review) and snow products (Franz et al., 2014; Slater and Clark, 2006; Thirel et al., 2013), has progressively been tested in recent years. Whereas not so many studies have evaluated the impact of assimilating hydraulic information such as remotely-sensed surface water extent data. Some studies (see Table 1) water extents [1–6]. Other studies have also explored the possibilities of using the surface water height and inundation extent data from the future Surface Water and Ocean Topography (SWOT, https://swot.jpl.nasa.gov/) [7–8] satellite mission, showing promising applications. One study has previously also tested to directly assimilate low resolution remote sensed flood extents-as intendent in this study- into a 2-D flood model, by using MODIS derived data [9]. In addition, to the authors' knowledge only one study has attempted to assimilate passive-microwave surface water extent changes derived from the Global Flood Detection System (GFDS) within a rainfall-runoff model derived water levels were used as a proxy for *in situ* streamflow at a specific point location, instead of using the satellite-retrieved raw spatial signal as is the objective in this study. However, most of these studies focus solely on a single river reach or catchments, and often on specific flood events due to limited temporal availability and cost of high resolution satellite imagery.flood events due to limited temporal availability and cost of high resolution satellite imagery.

Surface water extent from the Global Flood Detection System (GFDS) is observed using a range of passive microwave remote sensors. The methodology uses the brightness temperature, as water bodies have a lower emissivity. In a time series, the satellite signal is expected to vary with changes in water surface, and anomalies can be correlated with flood events. The GFDS data have been previously used for a range of applications such as estimating streamflow (Brakenridge et al., 2007; Revilla-Romero et al., 2014), river discharge nowcasting and forecasting (Hirpa et al., 2013), model calibration, validation of floods events.

We implemented a data assimilation scheme with the aim to improve the prediction of the flood peak. However, we test it using a climatology forcing as a first step, although the effects using a probabilistic meteorological forecast should be further investigated. Therefore, we examined the feasibility of using surface water changes from the Global Flood Detection System (GFDS) for data assimilation using the ensemble Kalman filter (EnKF) within a rainfall-runoff model for the African and South American basins. The aim of this proof-of-concept study is to test whether assimilation of exclusively satellite-derived surface water changes will positively impact the skill of the simulated streamflow to reproduce the hydrograph, especially during flood peaks on large (>10,000 km^2) and slow-motion catchments. The reason that drove this decision is that there are large regions of the world ungauged, and those gauged with publicly provided real-time data are also scarce, and we wanted to design a framework also valid from those areas. Therefore, assimilating satellite-derived information into the hydrological model have an important added value for those regions where *in situ* measurements are not available; and it can be implemented independently of these datasets.

The rainfall-runoff model employed in this study is the recently upgraded LISFLOOD global version. It runs at a daily time step using the Watch WFDEI dataset as the meteorological forcing (Weedon et al., 2011). LISFLOOD Global currently incorporates a module for data assimilation which has been successfully applied using soil moisture (Wanders et al., 2014b) within the European Upper Danube catchment for the European Flood Awareness System (EFAS). However, the new set up of LISFLOOD Global used here is currently not yet incorporated within a continental or global flood forecasting system such as the Global Flood Awareness System (GloFAS).

In Section 2 we present the data used and study regions. Section 3 describes the methodologies including the model, data assimilation framework, and assessment procedures. Results and discussion are presented in Section 4, and finally conclusions are summarised in Section 5.

2. Data and study region

2.1. Study region

The rainfall-runoff LISFLOOD Global model was used in this study (Van Der Knijff et al., 2010). However, for testing the effects of assimilating satellite-derived surface water extent on the simulation of the streamflow, we focus on African and South American catchments due to the potential benefits that an improvement of the streamflow simulations can bring to those regions, as many of their water authorities lack of a catchment-wide hydrological model. Fig. 1 shows the studied river basins, main rivers from the Global Runoff Data Centre (GRDC), and the ground river gauges.

2.2. Ground streamflow data

Daily ground streamflow time series were obtained from the Global Runoff Data Centre (GRDC, 2015). For this proof-of-concept study, only one year of data was used, although the GFDS signal is available for most of the globe since 1998. We choose 2003 in order to have the largest number of *in situ* gauges data for validation, especially within the African continent. Many of these cease to either record or provide data to GRDC after 2004 due to an smaller gauging network coverage and more restricted access to national scale information (Hannah et al., 2011).

Furthermore, based on previous research of GFDS (Revilla-Romero et al., 2014) and LISFLOOD global model recommendations (Alfieri et al., 2013), our criteria was to selected only stations with a daily mean average discharge larger than 500 m^3 s^{-1} and an upstream area larger than 10,000 km^2. The reason behind this criteria is that due to the resolution of the satellite data and of the hydrological model, the performance of both is generally better for large and unregulated rivers. Although for there are some small rivers with good performance for broad and low gradient river systems. For this study, the remaining stations for validation are six for Africa and 95 for South America.

2.3. Satellite data

Remotely sensed surface water extent provided by the Global Flood Detection System (GFDS, http://www.gdacs.org/flooddetec-