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Satellite-supported flood forecasting in river networks: A real case study

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SUMMARY

Satellite-based (e.g., Synthetic Aperture Radar [SAR]) water level observations (WLOs) of the floodplain can be sequentially assimilated into a hydrodynamic model to decrease forecast uncertainty. This has the potential to keep the forecast on track, so providing an Earth Observation (EO) based flood forecast system. However, the operational applicability of such a system for floods developed over river networks requires further testing. One of the promising techniques for assimilation in this field is the family of ensemble Kalman (EnKF) filters. These filters use a limited-size ensemble representation of the forecast error covariance matrix. This representation tends to develop spurious correlations as the forecast-assimilation cycle proceeds, which is a further complication for dealing with floods in either urban areas or river junctions in rural environments. Here we evaluate the assimilation of WLOs obtained from a sequence of real SAR overpasses (the X-band COSMO-Skymed constellation) in a case study. We show that a direct application of a global Ensemble Transform Kalman Filter (ETKF) suffers from filter divergence caused by spurious correlations. However, a spatially-based filter localization provides a substantial moderation in the development of the forecast error covariance matrix, directly improving the forecast and also making it possible to further benefit from a simultaneous online inflow error estimation and correction. Additionally, we propose and evaluate a novel along-network metric for filter localization, which is physically-meaningful for the flood over a network problem. Using this metric, we further evaluate the simultaneous estimation of channel friction and spatially-variable channel bathymetry, for which the filter seems able to converge simultaneously to sensible values. Results also indicate that friction is a second order effect in flood inundation models applied to gradually varied flow in large rivers. The study is not conclusive regarding whether in an operational situation the simultaneous estimation of friction and bathymetry helps the current forecast. Overall, the results indicate the feasibility of stand-alone EO-based operational flood forecasting.

1. Introduction

While there are recent advances in low-cost telemetered networks for long-life flood monitoring and warning applications, oriented to be deployed over large areas (e.g., Marín-Pérez et al., 2012), the actual number of operational gauges is actually declining in the world (Vörösmarty et al., 2001). On the other hand, in recent times, the technology of earth observation (EO) has begun to be adopted to improve flood visualization and reduce flood modeling uncertainties (e.g., Raclot, 2006, Schumann et al., 2007, 2011, Mason et al., 2010a). EO techniques for flood detection include, for example, high resolution Synthetic Aperture Radar (SAR) (such as TerraSAR-X), altimetry (such as RA-2 on Envisat, or Poseidon 3 on Jason-2), though the footprints are such that they are limited to level measurements in rivers >1 km wide, or even gravimetry (GRACE) for very large flood events. Specifically, in real-time mode, the assimilation of water level observations (WLOs) derived from EO may serve to keep forecasts obtained from flood simulations on track and, in hindcast mode, to obtain better estimates of the dynamic footprints of past flood events. The forecast mode may be used by civil protection services and industry for operational uses, while the post-flood mode may be used in damage assessment and flood defence design studies (Mason et al.,

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2014). In both modes, the key variable to forecast is the water level (and hence flood extent) (e.g., Hostache et al., 2010; Biancamaria et al., 2011). However, the assimilation of EO-based WLOs for the water level estimation problem, mostly in a forecast situation, is plagued by problems derived from errors in (a) inflows (discharge) into the modeled domain, and (b) model parameters (mostly friction) and bathymetry. Thus, the estimation and correction of (a) and (b), in a data assimilation (DA) context, have become themselves a major or secondary objective in recent studies. In an alternative scenario, with a focus on large rivers and longer timescales, discharge estimation, in itself, is a important objective for land surface water budget analyses (e.g., Andreadis et al., 2007; Balsamo et al., 2013). Overall, the estimation of water levels, water discharge and model parameter estimation are all inter-related in the abovementioned contexts. For example, Neal et al. (2009) conducted a case study of simultaneous water level and inflow estimation from EO-based WLOs, in a 10-km river reach. Also, Matgen et al. (2010) and Giustarini et al. (2011), in a synthetic case and a real case respectively, showed that the simultaneous correction of inflow errors led to improved water level forecast in a 19-km river reach. García-Pintado et al. (2013) conducted a synthetic sensitivity analysis of the flood forecast skills at different time horizons to satellite-based SAR acquisitions (first visit and revisit times) in order to support the scheduling of satellite imaging for operational uses. There is not real dataset yet available to conduct a similar kind of study.

Regarding bathymetry estimation, Durand et al. (2008), in a proof-of-concept study, indicated that bathymetry is a significant source of uncertainty in estimating discharge. They conducted two synthetic experiments to assimilate EO-based WLOs, assuming known inflows, in order to estimate a mean bathymetric slope and bathymetric depth at 5 specific locations in a 250-km reach in the Amazon river. Specifically, they used synthetic observations of the proposed Surface Water and Ocean Topography (SWOT) mission. The experiments were successful, and they concluded that model errors will likely dominate over SWOT-like WLO errors. Roux and Dartus (2008) succeeded in calibrating the mean bathymetry in a channel reach using real satellite-based flood extent data, and Gessese et al. (2011) directly obtained an explicit partial differential equation (PDE) for the 1-D inverse problem, and successfully estimated the depth of a rectangular horizontal channel with a bump, with known inflow and known downstream slope. Later, Durand et al. (2014) used real SAR-based WLOs to simultaneously estimate bathymetry and lateral inflows, along with channel roughness, for a major out-of-bank flood event in a river. They treated the river in term of reaches, so that they estimated mean values for three transects along the river, and assumed the major upstream inflow was known. Their results suggest that it should be possible to estimate river discharge via EO. In closely related work, the estimation of bathymetry in river estuaries through the assimilation of SAR-based waterlines with morphodynamic models has also been evaluated (Thornhill et al., 2012; Smith et al., 2013).

On the other hand, the chosen DA method itself may have intrinsic problems. Specifically, in recent years there has been a growing interest in DA ensemble schemes for flood studies. From these, the various methods derived from the Kalman filter are generically known as Ensemble Kalman Filters (EnKFs) (Evensen, 1994). These filters use a limited-size ensemble representation of the forecast error covariance matrix. This is updated as each set of observations is assimilated. The ensemble-based error covariances tend to underestimate the forecast error variance and develop physically unrealistic or spurious correlations. This may lead to ensemble collapse and filter divergence. Filter localization is often used to reduce the problem of spurious correlations. This increases the degrees of freedom available to fit nearby observations in the analysis by decreasing the weight given to observations far from the physical location of the estimated state variable (Hamill et al., 2001).

While previous experiments are encouraging regarding EO capabilities for flood and river flow monitoring and forecasting, they focus on specific single river reaches, albeit ones that are sometimes very large or subject to secondary lateral inflows. Our new contribution is to carry out a case study assimilating real EO data for the sequential monitoring and forecast of a flood developing on a river network with tributaries. In our case, uncertain forecasts from upstream rainfall-runoff models provide the discharge at seven catchments contributing to the flood. The case is based on possibly the best example of sequential monitoring of a flood extent by high-resolution Synthetic Aperture Radar (SAR) images currently available in the world. This is a 7-image set from the COSMO-Skymed constellation, which was acquired during a flood that occurred in November 2012 around the confluence of the Severn and Avon catchments in the western UK.

The assimilation is conducted via a Local Ensemble Transform Kalman Filter (LETKF) (Hunt et al., 2007) applied to a 2-D flood model. Our objective is to evaluate a number of strategies for real-time flood forecasting by assimilating high-resolution EO-based WLOs with the flood simulations assuming uncertain model parameters. That is, we want (a) to evaluate if localization is strictly required for avoiding problems arising from spurious correlations; (b) to evaluate if the flood forecast improves by jointly estimating inflow boundary condition errors simultaneously with the water level; and (c) to evaluate if, with an imminent flood situation, it is better to focus on state estimation (water levels), joint state-inflow estimation, or joint state-parameter estimation, where at the same time uncertain friction and bathymetry are estimated.

Regarding objective (a), it is noted that filter localization requires a distance metric for moderating the weights given to the observations. In this paper we introduce an along-network distance metric for filter localization, which is new to the DA literature. The proposed metric is physically meaningful for the flood over a network problem and, accordingly, we evaluate its influence on the forecast. Regarding objective (b), it is noted that the online correction of inflow errors into the flood model domain does not affect the hydrologic simulations of the upstream catchment-scale rainfall-runoff processes.

2. Methods

2.1. Study domain

This study focuses on an area of the lower Severn and Avon rivers in the South West United Kingdom, over a 30.6 × 49.8 km (1524 km^2) domain. Fig. 1 depicts the study area for the flood model. Four our investigation, we used a real case based on an event that occurred in November 2012. We used a previous event in July 2007 in the same location as a calibration scenario. In the calibration event, the two major rivers suffered a substantial degree of overbank flooding, and a maximum water depth of 5.90 m was recorded at the Saxon's Lode gauge near Tewkesbury. The event of 23 November–4 December 2012 recorded a maximum water depth of 5.21 m at the Saxon's Lode. Also both the Severn and Avon were in flood in this event. Tewkesbury lies at the confluence of the Severn, flowing from the Northwest, and the Avon, flowing from the Northeast.

2.2. Rainfall-runoff model and inflow generation

In the experimental setup we emulated a real forecast scenario, in which the precipitation data came from a network of tipping-