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Development and evaluation of a framework for global flood hazard mapping

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ABSTRACT

Nowadays, the development of high-resolution flood hazard models have become feasible at continental and global scale, and their application in developing countries and data-scarce regions can be extremely helpful to increase preparedness of population and reduce catastrophic impacts.

The present work describes the development of a novel procedure for global flood hazard mapping, based on the most recent advances in large scale flood modelling. We derive a long-term dataset of daily river discharges from the hydrological simulations of the Global Flood Awareness System (GloFAS). Streamflow data is downscaled on a high resolution river network and processed to provide the input for local flood inundation simulations, performed with a two-dimensional hydrodynamic model. All flood-prone areas identified along the river network are then merged to create continental flood hazard maps for different return periods at 30′′ resolution. We evaluate the performance of our methodology in several river basins across the globe by comparing simulated flood maps with both official hazard maps and a mosaic of flooded areas detected from satellite images. The evaluation procedure also includes comparisons with the results of other large scale flood models. We further investigate the sensitivity of the flood modelling framework to several parameters and modelling approaches and identify strengths, limitations and possible improvements of the methodology.

1. Introduction

River floods are recognized as one of the major causes of economic damages and loss of human lives worldwide (European Commission, 2007; UNISDR and CRED, 2015). Over the period 1980-2013, flood losses exceeded $1 trillion globally, and resulted in ca. 220,000 fatalities (Re, 2014). Moreover, the impact of floods in next decades could dramatically increase due to the ongoing socio-economic and climatic changes (UNISDR 2009; Jongman et al., 2012).

The catastrophic impacts of river floods can be reduced thanks to mathematical models for predicting and mapping flood hazard and risk (European commission, 2007). Flood hazard maps (showing the probability and magnitude of flood events over an area) and flood risk assessment maps (showing potential consequences of a flood event in terms of affected population and assets, and expected economic damages) can increase preparedness and improve land use planning and management in flood prone areas. On the other hand, reliable and fast flood forecasting tools are crucial to develop effective emergency response strategies and to prevent and reduce impacts.

Until recent years, flood mapping and forecasting tools were available only in few areas of the globe, given their high demand of resources and data for development and maintenance. However, the situation is radically changing nowadays: thanks to the constant increase of computational power and precision of remotely sensed datasets, the application of large-scale, high-resolution (i.e. 1 km or less) flood models have become feasible (Wood 2011), and different studies at continental and global scale have been proposed in the literature. Pappenberger et al. (2012) coupled a land surface rainfall-runoff model with a river routing algorithm, to produce floodplain and flood flow across the river network, based on a 30 years meteorological forcing data. Annual maxima were used to derive peak flow return periods on a 25×25 km grid, which was then reprojected onto a 1×1 km grid to derive flood maps of higher resolution. Winsemius et al. (2013) proposed a similar framework for global flood risk assessment, using a cascade of climate forcing datasets, hydrological and hydraulic modelling, extreme value statistics, derivation of inundation maps, and flood impact modelling.

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More recently, large-scale flood modelling approaches have begun to couple the hydrological modelling component with large-scale flood inundation models, in order to provide more accurate flood mapping. Yamazaki et al. (2013) applied a new river routing model to improve the global flood hazard maps derived by Pappenberger et al. (2012), while Hibarayashi et al (2013) applied the same model to produce global flood risk estimations for the end of this century based on the outputs of 11 climate models. Schumann et al. (2013) used ensemble forecast data to force a hydrologic model and produce boundary daily flow conditions for the 2-D hydrodynamic model LISFLOOD-FP (Bates et al., 2010; Neal et al., 2012). The modeling system was calibrated and successfully applied over a reach of the Zambezi River. Recently, a similar flood modelling framework has been applied by Sampson et al. (2015) to produce global flood hazard maps at 3arcseconds resolution. The hydrological input in their work was given by a regionalised flood frequency analysis based on a global dataset of stream gauging stations. The resulting dataset provided the necessary input for a modified version of the LISFLOOD-FP model, which was used to derive global hazard maps for several return periods. Alfieri et al. (2014) derived a flood hazard map for Europe using the long-term streamflow simulation (23 years) developed for the European Flood Awareness System (EFAS). Streamflow data were downscaled and used as input for the LISFLOOD-FP model to compute local flood maps, which were then merged into a pan-European flood hazard map.

Another global flood model has been developed for the Global Assessment Report on Disaster Risk Reduction (GAR). The methodology used in the latest version for 2015 (Rudari et al., 2015) makes use of a global database of stream-flow data, elaborated with downscaling techniques and statistical regional analyses to compute extreme discharges at global scale. A global hydrologic model was used to improve the estimations and produce input discharges for a simplified hydraulic flood model, which interpolates flood levels considering stream flow in hydraulic cross-sections and local morphology, taking into account hydraulic connectivity and back water effects. Flood hazard maps were produced for return periods from 25 to 1000 years.

Large scale flood modelling techniques can also be a key development for global flood forecasting systems. Currently, forecasts are mostly given in terms of hydrological parameters such as river discharge, but there is a demand from end users (e.g. emergency services, local institutions) for risk based forecasts, for example in terms of flood-prone areas, assets, and population. Several global flood forecasting and warning systems are now being developed towards this goal. For instance, the Global Flood Monitoring System (GFMS) uses satellite precipitation data in combination with coupled land surface and river routing models to provide near-real time flood detection and flood inundation mapping (Wu et al., 2014).

Here, we present a flood hazard mapping methodology based on the hydrological information produced by the Global Flood Awareness System (GloFAS; Alfieri et al., 2013). GloFAS is a probabilistic flood early warning system running at global scale, developed in a collaboration between the Joint Research Centre (JRC) and the European Centre for Medium Range Forecasts (ECMWF). The system is running since 2011 for research purposes, and since May 2015 GloFAS forecasts are displayed in real time on a dedicated web platform (http://globalfloods.eu/).

Streamflow data available from long term GloFAS simulations is downscaled on a higher resolution river network and processed to provide the input for the flood simulations following the approach proposed by Alfieri et al. (2014). For each river basin considered, the drainage network is divided in river sections where local simulations are run in parallel. Simulations are performed with a two-dimensional hydrodynamic model, designed to ensure an accurate representation of flow processes in the river network and flood prone areas. The local flood maps produced are merged together to produce continental maps for different return periods at 30 arc seconds resolution, including areas at latitudes above 60 degrees.

The developed global maps are tested in several river basins located in different continents, in order to have a comprehensive assessment of the modelling framework. Where possible, we use official flood hazard maps as a reference, and we compare the performance of the produced maps against the results obtained by other global models (Alfieri et al., 2013; Winsemius et al, 2016; Sampson et al., 2015) Where official maps are not available, we produce basin-scale flood extent maps derived for the period 2000-2013, and we compare these maps with a mosaic of flooded areas detected from satellite images for the same reference period. Such evaluation strategy allows for investigating the performances of the modelling framework in areas where no previous evaluations of global flood hazard models were done.

In addition, we investigate the sensitivity of the modelling framework by providing a quantitative evaluation of the influence of various parameters, such as the hydrological input and the grid resolution. The performance of the modelling framework emerging from these analyses are discussed to identify strengths, limitations and possible improvements. Finally, future applications and developments of the methodology are presented.

2. Data and methods

The proposed framework is based on a cascade of modelling components with an increasing level of detail. The hydrological input is provided by the streamflow climatology of GloFAS simulations, based on meteorological reanalysis datasets (Section 2.1). Streamflow data is processed at global scale and then downscaled at higher resolution in the main river basins and hydrological regions of the globe (Section 2.2). Flood simulations are performed in parallel with a hydrodynamic model using the downscaled information and incorporating river network geometry derived from high resolution terrain data (Section 2.3). A general scheme of the proposed methodology is provided in Fig. 1. Note that two different hydrological datasets are used within the flood mapping methodology, to produce two different sets of flood maps. The analysis of extreme discharge values is used for deriving flood hazard maps for different return periods, as described in this section, while the analysis of discharge maxima for the period 2000–2013 is used to generate flood extent maps which are applied for testing the procedure (see Section 3 for more details).

2.1. Hydrological datasets

Hydrological simulations in GloFAS are performed by coupling two distributed global models. The land surface model HTESSEL (Balsamo et al., 2009, 2011) estimates the surface water and energy fluxes and the temporal evolution of soil temperature, moisture content and snowpack conditions in response to atmospheric forcing. Surface and sub-surface runoff from HTESSEL are then used as input to LISFLOOD Global, which simulates the groundwater and routing processes and produces streamflow simulations along the stream network of large global rivers at 0.1 degree grids (Alfieri et al., 2013).

The long term streamflow simulations of GloFAS are based on the global atmospheric reanalysis dataset ERA-Interim (Dee et al., 2011; Balsamo et al., 2015), and cover the period from 1980 to 2013, at 0.1 degrees resolution (approximately 11 km at the Equator). For running GloFAS simulations, the ERA-Interim dataset has been bias-corrected using the Global Precipitation Climatology Project (GPCP) (Huffman et al., 2009; Balsamo et al., 2015).