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Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite-based rainfall

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SUMMARY

A fully-distributed, multi-physics, multi-scale hydrologic and hydraulic modeling system, WRF-Hydro, is used to assess the potential for skillful flood forecasting based on precipitation inputs derived from the Weather Research and Forecasting (WRF) model and the EUMETSAT Multi-sensor Precipitation Estimates (MPEs). Similar to past studies it was found that WRF model precipitation forecast errors related to model initial conditions are reduced when the three dimensional atmospheric data assimilation (3DVAR) scheme in the WRF model simulations is used. A comparative evaluation of the impact of MPE versus WRF precipitation estimates, both with and without data assimilation, in driving WRF-Hydro simulated streamflow is then made. The ten rainfall–runoff events that occurred in the Black Sea Region were used for testing and evaluation. With the availability of streamflow data across rainfall–runoff events, the calibration is only performed on the Bartin sub-basin using two events and the calibrated parameters are then transferred to other neighboring three ungauged sub-basins in the study area. The rest of the events from all sub-basins are then used to evaluate the performance of the WRF-Hydro system with the calibrated parameters. Following model calibration, the WRF-Hydro system was capable of skillfully reproducing observed flood hydrographs in terms of the volume of the runoff produced and the overall shape of the hydrograph. Streamflow simulation skill was significantly improved for those WRF model simulations where storm precipitation was accurately depicted with respect to timing, location and amount. Accurate streamflow simulations were more evident in WRF model simulations where the 3DVAR scheme was used compared to when it was not used. Because of substantial dry bias feature of MPE, as compared with surface rain gauges, streamflow derived using this precipitation product is in general very poor. Overall, root mean squared errors for runoff were reduced by 22.2% when hydrological model calibration is performed with WRF precipitation. Errors were reduced by 36.9% (above uncalibrated model performance) when both WRF model data assimilation and hydrological model calibration was utilized. Our results also indicated that when assimilated precipitation and model calibration is performed jointly, the calibrated parameters at the gauged sites could be transferred to ungauged neighboring basins where WRF-Hydro reduced mean root mean squared error from 8.31 m^3/s to 6.51 m^3/s.

1. Introduction

Floods are among the most frequent natural disasters and often cause serious economic losses to property, commerce as well as loss of human life (Morrs, 2010). With changing climate these extreme events are expected to occur more frequently at different times and locations on the Earth and become more catastrophic (IPCC, 2007). Heavy rainfall events and their consequent floods are a significant concern in the western Black Sea Region of northern Turkey. In addition to coastal areas, severe floods also affect many inland catchments of the region away from the sea imposing significant damage to infrastructure and often fatalities (Komuscu and Celik, 2012). Given these threats, it is critically important to develop reliable forecasts of rising streams and rivers prior to occurrence of dangerous conditions. Real-time flood forecasting systems are becoming a critical tool for emergency preparedness and decision making where life and property are in jeopardy in

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addition to everyday operation and management of water control systems.

A reasonably long lead-time for flood forecasts that enables timely issuance of flood warnings and preparative actions is a necessity because of the numerous logistical complexities in securing areas that will be impacted (Morss et al., 2010). While precipitation observation systems can provide some advanced warning, procedures to maximize warning lead time, particularly for small watersheds, must employ rainfall prediction methodologies, such as those from numerical weather prediction models or multi-sensor nowcasting systems, provided those predictions are skillful. One way in which warning lead time can be extended is by translating mesoscale (order 1–10s of km) numerical weather prediction (NWP) model precipitation forecasts with a spatial resolution compatible with that of the hydrologic model into streamflow forecasts (Jasper et al., 2002; Wardah et al., 2008). Regional NWP models have been successfully applied to the forecasting of hydrological phenomena and quantitative precipitation forecasts (Fovell, 2006; Marchok et al., 2007; Weisman, 1993). A nested, high-resolution, regional NWP model can provide a plausible method for modeling flood events at the watershed scale by capturing synoptic-scale (order 100s to 1000s of km) ingredients and triggers for heavy rainfall over the entire domain and downscaling those processes to capture fine-resolution mesoscale features over the region of interest (Lowry and Yang, 2008).

However, precipitation is usually one of the single most difficult and erroneously modeled variables in NWP models (Wang and Seaman, 1997; Nielsen-Gammon et al., 2005). Errors arise from a host of sources such as from initial and boundary conditions and uncertainty in model physics. Skillful forecasts of precipitation timing and magnitude are strongly linked to the ability of the NWP model to accurately depict the size and evolution of larger scale disturbances (Meneguzzoa et al., 2004; Fiori et al., 2014). Hence, assimilation of suitable observations into NWP models of even large scale atmospheric conditions can significantly reduce errors of initial conditions of the mesoscale model and therefore greatly improve model forecast skill (Sokol, 2009; Romine et al., 2013; Yucel and Onen, 2014). In this study we explore the degree to which precipitation forecasts from an NWP model with active data assimilation can help improve simulated runoff and streamflow as depicted by a physics-based hydrological model. Particular attention is focused on assessing whether or not the fine-scale (order 1s of km) spatial patterns, timing and amount of precipitation from such NWP forecasts are sufficiently accurate to produce reliable hydrological predictions from a model that has demonstrated skillful streamflow simulations from precipitation observations. In doing so, this work extends recent flash flood prediction work in complex terrain by Moreno et al. (2014).

Physics-based, hydrometeorological systems that integrate hydrological models with atmospheric models through coupled, two-way interacting or uncoupled configurations are now operational in many areas (Dale et al., 2012). Coupling of high-resolution hydrological models with fine-scale meteorological models reduces uncertainties associated with the localization and timing of heavy rainfall driven flood responses that coarser resolution, ‘lumped’ models may suffer from. This is particularly true for catchments in areas of complex terrain where runoff generation mechanisms are highly heterogeneous and whose response times are very short (Vivoni et al., 2008; Moreno et al., 2012). Additionally, terrain routing of surface and sub-surface flows is often neglected in calculating local soil water budgets within hydrometeorological systems especially when they are implemented on coarse grid scales (e.g. >10 km). However, neglect of these processes is not valid for finer resolution applications (e.g. $\leqslant$1 km) particularly in complex terrain, when the lateral component of flows can become an important contributor to local water budgets (Maxwell et al., 2011). Neglect of the subgrid-scale variability of precipitation has been shown to result in an underestimation of the total volume and runoff, and consequently, an overestimation of the evapotranspiration as reported by Wang et al. (2005). Errors in modeled evapotranspiration can conceivably propagate into errors in atmospheric responses to surface energy and moisture flux partitioning (Maxwell et al., 2007). As such, fine-scale, coupled hydrometeorological models operating at effective grid resolutions of a few km or less in complex terrain regions need to incorporate lateral transfer processes in their surface hydrology model components. Several modeling systems are now incorporating such fine-scale processes and these approaches are beginning to show some potential ability to function as reliable flood forecasting systems (e.g. Wardah et al., 2011; Vivoni et al., 2008, 2011).

The community Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) developed by the U.S. National Center for Atmospheric Research (NCAR) is a widely used regional atmospheric model in mesoscale weather research and forecasting as it has demonstrated significant skill in representing a wide variety of precipitation processes (Chen et al., 2010; Liu et al., 2013; Yucel and Onen, 2014). In this study, the WRF model is used to reproduce fine-scale heavy rainfall of 25 different events from 2000 to 2011. High resolution (4 km) precipitation obtained from WRF model with and without 3DVAR data assimilation method and from the EUMETSAT’s Multi-sensor Precipitation Estimate (MPE) satellite rainfall algorithm (Heinemann et al., 2002) are used as forcing for NCAR WRF-Hydro modeling system (Gochis and Chen, 2003; Gochis et al., 2014) that accounts for three dimensional, variably saturated flow through the surface, sub-surface and channels to predict river flow. Among 25 heavy rainfall events the 10 events producing significant runoff at available stream gauge stations are used in the evaluation of WRF-Hydro model. Analyses focus on evaluating the capability of the WRF model and the WRF-Hydro system in predicting flood responses in widely varying hydrological settings of the 10 different events in the western Black Sea Region of Turkey. Due to streamflow data availability across 10 rainfall–runoff events, the calibration is only performed in one of the sub-basins in the study area using two events at two stream gauge stations. The calibrated parameters are then transferred to other neighboring sub-basins to provide an initial assessment of the transferability of the calibrated parameters to the neighboring ungauged basins in the study area. The rest of the events available in all sub-basins are used to evaluate the performance of the WRF-Hydro system with the calibrated parameters. A main goal of this study is to evaluate the usefulness of WRF-derived precipitation before and after data assimilation in predicting flood hydrograph features such as volume, peak flow rate, and timing. Additionally, the study emphasizes the role of understanding the use of improved precipitation forecasts, as obtained through 3DVAR data assimilation, in simulating flood hydrographs. Also, the appropriateness of using satellite-derived rainfall forcing in predicting river flow from WRF-Hydro is evaluated in an effort to determine whether or not these products have value in comparison to the WRF predicted precipitation.

2. Methods

2.1. Study area and data

The study area and the nested configuration of the WRF model domains at 12 km and 4 km resolutions are shown in Fig. 1(a) and the detailed view of fine domain together with the studied sub-basins and locations of raingauge stations in the western Black Sea Region of Turkey are shown in Fig. 1(b). The region is impacted by both polar air masses of continental origin (Iceland Low and