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Surrogate modeling of joint flood risk across coastal watersheds

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ABSTRACT

This study discusses the development and performance of a rapid prediction system capable of representing the joint rainfall-runoff and storm surge flood response of tropical cyclones (TCs) for probabilistic risk analysis. Due to the computational demand required for accurately representing storm surge with the high-fidelity ADvanced CIRCulation (ADCIRC) hydrodynamic model and its coupling with additional numerical models to represent rainfall-runoff, a surrogate or statistical model was trained to represent the relationship between hurricane wind- and pressure-field characteristics and their peak joint flood response typically determined from physics based numerical models. This builds upon past studies that have only evaluated surrogate models for predicting peak surge, and provides the first system capable of probabilistically representing joint flood levels from TCs. The utility of this joint flood prediction system is then demonstrated by improving upon probabilistic TC flood risk products, which currently account for storm surge but do not take into account TC associated rainfall-runoff. Results demonstrate the source apportionment of rainfall-runoff versus storm surge and highlight that slight increases in flood risk levels may occur due to the interaction between rainfall-runoff and storm surge as compared to the Federal Emergency Management Association's (FEMAs) current practices.

1. Introduction

Tropical Cyclones (TCs) can cause tremendous damage due to the storm surge and heavy rainfall they produce. While significant research has focused on the risk associated with TC storm surge as a result of the destructive 2005 hurricane season, few studies have evaluated flood risk due to the joint occurrence of TC storm surge and rainfall-runoff, or joint flooding, which routinely occurs during TC events. Such research is crucial given that post-storm damage assessments (Rappaport, 2014) indicate that roughly 27% of human losses due to TC's are caused by rainfall flooding. Two critical areas lacking information regarding joint TC flooding, include probabilistic flood forecasts and flood risk analysis. The objective of this paper is to develop a methodology for representing probabilistic joint flood risk levels that can easily be applied to any watershed along the U.S. Gulf and Atlantic coast.

Current coastal risk or return period products such as that provided by the Federal Emergency Management Association (FEMA, 2017b) do not represent the joint occurrence of TC storm surge and rainfall-runoff. Recent research on joint flood risk has been limited to a few point locations with long observational records of both stage and rainfall-runoff (i.e. Wahl et al., 2015; Zhong et al., 2013). Such analyses, even for areas with long observational records, will be highly sensitive to a small sample of all possible TC's for a given area. These limitations have required that TC risk assessments utilize additional sources of information that allow for a continuous, spatial representation of flood levels from synthetic storms based on a given regions historical or possible TC characteristics (Myers, 1975; Ho and Myers, 1975). In the Joint Probability Method (JPM), distributions of a regions possible TC characteristics are developed, from which storms are sampled and subsequently simulated in a hydrodynamic model for risk analysis. Storms can be sampled using a Monte Carlo approach which requires the use of less accurate, but faster hydrodynamic models (i.e. SLOSH, Lin et al., 2010), or by employing Optimal Sampling techniques (Resio et al., 2009; Niedoroda et al., 2010; Toro et al., 2010) that reduce the number of simulations required for surge risk analysis with high-fidelity hydrodynamic models.

In order to allow for high-fidelity representations of probabilistic storm surge forecasts or risk levels, researchers have recently investigated the use of surge response functions (SRFs) and other surrogate modeling approaches based on supervised machine learning techniques. Surrogate models are defined as computationally efficient models that are trained to represent the input/output relationship that is typically determined from high-fidelity physics-based numerical models. For TC storm surge analysis,

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these surrogate models can rapidly estimate the peak surge expected from a TC based on its landfall characteristics. SRFs were first proposed as a method to allow for the estimation of storm surge levels of a given TCs characteristics in order to aid in FEMA flood risk analysis (Resio et al., 2009), and later adapted for flood forecasting purposes (Irish et al., 2011). However, SRFs are limited to estimates at point locations and have resulted in low levels of accuracy for complex environments such as bays (Taylor et al., 2015).

Recently, supervised machine learning methods, including artificial neural networks (ANNs) (Hsieh and Ratcliff, 2013; Kim et al., 2015) and kriging (Jia and Taflanidis, 2013, Jia et al., 2016) have been proposed as alternatives to SRFs for forecasting purposes. In these ANN and kriging studies, ADCIRC was coupled with the steady-state spectral wave model (STWAVE) to provide surge predictions throughout the New Orleans area. These supervised machine learning studies resulted in high predictive accuracy owing to their ability to develop complex functions that map the relationship between a TC's landfall characteristics and its peak surge response simulated with high-fidelity hydrodynamic and wave models. Such techniques allow for rapid and accurate predictions of a TC's peak surge; however, to date, joint flooding in coastal watersheds due to rainfall-runoff and its interactions with storm surge have not been incorporated into predictive models capable of rapid simulations for probabilistic analysis.

In this study a surrogate or predictive model is developed based on high-fidelity simulations of storm surge and waves (ADCIRC + SWAN) coupled with inland hydrologic and hydraulic models that represent TC rainfall-runoff and its interactions with storm surge. By employing a supervised machine learning approach based on coupled hydrodynamic and hydrologic modeling results, this study provides the first method capable of providing rapid, probabilistic estimates of joint flooding from TCs at the watershed scale. This surrogate model is then utilized to provide rapid estimates of joint flooding for probabilistic flood risk analysis, which is currently limited to probabilistic representations of only storm surge. The study is performed for coastal watersheds located in southeast (SE) Houston, TX, but the proposed methodology can be applied to other coastal watersheds due to its use of open-source models and data that are available for the majority of the U.S. Gulf and Atlantic coast.

Section 2 discusses the modeling approach and methodology used to represent joint flooding from TCs, Section 3 discusses results from applying the joint flood model for risk analysis, Section 4 discusses limitations and suggestions for future work, and Section 5 ends with conclusions from this study.

2. Methodology

In this study several models were loosely coupled (Fig. 1) to represent joint flooding of the full range of TC characteristics that could impact the SE Houston study area (Fig. 2). This study area includes a population of roughly 300,000 people, and because of its connection to Galveston Bay is exposed to storm surge that can be introduced via the Gulf of Mexico. The study area's shallow slope, loamy to clay soils, and 67% development exacerbate rainfall-runoff and storm surge flooding. The 223 synthetic wind- and pressure-fields developed for FEMAs north Texas Flood Insurance Study (FEMA and USACE, 2011) were used as a forcing for the coupled modeling framework. These TCs have a 2-km resolution across the majority of the Gulf of Mexico and corresponding inland areas, and represent the full range of TC storm characteristics that could develop and impact the north Texas coast, which includes the SE Houston study area (Fig. 3). As shown in Fig. 3, the minimum pressure of the storms range from 994 to 900 mb, which corresponds to maximum wind speeds ranging from 29.8 m/s (66.6 mph) to 71.6 m/s (160 mph) at landfall. The open-source models utilized in this study, including ADCIRC + SWAN, the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS), were chosen in order to allow for the application of this study's methodology to the majority of the coastal U.S. Gulf and Atlantic, where FEMA and U.S. Army Corps of Engineers (USACE) flood insurance studies have led to the development of such models for inland riverine and coastal storm

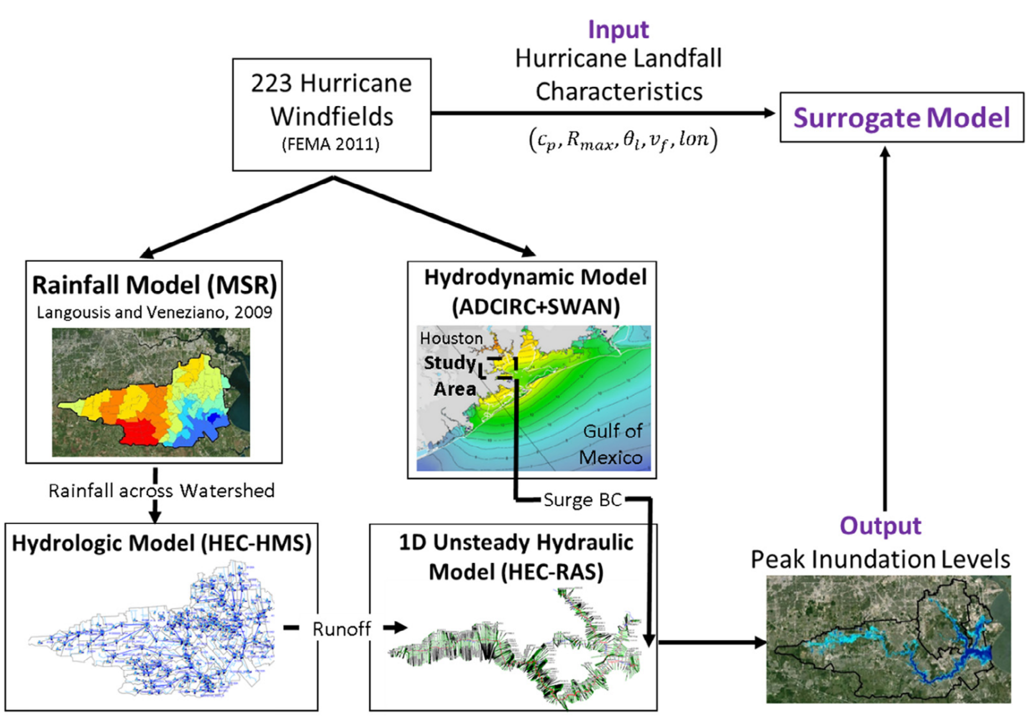

Fig. 1. Schematic of the loosely coupled numerical models employed to represent peak joint flood levels and the input/output data utilized to train a surrogate model to represent a TCs flood response.