Coastal Dynamics 2017
Paper No.037

PREDICTING TROPICAL CYCLONE FORERUNNER SURGE

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Abstract

In 2008 during Hurricane Ike, a 2-m forerunner surge, early surge arrival before tropical cyclone landfall, flooded essential roadways and stranded many people on Galveston Island. While significant forerunner surge can unexpectedly impact coastal communities, the conditions leading to large forerunner surge are not well understood. The significance of predicting forerunner surge will become increasingly important with sea level rise. This study focuses on analyzing modeled surge time series results in Galveston, Texas (USA) using synthetic tropical cyclone wind and pressure fields developed from storm track information such as central pressure and radii to maximum wind. Results show that Coriolis force induced Ekman setup dominates forerunner surge under a large range of storm conditions, and that more intense and larger tropical cyclones tend to generate larger forerunner surge.
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Key words: tropical cyclone, forerunner surge, surge forecasting, numerical modeling, coasts and climate

1. Introduction

The decision of when and where to evacuate in advance of a tropical cyclone is typically informed by predictions of expected peak wind speeds and peak surge, with little to no attention given to the timing of surge arrival. This limitation unexpectedly stranded many in Texas (USA) during Hurricane Ike in 2008. Kennedy et al. (2011) reported that water levels of more than 2 m above normal were reached in coastal Texas 15 hours prior to Hurricane Ike's landfall. Photos (J. Augustino, September 12 2008) showed this early flooding made roadways impassable at least 12 hours prior to landfall. Forerunner surge—a storm-induced increase in water level well in advance of tropical cyclone landfall—occurs relatively frequently along the Texas coast and occurs in other surge-prone regions. In 2012, for example, Hurricane Sandy's surge in coastal New Jersey (USA) reached 0.8 m above normal almost 1 day before landfall and exceeded 1 m by 12 hours before landfall (interpreted from data in Fanelli et al. (2013)).

As sea level rises, the significance of predicting forerunner surges cannot be overlooked. In the past century, a mean global sea level rise of 0.17 m was reported (Church and White, 2006). And different projections show a wide range of possible sea level rise between 0.3 m and 2.0 m till the end of this century (Kopp et al., 2014; Parris et al., 2012). In a low-lying coastal community, a 1-m forerunner surge under a future 1 m sea level rise scenario can flood a much larger area than under current conditions. Therefore, we expect the forerunner surge hazard to become more significant in the future in surge prone areas.

2. Methods

Herein, we identify the meteorological conditions under which significant tropical cyclone forerunners develop. A suite of idealized tropical cyclone wind and pressure fields are generated using a parameterized wind model (Thompson and Cardone, 1996) to span a range of tropical cyclone pressure deficits and radii of maximum wind along the upper Texas coast. Other storm parameters including forward speed, landfall location, track angle, and Holland B parameter (Holland, 1980) are not varied. Storm surge is simulated using the coupled spectral wave and shallow-water circulation model. The impacts of astronomical tides

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and rainfall runoff are not modeled in order to simplify the problem.

2.1. *Numerical modeling*

The computational model adopted here to generate surge time series data is the widely used tightly coupled SWAN+ADCIRC model (Dietrich et al., 2012; Sebastian et al., 2014; Irish et al., 2009). The finite element numerical model ADCIRC (Advanced CIRCulation) solves the two-dimensional depth-integrated shallow water equations to calculate storm surge (Luettich et al., 1992):

$$\begin{cases} \frac{\partial \zeta}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \\ \frac{\partial UH}{\partial t} + \frac{\partial UUH}{\partial x} + \frac{\partial UVH}{\partial y} - fVH = -H\frac{\partial}{\partial x}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + M_x + D_x + B_x + \frac{\tau_{sx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} \\ \frac{\partial VH}{\partial t} + \frac{\partial VUH}{\partial x} + \frac{\partial VVH}{\partial y} + fUH = -H\frac{\partial}{\partial x}\left[\frac{p_s}{\rho_0} + g(\zeta - \alpha\eta)\right] + M_y + D_y + B_y + \frac{\tau_{sy}}{\rho_0} - \frac{\tau_{by}}{\rho_0} \end{cases} \quad (1)$$

Where ζ is free surface elevation, H is total water depth, U and V are depth-averaged horizontal velocities, f is the Coriolis coefficient, p_s is the atmospheric pressure at the free surface, ρ_0 is the reference density of water, g is the acceleration of gravity, α is the effective Earth elasticity factor, η is the Newtonian equilibrium tide potential, M_x and M_y are depth-integrated horizontal momentum diffusion, D_x and D_y are momentum dispersion terms, B_x and B_y are depth-integrated baroclinic forcing, τ_{sx} and τ_{sy} are wind stresses applied at the water surface, and τ_{bx} and τ_{sy} are bottom stresses.

To incorporate the effects of wave setup, the spectral wave model SWAN (Booij et al., 1996) was utilized, and a coupled SWAN+ADCIRC model was used. The Planetary Boundary Layer (PBL) model was used to simulate parametric storm wind and pressure fields (Thompson and Cardone, 1996). The PBL model takes storm parameters along storm tracks as input and produces parametric wind and pressure fields for tropical cyclones, and thus can be used for surge forecasting and our storm track parameter study.

As indicated by Equation (1), tropical cyclone storm surge includes multiple components including barometric surge, wind setup, Ekman setup, wave setup, and tides. While Kennedy et al. (2011) has shown that the origin of Hurricane Ike's forerunner surge is Coriolis force induced Ekman setup, we further hypothesize that for any given tropical cyclone in the study area, Ekman setup is the dominating process of the forerunner surge, and test this hypothesis by comparing simulations with and without modeling the impact of Coriolis force.

2.2. *Study Area and storm scenarios*

We focus our study in and near Galveston, Texas (USA), where significant forerunner surges have been frequently observed (during the 1900 Galveston Hurricane, the 1920 Galveston Hurricane, and Hurricane Ike in 2008). In the study area, coupled SWAN+ADCIRC was used to simulate surge time series from synthetic tropical cyclones. The computational mesh used herein consists of over 6 million elements and more than 3 million nodes, with the highest resolution in tens of meters within Galveston Bay. Twenty-seven coastal locations at 3-m depth were selected for analysis of surge time series results, and representative results are shown at location 18 below. All the simulated synthetic tropical cyclones are along the same track, making landfall near Galveston with a moderate forward speed (5.66 m/s) and a perpendicular heading with respect to the coastline, shown as the red line in Figure 1. The synthetic tropical cyclones have 27 different combinations of intensity (represented by pressure deficit) and storm size (represented by radii of maximum wind), covering possible parameter range based on historical records. By comparing surge time series data for tropical cyclones with different parameters (intensity and size), we show how storm parameters affects the magnitude and timing of forerunner surge, and how we can use the results to identify meteorological conditions under which significant forerunner surge happens.

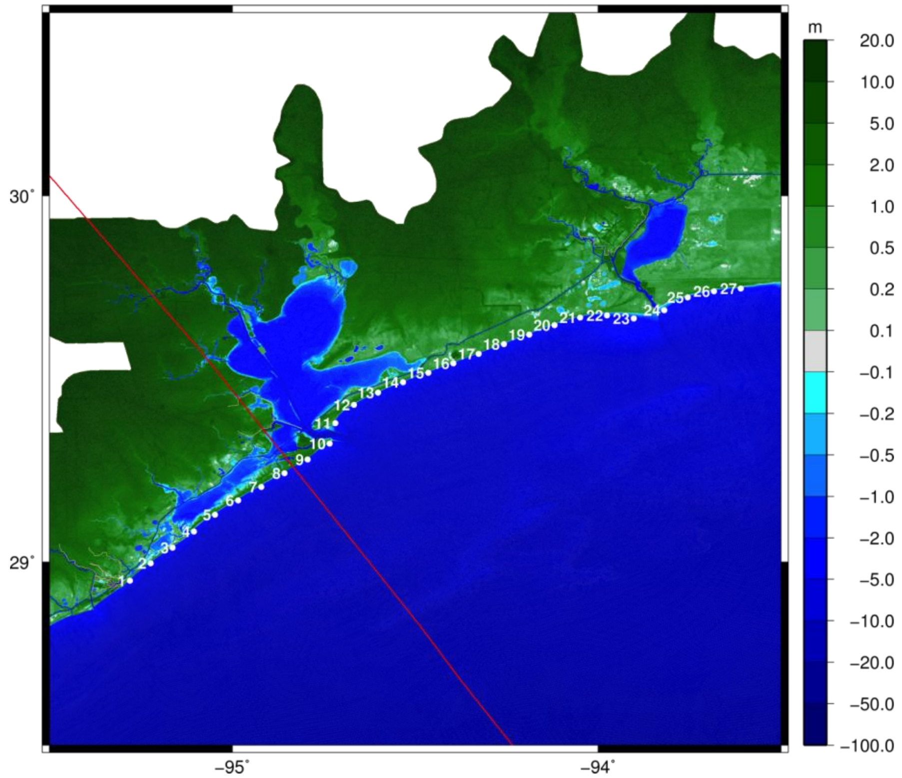
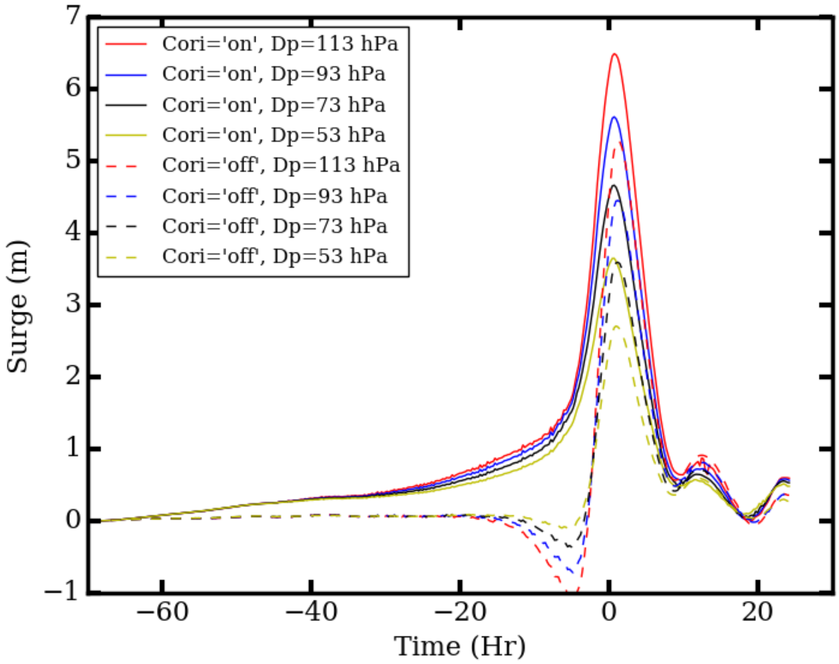


Figure 1. Galveston, Texas study area with location numbers and storm track.

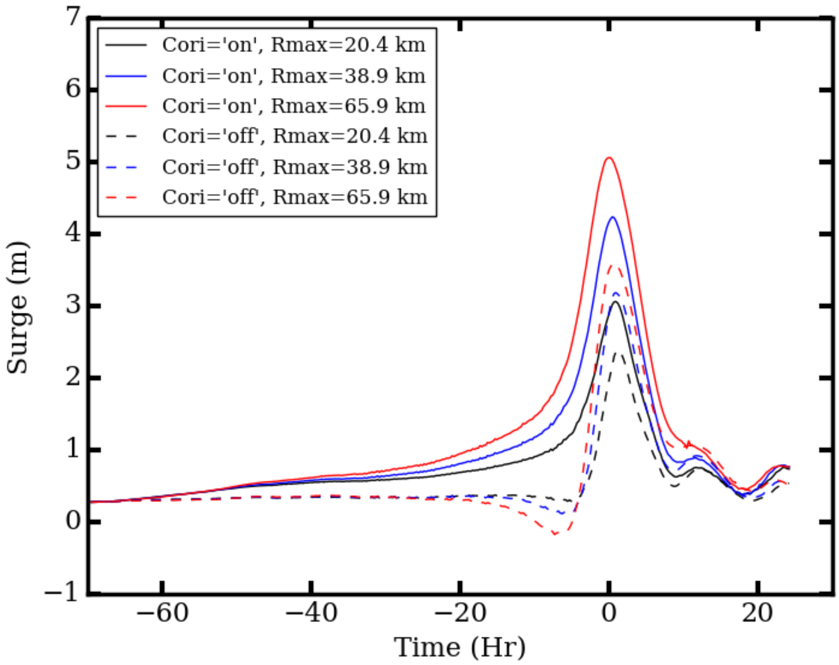
3. Preliminary Results

The surge time series results for different storm scenarios are shown in Figure 2, where Figure 2a shows surge time series for tropical cyclones with the same size (radius to maximum wind of 32.8 km) but different intensity (pressure deficit), and Figure 2b shows surge time series for tropical cyclones with the same intensity (pressure deficit of 53 hPa) but different size. The preliminary findings are threefold. First, both intensity and storm size have a positive effect on the magnitude of forerunner surge, i.e., the larger the pressure deficit and the storm size, the larger the forerunner surge. Second, the influence of storm size is more significant than the influence of intensity, as can be observed by comparing Figure 2a and Figure 2b. Specifically, for two tropical cyclones with the same size (32.8 km), increasing the pressure deficit from 53 hPa to 113 hPa only increases the forerunner surge by 0.26 m 12 hours before landfall. For two tropical cyclones with the same intensity (53 hPa), increasing the storm size from 14.8 km to 47.8 km increases the forerunner surge by 0.47 m 12 hours before landfall. Third, by comparing surge time series with and without Coriolis force in Figure 2 for all the 7 tropical cyclones shown here (dashed lines), it is obvious that forerunner surge disappears when Coriolis force is not considered, meaning that the dominating process for forerunner surge is indeed Ekman setup for all tropical cyclones simulated herein.

Results plotted in Figure 3 further confirm that forerunner surge development along the upper Texas coast is influenced more by storm radius than by storm pressure deficit, because the contour lines show a steeper slope along the size axis (x axis). From these preliminary results, we conclude that significant forerunner surge—defined here as a water elevation of 1 m or more above normal—will occur along the upper Texas coast when storm landfall conditions are characterized by pressure deficits above 80 hPa when storm radius exceeds 40 km. Under these conditions, significant flooding can be expected 12 hours or more before tropical cyclone landfall.



(a)



(b)

Figure 2. Simulated surge time series at location 18 with (solid lines) and without (dashed lines) Coriolis Force for (a) tropical cyclones with the same storm size (radius to maximum wind of 32.8 km) but different intensity (central pressure), and (b) tropical cyclones with the same intensity (pressure deficit of 53 hPa) but different storm size.

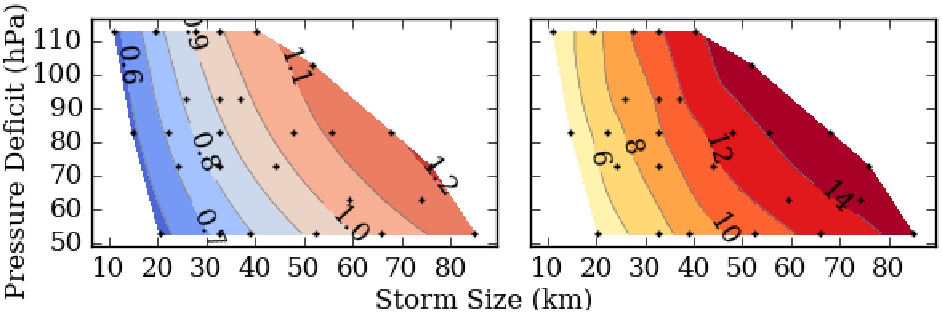


Figure 3. For location 18, left pane: Surge elevation above normal level (in m) 12 hours before landfall, as a function of pressure deficit and storm radius to maximum wind. Right pane: Time of arrival for a 1-m flood elevation (above normal level) in hours before storm landfall, as a function of pressure deficit and storm radius to maximum wind. Plus symbols indicate discrete SWAN+ADCIRC simulations.

Acknowledgements

This material is based on work supported by the National Oceanic Administration's, U.S. Department of Commerce, National Sea Grant College Program via the Mid-Atlantic Coastal Storms Fellowship program (Grant No. NA14OAR4170093, 71858M-712685) and by the National Science Foundation under Grant No. CMMI-1206271. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of these funding sponsors. This work used resources of Advanced Research Computing at Virginia Tech (URL: http://www.arc.vt.edu).

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