Probabilistic hurricane surge forecasting using parameterized surge response functions

Jennifer L. Irish,[1] Youn Kyung Song,[1] and Kuang-An Chang[1]

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[1] A method is proposed for rapidly determining probabilistic maximum hurricane surge forecasts based on surge response functions, available meteorological information, and joint probability statistics. In using this method for Hurricane Ike, surge forecasts prior to landfall were computed in a matter of seconds. From a theoretical standpoint, surge response functions are scaling laws derived from high-resolution numerical simulations. Surge response functions allow rapid algebraic surge calculation while guaranteeing accuracy and detail by incorporating high-resolution computational results into their formulation. The Hurricane Ike example presented here shows that this method has the potential to improve evacuation planning and public early warning of hurricane flooding by providing rapid and accurate probabilistic projections of maximum surge. **Citation:** Irish, J. L., Y. K. Song, and K.-A. Chang (2011), Probabilistic hurricane surge forecasting using parameterized surge response functions, *Geophys. Res. Lett.*, *38*, L03606, doi:10.1029/2010GL046347.

1. Introduction

[2] Recent Gulf of Mexico hurricanes, including Katrina (2005) and Ike (2008), caused widespread flooding and some of the highest surges on record. These storms demonstrated weaknesses in current public early warning practices, including prioritization and timing of evacuations and staging of post-storm recovery. Community and individual evacuation decisions rely heavily on surge forecast information, yet existing approaches for developing forecasts are limited by either time and computational constraints or by spatial detail, both of which impact forecast accuracy.

[3] Single [e.g., *Mattocks and Forbes*, 2008], ensemble [e.g., *Flowerdew et al.*, 2009], and neural network [e.g., *Tseng et al.*, 2007] surge forecasting with physics-based computational models [e.g., *Jelesnianski et al.*, 1992; *Weisberg and Zheng*, 2006] are typically used to develop predictions. When physics-based numerical models are used to produce forecasts based on multiple storm simulations, horizontal resolution, hence surge prediction accuracy, is often sacrificed to reduce computational burden. In other cases, when high-resolution is used, computational resources limit the number of forecast tracks considered. For example, a surge simulation for the Texas coast using ADCIRC [*Luettich and Westerink*, 2004] requires about 1,000 computational hours to simulate hurricane passage over four days (1.3 million nodes with high resolution [50 to 1000 m] over the continental shelf and coastal areas). Thus, while physics-based numerical models have the capacity to provide more accurate and reliable surge prediction for a given hurricane scenario, their application for high-resolution simulation over a near-continuous hurricane parameter space is limited both by time and computational resources.

[4] We propose the use of scaling laws and joint probability statistics to develop continuous probability density functions from high-resolution, physics-based model simulations to rapidly forecast maximum hurricane surge probability. The advantage of this method is the speed and relative simplicity of making surge forecasts while maintaining accuracy afforded by existing numerical computations. We present forecasts using this method for Hurricane Ike (2008).

2. Methods

[5] Hurricane surge depends on geographic features and on hurricane meteorological characteristics: central pressure (c_p), radius to maximum wind ($R_{\max}$), forward speed, and track angle. Surge response functions (SRF) are used for forecasting where the influence of forward speed and track angle are assumed small with respect to other factors [*Irish et al.*, 2008; *Niedoroda et al.*, 2010]:

$$\zeta'(x') = \frac{\rho g \zeta(x)}{(P_{far} - c_p)} + m_x \frac{(P_{far} - c_p)}{(P_{far} - c_{p-\max})} \quad (1a)$$

where ζ' (x') is dimensionless maximum surge, ρ is water density, g is gravity, $\zeta(x)$ is maximum surge, P_{far} is the far-field barometric pressure, $c_{p\text{-}\max}$ is a constant minimum possible central pressure based on a maximum possible intensity argument, and m_x is a location-dependent constant; and

$$x' = \left(\frac{[x - x_o]}{\alpha R_{\max}} - \lambda\right) - F\left(1 - \frac{R_{\max}}{R_{thres}}\right) \quad (1b)$$

where x' is a dimensionless alongshore function, x is location of interest measured on an axis running alongshore, x_o is x at the landfall position, α scales pressure radius [*Thompson and Cardone*, 1996] with $R_{\max}$, λ is a regional constant [*Song*, 2009], F is a location-dependent fitting kernel function, and R_{thres} is a constant. SRFs reproduce maximum surge with R^2 of 0.94 or higher and root-mean-square errors less than 0.25 m (less than 9% of maximum surge), with respect to ADCIRC simulations. A complete discussion of the development of equations (1a) and (1b) is given by *Irish et al.* [2009].

[6] Equations (1a) and (1b) specifies maximum hurricane surge continuously over the hurricane parameter space (c_p, $R_{\max}$, x_o), lending itself to joint-probability statistics use. The probability (p) of a hurricane generating a particular

[1]Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, USA.

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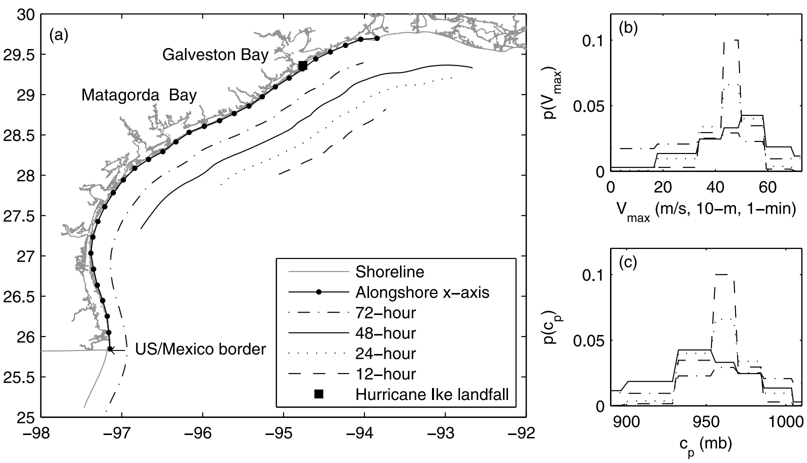

Figure 1. Texas study area showing (a) forecasted track cone, (b) probability distributions for wind speed ($V_{\max}$) at landfall (http://www.nhc.noaa.gov/pastall.shtml), and (c) probability distributions for hurricane central pressure (c_p). Alongshore x-axis ticks are every 20 km with bottom-most tick at x = 0 km (Texas/Mexico border) and top-most tick at x = 580 km (Texas/Louisiana border).

surge value is based on the following joint probability distribution [*Resio et al.*, 2009], where the influence of forward speed and track angle on surge is assumed to be small with respect to other factors:

$$p = p(c_p) \cdot p(R_{\max}) \cdot p(x_o) \qquad (2)$$

SRFs allow for fast surge computation, by simple algebraic calculation using as input only the landfall meteorological parameters c_p, $R_{\max}$, and x_o, while retaining accuracy gained by high-resolution numerical simulation. Thus, equations (1a), (1b), and (2) allow for the near-instantaneous calculation of accurate probabilistic representations of maximum hurricane surge throughout a region of interest.

3. Method Application for Hurricane Ike

[7] Hurricane Ike made landfall at Galveston, Texas (Figure 1a), on September 13, 2008 at 0700 UTC [*Berg*, 2009], as a Category 2 hurricane. At landfall, Hurricane Ike's central pressure, radius to hurricane-force winds (R_{33}), and forward speed were 950 mb, 195 km, and 4 m/s, respectively [*Berg*, 2009] (see also http://www.nhc.noaa.gov/pastall.shtml). Due to its size and its landfall in an area fronted by a wide continental shelf, Hurricane Ike generated high surges throughout the upper Texas coast. Maximum flood elevations at the open coast were reported on Bolivar Island east of Galveston.

3.1. Surge Response Function Development for Texas Coast

[8] We developed SRFs for the open coast of Texas. Surge input for SRF development was generated with ADCIRC using a high-resolution (as fine as 50 m in coastal areas) geographic grid [*Westerink et al.*, 2008]. ADCIRC was forced with wind and barometric pressure fields [*Thompson and Cardone*, 1996] for 166 synthetic hurricanes spanning the (c_p, $R_{\max}$, x_o) parameter space; a total of 166 ADCIRC simulations were executed. To simplify the analysis, wave setup and astronomical tides were not considered.

[9] SRF surge estimates for five historical hurricanes were compared with gauge measurements collected by the U.S. Geological Survey (USGS) [*East et al.*, 2008; *McGee et al.*, 2006] and high water marks (HWM) collected by the Federal Emergency Management Agency (available at http://dig.abclocal.go.com/ktrk/hwmtype_11x17_fema.pdf), the U.S. Army Corps of Engineers [*United States Army Corps of Engineers*, 1961, 1983], and the National Oceanic and Atmospheric Administration [*National Oceanic and Atmospheric Administration*, 1982] (Figure 2). The five storms are Hurricanes Carla (1961), Alicia (1983), Bret (1999), Rita (2005), and Ike (2008). Observed landfall characteristics were used as input (see auxiliary material).[1] Short waves were removed from the gauge time series by applying a moving average. Two types of HWM were reported: those representing the quasi-steady water level inclusive of wave setup (HWM (stillwater)), and those including additional contributions by short waves (HWM (runup)).

[10] For Hurricanes Bret, Rita, and Ike, measured wave conditions offshore of Freeport and Corpus Christi, Texas (see http://www.ndbc.noaa.gov/station_page.php?station=42019), allowed estimation of wave setup. This estimation was achieved by first using linear theory to transform waves to the point of breaking, assuming the ratio of wave height to water depth is 0.78. Second, we assume 20% of the breaking wave height as an upper bound for wave setup. In the case where the barrier island land mass is fully inundated, for example on Bolivar Peninsula, actual wave setup is likely lower.

[11] SRF estimates match observations with respect to both surge magnitude and alongshore distribution. For example, of the 41 Hurricane Ike observations, 85% (35) fall in the range between the final SRF-computed surge and the sum of the final SRF-computed surge and the estimated wave setup. Similarly for Hurricanes Carla and Alicia, SRF estimates capture the overall alongshore surge magnitude and trend. SRF magnitude for Hurricane Carla appears to be somewhat high, given that wave setup is not included in the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL046347.

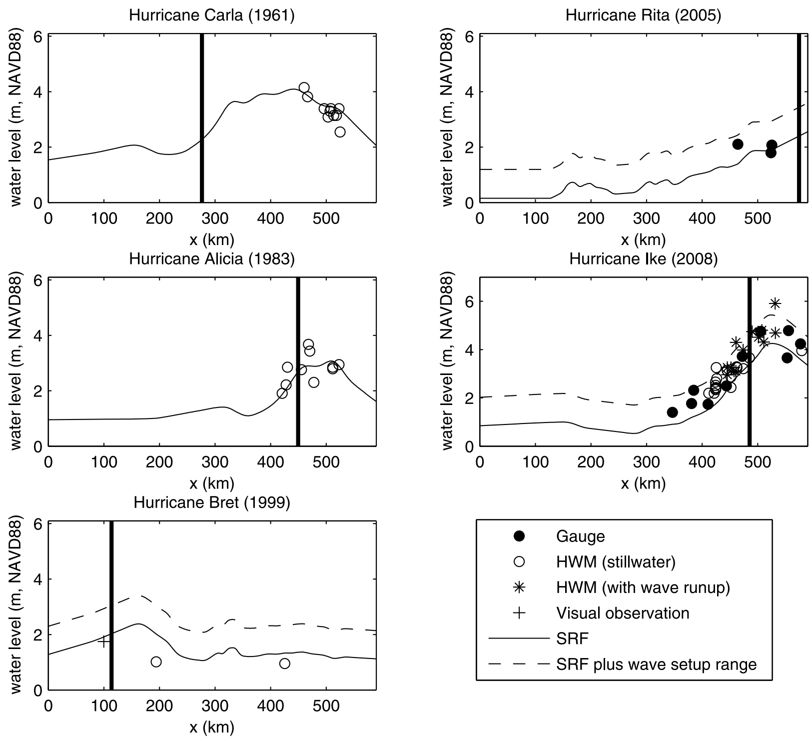

Figure 2. Surge response function estimates using reported landfall statistics for five historical hurricanes versus water level observations and high water marks (see auxiliary material); historical data were adjusted for sea level rise. Dashed lines show approximated wave setup contributions. See Figure 1a for x-axis position: x = 0 km is Texas/Mexico border, x = 180 km is near Corpus Christi, x = 300 km is near Matagorda Bay, x = 495 km is Galveston Bay entrance, x = 530 km is Rollover Pass, x = 580 km is Sabine Pass. Vertical lines represent landfall position.

SRFs; this is likely explained by bathymetric changes in the last 50 years and by interannual sea level trends (see http://www.tidesandcurrents.noaa.gov). Hurricanes Bret and Rita generated lower surges on the Texas coast with respect to the other hurricanes considered here. While HWMs for Hurricane Rita show surge increasing towards the location of landfall, HWMs for Hurricane Bret do not indicate an alongshore variation in surge. Yet, a visual observation [*Lawrence and Kinberlain*, 2001] suggests the region of highest surge was near the landfall location, a pattern captured by the SRF estimate.

[12] The SRF estimates for these storms reveal two interesting features of surge along the Texas coast. First, a recurring pattern in the alongshore surge distribution is relatively higher surge near x = 150 km, south of Corpus Christi, and near x = 325 km, Matagorda Bay. Near Corpus Christi, the coastline turns to the east while the continental shelf widens slightly with respect to conditions to the south. Additionally, the continental shelf triples in width between Matagorda Bay and the Texas/Louisiana border. These along-coast discontinuities result in discontinuities in the surge response. We hypothesize that this is a contributing factor to Hurricane Carla's large alongshore extent of high surge. Second, the SRF estimates reveal that the upper Texas coast is more prone to higher surges than the lower Texas coast. SRF surges for Hurricanes Bret and Alicia show that weaker storms making landfall on the upper Texas coast (Alicia) generate higher surges than stronger storms of comparable size making landfall on the lower Texas coast (Bret). This increased surge vulnerability can be attributed to the relative widening of the continental shelf from the lower to upper Texas coast. This finding is echoed when comparing surges from Hurricanes Carla and Ike, who were of comparable size but different strengths, yet generated comparable peak along-coast surges.

3.2. Probabilistic Surge Forecasts for Hurricane Ike

[13] Probabilistic surge forecasts for Hurricane Ike were constructed at 72, 48, 24, and 12 hours prior to landfall. Meteorological forecasts were based on publicly available wind speed probability and track cone forecasts (see http://www.nhc.noaa.gov/pastall.shtml), and no change in hurricane radius with storm movement was considered. For each forecast, storm size was held constant at the value specified in the respective hurricane advisory (Table 1); specifically, $R_{\max}$ was taken as the reported value at the time of forecast such that the probability $p(R_{\max})$ is unity at the reported value and zero elsewhere. For forecast calculation, the meteorological parameter space was represented by 51 unique values of c_p and 120 unique values of x_o to represent 6,120 unique hurricanes; nearly 38 times the number simulated with ADCIRC. The probability $p(c_p)$ was estimated from reported wind speed probability based on curve-fitting to historical central pressure and wind speed observations [*Powell and Reinhold*, 2007] and by assuming that the probability assigned to each wind range (Category 1, 2, etc.) was equally distributed over the wind-speed interval (Figures 1b and 1c). The probability $p(x_o)$ was estimated from the alongshore extent of the track cone (Figure 1a) by assuming a triangular distribution where probability is greatest at the cone center. Finally, joint probability for surge was determined using equation (2) and the SRFs.

Table 1. Reported R_{33} and Estimated R_{max} for Hurricane Ike

Time Before Landfall (h)	R_{33}[a] (km)	R_{max}[b] (km)
72	55	13
48	185	32
24	188	33
12	195	35
Landfall	195	35

[a]From hurricane advisories (http://www.nhc.noaa.gov/pastall.shtml).
[b]Estimated by curve-fitting to historical hurricane observations [*Powell and Reinhold*, 2007].

[14] Figure 3 shows the forecasts for Hurricane Ike as cumulative surge probability (P) versus alongshore position. Each forecast, representing SRF-computed surges for 6,120 unique hurricanes, required 15 computational seconds to execute (in Fortran on a 3.2-GHz Xeon processor). The 72-hour forecast shows surge slowly varies along this stretch of coastline due largely to the long alongshore extent of the 72-hour track cone (Figure 1a). Toward the south, the relative narrowing of the continental shelf causes relatively lower forecasted surge. The 72-hour forecast shows that the P = 0.50 estimate reflects the final surge response in that final surge at nearly all locations are at least this level.

[15] Over the next 24 hours, Hurricane Ike tripled in size to R_{33} = 185 km. This size increase and northward shift and shortening of the track cone led to a forecast that reasonably conveys flood hazard for this storm (48-hour forecast in Figure 3). The 48-hour forecast also reflects the final surge response in that final surge probability at all locations was about $P \geq 0.50$. Furthermore, this 48-hour forecast captures completely the final surge response such that the final peak alongshore surge probability is about P = 0.90.

[16] As time progresses, the meteorological forecast becomes more refined, echoed in the probabilistic surge forecasts at 24 and 12 hours. By the 12-hour forecast, the alongshore distribution in the final surge response is fully captured by the surge forecast, and differences between the P = 0.50 and 0.90 estimates were on the order of 1 m or less. The probabilistic 12-hour projection gives the peak final alongshore surge estimate of 4.25 m, NAVD88 (at x = 520 km) a probability of P = 0.90.

3.3. Surge Response Function Sensitivity to Uncertainty in Meteorological Conditions

[17] Surge forecasts carry forward the uncertainty in meteorological projections. To evaluate SRF sensitivity to changes in forecasted landfall position, central pressure, and storm size, the surge forecasts for Hurricane Ike were repeated by assuming percent changes in these input conditions (see auxiliary material). We conclude the following:

[18] 1. For every 1.0% change in track cone extent, surge changes by less than 0.2%.

[19] 2. For every 1% change in central pressure deficit, surge changes between 0.7 and 1.4%, depending on location. This is consistent with equation (1a) (first term).

[20] 3. For every 1% change in hurricane size, surge changes by less than 0.3%. Consistent with *Irish and Resio* [2010], the SRF sensitivity to changes in storm size depends on continental shelf width, where the highest along-coast surge increases with storm size only when storm radius is smaller than the continental shelf width.

[21] In summary, uncertainty in the surge forecast is most sensitive to uncertainty in the forecast of central pressure.

4. Summary

[22] The above method offers a rapid and accurate means for determining probabilistic maximum surge forecasts for impending hurricanes. There are three main advantages of this approach. First, the accuracy afforded by high-resolution

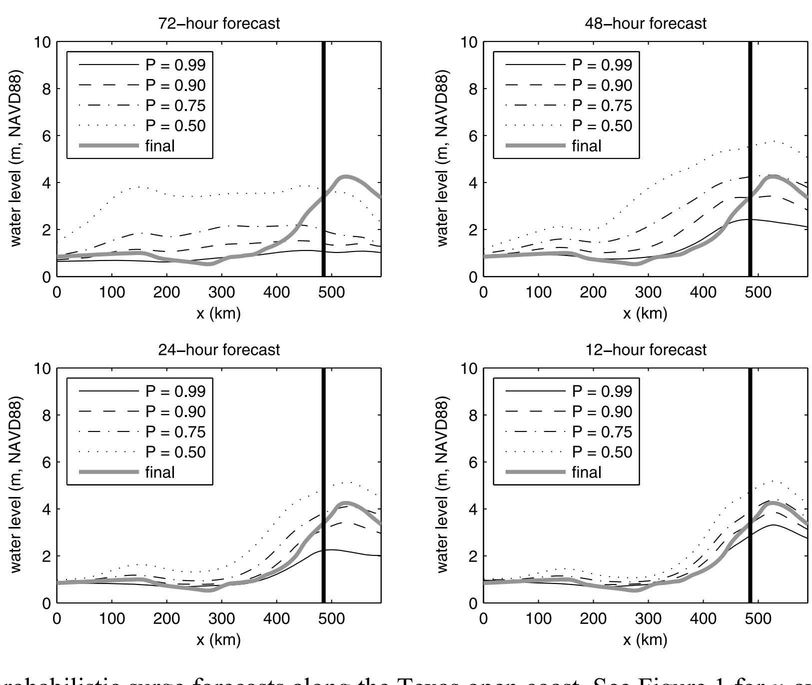

Figure 3. Estimated probabilistic surge forecasts along the Texas open coast. See Figure 1 for x-axis position: x = 0 km is Texas/Mexico border, x = 180 km is near Corpus Christi Bay, x = 300 km is near Matagorda Bay, x = 495 km is Galveston Bay entrance, x = 530 km is Rollover Pass, x = 580 km is Sabine Pass. Vertical lines represent landfall position.

simulation is maintained while eliminating the need for real-time simulation. Instead, a reduced number of high-resolution simulations, in this case 166 simulations to represent 6,120, is completed well before an impending event. We have shown that these probabilistic forecasts can be generated in a matter of seconds, given publicly available meteorological forecasts. Second, the meteorological input required to develop a forecast is limited to three landfall quantities: central pressure, size, and position. Third, this approach shows how surge varies from storm condition to storm condition and from location to location along the coast, without the requirement that each storm be simulated separately, while retaining the ability to consider all hurricane possibilities simultaneously. The SRF method can be used to identify under which set of meteorological scenarios highest surge will result and to identify which portions of the coast are most vulnerable to high surges. These probabilistic forecasts, therefore, appropriately reflect changes in the surge response with regional and local topographic variation.

[23] The robustness of the SRF approach indicates that this method can be successfully applied to other hurricane-prone regions for surge forecasting. This approach can also take advantage of existing simulated surges from any numerical surge model to develop SRFs for any location. The general SRF form in equations (1a) and (1b) captures the relative influence of the main hurricane forcing parameters for surge generation, and the specific form of the SRFs predicts the alongshore variation in surge, due to specific geographic characteristics. Finally, for general operational use in early flood warning, the proposed forecast method should be expanded to include (1) the influence of hurricane forward speed and track angle, wave setup, and tide contributions; (2) possible conditional probability among the hurricane parameters; (3) surge timing; and (4) meteorological forecast and model uncertainty.

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K.-A. Chang, J. L. Irish, and Y. K. Song, Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136, USA. (kchang@civil.tamu.edu; jirish@civil.tamu.edu; mudai@tamu.edu)