GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L08608, doi:10.1029/2011GL047090, 2011

Origin of the Hurricane Ike forerunner surge

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Received 11 February 2011; revised 14 March 2011; accepted 16 March 2011; published 21 April 2011.

[1] A large, unpredicted, water level increase appeared along a substantial section of the western Louisiana and northern Texas (LATEX) coasts 12–24 hrs in advance of the landfall of Hurricane Ike (2008), with water levels in some areas reaching 3 m above mean sea level. During this time the cyclonic wind field was largely shore parallel throughout the region. A similar early water level rise was reported for both the 1900 and the 1915 Galveston Hurricanes. The Ike forerunner anomaly occurred over a much larger area and prior to the primary coastal surge which was driven by onshore directed winds to the right of the storm track. We diagnose the forerunner surge as being generated by Ekman setup on the wide and shallow LATEX shelf. The longer forerunner time scale additionally served to increase water levels significantly in narrow-entranced coastal bays. The forerunner surge generated a freely propagating continental shelf wave with greater than 1.4 m peak elevation that travelled coherently along the coast to Southern Texas, and was 300 km in advance of the storm track at the time of landfall. This was, at some locations, the largest water level increase seen throughout the storm, and appears to be the largest freely-propagating shelf wave ever reported. Ekman setup-driven forerunners will be most significant on wide, shallow shelves subject to large wind fields, and need to be considered for planning and forecasting in these cases. **Citation:** Kennedy, A. B., U. Gravois, B. C. Zachry, J. J. Westerink, M. E. Hope, J. C. Dietrich, M. D. Powell, A. T. Cox, R. A. Luettich Jr., and R. G. Dean (2011), Origin of the Hurricane Ike forerunner surge, *Geophys. Res. Lett.*, *38*, L08608, doi:10.1029/2011GL047090.

1. Introduction

[2] Hurricane storm surge is usually attributed to the strong onshore winds that accompany a hurricane near the time of landfall. This primary coastal surge will peak around the time of landfall, with the largest response found to the right side of the storm track in the northern hemisphere. Smaller increases in water level have also been observed up to several days before landfall: these *forerunners* are well known but typically have amplitudes under 1 m, and have been thought relatively innocuous [*Redfield and Miller*, 1957; *Bunpapong et al.*, 1985].

[3] However, residents along Hurricane Ike's track faced widespread inundation beginning at a full day before landfall [*Standridge*, 2010] while the center of the storm was more than 400 km distant and winds were still shore-parallel and relatively weak. Although the National Hurricane Center forecast a large primary surge at landfall, the forerunner was not addressed by forecasts or anticipated by emergency personnel. Ike's forerunner was similar to descriptions of the historical 1900 and 1915 Galveston Hurricanes [*Garriott*, 1900; *Stewart*, 1915; *Cline*, 1920], both of which began flooding well before landfall when winds were seemingly from the wrong heading (5, 7 ft (1.5, 2.1 m) forerunners at 12 hours prior to landfall, respectively). Figure 1 shows that tracks for all three storms were quite comparable, suggesting that the path of the storm may be important. It should also be noted that all three storms had large wind fields, which will also be shown to be significant.

2. Hurricane Ike Forerunner Observations

[4] Two days prior to Ike's landfall, the authors placed nine wave/surge gauges in depths of 9–15 m along 370 km of the Texas coast between Port Aransas (R) and the Louisiana-Texas border (Z), retrieving all but one gauge post-storm. (See *Kennedy et al.* [2010] for instrumentation and deployment details.) Figure 1 shows locations for both these gauges and NOAA tide stations used here, while Figure 2 shows time series of the water level anomaly (measured water level minus predicted tide) for Hurricane Ike at these stations. The anomaly, with a maximum of 4.3 m at the gauges shown, was largest on the right side of the storm between gauges X and 8768094, a distance of around 150 km. Water levels peaked as Ike approached the coastline, and the surge at landfall thus fits well with prevailing descriptions of storm surge being forced by cross-shelf wind stress.

[5] However, a large forerunner surge began to increase strongly at 24 hours before landfall over much of the region. At 15 hours before landfall, the water level anomaly was 2.2 m at gauge Z, which is 6 km offshore, and reached an absolute shoreline elevation of 3.2 m NAVD88 (3.0 mMSL) by 12 hours before landfall at USGS gauge GAL-1 on what is normally dry land [*East et al.*, 2008] (Figure S1 of the auxiliary material); this appears to be the largest forerunner

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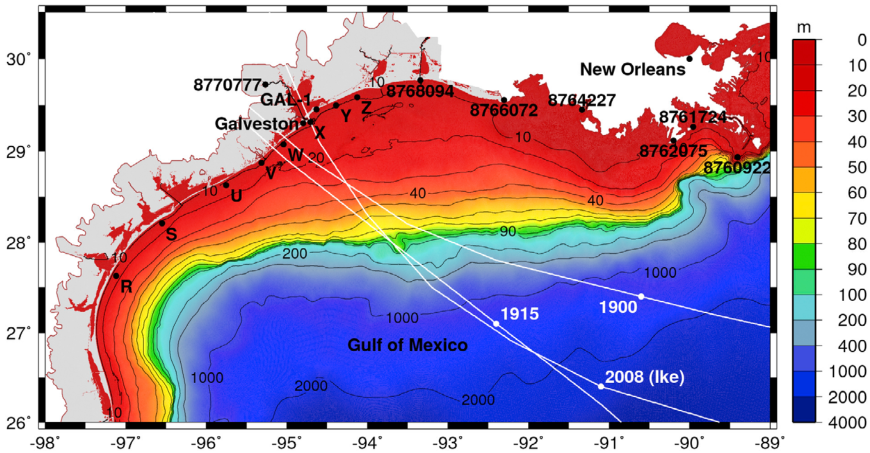

Figure 1. Bathymetry of LATEX shelf, with tracks of Hurricane Ike, and the 1900 and 1915 Galveston Hurricanes. (R-Z) rapidly installed gauges; (numbers) NOAA stations; (GAL-1) temporary USGS gauge.

ever reported in the literature, surpassing the previously-mentioned 1915 Galveston Hurricane [*Cline*, 1920].[1] Winds at these times were either shore-parallel or slightly offshore (Figure S1); thus, cross-shore wind stresses did not force the forerunner.

[6] Along the Texas coast to the south of the storm track, the forerunner surge appeared to propagate as a slowly dissipating free wave with crest anomaly exceeding 1.4 m and average speed of 5–6 m/s, (Figure 2, line 2), and was by the time of landfall 300km in advance of the storm center. Propagating forerunner waves have been observed in advance of a tropical cyclone with speeds of 400–600 km/day (4.6–6.9 m/s) [*Fandry et al.*, 1984], but never with such large amplitude. Second and third smaller waves (lines 3,4) propagate after the storm with speeds similar to the first wave and periods of around 33 hours, making them sub-inertial. Continental shelf wave speeds were computed to be 4.3 m/s and 8.0 m/s at gauges R and X using idealized solutions [*Pedlosky*, 1990] – these bracket well the observed speeds for lines 2–4. Thus, we identify lines 2–4 as sub-inertial, barotropic, continental shelf waves, which have a geostrophic balance between the alongshelf current velocities and surface elevations [*Pedlosky*, 1990]. Continental shelf waves are nondispersive and are much slower than barotropic Kelvin waves: a Kelvin wave with 6m/s speed would require a depth of less than 4 m, which is not believable. Similarly, Helmholtz seiching modes [*Bunpapong et al.*, 1985] travel much faster than observed here. The continental shelf wave of line 2 would appear to have the largest crest elevations ever reported: typical crest-trough heights for freely propagating waves are cm to tens of cm. Some of the largest reported in the literature are given by *Fandry et al.* [1984] (~75 cm), *Thiebaut and Vennell* [2010] (~90 cm), and *Eliot and Pattiaratchi* [2010] (~63 cm). It should also be noted that *Morey et al.* [2006] computed a crest height of 1.4 m for a forced topographic wave traveling parallel to Hurricane Dennis.

[7] Potential forerunner explanations include inverse barometric surge from lowered atmospheric pressures, wave setup, large scale seiching modes, and Ekman setup. Barometric effects are readily dismissed, as areas of low pressure were still far offshore at the time of the forerunner. Breaking wave setup plays a role, particularly near the shoreline. However, simulations described in the next section with and without wave effects showed only small differences (0.1–0.33 m) at the gauges of Figure 2 [see also *Bunya et al.*, 2010; *Dietrich et al.*, 2010, 2011]. Large scale seiching modes arising from the sudden entrance of a hurricane into the Gulf of Mexico have been proposed as the cause of forerunner surge. These certainly exist with amplitudes of several tens of cm [*Bunpapong et al.*, 1985], and will affect in particular very early water levels more than a day before landfall; however, the observed forerunner is not Gulf-wide but is instead closely tied to the storm location and is again far too large for this to be plausible.

3. Ekman Setup

[8] Ekman setup, due to an approximately geostrophic balance between the Coriolis force acting on the along-shelf current and the across shelf pressure gradient [e.g., *Freeman et al.*, 1957], is the only process with the potential to produce the large forerunner observed during Ike. The Ekman setup at the coast, η_c, may be computed from across-shelf momentum equations as

$$\eta_c = \int fV/g \; dx, \tag{1}$$

where x increases along a transect toward shore, f is the Coriolis parameter, g is gravitational acceleration and V is the depth-averaged alongshelf velocity. Thus, a large Ekman setup will be forced by strong winds generating rapid alongshelf currents over a wide shelf: a depth-averaged current of 1 m/s at 30 degrees north latitude with the shore on the right hand side would force a setup of 1.5 m on a 200 km wide continental shelf. These numbers are plausible here because of the wide and shallow LATEX shelf and, as will be shown, Ike's enormous wind field. We note that the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047090.

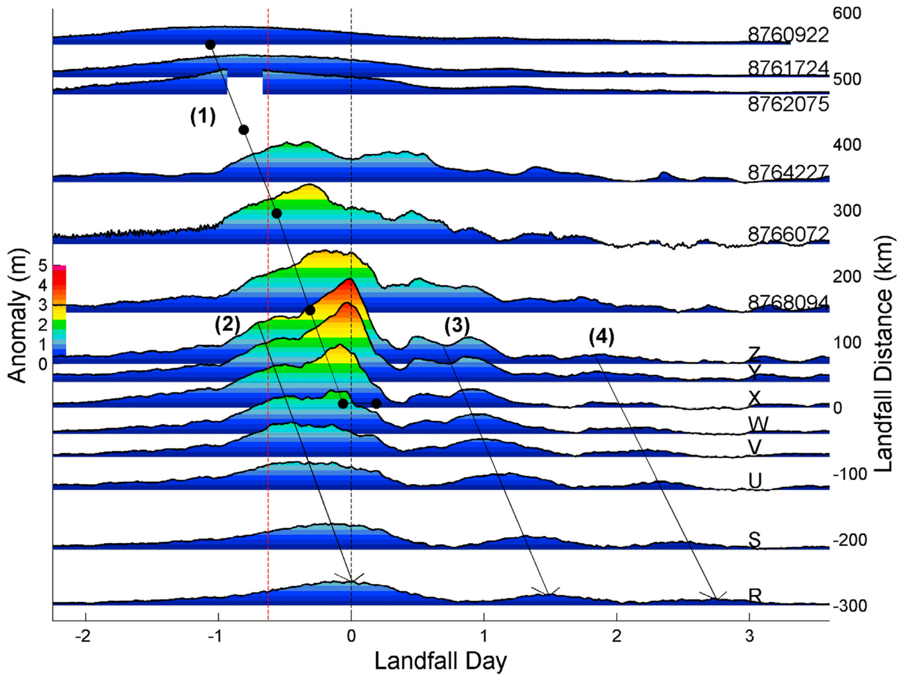

Figure 2. Water surface elevation anomaly over time (water surface elevation minus predicted tides) for open coast stations shown in Figure 1. Vertical offsets between the plots are proportional to the coastline distance between gauges. Line 1: approximate shoreline position of Hurricane Ike. Line 2: propagating forerunner wave. Lines 3–4: propagating resurgence waves. The red dashed line indicates 15 hours before landfall.

bowl-shaped LATEX coastline in Figure 1 allowed winds to be approximately shore-parallel over a long stretch of coastline, even when the hurricane was quite distant. To the right of landfall (positive distances in Figure 2), the forerunner appeared to be primarily a forced Ekman response from winds on the shelf, while to the left of landfall it was clearly a free wave as it passed through regions that never experienced strong wind forcing.

[9] We investigate these processes through simulations with the tightly-coupled, depth-averaged, SWAN + ADCIRC wave and circulation model [*Westerink et al.*, 2008; *Bunya et al.*, 2010; *Zijlema*, 2010; *Dietrich et al.*, 2011], run on a 3,323,388 node unstructured grid with resolution to 30 m in the nearshore. Wind forcing was taken from a H*Wind post-storm reconstruction embedded into a larger scale wind field [*Cox et al.*, 1995; *Powell et al.*, 1998], which combines all available wind observations into a common marine framework at 10 m height. Though rated only a Category 2 on the Saffir-Simpson (SS) scale at landfall with maximum winds of 95 knots (49 m/s), Ike's wind field was among the largest observed for a landfalling hurricane in the Atlantic basin over the past thirty years. Tropical storm strength winds extended 400 km from the center at one day before landfall [0600 UTC, 12 Sept.] with an integrated kinetic energy [*Powell and Reinhold*, 2007] of 130 TJ, surpassing SS Category 5 Hurricane Katrina's peak value of 117 TJ at 18 h before landfall.

[10] Figure 3a shows the reconstructed wind field at 15 hours prior to landfall, while Figure 3b shows the computed water level anomaly. Winds at this time were close to shore-parallel, while the computed anomaly increased strongly toward shore as expected from the geostrophic balance, and exceeded 1.5 m. A strong, predominantly shore-parallel, current exceeding 1m/s was predicted in Figure 3c over most of the shelf with the strongest currents in depths of 20–80 m. Magnitudes decrease in shallower water because of increased bed friction and lower wind speeds, and in greater depths because of insufficient time to accelerate the entire water column.

[11] The forerunner's geostrophic nature may be shown conclusively by recomputing the model surge without Coriolis forcing and comparing the two simulations. Figure 3d shows that, at 15 hours before landfall, there would have been essentially no coastal surge over the region in the absence of Coriolis forcing. This comparison removes all doubt about the nature of the forerunner and may also be seen in more detail in Animations S1 and S2.

[12] These effects are also apparent in the computed time series of water level anomaly shown in Figure 4. At all locations, the forerunner is large with Coriolis included but vanishes without Coriolis forcing. Surge at Manchester Houston (8770777), almost 40 km along shipping channels from the head of Galveston Bay and 80 km from the open Gulf of Mexico, shows more than a 2 m increase in peak surge from Coriolis-effects, and a near-tripling of the overall surge. This occurs because the longer time scale of the forerunner filled Galveston Bay in advance of the primary surge, which had a duration of only 10–12 hours on the open coast. With the Bay already filled, the localized wind driven surge became even more catastrophic. This increased surge in inland, narrow-entranced, bays needs to be accounted for in predictions and emergency planning. It should be noted that agreement shown in Figure 4 although good, is not perfect, with simulations underestimating

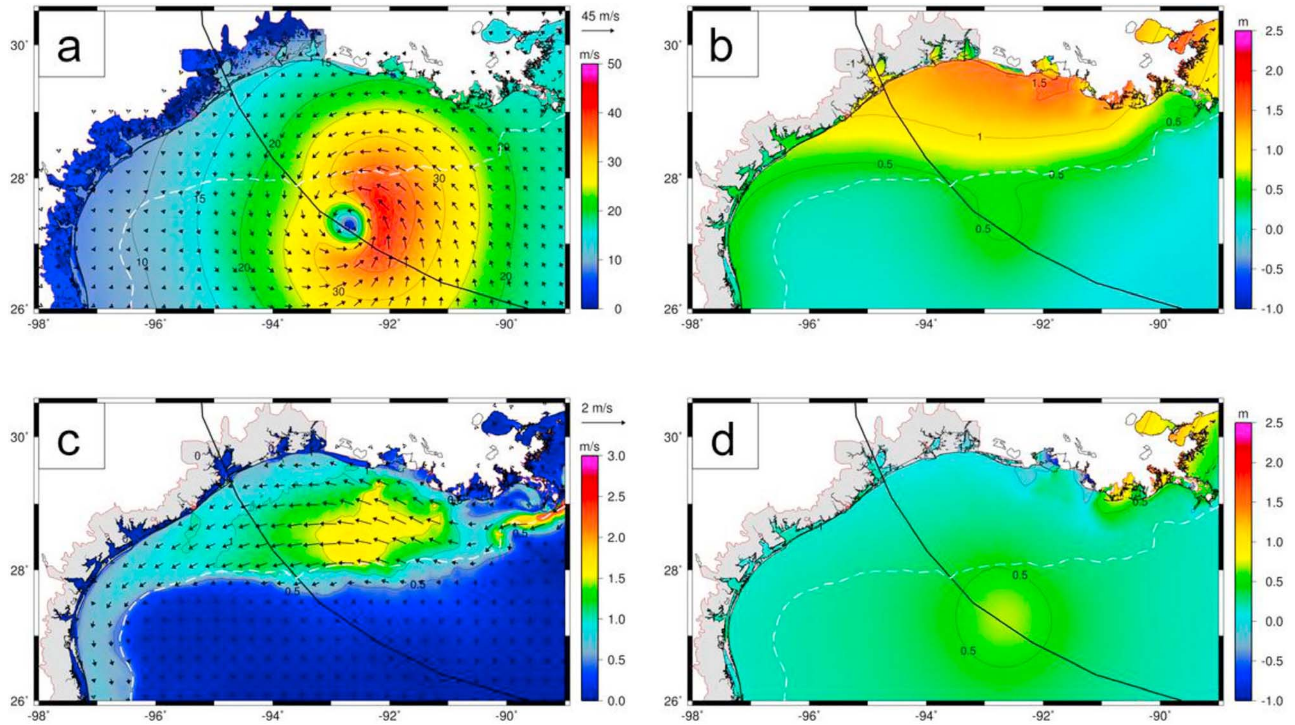

Figure 3. (a) Data assimilated wind field; (b) computed water level anomaly; (c) computed depth-averaged current field; and (d) computed water level anomaly without Coriolis forcing, all at 15 hours before Hurricane Ike's landfall. The 100 m depth contour is given by the dashed line.

somewhat the forerunner magnitude. From equation (1) Ekman setup is dependent on current velocity, which is itself sensitive in shallow depths to poorly known bottom friction coefficients. Agreement could likely be improved with further coefficient calibration; however here we use a set of coefficients tested against a variety of storms. Additional processes neglected here, such as three dimensional velocities, will also play a role but appear to be second order

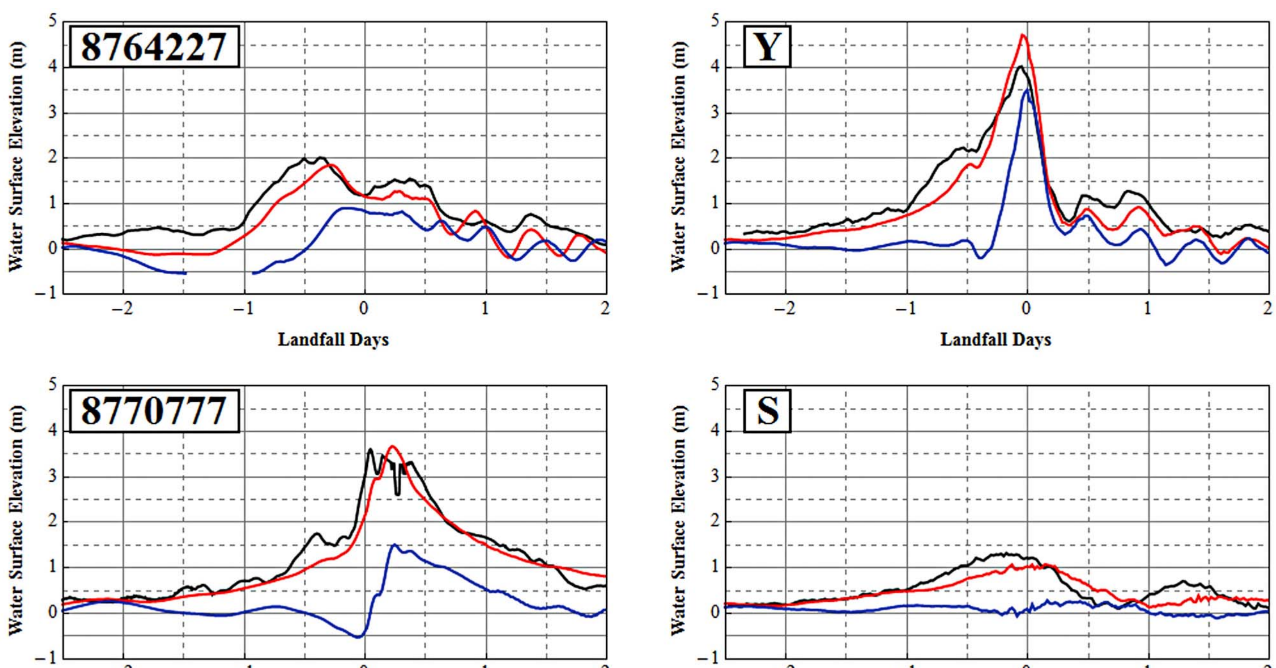

Figure 4. Time series of measured (black) and computed water level anomaly with (red) and without (blue) Coriolis forcing. Gauge 8764227 (Atchafalaya Bay); Gauge Y (High Island); Gauge 8770777 (Manchester Houston); and Gauge S.

effects when compared to the two-dimensional geostrophic balance presented above.

4. Discussion and Conclusions

[13] Although small forerunners are common, dangerous forerunners are relatively infrequent and will arise from large, strong, storms moving with moderate speed near wide, shallow, and smooth shelves. In the United States, this will certainly be important on the LATEX shelf, and is likely to be important for much of the West Florida shelf. Surge due to Ekman setup has already been noted here by *Morey et al.* [2006] for Hurricane Dennis, and by *Cline* [1920] for a storm that generated a forerunner "4.9 ft (1.5 m) above any previous high water" on Tampa Bay.

[14] The forerunner surge during Hurricane Ike occurred over a much larger area and prior to the primary coastal surge which was driven by onshore directed winds to the right of the storm track. It caused early flooding of coastal regions, and allowed much more effective penetration of flooding into narrow entranced bays – these had already been filled by the forerunner before being subject to the primary surge.

[15] A portion of the Hurricane Ike forerunner traveled well in advance of the storm as a continental shelf wave that appears to be the largest ever reported. Dangerous forerunners are most important for large storms and need to be considered for these worst case scenarios.

[16] **Acknowledgments.** This research was funded by NSF grants 0902264 and 0746232, Florida Sea grant R/C-S-46, the Florida Bureau of Beaches and Coastal Systems, the USGS Center for Coastal Geology, and the US Army Corps of Engineers.

[17] The Editor thanks Cheryl Ann Blain and an anonymous reviewer for their assistance in evaluating this paper.

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