Waves, Surge and Damage on the Bolivar Peninsula During Hurricane Ike

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1. Introduction

At 7:10 UST on September 13 (2:10 AM local), Hurricane Ike made landfall at the east end of Galveston Island, Texas. Figure 1 shows the path of Ike as it made landfall and the locations of five gauges installed prior to landfall by the US Geological Survey (GAL-1, GAL-2), and by the present authors' team (X,Y,Z). These five gauges were part of a much larger deployment extending from Louisiana to Southern Texas, but Ike's effects were disproportionally felt near the long, low-lying Bolivar Peninsula which has typical elevations around 2m. Despite being only a strong category 2 storm with maximum winds at landfall of 95 knots (49m/s, Berg, 2009), Ike's large, long-lasting surge and waves devastated large parts of Bolivar. These waves, surge, and the associated damage form the basis for this paper. In particular, we search for the dividing line between building survival and destruction, which seems to occur over a relatively small elevation range. The Bolivar Peninsula was just to the right of landfall, placing it on the strong side of the hurricane. H*Wind reconstructions (Powell et al., 1998) show winds blowing strongly from offshore-to-onshore for most of the storm, which acted to increase both surge and waves. Surge is extremely important for the particular case of the Bolivar Peninsula, as it allowed large waves to penetrate inland into areas they could not otherwise have reached.

Figure 2 gives an example of the destruction, with pre-and-post-storm satellite photos of the same area near the USGS gauge GAL-1 by the Gulf of Mexico. Shoreline erosion was around 75 m, which undermined the piled foundations of oceanfront buildings. Most other houses in this area were reduced to either piles or slabs by large waves riding on surge, with only a few remaining more or less intact.

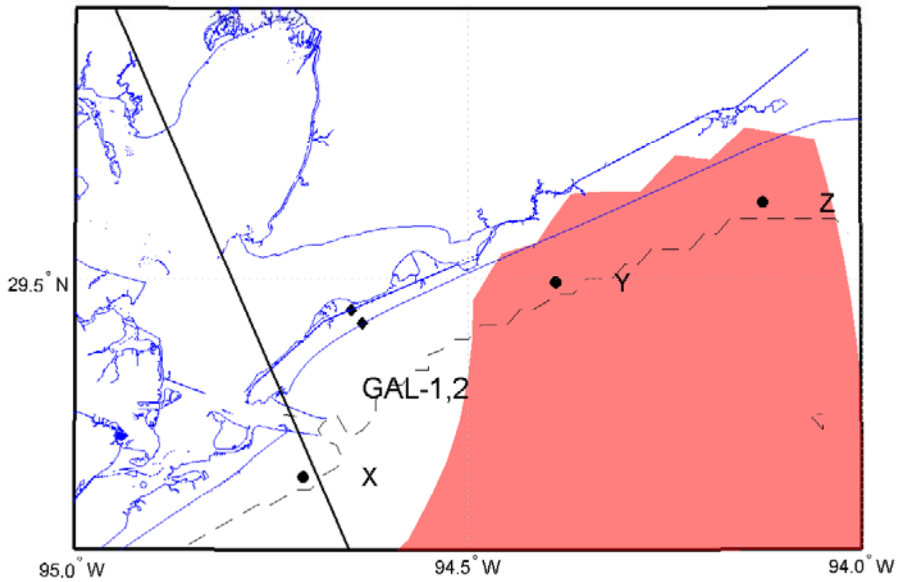

Figure 1. Hurricane Ike's track, the extent of hurricane force winds, and wave/surge measurement locations (symbols). The shaded region shows areas that experienced Category 2 winds, while the rest of the figure experienced Category 1 winds.

Ike is not the only severe hurricane known to have impacted Bolivar: the Great Galveston Hurricane of 1900, which killed 5000-8000 people on Galveston Island, also inundated the much more lightly populated Bolivar Peninsula and killed entire families (Daniels, 1985). The less-remembered 1915 hurricane was said to have been even worse than the 1900 storm, and had recorded surge of 14.4 ft at High Island on the east end of the Bolivar Peninsula. (US Weather Bureau, 1915). However, no storms of this magnitude had impacted Bolivar since, and by Ike's arrival almost no one on Bolivar had first-hand knowledge of the catastrophic inundation resulting from a severe hurricane.

Figure 2. Google Earth images of the same location at GAL-1 taken before the storm (left); and after (right).

2. Waves and Surge

Figure 3 shows measured waves and surge at pressure gauges X,Y, and Z, which were 5-6km offshore in mean depths of around 9m. These spanned the length of the Bolivar Peninsula and give a good indication of coastal conditions. Surge at all gauges rose early, with 2m surge (NAVD88) occurring at gauges Y and Z around 18 hours before landfall. This early surge was essential to allowing waves to remove the protective dunes in parts of Bolivar before landfall, and increasing the time waves could impact shores and structures. Peak coastal surges reached 4.6m at Z, 4.3m at Y, and decreased somewhat with gauge X to the west near Galveston. (It should be noted that gauge X appears to have been on a bed that eroded approximately 0.5m, from the change in measured water levels before and after the storm.) Coastal significant wave heights were also quite large in this region, with maxima approaching 4-5m in areas with mean depths of near 10m. These heights were undoubtedly increased by surge increasing water levels by up to 40%. Wave spectra (not presented here) show relatively simple strongly-peaked spectra for gauges Y and Z on the strong side of the storm. Gauge X at landfall shows a more complex spectral evolution arising from the rapidly changing wind fields, with very broad and double-peaked spectra presumably the result of local and remotely generated waves. High resolution hindcasts of the combined wave-surge behavior are presently underway, and will be reported on in the near future.

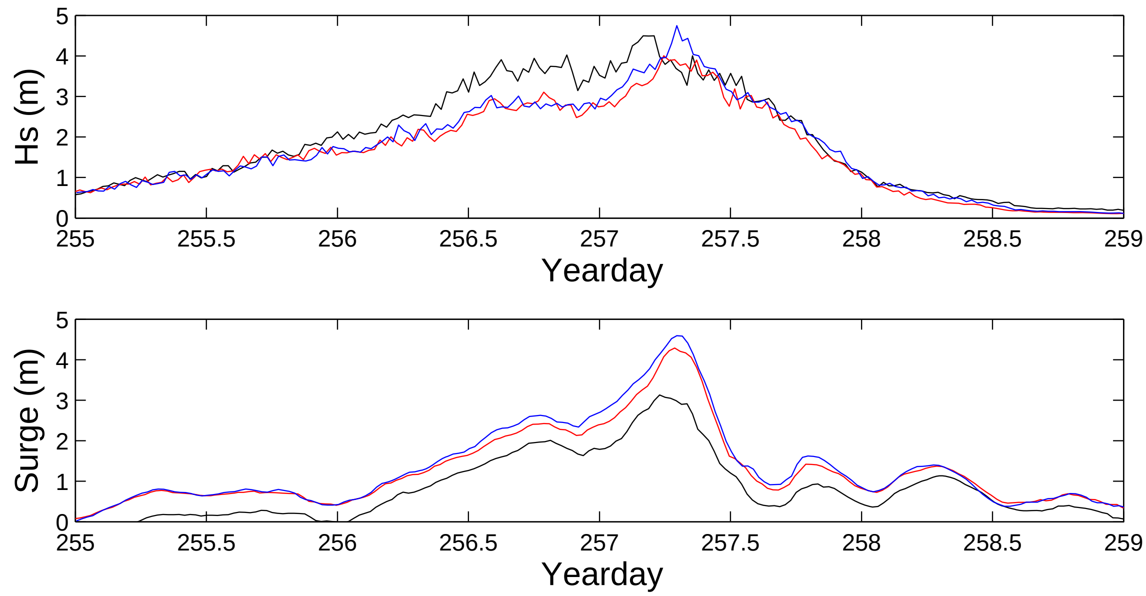

Figure 3. Time Series of (a) Offshore Waves at gauges X, Y, Z; and (b) Surge. Landfall was at yearday 257.3. (black) Gauge X; (red) Gauge Y; (blue) Gauge Z.

Although the coastal waves shown in Figure 2 are useful for showing overall hydrodynamic characteristics and are essential for validating wave and surge models, wave damage to houses occurs in areas that are normally dry. Fortunately, the USGS gauges GAL-1 near the Gulf of Mexico shoreline at the first row of beachside houses, and GAL-2 on the Intracoastal Waterway (East et al., 2008) were in built-up areas and give direct measurements of landfalling surge. Pressure measurements were infrequent enough (1/minute) that no frequency information may be extracted, but we may still find the overall variance during 30 minute periods. If we assume that waves in these shallow areas are more or less hydrostatic, we may convert the variance into a lower bound limit for the significant wave height. This will have error, but it is a useful estimate to extract wave information from an experiment that was only designed to capture surge levels. If characteristic peak periods are estimated and Rayleigh distributed waves are assumed, we may then compute the largest single wave height during any 30 minute period using standard methods, with a cutoff for depth-limited waves. The maximum inundation during any 30 minute period may then be calculated as the sum of the surge level and the crest elevation (assumed conservatively to be 70% of the wave height) arising from the maximum wave. These values may be compared with measured elevations of surviving and destroyed buildings to delineate the effects of waves and surge during this severe storm.

Figure 4 shows waves, surge, and estimated maximum inundation elevations for gauges GAL-1 and GAL-2. For GAL-1, which was immediately beside the Gulf of Mexico (see Figure 1), surge reached a maximum of 4.8m, while GAL-2 on the back side of Bolivar at the Intracoastal Waterway had a slightly lower maximum surge of 4.0m. A slightly larger surge on the exposed side of the Peninsula is as expected given the largely offshore-to-onshore winds. However, the wave heights are extremely different: GAL-1 has 1.8m maximum significant wave height, while GAL-2 has less than a 0.2m maximum. (It should be noted that the long wave assumption is probably overly conservative for GAL-2: using reasonable values of peak period may increase significant wave heights to 0.5m.) These huge differences in wave heights between the open coast location of GAL-1 and the more sheltered location of GAL-2 will be seen to lead to corresponding differences in damage. Inundation estimates top 6m at GAL-1, and are much less at 4.2m for GAL-2.

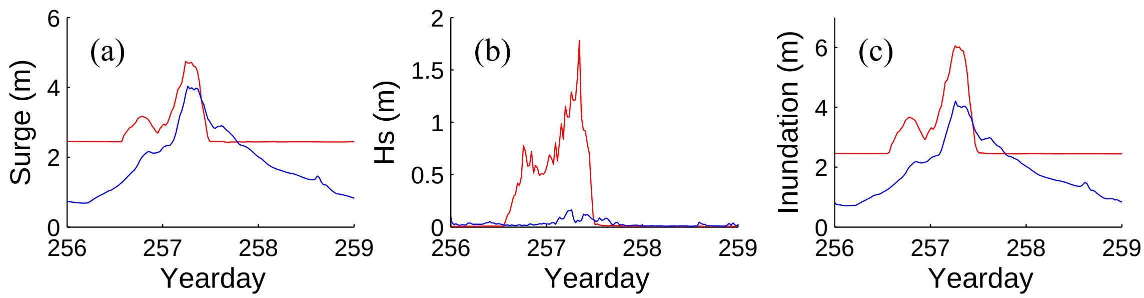

Figure 4. Time series of (a) surge; (b) wave height; and (c) Estimated maximum wave plus surge inundation. (Red) GAL-1; (blue) GAL-2.

Damage levels at GAL-1 and GAL-2 were correspondingly different as well. Figure 5 shows ground level photos taken from the same location before and after the storm immediately next to GAL-1. Estimates of the inundation level superimposed on the photograph show wave crests reaching nearly to the roof. With measured significant overland wave heights of 1.8m at this very location, it is not a surprise to see that the elevated house was completely destroyed. This destruction was made easier by the complete removal of the dune during the storm.

Figure 5. The same location at Crystal Beach, Texas before and after Hurricane Ike. The USGS surge gauge GAL-1 was located just to the right of this house. Note the complete removal of the protective dune fronting the island. Photos courtesy USGS.

A much different picture is found in Figure 6 taken nearby GAL-2. Here, an at-grade house was inundated to partway up its roof, and survived with no apparent structural damage (although certainly major interior damage), and little damage to even its flimsy picket fence. The major difference between GAL-1 and GAL-2 here was the wave height: waves at GAL-1 were large, and waves at GAL-2 were tiny after presumably dissipating overland. This difference in wave height (and consequently breaking waves changing to non-breaking waves) led to corresponding differences in damage, leading to large differences in building survival.


Figure 6. Surviving at-grade house less than 100m from gauge GAL-2 on the GIWW. Note debris lines on roof showing the extent of inundation, and the survival of a presumably flimsy picket fence. Maximum wave heights here were approximately 0.2-0.5m.

3. Waves, Surge and Building Survival

To investigate the effects of waves and surge on buildings, the elevations of more than 1000 buildings on Bolivar were either surveyed directly using rods and postprocessed kinematic GPS, or estimated through Texas GLO lidar elevation maps combined with pre-storm photographs of houses. Buildings were classified as either surviving, destroyed (most or all of house is gone) or surviving with obvious wave damage. All results shown here are for single family houses, typically on elevated piling foundations.

Building elevation proved to be a very good delimiter between survival and destruction. The floor elevation from grade could be measured directly on surviving houses, and could be estimated reasonably accurately on many houses that were largely destroyed. Figure 7 shows survival and destruction near gauge GAL-1 compared to elevation and distance from the nominal pre-storm shoreline. The maximum inundation elevation of 6.0m at GAL-1 is shown for comparison. The first observation is that houses with high elevations survived well, and those with low elevations were destroyed. With one exception of a house at elevation 6m destroyed near the shoreline, all houses with floor elevations over 5.5m survived. All houses with floor elevations less than 5.5m were destroyed. These general points were repeated at many other exposed Gulf Coast shoreline locations: all houses below some minimum floor elevation were destroyed, and houses survived well at higher elevations. The transition between completely destroyed and surviving houses occupied a very small range on these exposed locations, and was around 0.5m. This indicates the destructive power of these waves once they were able to reach flooring systems and remove structural supports.

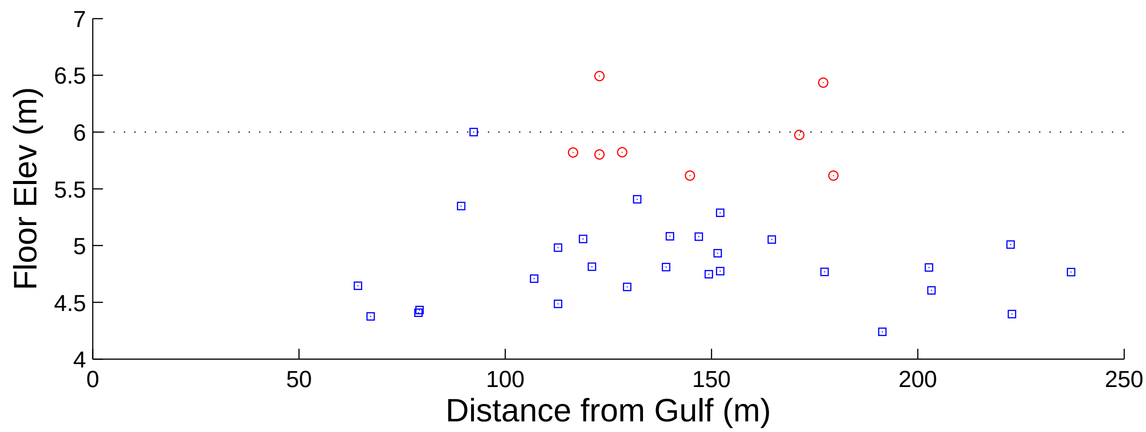

Figure 7. Survival and destruction of houses around Crystal Beach near gauge GAL-1. (o) Surviving Houses; (□) Destroyed. The dashed line indicates the predicted maximum inundation elevation at GAL-1.

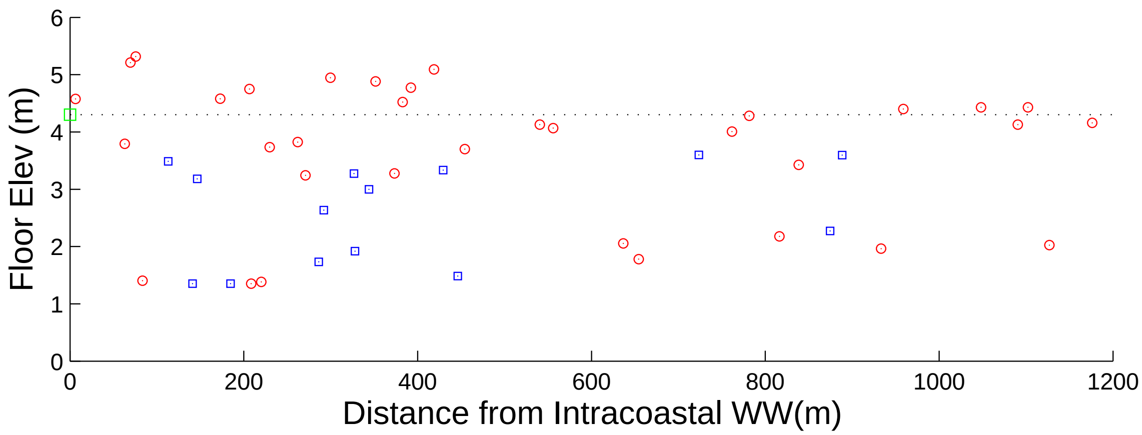

Figure 8. Survival and destruction of houses near gauge GAL-2 on the Gulf Intracoastal WW. (o) Surviving Houses; (□) Destroyed. The dashed line indicates the predicted maximum inundation elevation at GAL-2.

A very different picture is seen in Figure 8 for houses near gauge GAL-2. Here, surviving houses are found at all elevations from the at-grade house of Figure 6 to more highly elevated structures. However, of the houses that were destroyed, all were below the level of the maximum inundation elevation at gauge GAL-2. Above this line, all structures survived well. The reasons lie in the wave heights, which were very small at gauge GAL-2 as shown in Figure 4. These nonbreaking waves were too small to cause strong wave damage to even the houses that were inundated. Because of this, many well built houses survived even with significant inundation. It is impossible to determine the exact mechanism of destruction for houses that did not survive; however, some were likely to have been detached from their pilings by the upward buoyant forces, as was observed for several houses in other locations.

The differences between GAL-1 where waves were large (with many presumably breaking), and GAL-2 where waves were small (and presumably nonbreaking), are significant. They suggest that well-built houses can survive in relatively calm waters even when inundated strongly, but that large or breaking waves will destroy any house they encounter. Because of this, building elevation is of greatest importance in areas where waves are large, and is the overwhelming consideration for survival. In areas with small waves, elevation is still important but well constructed houses may survive inundation when attached well to their foundations.

The importance of elevation may be seen in Figure 9, which plots the survival of houses in the first 150m from the Gulf of Mexico. Although there is some scatter, a clear division between survival and destruction may be seen along the peninsula. Once again, the more elevated houses survive, while lower elevations are destroyed. In most areas, the dividing line between survival and destruction is at around 5.5m NAVD88, although at around 94.62°W, there are numerous houses destroyed with floor elevations over 6m. The area at the SW tip of Bolivar around 94.75°W has two additional points of interest: (1) general survival elevations are much lower; and (2) the division between survival and destruction is not as clear as in some other locations.

Survival elevations appear lower here as surge had begun to decrease. Ike's eye passed very near to this area, and winds were not as consistently from offshore-to-onshore. This led to houses surviving at 4mNAVD88 and below, which is much lower than other open coast areas. The dividing line between survival and destruction also does not appear clear here. This appears to be because of very local sheltering effects: houses on the SW side of the jetty were exposed to relatively deep water waves approaching unimpeded through the Houston Ship Channel. Houses just 100m away on the NE side of the jetty were sheltered from ship channel waves by the jetty itself, and from Gulf of Mexico waves by a marsh which had grown up along the NE side of the jetty. Surge levels were likely similar on both sides of the jetty, but the different wave climate led to survival or destruction at very different building elevations.

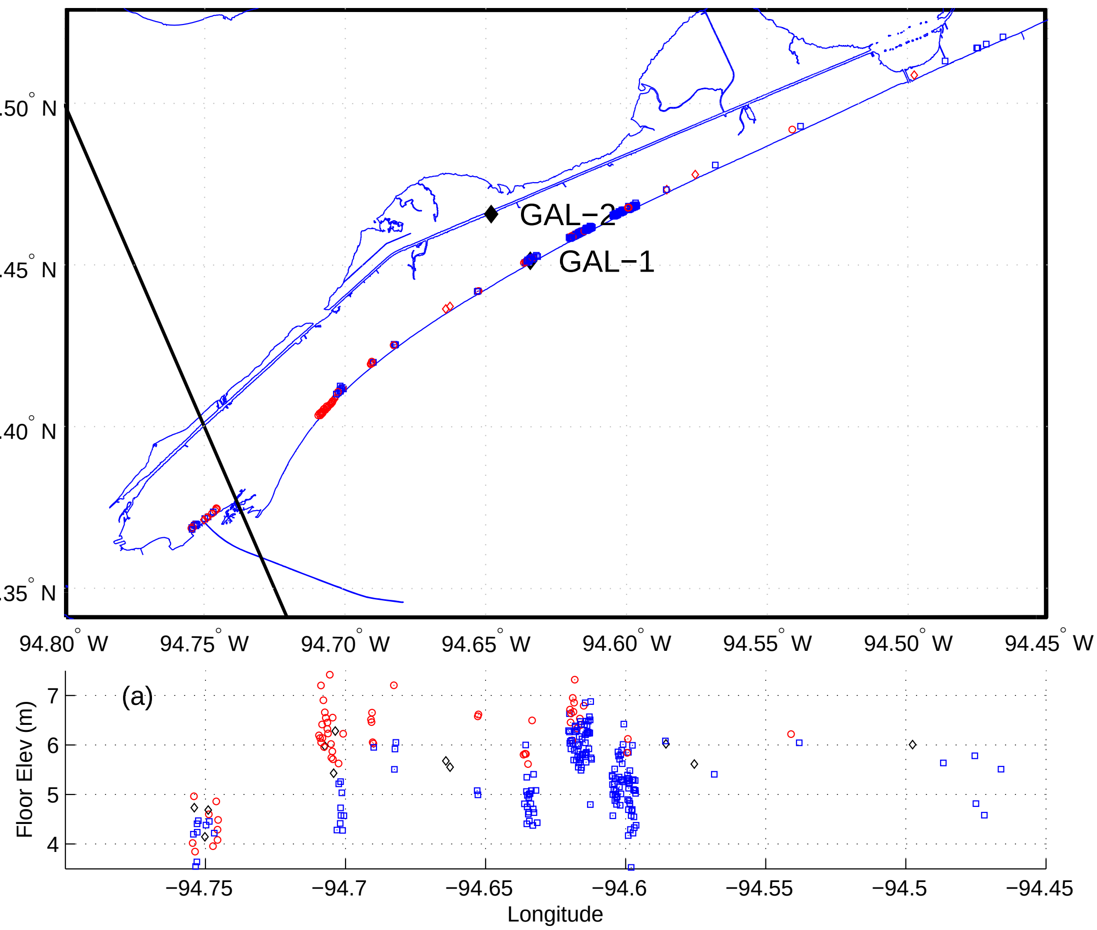

Figure 9. Survival and destruction of houses 0-150m from the Gulf of Mexico. (Top) Surveyed houses; (bottom) elevations vs destruction. (o) Surviving Houses; (□) Completely Destroyed; (◊) Surviving with wave damage.

4. Discussion and Conclusions

This work has shown clearly the wave and surge climate at selected locations around Bolivar during Hurricane Ike. Both were large over long periods of time, which unquestionably contributed to the great destruction. We have additionally reinforced the importance of elevation: assuming adequate foundation pilings and building connections, the primary safety factor for small building is elevation. In exposed locations this gave clear elevation divisions between survival and destructions. In more sheltered locations with low wave action, elevation was seen to still be important but well-built houses could still survive even if strongly inundated.

However, although the basic picture is clear several important questions necessary for risk assessment still remain unresolved:

- What is the decay of waves overland through subdivisions, bushes, trees, debris piles, cars, and storm detritus? This question is crucial to the level of wave action expected at inundated inland locations, but present prediction methods are difficult to defend. The lack of good measurements for overland wave decay complicates matters further.
- What is the damage vs inundation level vs wave height fragility function for flooring systems of wood-framed buildings? As well as can be determined, floor framing systems and floor-pile connections represented the key points of failure on most houses yet the wave and water levels causing this damage are known only relatively crudely. The data available here can show well how elevation changes survivability, but the water levels and wave heights at most locations are not known accurately. Of particular importance are conditions where waves stop battering down wood-framed buildings and instead transmit loads that maybe surviveable for well-built structures.
- What is the role of wave-borne floating debris in building damage? Huge amounts of debris were generated during Ike, and initial indications are that debris can increase damage over purely hydrodynamic forcing. However, the extent is unknown.

Resolution of these issues would aid in assessing risk, and would be useful for people ranging from individual homeowners to planners, insurers, and those revising codes. Other wave-related questions deal with how to predict in advance both large scale erosion and local scour in complex areas with complex sediments and in the presence of structures.

Tightly coupled simulations of the wave-surge-current field during Hurricane Ike are underway, and will be reported on shortly, perhaps even at the 11th Wave Workshop.

Acknowledgements

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References

Berg, R., 2009. Tropical Cyclone Report. Hurricane Ike. NHC Report AL092008, 51 pp.

Daniels, A.P., 1985. Bolivar! Gulf Coast Peninsula. Peninsula Press of Texas, Crystal Beach, 113 pp.

East, J.W., Turco, M.J., and Mason, R.R., 2008. Monitoring inland storm surge and flooding from Hurricane Ike in Texas and Louisiana, September 2008. USGS Open-File Report 2008-1365. http://pubs.usgs.gov/of/2008/1365/

US Weather Bureau, 1915. Record of High Water Marks on Galveston Island. 2 pp.