# 7A.2 On the Use of Wave Parameterizations and a Storm Impact Scaling Model in National Weather Service Coastal Flood and Decision Support Operations

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## 1. INTRODUCTION

National Weather Service (NWS) Weather Forecast Offices (WFO) are responsible for issuing Coastal Flood Watches, Warnings, Advisories, and Informational Statements when rising water levels are expected to threaten life and/or property. These Coastal Flood products are issued when non-tropical weather systems and astronomical forcing allow water levels to meet or exceed local criteria. During tropical cyclones, WFOs describe forecasted water levels and the associated impacts in Hurricane Local Statements (HLS) in collaboration with the National Hurricane Center (NHC). These forecasts are primarily based on computer models and other applications that incorporate storm surge and tidal contributions only. While there have been significant improvements in these modeling efforts over the past several years, the effects of waves (specifically wave runup and wave setup) are still largely a missing component. This is critical given that the effects of waves have been shown to contribute a significant amount of the total water levels observed during select high impact events (Stockdon et al. 2007).

Wave action is the ultimate cause of most structural damage and beach erosion (Fitzgerald et al. 1994 and Dolan and Davis, 1992). In the presence of large breakers in the surf zone, water is forced shoreward by the momentum of the waves causing water to pile up. Debris can be tossed onto structures and properties undermined as erosion occurs. Localized water level rises generated by wave action can be significant as well and is governed by bathymetry and exposure to large, battering waves (Mignone and Lericos 2011).

In order to address the role of wave action in producing NWS coastal flood products, empirical techniques have been developed that incorporate historical data and case studies to develop nomograms that aid forecasters. In a recent study on coastal flooding along the Massachusetts shoreline, an empirical forecasting technique was developed from coastal flood events from 1986 to 2003 (Nocera et al. 2005). The predictors for these techniques were wind speed, tidal cycle and offshore wave heights. Cannon (2007) also developed an empirical nomogram in which water levels and waves were correlated with damage along the Northern New England coastline. The synergistic effects of storm tides with large, battering waves were predominantly caused by extra-tropical storms in these studies.

As an offshoot project from the North Atlantic Regional Team (NART), Thompson (2011) combined facets from these research initiatives to enhance the value of coastal flood warnings in the modern gridded era. Matrices were developed which included output from water level and wave height models to forecast impact categories for “hot spots” along the coastline. The output can then be adjusted in an operational setting by warning meteorologists via the NWS Graphical Forecast Editor, thus allowing for detailed, state of the art information services for users.

Despite these focused initiatives in New England, the effects of waves in relation to total water level forecasts remain complex and not fully understood. In addition, there is a need for including the effects of waves into water level predictions in NWS areas of responsibility beyond the Northeast States where these previous efforts have been focused. Therefore, the goal of this research is to improve the understanding and prediction of wave action in NWS total water level predictions and the associated impacts by utilizing wave parameterizations and a storm impact scaling model that were recently developed by the United States Geological Survey (USGS). This paper applies these techniques to two cases that led to ocean overwash in the Outer Banks, NC in 2009 to simulate its potential effectiveness in an operational environment. These cases along with a preliminary look at applying the USGS techniques to New England’s unique topographical shoreline and future work will be discussed.

## 2. Wave Paramaterizations

This study utilizes the wave parameterizations for setup, swash, and runup that were developed by Stockdon et al. (2006). These parameterizations were developed using a shoreline water-level time series collected during 10 different field experiments that included locations on both the Atlantic and Pacific coasts of the United States, and a location on the

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North Shore of the Netherlands exposed to the North Sea.

Wave setup is defined as the super elevation of the mean water level driven by the cross-shore gradient in radiation stress that results from wave breaking (Longuet-Higgins and Stewart, 1964). Swash is the layer of water that washes up on the beach after waves break. Wave runup is defined as the set of discrete water-level elevation maxima that results from setup and swash (Stockdon et al. 2006).

The expression used in this work is equation 1 from equation 19 in Stockdon et al. (2006):

$$R_2 = \left(0.35B_f\,(H_0\,L_0)^{1/2} + \frac{\left[H_0\,L_0\left(0.563\beta_f^2 + 0.004\right)\right]^{1/2}}{2}\right) \quad (1)$$

where $R_2$ is the 2% exceedence level for vertical wave runup, $\beta_f$ is foreshore beach slope, $H_0$ is reverse-shoaled nearshore wave height, and $L_0$ is peak wavelength. This is the expression that is recommended over a full range of beach conditions. It should be noted that this equation incorporates both incident and infragravity wave energy.

The runup parameterizations were tested at 10 sites as described in Stockdon et al. (2006) using water-level data collected along a single transect. The mean difference between the modeled and observed runup was -17 cm. More detailed verification of the parameterizations is provided in Stockdon et al. (2006 and 2007).

## 3. Storm Impact Scaling Model

The wave parameterizations described in Section 2 are incorporated into a conceptual model that scales the impacts of storms on barrier islands using observed data from Nor'Ida and the Hurricane Bill swell event. This storm impact scaling model (Sallenger 2000) provides NWS forecasters with pertinent information related to their coastal flood program. Specifically, the model compares the elevation of storm induced total water levels ($R_{high}$ and $R_{low}$) to LIDAR derived elevations of dune crest ($D_{high}$) and dune toe ($D_{low}$) to infer if erosion, dune overwash, and/or inundation will occur. $R_{high}$ is the maximum water-level elevation expected during an event and includes the combined effects of astronomical tide, storm surge, and wave runup. $R_{low}$ is an effective still-water level during a storm and is composed of the astronomical tide, storm surge, and wave setup. A schematic of these components is provided in Figure 1.

As described in Sallenger (2000), four impact regimes can be determined by comparing how $R_{high}$ and $R_{low}$ relate to $D_{high}$ and $D_{low}$: swash, collision, overwash, and inundation. The swash regime is considered to have the least potential hazard and occurs when wave runup is confined to the foreshore region ($R_{high} < D_{low}$). The collision regime occurs when the maximum water level exceeds the base of the dune ($D_{high} > R_{high} > D_{low}$). This regime occurs when wave runup collides with the dune that leads to erosion. The overwash regime occurs when $R_{high} > D_{high}$. Overwash transports sediment from the dune inland and led to road closures during the Nor'Ida and Hurricane Bill events as described in sections 4 and 5. The final and most severe impact is the Inundation regime which occurs when $R_{low} > D_{high}$. The beach and dunes are effectively underwater during the inundation regime.

## 4. Nor'Ida Event

Tropical Storm Ida exited the Gulf of Mexico and became a northeaster ("Nor'Ida") along the East Coast in November of 2009 that led to significant coastal impacts for many locations along the East Coast due to the interaction between slow moving low pressure off of North Carolina and high pressure to the north (Figure 2). The remnants of Tropical Storm Ida moved out of the Gulf of Mexico then across the Southeastern States on 11 November. Simultaneously strong high pressure (1035 hPa) was moving from the Great Lakes toward New England. During the 12$^{th}$ the high pressure ridge became elongated and stretched from the Eastern Great Lakes, across New England and into the North Atlantic. As the remnants of Ida move northeastward a significant fetch of E to NE winds developed off the Mid Atlantic States during the evening of 11 November extending northeastward from North Carolina to the vicinity of 40N 65W, with a wave height maximum of 6.1m located 50 nautical miles east of the Delaware Coast. By late in the evening of November 12$^{th}$ the fetch became more elongated to the east as the high stretch further into the Atlantic with wave heights exceeding 9.1m. The fetch persisted through November 13$^{th}$ into the 14$^{th}$ and became oriented in a more southeast to northwest direction in response to the changing orientation of the high. This prolonged onshore fetch led to significant coastal flooding over east exposed portions of the Mid Atlantic and North Carolina coast.

The USGS wave parameterizations and storm impact scaling model were applied for Nor'Ida in the "S Turns" vicinity where Rodanthe converges with Pea Island (Figures 3 and 4). This was accomplished by using archived buoy data from the Scripps Institution of Oceanography Waverider buoy 44100 east of Duck, NC and water level data from the National Ocean Service tide gauge at the Duck Pier. Dune information and foreshore beach slope were extracted from LIDAR data collected from the CHARTS lidar system and based on August 2009 measurements by the Army Corps of Engineers. The elevation, tide, and $R_{high}$ values presented are relative to the North American Vertical Datum of 1988 (NAVD88). The "S Turns" area is also known as Mirlo Beach and was chosen due to its vulnerability to ocean overwash. The area often experiences the overwash regime during coastal storms which leads to the closure of Highway 12, the only road that connects the barrier island to the mainland. Highway 12 was severely flooded and destroyed in the S-Turns vicinity due to the ocean overwash associated with the Nor'Ida event (NCDC 2011).

Figure 4 represents the application of the USGS techniques at a single point (35.607N, 75.465W) in an effort to replicate what could have been forecasted at a particular hotspot to predict total water levels and potential impacts. The location of the hotspot used is depicted in Figure 3. This was the location in the LIDAR data nearest to the infamous "Serendipity" home that starred in the "Nights in Rodanthe" film in 2008. Serendipity was relocated in 2010 due to the ocean overwash and erosion problems that frequent the area and were threatening the home (Nolan 2010).

Our calculations using archived data suggested the overwash regime ($R_{high}$>$D_{high}$) would occur at this location several times during 12-14 November, though mainly during high astronomical tides (Figure 3). This is consistent with the NWS local storm reports compiled by the office in Newport/Morehead City, NC (NCDC 2011). A peak $R_{high}$ elevation of 4.21m was predicted at 0700 UTC 13 November 2009, which also the same time as the wave height peak (6.49m at 14 seconds) at buoy 44010. It should be noted that wave runup (3.22m) resulted in 76 percent of the total water level elevation at this time. Surge (0.82m) and tide (0.17m) contributed 20 and 4 percent of the total water level, respectively. This suggests that total water levels can be significantly underestimated if only tide and surge are included.

A timestack that shows the spatial and temporal distribution of collision and overwash was also constructed for the S Turns/Mirlo Beach vicinity (Figure 5). Unlike the more deterministic approach in Figure 4, this shows the probabilities of collision and overwash by taking into account the uncertainty in dune elevations, beach slopes, waves, and storm surge (USGS 2011). The highest probabilities for overwash using this technique also coincided with times of high tides during 12-14 November with a peak during the early morning hours on 13 November. There was a high probability for the collision regime during much of the time from 12 November – 14 November suggesting that significant erosion was likely.

**5. Hurricane Bill Swell Event**

Hurricane Bill was a major hurricane that recurved well east of the Eastern Seaboard during 19-24 August 2009 (Figure 6). While Bill was never a direct threat to the United States, its unique combination of track, size, and intensity sent a significant long period swell to the East Coast during 21-24 August 2009. This led to high surf in excess of 6 meters and dangerous rip currents that claimed two lives and injured at least 16 people along the Eastern Seaboard (Willis et al. 2010).

In addition to the surf zone hazards, the long period swell event led to significant dune overwash that resulted in the closure of Highway 12 on Ocracoke Island, NC (NCDC 2011). Similar to the Nor'Ida event, the USGS techniques were applied to both a particular hotspot (Figure 7) and to a larger region via a timestack (Figure 8) on Ocracoke Island during the Bill swell event. The archived data sources used for this event were the same as in the Nor'Ida case, except wave data was extracted from the National Data Buoy Center station 41025 (Diamond Shoals) due to its proximity to Ocracoke and exposure to SE swell.

The hotspot chosen on Ocracoke (35.1706N, 75.811W, also shown in Figure 4) was selected due to its proximity to the North Carolina ferry terminal that connects Ocracoke and Hatteras Islands. NWS local storm reports suggested that portions of this area were flooded and closed due to overwash. The overwash regime ($R_{high}$>$D_{high}$) was depicted during two distinct timeframes at this location using the USGS wave parameterizations and storm impact scaling model, both coinciding with times of high tide on 22-23 August (Figure 7). The peak $R_{high}$ value predicted was 3.74m at 1500 UTC 22 August 2009 which was consistent with observations of ocean overwash during this time (The Weather Channel 2011). Wave runup (3.23m) accounted for 86 percent of the total water level during the peak while tide (0.47m) and surge (0.04m) accounted for 13 and 1 percent, respectively. This was to be expected given Hurricane Bill's distant track, but again portrays the importance of incorporating wave effects into total water level and impact predictions.

Similar to the results portrayed in Figure 7 at the hotspot near the NC ferry terminal, the highest probabilities for overwash represented in the timestack (Figure 8) also coincided with the high tides that occurred on 22-23 August. However, the timestack also depicted two main areas that would be most vulnerable to overwash. In addition, high probabilities for erosion were much longer lasting than the overwash. Thus, important information about the timing, spatial distribution, and specific coastal impacts can be extracted from these techniques which in turn can be used to improve NWS products and services.

**6. SUMMARY AND FUTURE WORK**

The proof of concept work described in this paper suggests that the USGS wave parameterizations and storm impact scaling model would be helpful in NWS coastal flood operations. These techniques proved to be skillful when compared to the overwash observed during Nor'Ida and the swell event associated with Hurricane Bill.

Wave runup accounted for the majority of the total water levels during these events. Thus, using the sum of the surge and tides solely as an indicator for erosion, inundation and overwash is not recommended. Wave processes must be included in total water level predictions. Elevations of sand dunes must be included to infer coastal impacts on barrier islands.

Future applications of the USGS wave parameterizations are already underway to test impacts from extra-tropical storms in northern latitudes with different beach strata. Along the northern coast of Maine, beaches with cobblestone versus sandy areas of the Carolina's are being investigated. A couple of additional areas are being viewed as potential test sites. Vulnerable beaches that have lost their dune structure and require jersey barriers for support in southern Maine are also undergoing examination. An Eastern Massachusetts beach composed of sand and cobble mix will also be investigated. Results from these prototype test sites may yield a limitation of the parameterization as it is currently configured. The scheme was designed from empirical study on sandy, unmitigated beaches. To investigate this further the parameterization will be tested at several sites that have been surveyed in and around Arcadia National Park during future storm events.

Loss of a significant amount of wave energy prior to reaching the surf zone has been observed. It is recommended that use of a high resolution, shallow wave model such as the SWAN or a similar near shore model be used to determine significant wave height closer to the surf zone. It is also recommended that a standard depth seaward of the surf zone, such as 10 meters be used for input into the storm impact scaling model. This possibility will also be investigated during future storm events. Confidence of this enhancement would increase if one or more shallow water sensors could be deployed to validate shallow water wave model output.

While both events described in this paper consisted of wave energy confined to relatively narrow spectral groups a much broader range of wave frequencies will likely be encountered in some extra-tropical and tropical storm systems. The need to partition wave energy into frequency ranges before input into the parameterization will require further investigation.

Field testing described above is being conducted using a manual tool that requires input of astronomical tide levels, storm surge, deep water wave height, and beach slope. The ultimate goal is to develop a standalone model that will incorporate data sets already used by the National Weather Service and allow predictions over either a wide area of specific hot spots. This model would calculate total water levels at the shoreline including the contribution from waves. It would then determine the vulnerability of beaches and dunes to erosion, overwash, and inundation. Additionally the model would also be user friendly with flexible input/output and appropriate for use during all types of wave conditions from calm weather to extra-tropical storms to hurricanes.

## 7. ACKNOWLEDGMENTS

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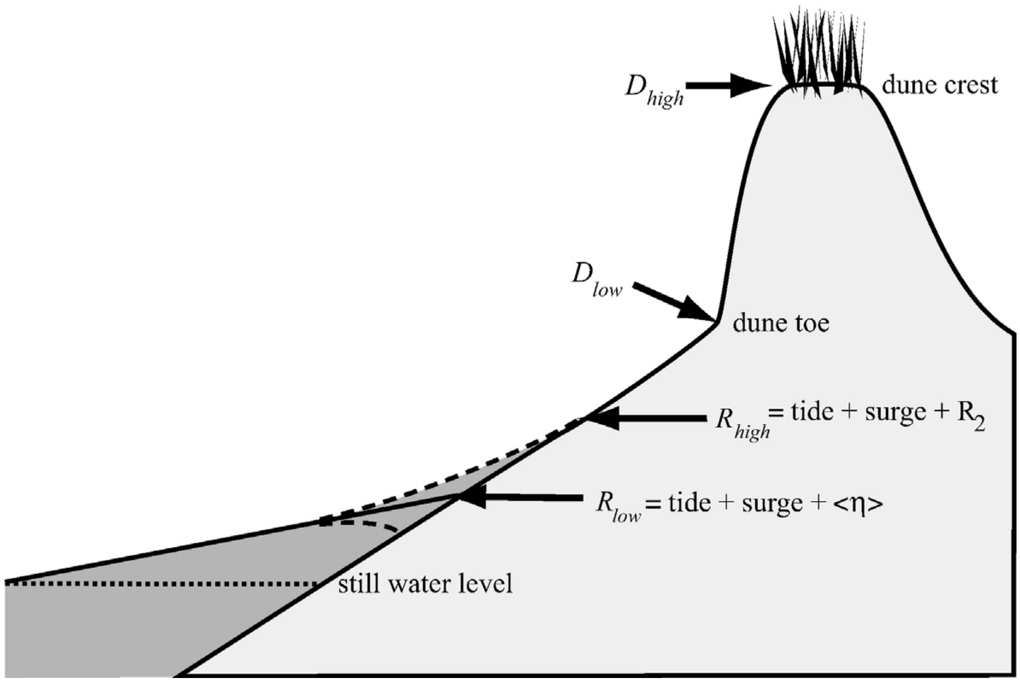


**Figure 1. Schematic showing the elements of the storm impact model. From Stockdon et. al. (2007).**

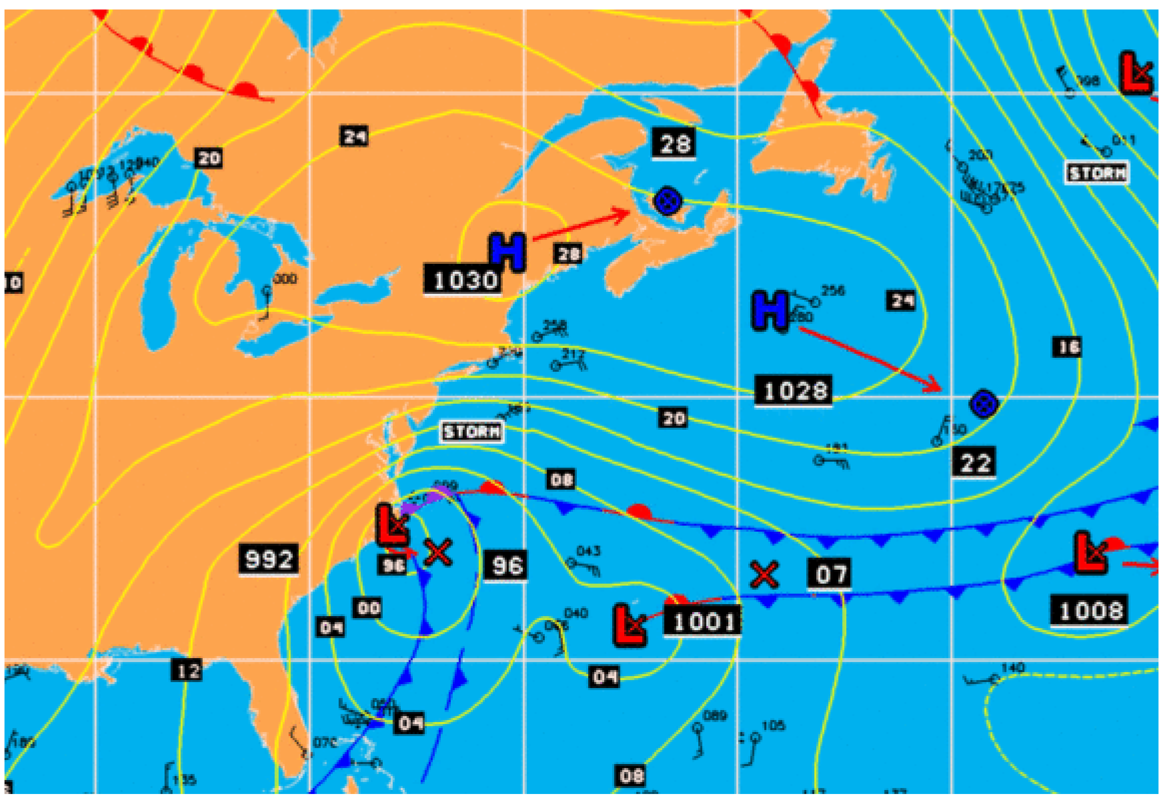

**Figure 2. NCEP Unified Surface Analysis from 1800 12 November 2009.**

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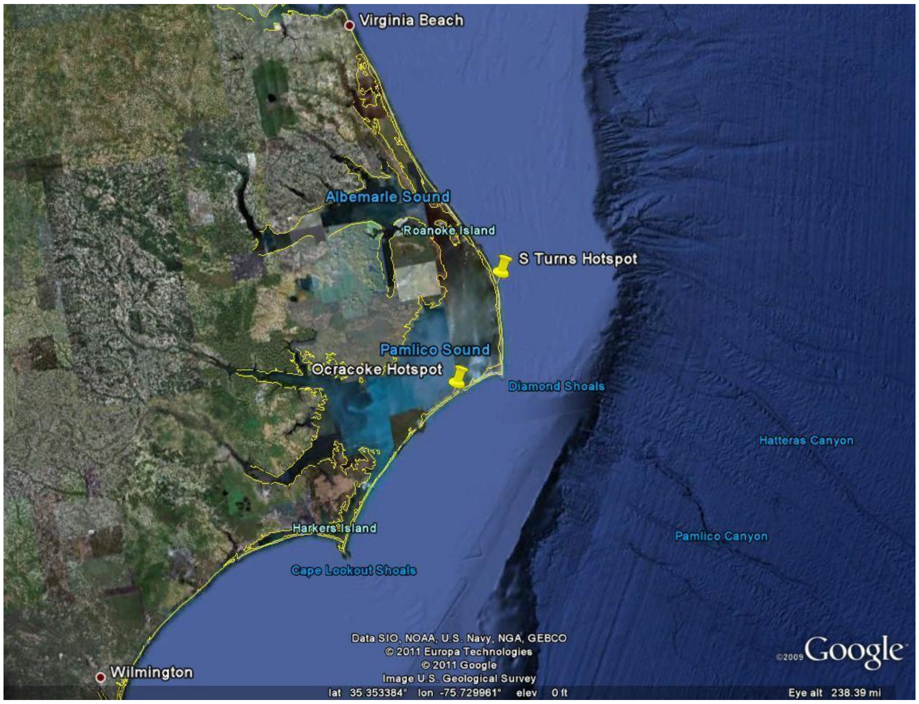


**Figure 3. Map of hotspot locations used in Figures 4 and 6.**

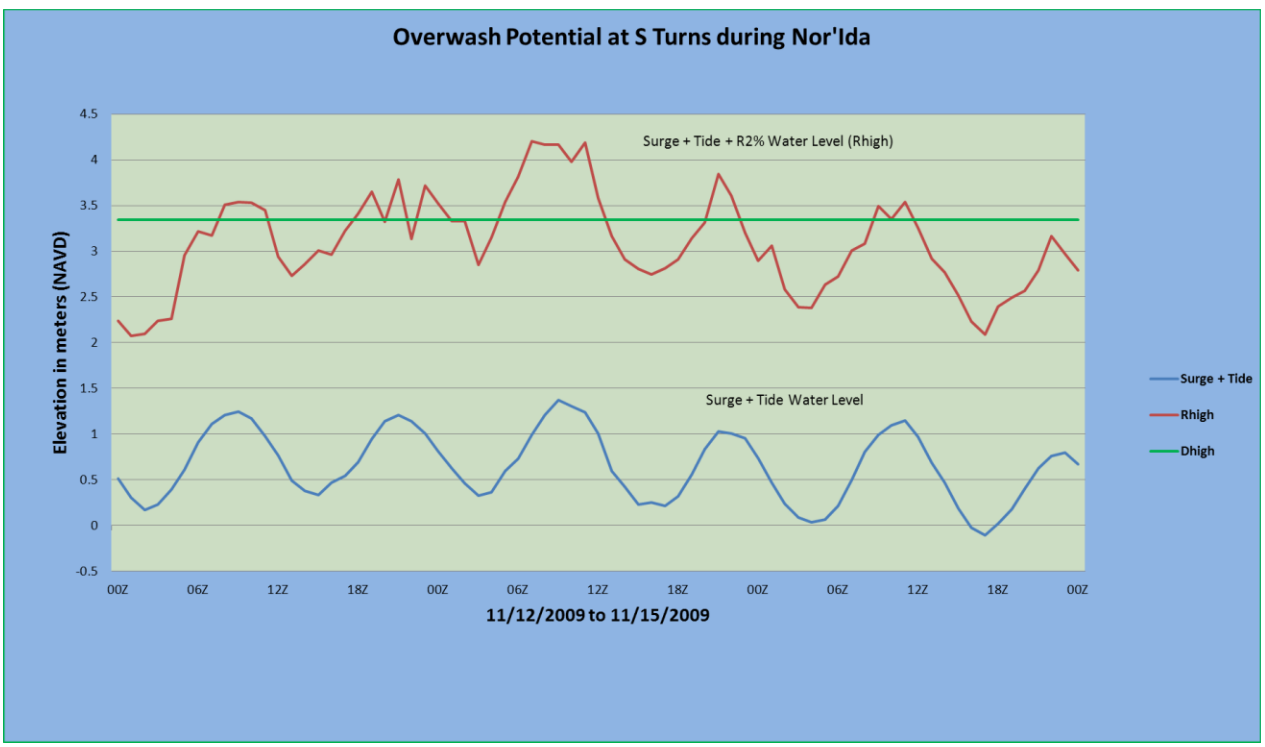


**Figure 4. Overwash Potential at 35.607N, 75.465W (S Turns, NC Hotspot as depicted in Figure 5) from 12-15 November 2009. Periods where red line ($R_{high}$) is greater than green line ($D_{high}$) represent times when overwash will occur.**

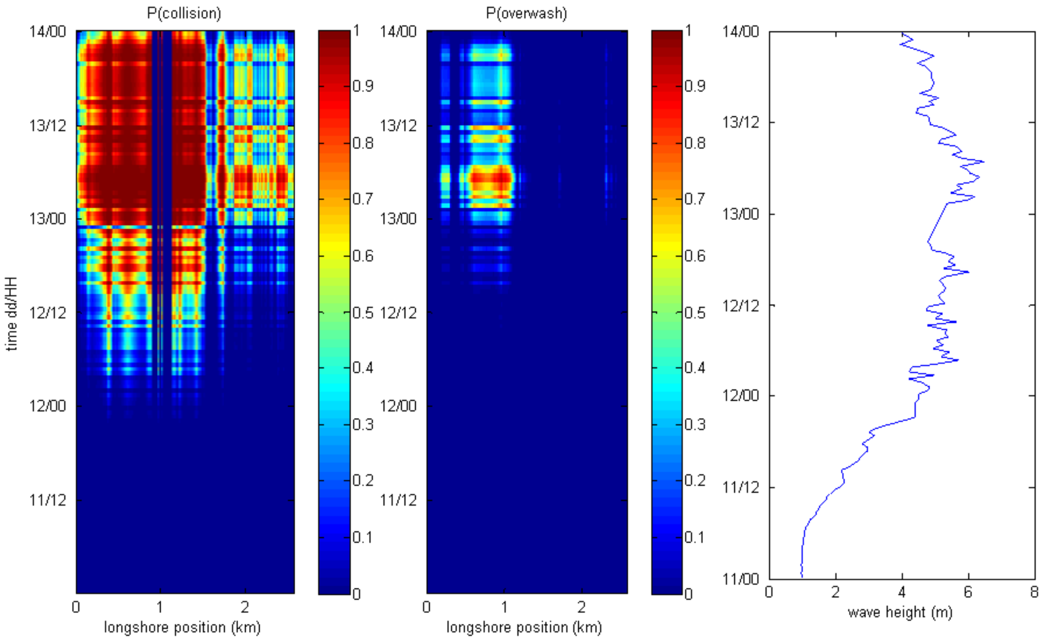


**Figure 5. Timestack from Nor'Ida for S Turn, NCs area showing probability of collision and overwash during the storm (left two images). Wave height from buoy 44100 shown in right image.**

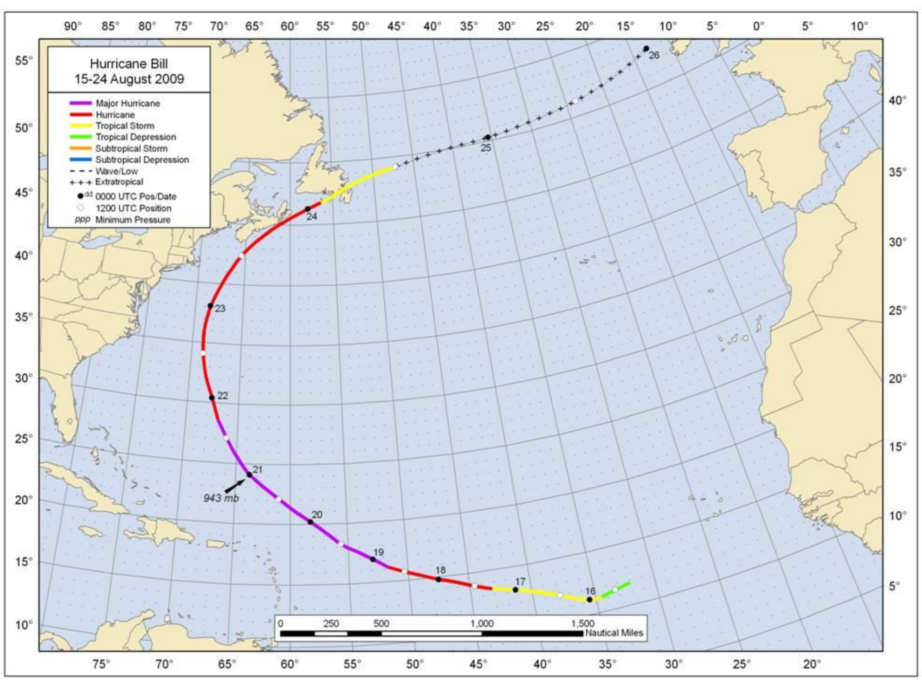


**Figure 6. National Hurricane Center's  Best Track of Hurricane Bill.**

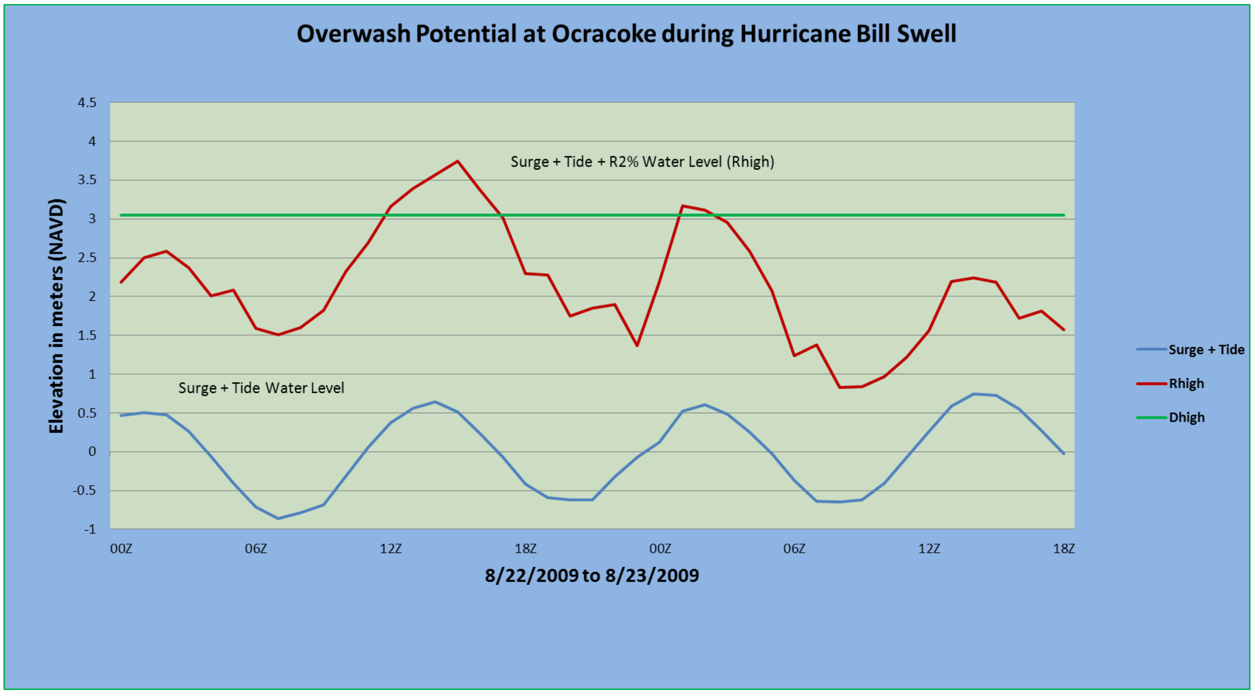


**Figure 7. Overwash Potential at 35.1706N, 75.811W (Ocracoke, NC Hotspot as depicted in Figure 5) from 22-23 August 2009. Periods where red line ($R_{high}$) is greater than green line ($D_{high}$) represent times when overwash will occur.**

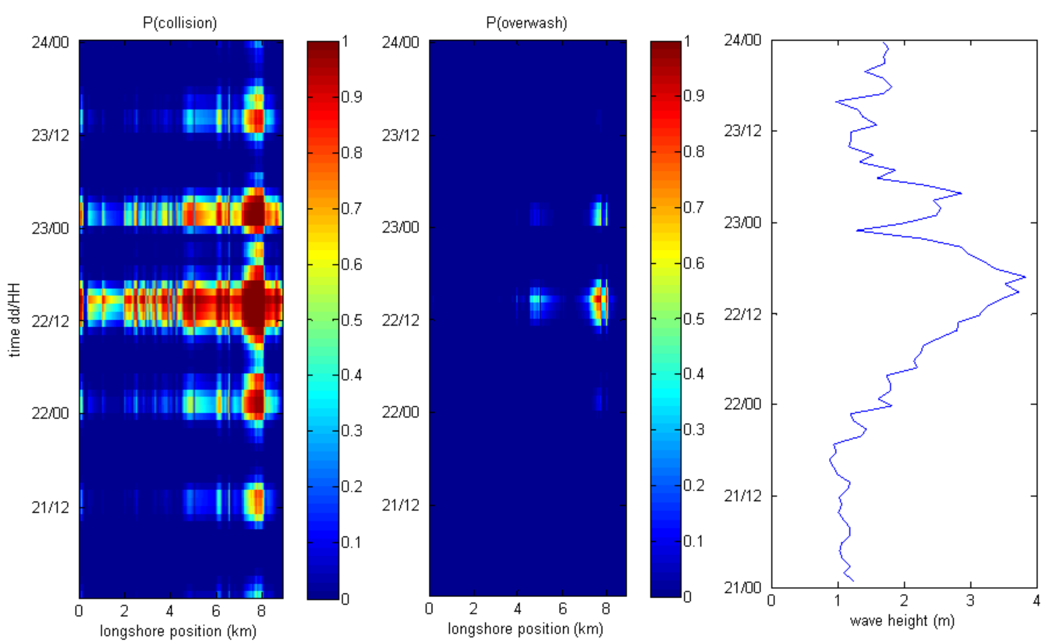


**Figure 8. Timestack from Hurricane Bill swell event for Ocracoke, NC area showing probability of collision and overwash (left two images). Wave height from buoy 41025 shown in right image.**