2003

Simple models for predicting dune erosion hazards along the Outer Banks of North Carolina

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Simple Models For Predicting Dune Erosion Hazards Along The Outer Banks Of North Carolina

by

Lauren Mckinnon Wetzell

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
College of Marine Science
University of South Florida

Major Professor: Peter A. Howd, Ph.D.

Date of Approval:
November 13, 2003

Keywords: storm impact scale, overwash, cape hatteras, wave runup, swan, lidar, deep water wave models, hurricanes, dunes, coastal vulnerability

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Dedication

This thesis is dedicated to my mother, Nancy Lynn Oxley Wetzell, who taught me to always believe in myself, angels, and sometimes the things worth searching for are found outside the box.
Acknowledgements

I would like to thank my committee Peter Howd, Abby Sallenger, and Al Hine for their support and guidance. My research extends from employing meteorology to oceanography concepts, quantitative programming, broad range of GIS applications, wave modeling techniques, to imaging software. Numerous people facilitated this learning curve and at many times my project depended greatly on their guidance. I would like to recognize the following individuals for their help: Nicole Elko, Sherryl Gilbert, Kristy Guy, Mark Luther, Karen Morgan, Meg Palmsten, Hilary Stockdon, and Jyotika Virmani. Also, I would like to acknowledge Roy Burton IV for his love and support.

This research was funded by the United States Geological Survey for the National Assessment for Coastal Change Hazards project.
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Simple Models for Predicting Dune Erosion Hazards Along the 
Outer Banks of North Carolina 
Lauren McKinnon Wetzell 

Abstract

Hurricane hazards result from the combined processes of wind, waves, storm 
surge, and overwash (Lennon et al., 1996). Predicting the severity of these hazards 
requires immense effort to quantify the processes and then predict how different coastal 
regions respond to them. A somewhat simpler, but no less daunting task is to begin to 
predict the hazards due to potential erosion of barrier islands. A four-part scale has been 
developed by Sallenger (2000) to provide a framework for understanding how barrier 
islands might respond during extreme storm events. These four regimes describe how 
beach and dune elevations interact with surge and wave runup. This study will produce 
estimates of potential hazards through combining lidar surveys of dune elevation with 
modeled elevations of storm water levels.

Direct measurements of maximum wave heights during hurricanes are rare. We 
evaluated three simple equations proposed by Kjerfve (1986), Young (1988), and Hsu 
(1998) to forecast the maximum wave height ($H_{\text{max}}$) generated by three 1999 hurricanes. 
Model results were compared to wave data recorded by the National Oceanic and 
Atmospheric Administration (NOAA) wave rider buoys. The radius of maximum winds, 
wind speed, forward velocity, distance from buoy to the storm’s eye-wall ($r$), and buoy’s 
position relative to the quadrant of the storm ($Q$) were found to have significant and 
direct roles in evaluating recorded hurricane induced wave heights ($H$) and thus, were 
individually examined for each comparison. The implications of the $r$ and $Q$ on $H$ were 
assessed when determining the overall effectiveness of the modelers’ equations.

Linear regression analyses tested the accuracy of each modeled prediction of the 
$H_{\text{max}}$, comparing it to the observed wave heights. Three statistical criteria were used to
quantify model performance. Hsu’s model was the most reliable and useful forecasting technique.

Despite the predictive skill of Hsu’s model, direct observations of the maximum wave conditions, when available and appropriate, are preferred as inputs for SWAN, a 3rd generation shoaling wave model. Outputs from SWAN are used to calculate the empirical relationships for wave runup. For our test case, pre and post-storm topographies were surveyed as part of a joint USGS-NASA program using lidar technology. These data sets were used to calculate changes in the elevation and location of the dune crest ($D_{\text{high}}$) and dune base ($D_{\text{low}}$) for the North Carolina Outer Banks. We hindcast potential coastal hazards (erosional hot spots) using the pre-storm morphology and modeled wave runup and compare those estimates to the measured results from the post-storm survey. Links among the existing topography and spatial variations in wave runup were found to be 95% correlated for the north-south and east-west facing barrier islands. Application of Sallenger’s (2000) four-part Storm Impact Scale to the pre-storm $D_{\text{high}}$ elevation survey and wave runup extremes ($R_{\text{high}}$ and $R_{\text{low}}$) were found to accurately predict zones of overwash and showed potential to forecast the inundation regime.
Chapter 1
Introduction

I. Background

The eastern U.S. coastline, extending from Texas through Maine, has more than 45 million permanent residents, with the population growing most rapidly from Texas through the Carolinas (Moran and Morgan, 1997). Unfortunately, the relative hurricane-free period from the 1960’s through the 1980’s contributed to a disregard of the potential hazards that hurricanes pose to the coastal residents and property owners (Lennon et al, 1996). Not only have the risks been neglected, but the amount of people and construction have more than doubled since the 1960’s, intensifying the risks of coastal change hazards. Approximately 80-90% of today’s Atlantic and Gulf Coasts residents have never experienced the full impact of a major hurricane (Komar, 1998).

The National Hurricane Center (NHC) and National Oceanographic and Atmospheric Administration (NOAA) report that on average ten tropical storms will develop over the Atlantic Ocean, Caribbean Sea, and Gulf Coasts per year, and six of these storms will intensify into major hurricanes (i.e. a hurricane classified as a Category 3 or higher according to the Saffir Simpson Scale of Hurricanes). To be prepared for these extreme events, current predictive techniques need improvement. Methods used in predicting coastal change vulnerability need a more efficient tool to measure wave responses to hurricane forcing. Numerous mathematical models attempting to study and predict hurricane-forcing effects are available, however, these sophisticated computational designs are expensive and time-consuming.

Understanding the fundamental processes involved with coastal hazards will
facilitate developing improved forecasting techniques. Storm systems, typically characterized by extreme winds, waves, storm surge, and overwash, have the potential to alter barrier-island morphology (Lennon et al., 1996). The storm surge is the most dangerous part of the hurricane to both life and infrastructure. The increased water levels combine with hurricane generated waves and currents to remove sediments from the fronting beach. With severe storms, this transport may result in the formation of an overwash fan along the landward facing slope of the barrier island (Komar, 1998). Overall, the effects of severe storms move barrier islands landward. Additionally, storm impacts can drastically differ from one location to another and thus, these differences in beach morphology need to be identified in order to assess coastal vulnerability. For example, a category one hurricane (as defined by the Saffir Simpson scale of Hurricanes) making landfall over Duck, NC, will cause less change in beach morphology compared to the same storm making landfall over Louisiana coast (Sallenger, 2000A). The discrepancy revolves around the differences in the morphology of the barrier islands. For example, dune elevations for are typically low-lying (1.5 m above mean sea level, MSL) for coastal Louisiana whereas, for Duck, NC, the foredune ridge is 5 times higher (Sallenger, 2000).

II. Study Area

The study region extends approximately 65 km along the Outer Banks of NC from Cape Hatteras to Ocracoke Inlet (Figure 1). The NC coastline is characterized by protruding barrier islands with cuspate-shaped features along its shoreline (White and Wang, 2002). The study region was divided into two areas north and west of Cape Hatteras shoal. The north-south trending barrier extends 17 km from Avon to the Cape Hatteras shoal and is referred to as N.Cape. About 45 km of the east-west trending barrier island, South Cape (S. Cape), was studied and includes the area from the Cape Hatteras shoal to north of Ocracoke Inlet.
The following description of the geologic framework within the Outer Banks region was obtained from the work done by Riggs et al. (1995), who have hypothesized that barrier island morphology and shoreface dynamics are significantly influenced by basic structural and stratigraphic characteristics. The shallow geology of NC is composed of a thick, 50 to 70 m, Quaternary sequence that fills the Albemarle Embayment, a regional depositional basin. Paleo-drainage systems cut into the regional stratigraphy and most likely date to the last glacial period, have been filled with younger sediments. In NC, significantly large portions of the barrier islands are underlain by estuarine deposits of peat and mud. During the Holocene transgression the estuarine units were overrun by barrier island systems migrating upwards and westwards. Overall, the sediments within this system vary from compact peat and mud to indurated sands and gravels. One indication that relict sediments are being eroded from the shoreface lies within the barrier island’s general grain size. Specifically, the older sediments crop out on the eroding shoreface and commonly occur along the inner shelf as bathymetric highs seaward of modern shoreface and thus, modify the incoming waves. During storms, ancient strata cropping out on the shoreface also provide for an immediate source of ‘new’ sediment to the modern beach system, a process called shoreface bypassing by Swift (1976).

Furthermore, barriers from Orgen Inlet to Cape Hatteras are suggested to be eroded and modified primary barriers (i.e. the barriers were constructed over pre-existing sediments, Figure 1. Location map of the Outer Banks of North Carolina where coordinates are measured in UTM. The two study areas north and south of Cape Hatteras point are shaded blue and yellow, respectively.
forming paleotopographic highs that had been exposed to weathering). Rapidly receding beach segments occur between the major cape structures at Avon (the northernmost town in this study) and Rodanthe (a town north of Avon and excluded from this study). From Cape Hatteras to Rodanthe, the shoreline change characteristics may be controlled by gently dipping Pleistocene sediments in the shallow subsurface. During winter storms much beach sand is transported off the beach and stored in bars, exposing the semi-indurated, back-barrier sediments, that presently occur in the surf zone. Relict sediments exposed on the inner shelf influence modern shoreface dynamics and the composition results in bathymetric highs and lows.

The transgressive barrier islands of the Outer Banks are primarily microtidal and the tidal range is less than 2 m (Meredith et al., 1999). Hatteras Inlet and Ocracoke Inlet are wave dominated characterized by wide throats with multiple sand bodies and significant inner shoals, contributing to landward sediment transport (Nummedal et al., 1977). The spits at the southern tips of the capes frequently change orientation in response to the non-tidal currents which are produced from winds at least of gale-force, 63 km/hr to 87 km/hr (El-Ashry and Wanless, 1968). Processes such as wave forcing and aeolian transport modify the shape of the barrier islands, making them highly dynamic (White and Wang, 2002). Furthermore, barrier islands are susceptible to breaching, eroding, and migrating in response to waves generated by hurricanes and other major storms events (El-Ashry and Wanless (1968); Leatherman, 1988; Inman and Dolan, 1989).

In 1937, Work Progress Administration and Civilian Conversation Corps began dune stabilization from the VA/NC border, to northern Ocracoke Inlet (Tebbens et al., 2002). The barrier island morphology was altered by the new artificial multi-ridged dune system (Andrews, et al., 2002), including a continuous vegetated line of dunes ranging in heights and widths from 3 to 8 m and 25 to 100 m, respectively (Tebbens et al., 2002). Once created, the dunes were later supplemented with grass, trees, and
shrubs. Stabilization efforts have decreased, except in the more developed regions, primarily north of Cape Hatteras (Tebbens et al., 2002). The 1937 dune stabilization effort transformed the overwash-dominated system to a swash and aeolian-dominated system (Andrews, et al., 2002). As a result of this change in morphology, controversy arose, suggesting the constructed dunes prevented overwash and stabilized the landward end of the beach profile. Consequently, the dune stabilization efforts caused a narrowing of the beach and increased dune erosion (Andrews et al., 2002, and Leatherman, 1979).

Characterized by the decades of dune stabilization and beach backed by vegetated foredunes, the barrier islands have been classified as high-profile. Instead of sediment deposition on the leeward side of the dune during overwash, storm erosion results in the cutting back of the dune with sand deposition offshore (Komar, 1998).

Konicki and Holman (2002) conducted numerous studies at Duck, located approximately 109 km north of the Cape Hatteras Shoal, and describe the area as a dune backed beach with a fairly steep foreshore having an intermediate wave climate. The beaches are relatively narrow, ranging between 20 to 60 m in width, and depending on the year and season, and they are eroding at a rate of 1.5 to 3.0 m/yr (Inman and Dolan, 1989). The mean tidal range and mean wave height have been calculated as 0.97 and 0.9 m, respectively (Birkemeier et al, 1985). Annual averages in wave height and spectral peak periods have been calculated as $1.0 \pm 0.6$ m (1981 – 1990) and $8.3 \pm 2.6$ s (Leffler et al., 1993). Williams et al. (1976) examined particle sizes for 1.5 km north and west of the Cape Hatteras shoal where they found the longshore beach drift to be dominant in the southwest direction for the N.Cape and northeast in direction for the S.Cape. The zone of accumulation is called the Cape Hatteras Shoal. They also used a population test to examine the differences in grain size for the two areas. The tight distribution indicated minimal differences in grain size for the two barrier islands (N.Cape = 0.1Φ to 1.2 Φ and S.Cape=-0.8 Φ to 1.3 Φ).

The underlying motivation of this project is to determine the vulnerability
of coastlines as it compares to spatial variability of change forced by severe storms. Emphasis has been placed on the overwash regime involving the condition where the crest of the fronting dune (or berm if fore-dune is absent) is overtopped by wave runup and sand is deposited landward of the dune (Sallenger, 2000). In establishing an accurate wave run up forecasting technique, hurricane deep-water wave heights were examined and are discussed in Chapter 2. Wave outputs computed from a 3rd generation wave model, SWAN (Simulating Waves Nearshore), were used to calculate a series of wave runup heights. These values were compared to beaches varying in morphology, before and after Hurricane Dennis and used to hindcast coastal change hazards (Chapter 3). The results from this study have shown to be accurate and efficient in predicting dune vulnerability and are sufficient for future applications in forecasting coastal change hazards (Chapter 4).
Chapter 2
Deep Water Wave Models

I. Background

1. Hurricane Characteristics

Hurricanes are difficult to observe and no lab analogue has been discovered. Thus, hurricanes remain one of the outstanding enigmas of fluid dynamics (Emanuel, 1991). Due to the requirement of high sea surface temperature, hurricanes are seasonal and occur between latitudes 5° to 35° in the northern and southern hemispheres (Moran and Moran, 1997). The rate of transfer of heat from ocean to atmosphere is a function of wind speed and it’s this principal feedback mechanism that results in development of a hurricane (Emanuel, 1991). Structurally, air is drawn up in a strong vortex motion, forming the eye of the hurricane, where surface winds are absent and atmospheric pressure is minimum (Silvester and Hsu, 1993). Outside this eyewall, clouds and precipitation are usually organized in one or more cyclonically curved spiral bands extending 10 km in width and ranging in height from 3 to 15 km (Emanuel, 1991). From the eye of the storm to its outer edge, the winds rapidly decrease in strength (Silvester and Hsu, 1993). Although the geometric size of the hurricane can range over an order of magnitude, it bears no perceptible relation to intensity (Emanual, 1991). H. S. Saffir, a consulting engineer, and R. H. Simpson, former director of NHC, developed a scale that classifies hurricane intensity as a function of both wind speed and central atmospheric pressure. Referred to as the “Saffir-Simpson Hurricane Intensity Scale”, it ranks hurricanes into categories 1-5 where category 1 is considered a minor threat and category 5 is considered a major threat.
Figure 2. Hurricane Bret, a 1999 storm, traveled across the Gulf of Mexico making landfall over Padre Island, TX. Wave rider buoys = triangles, hurricane center = closed circles, and arrows indicate the hurricane’s path.

Figure 3. Hurricane Dennis headed north along the Atlantic Coast and made landfall in Cape Fear, NC, September 4th, 1999. Wave rider buoys = triangles, hurricane center = closed circles, and arrows indicate the hurricane’s path.

Figure 4. Hurricane Floyd was another storm to travel the northern Atlantic Coast, making landfall along the Outer Banks, NC. Wave rider buoys = triangles, hurricane center = closed circles, and arrows indicate the hurricane’s path.

(Dolan and Davis, 1992; Moran and Moran, 1997). Furthermore, the Saffir-Simpson scale attributes are standardized in the data collection of the following programs: National Weather Service (NWS), National Hurricane Center (NHC), National Oceanic and Atmospheric Administrations (NOAA), and Army Corps of Engineers (Dolan and Davis, 1992). Of the 126 tropical storms and hurricanes that struck the U.S. coast (Gulf of...
Mexico and Atlantic), between 1949 -1990, 25 (19.8%) were classified as a category 3 storm or higher (Moran and Moran, 1997).

The centers of the hurricanes are in motion adding to the wind speed on one side, where the larger waves are generated (Silvester and Hsu, 1993). Thus, for a storm moving directly north, the smallest waves, in the vicinity of the radius of maximum wind, occur in the southwest quadrant and the largest waves occur in the northeastern quadrant (Wright, 2001; Hsu, 1998; Moran and Moran, 1997; Silvester and Hsu, 1993; Shore Protection Manual, 1984). Nilsson (1995) describes wind fields within a hurricane to be seldom steady; however, the movement of the wind field dominates the rate of change at a fixed point. Furthermore, when considering the ocean response and a hurricane moving with a uniform velocity, it is appropriate to describe the wind field as being steady.

Meteorological data were acquired from the NHC for three 1999 hurricanes Bret, Dennis, and Floyd. Each of these storms varied in intensity, forward velocity, and track. Data recorded from these storms were incorporated into the modelers’ predictions of the maximum wave height generated from a hurricane.

The Tropical Prediction Center (TPC) Atlantic Preliminary Report describes Bret as a slow moving small hurricane from August 22nd, 0700Z, until it made landfall, August 22nd, 2300Z (Figure 2). At its peak, R extended 48 to 64 km from the center in the north semicircle and 16 to 32 km in the south semicircle. Shortly after strengthening to a Category 4 hurricane on the morning of the 22nd, Bret interacted with two mid-tropospheric systems causing the hurricane to decrease in velocity.

Dennis was a larger than average western Atlantic hurricane that reached hurricane strength on August 24th. Dennis become a Category 2 storm status and then later deteriorated into a marginal hurricane. The hurricane made landfall south of Cape Hatteras, NC, on September 4th (Figure 3). Dennis was erratic in movement and remained roughly 204 km offshore the northern Outer Banks for approximately four days, generating prolonged high surf.
Reaching the top end of Category 4 intensity, on the Saffir Simpson Hurricane Scale, Floyd was considered a fast and intense storm. By the afternoon of September 15th, Floyd had paralleled the Florida coast and headed to the Carolinas, steadily increasing in speed from 5.8 m/s to 8.2 m/s. Approaching landfall, Floyd diminished in intensity and was downgraded to a Category 2 storm (Figure 4).

2. Deep Water Wave Models

The equations used by Hsu, Kjerfve, and Young all have the following variables in common: radial distance from storm center to area of maximum winds (km), \( R \); maximum wind speed (m/s), \( U_R \); storm’s forward motion (m/s), \( V_f \), and predicted maximum deep water significant wave height (m), \( H_{\text{max}} \). The differences among each modelers’ equations are addressed briefly below, for further detail see their listed references.

2a. Hsu – 2000

Hsu tests the validity of equations given in the US Army Corps of Engineers (USACE) Shore Protections Manual, 1984, with observed wave heights generated by 1998 Hurricane Georges. The USACE suggests using a numerical model as the best method for calculating wave conditions in a hurricane; however, for slow-moving hurricanes, the following equation is a simple method to approximate the maximum wave height:

\[
H_{\text{max}} = 5.03 \ e^{R \Delta P/4700} \left[ 1 + 0.29a \frac{V_f}{\sqrt{U_R}} \right] \tag{2-1}
\]

where the change in pressure, \( \Delta P \), is calculated by taking the difference between the pressure on periphery of storm, \( P_n \) (760 mmHg) and the central pressure of the hurricane, \( P_o \) (mmHg). If storm is slow moving, \( \alpha \) is taken as 1, compensating for a slight increase
in fetch length (Bretschneider, 1957). The maximum sustained wind speed (m/s), \( U_{R*} \), is calculated for 10 m above mean sea surface at R. When meteorological observations fail to observe R, USACE (1984) and Hsu (2000) have shown the following predictive equation developed by Schloemer (1954) and Harris (1958) as an acceptable substitute:

\[
R = \frac{r \ln \left( \frac{P_n - P_o}{P - P_o} \right)}{1 - 2}
\tag{2-2}
\]

where \( P \) is the pressure at a point located at distance \( r \) from storm center.

2b. Kjerfve – 1986

The maximum wave height equation accounts for the hurricane’s forward motion,

\[
H_{\text{max}} = H_R \left( 1 + \frac{1.17 V_f^{0.63} \cos \theta}{U_R} \right)^2
\tag{2-3}
\]

where \( \theta \) is defined as the angle measured counterclockwise from the direction of the storm’s forward motion (degrees). For a stationary storm, the significant wave height, \( H_R \), is assumed to be located at R, was determined by

\[
H_R = K' \sqrt{(R \Delta P)}
\tag{2-4}
\]

where \( K' \) is an empirical function of \( C \frac{R}{U_R} \) and \( C \) is defined as the Coriolis parameter,

\[
C = 2 \omega \sin \phi
\tag{2-5}
\]

\( (\omega = 7.95 \times 10^{-5} \text{ s}^{-1} \text{ and } \phi = \text{latitude in degrees}) \) (Breitschneider and Tamaye, 1976). An approximate relationship where \( K' \) is regressed on the empirical function is defined as

\[
K' = 0.0352 \left( \frac{CR}{U_R} \right)^2 - 0.0247 \left( \frac{CR}{U_R} \right) + 0.0083
\tag{2-6}
\]
The following variables were defined by Young as the parameters within the wind field: \( U_r \), \( V_f \), and \( R \). Young adopted the fetch-limited growth equation from Hasselmann et al. (1973) and solved for \( H_{\text{max}} \) as

\[
H_{\text{max}} = 0.0016 U_r \sqrt{\left( \frac{F}{g} \right)} \quad (2-7)
\]

The equivalent fetch, \( F \), is calculated by

\[
\frac{F}{R'} = a U_r^2 + b U_r V_f + c V_f^2 + d U_r + e V_f + f 
\]

where the coefficients, a-f, are: \( a = -2.175 \times 10^{-3} \); \( b = 1.506 \times 10^{-2} \); \( c = -1.223 \times 10^{-1} \); \( d = 2.190 \times 10^{-1} \); \( e = 6.737 \times 10^{-1} \); \( f = 7.980 \times 10^{-1} \). The nonlinear source term, \( R' \), is thought by Young to be an important parameter modeling the effects of rapidly turning winds within the hurricane. \( R' \) is treated as an empirical parameter (SWAMP 1985) and is further discussed in Young (1987a, 1987c) and is defined as

\[
R' = 22.5 \times 10^3 \log R - 70.8 \times 10^3 \quad (2-9)
\]

### II. Methods

1. Guidelines

The study area stretches from the offshore regions of Texas to North Carolina. For consistency, each modeler’s equations used the same meteorological and buoy data (i.e. each observation is coincident in time and from the same sources). Repeated references are made to a buoy’s position relative to the storm’s path. The storm is divided into four quadrants (Q) and depending upon the storm’s direction and buoy location determines which quadrant is nearest to the buoy (Figure 5). The data used to determine
Table 1. Meteorological data used as coefficients for the modeled predictions of $H_{\text{max}}$.

<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Date &amp; Time</th>
<th>Q</th>
<th>$U_r$ (m/s)</th>
<th>$V_f$ (m/s)</th>
<th>Po (mmHg)</th>
<th>R plane (km)</th>
<th>R sat (km)</th>
<th>Young: HF(km)</th>
<th>Hsu: equation (2-2) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bret</td>
<td>08/22/13Z</td>
<td>1</td>
<td>61.7</td>
<td>4.7</td>
<td>709</td>
<td>22.2</td>
<td>13.9</td>
<td>110.0</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>08/22/15Z</td>
<td>1</td>
<td>61.7</td>
<td>4.7</td>
<td>709</td>
<td>28.7</td>
<td>13.9</td>
<td>110.0</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>08/22/19Z</td>
<td>1</td>
<td>61.7</td>
<td>3.6</td>
<td>709</td>
<td>16.7</td>
<td>13.9</td>
<td>110.0</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>08/22/21Z</td>
<td>1</td>
<td>61.7</td>
<td>3.6</td>
<td>710</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>08/22/23Z</td>
<td>4</td>
<td>56.3</td>
<td>3.6</td>
<td>712</td>
<td>17.6</td>
<td>N/A</td>
<td>130.0</td>
<td>23.3</td>
</tr>
<tr>
<td>Dennis</td>
<td>08/29/03Z</td>
<td>3</td>
<td>46.3</td>
<td>3.1</td>
<td>727</td>
<td>63.9</td>
<td>32.4</td>
<td>191.3</td>
<td>55.8</td>
</tr>
<tr>
<td></td>
<td>08/29/06Z</td>
<td>3</td>
<td>46.3</td>
<td>3.1</td>
<td>728</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>08/30/07Z</td>
<td>2</td>
<td>46.3</td>
<td>5.4</td>
<td>722</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>79.5</td>
</tr>
<tr>
<td></td>
<td>08/30/09Z</td>
<td>3</td>
<td>43.7</td>
<td>5.4</td>
<td>722</td>
<td>----</td>
<td>41.7</td>
<td>220.0</td>
<td>42.6</td>
</tr>
<tr>
<td>Floyd</td>
<td>09/15/23Z</td>
<td>3</td>
<td>51.4</td>
<td>7.6</td>
<td>712</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>50.2</td>
</tr>
<tr>
<td></td>
<td>09/16/03Z</td>
<td>2</td>
<td>51.4</td>
<td>7.2</td>
<td>714</td>
<td>63.0</td>
<td>37.0</td>
<td>410.0</td>
<td>----</td>
</tr>
</tbody>
</table>
the hurricanes’ time, location, $U_r$, $V_p$, $R$, $P_o$, and $Q$ were available from the NHC (Table 1). NOAA wave rider buoys were used for values of $P$ and $H$ (Table 2). This study incorporates wave data from buoys located less than 90 km from the storm’s center.

### Table 2. Data recorded from the NOAA wave rider buoys.

<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Date &amp; Time</th>
<th>$H$: Buoy (m)</th>
<th>$P$: (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bret</td>
<td>08/22/13Z</td>
<td>5.9</td>
<td>751</td>
</tr>
<tr>
<td></td>
<td>08/22/15Z</td>
<td>7.0</td>
<td>747</td>
</tr>
<tr>
<td></td>
<td>08/22/19Z</td>
<td>8.2</td>
<td>737</td>
</tr>
<tr>
<td></td>
<td>08/22/21Z</td>
<td>6.8</td>
<td>745</td>
</tr>
<tr>
<td></td>
<td>08/22/23Z</td>
<td>6.5</td>
<td>745</td>
</tr>
<tr>
<td>Dennis</td>
<td>08/29/03Z</td>
<td>7.5</td>
<td>743</td>
</tr>
<tr>
<td></td>
<td>08/29/06Z</td>
<td>7.3</td>
<td>735</td>
</tr>
<tr>
<td></td>
<td>08/30/07Z</td>
<td>8.9</td>
<td>738</td>
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<tr>
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<td>08/30/09Z</td>
<td>8.3</td>
<td>733</td>
</tr>
<tr>
<td>Floyd</td>
<td>09/15/23Z</td>
<td>11.0</td>
<td>732</td>
</tr>
<tr>
<td></td>
<td>09/16/03Z</td>
<td>8.3</td>
<td>734</td>
</tr>
</tbody>
</table>

2. Available Meteorological Data

Coefficients used in the modeled predictions of $H_{max}$ equations are limited due to meteorological constraints where one or more of the variables needed to calculate $H_{max}$ was not available (Table 1). The most limiting variable was observed values for $R$. Two different instruments were used to record $R$: 1) dropwindsondes from the NOAA airplane (plane) and 2) NOAA satellite radar imagery (sat). Global positioning systems (GPS) dropwindsondes are expendable probes used to measure atmospheric and thermodynamic profiles within hurricanes (Uhlhorn and Black, 2003). Operators from the Aircraft Operations Center (AOC) of NOAA use the observed atmospheric data to determine $R$, specifically by calculating the distance between the observed maximum wind at flight
level to the hurricane’s center (where the lowest pressure is measured and wind speeds are near zero). For satellite imagery the R is determined by the precipitation free area of the eye and measurement of that diameter (personal communication: Barry Damiano, Flight Director/Meteorologist from OMAO, Aircraft Operations Center, MacDill Air Force Base, FL). Observed winds exceeding hurricane force values were acquired from NHC and incorporated into the Young’s H_{max} equations. The following naming convention identifies the R value used to calculate H_{max}: 1) “Hsu_plane”, 2) “Hsu_sat”, 3) Kjerfve_plane”, 4) “Kjerfve_sat”, 5) “Young_plane”, 6) “Young_sat” and 7) “Young_HF”. Special interest was placed in further testing Hsu’s H_{max} equation, for the set of equations offered an additional predictive equation for R. This extra equation allows for more data points to be included and thus, it is examined separately. Those results are referred to as “Hsu_eq”.

4. Available Buoy Data

The coefficients needed from the buoy data include P and H. Kjerfve’s and Hsu’s models depended on P recorded at r distance from the storm. In order to determine the skill of the modeled predictions of H_{max}, the estimates were compared to H. Due to the destructive storm winds and waves, several buoys were inoperable and thus limited the number of data points available for the wave height comparisons. The distance from the buoy to the storm also imposed limitations where for a given distance the larger wave heights would not be observed. For consistency, data points were limited to those where r < 90 km.

5. Statistics

Linear regression analyses were used to test the agreement of the model prediction of H_{max}, with observed H. The R^2 and P values were calculated in order to measure the strength of this relationship. To further validate these equations, two additional statistical
quantities were calculated, the rms error and the Scatter-Index (SI). The rms error is
defined as

\[ \text{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i)^2} \]  \hspace{1cm} (2-10)

where \( N \) is the number of observations of the observed value, \( X \), and computed value, \( Y \), at
time \( i \). The scatter index examines the rms error while taking into account the magnitude of
error. The equation used to calculate the scatter index is shown as

\[ \bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \] \hspace{1cm} (2-11)

where \( \bar{X} \) is calculated as

\[ \text{SI} = \frac{\text{rms}}{\bar{X}} \] \hspace{1cm} (2-12)

The statistical results for the \( R^2 \), \( P \), rms error, and scatter index, are shown in Table 8 for
the predictive equations: Hsu (equation 2-1), Kjerfve (equation 2-3) and Young (equation
2-7).

III. Results
Deep Water Wave Models
1. Hsu’s Equations

The \( R^2 \) and \( P \) statistic for the Hsu_plane and Hsu_sat were low and were not
statistically significant when compared to \( H \); however, the rms error and SI were both
low, indicating the estimates were fairly accurate. For example, for Hsu_plane, the \( R^2 \)
and P statistic were 0.33 and 0.6835, respectively, and for Hsu_sat, those values were calculated as 0.32 and 0.2416, respectively. The rms error for Hsu_plane and Hsu_sat were slightly larger than the H as 2.77 m and 0.90 m, respectively, and the SI for the models was 0.38 and 0.12, respectively. Hsu’s modeled predictions of $H_{\text{max}}$ results are summarized in Table 3 and Figure 6A.

The rms error and scatter index were 1.27 m and 0.16, respectively, for Hsu_eq. The calculated $R^2$ value, 0.78, and P statistic, 0.0007, suggests a strong correlation with $H_{\text{max}}$ and H at the 99% confidence level. The Hsu_eq estimates of $H_{\text{max}}$ are shown in Table 3 and Figure 6B.

2. Kjerfve’s Equations

Kjerfve_plane predictive equations of $H_{\text{max}}$ were statistically significant at a 95% CI, with $R^2$ and P statistic values of 0.81 and 0.01470, respectively. However, the rms error was calculated as 3.25 m, with a SI of 0.45. According to the $R^2$ and P statistic, those estimates using Kjerfve_sat performed poorly with a $R^2 = 0.33$, and P statistic = 0.1741. However, the rms error, 2.25 m, was moderate in comparison to the H and SI (0.31). The results from Kjerfve’s $H_{\text{max}}$ calculations are summarized in Table 3 and Figure 6C.

3. Young’s Equations

Overall estimates of $H_{\text{max}}$ as calculated by Young_plane, generally deviated greatly when compared to H. For example, the rms error (8.21 m) and SI (1.14) are considered poor representations of Hmax. Additionally, the $R^2$ and P statistic, 0.028 and 0.7506 respectively, are not statistically significant at a 95% CI and are indicative of a poor relationship. The results slightly improve with Young_sat modeled prediction of $H_{\text{max}}$, although, no statistical relationship was supported ($R^2 = 0.16$ and $P = 0.44$). The rms error, 6.62 m, and SI, 0.88, were high in error and variability. Incorporating the hurricane
force winds (as observed from the NHC) into the predictive equations improved the strength in the linear test. However, the statistics indicated no relationship between $H$ and $H_{\text{max}}$. For example, the $R^2$ and $P$ statistic were computed as 0.18 and 0.3439, respectively, and the rms error and SI were 4.47 m and 0.61. Young’s modeled predictions of $H_{\text{max}}$ are shown in Table 3 Figure 6D.

Figure 6. Plots A-d are results from the linear regression analysis comparing observed wave heights to the modelers’ predictions of the $H_{\text{max}}$ (m). The black dotted line indicates where a 1:1 relationship would be expected: Hsu’s model: Hsu_eq (A), Hsu’s model: Hsu_plane and Hsu_sat (B), Kjerfve’s model: Kjerfve_plane and Kjerfve_sat (C), and Young’s model: Young_plane, Young_sat, and Young_HF. Sources used for the R are identified as the following: plane (squares), satellite (circles), equation 2-2 (triangles), hurricane fetch (up-side-down triangles).
Table 3. Results from the modelers’ prediction of the $H_{\text{max}}$.

<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Date &amp; Time</th>
<th>$H$: Buoy (m)</th>
<th>$H_{\text{max}}$ (m): Hsu’s Models</th>
<th>$H_{\text{max}}$ (m): Kjerfve’s Models</th>
<th>$H_{\text{max}}$ (m): Young’s Models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hsu_plane</td>
<td>Hsu_sat</td>
<td>Hsu_eq</td>
</tr>
<tr>
<td>Bret</td>
<td>08/22/13Z</td>
<td>5.9</td>
<td>7.5</td>
<td>6.9</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>08/22/15Z</td>
<td>7.0</td>
<td>8.1</td>
<td>6.9</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>08/22/19Z</td>
<td>8.2</td>
<td>6.9</td>
<td>6.6</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>08/22/21Z</td>
<td>6.8</td>
<td>-----</td>
<td>-----</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>08/22/23Z</td>
<td>6.5</td>
<td>6.9</td>
<td>-----</td>
<td>7.2</td>
</tr>
<tr>
<td>Dennis</td>
<td>08/29/03Z</td>
<td>7.5</td>
<td>2.3</td>
<td>7.2</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>08/29/06Z</td>
<td>7.3</td>
<td>-----</td>
<td>-----</td>
<td>8.6</td>
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<td></td>
<td>08/30/07Z</td>
<td>8.9</td>
<td>-----</td>
<td>-----</td>
<td>11.8</td>
</tr>
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<td>08/30/09Z</td>
<td>8.3</td>
<td>-----</td>
<td>8.7</td>
<td>8.8</td>
</tr>
<tr>
<td>Floyd</td>
<td>09/15/23Z</td>
<td>11.0</td>
<td>-----</td>
<td>-----</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>09/16/03Z</td>
<td>8.3</td>
<td>12.0</td>
<td>9.3</td>
<td>-----</td>
</tr>
</tbody>
</table>
IV. Discussion

1. Wave Buoy Limitations & Hurricane Characteristic Variability

The relative positions of the hurricane and location of wave observations (buoy), determine how well or poor the observed wave height compares to $H_{\text{max}}$. For example, an ideal comparison of the $H$ to $H_{\text{max}}$ would occur under the conditions where the buoy was positioned in the eyewall of the northeastern quadrant of a slowly northern moving storm; however, not all of these conditions could be met. Therefore, a point system was developed based on $r$, $V_f$, and $Q$ to determine when the wave observations were favorable (3 points), fair (4 to 6 points), or unfavorable (7 points) in observing the larger wave heights (Table 4). Then for each modeled prediction, the percent error was calculated (Table 5). During favorable comparisons, the modeler’s estimates of $H_{\text{max}}$ is expected to best approximate $H$. Specifically, if the modeled prediction was less than 20% in error, then it was considered a good estimate of $H_{\text{max}}$. The modeler’s estimates of $H_{\text{max}}$ are expected to be a close approximation, but slightly greater than $H$ during fair conditions. Thus, an acceptable modeled estimate would range between 5% to 25% greater than $H$. During unfavorable conditions, estimates of $H_{\text{max}}$ are expected to be slightly greater than the $H$. A reasonable modeled estimate would be greater than $H$ and thus, expected to range in error from 10% to 30%.

Increased distance from the buoy to the storm was found to decrease the likelihood of the larger wave heights to be observed. The $r$ was scored as described by the following: 1) $r \leq 50 \text{ km} = 1$ point, 2) $50 \text{ km} < r \leq 70 \text{ km} = 2$ points, and 3) $r > 70 = 3$ points. The three modeler’s equations were designed for slow moving hurricanes (i.e. $V_f$ less than 6.8 m/s). Hurricanes Bret and Dennis are examples of slow moving storms, however, the data acquired from Floyd exceeded this criteria. Data where $V_f \leq 6.8$ m/s scored 1 point and $V_f > 6.8$ m/s scored 3 points. As previously mentioned, a storm moving directly north, the smallest waves, in the vicinity of the radius of maximum wind, occur in the southwest quadrant (Q=3) and the largest waves occur in the northeastern
quadrant (Q=1). For the above example, if the buoy was located in the southwest quadrant then it would observe smaller wave heights than if it were located in the northeastern quadrant. Data occurring in the following Q were scored as 1) Q=1 = 1 point, 2) Q=2 or Q=4 = 2 points, and 3) Q=3 = 3 points.

1a. Favorable Conditions

The favorable conditions occurred on 8/22/15Z (Bret) and 8/22/19Z (Bret). One of the two modeled predictions was less than 20% in error for Hsu_plane, Kjerfve_plane, and Kjerfve_sat, and thus, showed reasonable agreement when compared to H. The other estimate from Hsu_plane and Kjerfve_sat and the Hsu_sat predictions underestimated $H_{\text{max}}$ (i.e. the calculated wave heights were smaller than the observed wave heights). Young’s modeled estimates along with the other Kjerfve_plane estimate exceeded the <20% error limit and thus, poorly represents $H_{\text{max}}$.

The above mentioned times apply for the Hsu_eq as well as an additional observation, 8/22/21Z (Bret). Hsu_eq estimates showed excellent agreement during the favorable occurrences (percent error ranged from 3.4% to 9.6%).

1b. Fair Conditions

Fair conditions occurred during 8/22/13Z (Bret), 8/22/23Z (Bret), and 8/30/09Z (Dennis). One prediction from Hsu_plane and two predictions from Hsu_sat, were reasonable estimates of $H_{\text{max}}$ (percent error was >5% and < 25%). Kjerfve_sat and Young’s modeled predictions along with the other results from Hsu’s models poorly estimated $H_{\text{max}}$ and thus, the percent errors were greater than 25%. Modeled results from the Kjerfve_plane were smaller than the observed wave heights.

Additional occurrences for the Hsu_eq were during Dennis at 8/29/06Z and 8/30/07Z. Four out of Hsu_eq’s five modeled predictions agreed reasonably well where the estimates were slightly greater than the observed wave heights (percentage error ranged
Table 4. Data used to determine how well the recorded wave heights represents larger wave heights generated by the hurricane.

<table>
<thead>
<tr>
<th>Model</th>
<th>Date &amp; Time</th>
<th>Q</th>
<th>r (km)</th>
<th>$V_f$ (m/s)</th>
<th>Comparison</th>
<th>Score Cared</th>
<th>Storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favorable: Points = 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>08/22/15Z</td>
<td>1</td>
<td>46</td>
<td>4.7</td>
<td>favorable</td>
<td>3</td>
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<td>1</td>
<td>41</td>
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<tr>
<td>Hsu_eq</td>
<td>08/22/21Z</td>
<td>1</td>
<td>46</td>
<td>3.6</td>
<td>favorable</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

| Fair = 4 ≤ Points ≤ 6 |             |   |        |             |            |             |       |
| All       | 08/22/13Z   | 1 | 84     | 4.7         | fair       | 5           | Bre  |
| All       | 08/22/23Z   | 4 | 61     | 3.6         | fair       | 5           |       |
| Hsu_eq    | 08/29/06Z   | 3 | 52     | 5.4         | fair       | 6           | Den  |
| Hsu_eq    | 08/30/07Z   | 2 | 74     | 3.1         | fair       | 7           |       |
| All       | 08/30/09Z   | 3 | 33     | 5.4         | fair       | 5           |       |

| Unfavorable: Points ≥ 7 |             |   |        |             |            |             |       |
| All       | 08/29/03Z   | 3 | 80     | 3.1         | unfavorable| 8           | Den  |
| All       | 09/15/23Z   | 3 | 59     | 7.6         | unfavorable| 8           | Flo  |
| All (except Hsu_eq) | 09/16/03Z   | 2 | 90     | 7.2         | unfavorable| 8           |       |
Table 5. Percent error of the modelers’ prediction of the Hmax. Negative percents indicate where the modeled H<sub>max</sub> was lower than the H.

<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Date &amp; Time</th>
<th>H: Buoy (m)</th>
<th>Hsu's Models (%)</th>
<th>Kjerfve's Models (%)</th>
<th>Young's Models (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hsu_plane</td>
<td>Hsu_sat</td>
<td>Hsu_eq</td>
</tr>
<tr>
<td>Bret</td>
<td>08/22/13Z</td>
<td>5.9</td>
<td>27.5</td>
<td>16.4</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>08/22/15Z</td>
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<td>----</td>
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<td>----</td>
<td>----</td>
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<tr>
<td></td>
<td>09/16/03Z</td>
<td>8.3</td>
<td>45.5</td>
<td>12.8</td>
<td>----</td>
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</table>
from 5.5% to 19.0%). The other predicted wave height exceeded the observed value by 39% and consequently, it serves as a poor estimate.

1c. Unfavorable Conditions

Unfavorable conditions occurred during 8/29/03Z (Dennis) and 9/16/03Z (Floyd). One prediction for Hsu_sat was in reasonable agreement when compared to the observed wave height (percent error 12.8%). The other result for Hsu_sat along with both Hsu_plane’s predictions was less than the observed wave height and thus, is an unacceptable estimate of $H_{\text{max}}$. Kjerfve’s modeled estimates performed poorly (error ranged from 32% to 72%). Young’s predictions greatly deviated from $H$ (error ranged from 39% to 103%) and are considered poor estimates.

For the Hsu_eq, the two unfavorable occurrences were during 08/29/03Z (Dennis) and 09/15/23Z (Floyd). The modeled predictions accurately estimate $H_{\text{max}}$ where the percent error was 12.7% and 13.9%.

V. Conclusions

Three simple, different, predictive wave height equations were compared to data recorded during three 1999 hurricanes. These equations are designed to predict the maximum wave height generated by a hurricane. A validation technique was developed based on $r$, $V_f$, and $Q$ to determine when wave observations were favorable, fair, or unfavorable in observing larger wave heights. The results produced from Young’s equations showed no statistical relationship and greatly deviated from $H$. However, the degree of error was lessened when substituting hurricane force (as determined by the NHC) for the calculated hurricane’s fetch (equation 2-8). Kjerfve’s modeled predictions as well as Hsu_plane and Hsu_sat results show potential to reasonably estimate $H_{\text{max}}$. However, several occurrences greatly underestimated and overestimated $H_{\text{max}}$ and thus, more tests are recommended to further validate the models’ skill. The Hsu_eq equation
negates the dependency upon NOAA meteorological observations of R and consequently, more data points were available to be compared to H. Overall, this wave height equation produced the most agreeable results and its simple design allows for rapid application. More studies are recommended to further examine the modelers’ equations skill in predicting the maximum deep water wave height generated by a hurricane.
Chapter 3
Coastal Vulnerability

I. Introduction

Topographic data from a scanning airborne lidar were used to describe the dune morphology for approximately 65 km of the Outer Banks, NC. Dune thresholds, $D_{\text{high}}$ and $D_{\text{low}}$, were compared to estimates of extreme wave runup, $R_{\text{high}}$ and $R_{\text{low}}$, resulting from Hurricane Dennis. Dennis was a Category 2 hurricane on the Saffir Simpson Hurricane Scale that lasted from August 24 to September 7, 1999. It lingered 204 km east of Cape Hatteras for about 4 days causing prolonged high surf, before making landfall over the Cape Lookout National Seashore as a Tropical Storm (Beven, 2000). Water levels measured during Dennis rank as some of the most extreme over an 18 year record at Duck, NC (Figure 7). These hindcast techniques were used to test the hypothesis that spatial variations in dune elevations can be used to predict occurrences of overwash, according to Sallenger’s (2000) Storm Impact Scale.

II. Background

1. Storm Impact Scale

![Figure 7. Probability density function showing 18 years of recorded wave runup data from FRF, Duck, NC. Wave runup during Dennis measured approximately 4 m, a rare and extreme event (Sallenger et al., 2000).]
The Storm Impact Scale (Sallenger, 2000) has the potential to quantitatively predict the severity of storm hazards. Also, the scale describes how different coastal regions respond to hurricanes or other storms and highlights factors that might influence these changes, such as spatial variation in dune height. Four regimes are defined in the Storm Impact Scale, which categorize each regime’s expected pattern and magnitude of coastal change. The foredune located on the barrier island serves as the first line of defense (if no dune is present then the elevation of the berm would be considered). Two parameters, $D_{\text{high}}$ and $D_{\text{low}}$, are used to identify the elevation of the dune’s crest and base, respectively (Figure 8). Other additional variables, $R_{\text{high}}$ and $R_{\text{low}}$, describe the range of extreme wave runup relative to a fixed vertical datum. The Storm Impact Scale defines the morphological responses in $D_{\text{high}}$ and $D_{\text{low}}$ influenced by the interactions in $R_{\text{high}}$ and $R_{\text{low}}$ (Figure 9). Specifically, the swash regime occurs when the extreme wave runup, $R_{\text{high}}$, is confined to the foreshore (Figure 10). The collision regime occurs when $R_{\text{high}}$ exceeds the base of the dune,
Dune did not erode significantly.

Figure 10. This post-Dennis photograph shows an example of the swash response (http://coastal.er.usgs.gov).

Figure 11. This photograph was taken after Hurricane Isabel (2003) south of the Cape Hatteras Shoal, and serves as a good example to illustrate the collision response.

Figure 12. The above photograph shows an overwash fan that occurred post-Isabel along the Outer Banks, NC. Notice how the fan extends from the ocean to the sound.

Figure 13. The above aerial photograph was taken of Isle Dernieres, a barrier island located in LA, before and after Hurricane Andrew as an example of the inundation regime (http://coastal.er.usgs.gov).
D<sub>low</sub> (Figure 11). In the overwash regime, R<sub>high</sub> exceeds the crest of the dune, D<sub>high</sub> (Figure 12). The fourth regime, inundation, occurs when R<sub>low</sub> exceeds D<sub>high</sub> and the island is submerged (Figure 13) (for further details see Sallenger, 2000).

2. Airborne Laser Survey

LIDAR, Light Detection and Ranging, is a technological advancement in topographic mapping allowing researchers to gather spatially dense and highly accurate data in a timely, cost-efficient manner (Flood and Getelius, 1997; Meredith et al., 1998; Merideth et al., 1999; Sallenger, 2000; Sallenger et al., 2000; Stockdon et al., 2002; Woolard and Colby, 2002). It serves as an active remote sensing system, like radar, which uses pulses of light rather than microwave energy to illuminate the terrain (Lillesand and Keifer, 1994). An airborne topographic mapper (ATM), supplied by the National Aeronautics and Space Administration, is mounted on a twin otter (Figure 14). The ATM calculates the elevation of the terrain approximately every 2 m<sup>2</sup>, based on the return time to the aircraft (Elko et al., 2002A). The elevation data can be created with very fine spatial (x, y, z) resolution and vertical accuracy of 15 cm rms (Sallenger et al., 2000; White and Wang, 2002). For more details on laser mapping see Sallenger et al. in press.

ATM data, initially used to map ice sheets in Greenland (Krabill et al, 1995), are increasingly being used to measure beach change (Sallenger, 2000; Sallenger et al., 2000; Sallenger et al. in press; Krabill et al., 2000; Merideth et al., 1998; Merideth et al., 1999; White and Wang, 2002; Woolard and Colby, 2002). For example, a cooperative effort between USGS, NASA, and NOAA used the ATM to measure and examine changes in
beach morphodynamics resulting from El Nino storms on the US West Coast and severe northeaster storms on the East Coast (Sallenger et al., in press). Estimates of elevation have been compared to other advanced survey techniques (Merideth et al., 1998; Sallenger et al., 2000) and have shown to be sufficient for determining magnitudes of beach change (Sallenger et al., 2000). Furthermore, multiple 350-m wide swaths provide coverage of the beach and foredune ridge covering hundreds of km of coast within a few hours (Elko, 2002B; Sallenger et al., 2000). In summary, numerous studies have shown the response of barrier island beach morphology, to storm events, to be accurately measured through the use of airborne lidar data.

3. Nearshore Wave Model

SWAN (Simulating WAves Nearshore) is a phase-average spectral wave model calculating the change in wave spectra over complex nearshore bathymetry while maintaining computational efficiency. Utilizing a Eulerian formation, the model assumes wave properties vary slowly over a wavelength (Booij et al., 1999). The formulations within this phase average model include wave shoaling processes, specifically, wave generation, dissipation, and wave-wave interactions (Booij et al., 1999). The wave spectrum is propagated over geographic space, taking into account variations in water depth and depth averaged horizontal currents regardless of non-linear wave-wave interactions that may occur (e.g. in the surfzone) (Booij et al., 1999). The waves are characterized by a 2-d action density spectrum,

\[
\frac{\partial}{\partial \zeta} N + \frac{\partial}{\partial x} C_x N + \frac{\partial}{\partial y} C_y N + \frac{\partial}{\partial s} C_s N + \frac{\partial}{\partial q} C_q N = \frac{S}{s} \quad (3-1)
\]

where the first three terms from the left describe the local rate of change of the action density in time in geographical space, \(N\), and velocities (\(C_x N\) in x space and \(C_y N\) in y space) (Ris et al., 1999). The last two terms from the left describe the following: 1) the
shifting of relative frequencies due to variation in water depth and currents and 2) depth-and current-induced refraction (Ris et al., 1999). The right term accounts for generation, dissipation, and nonlinear wave-wave interactions (Ris et al., 1999). This energy source term is further defined as

\[ S = S_{in} + S_{ds} + S_{nl} \]  

(3-2)

where \( S_{in} \), \( S_{ds} \), and \( S_{nl} \), account for wind, dissipation, and nonlinear wave interactions, respectively. For further explanation regarding the formulations used in SWAN the reader is referred to Booij et al. (1999) and Ris et al. (1999). This wave model serves as the link between offshore wind and wave conditions and the shoaled waves in the nearshore that drive runup.

II. Methods

1. Dune Morphology

Elevation measurements were collected for barrier islands from Avon, NC, to north of Ocracoke Inlet, during September 1998 and immediately following Hurricane Dennis in September 1999. The highly dense topographic data underwent a suite of processing steps prior to generation of digital elevation models (DEMs). The DEMs were used to estimate \( D_{high} \) and \( D_{low} \) and beach change. A GIS-based analysis program was used to differentiate between the crest and base of the foredune ridge (or berm if foredune is absent) by concating slope and aspect images. Spatial locations, \( D_{high} \) and \( D_{low} \), were digitized on the aspect and slope images, respectfully (Figure 15). Then a model was applied to refine the spatial locations and elevation values for \( D_{high} \) and \( D_{low} \) that are calculated at 1 m alongshore intervals. The model is GUI-driven and applies algorithms to refine the spatial location of the dune crest and base heights from the digitized line, for further explanations, see Elko, 2002A. Several ESRI software applications (ARC Info v.3.2 and IMAGINE v.8.6) were combined in order to extract the locations and elevations from the digitized lines.
Figure 15. Examples of the process applied to extract dune elevations and cross shore profiles for \(D_{\text{high}}\) and \(D_{\text{low}}\) using IMAGINE v. 8.6. The gray-scaled elevation image where the yellow crosshair indicates the position of \(D_{\text{high}}\) and the green line perpendicular to shore represents the cross shore profile (A). In the aspect image (B) dark grays = seaward slopes and light grays = landward slopes. The red line indicates the location of the digitized \(D_{\text{high}}\). In the slope image (C) dark grays = relatively flat slopes (beach) and light grays = relatively steep slopes (dune face). The blue line indicates the location of the digitized \(D_{\text{low}}\). This example was taken from FRF, Duck, NC (D). The digitized parameters can be verified upon examining the associated cross shore profiles where for \(D_{\text{high}}\) (E) yellow line = digitized location of \(D_{\text{high}}\) and for \(D_{\text{low}}\) (F) yellow line = digitized location of \(D_{\text{low}}\) (Elko et al., 2000A).
2. Nearshore Wave Model

In SWAN, the wind speed and direction are specified at each grid point. The user defines this parameter and for this study, the data were obtained from NOAA observed data. Dissipation is characterized by three source terms: 1) whitecapping, 2) bottom friction, and 3) depth-induced breaking. The Janssen formulation was selected for calculating whitecapping. The Madssen formulation was used for the bottom friction source term since it is considered by Luo and Monbalui (1994) to be the most physically accurate (of the choices). For depth-induced breaking an expanded version of the bore-based model of Eldeberky and Battjes (1995 and 1978) was used which includes direction. For details regarding the choices and descriptions of the formulation methods, see Booij et al. (1999) or Ris et al. (1999).

The parametric spectrum was defined by the incoming wave components (H, T, wave direction, and directional spreading) occurring at the most eastern boundary. The H and T were obtained from recorded observations from NOAA wave rider buoy 41001, 150 nm East of Cape Hatteras. The peak wave direction was a calculated estimate from WAM (Wave Model, WAMDI Group, 1988), on August 30th, 1999, at 1200 GMC. Six degrees was used for the directional spreading because it is the directional boundary found between wind- and swell-generated waves (Booij et al., 2003). The geographical and spectral space of a large rectangular grid was used in order to avoid erroneous lateral boundaries. Since this error affects typically triangular regions, with the apex at the corners to the shore at 30 or 45 degrees (Booij et al., 1999), we extended the lateral boundaries from the area of interest. The spectral grid is 500 m in resolution, including length in x (Eastings) and y (Northings) of 314500 m and 415000 m, respectively. Geographically, this region entails the beach area approximately from Duck, NC, to Cape Fear, NC, and several km beyond the Atlantic continental shelf. The area of interest, north of Cape Hatteras to north of Ocracoke Inlet, was extracted from the aforementioned, larger grid, (see box outlined in Figure 16).
Figure 16. Extended bathymetric grid used to derive smaller grid (gray square) limiting the area of interest from Cape Hatteras to Ocracoke.
3. Wave Runup

An extensive data set of wave runup was measured on a natural beach at the U.S. Army Corps of Engineers Field Research Facility (FRF) located at Duck, NC (Holman, 1986). The results were a series of empirical relationships used to calculate the range in extreme wave runup, $R_{\text{high}}$ and $R_{\text{low}}$ (Holman, 1986; Sallenger et al., 2000). The following equation was used to solve for $R_{\text{high}}$:

$$R_{\text{high}} = H (0.83 \xi + 0.2) + \eta_{\text{mean}} \quad (3-3)$$

where $\eta_{\text{mean}}$ = astronomical tides and storm surge. $R_{\text{low}}$ is given by

$$R_{\text{low}} = R_{\text{high}} - H (0.83 \xi + 0.06) \quad (3-4)$$

Inputs used for this study, significant wave height and period, were computed from SWAN (extracted along the 10 m isobath) and the value for storm surge + astronomical tides were obtained from a tide gauge on Cape Hatteras Pier. The following calculation was used to solve for the Iribarren number, $\xi$:

$$\xi = \frac{b}{\left( \frac{H}{L} \right)^{1/2}} \quad (3-5)$$

where $\beta$ is the beach slope taken to be 0.08. The slope resulting from overtopping of a dune may be steeper than the natural beach from which the above empirical relationships were derived. We assume that parameterization of dune overtopping would scale similar to overtopping of the berm, where the seaward-facing foreshore has slope typical of the beach and $D_{\text{high}}$ does not change during a storm, (see Sallenger et al. (2000) and Sallenger (2000) for more details). $L$, the wavelength is given by,
where $g = \text{gravity}$, and $T = \text{wave period}$ as observed at the wave rider buoy.

4. Statistics

Measurements of the mean, median, variance, standard deviation, minimum, and maximum were calculated for the dune parameters, $D_{\text{high}}$ and $D_{\text{low}}$, as well as the solutions for the wave runup, $R_{\text{high}}$ and $R_{\text{low}}$, for the N.Cape and S.Cape region before and after Dennis.

A student’s t-test was used to test the differences in the means between the N.Cape and S.Cape regions for the dune elevations and wave runup heights. We assumed the data to be normal distributed. The student’s t-test, $T$, is defined as

$$T = \frac{\bar{m}_1 - \bar{m}_2}{sd \sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

(3-7)

where $\bar{m}_1$ and $\bar{m}_2$ are the means for the two samples, and $n_1$ and $n_2$ are the samples’ numbers of observations, respectively. The standard deviations, $sd$, of the two samples are calculated from the data.

The locations of wave runup estimates are consistent with the grid cell size used in SWAN. We assumed each wave runup data point would traverse perpendicular to the beach. To locate the corresponding dune we found shortest distance, $d$, between each wave runup point $(x_1, y_1)$ and nearby dune heights $(x_2, y_2)$ using the following distance equation,

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

(3-8)
Once the paired dune height and runup points were established, then an average dune height was calculated. An average dune height was calculated for a length of 500 m (along the dunes) equal to the grid resolution for runup. The correlations between runup and two dune parameters (post-storm dune height and change in dune height) were calculated. The correlation test is defined as

\[ R(i, j) = \frac{C_{cov}(i, j)}{\sqrt{(C_{cov}(i, i)C_{cov}(j, j))}} \]  

(3-9)

where \( R \) is the correlation coefficient and \( C_{cov} \) is the covariance of the two samples, \( i \) and \( j \).

II. Results

1. Dune Morphology

Changes in coastal morphology were examined from Ocracoke Inlet north to Avon, NC. Elevation data measured by airborne lidar extended in length approximately 17 km north of the Cape Hatteras point (N.Cape) and 45 km south of the Cape Hatteras point (S.Cape). Substantial spatial variations in \( D_{\text{high}} \) and \( D_{\text{low}} \) exist for both 1998 and 1999 surveys (Figures 17 and 18).

The results from a student’s t-test suggest the means for the dune morphology and the wave runup for the N.Cape and S.Cape regions were different (Table 6). For the N.Cape region, the calculated pre-storm mean elevations for \( D_{\text{high}} \) and \( D_{\text{low}} \) for the N.Cape region were 5.5 m and 3.3 m, respectively. After the storm, both the means for the \( D_{\text{high}} \) and \( D_{\text{low}} \) were statistically different and increased in elevation (5.9 m and 3.5 m). The variance and standard deviations decreased for the post-storm elevations (Table 7). For the S.Cape region, the pre-storm mean \( D_{\text{high}} \) (4.6 m) were lower in elevation compared to post-storm mean \( D_{\text{high}} \) (4.8 m), and were statistically different. For the two regions, the \( D_{\text{low}} \) means, 2.2 m pre-storm and 2.3 m post-storm, also were shown to be statistically different. The standard deviation for \( D_{\text{high}} \) increased but decreased for \( D_{\text{low}} \) (Table 7).
For both the N.Cape and S.Cape regions, the increase in mean dune height was due to the erosion of low dunes or berms during the storm, and can be seen in the histograms (Figures 19 and 20).

Figure 17. $D_{\text{high}}$ (green) and $D_{\text{low}}$ (blue) profiled every meter for the S.Cape study region in 1998 (A) and 1999 (B).
Figure 18. $D_{\text{high}}$ (green) and $D_{\text{low}}$ (blue) profiled every meter for the S.Cape study region in 1998 (A) and 1999 (B).
Table 6. Student’s T-test comparing N.Cape to S.Cape surveyed dune and runup elevations.

<table>
<thead>
<tr>
<th>Outputs</th>
<th>$D_{\text{high}}$</th>
<th>$D_{\text{low}}$</th>
<th>$R_{\text{high}}$</th>
<th>$R_{\text{low}}$</th>
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<tr>
<td></td>
<td>Pre-Storm</td>
<td>Post-Storm</td>
<td>Pre-Storm</td>
<td>Post-Storm</td>
</tr>
<tr>
<td>H</td>
<td>Non-Related</td>
<td>Non-Related</td>
<td>Non-Related</td>
<td>Non-Related</td>
</tr>
<tr>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CI</td>
<td>0.89-0.94</td>
<td>1.3-1.4</td>
<td>1.0-10.4</td>
<td>1.2-1.2</td>
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<td>103.8</td>
<td>201.7</td>
<td>268</td>
</tr>
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<td>df</td>
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<td>68427</td>
<td>67256</td>
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Table 7. Computed mean, variance, standard deviations, minimum and maximum values for the dune parameters before and after the storm.

<table>
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<th>Region</th>
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<th>Post-Storm</th>
</tr>
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<td></td>
<td></td>
<td>$\mu$</td>
<td>$\sigma^2$</td>
</tr>
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<td>$D_{\text{high}}$</td>
<td>N.Cape</td>
<td>5.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>S.Cape</td>
<td>4.6</td>
<td>2.4</td>
</tr>
<tr>
<td>$D_{\text{low}}$</td>
<td>N.Cape</td>
<td>3.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>S.Cape</td>
<td>2.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Figure 19. Probability density functions for the N.Cape dune parameters (A=pre-storm $D_{\text{high}}$, B=post-storm $D_{\text{high}}$, C=pre-storm $D_{\text{low}}$, and D=post-storm $D_{\text{low}}$).
Figure 20. Probability density functions for the S.Cape dune parameters (A=pre-storm $D_{\text{high}}$, B=post-storm $D_{\text{high}}$, C=pre-storm $D_{\text{low}}$, and D=post-storm $D_{\text{low}}$).
2. Nearshore Wave Model

The outputs calculated from SWAN are shown in Figure 21. Wave data also were recorded by a wave rider in 18 m of water located at the US Army Corps of Engineers Field Research Facility at Duck, NC, located approximately 109 km from the Cape Hatteras point. On August 31st, the highest recorded significant wave height was 6.3 m and related period was 14.3 s. The SWAN computed wave height was approximately 6 m and the T was calculated as 15 s. No instrument was available to validate the peak wave direction.

3. Wave Runup

The H and T were extracted from SWAN along the 10 m isobath along the Outer Banks and combined with η recorded at the Cape Hatteras Pier, yielding estimates of R_{high} and R_{low} using equations 3-3 and 3-4). A student’s t-test shows the runup in the N.Cape region to be significantly different than the runup in the S.Cape region (for details see Table 8) with mean R_{high} and R_{low} larger in the N.Cape region. Overall, the variability was small in both regions for R_{high} and R_{low} (i.e. the variances were approximately zero). A satellite image observed breaking waves alongshore the N.Cape region and for the S.Cape region, breaking waves occurred around Ocracoke Inlet. Breaking waves, however, were not observed eastward of the Cape Hatteras shoal (Figure 21).

The runup calculations were compared to the pre-storm D_{high} elevations to reveal areas vulnerable to overwash (Figures 23 and 24). Regions of overwash (R_{high} > D_{high}) were predicted to be infrequent. Locations where overwash was not predicted, the morphologic responses were either consistent with swash confined to the beach (for example, see Figure 25) or no alterations were observed (Figure 26).

The correlations between wave runup and the dune parameters were significant at 99% and 90% for the N.Cape and S.Cape regions, respectively (see Table 9 and Figure 27).
Figure 21. Wave outputs calculated from SWAN where the significant wave height, period, and peak wave direction are measured in m, m/s, and direction (in degrees) waves are traveling from.
Figure 22. Satellite image of the Outer Banks, NC, illustrating wave breaking and direction. Breaking wave heights extend from the N.Cape region to the southern end of the Cape Hatteras Shoal and then break near the western extent of the S.Cape region. Notice the lack of breaking for the area adjacent and westward of the shoal. These observations are consistent with the SWAN computed results.
Figure 23. Comparing pre-storm dune elevations ($D_{\text{high}}$) to the estimated extremes in wave runup ($R_{\text{high}}$ and $R_{\text{low}}$) for the N.Cape region. $D_{\text{high}}$ data that fall below $R_{\text{high}}$ are predicted to overwash.
Figure 24. Comparing pre-storm dune elevations ($D_{\text{high}}$) to the estimated extremes in wave runup ($R_{\text{high}}$ and $R_{\text{low}}$) for the S.Cape region. $D_{\text{high}}$ is predicted to respond according to the overwash ($R_{\text{high}}$ exceeds $D_{\text{high}}$) regime or inundation regime ($R_{\text{low}}$ exceeds $D_{\text{high}}$), as described by Sallenger’s (2000) Storm Impact Scale.
Figure 25. Cross shore profiles comparing pre (black) and post (blue) storm surveys where swash and/or collision would be expected for the N.Cape region (A) and S.Cape region (B and C). Positions are alongshore distance from the Cape Hatteras Shoal.
Figure 26. Cross shore profiles comparing pre (black) and post (blue) storm surveys where overwash was not predicted for the N.Cape region (A and B) and S.Cape region (C and D). Positions are alongshore distance from the Cape Hatteras Shoal.
Correlation: N.Cape

\[ R = 0.51 \]

Correlation: S.Cape

\[ R = 0.39 \]

Figure 27. Correlation plots showing the results for the N.Cape region (A) and S.Cape region (B).

Table 8. Computed mean, variance, standard deviations, minimum and maximum values for the extremes in runup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Region</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( \sigma^2 )</th>
<th>minimum (m)</th>
<th>maximum (m)</th>
</tr>
</thead>
<tbody>
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<td>( R_{\text{high}} )</td>
<td>N.Cape</td>
<td>3.1</td>
<td>0.0</td>
<td>0.1</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>S.Cape</td>
<td>2.8</td>
<td>0.0</td>
<td>0.0</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td>( R_{\text{low}} )</td>
<td>N.Cape</td>
<td>0.8</td>
<td>0.0</td>
<td>0.2</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>S.Cape</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 9. Correlations between wave runup and dune parameters (i.e. post-storm dune height and change in dune height).

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Dhigh</th>
<th>Dlow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N.Cape</td>
<td>S.Cape</td>
</tr>
<tr>
<td>( R )</td>
<td>-0.51</td>
<td>-0.39</td>
</tr>
<tr>
<td>( P )</td>
<td>0.0013</td>
<td>0.0981</td>
</tr>
<tr>
<td>Lower</td>
<td>-0.72</td>
<td>-0.72</td>
</tr>
<tr>
<td>Upper</td>
<td>-0.22</td>
<td>0.08</td>
</tr>
</tbody>
</table>
IV. Discussion

1. Dune Morphology:

Longshore spatial variations of several km to 10s of km exist for $D_{\text{high}}$ in both pre- and post-storm surveys (Figures 17 and 18). Elevations of $D_{\text{low}}$ are generally less variable than those observed for $D_{\text{high}}$. These observations in spatial variability result from $D_{\text{high}}$ values representing either dune crests or berm elevations (in the absence of dunes). These results are consistent with a similar investigation where airborne lidar survey measurements observed spatial variability in the dune morphology for the southeastern coast, by Elko et al. 2002A. Dune morphology for the two barrier islands, N.Cape and S.Cape, was found to be statistically different and consequently, each region responded differently to storm forcing (Table 6). Before and after the storm, dune elevations on average were higher for the N.Cape area than the S.Cape area (Table 7).

Prior to Dennis, the N.Cape region dune system was characterized by large dunes and dominant berms, see Figure 14 where two dominant peaks in $D_{\text{high}}$, represent the berm ($\sim 3$ m) and dune ($< 7$ m). After the storm, for the N.Cape region, the lower elevated dunes (or berms) were overwashed and some occasions, inundated, reducing the distribution of ranges in elevations and consequently, decreasing the variance. Overall, most coastal change from Dennis occurred seaward of the foredune, representing swash and collision responses as described by the Storm Impact Scale (Figure 25A). As predicted, the N.Cape region experienced overwash responses south of Avon (Figure 28A and 28B), north of groins (town of Cape Hatteras) and low-lying areas adjacent to the Cape Hatteras shoal. North of Cape Hatters shoal, the overwash responses are extreme in that the spatial extent encompassed approximately 4.5 km of shoreline (Figure 29). These alterations in beach morphology generally result in a flatter beach.

For the S.Cape region, occurrences of dunes (or berms) lower in elevation were less common after the storm and consequently, responded to the storm forcing as described by the overwashed (Figure 28C and 28D) or inundated regimes (Figure 30).
Figure 28. Cross shore profiles comparing pre (black) and post (blue) storm surveys where overwash was predicted for the N.Cape region (A and B) and S.Cape region (C and D). Positions are alongshore distance from the Cape Hatteras Shoal.
Figure 29. Overwash is considered extreme in that spatially it extended approximately 4 km in length for the N.Cape area adjacent to the Cape Hatteras shoal. This area was predicted to overwash.

Figure 30. This cross shore profile was extracted in the S.Cape area where inundation was the resulting dune response. These few occurrences support the prediction (i.e. \( R_{low} > D_{high} \) = inundation regime).

Figure 31. Pre-storm (A) and post-storm (B) low-profile areas adjacent to Ocracoke Inlet. Notice the perched fans (http://coastal.er.usgs.gov).
2. Dune Response due to Storm Forcing

The calculations of wave runup for the N.Cape region were statistically different than the S.Cape region where wave runup was slightly lower in elevation and consequently, the geomorphologic responses for the two regions were different (Table 1). Correlations existed between runup and the dune parameters (post-storm $D_{\text{high}}$ and the change in $D_{\text{high}}$) for both regions. Thus, when the estimated wave runup was greater in elevation than that of the dune crest (or berm in absence of the dune) overwash responses resulted and alternatively, where wave runup was lower than $D_{\text{high}}$, typically overwash was not observed (Figures 25 and 26). High-profiled areas (i.e. dunes characterized by high elevations and
developed vegetation) showed to less likely be overtopped by wave runup, however, the potential to respond to storm forces as described in the swash and collision regimes were evident (Figure 25). Lidar estimates, much like our analysis with $D_{\text{high}}$, showed the potential to predict occurrences defined by the collision and swash regimes using $D_{\text{low}}$. Correlations were significant for the N.Cape region (94%), although, not significant for the S.Cape region (66%) (see Table 6).

The predictive technique, using $D_{\text{high}}$ coupled with wave runup, works well with typical beach morphology and thus, serves as an adequate method to forecast coastal change hazards. However, the technique should be applied with caution when long-shore processes dominate. For example, north of the Cape Hatteras shoal, where the low elevated dunes (or berms) were predicted to overwash, instead, responded as described by the inundation regime. Alternatively, south-west of the shoal (the S.Cape region) the morphologic response experienced accretion (Figure 32).

Post-storm $D_{\text{high}}$ and $D_{\text{low}}$ slightly increased in both regions. This response does not indicate that storm forcing results in dune building. The following factors discussed below may have a role in the increase, however, the possibilities are numerous and to differentiate the likelihood of occurrence was not the scope of this project.

a. When low elevations for $D_{\text{high}}$ are approximately equal in to its berm, the berm receives the full impact from the wave runup, resulting in the berm being overwashed and the dune relatively unaltered. The problem arises in digitizing the dune parameters. For example, the digitized pre-storm $D_{\text{high}}$ would be the berm and the digitized post-storm $D_{\text{high}}$ would be the dune. Consequently, the $D_{\text{high}}$ appears to have increased in elevation and thus, areas predicted to overwash would be erroneously identified. Consequently, these errors would decrease the skill in forecasting coastal change hazards.
b. The pre- and post-storm surveys were taken a year apart. Thus, numerous environmental factors could have caused modifications within the dune system including, but not limited to, hurricanes, nor’easters, and series of low and high-pressure systems, aeolian transport and increased vegetation. Northeaster storms generally move slower than hurricanes and are more frequent (Dolan and Davis, 1992). El-Ashry and Wanless (1968) suggest major storms are most important in modifying the configuration of the NC coastline and during periods of calm weather normal shore processes tend to re-develop the original smooth outline of the coast. During fair weather, commonly in the summer, sediment may be pushed shoreward by waves. Aeolian processes transport the sediment, slowly rebuilding the dunes (Lennon et al., 1996).

c. The pre-storm survey was initiated after Hurricane Bonnie, a borderline Category 2/3 on the Saffir Simpson Hurricane Scale. Bonnie made landfall south of the study area near Wilmington, NC, August 27, 1998 (TPC Preliminary Report). The problem arises in comparing coastal change from two post-storm lidar surveys. For example, typically, the beach flattens after a storm (Pilkey et al., 1978) and thus, the digitized pre-storm dune heights (or berms) would be minimal in elevation. However, after the storm, the beach undergoes the natural process of recovery where sand bars migrate transgressively and eventually, becomes the berm (Lennon et al., 1998). For this example, the prediction method for overwash would identify falsely the initial flattened areas as coastal change hazards. Consequently, when the two sets of surveyed dune elevations are compared to runup, the skill of the prediction technique would decrease.

d. The lidar data were filtered, removing irregularities such as return signals off birds, clouds, and tall buildings (Tebbens et al., 2002). However, possible
occurrences such as new construction (i.e. houses, walk-overs, etc.) may have remained the surveys (Figure 33).

e. Anthropogenic influences may also contribute to the higher dune elevations where beach nourishment and/or bulldozing sediment after a storm is common, particularly in developed areas (Figure 34A and 34B). Also, groin fields and sand bags near the town of Cape Hatteras effect the changes in dune morphology where erosion and accretion were observed north and south of the line of groins, respectively (Figure 34C).
V. Conclusions

The study region was divided due to the differences in the barrier islands orientation to the Atlantic Ocean. Specifically, the north-south trending barrier island and east-west trending barrier island were divided at the Cape Hatteras point and are referred to as N.Cape region and S.Cape region. The dune systems for each barrier were statistically shown to be unique to one another. High-profile dune system, where dunes elevations on average are high (< 6 m) and vegetation is well developed, describes the N.Cape region’s dune system. In contrast, a low-profiled dune system, were dune heights on average are low (< 5 m) and vegetation was not prolific, characterizes the S.Cape region.

Variations in bathymetry and wave shoaling were accounted for by applying a nearshore wave model, SWAN. The model accurately estimated H and T and these results were confirmed when compared to the observed H and T (values were recorded at the FRF Research Facility in Duck, NC). The model outputs were incorporated into Holman’s (1986) equations and estimate the extremes in wave runup. The extreme runup was found to be non-uniform alongshore and statistically different for the two study regions.

Observations show links with erosion hotspots and its existing topography. The correlation between runup and two dune parameters (post-storm dune height and change in dune height) was found to be statistically significant for the N.Cape (99% CI) and S.Cape (90% CI) regions. Zones of overwash were shown to be accurately predicted using Sallenger’s (2000) Storm Impact Scale and shows potential to forecast other geomorphologic responses to storm forcing such as defined by the collision and inundation regimes.
Chapter 4
Conclusions

I. Deep Water Wave Models

Three simple, different, predictive wave height equations were compared to data recorded during three 1999 hurricanes. These equations are designed to predict the maximum wave height generated by a hurricane. A validation technique was developed based on $r$, $V_f$, and $Q$ to determine when wave observations were favorable, fair, or unfavorable in observing larger wave heights. The results produced from Young’s equations showed no statistical relationship and greatly deviated from $H$. However, the degree of error was lessened when substituting hurricane force (as determined by the NHC) for the calculated hurricane’s fetch (equation 2-8). Kjerfve’s modeled predictions as well as Hsu_plane and Hsu_sat results show potential to reasonably estimate $H_{\text{max}}$. However, several occurrences greatly underestimated and overestimated $H_{\text{max}}$ and thus, more tests are recommended to further validate the models’ skill. The Hsu_eq equation negates the dependency upon NOAA meteorological observations of $R$ and consequently, more data points were available to be compared to $H$. Overall, this wave height equation produced the most agreeable results and its simple design allows for rapid application. More studies are recommended to further examine the modelers’ equations skill in predicting the maximum deep water wave height generated by a hurricane.

II. Assessing Coastal Change Hazards

The study region was divided due to the differences in the barrier islands...
orientation to the Atlantic Ocean. Specifically, the north-south trending barrier island and east-west trending barrier island were divided at the Cape Hatteras point and are referred to as N.Cape region and S.Cape region. The dune systems for each barrier were statistically shown to be unique to one another. High-profile dune system, where dune elevations on average are high (< 6 m) and vegetation is well developed, describes the N.Cape region’s dune system. In contrast, a low-profiled dune system, were dune heights on average are low (< 5 m) and vegetation was not prolific, characterizes the S.Cape region.

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III. Future Work

Further understanding of the meteorological implications using R as observed from either the AOC/NOAA dropwindsones or satellite imagery may improve the comparisons between H and $H_{max}$. Also, adding storms that move in close proximity to
the wave rider buoy would is recommended to further evaluate the skill in the modeled predictions. For example, on October 3rd, 2002, a Category 4 storm, Hurricane Lili, at its most intense state passed over a wave rider buoy. The buoy remained operable and recorded the wave height. This rare observation would be more representative of the $H_{\text{max}}$ than the data points used in this study and thus, it could provide greater insight in determining which model performs the best.

Despite the predictive skill of Hsu’s model, direct observations of the maximum wave conditions were used as inputs for the nearshore wave model. If wave observations fail (i.e. a buoy becomes inoperable), comparing the nearshore wave model outputs using predicted wave data and observed wave data may prove useful. Thus, testing the skill in using Hsu’s modeled predictions as inputs for the nearshore wave model is recommended for future work.

Comparing two post-storm surveys complicates predicting and assessing dune vulnerability. The 1998 survey was collected approximately 10 days after Hurricane Bonnie, a strong Category 2 storm. This method is poorly designed for numerous reasons. For example, during this interval bulldozers will have already begun pushing the overwash sediment towards the beach in attempt to rebuild the loss dunes. More appropriately, a pre-storm survey should be collected soon before the hurricane.

A constant value was used for the beach slope rather than measured for both study regions. The surveyed beach slope could be extracted using the spatially dense topographic lidar data. A higher resolution bathymetric grid used as an input for SWAN would result in the extreme wave runup values to be more tightly spaced These improvements would significantly improve spatial variations in wave runup. Moreover, the results coupled with the measured topographic dune morphology would allow Sallenger’s (2000) Storm Impact Scale to be more applicable to smaller scaled areas.
References


Elko, N.A.; Sallenger, A.H.; Guy, K.; Stockdon, H.F., and Morgan, K.L. *Barrier Island*


