Alongshore Variations in Foreshore Morphology, Grain Size, and Wave Dissipation at a Shore Line Erosional Hotspot

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Abstract

Accurate prediction of beach response to storms requires synthesizing complex relationships among nearshore hydrodynamics, underlying geology, nearshore bathymetry, beach topography, and sediment characteristics. Previous research on the Outer Banks of North Carolina has correlated the presence of underlying paleo-channels, nearshore heterogeneous sediment, and shore-oblique bars with shoreline erosional hotspots and undulations in the shape of the shoreline (megacusps and embayments on the scale of 1000m). Despite the documented relationships among these features, the morphodynamic link between the persistent nearshore bathymetry, shoreline morphology, and long-term erosion is unknown. This study quantifies the spatial and temporal variations between foreshore topography, slope, grain size, shoreline dissipation width, and maximum runup during an extra-tropical storm along the Kitty Hawk, NC erosional hotspot.

Analysis of topographic data suggests that during the storm the lower foreshore eroded and flattened and the upper foreshore accreted and steepened, with erosion focused on the megacusp horns and embayments. No obvious alongshore patterns exist in mean grain size, and foreshore slope and mean grain size were not related during or after the storm. Foreshore slope, swash dissipation width, and maximum runup were not related after the storm, which suggests that common expected parameter relationships are not applicable in this region of irregular surf zone bathymetry. Results from this study suggest that other parameters, such as alongshore variations in wave setup, should be included in calculations of maximum runup for models of alongshore variability in shoreline erosion in response to storm events.
1. Introduction

Coastal erosion in response to storm events is an expensive and pervasive problem along the world’s coasts. In order to be effective, policy and mitigation strategies must be based on a complete understanding of the whole nearshore system, including the interactions between underlying geology, nearshore bathymetry, incoming wave fields, bar morphodynamics, and foreshore beach response. Dynamic shorelines like the Outer Banks of North Carolina have unexplained erosional hotspots along linear stretches of beach that experience similar wave forcings. Erosional hotspots are defined as areas of shoreline that undergo high net erosion and may also exhibit high variance relative to adjacent regions (McNinch, 2004) (Figure 1).

Figure 1. Erosional Hotspots, Accretional Hotspots, and Hotspots

Diagrammatic illustration of temporal shoreline change at one location, showing variance with net erosion (A: erosional hotspot); variance with net accretion (B: accretional hotspot); and variance with minimal net change (C: hotspot) (McNinch, 2004).
These stretches of beach are often located adjacent to beaches that have lower erosion rates. For example, on a relatively straight stretch of the Outer Banks, the beaches at Kitty Hawk exhibit setback rates of 3.0 to 4.0 feet per year while the beaches at Duck have setback rates of 2.0 feet per year (Division of Coastal Management) (Figure 2).

Figure 2.1 and 2.2. Setback Factors for Kitty Hawk and Duck, North Carolina

Top figure depicts setback rates for Kitty Hawk, NC (3-4 feet per year). Bottom figure depicts setback rates for Duck, NC (2.0 feet per year) (Division of Coastal Management).
These anomalous erosion rates suggest some type of external control on the shoreline besides storm wave forcing. This spatial variability in shoreline change rates has prompted investigation into the mechanisms driving erosional hotspots, so that successful storm damage predictions and policy decisions can be made.

Predicting the response of a beach to storm events is critical for protecting property and lives in the coastal zone. Accurate modeling of beach response to storm events relies on understanding the physical processes that control the spatial variability in shoreline erosion. These physical processes have not been studied extensively, which necessitates research aimed at quantifying the relationship between these processes and shoreline response. Models focused on predicting how the foreshore responds to storm events are necessary to predict shoreline erosion because this zone represents the interface between the ocean and the land. The foreshore is the region where wave forcing removes sediment from the beach and transports it offshore, thus understanding how this region responds to storm events is crucial to predicting shoreline erosion. The results presented in this thesis document how foreshore slope, topography, grain size, and runup change during a storm event at a shoreline erosional hotspot as well as how these parameters relate to each other. The relationships among these parameters suggest that many factors must be taken into account when predicting shoreline response to storm events and that simplified models based on one or two parameters do not accurately explain the spatial variability in shoreline erosion.
2. Background

2.1 Geologic Control in the Nearshore

Alongshore variability in shoreline erosion persists along the Outer Banks of North Carolina. Shoreline erosional hotspots have been observed in Kitty Hawk, NC (List, 2006) and have been spatially correlated with shore-oblique sandbars (McNinch, 2004) (Figure 3).

**Figure 3. Spatial Correlation between Shore Oblique Bars and Shoreline Erosion**

Spatial relationship between offshore bathymetry (alongshore gradient) and heightened shoreline erosion in the Outer Banks of North Carolina. Lower panel depicts bathymetric relief alongshore. Upper panel depicts shoreline change rates. Shaded area shows study site. (McNinch and Miselis, *In Press*).

The shore-oblique bars were discovered using swath bathymetry surveys that mapped more seafloor than previous echosounder surveys (Figure 4).
Swath bathymetry image of the shore-oblique bar field. Warm colors indicate shore-oblique bars and cool colors indicate shore-oblique troughs (McNinch, 2004).

Remote sensing of the bar field over several years using Bar and Swash Imaging Radar (BASIR) (McNinch, 2007) has shown that shore-oblique bars to persist during storm events and over long temporal scales (Brodie and McNinch, 2008). The persistence of these bars is unique given that they are composed of unconsolidated sediment and exposed to high wave energy conditions, suggesting that the underlying geology is exerting a control on bar stability (Browder and McNinch, 2006). This situation differs from the traditional shore-parallel bar system that forms in response to storm events moving sand offshore, but is destroyed as the beach recovers from storm events. The potential for an offshore-buried feature to exert a control on nearshore morphodynamics
contradicts the previously held idea that shoreface slope and bedforms respond only to wave energy and mean sediment size (Pilkey et al., 1993; Komar, 1998).

Underlying the shore-oblique bars is the paleo-Roanoke-Albemarle fluvial system (Browder and McNinch, 2006). This paleo-channel system was observed using a Chirp sub-bottom profiler, which allowed for identification of the spatial relationship between the shore-oblique bars and the paleo-channels and channel fill (Figure 5).

**Figure 5. Sub-bottom Profile of Paleo-channel off of Kitty Hawk, NC**

Chirp cross-section of a nearshore channel in Kitty Hawk, NC. Potentially the main thalweg of the paleo-Roanoke-Albemarle fluvial system (Browder and McNinch, 2006). The width of the paleo-channel appears to be the dominant factor in correlating the presence of paleo-channels to shore-oblique bar formation (Browder and McNinch, 2006). Seismic data from oblique bar fields suggests that older strata were reworked from river downcutting during Pleistocene sea level regression. Several potential mechanisms exist for the spatial relationship between shore-oblique bars and paleo-channels, which include modification of the hydrodynamic environment by submarine groundwater discharge and exposure of coarse channel fill and subsequent self-organization of bedforms (Browder and McNinch, 2006).
Shore-oblique bars offshore of the Outer Banks are large features with relief up to 3m and widths of several kilometers (Schupp et al., 2006). Gravels from the Pleistocene-river channels crop out in the troughs of the shore-oblique bars with a thin layer of sand overlying the gravels on the bars (Schupp et al., 2006). The location of these gravel outcrops is relatively stable over time and are strongly related to shore-oblique bar morphology, suggesting that the gravel exposures are expressions of the underlying strata rather than random deposits (Schupp et al., 2006). Gravel outcrops exhibit similar shape and movement to the troughs; for example, troughs that are wide in the longshore direction and shorter in the cross-shore will be associated with wider, shorter gravel exposures (Schupp et al., 2006).

Shore-oblique bars, represented by an alongshore-steepness metric have been correlated with shoreline change (McNinch and Miselis, in press). Areas of increased shoreline erosion spatially correlate with shore-oblique bars offshore. Kilometer-scale megacusps and embayments are temporally persistent and correlate spatially with shore-oblique bar crests and troughs, respectively (Brodie and McNinch, 2008) (Figure 6).
Spatial relationship between offshore bathymetry (top panel) and shoreline morphology (bottom panel), Brodie and McNinch, 2008.

The spatial relationships between the shore-oblique bars and shoreface behavior are well documented, but the physical processes that relate nearshore bathymetry to shoreline response are not well understood. Future work aimed at understanding these physical processes is vital in understanding shoreline response to storm events in areas with irregular surf zone bathymetry.

2.2 Alongshore-Variable Shoreline Change

One of the fundamental goals of coastal science is to predict the shoreline response to storm events in a variety of beach environments. The general response of the beach to storm events is well understood, but explanations are still needed for alongshore variability in erosion. As wave energy increases during storm events, the beach flattens from a reflective profile to a more dissipative profile in order to dissipate the increased wave energy (Komar, 1998). This flattening of the profile allows for the waves to dissipate over a larger area, thus reducing the potential for storm erosion.
The interface between the waves and the beach lies in the swash zone, suggesting that understanding the processes in this zone is crucial for predicting shoreline response to storm events. During a storm event, greater breaking wave energy increases the mean water level above the still water-level producing wave set-up (Masselink et al., 2003). As the waves break against the shoreface, the energy is dissipated as potential energy in the swash zone as runup, which is the time-varying location of the shoreline water level about the still-water level (Holman and Sallenger, 1985). Wave runup is important for coastal planners, nearshore oceanographers, and coastal engineers because it is this motion that delivers much of the energy responsible for dune and beach erosion (Ruggiero et al., 2001; Sallenger, 2000).

Attempts have been made to model alongshore spatial variability in shoreline erosion using simple models based on comparing the elevation of maximum runup to beach and dune topography (Sallenger, 2000). This model defines four storm-impact regimes (swash, collision, overwash, and inundation) based on the relationship between beach topography (elevation of the berm and dune) and storm-induced water levels (Stockdon et al., 2007). Storm-induced water levels are defined as the sum of astronomical tide, storm surge, wave setup, and wave runup (Sallenger, 2000).

Stockdon et al (2007) provided a test of the Sallenger storm-impact scaling model, in which runup maxima are estimated based on deep-water wave height ($H_o$), wave period ($T_o$), and the foreshore beach slope ($\beta_f$) and can be calculated using the 2% exceedence level for runup. In this model test, foreshore slope is thought to be the primary control on alongshore variability in runup maxima because the other parameters $H_o$ and $T_o$ are unlikely to vary as much as $\beta_f$ alongshore. Using this parameterization,
Stockdon et al concluded that Sallenger’s model correctly predicts the overall hurricane-impact regime 55.4% of the time, but the model sensitivity varied widely between regimes (Stockdon et al, 2007). The model most accurately predicted the response for the overwash regime (87%), but poorly predicted the responses for the collision and swash regimes (55.8% and 1.5%). This poor prediction was almost always manifested in overprediction of the regime and is likely due to oversimplification of model inputs.

Results like these suggest that models of spatial variability in shoreline erosion must take into account many processes and parameters that are at work in this dynamic setting. Shoreface parameters, such as foreshore morphology, foreshore slope, mean grain size, and maximum runup as well as offshore parameters, such as nearshore bathymetry and wave energy changes during storm events must be incorporated into models in order to make accurate predictions of beach response to storm events.

3. Questions and Expected Relationships

This thesis presents results that build on our current understanding of the relationships and responses between foreshore parameters during storm events. Understanding these relationships can offer important clues regarding the physical processes that may link nearshore bathymetry to shoreface response. Specifically, the questions asked in this thesis are:

- What are the spatial and temporal relationships among foreshore slope, grain size, wave runup, and morphology during a storm event?
- Do these parameters account for the alongshore variation in observed maximum runup?
The expected relationships between these parameters are generally understood in areas with homogenous sediments, but are not well documented on beaches with heterogeneous sediments. As foreshore slope flattens, it is generally expected that mean grain size will fine, while foreshore steepening will result in a coarsening of sediment (Wiegel, 1964) (Figure 7).

**Figure 7. Common Relationship between Foreshore Slope and Mean Grain Size**

Paradigm relationship between foreshore slope and mean grain size. As foreshore slope flattens grain size fines and as foreshore slope steepens grain size coarsens. (Wiegel, 1964).

Flat shoreface slope and finer mean grain size also are expected to correspond with embayments, whereas steeper slopes and coarser grain sizes correspond with the horns of megacusps. Maximum runup and shoreline dissipation width are also expected to vary based on foreshore slope, morphology, and grain size. Greater maximum runup and shoreline dissipation width are expected on the flatter slopes, and finer mean grain size of embayments and lower maximum runup and dissipation width are expected on the steeper slopes and coarser mean grain size of megacusp horns.
4. Study Area

4.1 Physical Setting

The Outer Banks of North Carolina are a predominantly linear barrier island system that is generally oriented NNW-SSE and is storm and wave dominated (Schupp et al., 2006; Browder and McNinch, 2006) (Figure 8).

Figure 8. Study Site Location

Study site in Kitty Hawk, NC along the Outer Banks of North Carolina (McNinch, 2004)
The majority of storm events are extratropical and occur during the fall and winter with a dominant northeast wave direction (Browder and McNinch, 2006). The beaches exhibit the traditional dissipative profile during the winter and a broader, reflective profile during the summer. The section of the Outer Banks near Kitty Hawk, NC is microtidal (Hayes, 1979) with a mean tidal range of 0.97 m (Birkemeier at al., 1985). The beaches of the Outer Banks are relatively straight and steep (1:10) with a planar (1:500) offshore region (Holland et al., 2001). The linearity of the Outer Banks is punctuated in certain areas by tidal inlets that breach the barrier islands. Rhythmic shoreline topography is evident along the Outer Banks ranging from meter to kilometer scale and has been linked to variations in nearshore morphology.

4.2 Geologic Setting

The Outer Banks of North Carolina are underlain by Quaternary strata that slopes to the E-SE (Riggs et al., 1992; Boss et al., 2002). These strata are overlain by a thin layer of Holocene sands that thins seaward and southward (Riggs et al., 1995; Rice et al., 1998). The Quaternary strata are cut by a series of Pleistocene paleo-fluvial systems that were back filled by Pleistocene and Holocene sediments during rising sea level (Browder and McNinch, 2006). Surficial sediments along this stretch of the Outer Banks are bimodal with a mixture of medium quartz sand and small pebbles that progressively fine offshore (McNinch, 2004).
5. Methods

5.1 Real-Time Kinematic Global Positioning System (RTK-GPS) Topographic Surveys

Real-Time Kinematic Global Positioning System (RTK-GPS) surveys were used to analyze spatial and temporal changes in shoreline morphology and slope along a 4 km stretch of beach in Kitty Hawk, NC during a nor’Easter that occurred in late February and early March of 2009 (Figure 9). The accuracy of RTK-GPS surveys was necessary in order to derive the subtle changes in beach topography. All surveys were conducted at low tide in order to survey as much of the swash zone as possible. The surveys were completed using an all-terrain vehicle (ATV) equipped with a RTK-GPS system. Alongshore survey lines were spaced approximately every 5 meters and ranged from the swash line to the berm break. Cross-shore lines were spaced approximately every 50m along the 4km stretch of beach. Tie lines between cross-shore lines were used to gain more foreshore coverage.

Figure 9. Wave Data for February-March Nor’Easter

Figure depicts wave data for surveys. Dates are plotted on the x-axis and wave height (m) is plotted on the y-axis. The blue curve represents the significant wave height in 8m water depth and the red lines represent survey dates. The break in data represents a loss of communication with the 8m wave buoy.
5.2 Grain Size Sampling

Sediment sampling was conducted in conjunction with the RTK-GPS surveys in order to analyze the spatial and temporal changes in mean grain size. Grab samples were taken approximately every 50m along the foreshore in the swash zone and at the berm break. Samples were run through a Rapid Sediment Analyzer (RSA), a settling column used to determine grain size, and processed using a Matlab script that provides descriptive statistics such as mean, standard deviation, and d50 as well as weight percentage and cumulative weight percentage histograms. Sediment composition was also analyzed for differences in sorting and rounding.

5.3 Bar and Swash Imaging Radar (BASIR)

Bar and Swash Imaging Radar (BASIR), a mobile x-band radar system, was used to analyze the spatial and temporal changes in maximum runup and shoreline dissipation width. BASIR is able to resolve these parameters by mapping the reflections from breaking and dissipating waves. It is particularly useful in this study because it can be used easily during storm events in areas where traditional time-lapse images (i.e. ARGUS camera images) cannot be compiled. BASIR data was collected for the last two days of the storm, which provides data for post-storm recovery. The position of the maximum-runup defined shoreline and ocean-side of the swash edge was digitized from the BASIR time-averaged data and used to calculate swash zone width. The elevation of maximum runup was found by interpolating the RTK-GPS beach topography data at the location of the digitized maximum runup line. If the position of maximum runup did not intersect the extent of foreshore topography data collected, the elevation was extrapolated using...
the mean foreshore slope at that cross-shore position and the most seaward recorded data point.

6. Results

6.1.1 Topography Data

The RTK-GPS topographic surveys allowed for analysis of the topographic changes to the beach during a nor’Easter from February 28 to March 3, 2009. Little erosion occurs from the pre-storm to first storm day survey (Figure 10). The erosion that does occur during this period is focused in the embayment in the southern portion of the study area. During this period accretion occurs on the upper foreshore throughout the entire study area. Between the first and second day of the storm erosion begins to occur throughout the entire study site (Figure 10). Erosion occurs on both the lower foreshore and upper foreshore, but mild steepening appears to occur on the seaward edge of the foreshore. High erosion occurs in the southern embayment and megacusp both on the lower and upper foreshore. From the second to third day of the storm, erosion occurs on the lower foreshore throughout the study site, while the upper foreshore does not experience much change in the northern and mid-sections. The upper and lower foreshore exhibits high erosion in the southern embayment. Shoreline erosion occurs throughout the entire study site with locally higher amounts on the megacusp horns and in the embayments (Figures 11 and 12). Overall, the lower foreshore erodes and the upper foreshore accretes throughout the entire study site from pre to post storm (Figure 13 and 14). Higher amounts of erosion occurred on the megacusp horns and in the embayments, with the most erosion occurring in the southern embayment (Figure 14).
Figure 10. Daily Foreshore Topography Change

Topography data for pre-storm to first day (top), first day to second day (middle), and second day to post-storm (bottom). Topography data was collected using RTK-GPS topographic surveys. X-axis denotes distance alongshore (m) from north (3000) to south (7500) and y-axis denotes cross-shore distance (m). Warm colors indicate accretion of the beach and cool coolers indicate erosion. Northern
Figure 11. Foreshore Profile on Megacusp

Cross-section depicts pre-storm (blue line) to post-storm (green line) profile changes on a megacusp. Cross-shore distance (m) is represented on the x-axis and elevation (m) is represented on the y-axis. Accretion occurs on the upper foreshore and erosion occurs on the lower foreshore.

Figure 12. Foreshore Profile on an Embayment

Cross-section depicts pre-storm (blue line) to post-storm (green line) profile changes on an embayment. Cross-shore distance (m) is represented on the x-axis and elevation (m) is represented on the y-axis. Accretion occurs on the upper foreshore and erosion occurs on the lower foreshore.
Figure 13. Pre-storm to Post-Storm Shoreline Morphology

Shoreline morphology for pre-storm (blue curve) and post-storm (red curve) surveys. Profiles indicate higher erosion on the megacusp horns and in the embayments. Alongshore distance (m) is represented on the x-axis and cross-shore distance (m) is represented on the y-axis.

Figure 14. Foreshore Topography Change Pre to Post Storm

Topography data for pre-storm to post-storm. Topography data was collected using RTK-GPS topographic surveys. X-axis denotes distance alongshore (m) and y-axis denotes cross-shore distance (m). Warm colors indicate accretion of the beach and cool colors indicate erosion.
6.1.2 Slope Change Data

RTK-GPS topographic surveys were used to analyze slope changes during the nor’Easter. Slope change varies alongshore during the course of the storm. There is significant flattening of the lower foreshore in the northern sections from the pre-storm survey to the first day (Figure 15). From the pre-storm to first day the southern embayment flattens, but not as much as the northern sections. The entire study site experiences significant flattening from the first day to second day of the storm (Figure 15). The highest flattening occurs on the megacusp horns and in the embayments. Along the study site it appears that the lower foreshore flattens more than the upper foreshore during these days. From the second to third day of the storm the beach begins to steepen (Figure 15). Steepening occurs mostly on the lower foreshore, while flattening continues to occur on the upper foreshore. From pre-storm to post-storm the southern embayment appears to steepen during the storm, while the northern embayment and cusp horn flatten. Overall, the response of the beach from pre to post storm was a general flattening of the lower foreshore and steepening of the upper foreshore (Figures 11, 12, and 16)
Figure 15. Foreshore Slope Daily Change

Slope change data for pre-storm to first day (top), first day to second day (middle), second day to post-storm (bottom). Slope change data was calculated using RTK-GPS topography data. Alongshore distance (m) is represented along the x-axis and cross-shore distance (m) is represented along the y-axis. Warm colors indicate flattening of the beach and cool colors indicate steepening of the beach.

Figure 16. Slope Change Pre to Post Storm

Slope change data for pre-storm to post-storm showing overall flattening of the lower foreshore and steepening of the upper foreshore. Slope change data was calculated using RTK-GPS topography data. Alongshore distance (m) is represented along the x-axis and cross-shore distance (m) is represented along the y-axis. Warm colors indicate flattening of the beach and cool colors indicate steepening of the beach.
6.1.3 Grain Size

During-storm and post-storm sediment samples (March 1 and 3, 2009) show significant alongshore variations in sample means and d50 (Figures 17 and 18). The standard deviation does not vary significantly alongshore for both surveys, which suggests that sediment sorting does not vary greatly alongshore (Figures 17 and 18). Despite alongshore variations in sample means no alongshore patterns with respect to morphology or location along the study site are apparent. For the during-storm survey, there appears to be more gravel at the southern portion of the study site, which is consistent with observation of the beach during surveying (Figure 17).

Figure 17. During-storm Grain Size Data

![Figure 17. During-storm Grain Size Data](image)

Mean grain size with error bars indicating +/- 1 standard deviation and d50 for the during-storm survey calculated from sediment grab samples taken ~50m alongshore. Alongshore distance (m) is represented on the x-axis and grain size (psi) is represented on the y-axis. Blue stars indicate grain size, blue bars indicate 1 standard deviation, red circles/line indicate d50, and green triangles indicate percent gravel.
6.1.4 Swash Dissipation Width and Maximum Runup Elevation

During-storm BASIR surveys (March 2, 2009) demonstrate significant alongshore variability in swash zone dissipation width and maximum runup (Figure 19). These parameters become highly variable at the southern portion of the study site. The majority of the swash zone dissipation widths lie within the range of 50m to 100m. The swash dissipation width is lower at the northernmost portion of the study site as well as in the southern portion. A shore-parallel bar welds onto the shoreline on the horn of the first megacusp, causing the shoreline dissipation width to increase greatly, but has no obvious effect on maximum runup. Maximum runup generally lies within the range of 1m to
1.5m. Maximum runup potentially decreases in the southern portion of the study site, but the magnitude of this change could be affected by extrapolation of sample data.

**Figure 19. Swash Zone Dissipation Width and Maximum Runup for March 2, 2009 BASIR survey**

Top panel shows during-storm topography data (warm colors indicate higher elevations and cool colors indicate lower elevations) and maximum runup elevation digitized from BASIR. The middle panel shows swash zone dissipation width alongshore. Bottom figure shows maximum runup elevation alongshore. Alongshore distance is represented on the x-axis and cross-shore distance is represented on the y-axis for all figures. Figure courtesy of Kate L. Brodie.

Data from the post-storm (March 3, 2009) BASIR surveys suggest that maximum runup elevation and swash dissipation width vary greatly alongshore (Figure 20). Despite this alongshore variation in maximum runup elevation and swash dissipation width there are no obvious alongshore trends. The inner surf-zone morphology varies greatly alongshore: a shore parallel bar moves onshore at ~4500m and welds to the beach.
at ~6000m. This appears to increase the shoreline dissipation width, but maximum runup elevation does not change and remains variable alongshore.

**Figure 20. Post-storm Shoreline Dissipation Width and Maximum Runup Elevation**

Top figure depicts foreshore topography and maximum runup elevation determined through RTK-GPS topography data and BASIR images. Warm colors are higher elevations and cool coolers are lower elevations. Upper middle figure is a digitized schematic of the shoreline and surf zone configuration. Lower middle shows the foreshore slope and shoreline dissipation width alongshore as calculated from RTK-GPS topography data and BASIR images. Bottom figure shows foreshore slope and maximum runup elevation alongshore calculated from RTK-GPS topography data and BASIR images. Figure courtesy of Kate L. Brodie.

**6.2 Parameter Relationship Results**

**6.2.1 Foreshore Slope to Shoreline Morphology**

Comparison of the foreshore slope to shoreline morphology for the post-storm (March 3, 2009) survey suggests a relationship between the two parameters (Figure 21). Embayments correspond with steeper slopes, while the megacusps correspond with flatter slopes. There appears to be an alongshore lag towards the southern section of the study site, where the slope change lags behind the morphology change.
Comparison of foreshore slope to shoreline morphology for post-storm (March 3, 2009) survey. Distance alongshore (m) is represented on the x-axis, foreshore slope is represented on the left y-axis, and cross-shore distance (m) is represented on the right y-axis. The blue curve represents shoreline morphology at the 1m contour and the green curve represents the 200m smoothed foreshore slope.

### 6.2.2 Foreshore Slope to Grain Size

Foreshore slope and grain size data from the during-storm survey and post-storm surveys suggest that there is no relationship between the two parameters (Figures 22 and 23). For any given slope, a variety of grain sizes are observed. A regression analysis returned an r-squared value of 0.0035 for the during-storm survey and 0.003 for the post-storm survey, which further indicates the lack of a relationship between the two parameters.
Figure 22. Relationship between Foreshore Slope and Mean Grain Size: During-Storm

Comparison of foreshore slope to mean grain size for the during-storm survey. Grain size (psi) is represented on the x-axis and foreshore slope is represented on the y-axis.
Figure 23. Relationship between Foreshore Slope and Mean Grain Size: Post-Storm

Comparison of foreshore slope to mean grain size for the post-storm survey. Grain size (psi) is represented on the x-axis and foreshore slope is represented on the y-axis.

6.2.3 Shoreline Morphology to Mean Grain Size

Data from the post-storm survey suggests a possible relationship between shoreline morphology and mean grain size (Figure 24). The relationship is strongest in the northern section of the study site, where finer sediments are located in the embayment and coarser sediments are located on the megacusp. This relationship still exists in the southern section of the study site, but is less pronounced. Standard deviation does not appear to vary alongshore with respect to morphology, which suggests that the degree of sediment sorting does not vary significantly alongshore.
Comparison of shoreline morphology to grain size for the post-storm survey. Alongshore distance (m) is represented on the x-axis, cross-shore distance (m) is represented on the left y-axis, and grain size (psi) is represented on the right y-axis. Dark blue bars represent raw data for mean grain size. Dark blue curve represents mean grain size smoothed alongshore. Light blue curve represents standard deviation. Dark green curve represents smoothed shoreline position. Light green curve represents raw shoreline position.

6.2.4 Swash Dissipation Width to Foreshore Slope

During-storm BASIR and topographic surveys suggest that there is a relationship between swash dissipation width and foreshore slope (Figure 25). This relationship is relatively weak with an r-squared value of 0.4141. It appears that as foreshore slope flattens, shoreline dissipation width increases. Swash zone dissipation exhibits a wide range of widths throughout the study site, which range from around 10m to around 100m.
Comparison of shoreline dissipation width to foreshore slope for March 2, 2009 during-storm survey. Shoreline dissipation width was calculated using Bar and Swash Imaging Radar (BASIR) and foreshore slope was determined using RTK-GPS topography data. R-squared value - 0.4141.

The post-storm BASIR and topographic surveys suggest that there is no relationship between swash dissipation width and foreshore slope (Figure 26). For any given slope there is a wide range of swash dissipation widths that are observed. The majority of swash dissipation widths that are associated with the foreshore fall around 20m. A portion of the swash dissipation width data represents dissipation over the inner bar and foreshore where the bar welded to the shoreline, and thus does not represent dissipation over the beach (Figure 26).
Figure 26. Relationship between Post-storm Swash Dissipation Width and Foreshore Slope

Comparison of swash dissipation width to foreshore slope for post-storm survey. Swash dissipation width was calculated using Bar and Swash Imaging Radar (BASIR) and foreshore slope was determined using RTK-GPS topography data. Green points indicate embayment samples and blue points indicate megacusp samples. R-squared value - 0.0538.

6.2.6 Maximum Runup to Foreshore Slope

During-storm BASIR and topographic surveys suggest that there is a relationship between maximum runup and foreshore slope (Figure 27). This relationship is relatively weak with an r-squared value of 0.1119. The general trend appears to be higher runup elevations on flatter portions of the beach. This relationship appears to be independent of morphology, which is suggested by the lack of marked differences in maximum runup elevations between the megacusps and embayments. Most runup elevations, both in embayments and on megacusps, fall between 1m and 1.5m. Maximum runup elevations for the embayments appear to be more tightly clustered than the megacusp elevations.
indicating that the embayments are characterized by less variation in slope and maximum runup elevation than the megacusps.

**Figure 27. Relationship between During Storm Maximum Runup and Foreshore Slope**

Comparison of maximum runup to foreshore slope for during storm survey. Maximum runup elevation was calculated using Bar and Swash Imaging Radar (BASIR) and foreshore slope was determined using RTK-GPS topography data. Green points indicate embayment samples and blue points indicate megacusp samples. R-squared value- 0.1119

Post-storm BASIR and topographic survey data suggest that there is no relationship between maximum runup and foreshore slope (r-squared value of 0.0029) (Figure 28). For a given slope there are a wide variety of maximum runup elevations. The post-storm data does not exhibit the differences in megacusp and embayment maximum runup elevations. Most of the maximum runup elevations for both embayments and megacusp range from 0.2m to 1.4m, which span a much larger range than the during storm elevations. Embayment samples are no longer tightly clustered and exhibit a similar range to the megacusp samples.
Comparison of maximum runup elevation to foreshore slope for post-storm survey. Maximum runup elevation was calculated using Bar and Swash Imaging Radar (BASIR) and foreshore slope was determined using RTK-GPS topography data. Green points indicate embayment samples and blue points indicate megacusp samples. R-squared value- 0.0029.

7. Discussion

Previous research in Kitty Hawk revealed that spatial heterogeneities in nearshore sediments were correlated with the presence of an underlying paleo-channel (Browder and McNinch, 2006). These heterogeneous sediments have been correlated with nearshore shore-oblique sand bars, which are hypothesized to form from self-sorting and organization (Browder and McNinch, 2006; Miselis and McNinch, 2006). Specifically, underlying strata composed of fluvial gravel infill was found to be exposed in the troughs, while more typical beach sand was found on the bars (Browder and McNinch, 2006). This bimodal sediment distribution has also been found to persist on the beach itself in Kitty Hawk, and is spatially variable in both the horizontal and vertical directions.
(Browder and McNinch, 2006). The shore-oblique bar field has also been spatially correlated with both shoreline erosional hotspots and persistent shoreline megacusps and embayments (McNinch, 2004; Brodie and McNinch, 2008). These relationships are well documented, but it is not well understood: (1) how the hotspots explicitly change during storm events; (2) if and how the irregular nearshore bathymetry and distribution of heterogeneous sediments on the beach influence beach slope and behavior; and (3) how beach slope and grain size variations influence runup and dissipation during a storm event, two factors likely to contribute to the hotspot type erosion.

The RTK-GPS topography data was used to identify specific changes in elevation and slope along the shoreline hotspot during a storm event. The topographic data for this storm demonstrates a typical beach response to a storm event. As the waves build, accretion occurs on the upper foreshore as sediment is moved from the upper beach seaward. As the storm progresses, erosion begins to occur throughout the entire study site as sediment is moved offshore, but is focused in the embayments. This embayment-focused erosion is consistent with current models that suggest during-storm pressure-driven currents converge in the embayments, driving erosion, and flow down and seaward through the troughs (McNinch and Brodie, 2008). While erosion was focused in the embayments, the evolution of foreshore slope was similar for both the embayments and megacusps. The lower foreshore flattened throughout the entire study site, which is the expected response of the beach to storm events. In contrast, the upper foreshore steepened, perhaps due to sediment being moved from the upper beach and deposited on the upper foreshore. The southern embayment-megacusp system responded slightly differently, as the foreshore slope seemed to steepen during the storm and increased
erosion was also present. This could potentially be due to an inner bar welding to the shoreline, which altered the beach response in this region.

Grain size, foreshore slope, and shoreline morphology data were used to understand if and how the irregular surf zone bathymetry and the distribution of heterogeneous sediments on the beach influence foreshore slope and behavior. There appears to be a general trend between foreshore slope and shoreline morphology: embayments are steeper and megacusp horns are flatter. This trend does not follow the typical relationship between slope and morphology where embayments are flatter and megacusps are steeper (Komar, 1998). Instead, the steeper embayments appear to be a continuation of the surf-zone bathymetry onto the beach, such that both the surf zone and beach are steeper in the trough/embayment regions and flatter in the bar/megacusp regions. Irregular surf-zone bathymetry is clearly influencing general trends in beach slope and morphology, but these trends may be locally complicated by inner surf zone morphology, such as an inner bar welding to the shoreline. For example, a spatial lag between foreshore slope and shoreline morphology exists in the southern section and is characterized by foreshore slope lagging behind shoreline morphology in the southern alongshore direction. This lag only exists onshore of the region where the inner bar welds to the shoreline in the southern portion of the study site.

There also appears to be a general trend between shoreline morphology and mean grain size: finer grains are located in embayments and coarser grains are located on megacusp horns. This relationship is important because the fine grains located in the embayments could be subjected to scouring from the proposed during-storm erosive embayment currents, potentially exposing underlying coarser sediments. Scouring
processes could also introduce a temporal lag that may alter the expected relationship between foreshore slope and mean grain size, in which the foreshore slope does not adjust instantaneously to newly exposed sediment characteristics. No relationship between foreshore slope and grain size was found, contradicting the expected relationship of finer grains being located on flatter slopes and coarser grains on steeper slopes. This suggests that on beaches with both horizontally and vertically mixed sediment, foreshore slope and grain size may not be directly correlated.

Runup and dissipation are generally considered to be dependent on factors such as foreshore slope, grain size, and shoreline morphology, and are ultimately responsible for driving beach erosion. Current models of storm-induced alongshore variable erosion are based on the relationship between beach topography and runup elevation, the later predicted using foreshore slope as the main control on alongshore variations in runup elevation (Stockdon et al., 2007). Shoreline dissipation width and maximum runup elevation are expected to be higher in areas with flatter foreshore slopes.

The relationships among foreshore slope, shoreline dissipation width, and maximum runup suggest that the irregular surf zone bathymetry is exerting a control on beach response during storms through alongshore variations in wave energy. In this region of irregular surf zone bathymetry we would expect to see greater dissipation width and higher maximum runup elevations in areas with flatter slopes, which was the during-storm observed response: during the storm, a weak positive relationship was observed between both foreshore slope and dissipation width ($R^2 = 0.4$) and foreshore slope and maximum runup ($R^2 = 0.1$). As wave energy decreases following a storm event, the irregular surf zone bathymetry exerts less of a control on shoreline dissipation width and
maximum runup. Embayments and megacusps were observed to have similar shoreline dissipation widths after the storm, suggesting that after a storm, or during the waning portion of the storm, the beach is flattened in a similar way alongshore, allowing for similar shoreline dissipation widths. There also was no observed relationship between foreshore slope and maximum runup post-storm. The lack of relationship between post-storm foreshore slope, shoreline dissipation width, and maximum runup, may result from local alongshore variable controls, such as foreshore slope, grain size, and inner surf zone morphodynamics. This suggests that explaining alongshore variability in maximum runup in terms of variations in foreshore slope may not be the most robust explanation in areas with irregular surf zone bathymetry.

These results suggest that models like Stockdon et al (2007) need to be revised for areas with irregular surf zone bathymetry. Important parameters for this model, such as maximum runup and foreshore slope, do not appear to be consistently related in this region. The relationship between shoreline morphology and foreshore slope, foreshore slope and shoreline dissipation width, and the lack of relationship between foreshore slope and mean grain size, suggest that other parameters must be incorporated into this model. Offshore features, such as shore-oblique bars, may be exerting a control on the shoreline that overwhelms smaller scale relationships, leading to results that differ from the expected response. Therefore, it seems unlikely that current storm-response prediction models will work in these locations because wave energy and beach characteristics are strongly controlled by irregular surf-zone and nearshore (0 to 10m water depth) bathymetry. Including more parameters, such as a metric for alongshore
variable setup in response to irregular nearshore bathymetry, into the model for storm-
response is necessary for accurate predictions of beach response.

8. Conclusion

Results from this study suggest that other parameters, such as alongshore
variations in wave setup over irregular nearshore bathymetry, need to be included in the
prediction of maximum runup for models of alongshore variability in shoreline erosion in
response to storm events. The lack of a relationship between foreshore slope and mean
grain size and between post-storm foreshore slope and swash dissipation width and
maximum runup suggest that the common expected parameter relationships are not
applicable in this region of irregular surf zone bathymetry. Alongshore variability in
parameter relationships is likely controlled by irregular surf zone bathymetry, which is
currently unaccounted for in the previously mentioned models, but that this control can
be locally overruled by inner surf zone morphology, such as a shore-parallel bar welding
to the shoreline. Sampling interval and data collection methods must also be considered
with regard to spatial and temporal resolution of parameter relationships. Accurate
modeling of beach response to storm events depends on collection of accurate parameter
data that relates nearshore bathymetry to shoreface response.
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10. References


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