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Comparison of Beach Changes Induced by Two Hurricanes along the Coast of West-Central Florida

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Comparison of Beach Changes Induced by Two Hurricanes along the Coast of West-Central Florida

by

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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science
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DEDICATION

To my eternally supportive parents, Jiayong and Shuo,

my grandparents, Fuhan and Shichen,

my aunts and the friends who have been

by my side through every challenge and triumph
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I would like to thank my major professor Dr. Ping Wang for his advice during the entire process. He guided me to complete this thesis. During the last two years, he has given me a lot of encouragements in my course and thesis work. He has always been there whenever I needed advice and suggestions. I also want to thank Dr. Jun Cheng. He has given me a lot of ideas to explore during my thesis research. I would like to thank my committee members Dr. Philip Van Beynen and Dr. Ruiliang Pu for their insightful and helpful suggestions. I would also like to thank my lab members Zachary Westfall, Denise Davis and Mathieu Vallée who have been my supportive colleagues and friends. They have collected the field data, which I have used in this thesis. And last, I would like to especially thank my parents for their love and support. I would never be who I am without their hard work and 24 years of education they provided for me.
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ABSTRACT

The beach profiles pre-and post-the Hurricane Hermine (2016) and Irma (2017) along the Sand Key barrier island were collected to quantify longshore variations in storm induced beach changes as well as to compare the beach changes caused by hydrodynamic conditions of the two different hurricanes.

Cross-shore beach profile are examined in 4 sections including dune field, dry beach, sand bar and whole beach to calculate beach change. The volume change for each section and shoreline contour change before and post the hurricane was computed. Hydrodynamic conditions were obtained from adjacent NOAA’s tide and wave gauges.

Both hurricanes generated high offshore waves, with Hurricane Hermine generated waves mostly from southwest, and Irma generated waves dominantly from northeast. Hurricane Hermine generated a storm surge of up to 1 m. While hurricane Irma generated negative surge of -1.1 m.

Several beach profile parameters such as the foreshore slope, as well as volume changes of dune field, dry beach and sand bar induced by the two hurricanes were computed. Under both storms, the foreshore slope became steeper after the storm north of the headland, while the foreshore slope became gentler south of the headland. Storm surge plays an important role in
inducing beach erosion. Hurricane Hermine with 1 m surge caused significant dune erosion in terms of dune volume loss and dune line retreat. On the other hand, hurricane Irma with negative surge only caused minor dune erosion. Sand bar moved seaward during both hurricanes, with Irma induced a much greater offshore movement than that of Hermine. In addition, the sand bar height decreased significantly during Irma. In contrast, during Hermine the sand bar height remained largely similar before and after the storm.

Large alongshore variations in beach erosion was observed during both hurricanes as influenced by background erosion rate and direction of incident waves as they approaching the curved shoreline. For both storms, the erosional hot spot at North Sand Key with the highest background erosion rate suffered the most sand loss over the entire profile. More sand was eroded from the dry beach along the broad headland than along the beaches both north and south of it. Corresponding to the higher volume of dry beach erosion, shoreline retreat was also the largest around the headland. During Hurricane Hermine, the headland sheltering of the southerly approaching waves resulted in more erosion to the south than to the north. The opposite happened during Hurricane Irma with northerly approaching wave. More erosion occurred to the north of the headland than that to the south. Systematic measurement of beach profile beach and after hurricanes can improve our understanding on beach morphodynamics on storm induced beach changes.
Chapter 1: INTRODUCTION

Almost 66.7% of the world population live within sixty-kilometers of the shoreline (UN Atlas of the Oceans: Facts, 2018). Beaches make a large contribution to America’s economy. In 2014, the coastal states (there are thirty coastal states bordering the Pacific, Atlantic, Gulf of Mexico and the Great Lakes) comprised 57% of the U.S. land area but more than 82% of the population and economy (Kildaw, 2016). In general, Coastal states receive about 85% of tourist-related revenues in the U.S. largely because beaches are tremendously popular (World Almanac, 2007). Within the coastal states, the 445 counties within the Coastal Zone Management Program as defined by the individual states (aka, coastal zone counties), account for 48% the U.S. GDP (Kildaw, 2016). The 357 counties immediately adjacent to the shore, including the large number of cities in shore adjacent counties, contributed 43% percent of the U.S. GDP (Kildaw, 2016). The coastal zone counties accounted for 42% of the U.S. employment and the shore adjacent counties contained 37% of both U.S. employment and population (Kildaw, 2016).

Beaches plays an essential role in the economy of the State of Florida. For example, Miami Beach reported more tourist visits (21 million) in 2007 than any National Park Service property (National Park Service, 2007). Miami Beach has more than twice as many tourist visits as the combined number of visits to Yellowstone (2.9 million), the Grand Canyon (4.3

Beaches are among the most dynamic environments on the earth surface and change rapidly and complicatedly in space and time. Shoreline delineates the margin of the land and the sea and it is constantly changing. Beach erosion can occur at a range of timescales. Individual storms will generally result in rapid short-term erosion, followed by short-term beach recovery. If sediment deficiencies persist for long periods of time (e.g. due to longshore gradients in sediment transport, reduction of fluvial sediment supply to the coast), chronic erosion can result. Based on Luijendijk et al. (2018), 24% of the world’s sandy beaches are persistently eroding at a rate exceeding 0.5 m/yr over the period from 1984 to 2016, particularly in marine protected areas. Domestically, approximately 86% of U.S. East Coast barrier beaches (excluding evolving spit areas) have experienced erosion during the past 100 years (Galgano et al., 2004). There are many mechanisms that contribute to beach erosion including, sea-level rise, scarcity of available sediments, storm impacts, beach and inlet interactions, and human activities. Between 80 and 90% of the American open-ocean shoreline is retreating in a landward direction because of sea-level rise and coastal erosion (Bush et al, 2001). Under the threat of increasing frequencies of severe storm events (Zhang et al., 2000), it is of significance to systematically document storm induced beach changes.

This thesis is organized as follows. Chapter 1 provides an introduction, a literature
review, and the objective of this study. Chapter 2 describes the study area including general geological setting and oceanographic conditions. Chapter 3 discusses the field and laboratory methods used in this study. Chapter 4 presents the results of this study documenting the beach changes induced by the two storms. Chapter 5 discusses the factors that control the storm-induced beach changes. Chapter 6 provides the conclusions.

1.1 Literature Review

This section discusses the existing work on storm impacts on beach environments. This literature review is organized based on different sub-environments of a barrier island including, from sea to land, sandbar, beach, dune, overwash platform (Figure 1). Since most of the Florida beaches, including the one studied here, are heavily developed, the influence of human activities on sandy beach environments are also reviewed.

Figure 1. Terms used to describe a beach profile (modified from Komar, 1998)
1.1.1 Beach

Beaches are a challenging environment to study due to their very dynamic nature. They change under both normal weather and storm conditions. For Florida, hurricane induced beach changes are especially important. Therefore, it is crucial to investigate and quantify hurricane impacts on beaches and various engineering measures to cope with and mitigate storm-induced beach erosion. Numerous studies have been conducted to understand beach morphodynamics. Cheng (2015) summarized beach morphodynamics at multiple temporal-spatial scales and illustrated four scales including microscale, mesoscale, macroscale and megascale. The microscale beach dynamics examine wave-breaking induced turbulence and its contribution to nearshore sediment transport (Cheng and Wang, 2015). The mesoscale beach dynamics examine the evolution of beach profile and the migration of sandbar and subsequent equilibrium state of a stable bar as observed from a laboratory study (Cheng et al, 2016). The macroscale beach dynamics focus on the beach changes and morphodynamics of nearshore bar at storm and seasonal scales (Cheng and Wang, 2018). The megascale beach dynamics describe beach-profile evolution at multi-year to decadal scale (Cheng, 2015). This study examines storm-induced beach changes at the macroscale.

Sand is the major component of beaches, especially for those along the Florida coast. Grain size, in this case sand, has a significant control on the rate of sand transport (Van Rijn, 1993). McLean and Kirk (1969) documented the relationship between the mean grain (0.25-16mm) size and foreshore slope. In general, the foreshore slope tends to be steeper with
increasing grain size.

Longshore transport rate and its spatial gradient play a significant role in beach-inlet interaction and longer-term beach changes (Wang and Beck, 2012). Various empirical formulas were developed to calculate longshore sand transport rate (Kamphuis, 1991; Wang et al., 1998). The angle between wave and shore have significant influences on the rate of longshore sediment transport. Breaking-wave height plays a dominant role in the transport rate as the rate is proportional to the 2.5 power of the wave height (Kamphuis, 1991; Wang et al., 1998).

Cross-shore sand transport typically becomes dominant during storm conditions as compared to longshore transport (Komar, 1998). Computing the rate of cross-shore sand transport is more difficult than that of longshore sand transport and there is no simple empirical formulas as those of longshore transport. During storm impacts, morphological consequences of net cross-shore sand transport are clearly demonstrated as cross-shore sand bar movement and overwash (Sallenger, 2000; Cheng, 2015), as discussed in more detail in the following.

Wright and Short (1984) and Short (2001) classified beaches into three types, reflective, intermediate and dissipative beaches based on the study by Sonu and van Beek (1971). The reflective beach tends to be composed of coarse sediment, very steep, stable and typically occurs in sheltered areas. Comparing to the reflective beach, the dissipative beach is relatively flat and is usually driven by high wave energy. Fine sands are the major sediment component of such a beach. The intermediate beach has many different sub-types classified based on the complicated sand bar morphodynamics. Owing to the different morphology of these three beach types, their hydrodynamic processes are quite distinct. On a typical dissipative beach,
shoreward decay of incident waves is accompanied by shoreward growth of infragravity energy; in the inner surf zone, currents associated with infragravity standing waves can dominate (Wright and Short, 1984). On a typical reflective beach, incident waves and subharmonic edge waves are dominant (Wright and Short, 1984). On intermediate beach, incident wave orbital velocities are generally dominant but significant roles are also played by subharmonic and infragravity standing waves, longshore and rip currents. Infragravity waves generally refer to a low frequency component in the wave spectra, which can have significant influence on wave groupness and therefore sediment transport and beach morphology (Reniers et al., 2010). The strongest rip currents and associated feeder currents occur in association with intermediate transverse bar and rip topographies (Wright and Short, 1984).

1.1.2 Dune

Sand dunes are an important part of many coastal areas. They play a crucial role in protecting infrastructures landward of the beach during storms. The size and morphology of coastal dunes is dependent on the complex interaction between controlling winds, sediment supply, and the geomorphology of the nearshore and beach environments (Claudino-Sales et al, 2008). Claudino-Sales et al. (2008, 2010) examined the interaction between morphological factors (such as height of the dune fields, width of the barrier island, the distance between dune and hurricane center) and hurricane features (such as intensity and duration) in controlling the survival of coastal dunes against storm impacts. Inundation and overwash are the major processes that can cause damage to coastal dunes. The responses of dune to storm impacts are
dependent upon all the above parameters. Typically, the dune with dense vegetation along the bay shoreline survives storms, while discontinuous vegetated dunes were severely damaged (Claudino-Sales et al., 2008). The profile of beach can also influence dune development. Dunes prefer to form landward of flat and wide beaches where there is enough place for sand storage.

The barrier islands along the west-central Florida coast have low dunes that are typically less than 4 m high (Kurz, 1942). The lack of continuous onshore winds and sediment supply are the main reasons for the low dunes. Besides, many islands cannot provide sufficient space for sand to accumulate. Low-lying barrier islands are vulnerable to storm overwash. Dune destruction results from storm overwash, deflation and wave erosion. Hummocky foredunes and dissected foredunes are typical remnants of storm overwash. Dune destruction can be classified into three categories: inundation, overwash and dune scarping according to the submerged degree of beach (Sallenger, 2000).

1.1.3 Overwash

Donnelly et al. (2006) conducted a comprehensive review on mechanisms of overwash and modeling of washover deposits. In the following, a brief summary of the Donnelly et al. (2006) review is provided. Coastal overwash occurs frequently around the world: it is typically related to hurricanes and winter storms. Overwash induced by storms can cause beach erosion, but on the other hand, overwash can also maintain the integrity of barrier islands and create wetland environments in the interior and along the landward side of the barrier island.
Predicting and simulating overwash and overwash deposits (washover) is a challenging task. Overwash is the flow of water carrying sediment over the crest of the beach that does not return to the original locations (ocean, sea, bay, or lake; hereafter, ocean). Overwash occurs when wave runup level and/or storm surge level are higher than beach/dune crest height. If the storm surge coincides with high tide, the surge level would be higher and hence potential for overwash is greater.

Washover is the sediment deposited inland of a beach or dune by overwash. Washover can be deposited over the berm crest, forming the so-called storm berm, or as far as the back barrier bay. The quantity and shape of washover are controlled by the relative levels of the beach crest, water level, and wave height, and the duration of the storm, together with the back beach morphology, vegetation, and wind strength and direction (Donnelly et al., 2006).

On low-lying barrier islands, overwash in the seaward direction may also occur during the subsiding phase of the storm as the storm water recedes and flows seaward across the island. Severe overwash occurs mostly in association with a major storm such as a hurricane, although large morphological change by non-storm washover is also possible as was observed on the Colombian Pacific coast by elevated sea level most likely caused by El Nino and extreme spring tides (Morton et al., 2000). A coast may get overwashed by: (1) excessive wave runup over the berm crest, typically associated with a lower-magnitude event, causing washover fans and terraces; or (2) mean water level exceeding the beach crest, generally during a greater-magnitude event, causing nearly continuous sheetflow and may even inducing barrier-island rollover. These two processes may occur during one storm, varying either spatially along a coast or at one
location during different phases of a storm (Donnelly et al, 2006).

Regional-scale overwash also occurs without being directly related to barrier-island breaching (Wang and Horwitz, 2007). For breaching-related washover, the processes are significantly influenced by the channelized connection of open-ocean to back barrier bay. Overwash can also cause significant sediment redistribution across a barrier island (Wang and Horwitz, 2007). Studying the deposition and erosion caused by regional scale overwash from multiple hurricanes is valuable to understand dynamics of barrier island (Wang and Horwitz, 2007).

The Sallenger (2000) scale has been widely used to evaluate whether overwash would occur and to what degree. The scale examines four parameters: \( D_{\text{High}} \), \( D_{\text{Low}} \), \( R_{\text{High}} \) and \( R_{\text{Low}} \). \( D_{\text{High}} \) and \( D_{\text{Low}} \) represent the highest level and base level of dune, respectively. \( R_{\text{High}} \) and \( R_{\text{Low}} \) are defined as high and low amplitude of swash, respectively. When \( 0 < R_{\text{High}}/D_{\text{High}} < D_{\text{Low}}/D_{\text{High}} \), the impact level is designated as 1, also referred to as swash regime. When \( D_{\text{Low}}/D_{\text{High}} < R_{\text{High}}/D_{\text{High}} < 1 \), the impact level is designed as 2, also referred to as collision regime. When \( R_{\text{High}}/D_{\text{High}} > 1 \) and \( R_{\text{Low}}/D_{\text{High}} < 1 \), level 3 impact occurs, as also referred to as overwash regime. When \( R_{\text{High}}/D_{\text{High}} > 1 \) and \( R_{\text{Low}}/D_{\text{High}} > 1 \), the most severe impact, level 4 or inundation region, occurs.

Some unique features associated with severe storm overwash have been observed. Morton (1978) documented large-scale rhomboid bed forms caused by hurricane overwash. The hurricane Ivan in 2004 and Dennis in 2005 caused extensive overwash deposits along the northwestern Florida barrier-island coast. Wang et al. (2006) investigated the impacts of
hurricane Ivan on the coast of northwestern Florida. They found that the overwash deposits originated from eroding beach/nearshore and dune field. Wang and Horwitz (2007) described detailed sedimentary structures associated with overwash deposits based on trenches and GPR imaging. Erosional surface and landward dipping bedding constitute the distinctive characteristics of overwash deposits.

1.1.4 Sandbar

Sandbar is a dynamic morphologic feature of sandy beaches generally resulted from the deposition of offshore-directed sand transport from the beach (Komar, 1998). Due to their control on wave breaking, sandbars influence the spatial distribution of turbulent kinetic energy generated by breaking waves as they propagate onshore (Cheng and Wang, 2015). Understanding the morphodynamics of sandbars is valuable to the coastal scientific and engineering community. Often regular seasonal variations in wave energy can result in a predictable beach profile shape for winter and summer seasons. A sandbar forms during energetic wave conditions in the winter and migrates onshore during relatively calmer wave conditions in the summer (Shepard, 1950; Sonu, 1973; Lippmann and Holman, 1990). This is referred to as the beach cycle (Roberts et al., 2013). During storm conditions, offshore sandbar migration typically occurs as a result of strong undertow associated with intense wave breaking and wave setup (Thornton et al., 1996). While under long-period swell conditions, typical of a summer season, the deformed wave-orbital velocities and wave asymmetry cause the sandbar to migrate onshore (Hoefel and Elgar, 2003; Hsu, Elgar, and Guza, 2006). Some of the earliest
studies on sandbars identified breaking waves as a primary mechanism for the formation of sandbars including the cross-shore location, and water depth over the bar (Evans, 1940; King and Williams, 1949; Shepard, 1950). Additional factors controlling sandbar formation, morphology, and migration include wavelength, wave period, and sediment fall velocity (Larson et al., 1988; Larson and Kraus, 1989; Gallagher et al., 1998) and gradients in wave acceleration skewness (Hoefel and Elgar, 2003).

Sandbars have several different morphologic forms. Wright and Short (1984) classified several bar types based on alongshore bar morphology, including linear bar and trough, rhythmic or crescentic bar, and transverse bar. Bars are considered part of a feedback mechanism in which the bar responds to local hydrodynamics and the local hydrodynamics also respond to the bar, and at variable temporal scales (Gallagher et al., 1998; Plant et al., 1999; Plant et al., 2001; Plant et al., 2006).

Some studies discussed the detailed behavior of the bar experiencing storm impact (Sallenger et al., 1985). They used a low energy barrier island as the study area and analyzed the bar morphology change before and after the storm. They concluded that the bar would migrate offshore quickly and sustain their shape with increasing wave height. Infragravity edge waves, wavelength, wave-induced undertow and sediment fall velocity have significant control on the morphology of the sandbar. Based on a large-scale three-dimensional laboratory study, Cheng et al (2016a) identified the typical patterns of near-bottom velocity skewness associated with the onshore migration of a sandbar. A recent study by Cheng and Wang (2018) on sandbar morphodynamics at a regional scale suggests that alongshore variations of sandbar movement
under a storm event is strongly influenced by the variations in pre-storm sandbar crest elevations.

1.1.5 Barrier Island

Narrow strips of sand generally parallel to the mainland coast are called barrier islands (Davis, 1994). Approximately 76% of worldwide barrier islands occur along coastal plains located on the training edges of continent and marginal sea coasts (Glaeser, 1978). The formation of a barrier island requires a balance between sea-level, basement geology, forcing (waves, currents, and wind) and sediment supply (Hayes, 1979). The exact mechanism of barrier-island formation is still not well known.

Barrier islands do not occur on macrotidal coasts (tidal range>4m). On microtidal coasts (tidal range<2m), which have the greatest abundance of barrier islands, the barrier islands tend to be long and linear with numerous storm washover fans. On mesotidal coasts (tidal range = 2-4m), the barrier islands tend to be short and stunted, often referred to as drumstick barriers (Hayes, 1979). The large ebb-tidal deltas that are common on mesotidal coasts of medium wave energy play an important role in shaping the morphology of adjacent barrier islands by storing large volumes of sand which becomes available to the island under certain circumstances (Hayes, 1979).

The above description is highly generalized. A more precise morphodynamic classification is based on the relative dominance of wave energy and tidal range (Hayes et al., 1974; Hayes, 1975; 1979; Davis and Hayes, 1984; Davis, 1994; Davis and Fitzgerald, 2004). When wave forcing dominates over tidal forcing, which often occurs along microtidal coast,
wave-dominated barrier islands develop. They tend to be long and narrow. When wave
forcing and tide forcing play a relatively equal role, mixed energy or drumstick barrier islands
develop.

The impact of a storm on a barrier island is dependent not only on the magnitude of storm
forced parameters, such as storm surge, wave height, and wave runup, but is also dependent upon
the morphology, particularly the vertical dimension, of the barrier island (Sallenger, 2000), as
discussed earlier about the impact scales. A single storm can result in many meters of shoreline
change within hours (Masselink and Heteren, 2014). A series of storms, for example during a
winter season, may cause a seasonal, cumulative shoreline response (Komar, 1998). Wang et
al. (2006) documented impact of hurricane Ivan along the northwest Florida coast. Beaches
profiles were surveyed 1.5 days before hurricane landfall and 1, 4 and 11 weeks after. They
used the Sallenger (2000) scale to describe the degree of hurricane impact. They found that the
impact levels, i.e., inundation, overwash, collision, and swash regimes, are strongly controlled by
the distances from hurricane center, as expected.

Beach erosion is a serious concern for coastal countries throughout the world. Over the
last three decades, beach nourishment has become one of the most commonly used methods to
mitigate beach erosion due to the typical minimal negative impacts to neighboring coast (e.g.
Roberts and Wang, 2012). Since the 1980s, after the failure of many hard measures in
protecting sandy beaches (such as groins, breakwaters, or sea-walls) in terms of negative impacts
to neighboring shoreline, it has become evident, that “soft” remedial measures such as beach
nourishment are far more advantageous than hard structures (Capobianco et al, 2002).
Florida, beach nourishment is by far the most commonly used method for mitigating beach erosion (Davis et al., 2000). The Sand Key beach studied here is maintained through periodical nourishment (Roberts and Wang, 2012).

2.1 Overall Research Objectives

This thesis investigates beaches morphology changes along the west-central Florida barrier-island coast induced by Hurricane Hermine in 2016 and Hurricane Irma in 2017. Beach profiles were surveyed and compared before and after the two hurricanes. The beach surveys were conducted approximately one month before and two weeks after the hurricanes. The objective of this study is to 1) investigate alongshore variations of hurricane induced beach changes; 2) examine the hurricane and morphological factors that cause longshore variations; 3) compare the different patterns of beach changes induced by the two different hurricanes; 4) investigate the causes of the different beach responses to the two hurricanes.
Chapter 2: STUDY AREA

2.1 Oceanographic and Morphologic Characteristics

The west-central Florida coast is consisted of a barrier-island chain, including both wave-dominated and mixed-energy barrier islands despite the overall microtidal setting (Davis and Bernard, 2003). Sand Key is one of the barrier islands bound to the north by Clearwater Pass inlet and separated to the south from Treasure Island by John’s Pass inlet (Figure 2). Sand Key illustrates a characteristic shoreline orientation change of 65 degrees from northwest-facing to southwest-facing beaches. Both inlets at the two ends are mixed-energy with large ebb-tidal deltas (Gibeaut and Davis, 1993). A broad bedrock headland located in Indian Rocks area (Figure 2) on Sand Key is composed of the Miocene Tampa Limestone (Roberts and Wang, 2012). The underlying geology also influences the gradient of the inner continental shelf. Offshore sand ridges in the west of Sand Key and ancient ebb-tidal deltas from closed inlets introduce additional variability to the overall inner continental shelf and nearshore bathymetry. Regional longshore transport along the west-central Florida coast is controlled by the frequent passages of winter cold fronts from north to the south. The beach sediment is typically bimodal composed of fine quartz sand (0.13-0.20 mm) and shell debris of various sizes. The Sand Key beach spanning the entire study area was last nourished in 2012.

The Sand Key is divided into seven sections from north to south: North Sand Key,
Belleair Shore, Indian Rocks Beach, the Headland, Indian Shores, North Redington Beach, and Redington Beach (Figure 2). Within the North Sand Key section, a reversal of the regional southward longshore sediment transport result from wave refraction over the large Clearwater Pass ebb shoal occurs, evident by the accretional fillet along the south side of the Clearwater Pass jetty (Roberts and Wang 2012). Belleair Shore is a 1.6 km section that was not nourished in 2012 and is characteristic of a narrow beach. Indian Rocks Beach is characterized as a straight and long section of Sand Key with a net southward longshore transport consistent with the overall regional trend (Roberts and Wang, 2012). The Headland section includes the broad westward protruding area exhibiting a change from northwest- to southwest-facing shoreline orientation (Figure 2). The southwest-facing beaches along Indian Shores are somewhat sheltered from northerly waves by the protruding headland to the north. Similar to Indian Rocks Beach, North Redington Beach is also a relatively long and straight beach (Roberts and Wang, 2012).
Figure 3 illustrates the statistical wind conditions obtained from a nearby NOAA station (#8726724) located approximately 5 km north of study area. Wind conditions measured from 2010 to 2014 were analyzed. The predominant wind directions are from east with wind speed typically less than 10 m/s. These winds are directed offshore and have little impact on coastal processes in the study area. The strong northerly winds that is faster than 15 m/s are typically related to the passages of cold fronts in the winter season. The cold front passages typically occur every 10 to 14 days. This northerly wind generates highly oblique incident waves and is largely responsible for the net southward longshore sediment transport in the greater study area. The westerly winds rarely generate onshore directed waves.
Figure 3. Wind rose composed from measurements at NOAA station (#8726724) at Clearwater Beach, approximately 5 km north of the study area.

Figure 4 illustrates statistical wave conditions obtained from computed wave conditions by WAVEWATCHIII (http://polar.ncep.noaa.gov/waves/index2.shtml) during 2000 to 2014. The numerical wave station is located near the southern end of Sand Key. Wang et al. (2016) compared the measured wave heights and the computed values at this location and found that the computed wave height was approximately 9% lower than the measured wave height. Therefore, in Figure 4 the WAVEWATCHIII wave heights were multiplied by 1.09 to improve the match with the measured values. The direction of the most frequent incident nearshore
waves were from the west, with an average wave height of lower than 0.5 m. The direction of higher incidents waves was from west-northwest, apparently associated with the strong wind associated with passages of winter cold fronts (Figure 4).

Figure 4. Wave rose composed from computed wave conditions by the WAVEWATCHIII (http://polar.ncep.noaa.gov/waves/index2.shtml) at approximately 7 km from the shoreline.

The study area is characteristic of a mixed tidal regime (Figure 5). The spring tide is typically diurnal with a range of roughly 0.8 to 1.2 m, whereas the neap tide is semi-diurnal with a range of 0.4 to 0.5 m. Although the spring tide tends to be diurnal, a short pause or slight
water-level fall typically occurs during the prolonged flooding phase, whereas the shorter ebbing phase is typically not interrupted. The magnitude of the slight water-level fall during the spring flooding phase increases as the tidal cycle changes to a neap cycle and eventually becomes a semi-diurnal tide during the neap phase (Figure 5).

![Graph of measured tides from July 23, 2008 to August 5, 2008 at approximately 3 km offshore John’s Pass, illustrating a mixed tide regime.](image)

Nearshore waves approximately 400 m offshore Blind Pass, just to the south of the Sand Key study area, were measured by Wang and Beck (2012) from November 25, 2003 to February 26, 2005. A total of 4,181 measurements were obtained with a measurement interval of 1.5 hours. This yields roughly 261 days of wave data (Figure 6). The average measured significant wave height was 0.26 m with an average peak wave period of 5.8 s which is similar to estimates made by Tanner (1960). The influences of cold-front passages are apparent as illustrated by the frequent high wave events during the winter season from October to March.
The spring season (March and April) can also have relatively high wave energy induced by the passage of late cold fronts. The summer of 2004 was exceptional in that the passage of three tropical storms in September and October, Frances, Ivan and Jeanne (Elko and Wang, 2007) resulted in three substantial, high-wave events. The distal passage of Hurricane Ivan generated long-period (12-16 s) swells (Figure 6, lower) which are rare for this coast. Although representing a short period of time, Figure 6 illustrates the typical pattern of wave conditions with the exception of the three tropical storms.

Driven by the specific wave conditions discussed above, sediment transport in the study area tends to be episodic as it is controlled by high-energy events typically associated with the passages of winter cold fronts (Walton, 1973; Davis, 1997; Elko et al., 2005; Elko and Wang, 2007). Sustained wind and waves during these events tend to come from a northerly direction providing the main driving force for the annual net southward longshore sediment transport. The rate of longshore sand transport along the Florida coast was estimated by Walton (1976). Interruption or local reversal of this southward net longshore transport plays an important role in beach morphodynamics.
Local variations of beach erosion and accretion along the Sand Key are controlled by the differences in nearshore wave field resulting from bathymetric changes as wave propagates from offshore including interactions of inlet and ebb-tidal delta and orientation changes in shoreline from northwest- to southwest. The variations of nearshore wave conditions were examined qualitatively based on CMS-Wave model (Lin et al., 2008). Under an idealized northerly approaching wave representing relatively energetic conditions typically associated with cold front passages, the headland on Sand Key shelters the adjacent beaches to the south dissipating incoming waves along south Sand Key (Figure 7). Along the north side of the headland, the
beach is sheltered to a certain degree from the southerly approaching waves, which represent the predominant wave conditions in the greater study area (Figure 8). Energetic southerly approaching waves tend to be generated during the prefrontal phase of winter storms and during the passages of tropical storms. At and around the headland, the waves are typically more energetic under both northerly and southerly approaching waves, resulting in a divergence zone there.

Figure 7. Idealized northerly approaching waves modeled in CMS-Wave for the study area (modified from Roberts and Wang, 2012).
2.2 Meteorologic and Oceanographic Characteristics of Hurricanes Hermine and Irma

The main topic of this study is to investigate and compare the impacts of hurricanes on beach erosion or accretion along Sand Key. Two recent hurricanes, Hermine in 2016 and Irma in 2017, are examined. In the following, relevant meteorological and oceanographic conditions associated with the passages of the two hurricanes are introduced in the following.

Based on NOAA’s National Hurricane Center data, Hurricane Hermine originated in the Florida Straits. The intensity of the storm increased to Category 1 offshore west-central Florida
coast after being a tropical storm and depression for a few days. Hurricane Hermine was the first hurricane that made a landfall along the Florida coast since Hurricane Wilma in 2005. From September 1st, Hurricane Hermine impacted the coast of Pinellas County with increased water level and higher nearshore waves for about two days, although the center of this Category 1 hurricane was more than 200 km from the shoreline. The peak wind speed and pressure at the landfall location just east of St. Marks Florida was 80 mph and 982 mbar, respectively.

Figure 9. Hurricane Hermine track by Robbie Berg (modified from Visin and Moore).

Hurricane Hermine generated energetic conditions along the Pinellas County coast, even though it did not make direct landfall in west-central Florida. Wind direction, wind speed,
wave direction, wave period and wave height during the passage of the hurricane were measured by the NOAA buoys in the Gulf of Mexico. The measured data from Station 42036, about 200 km WNW of Tampa, from August 27th to September 8th were downloaded and analyzed. Water level variations during the passage of the hurricane was measured at NOAA Clearwater Beach Station (8726724), about 5 km north of the Sand Key study area. Data from August 27th to September 8th were downloaded and analyzed.

Before the arrival of hurricane Hermine at the measurement station, the wind direction (Figure 10) was between 100° and 150°, or from ESE and SE which are the predominant wind direction for the greater study area (Figure 3). Because wave is generated by wind, the direction of wave (Figure 11) should be similar to the wind. The wind speed and wave height were 7 m/s and 1.4 m, respectively. The temporal variation of wave height also agreed with that of the wind speed (Figures 12 and 13). Wave period ranges from 5 s to 8 s (Figures 14). It is worth noting that ESE and SE incident wind and wave are directed offshore and should not have any significant influence on beach processes.

During the passage of hurricane Hermine offshore west-central Florida coast from 1st to 2nd in September. On September 1st, hurricane Hermine was moving through the middle of the Gulf of Mexico. The center of the hurricane was mostly more than 200 km from the shoreline. As the hurricane moved northward (Figure 9), measured wind and wave changed rapidly and significantly during these two days. Wind direction changed to 180°, or from the south, on the 1st and changed to 250°, or from the southwest, on 2nd as the storm continued to move northward. Wave direction was 200°, or SSW, on 1st. On 2nd, it was 250° for half a day and subsequently
decreased to 200°. Wind speed was about 8 m/s in the morning of September 1st. It reached a peak speed of 25 m/s in the evening which was about 3 times than that in the morning. The wind speed decreased to 5 m/s on the 2nd as the hurricane passed over the measurement station. Wave-height increased followed a similar pattern as that of the wind speed. Wave height reached 7.5 m as a peak height. It was about 7.5 times higher than that immediately before and after the passage of the hurricane. After September 2nd, the wave height decreased further to less than 1 m. Wave period increased from 8 s to 12 s on September 1st. It was about 2.4 times greater than that of the pre-storm conditions. After the passage of the hurricane it decreased to less than 6 s in one day.

After the passage of the hurricane, for example on September 5th, wind direction changed rapidly from 350° to 20° and remained between 50° to 100° for a few days. Wave direction demonstrated a similar trend with that of the wind direction. It changed from 250° to 60° and remained between 100° and 150°. Wind speed was between 4 m/s and 6 m/s after the hurricane. Wave height was roughly 0.8 m and wave period were about 5 s. This represents the typical wave conditions during the post-storm beach survey.
Figure 10. Wind direction during Hermine measured at Station 42036, about 200 km WNW of Tampa.

Figure 11. Wave direction during Hermine measured at Station 42036, about 200 km WNW of Tampa.
Figure 12. Wind speed during Hermine measured at Station 42036, about 200 km WNW of Tampa.

Figure 13. Wave height during Hermine at Station 42036, about 200 km WNW of Tampa.
Figure 14. Dominant wave period during Hermine measured at Station 42036, about 200 km WNW of Tampa.

Figure 15 illustrates water level variation measured at the NOAA Clearwater Beach station, about 5 km north of the study area, during the passage of the hurricane. Under the normal condition, the elevation of the tidal water level was between 0.1 m and 0.9 m above MLLW (Mean Lower Low Water). The Mean Sea Level (MSL) is about 0.45 m above MLLW in this area. Water level elevation increased rapidly from September 1st at 12:30 till 2nd at 8:00. Water level reached 1.7 m, or 1.25 m above MSL. It was about 1 m above the predicted value, indicating that Hurricane Hermine generated a storm surge of up to 1 m which means that the wave impact may reach much further landward and higher on the beach than during the normal conditions.
Figure 15. Tidal water level measured at NOAA Clearwater Beach Station (8726724), about 5 km north of the Sand Key study area. Elevation referred to MLLW, which is 0.45 m below mean sea level at this location.

Hurricane Irma remained as a Category 5 hurricane in the Caribbean Sea for several days and it impacted on Florida coast for several days (Figure 16). It made its first landfall the United States in the Florida Keys and then moved northward and made a second landfall just south of Marco Island. It arrived and influenced the study area for approximately four days from September 8th to 11th. Hurricane Irma stayed as above category 4 hurricane before it reached Florida peninsula. It decreased to category 2 hurricane when passing the study area. The data of wave direction, wind direction, wind speed, wave period and wave height were downloaded from NOAA Station 42036, about 200 km WNW of Tampa. This is the same
station where Hurricane Hermine data were obtained. The water level data were obtained from Clearwater Beach station, also same to the Hurricane Hermine data. Beach profiles were collected 21 days before and 14 days after Hurricane Irma. The profiles were analyzed to quantify changes of sand volume, shoreline and sandbar movement along the Sand Key.

Figure 16. Hurricane Irma track (modified from John P. Cangialosi et al).

Before Hurricane Irma passed the greater study area, wind direction as measured at the offshore station was between 300° and 350°, or from NW, representing pre-storm normal condition (Figure 17). Wave direction ranged from 180° to 340° (Figure 18). Wind speed was about 2.5 m/s before the hurricane (Figure 19). Wave height was roughly 0.3 m and wave
period was between 4s and 8s (Figures 20 and 21).

Wind direction changed from 350° to 40° rapidly on September 7th and remained between 40° and 60° during the passage of hurricane. Similar to the wind direction trend, wave direction was between 40° and 70°, or approaching from NE. Wind speed increased from 6 m/s to 21 m/s. Wave height ranged from 1 m to 5.5 m at this offshore station. The 5.5 m maximum wave height was considerably lower than the maximum Hermine wave of 7.5 m. During the passage of Hurricane Irma, wave period was considerably greater than in normal conditions. The shortest wave period was 3 s and the longest period was 10 s during the passage of the hurricane.

After the passage of the hurricane, on September 11th, wind direction changed from northerly to southerly, as typical of summer season. Wave direction followed a similar pattern of change. Wind speed remained about 3.5 m/s after the hurricane. Wave height was about 0.4 m and wave period was between 3s and 6s. There were some data missing in wave direction and wave period measurement. However, it was during the relatively calm period after the passage of the hurricane.
Figure 17. Wind direction during Irma at Station 42036, about 200 km WNW of Tampa.

Figure 18. Wave direction during Irma at Station 42036, about 200 km WNW of Tampa.
Figure 19. Wind speed during Irma at Station 42036, about 200 km WNW of Tampa.

Figure 20. Wave height during Irma at Station 42036, about 200 km WNW of Tampa.
Water level variation measured during the passage of Hurricane Irma was quite un-usual and was significantly different from that measured during the passage of Hurricane Hermine. Water level measured at the Clearwater Beach station, similar to that for Hurricane Hermine. Contrary to an elevated water level, i.e., storm surge, typically measured during a hurricane, depressed water level, i.e., a negative surge was measured during the passage of Hurricane Irma (Figure 22). Starting roughly at 07:00 on September 10th, the measured elevation of water level was lower than predicted value indicating a negative surge. The water level reached a minimum of -0.6 m on 11th at 02:00, or a negative surge of -1.1 m. The positive surge following the water-level depression was quite small as compared to a typical surge associated with a strong hurricane. The positive surge was mostly less than 0.5 m superimposed on a neap tide. The depressed water level had significant influence on spatial patterns of sediment
transport and subsequently beach-profile changes, as discussed in the following.

Figure 22. Tidal water level during Irma
Chapter 3: METHODOLOGY

3.1 Field Data Collections

Beach profiles along the west-central Florida coast were measured bimonthly by USF Coastal Research Laboratory (USF-CRL). The surveyed profiles were used to evaluate storm impacts on beach by comparing the pre- and post-storms profiles (Cheng et al, 2016b). In this chapter, the methods used for beach-profile surveys and for data processing are discussed.

The beach profiles were surveyed using a Topcon electronic total station. The profile survey procedure follows the traditional level-and-transit principle. A three-person team is needed to conduct the field survey, including one rod-person responsible for the land part, one swimmer for the water portion, and one instrument person to record the readings. A 4-m survey rod is used for this particular study. This relatively long survey rod is used to measure the profile to short-term closure depth, as discuss more in the following. It is worth noting that a 5-cm diameter flat footer is attached to the bottom of the survey rod. The flat footer is used to prevent the survey rod from sinking into the soft sand and also provides an average measurement of a small area over the sometimes uneven sand surface. Field observations indicate that the traditional sharp pointy ends often penetrate into the soft sand for 5-10 cm (Cheng et al., 2016b).

Real Time Kinematic Global Positioning System (RTK GPS) was used to establish the survey benchmark and the instrument location before conducting each beach profile survey.
This provides accurate elevation for survey line, as well as the real-world geographic locations for each survey point (Cheng et al., 2016b). Elevations of the profiles are referred to the North American Vertical Datum of 1988 (NAVD88) in meters. NAVD88 zero is 8.2 cm above mean sea level (MSL) in this area. The survey lines extend to roughly -3 m NAVD88, or short-term depth of closure (Wang and Davis, 1999). The depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore (Kraus et al., 1998). In order to accurately capture the cross-shore beach changes, beach profile is established to be perpendicular to the shoreline, as marked by the benchmark and instrument points (Cheng et al., 2016b). Two orange cones visible to the rod-person are set on the survey line (Figure 24). This helps the rod-person to remain on the survey line, although slight errors may be introduced by the visual estimation of the rod-person. Benchmark provided by FDEP spaced at about 300 m along the studied coast was used for beach profile survey.
Figure 23. Seven profiles on Sand Key from R61 at the north end to R109 at the south end.

Figure 24. Survey procedures include the use of an electronic level-and-transit total station and a 4-m survey rod (modified From Cheng et al., 2016b).
3.2 Beach-Profile Data Analysis

A total of 121 beach profiles were surveyed about every 300 m at R-monuments established by the State of Florida. In this study, 7 presentative profiles along Sand Key is analyzed. All the survey lines extended to at least -3 m NAVD88, or to the short-term closure depth in this area (Wang and Davis, 1999). This is to ensure that all the changes along the beach profile are captured by the time-series survey.

During each survey, it is important that detailed variations of elevation should be captured. The rod person plays the most important role in the overall survey accuracy. The rod person determines the locations of morphology change and a measurement is taken at all locations with slope change. This is more accurate than taking survey points with equal space intervals because it may miss important slope break such as scarps or bar crests. Therefore, a responsible rod-person is crucial to the survey accuracy. Typically, denser points are taken where slope changes occur (e.g. foreshore, berm crests, or sandbar), and fewer points are taken where topography is uniform (e.g. flat back beach). This procedure allows efficient measurement of the beach-profile changes (Cheng et al., 2016b).

Distance (d) from benchmark to each survey point is calculated as:

\[ d = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \]

\(X_1\) is easting coordinate of the benchmark and \(X_2\) is the easting coordinate of a certain measurement point. \(Y_1\) is northern coordinate of the benchmark and \(Y_2\) is the northing coordinate of each measurement point (Davis, 2013). The beach profile, illustrating distance to
benchmark and elevation, can be plotted using commonly available software such as Excel.

Several parameters were defined in this study to represent the beach profile configurations. The foreshore slope, which is the gradient between 0.5 m (high tide line) and -0.3 m (Low tide line) contours, was computed. Another important parameter is the dry beach width which is calculated as the horizontal distance between the location of 1 m contour line and that of the 0.3 m contour (relative to NAVD 88 zero). The part of the beach that is higher than 1 m elevation is referred to as dune. The 0.3 m elevation is roughly the high tide level. Some beach volume change parameters were also computed. The above zonation of the beach is somewhat subject. The zonation used by Roberts and Wang (2012) is adopted here.

The beach volume associated with dry beach, dune field (the area which over the elevation of 1 m NAVD88), before and post the hurricane impacts, was calculated by comparing the pre- and post-storm beach profiles. As sandbar is an important component of a beach profile, sandbar parameters were also computed including bar height \(H\), which is determined as the elevation difference between sandbar crest and trough, and bar distance which is the cross-shore position of the sandbar crest with respect to benchmark locations. Cross-sectional area of sand bar provides an indicator of the sand bar size. The change of sand bar size represents an important consequence of storm-induced beach changes. In this study, the sand bar size is calculated as the cross-sectional area of the sand bar extending from the bottom of the trough seaward to where it intersects with the seaward slope (Figure 25).
Figure 25. The area of sand bar height.
Chapter 4: RESULT

Coastal erosion is a process that the sediments from dunes or beaches move seaward or alongshore and result in a sediment-volume loss on the specific beach and dune. Waves and currents provide this erosive process, especially during storm conditions. Waves play an important role in inducing active sediment transport and therefore cause erosion or accretion. For example, the undertow which has a positive correlation with beach slopes can cause seaward sand transport in the surf zone and result in beach erosion. Significantly, undertow constitutes a major process for storm induced beach erosion. Rapid changes in beach morphology are a result of the interaction between beach shoreface and sediment transport driven by different waves. Waves can also landward sand transport which result in beach accretion (Thornton et al., 1996; Conley & Beach, 2003; Aagaard et al., 2013). However, the exact process of onshore sand transport is not well understood. When waves break at an angle to the shoreline, a longshore current is generated resulting in longshore sediment transport. Wave breaking, as well as breaking induced longshore and cross-shore current, can be influenced by Infragravity waves (Conley & Beach, 2003) which can subsequently influence beach changes.

There are two categories of beach erosion: Punctuated erosion and chronic erosion (Ciavola and Coco, 2018). Punctuated erosion always occurs in a short space of time, for example, during a storm. Punctuated erosion tends to be dominated by cross-shore transport,
e.g., by undertow. On the contrary, chronic erosion refers to the erosion that tends to last over a long period of time. Different from the punctuated erosion, chronic erosion is often related to longshore sediment transport as opposed to cross-shore sand transport.

This study investigates beach changes along Sand Key (Figure 23) caused by two hurricanes, Hurricane Hermine in 2016 and Hurricane Irma in 2017. As discussed earlier, the two hurricanes are quite different in terms of generation of storm surges. The 22-km Sand Key was divided into seven sections from north to south to distinguish the potential variations caused by the shoreline orientation change. The results are presented spatially using these seven sections. The seven sections are North Sand Key, Belleair Shore, Indian Rocks, Headland, Indian Shores, North Redington Beach and Redington Beach (Figure 5). By comparing pre-storm and post-storm beach profiles, hurricane impacts can be identified directly. One representative beach profile in each section is examined in detail. The seven beach profiles are R61, R67, R75, R84, R91, R105 and R109. In the following, beach profile changes measured before and after Hurricane Hermine and Hurricane Irma are discussed.

4.1 Beach Profile Volume and Contour Change during Hurricane Hermine

This section discusses the measured beach changes during Hurricane Hermine. Beach-volume and contour location changes were calculated. Sand volume changes in four sections of the beach were calculated. The landward most section is the dune field. The dune field sand volume change is represented by the volume change above 1.0 mNAVD88. The sand volume change on the dry beach is represented by the change between 1.0 m and 0.3 m NAVD88. The
sand bar volume change was calculated as illustrated in Figure 7. Finally, the volume change over the entire profile extending to the closure depth was also calculated. A loss or gain of sand volume over the entire beach profile to closure depth would indicate a net sand loss or gain due to longshore sediment transport. This indicates an overall erosion or accretion at a particular beach. If the sand volume remained constant above the depth of closure while losses or gains were measured at different sections, e.g., dune field or sand bar, this suggests net cross-shore transport.

North Sand Key is characteristic of a divergent zone (Roberts and Wang, 2012) resulting in an aggressive erosional hot spot. The chronic erosion is caused by wave refraction over the large ebb tidal delta of Clearwater Pass (Roberts and Wang, 2012). The profile R61 is located in the middle of this section and illustrates a typical example of a highly erosive beach caused by a large longshore sediment transport gradient. This profile demonstrates the greatest volume change over the entire profile in the study area. The dune line location, as represented by the 1.0 m contour, remained the same before and after the storm (Figure 26). However, the dune field experienced significant erosion. The sand dune at 7.8 m away from benchmark was eroded. The sand loss in the dune field was 3.0 m$^3$/m. Prior the hurricane, there was an active berm with an elevation of 0.7 m. It was completely eroded. The dry beach, which was quite narrow before the storm, lost ~1.9 m$^3$/m sediment volume. Sand loss across the entire R61 profile was 39.3 m$^3$/m and it was the largest loss along Sand Key. Most of the sand loss occurred in the nearshore area between approximately 0.3 m and -1.6 m NAVD88. Before the Hermine impact, the sandbar crest was at 100.0 m away from benchmark. The sand bar
migrated seaward for about 30.0 m and gained around 9.8 m³/m of sand. The sand bar moved into the deeper water, likely driven by the high wave from the hurricane. The foreshore slope was mostly stable increasing from 0.100 to 0.120. Shoreline, as represented by 0 m NAVD88, moved landward for about 5.2 m. Overall, this profile migrated landward because of a negative longshore transport gradient.

Figure 26. Beach profile change at survey line R61 due to Hermine.

Profile R67 is located in Belleair Shore. Different from the rest of the beach, this section has not been nourished (Roberts and Wang, 2012). The width of beach, as represented by the location of the 0 m NAVD88 contour, remained stable. Dune line, as represented by the 1.0 m contour location, retreated 6.0 m landward and dune field lost considerable sediment of
~7.2 m$^3$/m. There was a dune at approximately 10.0 m from benchmark and it was completely eroded, replaced by a gentle sloping beach after the hurricane. Dry beach between 0.3 m and 1.0 m lost sediment volume of ~1.4 m$^3$/m. The small loss is controlled by the narrow pre-storm beach. The pre-Hermine sandbar crest was ~90.0 m from the benchmark. The sandbar moved seaward for 10.5 m. Volume of the sandbar was largely stable before and after the storm, decreased ~0.1 m$^3$/m. The entire profile lost 7.9 m$^3$/m during the hurricane impact. The foreshore slope remained similar before and after the storm.

![R67 Pre- and Post-Hermine Profile](image)

Figure 27. Beach profile change at survey line R64 due to Hermine.

Profile R75 is located in the Indian Rocks Beach section between Belleair and Headland, or the northern flank of the headland. This section is ~3.0 km long with a straight beach.
(Figure 28). This section is dominated by southward net longshore sediment transport, similar to the regional trend (Roberts and Wang, 2012). The dune field above 1.0 m NAVD88 experienced erosion and lost about 8.7 m$^3$/m of sand during the hurricane impact. Pre-Hermine dune crest was 2.8 m high, which decreased to 2.4 m after the storm. Dune line experienced significant erosion and it moved landward 8.0 m. Sand loss of dry beach between 0.3 m and 1.0 m was 4.2 m$^3$/m. Pre-Hermine sandbar was at 118 m from benchmark. It migrated seaward for 12.1 m and located at 130.1 m from benchmark after the hurricane. Sandbar had a positive volume change of 6.3 m$^3$/m. Shoreline retreated 4.0 m and the entire profile lost about 12.0 m$^3$/m of sand. Foreshore slope remained similar.

Figure 28. Beach profile change at survey line R75 due to Hermine.
The Headland section (Figure 29) is located in the middle of Sand Key and extends 2.0 km. It is dominated by a longshore sediment transport gradient due to the shoreline orientation change. Davis and Barnard (2000) suggested that the headland is another divergent zone on Sand Key. However, it is not as distinctive as the North Sand Key divergent zone. The energy and height of wave is larger along this section due to the fact that the coast protrude into the sea (Figures 7 and 8). This section was impacted significantly by hurricane Hermine and lost substantial sand volume. Profile R84 is located in the middle of the Headland section. Dune field above 1.0 m NAVD88 suffered severe erosion because of scarping. Volume of sand loss was 8.9 m³/m. Dune crest height was unchanged. Dune line experienced a large erosion and migrated landward about 12.0 m. The active berm at 35.0 m from the benchmark was eroded and moved landward about 10.0 m. Dry beach lost about 9.3 m³/m of sand. The pre-Hermine sandbar was at 115 m from benchmark and moved seaward for 17.9 m. The sand bar gained 5.8 m³/m of sand. The entire profile lost roughly 5.4 m³/m of sand, suggesting that cross-shore transport was the dominant process driving the beach changes. Shoreline position remained largely stable before and after the hurricane. The foreshore slope changed from 0.032 to 0.025.
Indian Shore is south of the Headland and is 3.3 km in length. R91 is located in the northern portion of this section. This profile (Figure 30) shows that the dune field experienced erosion with the dune line retreated landward by 8.0 m. Dune field above 1 m lost about 10.8 m$^3$/m of sand. Similar to profile R84 (Figure 29), R91 had a active berm at about 60 m from the benchmark before the hurricane impact. The berm was eroded and was replaced by a gently sloping beach. The dry beach lost 8.2 m$^3$/m of sand. Dry beach, as represented by the 0.3 m NAVD88 contour, retreated about 9.0 m landward. During the hurricane impact, the sand bar moved offshore from 138.6 m to 153.0 m from the benchmark. Different from the profiles to the north, the sand bar at profile R91 lost 1.1 m$^3$/m of sand. Foreshore slope decreased 0.070. Shoreline moved landward for 15.0 m. The entire profile lost 12.2 m$^3$/m due to a longshore
transport gradient.

Figure 30. Beach profile change at survey line R91 due to Hermine.

North Redington Beach comprised profiles from R100 to R107 and is 2.1 km long. The width of the beach in this area decreases from north to south because it is located at the southern end of the Sand Key beach nourishment projects. The section of the beach is dominated by the regional southerly net longshore sediment transport (Roberts and Wang, 2012). Profile R105 is located near the southern end (R107) of the nourishment project. The intertidal zone and sandbar remained relatively stable before and after the storm (Figure 31). Dune field experienced modest erosion. Dune line retreated landward for about 5.0 m and the dune field lost about 1.6 m$^3$/m of sand. The pre-Hermine berm was located 59.4 m from the benchmark.
Similar to the other profiles, the berm was eroded and replaced by a gently sloping beach after the hurricane. Dry beach had a negative change of sand volume which was 4.0 m$^3$/m. Crest of sandbar remained relatively unchanged during the hurricane impact. However, its volume decreased 4.0 m$^3$/m. Overall, the entire beach profile shifted landward about 7.5 m, with a sand volume loss of 28.2 m$^3$/m above the depth of closure. The foreshore slope decreased 0.020.

![R105 Pre- and Post-Hermine Profile](image)

Figure 31. Beach profile change at survey line R105 due to Hermine.

Redington Beach is the southernmost section of the Sand Key study area and includes profiles from R107 to R116. The beach profile R109 (Figure 32) is used here to represent this section. Dune field did not experience severe erosion. Dune line was largely unchanged, with a small sand volume loss of 0.2 m$^3$/m. Dry beach experienced a modest erosion with a sand
volume loss of 3.9 m$^3$/m. An active berm at 20 m from the benchmark was eroded and replaced by a gently sloping beach. The pre-Hermine sandbar was 85.8 m from the benchmark and moved seaward about 3.7 m. The elevation of bar crest decreased 0.4 m and the volume of sand bar decrease 3.4 m$^3$/m. Different from the other profiles, R109 gained 15.5 m$^3$/m above the depth of closure. Change of foreshore slope was the largest as compared to the profiles, with a 0.260 decrease.

![R109 Pre- and Post-Hermine Profile](image)

Figure 32. Beach profile change at survey line R109 due to Hermine.

4.2 Beach Profile Volume and Contour Change during Hurricane Irma

As discussed earlier, Hurricane Irma generated very different storm surge as compared to Hurricane Hermine, mostly negative versus positive. The offshore waves were also lower...
during Irma than during Hermine. In this section beach profile changes caused by Hurricane Irma is described.

Profile R61 (Figure 33) on North Sand Key experienced substantial erosion during hurricane Irma. Dune field did not experience much erosion because the water and therefore wave activities did not quite reach the dune due to the negative storm surge. Dune line, as represented by 1.0 m NAVD 88 contour, retreated about 4.0 m landward from 15.0 m to 11.0 m from the benchmark. Dune field lost about 1.3 m$^3$/m of sand. It is worth noting that the 1 m contour level was defined somewhat arbitrarily here to maintain consistency. In this case here, it does not represent the vegetated portion of the dune. Dry beach experienced modest erosion and lost about 4.1 m$^3$/m of sand. The post-Irma sandbar moved offshore about 31.9 m with a sand-volume loss of 6.8 m$^3$/m. The pre-Irma sandbar crest elevation was -1.5 m. The sandbar crest was largely eroded away by the hurricane and elevation decreased to -2.3 m. This is a major difference comparing post-Hermine and post-Irma profiles, which is discussed in more detail in the next chapter. Shoreline moved landward about 4.2 m. The entire beach profile shows a negative volume change of 22.3 m$^3$/m. Also, the per- and post-Irma profiles are not converging at the seaward end, suggesting the substantial amount of sand was moved seaward of the short-term closure depth.
At profile R67, the dune line, as represented by 1.0 m NAVD 88 contour, moved landward about 10.0 m with a sand volume loss of about 3.0 m$^3$/m. However, similar to profile R61, the sand loss was not from the vegetated part of the dune. There was an active berm located at 22.7m from benchmark before Hurricane Irma. The elevation of the berm decreased about 0.2 m indicating that erosion occurred on dry beach. Dry beach lost about 4.1 m$^3$/m of sand. The sandbar which was located 100m from the benchmark before the storm moved seaward for 27.2 m after the storm. Similar to the case at profile R61, the sand bar was significantly flattened with the elevation of sandbar crest decreasing from -1.5m before Irma to -2.2 m after Irma. Sediment loss of sandbar was 5.7 m$^3$/m. The entire profile above the depth of closure had a significant sand loss of 31.9 m$^3$/m. It is the largest volume loss as compared to
the other profiles. At this profile, it is quite clear that the pre- and post-storm profiles did not converge at the short-term closure depth. Significant amount of sand was transported seaward of the short-term closure depth due to the very un-usual negative surge associated with Hurricane Irma.

Figure 34. Beach profile change at survey line R67 due to Irma

At profile R75, dune field (Figure 35) was largely stable. The dune line was mostly unchanged at 34.0 m from the benchmark, and dune field did not lose much sand. In the case of R75, the vegetated dune started at about 1.0 m contour with a steep slope just landward. Foreshore experienced significant erosion, with shoreline (0 m NAVG88) moved landward about 11.1 m from 48.8 m to 59.9 m from the benchmark. There was an active berm at 44.5 m from
benchmark and was eroded by the hurricane with the berm crest elevation decreasing 0.3 m. Sand loss on the dry beach was 7.5 m$^3$/m. The pre-Irma sandbar was located at 120.0 m from the benchmark. It moved seaward for 40.2 m and was significantly flattened. The elevation of sandbar crest decreased 0.9 m, with a sand-volume loss of about 1.9 m$^3$/m. Similar to the previous profiles, this profile also had a large negative volume change, with a sand-volume loss of about 20.9 m$^3$/m. Again, a considerable amount of sand was transported seaward beyond the short-term closure depth.

Figure 35. Beach profile change at survey line R75 due to Irma

Beach experienced severe erosion during hurricane Irma at profile R84 (Figure 36). Dune field above 1.0 m was largely stable with minimal sand volume change. The apparent volume
change landward of the dune crest was caused by inconsistency of survey coverage. Dune line was almost unchanged at 23.4 m from the benchmark. An active berm at 29.2 m was eroded and the elevation of the crest at the same location decreased 0.3 m. Foreshore experienced relatively large erosion. Sediment loss of dry beach was about 9.7 m$^3$/m during hurricane. Shore line at 0 NAVD88 contour moved landward 11.0 m from 44 m to 33 m from the benchmark. Prior the hurricane, elevation of sandbar crest was -1.2 m. Its elevation decreased to -2.0 m and the bar moved seaward 24.8 m after the hurricane. Sediment volume of sandbar decreased 8.7 m$^3$/m. Volume loss of the entire profile above the depth of closure was 11.6 m$^3$/m. Foreshore slope was almost unchanged. This profile illustrates an apparent divergence at the seaward end of the survey, suggesting that the short-term closure depth did not hold during the impact of Hurricane Irma, as controlled by the significant negative surge.

Figure 36. Beach profile change at survey line R84 due to Irma
Profile R91 (Figure 37) is located on Indian Shore. The measured beach-profile change is similar with that measured at R75. Dune field was relatively stable with minimal dune line location change and dune volume change. An active berm at 38.4 m from the benchmark was eroded. It was replaced by a gently sloping beach with the elevation of the berm decreased 0.3 m from 0.9 m to 0.6 m. Shoreline at 0 m NAVD88 retreated 8.0 m from 60.0 m to 52.0 m. Dry beach had a considerable negative volume change of 6.4 m$^3$/m. The sandbar was at 138.4 m from the benchmark before the storm and migrated seaward about 28.8 m. The sandbar height changed from 0.7 m to 0.4 m, indicating that it was substantially flattened. The sand bar had a significant volume loss of 14.0 m$^3$/m. The entire profile was stable and it didn’t lose sand during the hurricane. Similar to the previous profiles, the profiles are not apparently converging at the seaward end of the survey.

Figure 37. Beach profile change at survey line R91 due to Irma
North Redington Beach section includes profiles from R100 to R107. Based on beach profile R105 (Figure 38), dune field remained stable with little dune line position change and dune-volume change. The active berm at 65.0 m from the benchmark moved landward 10.0 m. At the location of approximately 80 m from the benchmark, ridge and runnel has started to develop shortly after the hurricane. Sand loss on the dry beach was 4.8 m³/m. Shoreline moved landward about 6.0 m. Very large sandbar movement was measured. It migrated seaward from 130.9 m to 173.4 m from the benchmark, or 42.5 m seaward migration. The sandbar height decreased 0.4 m and sand-volume loss was 9.9 m³/m. Different from the other profiles, R105 profile had a positive sand volume change which was 14.0 m³/m above the short-term depth of closure. Also different from the previous profiles, the pre- and post-storm profiles converged at the seaward end of the survey.

Figure 38. Beach profile change at survey line R105 due to Irma
The Redington Beach section is represented by profile R109. The dry beach experienced significant erosion during the hurricane. Similar to most of the previous profiles, dune field did not experience significant erosion. Dune height and dune line were almost unchanged. Therefore, the volume change of dune was nearly 0 during hurricane. Profile 109 illustrates clearly that dry beach was severely eroded with a sand volume loss of 5.9 m$^3$/m. It is worth noting that this is almost the entire pre-storm dry beach. Shoreline moved landward about 7.4m from 23.0 m to 15.6 m. The pre-hurricane active berm located at 11.4 m was eroded. Elevation of the berm crest decreased from 0.9 m to 0.6 m. Similar to the case at profile R105, a ridge and runnel system was starting to develop at about 30.0 m from the benchmark two weeks after the hurricane. The pre-Irma profile had a sandbar at 72.0 m from the benchmark. It moved seaward 33.9 m and was located at 105.9 m from the benchmark after the hurricane. Height of sandbar decreased 0.5 m. And sand-volume loss from the bar was about 10.3 m$^3$/m. Similar with R105, profile R109 had positive sand volume change of 4.4 m$^3$/m. Also similar to profile R105, the pre- and post-storm profiles converged at the seaward end of the survey.
Figure 39. Beach profile change at survey line R109 due to Irma
Chapter 5: DISCUSSION

As described in the previous chapters, Hurricanes Hermine and Irma are quite different in terms of strength and track, and therefore influenced the study area quite differently. The major difference is that Hermine generated a prolonged storm surge superimposed on high waves, while Hurricane Irma, although a much stronger hurricane based on Saffir–Simpson scale, generated a significant negative surge at the peak of the storm. In this chapter, the morphological impacts caused by the two hurricanes are compared and discussed.

5.1 Influence of Storm Surge on Beach Profile Changes

Comparing the water-level anomalies generated by Hurricanes Irma and Hermine, variation of water level during the two hurricanes was distinctly different. During Hurricane Irma, elevation of the water level was below the predict value during the peak of the hurricane (Figure 22). The offshore-directly strong NE wind (Figure 17) generated a negative surge of -1.1 m (Figure 22). On the contrary, Hurricane Hermine generated up to 1 m storm surge (Figure 15) by the onshore-directly SW wind. It is worth noting that for both hurricanes, the peak storm wind approached the coastline at a highly oblique angle. Therefore, impacts of Hurricane Hermine reflected the beach changes associated with high waves superimposed over a high water level. On the other hand, impacts of Hurricane Irma reflected beach changes
associated with high waves with a depressed water level.

As discussed earlier, Hurricane Hermine caused significant dune erosion in terms of dune volume loss (Table 1) and dune line retreat (Table 2), while Hurricane Irma only caused minor dune erosion (Tables 3 and 4). As discussed earlier, the large dune line change caused by Hurricane Irma at profile R67 was influenced by the artificial selection of the 1 m contour as dune line. In terms of morphology and vegetation line, this level sometimes does not accurately represent the dune line, as for the case of R67.

Table 1. Sand volume change caused by Hurricane Hermine ($m^3/m$)

<table>
<thead>
<tr>
<th>profile</th>
<th>61</th>
<th>67</th>
<th>75</th>
<th>84</th>
<th>91</th>
<th>105</th>
<th>109</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune</td>
<td>-3.0</td>
<td>-7.2</td>
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<td>-8.9</td>
<td>-10.8</td>
<td>-1.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>Dry Beach</td>
<td>-1.9</td>
<td>-1.4</td>
<td>-4.2</td>
<td>-9.3</td>
<td>-8.2</td>
<td>-4.0</td>
<td>-3.9</td>
</tr>
<tr>
<td>Sandbar</td>
<td>9.8</td>
<td>0.1</td>
<td>6.3</td>
<td>5.8</td>
<td>-1.1</td>
<td>-4.0</td>
<td>-3.4</td>
</tr>
<tr>
<td>Beach</td>
<td>-39.3</td>
<td>-7.9</td>
<td>-12.0</td>
<td>-5.4</td>
<td>-12.2</td>
<td>-28.2</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Table 2. Contour line position change caused by Hurricane Hermine (m)

<table>
<thead>
<tr>
<th>profile</th>
<th>61</th>
<th>67</th>
<th>75</th>
<th>84</th>
<th>91</th>
<th>105</th>
<th>109</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore line</td>
<td>-5.2</td>
<td>-0.6</td>
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<td>-1.0</td>
<td>-15.0</td>
<td>-7.5</td>
<td>1.0</td>
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<tr>
<td>Dune line</td>
<td>0.0</td>
<td>-6.0</td>
<td>-8.0</td>
<td>-12.0</td>
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<td>-5.0</td>
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<tr>
<td>Sand bar</td>
<td>24.0</td>
<td>10.5</td>
<td>12.1</td>
<td>17.9</td>
<td>14.4</td>
<td>2.5</td>
<td>3.7</td>
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<tr>
<td>Foreshore slope</td>
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<td>0.022</td>
<td>0.013</td>
<td>-0.160</td>
<td>-0.003</td>
<td>-0.010</td>
<td>-0.024</td>
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</tbody>
</table>
Table 3. Sand volume change caused by Hurricane Irma (m³/m)

<table>
<thead>
<tr>
<th>profile</th>
<th>61</th>
<th>67</th>
<th>75</th>
<th>84</th>
<th>91</th>
<th>105</th>
<th>109</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune</td>
<td>-1.3</td>
<td>-3.0</td>
<td>0</td>
<td>-4.8</td>
<td>0</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>Dry Beach</td>
<td>-4.1</td>
<td>-4.1</td>
<td>-7.5</td>
<td>-9.7</td>
<td>-6.4</td>
<td>-4.8</td>
<td>-5.9</td>
</tr>
<tr>
<td>Sandbar</td>
<td>-6.8</td>
<td>-5.7</td>
<td>-1.9</td>
<td>-8.7</td>
<td>-14.0</td>
<td>-9.9</td>
<td>-10.3</td>
</tr>
<tr>
<td>Beach</td>
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<td>0.0</td>
<td>14.0</td>
<td>4.4</td>
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</tbody>
</table>

Table 4. Contour line position change during Irma (m)

<table>
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<tr>
<th>profile</th>
<th>61</th>
<th>67</th>
<th>75</th>
<th>84</th>
<th>91</th>
<th>105</th>
<th>109</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore line</td>
<td>-4.2</td>
<td>-3.5</td>
<td>-11.1</td>
<td>-11.0</td>
<td>-8.0</td>
<td>-6.0</td>
<td>-7.4</td>
</tr>
<tr>
<td>Dune line</td>
<td>-4.0</td>
<td>-10.0</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Sandbar</td>
<td>31.9</td>
<td>27.2</td>
<td>40.2</td>
<td>24.8</td>
<td>28.8</td>
<td>42.5</td>
<td>33.9</td>
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<tr>
<td>Foreshore slope</td>
<td>0.020</td>
<td>0.006</td>
<td>0.010</td>
<td>-0.007</td>
<td>-0.007</td>
<td>-0.020</td>
<td>-0.026</td>
</tr>
</tbody>
</table>

The very different storm surge levels also had significant influences on the behavior of the sand bar during the storm impacts. The sand bar moved offshore at most locations during the two storms. However, during Irma the sand bar moved a much longer distance seaward than that during Hermine (Figures 33-39). More importantly, the sand bar height decreased significantly during Irma, while during Hermine the sand bar height remained largely similar before and after the storm (Figures 26-32). The suppressed water level during Irma allowed the
high waves to erode the sand bar significant and moved the eroded sand further offshore.

Another significant difference in the profile change during the hurricanes is reflected in the short-term closure depth. During the impact of Hurricane Hermine, the pre- and post-storm profiles converged at the short-term closure depth at most of the locations or showed an apparent trend of converging (Figures 26-32). During the impact of Hurricane Irma, the pre- and post-storm profiles did not converge at the short-term closure depth at most of the locations north of the headland (Figure 33 and 35) or did not show an apparent trend of converging (Figures 34 and 36). South of the headland, the pre- and post-storm profiles mostly converged at the short-term closure depth (Figures 38 and 39). The high waves on top of the negative surge during Hurricane Irma resulted in much more active sediment transport in the offshore portion of the profile, i.e., near the short-term closure depth, that does not experience active sediment transport during normal conditions or during a storm with a positive surge such as Hermine.

In summary, the positive surge during Hurricane Hermine allowed the high storm waves to reach the part of the beach that is typically dry. This resulted in considerable dune erosion and landward retreat of the dune line, which is a typical beach morphological response to hurricane impacts. The rather unusual negative surge associated with Hurricane Irma allowed the high waves to act on the portion of the beach that typically does not experience active sediment transport under normal conditions. This resulted in the erosion of the sand bar and significant reduction of the sand bar height in addition to considerable sediment transport and morphology change seaward of the short-term closure depth.
5.2 Influence of Background Erosion Rate and Shoreline-Orientation Change

Beach profile R61 is located within an aggressive erosional hot spot with large background erosion rate due to a divergence in longshore sand transport. During the impact of Hurricane Hermine, sand-volume loss at this profile, 39.3 m$^3$/m, was much larger than at other profiles on Sand Key (Table 1). During the impact of Hurricane Hermine, the storm waves approached from the south. The elevated longshore sand transport to the north generated by the storm may be responsible for the large erosion across the entire profile at R61.

During Hurricane Irma, the wave approached the coast from the north over a depressed water level. The profile R61 at erosional hot spot suffered the second most erosion with 22.3 m$^3$/m of sand eroded from the entire profile. The most erosion occurred at profile R67 just to the south of the erosional hot spot extending from R59 to R65 (Roberts and Wang, 2012). The elevated longshore sand transport to the south may be responsible for the large erosion at these two locations.

The broad headland, roughly in the middle of Sand Key, has a significant influence on the spatial patterns of sand volume change. During the impact of Hurricane Hermine, except at profiles R61 and R109, the sand volume losses over the entire profile were significantly greater to the south of the headland than those to the north (Table 1). As discussed above, profile R61 is located in an aggressive erosional hot spot with a significant influence from the large background erosion rate. Profile R109 is not too far north of John’s Pass ebb tidal delta, within 3.5 km. It gained the sediment volume of about 15.5 m$^3$/m and may have benefited from sand supply from the delta as well as wave sheltering by the large ebb delta.
During the impact of Hurricane Hermine, the waves approached from SSW (Figure 11). The protruding headland sheltered the southerly approaching waves resulting in higher wave along the southern flank as compared to the wave height along the northern flank. The wave modeling results illustrated this pattern well (Figure 8). Therefore, the greater erosion as caused by Hurricane Hermine south of the headland is related to higher waves while the relatively less erosion to the north of the headland is related to the smaller waves. Therefore, the sand loss of dune field increased from northern headland beaches to headland and decreased from headland to southern headland beaches (Table 1).

The spatial trend of sand volume change associated with Hurricane Irma is the opposite of the trend for Hermine as discussed above. The sand volume changes to the north of the headland is much greater than those to the south. Interestingly, some of the profiles to the south of the headland actually gained sand (Table 3).

Very different from Hurricane Hermine, the storm waves associated with Hurricane Irma approached from the north. The wave sheltering by the protruding headland resulted in higher waves to the north of the headland and lower wave to the south. This is well illustrated by the wave modeling results (Figure 7). The higher waves to the north of the headland resulted in the more erosion as measured by the pre- and post-storm surveys. The lower waves to the south of the headland resulted in less erosion. Furthermore, the beach to the south of the headland may have benefited from the southward longshore transport during the storm. This explains the profile volume gain measured as some of the profiles.

The protruding headland also had significant influences on dry beach sand volume
changes and shoreline position changes. More sand was eroded from the dry beach along the broad headland than along the beaches both north and south of it. This is true for both hurricanes (Tables 1 and 3) despite the very different wave incidence. As shown in the wave modeling results (Figures 7 and 8), the headland experiences relatively high wave regardless of north or south wave approach. Corresponding to the higher volume of dry beach erosion, shoreline retreat was also the largest around the headland (Tables 2 and 4). For Hurricane Hermine, the peak shoreline retreat occurred at profile R91 just to the south of the headland, most likely corresponding to the southerly wave approach during the storm. For Hurricane Irma, the peak shoreline retreat occurred at profiles R75 and R84 just to the north of the headland, corresponding to the northerly wave approach during the storm.

The headland also had an influence on foreshore slope. North of the headland, the foreshore slope became steeper after the storm, while the foreshore slope became gentler south of the headland (Table 2 and 4). This is the case for both storms. The reason for this foreshore slope change is not clear.

In summary, background erosion rate played a significant role in beach behavior during the storm impacts. For both storms, the erosional hot spot at North Sand Key with the highest background erosion rate suffered the most sand loss over the entire profile. The broad headland and associated shoreline orientation change also had significant influence on the beach behavior during the storm impacts via controlling wave propagation patterns. During Hurricane Hermine, the headland sheltering of the southerly approaching waves resulted in more erosion to the south than to the north. The opposite happened during Hurricane Irma with northerly...
approaching wave. More erosion occurred to the north of the headland than that to the south. Finally, the relatively high wave at the headland resulted in drier beach erosion and landward retreat of shoreline.

5.3 Morphodynamics of Sand Bar during the Storm Impacts

The sand bar behaved quite differently during the two storms, most likely controlled by very different storm surge conditions. During the impact of Hurricane Hermine the sand bar gained volume to the north of the headland and lost sand to the south (Table 1). The southerly wave approaching may have transported the sand from south to north along the sand bar resulting in sand gain in the northern section and loss in the southern section. The sand bar moved seaward significantly, ranging from 10.5 to 24.0 m, to the north of the headland (Table 2). While to the south of the headland, the sandbar only moved slightly seaward, less than 5.0 m in most locations.

The sand bar behaved very differently during Hurricane Irma, as compared to that during Hurricane Hermine. It is reasonable to assume that the significant negative surge allowed high storm waves to induce much more active sediment transport over the sand bar during Irma than during Hermine or normal conditions. This resulted in substantial reduction of sand bar height and subsequently sand volume loss at all profile locations (Table 3). The sand bar moved seaward significantly at all profile locations, ranging from 24.8 to 42.5 m, which is much greater than that during Hurricane Hermine.

In summary, the different storm surge condition resulted in different sand bar behavior
during the storm impacts. During the Hermine impact, the sand bar remained similar height but moved seaward. The seaward movement is much greater to the north of the headland than to the south. During the Irma impact, the sand bar was severely flattened resulting in substantial sand volume loss from the bar. The bar was also moved seaward significant by the storm.
Chapter 6: CONCLUSIONS

Storm surge plays an important role in controlling storm induced beach changes. Hurricane Hermine in 2016 generated positive surge which caused considerable dune erosion and dune line retreat. On the other hand, the Hurricane Irma in 2017 generated negative surge which caused sand bar erosion and a decrease in height. Moreover, the short-term closure depth moved seaward during the Irma. In addition, the variation of storm surge also caused the sand bar to behave differently during the two hurricanes. During the Hurricane Hermine, the sand bar moved seaward and the movement of sandbar along the northern flank of the headland was much greater than that along the southern flank. The sand bar height was almost unchanged. During the Irma, the volume of sand bar reduced significantly and the bar height was reduced and flattened.

The background erosion rate and shoreline-orientation change in the study area also influence the beach changes during the hurricane impact. North Sand Key had the highest background erosion rate along the entire Sand Key barrier island. Therefore, during the Hurricane Hermine and Irma, the most severe sand loss occurred in North Sand Key. In the middle of the Sand Key there is a broad headland with shoreline orientation change of 65 degree which induced a difference in beach erosion between the northern and southern flanks of the headland. During the Hurricane Hermine, the southern beaches experienced more severe
erosion than the northern beaches because the headland sheltered the southerly approaching waves. On the contrary, the northern beaches were eroded much more than the southern beaches during hurricane Irma as a result of the fact that the northerly approaching incident wave was sheltered by the headland. The findings of this study demonstrate that beach and nearshore environment can respond to storm impact quite differently as controlled by different characteristics of the storms and the specific beach morphology.
REFERENCES


