Impacts of Hurricane Mathew on adjacent developed and undeveloped barrier islands in southeastern North Carolina

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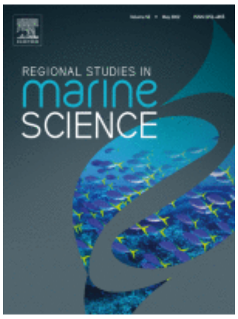

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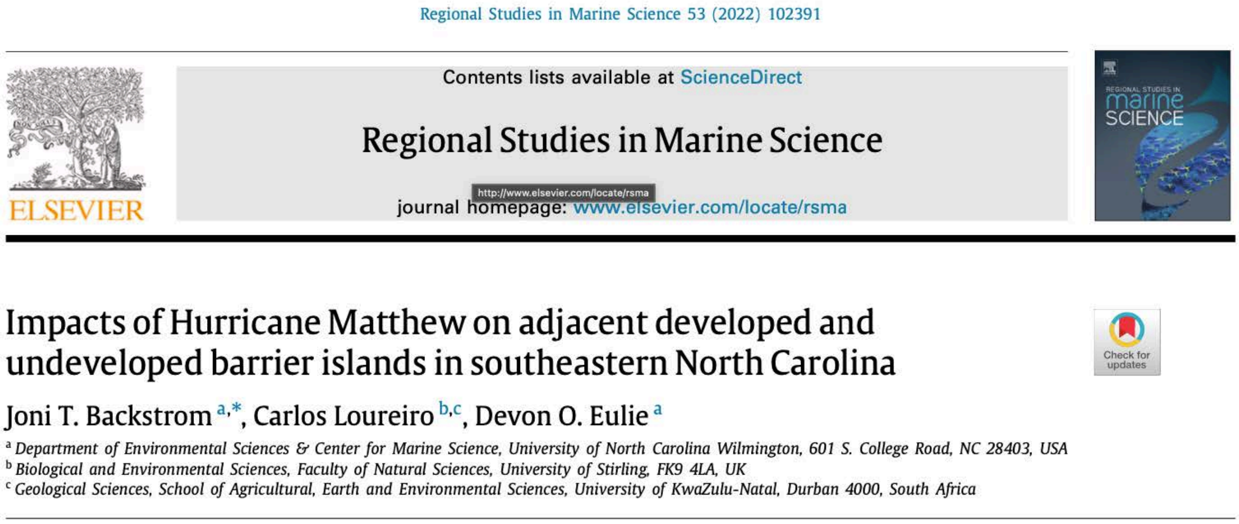

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Impacts of Hurricane Matthew on adjacent developed and undeveloped barrier islands in southeastern North Carolina

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Abstract: High-magnitude storms such as hurricanes can cause significant and potentially long-lasting morphological coastal change, particularly along low-lying barrier islands. This study investigated the impacts of Hurricane Matthew (2016) on neighboring undeveloped Masonboro Island reserve and engineered/nourished Wrightsville Beach barrier islands, located in southeast North Carolina. Using a combination of high-resolution pre- and post-storm RTK-GPS beach surveys, coupled with direct observations, storm surge calculations and aerial imagery, a range of contrasting storm-induced coastal changes and impact regimes were identified across the two adjacent barriers. Storm impacts were especially pronounced across low-lying undeveloped central/southern Masonboro Island, which was dominated by significant overwash processes, leading to landward directed barrier crest migration. In contrast, only short-lived and minor collision with the base was observed at Wrightsville Beach, were storm impacts were dominated by a swash storm regime resulting in significant beach erosion. Field- and aerial based observations match well with modeled storm surge height calculations. This study offers a real-time example of how geomorphologically different neighboring islands respond to specific storm events, and how storm impact regime type and duration helps explain differences in barrier responses. Similar storm impacts are likely at other locations with comparable barrier island settings and differing coastal management approaches.

Keywords: storms; overwash; coastal erosion; RTK-GPS; beach profiles; frontal dunes, NERRS

1. Introduction

High-magnitude storms such as hurricanes are known to cause significant impacts on low-lying coastal regions (Hayes, 2005). Impacts can range from minor swash-induced beach erosion to complete inundation and potential disintegration of entire barrier island systems (Sallenger, 2000). The severity of coastal storm impacts is most often determined by the magnitude of the event, especially significant wave heights (H_s) and storm surge levels (Fritz *et al*., 2007) and its interaction with the morphology of the coastal barrier (Sallenger, 2000). Coastal geomorphology, shoreline orientation and storm trajectories, in addition to local characteristics like sand supply, beach width and underlying geology, also undoubtedly play an important role in explaining site-specific, storm-induced coastal changes (Orford and Carter, 1982; Riggs *et al*., 1995; Theiler *et al*., 1995; Backstrom *et al*., 2008; Long *et al*., 2014; Backstrom *et al*., 2015; Hapke *et al*., 2016).

There are numerous studies of hurricane-induced coastal impacts on developed and undeveloped barrier islands. Some examples include the coasts of Louisiana (e.g. Stone et al., 1997), Florida (Wang et al., 2020; Bacopoulus and Clark, 2020) and the northeast coast of the United States (Williams, 2015). Several studies have also shown how differing coastal management strategies influence the morphologic evolution of adjacent barrier islands, e.g. along the Gulf coast of Florida (Elko and Davis, 2004), Ocean City/Assateague Island in Maryland (McNamara and Werner, 2008), Florida (Bacopoulus and Clark, 2020) and even locally along southeast North Carolina (USACE, 2000; White and Wang, 2003). These studies tend to show higher retreat rates for undeveloped barrier islands compared to developed ones, especially those which are periodically renourished.

Hurricane Matthew was one of the strongest Atlantic hurricanes of the 2016 season, causing significant coastal devastation across the Caribbean and the southeast coast of the United States, before eventually making landfall near the North Carolina/South Carolina border as a Category 1 hurricane. The main objective of this study was to examine and compare the direct coastal impacts of Hurricane Matthew on two adjacent barrier islands near Wilmington, North Carolina; Wrightsville Beach, which is developed and periodically re-nourished and adjacent Masonboro Island, an undeveloped and protected natural reserve. The geomorphological differences, contrasting coastal management approaches and bordering nature of the two islands make this an important study to understand site-specific storm responses between neighboring developed and undeveloped barrier islands.

2. Study Area

2.1 Regional Geologic and Oceanographic Setting

Wrightsville Beach and Masonboro Island are located along the high-energy, southwest flank of Onslow Bay, North Carolina (Figure 1). This moderate to high-energy embayment is dominated by a series of north-south orientated transgressive barrier islands separated by tidal inlets. The barrier islands are mostly low-lying and narrow, with the landward side often bordering marsh-filled lagoons. The coastal and shoreface sections are underlain by Late Cretaceous to Pleistocene aged units, comprising a mix of Oligocene siltstone, Plio-Pleistocene limestones and late Pleistocene *Coquina* outcrops (Snyder *et al*., 1994). The southern part of Onslow Bay is relatively sediment poor, with numerous offshore rock outcrops or 'hard bottoms' which are prevalent in the region (Cleary *et al*., 1996). The sandy barrier beaches are primarily composed of a combination of fine to medium quartz sand and carbonate shells and gravels, although larger limestone and siltstone lithoclasts are also deposited on the beach, especially after storm events.

Regional sediment transport is predominantly from north to south, although some northward driven longshore transport does occur during the summer months and episodic nor'easters in the winter. The numerous tidal inlets often trap the dominant southward moving sediment, resulting in wide accumulations of sand on either side of the inlets, depending on ebb channel orientation and the location of the offshore delta.

The southeast coast of North Carolina lies in the direct path of Atlantic tropical cyclones and nor'easters. Some notable hurricanes which have directly impacted the region include Hazel (Cat 4, 1954), Bertha (Cat 2, 1996), Fran (Cat 3, 1996), Floyd (Cat 2, 1999) and Matthew (Cat 1, 2016). More recently, the region has also been impacted by hurricanes Florence (Cat 1, 2018), Dorian (Cat 2, 2019) and Isaias (Cat 1, 2020).

Average significant wave heights and dominant wave periods, based on 10 years of local wave buoy observations (www.CORMP.org/ILM2), are 0.93 m and 7.7 s, respectively. Storm-driven significant wave heights can reach 5.0 m, with up to 18-20 s peak wave periods. According to NOAA tide station #8658163, located in Wrightsville Beach, this part of Onslow Bay is microtidal, with a mean tidal range of 1.2 m.

2.2 Wrightsville Beach (Island) and Masonboro Island

Wrightsville Beach is a 7.5 km long by approximately 500 m wide, well-developed barrier island located in southeast North Carolina (Figure 1). Wrightsville Beach is arguably one of the most engineered beaches in the USA in terms of sand placement, with the first nourishment taking place as early as 1965 (USACE, 2019). This initial project was followed by 1.1 million m^3 (1.4 million yd^3) of sand placement in 1970 and complete restoration in 1980/1981. The Water Resources Development

Act of 1986 extended the beach nourishment for 50 years through 2036, with a 4-year recurring cycle. To date, eight projects have been completed since 1986, with an average of 600,000 m^3 (780,000 yd^3) per nourishment (USACE, 2019), for a cumulative volume of 9.7 million m^3 (12.7 million yd^3) since 1965. The most recent beach nourishment took place in the spring of 2018, with the placement of approximately 651,000 m^3 (852,000 yd^3) of sand across the central reaches of the island (pers. com Stephen Fabian, USACE). Initially, sand for beach nourishment was dredged from the adjacent Banks Channel; however, since 1981 it has been obtained from Masonboro Inlet, a dual jettied inlet system which forms Wrightsville Beach's southern boundary and which separates it from Masonboro Island (Figure 1).

Beach nourishment has resulted in overall long-term accretion for Wrightsville Beach, with rates of about +0.5 to +2.0 meters per year (NCDCM, 2019). Wrightsville Beach is flanked to the north by Mason Inlet, a small rapidly migrating tidal inlet system which was artificially relocated (and stabilized) approximately one kilometer to the north in 2002 (Cleary and Fitzgerald, 2003). The far north end of Wrightsville Beach is classified as an Inlet Hazard Area (IHA) due to the unpredictable nature of sediment transport processes associated with Mason Inlet.

Maximum elevations along Wrightsville Beach are close to 5.4 m. The northern and southern parts of the island have wide, vegetated dune systems and are protected as bird-nesting sanctuaries. The central part of the island is fully developed, comprising a mix of single-family homes, motels, hotels and commercial developments. This study focused on the northern, central and southern sections of Wrightsville Beach, corresponding to WB01, WB02 and WB03 respectively, from north to south (Figure 1).

Masonboro Island is a 13 km long, low-lying, narrow and undeveloped barrier-island located just south of Wrightsville Beach (Figure 1). Masonboro is one of 29 protected coastal sites that forms part of the

National Estuarine Research Reserve System (NERRS), a network of coastal sites 'designated to protect and study estuarine systems.' Established *via* the Coastal Zone Management Act, the reserves comprise a partnership program between NOAA and the respective coastal states. The four main management priorities of the reserve system are: stewardship, research, training and education. Development is strictly prohibited and other anthropogenic activities are strongly regulated.

The far northern and southern ends of the island have only been nourished a few times with minimal volumes of sand, as part of adjacent inlet maintenance projects, and not nearly to the same extent as Wrightsville Beach to the north. Masonboro Island is separated in the south from Carolina Beach Inlet, which forms the northern boundary of Carolina Beach, which is also well-developed and periodically re-nourished. Maximum elevations across Masonboro Island range from approximately 5.0 m in the north (associated with the northern jetty inlet fillet) to near 2.5 m along the central and southern parts of the island, which form the focus of this work. Dune erosion, overwash processes, barrier breaching and washover are a common occurrence on Masonboro Island, especially during storm-induced inundation and surge events (Cleary and Hosier, 1979; Cleary *et al.*, 1993; Doughty *et al.*, 2006). Most beach sediments are composed of a combination fine-grained, reworked residual quartz and/or fine- to coarse-grained carbonate clasts, derived from bio-erosion of offshore hard bottom reefs, which are prevalent along the shoreface and further offshore (Cleary and Pilkey, 1968**;** Riggs *et al.*, 1995). Average annual beach erosion rates are high, reaching up to 10 m/year in some locations (Cleary and Hosier, 1979; Doughty *et al.*, 2006; NCDCM, 2019). According to the North Carolina Department of Coastal Management (NCDCM, 2019) the northern 300 m of Masonboro Island, situated in the lee of the jetty, is stable to accreting. However, the rest of the island is eroding rapidly, with rates ranging from about 1-3 m / year, increasing southwards. The far south end of Masonboro Island, also classified as an Inlet Hazard Area associated with Carolina Beach Inlet, has erosion rates as high as 10 m/year based on long-term comparisons from 1933 (NCDCM, 2019). This study examined three locations on Masonboro Island, corresponding to central MB01 & MB02 and southern MB03, from north to south, respectively (Figure 1).

Insert Figure 1 and caption

2.3 Hurricane Matthew

Hurricane Matthew initially formed as a tropical storm off the coast of Barbados on Sep 29th, 2016. By October 1st it had reached peak Category 5 status, with a minimum central pressure of 940mb and sustained winds of 71.5 m/s (160 mph) as it skirted off the northeast coast of Venezuela (Figure 2). It maintained Category 4 status as it turned north and made its way across Haiti and Cuba, before reaching the Bahamas as a Category 3 hurricane. Matthew maintained major hurricane status as it moved northward along and just offshore the Florida coast before finally making landfall on October 8th near McClellanville, South Carolina as a Category 1 storm with 33.5 m/s (75 mph) winds (Figure 2). It crossed into the south coast of North Carolina later on the same day, maintaining Category 1 status and 33.5 m/s (75 mph) winds before finally exiting into the North Atlantic as a post-tropical storm on Oct 8th.

Insert Figure 2 and caption

2.3.1 Hurricane Matthew - Meteorological and Oceanographic Data

Local continuously recorded meteorological and oceanographic data were obtained from the ILM2 offshore wave and weather buoy, operated by the Coastal Ocean Research Monitoring Program (www.CORMP.org/ILM2) at UNC-Wilmington. The buoy is located approximately 10 km east and offshore of Masonboro Island, in 15.2 m water depths. Peak significant wave heights (H_s) measured at ILM2 during Matthew reached 4.97 m (Figure 3), with corresponding wave periods of 11 s on the morning of October 8th. It is important to point out that the wave heights from Matthew were the largest recorded by the local buoy since the station became operational in 2008, making it the most significant storm in well over a decade to impact this part of North Carolina. Wave periods ranged from a minimum of 4 s, when the eye was located closest to the study area, to a maximum of 15 s as the storm moved away from the North Carolina coast. At the height of the storm, local maximum recorded wind speeds were 22 m/s (49 mph), switching from the south to the north as the center of the storm crossed the southern North Carolina coast, with barometric pressure dropping to 985 mb at the peak of the storm (Figure 3).

Insert Figure 3 and caption

Local storm surge and tide data, comprising part of regional southeast Hurricane Matthew storm investigations undertaken by the US Geological Survey (USGS), were also available for this study. Maximum storm surge measured at the Wrightsville Beach NOAA tide gauge reached 1.34 m above NAVD 88, and peak storm-tide high-water marks measured by the USGS, which reflected the combined storm-surge and wave forcing, reached 3.35 m at Wrightsville Beach (NCNEW18014) and 4.18 m further south at Carolina Beach (NCNEW18339) on October 8th (Frantz *et al*., 2016). Due to the undeveloped nature and difficulty of accessing Masonboro Island, no site-specific storm high-water mark observations were available. However, it is reasonable to assume similar peak storm water levels between 3.5 and 4 meters across Masonboro Island at the height of the storm.

3. Data Sources and Methods

High-resolution pre- and post-storm site visits to Wrightsville Beach and Masonboro Island were undertaken on Sep 29th/Oct 2rd and Oct 10th/14th respectively, approximately one week before and one week after Hurricane Matthew made landfall. The ability to capture high-resolution beach profiles within a few days before and after the storm provided an excellent dataset with which to evaluate the direct morphological impacts from the category 1 hurricane.

Cross-shore beach elevation surveys were recorded at six separate beach locations, representing northern (WB01), central (WB02) and southern (WB03) parts of Wrightsville Beach and central (MB01 & MB02) and southern (MB03) sections of Masonboro Island (refer to Figure 1). Elevation data were measured at low tide using a high-resolution Trimble R10 series real-time kinematic (RTK)-GPS survey system, with position and elevation accuracies of approximately ± 2 - 5 centimeters. The RTK surveys were set on 'continuous topo' mode, with elevation data collected every 2.0 meters along the profiles. Post-storm transects were surveyed by occupying the same pre-storm profile locations, resulting in spatially accurate and comparable pre- and post-storm transects. For Wrightsville Beach, the surveyed profiles extended from approximately the low water line, across the berm, and as far as the dune base (extended dune and back barrier topography of the profiles, presented in Figure 5, was obtained from a 2016 USACE Lidar survey and merged with the RTK-GPS data). The profiles for Masonboro Island extended across the entire width of the island, from approximately low tide as far landward as the back-barrier lagoon. A total of five parallel survey lines, with 25 m line spacing and up to 120 m in length, were collected for each of the six representative beach locations. Real-time corrections for the RTK-GPS were obtained from a nearby Continuously Operating Reference Station (CORS at https://geodesy.noaa.gov/CORS/), a network of stations operated by the US National Geodetic Survey. All beach elevation data were collected in NC State Plane (meters), relative to NAVD 88. Site visits also included over 100 pre- and post-storm GPS-enabled digital photos, capturing direct impacts of the storm shortly before and after landfall at all six locations. The profiles and photographs were complemented with high-resolution post-storm aerial photography collected by NOAA's Remote Sensing Division 'to support NOAA national security and emergency response requirements.'

An assessment of storm-response was based on Sallenger's (2000) Storm Impact Scale. Characterization and computing of the hydrodynamic forcing was performed by adopting: i) real-time water level data collected at NOAA's tide gauge, located off Wrightsville Beach and ii) wave data obtained from the CORMP ILM2 offshore wave buoy. Based on the time series of wave height and water level, maximum water levels were calculated for the period between the 7th and the 10th of October, with extreme runup (R_2) computed according to Stockdon et al (2006). Computations were performed from the continuous offshore ILM2 deep water wave measurements using standard linear wave theory. Beach face slope was obtained for each of the six pre-storm RTK survey locations at both barrier islands.

4. Results

The high-resolution monitoring of pre-storm and post-storm morphological changes across Wrightsville Beach and Masonboro Island enabled a detailed characterization of storm impacts and an identification of the primary morphodynamic mechanisms of storm-induced erosion. Overall, despite the close proximity of the study sites, Hurricane Matthew induced significantly different responses at each barrier island. Wrightsville Beach was subjected to only minor impacts to the dune and beach berm, while at Masonboro Island erosion was widespread and impacted the entire barrier, from the beach face to the backbarrier margin. The results for each study area and profile are presented in the following sections, detailing the dominant morphological changes observed visually during the field surveys and quantified through the barrier profile measurements and computed hydrodynamic forcing.

4.1 Wrightsville Beach

In terms of main impacts caused by Hurricane Matthew in Wrightsville Beach, the results from the monitoring program indicate that these were mostly limited to: i) minor dune erosion and scarping and

ii) berm removal and profile straightening. These were relatively consistent along the three sections surveyed, as outlined in Figures 4 and 5.

4.1.1 North Wrightsville Beach WB01

WB01 comprises the old location of Mason Inlet, situated within a defined Inlet Hazard Area. At the time of the pre-storm survey visit, the forebeach was wide and relatively flat, backed by a discontinuous and low elevation frontal dune ridge with moderate to low vegetation cover (Figure 4A). A post-storm site visit on October 13th showed that storm-induced surge only reached as far as the base of the frontal dunes, resulting in minor erosion and scarping, coupled with vegetation loss and/or burial from sediment deposition (Figure 4B). There was no evidence of dune breaching, channelization or overwash at the site which is consistent with extreme water levels computed for this profile which indicate that only swash and collision impacts were likely to be observed (Figure 5). Although collision with the dune was computed based on the combination of morphological and hydrodynamic data, i) the prevalence of a short duration collision regime and ii) the maximun extreme water level (R_{High}) only exceeded the base of the dune by a few centimeters (Table 1), supports the negligible storm impacts on the dune but consistent erosion of the beach under a swash storm impact regime in WB01.

Pre-storm beach profile RTK data showed a near-horizontal to convex profile shape, with a low-relief 30 m wide berm extending from the frontal dunes, and maximum and minimum elevations of 1.77 m and -0.10 m (NAVD 88), respectively (Figure 5). Post-storm RTK profiles showed moderate erosion across most of the beach, with the beach changing from an accretional convex to erosional concave profile shape, attributed to the removal of the pre-storm berm under a swash impact regime. The seaward and landward margins of the beach had minimal post-storm change (Figure 5).

Insert Figure 4 and caption

Insert Figure 5 and caption

4.1.2. Central Wrightsville Beach WB02

WB02 is located along the central part of the island, where mostly single-family or multi-story homes are located. Pre-storm observations showed a wide, almost horizontal berm that dropped steeply towards the water near the high-tide line (Figure 4C). Post-storm observations revealed a much steeper beach across the length of the profile, in addition to storm-induced deposition of shell gravel onto the beach (Figure 4D). The previously wide, flat berm was eroded. There was no evidence of dune erosion or scarping at the landward margin; instead fine-grained sand was deposited in the backshore region, near the base of the dunes. Similar to WB01, while the computed storm impact parameters indicate minimal occurrence of a collision regime, this was short lived (Table 1). Although extreme water levels exceeded the base of the dune at WB02 (Figure 5), the post-storm beach profile suggests that the impact of the storm at the dune base was accretional rather than erosional. A comparison of pre- and post-storm RTK profiles confirmed significant berm erosion, profile straightening and steepening (Figure 5), which are consistent with the long duration of the swash storm impact regime (Table 1). The maximum storm-induced vertical erosion was close to 1.0 m at the seaward cusp of the berm. The morphological changes observed also support some backshore and intertidal accretion, with the material likely derived from erosion of the pre-existing berm.

4.1.3 Southern Wrightsville Beach WB03

This location is adjacent to Oceanic Pier and situated just north of the undeveloped bird sanctuary which comprises the southern part of Wrightsville Beach. The post-storm survey revealed no obvious dune impacts at this southern location (Figures 4E and 4F). Extreme water levels did not exceed the base of the frontal dunes, as shown by the lack of storm debris (wrack) and no visible dune erosion or scarping. Survey and visual observations are supported by computed storm impact regimes, since only swash regime was estimated for this section of Wrightsville Beach (Table 1).

Pre- and post-storm beach profiles comparisons confirmed minimal storm-induced change (Figure 5), especially compared to WB01 and WB02 further north. Maximum vertical erosion was ~60 cm near the central part of the beach, resulting in a slightly more concave-shaped beach after the storm. There was no change along the backshore or dune base, confirming that extreme water levels (R_{High}) did not extend as far up the beach. The eroded berm material may have been transported seaward and redistributed along the intertidal area, shown by the 50 cm post-storm deposition at the seaward end (Figure 5).

4.2 Masonboro Island.

The impacts of Hurricane Matthew on Masonboro Island were far more significant than those observed across Wrightsville Beach, especially across the central and southern sections of the island. The main geomorphological impacts included severe dune erosion, cross-barrier channel incision, formation of temporary inlets, washover fan deposition across much of the back barrier, exposure of older underlying geological units and an overall lowering and shoreward extension of the island.

4.2.1 Central Masonboro Island MB01 and MB02

These two locations are analyzed jointly because of their similar geomorphological characteristics and identical storm response. Pre-storm observations revealed a low-elevation, continuous to semi-continuous and moderately vegetated dune system backing the main beach (Figure 6A). There was evidence of previously overwashed sections, comprising narrow, infilled channels with minimal vegetation growth, which often extended across the width of the island (Figure 6B).

A post-storm site visit, approximately one week after Hurricane Matthew, revealed significant impacts to the beach, dunes and back-barrier areas at both locations. The intertidal beach was significantly narrower and steeper and often overlain with coarse shell hash, shell fragments and whole shells. The majority of the frontal dunes were severely eroded and vegetation cover was either stripped or buried (Figure 6C). Channel breaching was also widespread, especially where previously infilled channels had been identified earlier (Figure 6D). The landward margin of the island had fresh washover fans and terraces which extended into the adjacent marsh (Figure 6E). Coastal impacts were particularly notable near MB02, comprising some of the lowest elevations along Masonboro Island. Other obvious storm impacts included exposure of underlying humate sandstone on the forebeach (Figure 6F), in addition to boulder-sized clasts of peat and *coquina* which were scattered across the island. Pre-storm elevations of the foredunes ranged from approximately 3.4 m to 2.6 m for MB01 and MB02, respectively (Figure 7). The total width of the island at these locations was 90-100 m, with the longer profile corresponding to MB01. The upper beach face and frontal dune was significantly steeper compared to the sub-horizontal back-barrier region behind the main dune system. The landward margins of the beach often dropped steeply into the marshes at the back end of the island (Figure 7).

Post-storm results showed significant, up to 50 cm, erosion of the dune crest (Figure 7), supporting the idea that MB01 and MB02 were subjected to collision and overwash regimes for substantial periods of time (Table 1). While collision dominated, overwash was prevalent during periods of 2:00 to 4:30 hours at MB01 and MB02, respectively. The eroded dune crest sediment was redistributed landward in the form of washover fans and/or sheet deposits (Figure 6C and 6E) though some eroded dune sand may have been deposited on the beach face, seaward of the dunes, due to backwash and/or outwash processes. Post-storm results also showed an overall landward translation of the barrier by approximately 2 to 5 meters, corresponding to the fresh washover terraces on the landward side of the island.

Insert Figure 6 and caption

Insert Figure 7 and caption

4.2.2 Southern Masonboro Island MB03

This southernmost study site, located within an identified Inlet Hazard Area, had the widest and most continuous dune system compared to the study areas further north. Pre-storm surveys revealed a long, wide beach face and extensive berm (Figure 6G). The frontal and main dunes were well-vegetated, as was the back barrier region which extended as far landward as the marsh. Post-storm observations showed minor change, mostly confined to the foredunes and foreshore. The beach berm narrowed in response to the storm (Figure 7), coupled with limited dune erosion (Figure 6H). Survey observations were consistent with a swash impact regime and minor, though significant, duration of the collision regime (Table 1). While the modeled maximum extreme water level reached an elevation of only a few centimetres lower than the dune crest, this part of the island was not overtopped during Matthew, which is supported by field data which showed that the frontal dune crest had not been impacted or eroded by the storm surge. Morphological change was mostly limited to the foreshore and foredunes, as indicated by the occurrence of swash and collision regimes, with maximum vertical erosion of about 80 cm. The berm was cut back by approximately 20 m, with corresponding minor dune scarping. No morphological change was measured at, or landward, of the 3.25 m high frontal dune ridge (Figure 7).

Insert Table 1 and caption

5. Discussion

The coastal impacts from Hurricane Matthew across the two adjacent barrier islands were significantly different in most cases. Impacts to Wrightsville Beach were mostly limited to forebeach erosion, berm removal, profile straightening and minor frontal dune scarping. No overwash was evident anywhere along the island, and in some cases calculated storm-induced extreme water levels (R_{High}) did not even reach the dune base, especially near the southern section of the barrier. In contrast, central/southern Masonboro's MB01 and MB02 locations had significant geomorphological impacts, including overwash of the foredune, severe erosion and scarping, channel incision, overwash fan deposition and exposure of older underlying geological units. The fundamental differences in storm impact across the two adjacent islands are attributed to a number of reasons, including: type and duration of different storm impact regimes, which are related to differences in island and beach width; the height and continuity of the existing frontal dune system and, importantly, the contrasting applied coastal management strategies between Masonboro Island reserve and engineered/re-nourished and developed Wrightsville Beach. These are summarized in Table 2.

Insert Table 2 and caption

The spatial differences in Matthew's storm response are in many cases attributed to the height, width and continuity of the foredune ridge, in addition to beach width, at each location. The width and elevation of frontal dunes play a critical role in whether storm response results in an overwash regime or less severe dune erosion and offshore sediment transport (Sallenger, 2000; Houser *et al.*, 2008; Matias *et al.*, 2014). According to the USGS, peak storm-induced high-water marks, which reflect the combined forcing of storm-surge and extreme wave runup, reached 3.35 m at Wrightsville Beach and 4.18 m in Carolina Beach, south of Masonboro Island. These values are similar to the maximum extreme computed wave levels (R_{High}) of 3.19 m and 3.11 m for profiles WB03 and MB03 respectively (Table 1). The location of USGS measurements and survey profiles in this study are not the same, so differences of a few centimeters to 1 m are to be expected given alongshore variation in nearshore bathymetry and barrier configuration in different sectors.

The relatively low and discontinuous dune ridge along MB01 and MB02, with maximum elevations of approximately +2.5 m NAVD 88, combined with chronic historical overwash, makes this part of the island particularly susceptible to future and potentially more severe storm impacts, and sea level rise, resulting in channel incision and net landward migration through classic barrier-island rollover mechanisms (Leatherman, 1983). High resolution aerial storm imagery collected by NOAA shortly after Hurricane Matthew shows the recent introduction washover fans and the narrow nature of Masonboro Island, especially between MB01 and MB02 (Figure 8A). The post-storm aerial imagery confirmed significant dune erosion, localized breaching and overwash from the storm, consistent with extensive periods during which overwash and collision storm regimes dominated (Table 1). In some locations, the dry beach was no wider than 10 meters. In contrast, extreme water levels from Matthew barely reached the base of the dunes along southern Wrightsville Beach (Figure 8B), with only short periods during which a collision storm regime was prevalent. There is no doubt that the central/southern section of Masonboro Island is particularly susceptible to future storm-induced overwash, chronic erosion and the possibility of permanent breaching. This would be likely if a more intense, or slower-moving hurricane impacts the area, increasing both the magnitude and duration of the more extreme storm impact regimes. The fact that Masonboro Island is a protected island reserve would imply that no emergency inlet infilling or nourishment would be undertaken, similar to breaches in Fire Island (New York) following Hurricane Sandy in 2012 (Hapke et al., 2013) or after Hurricane Hugo impacted undeveloped Cape Island, South Carolina in 1989 (Sexton and Hayes, 1991).

Insert Figure 8 and caption

The higher foredune ridges and wider beach at WB02 and WB03 along Wrightsville Beach and MB03 along southern Masonboro Island prevented the occurrence of overwash, since Hurricane Matthew's extreme water levels were not high enough to exceed and extend beyond the more robust dune systems. As a result, storm impacts at Wrightsville Beach were restricted to short-lived collision but extensive swash storm regimes. Presently, the more stable northern and southern sections of

Masonboro Island are more resilient to storm impacts, resulting in barrier-island stability or minor erosion, rather than extensive storm-induced overwash as seen along the central parts of the island. Ongoing long-term coastal change, increasing storm frequency (this part of NC has now been impacted by four hurricanes between 2016 and 2020), coupled with increasing sea levels, will most likely contribute to accelerated retreat rates for central/southern Masonboro Island, and potentially create a lateral 'offset' from areas further north and south over time (Figure 9). Long-term chronic erosion rates, as high as 10/year (NCDENR, 2019), that have been measured for decades along Masonboro Island, coupled with the fragile and narrow nature of the barrier, point towards faster landward (rollover) migration and erosion compared to other adjacent areas. Other low-lying, undeveloped and chronically eroding barrier islands are facing similar rapid landward retreat through overwash processes and inundation during storms.

Sallenger (2000) categorized storm impacts for barrier islands based on morphological features, storm surge and wave forcing. The Storm Impact Scale ranged from swash, to collision, overwash and inundation, depending on the severity of storm impacts. Application of Sallenger's model to Wrightsville Beach confirms that impacts were predominantly in the swash regime, with minor collision during short periods of time. RTK surveys and post-storm observations confirm that most impacts were limited to the swash zone and berm erosion, with only minor frontal dune erosion and scarping. Similar impacts were observed at MB03 in the southern extremity of Masonboro Island, comprising higher dunes and a wider beach, but in this location, more prolonged collision enhanced changes in the upper part of the beach profile and foredune face. The impact regimes during Hurricane Mathew in the central section of Masonboro Island (MB01 and MB02) were more severe, not only by a more extensive duration of the collision regime, but also because the overwash regime was prevalent during short, but significant periods, resulting in significant dune crest erosion, washover deposition and net landward migration of the barrier. These results point to an important, and not often recognized aspect that the magnitude, but also duration of extreme storm impacts, has a significant impact in storm-induced coastal response. Morphological parameters such as dune height, dune aspect ratio or beach width (e.g. Long et al., 2014; Itzkin et al., in review) are fundamental characteristics to determine storm impacts, but the temporal persistence of specific regimes also needs to be considered for a better understanding and prediction of coastal changes driven by storm events (Beuzen et al., 2019).

The results from this study are generally in line with previous geomorphological studies of Masonboro Island, which identified a cyclical pattern of storm-induced overwash, profile lowering and channel breaching, followed by slow frontal dune recovery and vegetation growth (Hosier and Cleary, 1977; Cleary and Hosier, 1979). The small geological headland located near the center of the island, which is occasionally exposed during storm events, may act as a hinge, causing the northern half of Masonboro to be more resilient to storms, compared to locations further south (pers. com W.J. Cleary). The differing long-term chronic erosion rates identified along Masonboro by the NCDCM (2019) supports this hypothesis. Comparable geomorphological dune erosion and overwash of low-lying barriers exposed to high-magnitude storm events are common and well-documented at various locations, including along the Gulf of Mexico, Atlantic and Caribbean coasts (e.g. Bush, 1991; Sexton and Hayes, 1991; Tedesco *et al.*, 1995; Morton and Sallenger, 2003; Wang *et al.*, 2006; Houser *et al.*, 2008). Leatherman (1983) found that overwash processes can be expected across Atlantic coast barrier islands which are less than 200 meters wide. Most of Masonboro Island is less than 200 m wide, making it particularly susceptible to overwash events and inundation during high-energy storms such as hurricanes. In contrast, Wrightsville Beach is of higher elevation, wider (up to 500 m in many cases) and periodically renourished, which precludes significant dune erosion and overwash even during moderate storm events.

There was evidence of numerous washover deposits and overwash channel incisions across the central/southern part of Masonboro Island. Post-storm observations revealed several temporary breaches, up to 25 m wide and 0.5 m deep, extending across the width of the island. Similar storm-induced washover channel incisions and temporary inlets have been documented at numerous barrier islands across the eastern United States, including for example Masonboro Island (Hosier and Cleary, 1977), Topsail Island, NC (Cleary, 1994); Biscayne Bay (Tedesco et al., 1995), Cape Romain (Sexton and

Hayes, 1991) and Cape Cod (Maio et al., 2016). Following Hurricane Matthew, boulder-sized peat blocks and ‘coquina’ lithoclasts were deposited across Masonboro Island, testifying to the high-energy, onshore directed sediment transport associated with the storm. An underlying outcrop of Oligocene siltstone was also exposed on the lower beach face, which is known to periodically crop out after moderate to large storm events. The combination of peat boulders and outcropping underlying geological units confirm the thin nature of modern Holocene sediments on Masonboro Island (Cleary, 1994; Riggs *et al*., 1995; Cleary *et al*., 2000). The limited nature, and low lying, surficial sand deposits are partly responsible for the long-term chronic erosion rates, limiting the island from growing in elevation and fully recovering between storm events. In contrast, Wrightsville Beach continues to accrete due to a combination of wide, vegetated dune systems and long-term periodic beach nourishments.

In summary, the contrasting geomorphological/physical characteristics and coastal management objectives of both islands has resulted in vastly different storm responses, supporting the growing body of work highlighting the complex, distinct but often interconnected dynamics of developed and undeveloped coastlines (USACE, 2000; Lazarus et al., 2016).

Insert Figure 9 and caption

6. Conclusions

This study provided important insights into hurricane impacts on two adjacent barrier islands with contrasting physical characteristics and coastal management strategies. The ability to capture high resolution RTK/GPS beach elevation data shortly before and after the storm, coupled with site visits, photographic records, and analysis of spatially and temporally variable extreme water levels, has shown that the storm impact responses were directly related to the prevalence of different storm impact regimes and linked to the different physical characteristics of each island. Although Hurricane Matthew was a relatively minor hurricane (though it was the most severe storm since locally continuous wave buoy data have been collected since 2008) impacts across the two adjacent barrier islands were highly variable. Developed and periodically renourished Wrightsville Beach had minimal impacts to the integrity of the island. The wide and robust accretionary dune ridge that exists along northern Masonboro Island (in the lee of the jetty) and along far southern Masonboro, makes these flanking areas currently more resilient to storms. However, the low elevation and narrow nature of central and southern Masonboro Island, coupled with a discontinuous, low elevation frontal dune system and chronic long-term erosion rates, makes this part of the island reserve particularly susceptible to future storms. The tenuous nature of the island will likely result in continued profile lowering and rapid landward migration, coupled with the possibility of temporary, or even permanent breaching. Other similar examples of low-lying protected barrier islands which are threatened by increasing sea levels, and increasingly more frequent storms, are likely to display similar geomorphological responses and coastal change patterns. The different coastal management strategies that are adopted for barrier islands along the east coast of the USA, and elsewhere, will have an impact on future island evolution and local barrier landscapes, especially during and after high magnitude storm events.

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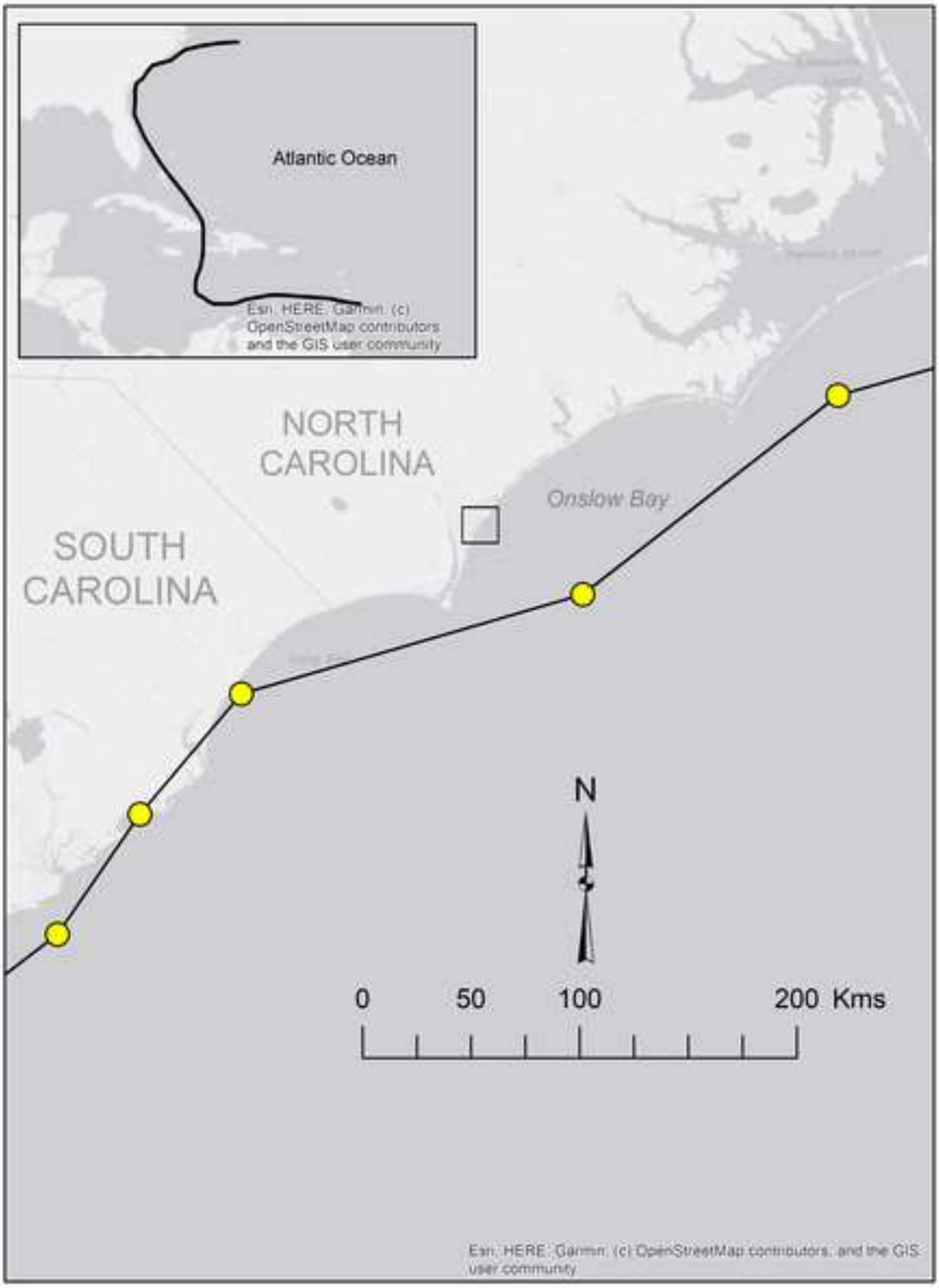
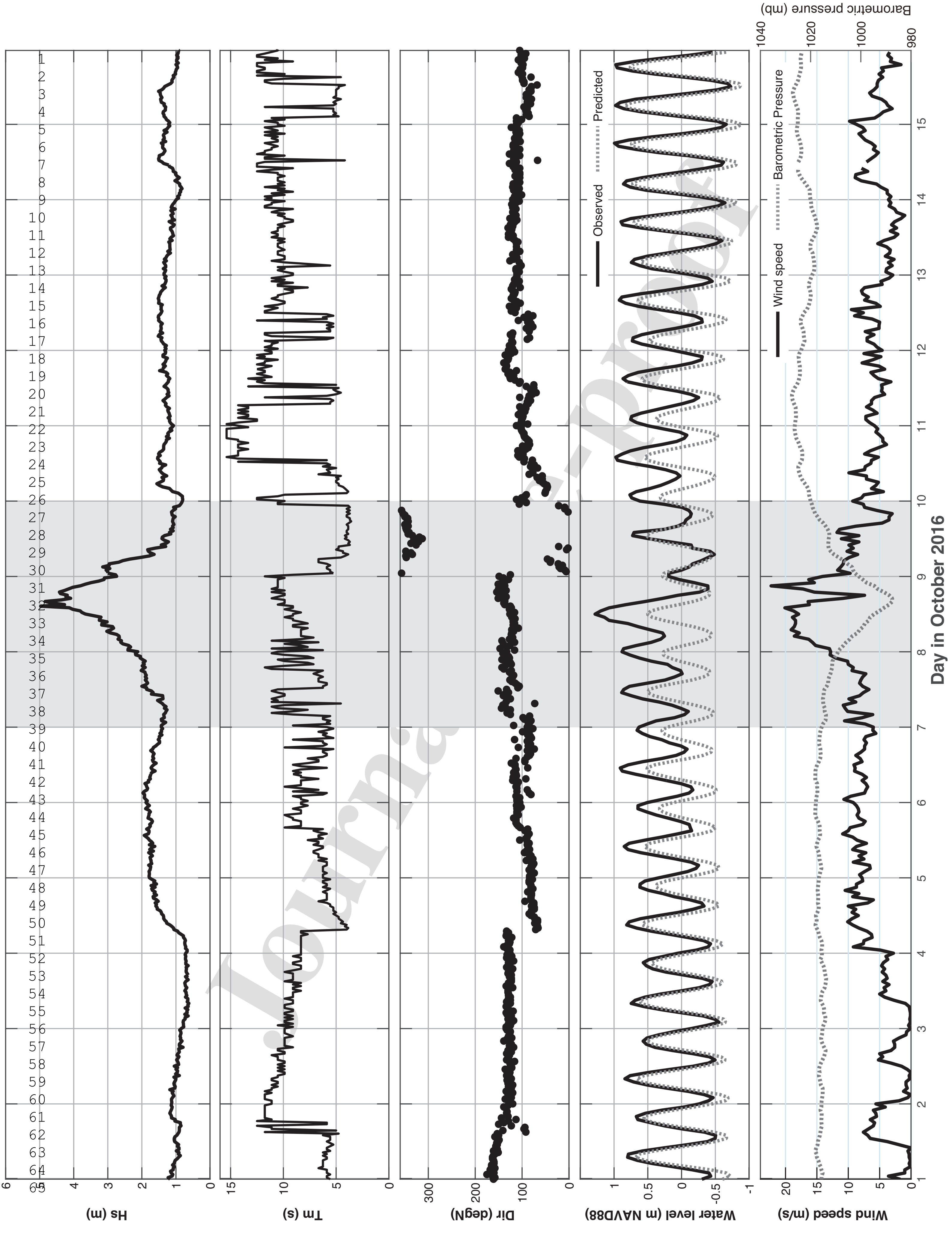
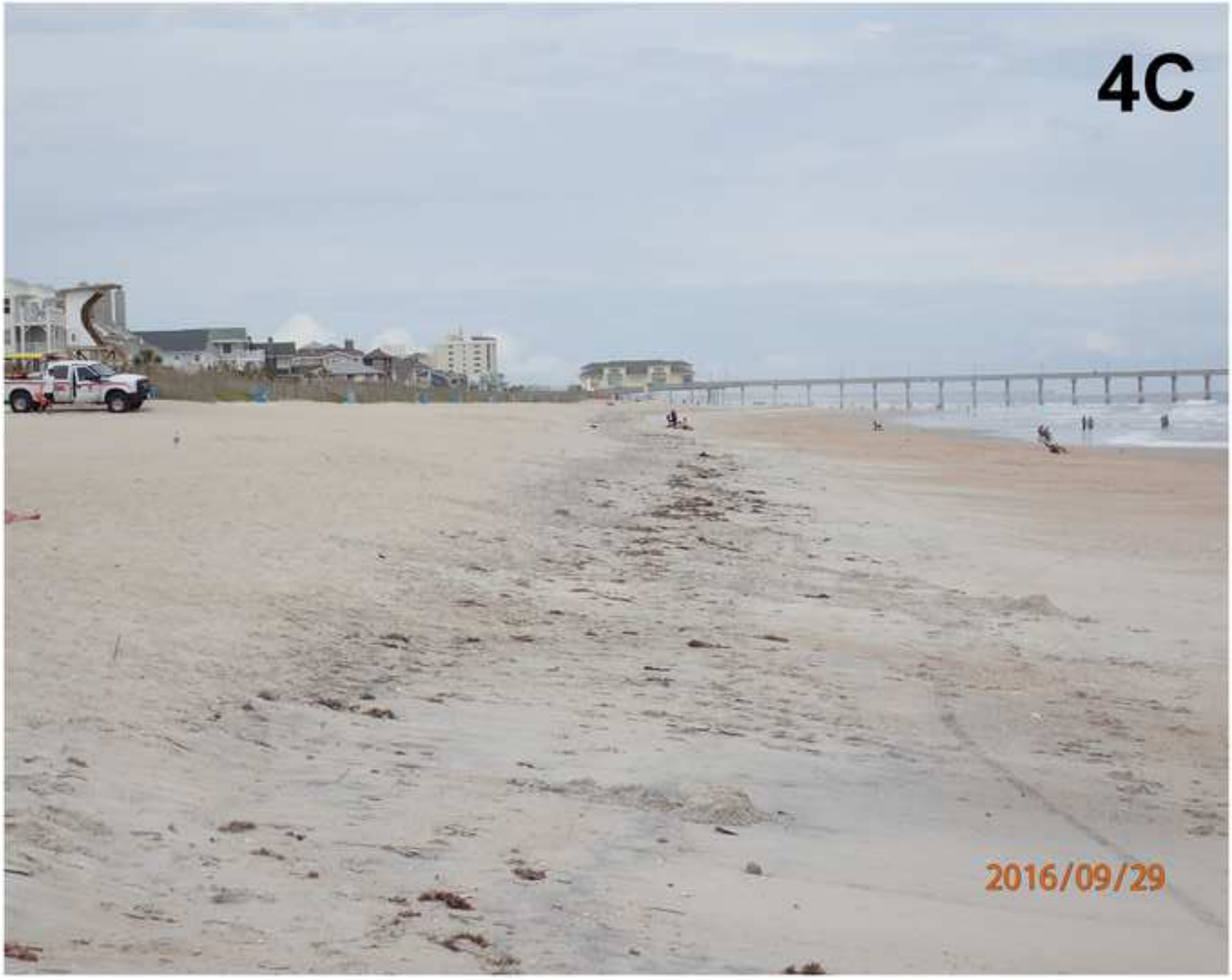
Mason Inlet
Wrightsville Beach
Masonboro Inlet
Masonboro Island
Carolina Beach Inlet
N
0
1.25
2.5
5
Kilometers
Survey Locations


Atlantic Ocean
Esri, HERE, Garmin, (c) OpenStreetMap contributors and the GIS user community
NORTH CAROLINA
Onslow Bay
SOUTH CAROLINA
N
0
50
100
200 Kms
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community


Hs (m)
0
1
2
3
4
5
6
Tm (s)
0
5
10
15
Dir (degN)
0
100
200
300
Water level (m NAVD88)
-1
-0.5
0
0.5
1
Observed
Predicted
Wind speed (m/s)
0
5
10
15
20
Wind speed
Barometric Pressure
Barometric pressure (mb)
980
1000
1020
1040
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Day in October 2016


4A
DO NOT CROSS ROPE BARRICADE
AND STAY OFF INTERTIDAL SHOALS
WATERBIRD
NESTING & FORAGING
AREA
Area regularly patrolled by
Town of Wrightsville Beach
2016/10/01


4B
2016/10/13


4C
2016/09/29

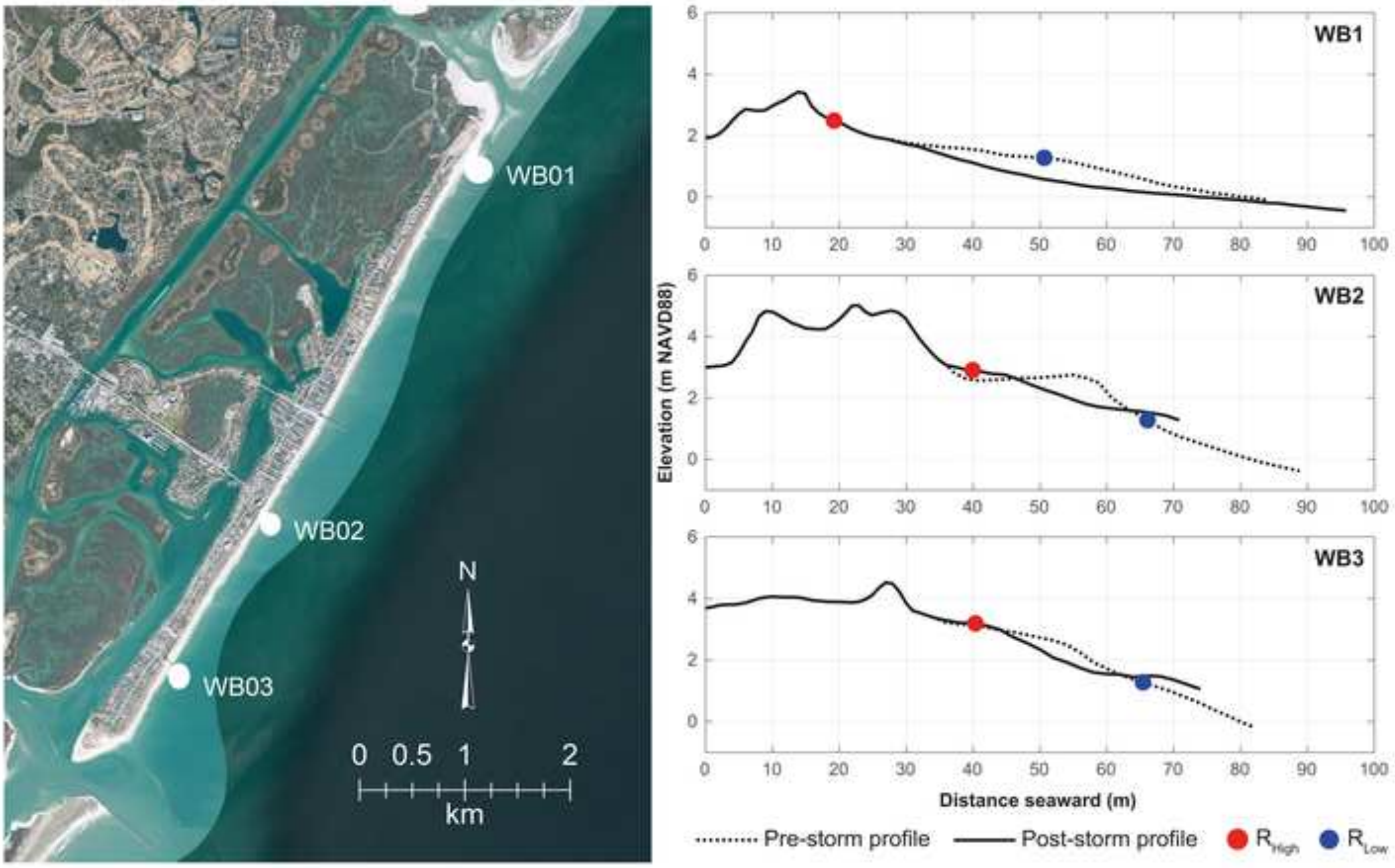
4D

2016/10/10

4E

2016/09/29


4F
2016/10/10


WB01
WB02
WB03
N
0 0.5 1 2
km
WB1
WB2
WB3
Elevation (m NAVD88)
Distance seaward (m)
0 10 20 30 40 50 60 70 80 90 100
0 2 4 6
Pre-storm profile
Post-storm profile
R_{High}
R_{Low}


6A
2016/10/07


6B
2016/10/02


6C
2016/10/14

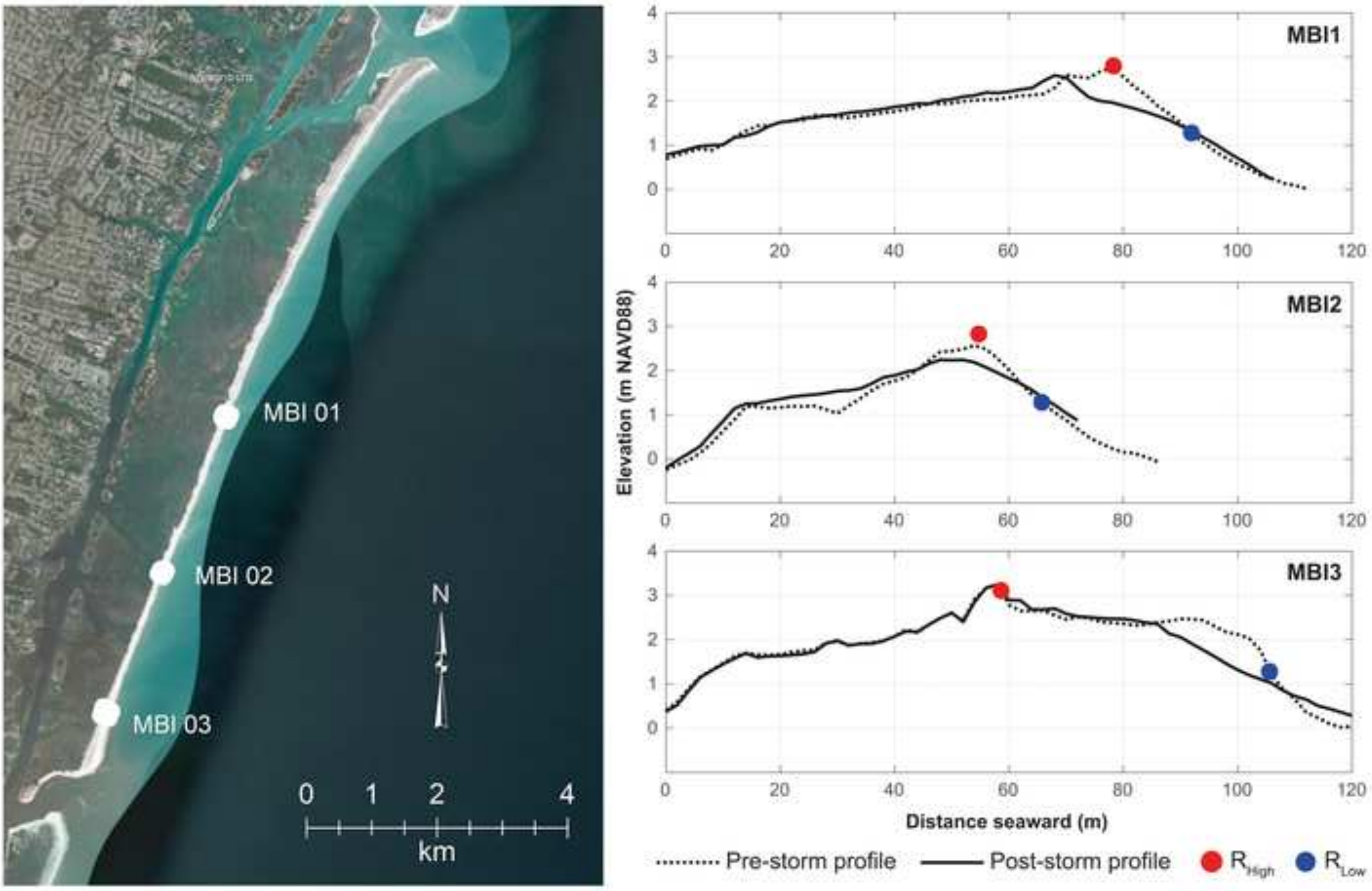
6D


6E
2016/10/14


6F
2016/10/14

6G


6H


MBI 01
MBI 02
MBI 03
N
0 1 2 4
km
MBI1
MBI2
MBI3
Elevation (m NAVD88)
Distance seaward (m)
0
1
2
3
4
0
20
40
60
80
100
120
Pre-storm profile
Post-storm profile
R_{High}
R_{Low}


8A
Atlantic Ocean
N
0 50 100 200 Meters


8B
Atlantic Ocean
N
0 50 100 200 Meters


Wrightsville Beach
IHA
Stable to accreting
Masonboro Island
Ongoing rapid retreat, possible break-up
IHA
N
0
1.25
2.5
5 Kms

Table 1. Synthesis of morphological change parameters, storm impact scale variables and duration of storm impact regimes during Hurricane Mathew in the surveyed profiles.

	Profile erosion		**Storm Impact Scale**				**Storm Impact regimes**[3]		
Profile	V_{max} (m)	H_{berm} (m)	D_{High} (m)	D_{Low} (m)	R_{High} (m)	R_{Low} (m)	Overwash (h)	Collision (h)	Swash (h)
WB01	-0.7	-15.4	3.43	2.43	2.49	1.28	0	1:30	70:30
WB02	-0.8	-10.8	5.02	2.63	2.91		0	3:00	69:00
WB03	-0.6	-5.8	4.52	3.60	3.19		0	0	72:00
MI01	-0.8	-10.2[1]	2.74	2.08[2]	2.80		2:00	9:30	60:30
MI02	-0.4	-6.0[1]	2.57	1.71[2]	2.83		4:30	15:30	52:00
MI03	-0.8	-11.7	3.25	2.65	3.11		0	6:30	65:30

[1] indicates dune crest erosion, as no discernible berm is identified in the pre-storm profiles.

[2] indicates an estimate based the post-storm profile, as no discernible dune based is identified in the pre-storm profiles.

[3] duration of each storm impact regime for the 72-hour period between 07/10/2016 and 09/10/2016

Table 2. A comparison of geomorphological differences, long-term erosion rates and coastal management strategies for Wrightsville Beach and Masonboro Island.

Parameter	**Wrightsville Beach**	**Masonboro Island**
Maximum width	500 meters (central part of island).	300 m (north end). Less than 200 m wide along most of island.
Hurricane Matthew Storm Impacts	Berm and minor frontal dune erosion, some scarping. Impacts mostly limited to main beach. Dunes mostly intact.	Berm erosion, significant dune erosion, scarping, overwash and channelization, exposure of underlying geological units, back-barrier deposition, landward translation of profile in some instances.
Maximum Height of Dunes (m, NAVD 88)	5.5 m	3.5 m
Dune Front Continuity & Vegetation	Wide, continuous and vegetated.	Narrow, semi-continuous and partially vegetated. Existing partially infilled breaches from previous storms.
Coastal Management Strategy	Four-year cycle of beach nourishment at least through 2036. Ongoing since 1965. Setbacks determined based on coastal structure type.	No regular beach nourishment – occasional minimal sand placement on north and south end, associated with inlet maintenance. Part of protected (NERRS) reserve system. Development prohibited.
Long-term erosion rates (NCDCM, 2019)	Stable to accreting.	Apart from far north end, chronically eroding, from 1 to 10 m/yr. Highest erosion rates along narrow, central section of island.