Decadal-scale evolution of a barrier island: Insights from storm overwash and shoreline change on Ocracoke Island, NC

By

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ABSTRACT

Eastern North Carolina has over 300 km of barrier islands that comprise the Outer Banks and act as an important buffer from the Atlantic Ocean and boundary to the Albemarle-Pamlico Estuarine System. These islands also draw millions of visitors and dollars to the state every year. With sea-level rise and the persistence of extratropical and tropical storms, it is critical to examine the recent decadal response to storm events and geologic evolution in order to best prepare for future change. In this study, multiple methods were used to evaluate the recent decadal evolution of Ocracoke Island, NC. Shoreline change rates were calculated using a transect based approach with imagery from 1949, 1974 and 2006. Other aerial imagery time steps were used to look at the spatial impact of historic storms and to select coring and trenching sites based on visible depositional history. The stratigraphic and sedimentological signature of recent and historic storm events was interpreted using seven vibracores and 32 trench excavations. Additionally, LiDAR data was used to assess morphologic change and to test a storm-impact scale based on storm surge, waves and maximum foredune height.

The average long-term shoreline change rate for Ocracoke is determined to be - 0.54 m/yr and the majority of the island is eroding (over 65% of transects) with rates becoming more erosive in the more recent time period. These rates highlight the narrowing of the island through time, and in some regions island width has decreased by as much as 70% (180 m). The island morphology has shown variable spatial and temporal response to storms, but was most impacted from 1940 - 1962.

Hurricane Isabel (2003) overwashed a total of 9% of the island with an average thickness of 0.24 m. The storm-impact scale shows a quantitative relationship of overwash and pre-existing dune conditions that vary alongshore. Isabel's sedimentation represents up to 26% of total backbarrier subaerial volume and can be correlated with dune volume loss. Isabel caused soundward migration of the foredune up to 40 m and substantial oceanside erosion representing 23% of longterm net change in some regions of the island.

Up to four other distinct storm deposits are interpreted within the cores using the sedimentological signatures of moderately to well-sorted fine to medium grained sand, coarse shell hash bases, and heavy mineral laminae. Stacked overwash deposits are spatially and temporally variable showing the complexity of barrier island evolution and the necessity to examine soundward migration in three dimensions.

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1. INTRODUCTION

The North Carolina coast, and particularly the Outer Banks, are an invaluable recreational, cultural and historical resource for the U.S., and are a key asset for the State. This 320-km chain of barrier islands compose the northeastern border of North Carolina, and act as a geologic buffer to the energetic Atlantic Ocean, while isolating and influencing the dynamics of the Albemarle-Pamlico estuarine system (Riggs et al., 2003). Responding to both chronic (i.e., sea-level rise, wave and tidal energy) and acute (i.e., tropical and extratropical storm events) processes, these sand-dominated islands are perpetually experiencing change (Fisher, 1962; Godfrey and Godfrey, 1976; Dolan et al., 1988; Riggs and Ames, 2003).

North Carolina has a long history of storms that have influenced the coast (Dolan et al., 1988; Inman and Dolan, 1989). During major atmospheric events (e.g., hurricanes), storm tides and large waves can cause a variety of effects. Storm-generated overwash is one process that can severely impact the coastal morphology as well as property and economic infrastructure (Godfrey and Godfrey, 1976; Donnelly et al., 2006). Overwash can be devastating to coastal communities, making roads impassable, washing away homes and creating new inlets, and these impacts can affect the social and fiscal well-being of residents and visitors (Riggs et al., 2009). Furthermore, with a low-lying coast, North Carolina is especially vulnerable to sea-level rise, which is estimated to currently be ~4 mm/yr in the region (Kemp et al., 2009), with a projected potential rise as great as 1 m over the next century (North Carolina Sea-level Rise Assessment Report, 2010; IPCC, 2013). As sea level continues to rise, the effects of landfalling hurricanes and Nor'easters will be amplified through greater storm surge inundation (Sallenger, 2000).

Additionally, expected climate change during the next century (IPCC, 2013) has been linked to the potential increase in storm intensity (Emmanuel, 2005; Mann et al., 2009; Knutson, 2010). Despite the possible growing risks, coastal development and tourism have continued to expand in most coastal areas, such as the Outer Banks (Ocean and Coastal Resource Management, 2009). A better understanding of historical storm impacts and barrier island dynamics, such as overwash processes, can provide valuable insight into the environmental and human risk and planning needs for future coastal hazards.

On September 18, 2003, Hurricane Isabel, one of the strongest hurricanes to impact the region in recorded history, passed over Ocracoke Island and much of the Outer Banks as category 2 storm on the Saffir-Simpson Hurricane Scale. Its destructive path caused an estimated 3.4 billion dollars of damage as it powered north from the Outer Banks to Canada (National Oceanic and Atmospheric Administration (NOAA), 2004).

Evaluation of the geologic response to the storm requires both field and laboratory data acquisition. Furthermore, it is helpful to place the impacts of Hurricane Isabel within the context of prior storms and the evolving island morphology through the analysis of remotely sensed data. A mix of spatiotemporal datasets coupled with geological observations are used in this research to give insight into the decadal-scale development of a barrier island system and help give context for future management decisions.

The specific objectives of this study are:

1) Evaluate the spatiotemporal variability and complexity of overwash deposition, specifically associated with Hurricane Isabel. A better understanding of overwash mechanics will provide greater insight into barrier island evolution, which can be used to evaluate potential impacts of future storms.

2) Characterize the sedimentological signature and preservation record of overwash event layers. Once the Isabel layer is distinctly characterized, it may be used to help interpret more historic storm deposits within the recent geologic record. The potential preservation of historic storm deposits can provide important insight into the recent change of barrier islands.

3) Examine the geologic evolution and response of the barrier island over the last several decades and identify the relative impact of decadal storm events. Morphologic change of the foredunes and backbarrier will be evaluated, along with the evolution of ocean and estuarine shorelines to provide insight into the most dynamic regions and responsible processes driving change.

2. BACKGROUND

2.1 Barrier Island Morphodynamics

Barrier islands represent 6% of the global ocean shoreline, and are extensive along the U.S. East Coast (Stutz and Pilkey, 2001). They are commonly (73%) located along trailing edge margins where the continental shelf is gently sloped (Stutz and Pilkey, 2001). Sediment that forms North Carolina's barriers was previously deposited on the shelf by fluvial processes through the Quaternary, much earlier than the last glacial maximum (~20,000 years BP) when sea level was much lower (~100m) and farther east (~100 km) (Riggs et al., 1995). During the Holocene sea-level transgression, river valleys were flooded and these sediments were unconformably draped on Pleistocene, and older strata (Riggs et al., 1995). Subsequent erosion and reworking, e.g., by longshore transport, helped form the modern elongate, barrier island system (Fisher, 1962).

The morphology of barrier islands is affected by multiple factors including wave energy, tidal currents, aeolian transport, vegetation, sediment supply, inlet dynamics, sea-level changes, anthropogenic activity and storms (Hoyt and Henry, 1967; Godfrey and Godfrey, 1976; Leatherman, 1979). The sandy beach face within reach of high tide is typically the most dynamic region of the barrier, along with the foredune and berm system (Godfrey and Godfrey, 1976; Mitasova et al., 2009).

2.2 Shoreline Change Analysis

Many researchers have focused on the calculation of oceanside erosion rates over long and short timescales to provide insight into barrier migration, beach loss and management of valuable property (Langfelder et al., 1970; Dolan et al., 1979, Leatherman, 1979, Everts et al., 1983; Inman and Dolan, 1989). In many coastal regions including NC, it is also critical to assess the estuarine shoreline change due to their ecological and economic importance and role in barrier island stability (Riggs and Ames, 2003). Several researchers have calculated estuarine shoreline change rates in NC and have suggested influencing parameters including shoreline type, geometry, bathymetry, vegetation, fetch, wave energy and storm magnitude and frequency (Bellis et al., 1975, Riggs et al., 1978; Hardaway, 1980; Schwimmer, 2001; Riggs and Ames, 2003; Cowart, 2010). This study couples estuarine and oceanside change rates in order to understand evolution of the total barrier evolution.

2.3 Remotely Sensed Data and Modeling

Aerial photography is invaluable when examining the decadal evolution of a barrier island system (Boak and Turner, 2005). In the case of coastal North Carolina, aerial photography dates back to the 1930's and has been collected relatively frequently providing a valuable dataset to gain insight into coastal change through time. Post-storm aerial images are very useful for capturing the spatial extent of erosion and nature of overwash such as overwash fan morphology, channelization and distinction between overwash and intertidal sand deposits.

The emergence of LiDAR (Light Detection And Ranging) technology has enabled a cost effective means to study large areas for morphologic change (Sallenger, 2003; White and Wang, 2003; Brock and Purkis, 2009). Time-series LiDAR surveys can provide the means for identifying geomorphic and volumetric changes, which is critical in understanding the evolution of barrier island systems in response to storms and sea-level rise (Woolard and Colby, 2002; Sallenger et al. 2003, Mitasova et al., 2009). Sallenger et al. (2003) evaluated the use of airborne topographic LiDAR for monitoring and quantifying coastal change and found a vertical accuracy of ± 15 cm, showing even fine-scale topographic changes can be assessed. Furthermore, analysis of past barrier island change may give insight into the vulnerability to future hazards (Sallenger, 2000; Stockdon et al., 2007).

2.4 Overwash Processes

Overwash is the transport of water and sediment over the crest of a beach ridge onto the back barrier or mainland (Leatherman and Williams, 1977). Overwash occurs when the water level of the adjacent water body (i.e., the Atlantic Ocean in this NC case) exceeds the local dune crest and/or back shore, and this most often occurs with storm surge (Leatherman and Williams, 1977). Typically, overwash travels through pre-existing natural or anthropogenic low areas in the foredune, developing a channel-like feature called the overwash throat (Donnelly, 2004). The internal structure of overwash deposits are reported to have a stratigraphy of sub-horizontal soundward-dipping layers (Sedwick and Davis, 2003). Overwash deposition is episodic, as it occurs with acute storm events that vary in intensity and track (Kochel and Wampfler, 1989). The lateral extent and thickness of the deposit is controlled by storm surge, tides, wave height and period (Maurmeyer et al., 1979), wind strength and direction, vegetation, nearshore bathymetry (Donnelly, 2006) and dune topography (Gares and White, 2005).

Storm-generated overwash is a primary process in barrier island sediment budgets, driving beach and dune volume changes, back-barrier sediment accumulation, and long-term soundward island migration, and all of these are processes important to the evolution of barrier islands with rising sea level (Godfrey and Godfrey, 1976; Inman and Dolan, 1989; Pilkey et al., 2008; Hippensteel, 2011). Numerous studies have observed the role of overwash in barrier island dynamics. Kochel and Wampfler (1989) conducted an overwash study on Assateague Island, Maryland over a four-year period which included two years of average storm activity, one year of stormy activity and one calm year. The researchers found overwash significantly contributed to the net accretion of sediment on the barrier island over the period and dominated over aeolian activity. Since the study period included variable climate, it provides insight into long-term barrier island sediment budgets (Kochel and Wampfler, 1989). These results differ from those of Leatherman (1976) who found aeolian processes dominating overwash at Assateague Island. Differences may be due to timing, as the Leatherman (1976) research was conducted during a non-stormy period. But, these two studies among others show complexity of barrier island sediment budgets and the need for long-term monitoring that considers climatic variability.

Foxgrover (2009) highlighted the importance of overwash processes in barrier island preservation at Onslow Beach, NC. Their overwash deposits were poorly sorted sediments containing heavy mineral laminae, shell hash and sharp basal contact and composed ~11% of the total sand prism (i.e., transportable sediments above the geologically defined peat layer). Barrier island rollover was observed associated with hurricanes Bertha (1996) and Fran (1996); these events eroded nearshore sediments and deposited the equivalent volume in the back-barrier

(Foxgrover, 2009). Based on work at Whale Beach, NJ, Donnelly et al. (2001b) found overwash was primarily responsible for soundward migration of ~2 m/yr over the past 150 years.

Historical storm deposits have been documented in a variety of geomorphic environments (e.g., Liu and Fearn, 1993; Donnelly et al., 2001b; Culver et al., 2006; Smith, 2004; Hale, 2008; Woodruff et al., 2008; Horton et al., 2009a) using sedimentological, stratigraphic, geochemical and foraminiferal methodologies (Hosier and Cleary, 1977; Leatherman and Williams, 1977; Liu, 1993; Donnelly et al., 2001; Donnelly et al., 2006). Sedimentological proxies have been successful in revealing preserved storm event strata (Liu and Fearn, 1993; Donnelly et al., 2001b). However, because of isolated research and minimal evaluation of modern recent events, the overall understanding of the variability in the nature of and controls for overwash deposition and preservation is limited, and this makes long-term storm reconstructions (and confidence in them) difficult. Thus, the approach of the present study is somewhat different: to examine the geological record of a relatively well-documented storm to determine the controlling conditions, lasting record and island evolutionary impact of overwash deposition.

2.4.1 Sedimentological Characteristics of Overwash Deposits

Multiple sedimentological characteristics can be used to identify overwash deposits within the stratigraphic record (Leatherman and Williams, 1977; Donnelly et al., 2004, Sedgwick and Davis, 2003; Hippensteel, 2011). The most commonly noted attributes are stratigraphic context (i.e., sand on marsh peat; e.g., Donnelly et al., 2004), fine-to-coarse grained sands with variable sorting (Hennessy and Zarillo, 1987; Sedgwick and Davis, 2003), horizontally layered laminations (Leatherman and Williams, 1977), heavy mineral laminae representative of hydraulic fluctuation during storm conditions (Leatherman and Williams, 1977; Kochel and Wampfler, 1989; Sedgwick and Davis, 2003), shoreface shell fragments (Sedgwick and Davis, 2003; Hippensteel, 2011) and variable grading (Leatherman and Williams, 1977, Sedgwick and Davis, 2003). Scouring and plant fragments have been observed between stacked overwash deposit layers (Leatherman and Williams, 1977). In back-barrier settings, overwash deposits are often indicated by the distinct contact with underlying muddy, organic-rich marsh sediments (Donnelly, 2001a; Liu, 2007; Hippensteel, 2011). The distinction between flood-tidal delta and overwash deposits has been problematic (Hennessy and Zarillo, 1987); primary differences include more plant fragments in overwash deposits versus ripple laminations, more mud and increased shell hash layers in flood-tidal delta strata (Hennessy and Zarillo, 1987; Liu, 2007; Smith et al., 2009).

2.4.2 Preservation Variability

Overwash deposits are subject to biological and physical reworking (Culver et al., 2004; Grand Pre, 2011, Hippensteel, 2011; Lane et al., 2011). Elevation of the barrier island and the position of the deposit relative to the lower intertidal or subtidal zone influence preservation potential (Sedgwick and Davis, 2003). Sea-level rise and subsequent storm activity (Sedgwick and Davis, 2003), bioturbation (Hippensteel, 2011) and aeolian processes (Leatherman, 1976, Grand Pre, 2011) are primary erosive mechanisms affecting overwash deposits. Preservation potential has been shown to increase in high marsh settings compared to low marshes, as higher marsh deposits are potentially subject to less physical mixing and bioturbation (Hippensteel, 2011). Overwash preservation potential likely increases with increased burial rates, which decrease the susceptibility to physical and biological reworking (Hippensteel, 2011); but barrier islands and other coasts are dynamic sedimentary environments, and human activities may often be the most influential factor on the integrity of the record.

2.5 Storm-impact Scale

Efforts by the USGS and others have tried to help quantify the impact or potential influence of storms on coastal areas. In particular, one approach appears to be useful for evaluating erosion or overwash. The Sallenger (2000) storm-impact scale incorporates both storm forcing processes (i.e. storm surge and wave conditions) and the geometry of the coast derived from LiDAR to predict coastal response to storms varying in magnitude. Specifically, the scale uses the highest (R_{high}) and lowest (R_{low}) water elevations due to astronomical tides, storm surge and the vertical height from wave runup from a storm event and elevation of the dune base (D_{low}) and beach crest (D_{high}) to predict the coastal impact regime (i.e., swash, collision, runup overwash, or inundation). Stockdon et al. (2007) used data before and after hurricanes Bonnie (1998) and Floyd (1999) on a 50-km section of NC coast from Masonboro Island to Topsail Island to test the Sallenger (2000) model and found ~87% accuracy for the overwash regime component of the model. Numerous other researchers have used the Sallenger storm-impact scale as a basis for barrier island evolution studies (e.g., Ruggiero et al., 2001; Houser et al., 2008; Roelvink et al., 2009). While work continues to improve (e.g., runup estimation) and validate the method, results suggest this can be a valuable tool for coastal management.

2.6 Study Site

2.6.1 Regional Geologic History

Riggs et al. (1995, 2006) demonstrated that the underlying geologic framework is a primary factor affecting the modern morphology and processes of NC’s barrier island system. Differences in the underlying geology cause morphologic differences between NC’s northern and southern coastal areas and barrier islands in terms of island length, width, amount of inlets, and properties of estuaries behind them (Riggs and Ames, 2006). The gentle slope and fill of the Albemarle embayment of the northern zone where the study site is located has produced long, narrow islands with few inlets and large back-barrier estuaries. The northern zone is also characterized by minimal saltwater exchange and wind tides. Contrarily, much older and higher sloped underlying lithologies in the southern zone formed short and wide islands with many inlets (18) and narrow back-barrier estuaries, with much greater flushing controlled by astronomical tides (Riggs and Ames, 2006).

2.6.2 Ocracoke Island, NC

Ocracoke Island is ~25 km long and averages about 1 km or less wide and is bound by Ocracoke Inlet to the south and Hatteras Inlet to the north (Fig. 1). Hatteras Inlet has remained active since it opened in the 1846 hurricane (Fisher, 1962). Ocracoke Inlet is visible in maps dating back to 1584 A.D. (Fisher, 1962) and has apparently remained in approximately the same location due to the underlying paleo-Pamlico Creek drainage channel (Mallinson et al., 2010). Two large sand shoals, Howard's Reef and Green Island, are located soundward of the island within ~3.5 km. Howard's Reef is located on the interstream divide between two tributaries of the paleo-Pamlico Creek drainage channel (Mallinson et al., 2010).

The island is mostly undeveloped with the exception of Ocracoke Village on the southwestern side. The Village, not surprisingly, was wisely established in an area of greater elevation; it is situated in a series of regressive beach ridges that likely formed ~ 3000 years BP

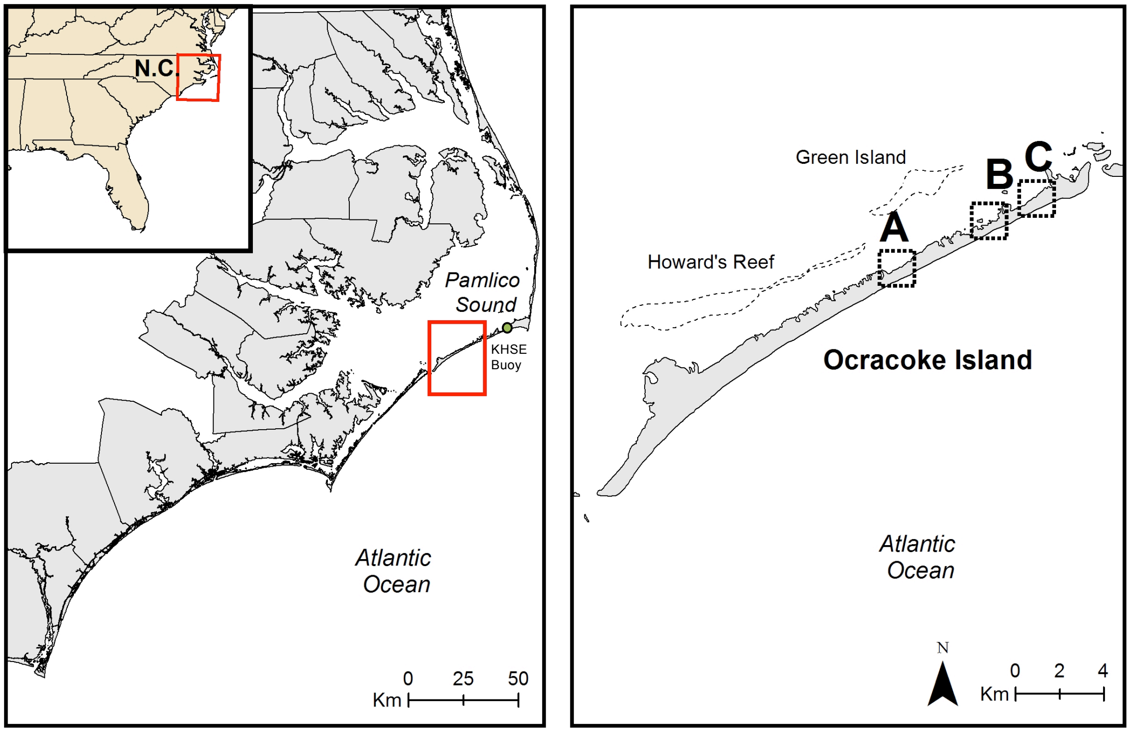


Figure 2. Site map of Ocracoke Island located in the Outer Banks, North Carolina. The location of study sites A, B and C are noted in panel B. The KHSE weather buoy in panel A was the source of meteorological data.

(Mallinson et al., 2011). The remainder of the island welded onto this region over the last ~500 years (Mallinson et al., 2011).

Other than the beach ridge area, Ocracoke is classified by Riggs and Ames (2008) as a simple barrier island due to its limited island width and dynamics influenced by overwash and inlet processes. The village region of the island is classified as a complex barrier region by Riggs and Ames (2008) because it contains younger overwash sediments that have accreted onto older pre-existing sediments creating a wider and more stable barrier type.

The first beach road was constructed on the Outer Banks in the 1930s, and Ocracoke Island had a roadway emplaced about this time (Birkemeier et al., 1984). Since then, the Outer Banks in general have experienced significant development, including the construction of an artificial dune line with sand fencing and stabilizing vegetation in the early 1930s. The primary goal of this work by the Civilian Conservation Corps was to prevent the island (and roadway) from destruction during storm events. Moreover, dune protection was thought to enhance stability and thus development and employment opportunities and allow for enhanced visitation of the Cape Hatteras National Seashore (Birkemeier et al., 1984). When the artificial dunes were emplaced, they ranged from 3 to 8 m in height and 25 to 100 m in width, along with an additional 1000 km of island-parallel fencing. Funded by emergency funds from the State of North Carolina, the 1930s artificial foredune construction was a massive undertaking as it extended from the Virginia border to Ocracoke Inlet; it required cooperation by a variety of agencies including the Transient Bureaus for NC and VA, the Works Progress Administration, the Civilian Conservation Corps and the National Park Service. The project was ultimately completed by 1940. Since original construction, portions of the dunes have been rebuilt countless times including extensive reconstruction and planting after the Ash Wednesday storm (Riggs and Ames, 2006; Birkemeier et al., 1984).

2.6.3 Storm History

The most frequent storms to impact the Outer Banks are extratropical storms, or nor'easters, between the months of December and April (Dolan, 1988). According to Bosserman and Dolan (1968), 30 to 35 nor'easters capable of eroding the beach and foredunes impact the Atlantic Coast barrier islands each year. Because of their frequency and long duration, these events control the net longshore transport along the N.C. coast (Dolan, 1988), and this is evidenced by spit growth patterns at Oregon Inlet and Cape Hatteras. The Ash Wednesday Nor'easter was one of the most destructive storms that impacted the Atlantic coast in the 20th century. This nor'easter had a long period of impact, extending from March 5th to the 8th, 1962.

Persisting at a time of spring tides, it caused over 200 million dollars in property damage and was responsible for 40 deaths (NOAA, 2003). The storm opened Buxton Inlet just north of Cape Hatteras (Mallinson et al., 2008), which was subsequently closed with human intervention. The northern Outer Banks were heavily impacted with extensive overwash; Ocracoke Island experienced local overwash.

Ocracoke Island's northeast-southwest trending shoreline orientation makes it vulnerable to hurricanes travelling north along the eastern U.S. coast. According to Riggs et al. (2008), east-west trending shorelines are subject to larger magnitude storm strikes, while north-south trending shorelines are impacted by smaller magnitude, but more frequent strikes. The Atlantic hurricane season runs from June 1st through November 30th (NOAA, 2004). North Carolina has been affected by many hurricanes in recorded history. From 1857 to 2014, a total of 47 Category 1 or greater hurricanes have passed within 120 km of Ocracoke. Of these storms, 23 were Category 1; 17 were Category 2; six were Category 3, and one (Hazel, 1954) was a Category 4 hurricane (NOAA Hurricane Tracks, 2014).

One of the most damaging hurricanes in recent history was Hurricane Isabel (Fig. 2). It made landfall near Ocracoke Island on September 18, 2003 (NOAA, 2004). The storm generated on 6 September 2003 in an area east of the Leeward Islands and developed to a Category 5 hurricane by September 11th. Isabel reached peak strength on September 12th with 140 knot (160 mph) sustained winds, but was reduced to a Category 2 with 100 mph winds and minimum pressure of 957 mb by landfall (Preller, 2003). Tropical storm force winds extended 555 km from the center of the large eye and hurricane force winds spread over 185 km from the center

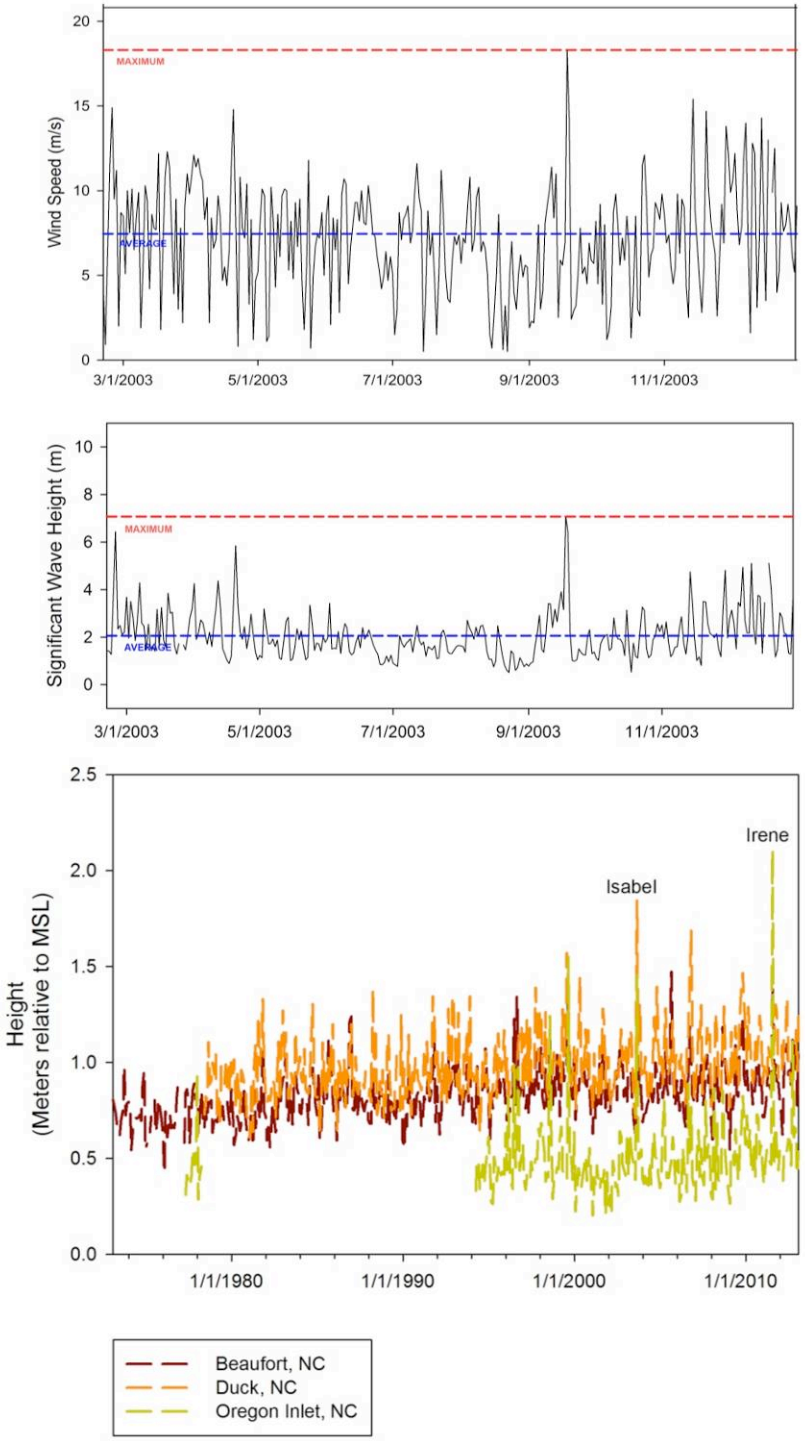


Figure 2. Top two panels include daily high wind speed and wave height over a 10-month period including Hurricane Isabel (Sept. 18th peak) collected from KHSE buoy (location noted on Figure 1). Bottom panel includes tide gauge data from three NC stations highlighting the Isabel storm surge (2003). Note difference in scales. Data obtained from National Data Buoy Center.

(Preller, 2003). In North Carolina and Virginia, rainfall of 15 to 30 cm was recorded (Preller, 2003). A storm surge of 1.5 to 2.5 meters and large waves of 4-8 meters influenced Ocracoke Island resulting in significant flooding and overwash (NOAA, 2004) (Fig 2). The Isabel storm surge created a new inlet between Frisco and Hatteras Village on Hatteras Island, the island adjacent to Ocracoke (Mallinson et al., 2008), and it caused significant damage to portions of Highway 12 along the Outer Banks (NOAA, 2004). More recently, hurricanes Irene and Sandy impacted the Outer Banks in 2011 and 2012, respectively (Fig. 2), although neither of these were major events for Ocracoke, both had significant consequences for areas to the north (e.g., Mulligan et al., in press).

3. METHODS

Aerial photography has proven to be invaluable for mapping immediate storm impacts and has provided a means to focus research on historical events (Donnelly, 2001; Mattias, 2009). Field sites to examine Isabel overwash deposition were chosen based on geo-referenced post-Isabel aerial photography (i.e., 2003 images; Fig. 3); Isabel depositional layers were invisible during field inspection in 2009 and in recent aerial images because of vegetation regrowth.

Aerial photography for different years was obtained from the Outer Banks History Center (1949), the National Park Service's Fort Raleigh National Historic Site (1974), Dare County Tax Office (1974), and Division of Coastal Management (2006). Photos were scanned at 600 dpi or were already available electronically with a comparable resolution. Rectification of the 1949 and 1974 aerial photography was conducted with the Georeferencing Tools in ArcGIS 10.0. At least 6 control points were added to each photograph, and second-order polynomial transformations were used whenever possible. The root-mean-square error was recorded for each rectified photograph and averages were calculated (1949 = 3.03 m; 1974 = 1.42 m).

Historic shorelines were mapped at the 1:300-500 scale using heads-up digitization in ArcGIS (Cowart et al., 2010; Geis and Bendell, 2010), and to quantify shoreline change, polylines were analyzed with AMBUR (Analyzing Moving Boundaries using R) (Jackson, 2010). This software casts perpendicular transects at user-defined intervals (50 m for this study) from an outer baseline to an inner baseline and through separation of shoreline intersection points, shoreline change rates are calculated. If a shoreline area was absent in imagery from one time step, that area was completely removed from analysis so an equal amount of shoreline change points could be compared between eras. Total error rates were determined as a combination of georeferencing and digitizing errors.

Since 1949 photography used both 1974 and 2006 photography for georeferencing, the error for both periods was included to calculate 1949 positional uncertainty (U_T). The uncertainty measures are further outlined by Genz et al. (2007) and Fletcher et al. (2003). Digitization error was calculated by repeat digitizing of a stretch of shoreline (9 and 18 km) and evaluating position offsets.

The total combined error of georeferenced images for 1974 was (mean ± SD) 1.42 ±1.14 m (*n*=81; SE=0.13), and 1949 georeferencing error was 3.03 ± 1.72 m (*n*=33; SE= 0.30). The 2006 imagery had a horizontal error of 1.31 ± 0.89 m (SE= 0.32). For 1949, digitization error was estimated to be 0.41 m, and the 1974 digitizing error was 0.24 m. Total uncertainty for the 1949-1974 period was ± 3.46 m, or ± 0.14 m for the annual shoreline change rates. Total error for the 1974-2006 period was ± 1.63 m, or ± 0.05 m annually. To be conservative, ± 0.14 m was used to indicate "no detectable change" for all temporal evaluations.

In 2009, a total of 32 trenches were excavated, and seven vibracores were collected (1.3 - 2.3 m length) along three transects (Figs. 1, 3). The sampling areas were widely vegetated at sampling time in 2009. The trenches and cores were photographed and logged to identify stratigraphic boundaries. Changes in grain size, organic and shell content, bedding and heavy mineral laminae were noted. The thickness of the surficial sandy (Isabel) unit was measured in the trenches at each transect, and trenches and cores were subsampled at 10 cm intervals and layer boundaries for subsequent sediment analyses. Sieving at 0.5 phi intervals with Ro-Tap machines was used to determine grain-size distributions.

To examine island elevation and change, LiDAR datasets were acquired from the NOAA (http://www.csc.noaa.gov/digitalcoast/) from 2004 (6 m cells) and 2009 (3 m cells). A 2001 dataset (3 m cells) was downloaded from the NC Floodplain Mapping Program (http://www.ncfloodmaps.com/). Downloaded data were in the NC State Plane North American Datum 1983 coordinate system with elevations relative to the North American Vertical Datum 1988 (NAVD88) with units in meters. Vertical and horizontal accuracies of ± 15 cm and < 2m, respectively, have been reported (NOAA Coastal Services Center, 2010). Digital elevation models (DEM) were downloaded as rasters and loaded into ArcGIS and various 3D and spatial analyst tools were employed to examine change. The Raster Math tool was used to difference layers from one another and produce cell-by-cell elevation change between time steps. The resulting elevation grid was symbolized to show larger scale patterns of erosion, accretion and no change. Elevation profiles were generated using the Profile tool in ArcGIS, and values were exported to be plotted with Sigma Plot.

As described above, the Sallenger (2000) storm impact scale incorporates both storm forcing processes and the geometry of the coast to predict coastal response to storms varying in magnitude. In this study, the scale was employed using pre-Isabel LiDAR (from 2001) along with several assumptions to evaluate vulnerability in comparison to impact. Beach slope and runup were assumed to be uniform and approximate values were used; this seems reasonable since a storm alters both parameters as it passes. A conservative combined storm surge and wave height (R_{high}) of 5.17 m (17ft) was determined based on offshore buoy data (Hs of ~3m) and surge observations (Rlow of ~2.1 m) from NOAA (2004). The dune crest (D_{high}) was extracted by creating contours from the the 2001 DEM, digitizing a line, using a Point method, then Zonal Statistics to find the maximum value within a 10 m buffer through ArcGIS. D_{high} was subtracted from R_{high} to evaluate the storm impact; positive values are indicative of the "overwash" regime, when water laden with sediment is expected to overwash the foredune (D_{high}).

4. RESULTS

The variety of data employed in this study demonstrate considerable island dynamics suggestive of different controlling processes over the last ~60 years. Three areas (sites A, B, and C, Fig. 1B) of considerable change are contrasted to highlight island variability.

4.1 Time-series storm impacts

4.1.1 Site A

Site A is located in the central portion of Ocracoke Island, at a relatively narrow section (~400 m) today (Figs. 1, 3). Presently the estuarine shoreline displays "molar tooth" morphology, delineated by a series of cusps and lobes in the marsh topography separated by channels or tidal creeks along the back-barrier (Riggs and Ames, 2006). Based on time-series aerial photographs, it appears Isabel is the only event to impact site A since 1940 (Figs. 1, 3).

4.1.2 Site B

This section of the island also displays "molar tooth" morphology (Riggs and Ames, 2006). Located in a narrow portion (<500 m) of the center of the island, site B has experienced frequent cross-island inundation and overwash, extending from ocean to the sound (Figs. 1,3). Site B has perhaps the most dynamic recent depositional history of the sites studied and aerial imagery suggests widespread impacts from several separate storm events.

The extent of overwash visible in time-series aerial images was similar, but the overwash locations varied. The Isabel event (captured in the 2003 imagery) shows a large, darker-colored area soundward of the beach, suggestive of thin sediment deposition produced by sheetwash, whereas images from 1955, following Hazel, have several bright reflectance areas indicative of larger fans with well-defined overwash throats. The Outer Banks Hurricane (1933) event seemingly overwashed some areas, although the photographs were collected seven years after so vegetation regrowth precludes accurate mapping of storm impacts (Fig. 3).

4.1.3 Site C

Site C is located on the northern end of the island near Hatteras Inlet and has been impacted by overwash (Figs. 1, 3). Imagery suggests the Outer Banks Hurricane (1933), Hurricane Hazel (1954) and the Ash Wednesday Storm (1962) all completely inundated the site, linking the sound and ocean. Moreover, an inlet was breached just east of the site following Hurricane Hazel. The Ash Wednesday storm arrived before inlet closure, causing the erosion of 1000 m of the island (shore-parallel). Post-Ash Wednesday aerials show the severing of Highway 12 east of site C where Isabel also overwashed (Fig. 3).

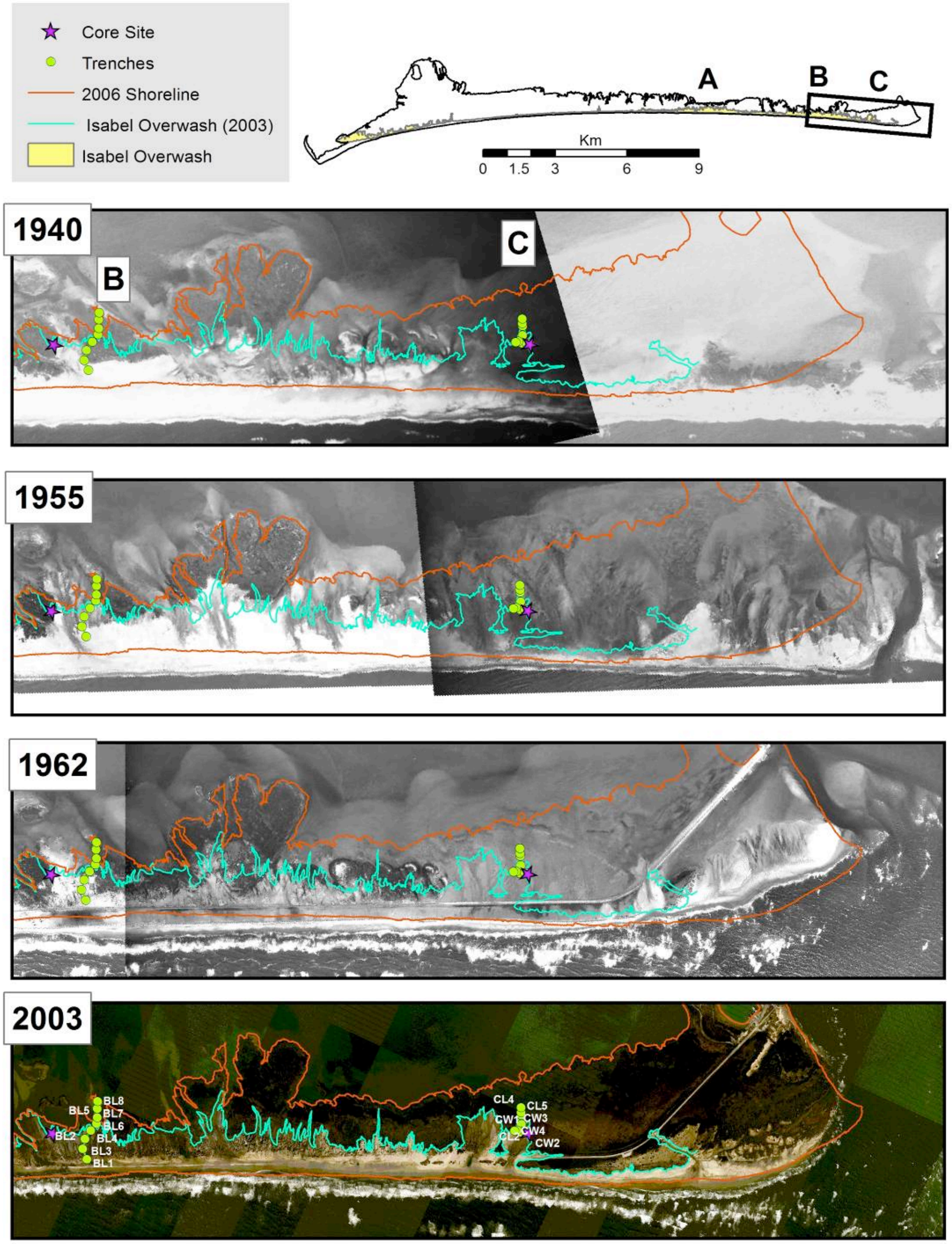


Figure 3. Time-series of the northeastern end of Ocracoke Island encompassing sites B and C. The position of the 2006 shoreline represented by the red line indicates oceanside erosion, some soundward migration and barrier shortening at Hatteras Inlet to the east. Note the additional inlet visible in the 1955 panel.

4.2 Shoreline Change

Long-term (1949-2006) shoreline change rate (SCRs) for the whole island average -0.54 m/yr (SE = 0.05) and range from -6.21 to 6.17 m/yr. The majority (70% of transects) of the island has exhibited long-term oceanside erosion at an average of -1.84 m/yr (SD = 1.45) (Fig. 4). A significant portion of the oceanside shoreline has also accreted (24%). The ends of the island have changed at the most rapid rates due to southerly migration of each bordering inlet. Average erosion increased over the time intervals (1949-1974 and 1974-2006) from -0.69 to -0.96 m/yr (SE = 0.09 and 0.09). Using a paired two sample for means T-test, this difference was determined to be statistically

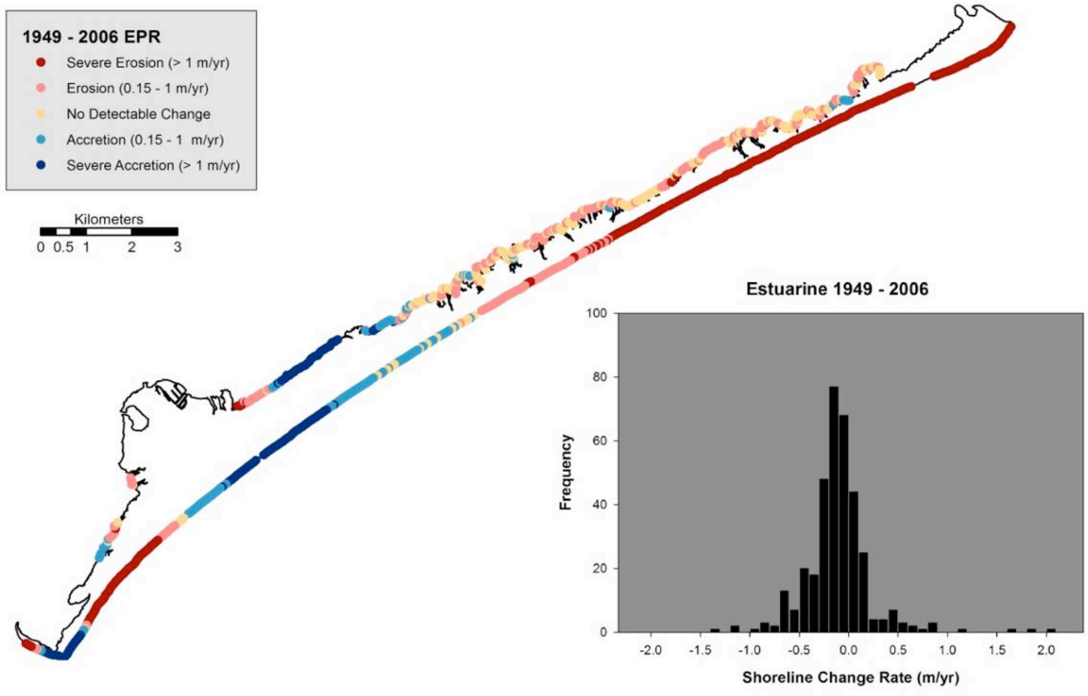


Figure 4. Long-term (1949-2006) shoreline change rates at approximately every 50 m of shoreline coupled with estuarine frequency rate distribution. Oceanside exhibits larger magnitude of change while estuarine shows more spatial variability.

significant (P-value < 0.01). The magnitude of estuarine shoreline change is generally less than the oceanside, averaging -0.11 ± 0.08 m/yr (SD = 0.34), with long-term SCR's ranging from -0.52 to 2.82 m/yr. But, results are more variable than the oceanside. SCR's fluctuate over a smaller lateral scale (Figure 4). Both time intervals (i.e., 1949-1974 and 1974-2006) contain a large percentage of erosive shoreline. In the early interval, 41% of transects were erosive; 30% were accretionary, and 28% fell within the error of the analysis (-0.14 to 0.14 m/yr). The later interval shows an increase in erosional transects (54%), with a decrease in accretionary transects (25%) and having 21% within error. It is notable that average estuarine erosion rate increased between the periods, from -0.08 to -0.13 m/yr (SD = 0.04 and 0.03). However, with a calculated P-value of ~0.08, the increase is not strongly significant.

In order to evaluate the impact of Hurricane Isabel, oceanfront shoreline change was analyzed for the 1998 to 2003 interval. The average change for this interval (-4.0 m/yr; SD = 0.85) was dramatically higher than the long-term (1949-2006) average of -1.84 m/yr (SD = 1.45).

4.3 Hurricane Isabel Overwash Deposition

Aerial photography collected soon after Hurricane Isabel captures the significant, but variable impact on the island. In several areas, extensive overwash of the island occurred, particularly along the northeastern half and southwestern-most end of the island (Figs. 3 and 5). When sampling occurred six years later (2009), although the Hurricane Isabel overwash areas were fully re-vegetated and would have been impossible to define from ground observations or new aerial photography, they were easily identified and measured through trenching (Fig. 6).

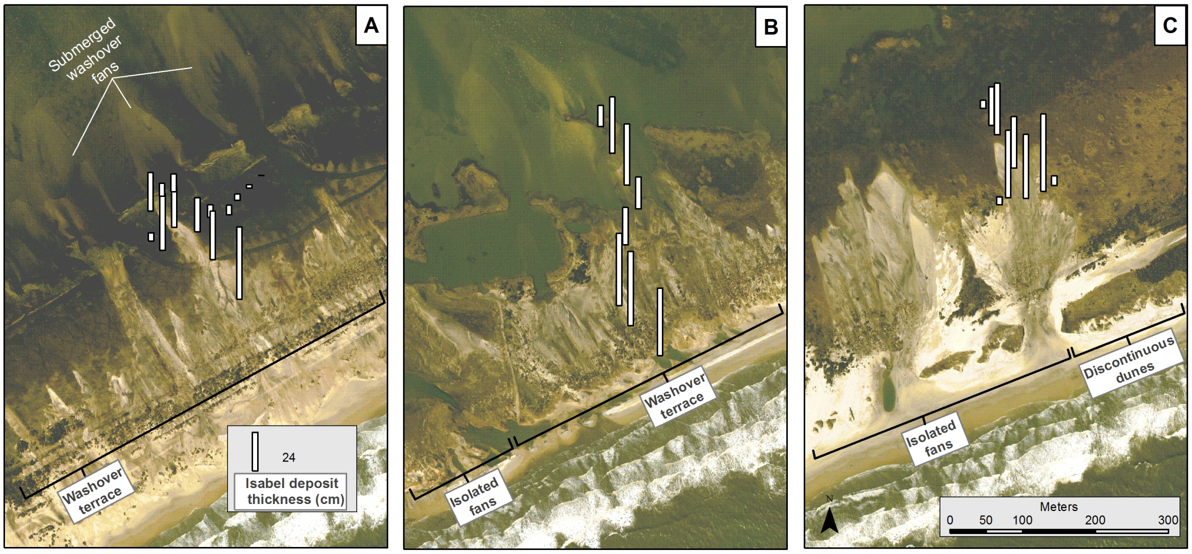


Figure 5. Hurricane Isabel overwash deposit thickness (cm) determined by measurements in trenches at three sites. Sites A and B exhibit sheetwash deposition, while site C contains two isolated lobes with pronounced overwash throats. Note, the submerged fans at site A and B. The physiographic annotations are also examples discussed in Figure 10.

Site A exhibited a complex morphology (Fig. 5), and overwash covered the largest area among sites (62,770 m^2). From the shoreline, the overwash extended approximately 390 m soundward, reaching into in Pamlico Sound. The distal portion (~160 m) of the fan is an elongated, linear deposit, possibly derived from rapid flow through the overwash throat. This sampled fan portion had the smallest average overwash thickness among sites of 13 cm, based on data from 14 trench excavations. The thickness ranged from 4 to 45 cm. Along the sound shoreline, the deposit was 4 cm thick.

The Site B overwash deposits displayed similar morphology to Site A (Figure 5). This terrace-like overwash deposit had an area of 10,200 m^2. This deposit had the greatest average thickness of 33 cm based on measurements from 14 trenches. However, the relatively high average thickness compared to the other sites may reflect the distribution of trenches; those at site B were located more proximal to the source area. Overwash thickness ranged from 13 to 46 cm, again with greatest values noted near the former dune location. The fan thinned in the estuarine direction and terminated before reaching the sound. Along-island width was >100 m, but the deposit was more poorly defined. Maximum soundward extent was ~420 m. The distal end of the deposit was relatively difficult to map in the post-storm aerial photography as it was masked by ponded water.

The site C fan covered 25,751 m^2 and had an average thickness of 26 cm based on measurements in 9 trench excavations (Figure 5). Deposit thickness ranged from 3 to 48 cm, and generally showed a decrease distally. The fan in Site C displayed the characteristic overwash lobe morphology, extending soundward ~400 m from the shoreline, but having a width of only 170 m. The fan terminated before reaching the sound.

4.4 Hurricane Isabel Sedimentological Signature

Isabel overwash deposition at most locations is prominently defined by the sharp basal contact between the organic-rich, muddy sand emplaced by prolonged marsh deposition and the overlying well-sorted sand of the overwash fan (Figure 6). On the Folk and Ward Scale, the Isabel overwash layer is typically fine- to medium-grained sand, with an average of 2.1 phi and is moderately to very well sorted. Most (73%) of the Isabel deposit trench samples (n = 32) are unimodal. Heavy mineral laminae and coarse shell hash are common at the deposit base. Grading is inconsistent. Most (70%) trenches contained finer grained particles in the lower half of the overwash unit (i.e., the unit coarsened upward, sometimes above an immediate coarse shell lag).

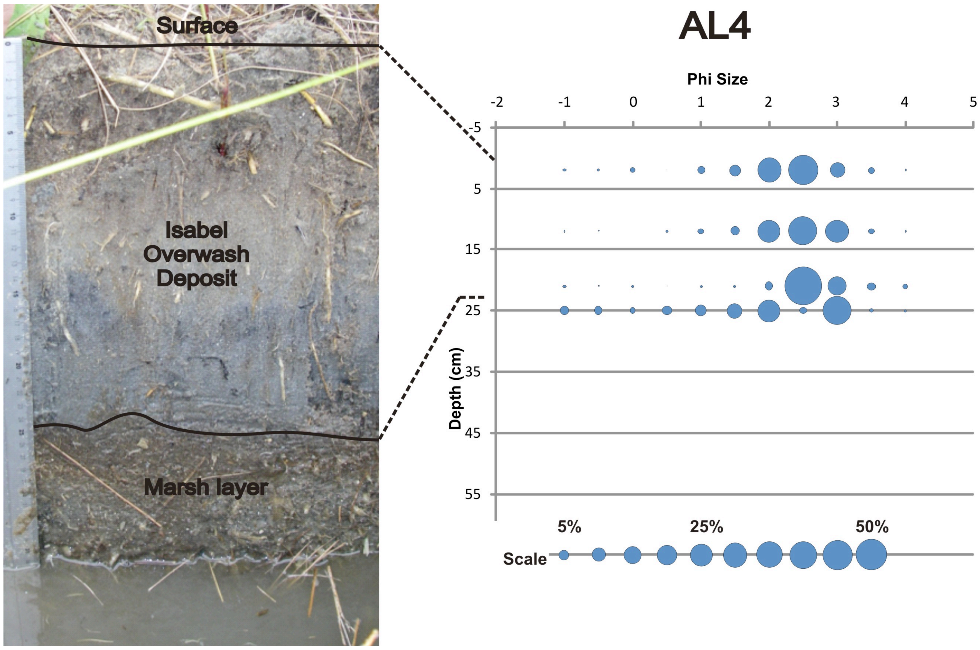


Figure 6. Hurricane Isabel deposit trench excavation at AL4. Grain size distribution correlates with contact between preexisting marsh and Isabel overwash sand. Notice coarse shell grain size signature at base of layer.

Furthermore, at half of the trench sites, better sorting is observed in the lower half of the unit.

The sharp contact at the underlying organic-rich layer is evident by the variation in phi distribution with depth (Figure 6). The organic-rich layer is composed of a wider range of grain sizes, reflecting poorer sorting and more mass from larger organic materials. This wider distribution is due to the presence of mud, sand, peat and root fragments.

The Isabel overwash deposit is also identified at the top of four out of seven cores across the island. Three of the four overwash deposits have an abrupt contact with underlying organic-rich (marsh) sediments. The thickness of the organic-rich marsh layer ranges from 14 to 34 cm in cores.

All cores were also analyzed for preserved storm deposits prior to Isabel. In the Chris's Hole core (C6), the inferred Ash Wednesday (1962) deposit is a normal-graded, medium-fine sand. This unit is marked by an increase in coarse shell hash at its base and heavy mineral laminae, both characteristics consistent with observations of overwash units by Kochel and Dolan (1992) and Sedgwick and Davis (2003). The top of the layer exhibits mottling, which is indicative of post-depostional reworking likely from recolonization of the marsh. Below the sharp contact of the Ash Wednesday unit, another normal-graded, fine muddy sand with a coarse shell hash base is thought to represent the Hurricane Hazel (1954) event (Fig. 7). This unit grades to a layer characterized by a fine sand with no grading, and a coarse shell hash that is likely indicative of the Great Atlantic Hurricane (1944). Ultimately, the Chris's Hole core and time-series aerials reveal a record of stacked overwash deposits.

C1 and C5 also contain event-layers representative of the Ash Wednesday storm and Hurricane Hazel (Fig. 7). Due to their close proximity, event-layers in C5 and C6 are well-correlated. Similarly to C6, each Ash Wednesday unit is marked by a coarse shell hash base and some stratification within the bedding. This unit at C5 also exhibits heavy mineral laminae. The Hazel unit is characterized by no grading. C1 and C5 likely contain less mud content throughout because they are more distant (seaward) from the organic-rich backbarrier than other sites.

4.5 Overwash Volume Estimates

Maps of overwash areas (based on post-hurricane aerial photographs and trench-based layer thicknesses), were used to estimate total deposit volume for each site (Table 1). It should be noted that because each trench transect was essentially shore-normal, and along-island variation was minimally investigated, these estimates are approximate and likely conservative.

An overall average thickness of 0.24 m was calculated for the Isabel overwash layer for all the deposits measured. Individual fan volumes for Sites A, B and C were estimated: 8,160 m^3, 10,200 m^3, and 6,695 m^3, respectively.

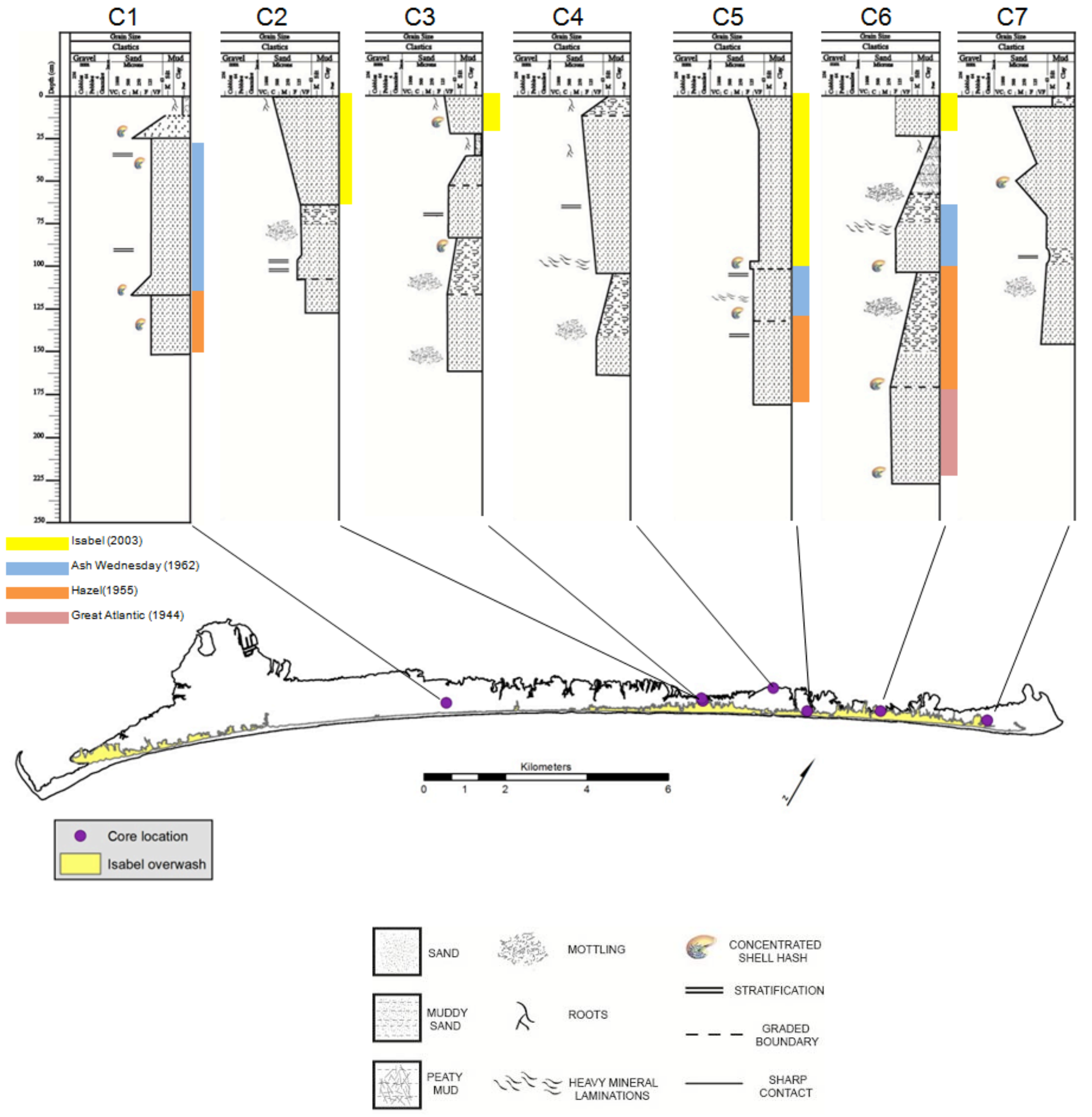
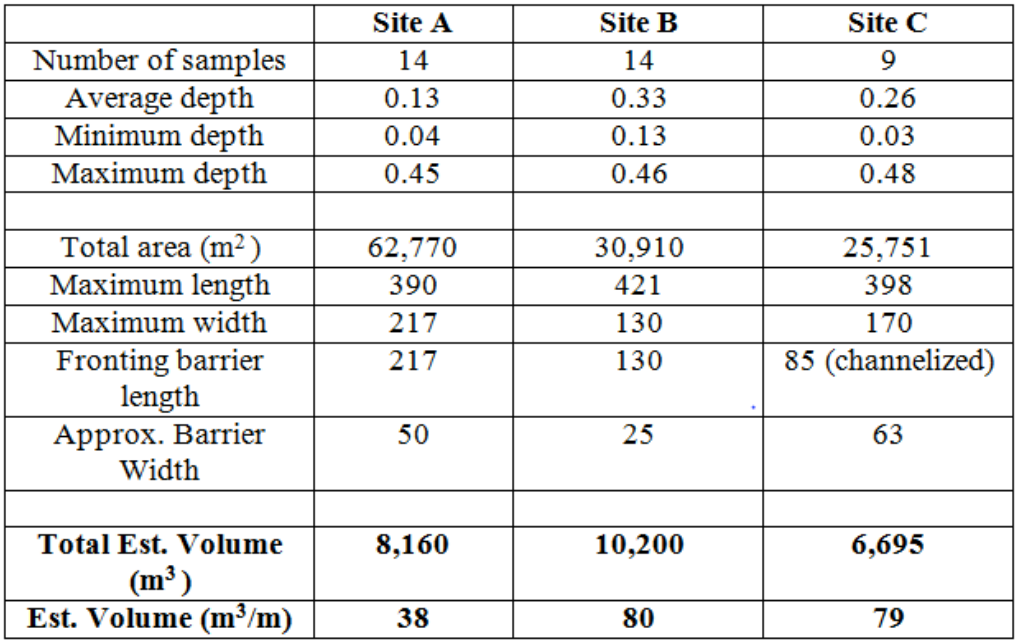


Figure 7. Core logs and locations. Additional interpreted event layers indicated by colored bars. Note, stacked overwash deposits at some core sites.

Table 1. Multiple overwash deposit parameters by site. m^3/m is estimated volume per linear meter of fronting foredune.



	Site A	Site B	Site C
Number of samples	14	14	9
Average depth	0.13	0.33	0.26
Minimum depth	0.04	0.13	0.03
Maximum depth	0.45	0.46	0.48
Total area (m^2)	62,770	30,910	25,751
Maximum length	390	421	398
Maximum width	217	130	170
Fronting barrier length	217	130	85 (channelized)
Approx. Barrier Width	50	25	63
Total Est. Volume (m^3)	**8,160**	**10,200**	**6,695**
Est. Volume (m^3/m)	**38**	**80**	**79**

Based on an average deposit thickness of all sites across the island and a mapped island-wide Isabel overwash area of 2.2 km^2, the total overwash volume is estimated to be 598,922 m^3. Thus, the deposits at Sites A, B and C (Figs. 1, 3 and 5) represent 1.4, 1.7 and 1.1 percent of the total mapped overwash volume.

Raster subtraction of the 2001 (Pre-Isabel) and 2004 (Post-Isabel) DEM's demonstrates volumetric change (Fig. 8). The most conspicuous displacement of volume is from the foredune; some accretion is visible along the soundward boundary of the mapped overwash, as well as along the soundside shoreline where overwash extended into the sound (Fig. 8).

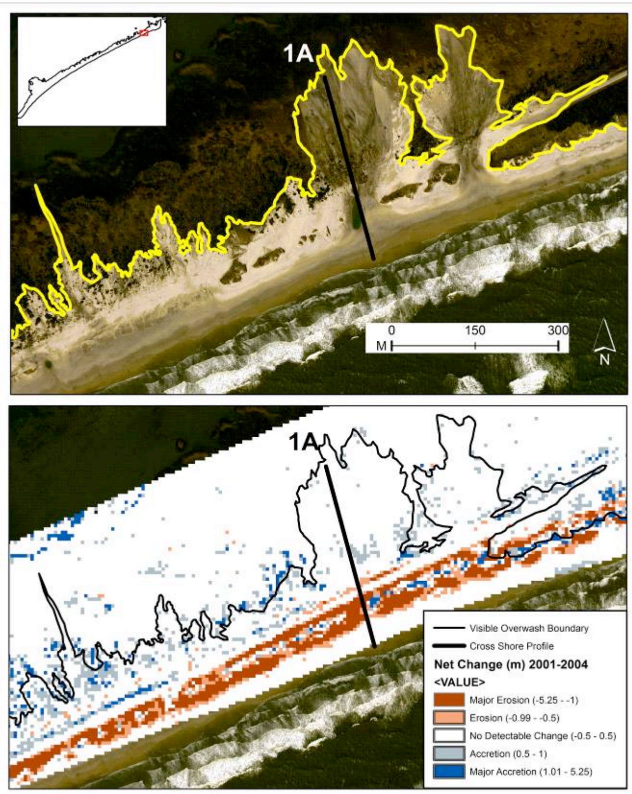


Figure 8. Top panel shows mapped Hurricane Isabel overwash on post storm imagery. The bottom elevation differencing from 2001 to 2004 displays extensive foredune volume loss and some backbarrier accretion. Cross shore profile is indicated by the bold black line (Figure 8).

4.6 Morphologic Change

From cross-shore profiles intersecting the 2001, 2004 and 2009 DEMs, morphologic change is visible through time (Fig. 9). It must be mentioned that bulldozing likely plays an important role in the observed variations. Soundward foredune migration of 40 m is visible at site A (Fig. 9). A smaller amount of dune position change is observed at B and C, but there is error in this approach, and it is likely a result of dune reconstruction by bulldozing, which is a common practice following a storm. Reduction of the foredune height among the sites ranged from 0.45 to 2.22 m over the period of 2001–2009. From 2004–2009 the foredune showed minimal change which ranged from 0.25m to 1m likely due to vertical error and the lack of a major storm.

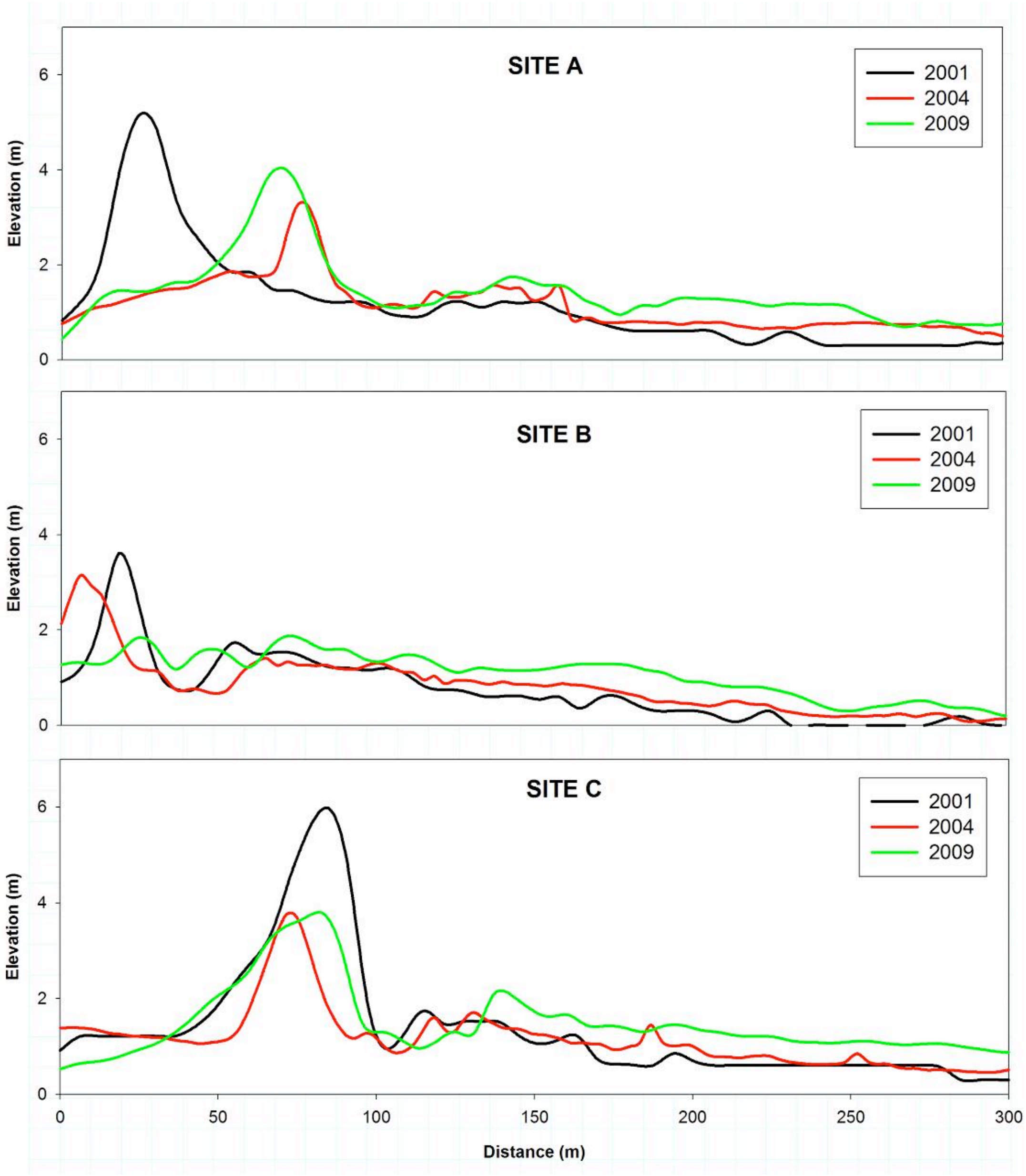


Figure 9. Cross-shore profiles from sites 1A, 1B and 1C. These locations are also indicated in Fig. 1. Note foredune erosion at each site and significant soundward migration (~40 m) at A.

5. DISCUSSION

5.1 Shoreline evolution

Considering all the areas examined, Ocracoke Island is eroding along more shoreline than it is accreting, and the average shoreline change is erosional (-0.54 m/yr, SE = 1.43), but there is much variability. Within the context of the Outer Banks system, Ocracoke Island shows relatively low estuarine erosion rates (i.e., -0.11 m/yr), about half the magnitude of other Outer Banks regions (Table 2). Cowart (2006) and Schwimmer (2001) reported average erosion rates more than double those of Ocracoke at Cedar Island, NC and Rehoboth Bay, Delaware, respectively. While rates in this study are lower, the probability distribution of rates is similar to that of Cowart (2006) (Figure 4).

Table 2. Average estuarine shoreline change rates (SCR's) in m/yr for the Outer Banks, Dare County, North Carolina. Unpublished Data, Governor's South Atlantic Alliance Report.

	Ocracoke	**Hatteras**	**South of Oregon Inlet**	**Bodie Island**	**Roanoke Island**
1949-1974 (m/yr)	**-0.08**	**0.02**	**-0.19**	**0.04**	**-0.51**
σ	0.68	0.8	0.9	0.7	1.18
1974-2006 (m/yr)	**-0.13**	**-0.36**	**-0.39**	**-0.28**	**-0.55**
σ	0.52	0.49	0.5	0.4	0.75
1949-2006 (m/yr)	**-0.11**	**-0.2**	**-0.31**	**-0.15**	**-0.53**
σ	0.34	0.47	0.4	0.35	0.76

Both datasets have the highest frequencies in -0.1 to -0.2 m/yr range, followed by 0 to -0.1, and -0.2 to -0.3. Ocracoke differs in that its distribution contains more accretionary measurements, which raises the average long-term rate of shoreline change.

The literature has identified several variables important to erosion, e.g., fetch and shore type. Qualitative analysis of these data reveals several factors that appear to reduce estuarine erosion rates on Ocracoke, including: nearshore shoals, overwash sedimentation in the sound, and oblique island orientation. More specifically, the widespread shoals (e.g. Howard's Reef and Green Island) in close proximity to the back-barrier marsh shoreline appear to play an important role in wave sheltering. These shoals mimic the orientation of the island for nearly its entire length and consequently serve as a buffer to wave action. Moreover, they are likely a large sink of sediment eroded from the shoreline. Also, wave action may act to redistribute sediment from the shoals back onto the island shore. In a few limited local areas where the island has narrowed substantially (e.g., sites A and B, Fig. 3), overwash during storm events may be able to traverse the island, adding sediment to the estuarine shoreline and reducing time-averaged erosion rates (Figure 5).

When the island is examined by regions (Fig. 10), several trends are observed. First, it is notable that many island segments are showing narrowing (i.e., net erosion when combining estuarine and ocean shoreline change). Many previous studies (e.g., Godfrey and Godfrey, 1976; Riggs and Ames, 2006; Smith et al., 2008) have suggested the common occurrence of narrowing on barrier islands, and the data here, at least locally, support this. In fact, narrowing (i.e., negative net area change) is correlated with current island width ($R^2 = 0.67$), revealing the thinnest regions of the island are eroding at the greatest rates (up to -182 m) from 1949-2006, suggesting that the overwash process is not able to keep pace with erosion. If historic change rates are maintained for the northeastern side of the island, complete breaching (i.e., inlet opening) will occur within ~100 yrs, even without accounting for sea-level change. Island narrowing suggests the island is not in a state of dynamic equilibrium with overwash flux (Carruthers, 2013).

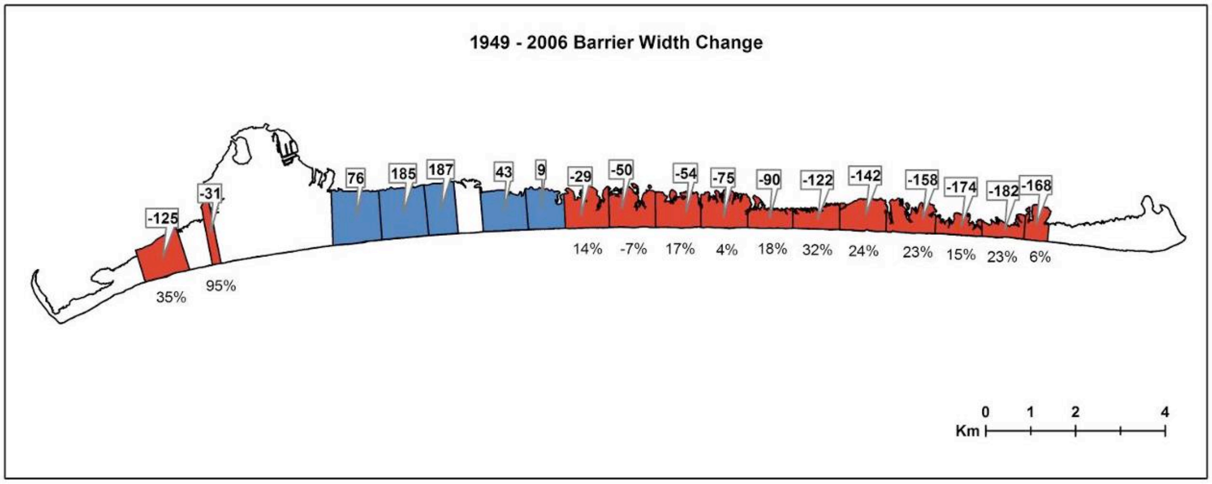


Figure 10. Barrier Island width change by 1000 m regions from 1949 - 2006 using combined estuarine and oceanside erosion rates. Upper boxed value shows change in meters of width. Values below island indicate percent of total change during the interval containing Hurricane Isabel for 1998-2003.

The undeveloped barrier islands of Core Banks and Portsmouth Island exhibit more equilibrium and soundward migration through overwash, oceanside erosion and estuarine accretion (Godfrey, 1973). However, Ocracoke also may reach a critical width, as suggested by Leatherman (1979), in which overwash begins to cause enhanced soundward migration and barrier widening, a process which appears to have initiated with Isabel. Interestingly, average measured foredune elevations in the regions from all three LiDAR time steps are positively correlated with oceanfront erosion rates, i.e., lower elevations are prone to more erosion ($R^2 = 0.82$ to 0.84). Additionally, foredune height change measured from 2001 to 2004 positively correlates to long-term oceanside change rates ($R^2 = 0.68$). These two observations suggest a relationship between the observed morphology and the processes, and help indicate how persistent and event-driven changes are driving foredune character. This, in turn, will influence overwash potential (i.e., by reducing D_{high}).

Hurricane Isabel, in particular, caused much oceanside erosion (and thus island narrowing) based on shoreline change between 1998 and 2003. On average among all sections, Isabel was responsible for 23% of the total island narrowing during the full analysis period (i.e., 1949-2006; Fig. 9). Although, some areas showed recovery from 2003-2006 following the storm, net narrowing was widespread.

5.2 Spatial and temporal variability in storm response

To evaluate the evolving island condition, the time-series aerial photographs were classified according to the geomorphic character following Hosier and Cleary (1977). Four classes are recognized: 1) Discontinuous dunes (*DD*) 2) continuous dune ridges (*CDR*) 3) isolated overwash fans (*IOF*) and 4) overwash terraces (*OT*) (Fig. 11) (see physiographic annotations in Fig. 5). From 1940 to 2006 for all imagery, the *IOF* and *OT* classes make up an average of 58% of linear beach distance on Ocracoke, reflective of recent storm impact (i.e., 23 % *IOF* and 35% *OT*) and a condition more vulnerable to subsequent overwash (Fig. 10). *DD* and *CDR* continuous dune ridges accounted for the remaining 42%. Among the specific study areas, site A was the least storm impacted, as reflected by a high percentage of *DD* (31%) and *CD* (25%); site B was dominated (56%) by post storm conditions (i.e., 12% *IOF* and 44% *OT*), and C had an even balance of dunes and overwash. Site C also contained the highest percentage of the most stable condition (i.e. *CDR*). Different observed geomorphic conditions among sites further show the alongshore complexity in temporal response to storms, and non-uniform island evolution.

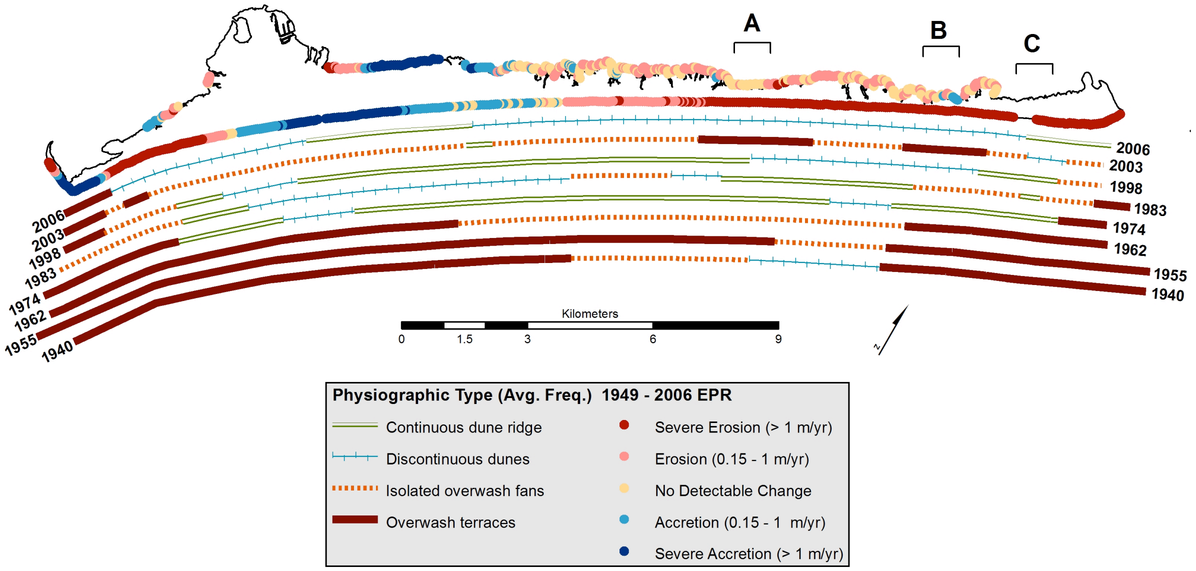


Figure 11. Oceanside physiographic conditions through time with 1949 – 2006 shoreline change rates. For aerial examples refer to Fig 5. Format adapted from Hosier and Cleary, 1977.

Physiographic conditions in 1940 (Figs. 3, 11) suggest a overwash-prone state following the Outer Banks Hurricane (1933), which was a major hurricane that made landfall and caused widespread overwash along the Outer Banks; the island state prior to the 1940 image is unknown. After widespread overwash on the Outer Banks by the Ash Wednesday storm (1962) (Fig. 3 and Riggs and Ames, 2008), significant physiographic change occurred; a majority of the island transitioned to *CD* and *DD*. This transition is attributed to bulldozing and re-emplacement of the dune with vegetation (Riggs and Ames, 2008), as well as natural stabilization through aeolian transport during a non-stormy period. A similar transition in the morphologic condition is recorded in the classification of the 2006 imagery (Fig. 11); dune reconstruction was initiated following the wide impact of Isabel. Importantly, this provides insight into the potential time for dune reestablishment following a major storm event. Hosier and Cleary (1977) suggest the transition to discontinuous dunes with scattered vegetation in an undisturbed system are the result of overwash within 1 to 10 years. The results here are consistent with this, although human intervention likely played a dominant role. The 1974 mapping contains the largest proportion (70%) of intact *CDR* throughout the intervals. From 1974 to 1983, it appears minor local overwash occurred disrupting the *CDR* and shifting more areas into *DD*. Changes were likely the result of multiple nor'easters in 1982 and 1983, with some offshore wave heights exceeding 7 m (Dolan et al., 1988). From 1983 to 1998, nearly all local overwash areas transitioned to discontinuous dunes or intact continuous ridge likely as result of conscientious island management for Highway 12 protection and the absence of an intense storm.

During more reduced storm periods (i.e., between Ash Wednesday in 1962 and Isabel in 2003), overwash penetrated only 5 – 40% of oceanside foredune barrier, and more of the dune system became stabilized (Fig. 11). Despite less visible overwash in the later period (1974-2006), higher erosion rates were measured when compared to 1949-1974. This implies that, while large historic tropical storms are certainly important drivers of erosion, chronic processes, like less strong (but far more frequent) storms (e.g., nor’easters) and sea-level rise also play a significant role. It is recognized that the numerous nor'easters annually are the dominant control on net longshore transport (Inman and Dolan, 1989), so it is not unexpected that they may also influence dune integrity.

Hurricane Isabel, a category 2 storm at landfall, impacted the island differently than prior storms. While Isabel’s overwash impacted 94% of the linear distance of the island foredune, the impacts (or combined impact) of the prior higher magnitude storms impacted up to 100% of linear distance (Fig. 11) as inferred from morphology in aerial photography. Aerial evidence suggests Hurricane Isabel caused significantly less inundation (26%) when compared to earlier storm intervals. Hurricane Hazel (1954) and prior combined storms resulted in 90% of island inundation, followed by 71% in 1940 imagery and 58% from Ash Wednesday Storm (1962) and prior events. These earlier storms were also in closer succession, which suggests less recovery time and lower elevation foredunes more prone to inundation. All of these storms essentially caused the complete destruction of the continuous dune ridge with only Isabel leaving a mere 3% intact (Fig. 11), showing long-term evolution dependent largely on storm impacts.

Observations suggest that human management has fundamentally altered the sedimentary functioning of the system. The dune system of 2003 is apparently more effectively preventing overwash (as designed by the DOT). But ultimately this is limiting overwash deposition and mid-island vertical growth (Godfrey and Godfrey, 1976; Leatherman and Williams, 1977). Other Outer Banks beaches north of Ocracoke (e.g., Nags Head, Kitty Hawk and Duck) have been persistently managed in terms of dune barrier maintenance and essentially prohibited from natural soundward migration. Despite the maintenance, sediment supply is not limitless and dunes in areas like Kitty Hawk have greatly diminished. Stopping barrier "roll over" by attempting to maintain the foredune has led to widespread shoreface erosion and has forced several of these tourism-dependent communities to implement multi-year and multi-million dollar beach nourishment plans (Young et al., 2014). Ocracoke is also on the verge of such action if storms and sea-level rise continue to impact the coast, especially in the case of a higher storm period occurring like observed from 1940-1962 (Fig. 11).

5.3 Utility of the storm-impact scale

Spatial and temporal variability in response to storms was observed long-term (Fig. 11), but potential factors for the differences are difficult to assess without LiDAR- derived elevations from the earlier periods. Now, however, with LiDAR data, Hurricane Isabel provided an opportunity to evaluate how pre-existing dune conditions contribute to alongshore variability in response to storms. Results from the storm impact scale in this study show pre-storm foredune maximum height is qualitatively and quantitatively correlative with susceptibility to overwash (Fig. 12).

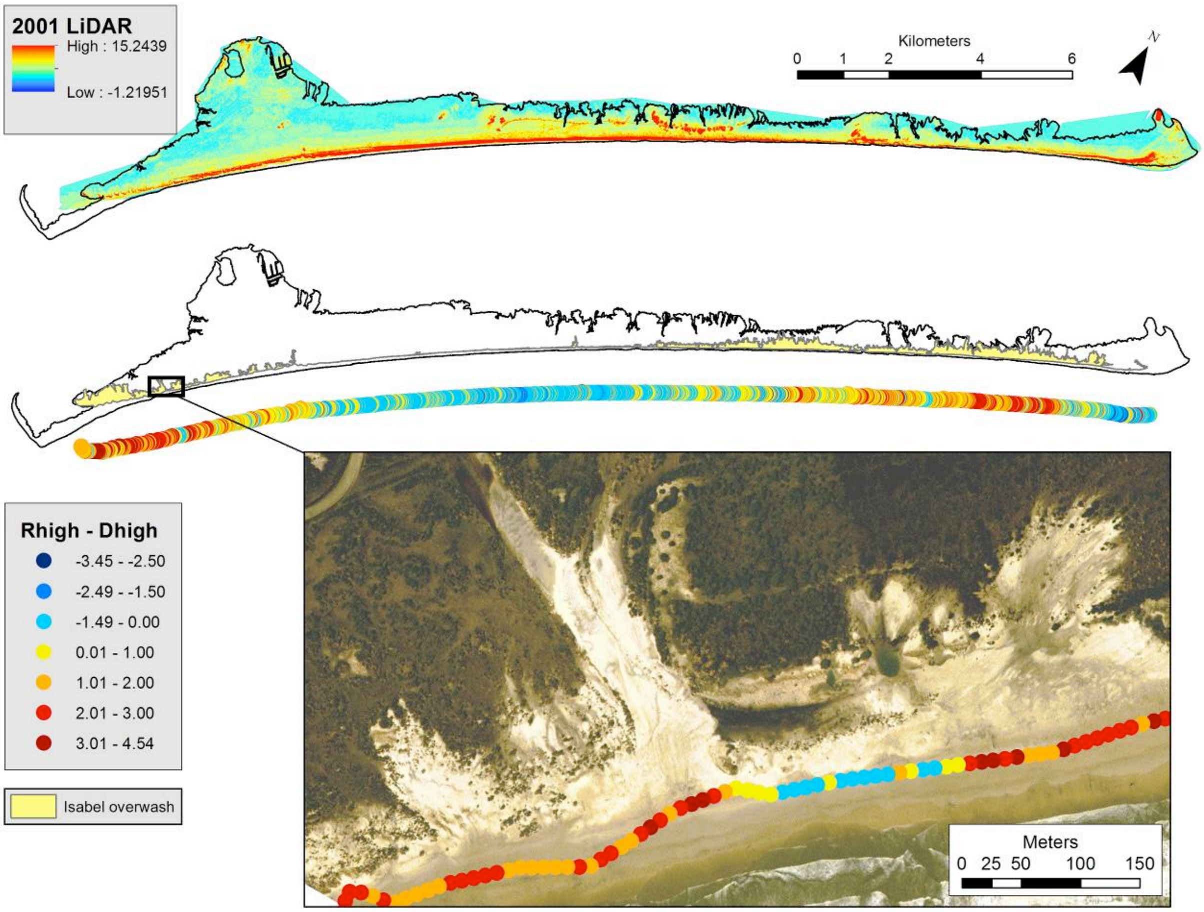


Figure 12. 2001 LiDAR, mapped Isabel overwash and storm impact scale based on Sallenger (2000). Positive R_{high} - D_{high} values are areas that are most likely to significantly overwash based on storm surge and waves exceeding the maximum dune crest. Note the predictive accuracy shown in the zoom.

Most areas with positive R_{high} - D_{high} values experienced overwash on Ocracoke (Figs. 12 and 13), and immediately adjacent areas also showed impact in many cases. Minor and isolated overwash occurred where there was a smaller or slightly negative R_{high} - D_{high} value. When evaluated by island regions, averaged R_{high} - D_{high} are correlated to mapped overwash area (n = 17, $R^2 = 0.42$ and P-value < 0.01). The discrepancy in slightly negative values exhibiting overwash is likely due to the additional energy contributed by wave setup, conservative R_{high} values, method error or topographic lows below the resolution of the LiDAR.

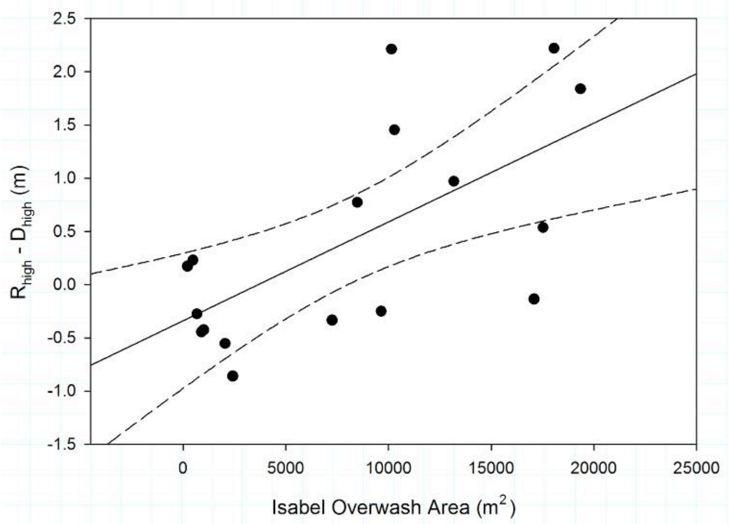


Figure 13. Averaged R_{high} - D_{high} values plotted against mapped Isabel overwash area by 1000 m regions as delineated in Fig. 9. Dashed lines are 95% confidence interval is included.

Ultimately, this method may be beneficial in effectively managing our coasts both before storms to assess most vulnerable regions and after to plan for future recovery of the barrier (Stockdon and Thompson, 2007). Furthermore, the response to storms of different magnitude can be evaluated to provide a potential spatial range of impact.

5.4 Hurricane Isabel impact

Hurricane Isabel induced spatially variable but widespread overwash throughout Ocracoke Island (Figure 3, 5). A total of 2.2 km^2 of overwash area was estimated, when delineated digitally from 2003 images in ArcGIS. This new deposition covered approximately 9% of the island.

Generally, the thickest sections of the overwash fans were measured in the most shoreline-proximal trenches. The few thickness measurements in the throat areas were apparently thinner (Fig. 5), probably as a result of this being a zone of enhanced sediment transport; material passing through the throat to the backbarrier commonly creates an elongated elliptically shaped deposit (Leatherman and Williams, 1977).

The fate of overwashed sediments is critical in barrier island sediment budgets and a comparison of the Isabel overwash deposit with eroded dune volumes suggests a correlation at two of the three sites. Box-model estimates at sites A and C show the relationship of dune volume loss to overwash fan volume (Table 3). At sites A and C, there is only a difference of 29 % and 1%, respectively, in measured overwash sediment and eroded dune volume. The substantial difference at site B (180 % more deposited than eroded) is likely a result of a much lower pre-existing foredune resulting in more sheetwash transport for a longer duration of the event and more beach face erosion and soundward transport (Donnelly et al., 2006).

Based on subaerial island volume estimates, the averaged Isabel overwash volume represents up to 26% of total subaerial back-barrier island volume at the study sites (Table 3). Cross-shore profiles show significant back-barrier accretion on the order of ~ 1 m from 2001 to 2009 (Fig. 9). However, it is notable that in areas where dune height was substantial (i.e. > ~5m) that island volume was not augmented. Overall, these observations emphasize how storm-driven sedimentation is critical for maintaining back-barrier island elevation and volume (Godfrey and Godfrey, 1976; Leatherman, 1979, Inman and Dolan, 1989), and this is a significant concern with the expected accelerated sea-level rise and possibly enhanced occurrence of major storms (Emmanuel, 2005; Kemp et al., 2009; Mann et al., 2009; Knutson, 2010).

Table 3. Volume change estimates using averaged trench and cross-shore profile data. Note, sites A and C show comparable loss/gain. Differences at B may reflect differing pre-existing foredune conditions and/or method error.

	Site A	Site B	Site C
Total overwash volume (m^3)	8,160	10,200	6,695
Total dune volume loss (m^3)	6,085	530	6,631
Percent volume difference in overwash and dune loss	29	180	1
Total subaerial volume (m^3)	60,953	39,865	41,799
Isabel Overwash percent of total subaerial back-barrier volume	**13**	**26**	**13**

5.5 Overwash event deposits and their preservation potential

While the observed Isabel overwash deposit is distinct (Fig. 5, 6), examining historic and ancient layers presents more of a challenge. In the case of Isabel on Ocracoke, the overwash deposit examined here was emplaced on top of a substantially different sedimentary environment. The sedimentological signature of the Isabel overwash deposit suggests two potential phases of deposition at some sites. This type of phased deposition has been noted by others in overwash deposits located in southwest Louisiana (Hurricane Rita) and Hatteras Island, Outer Banks, NC (Williams, 2009; Schwartz,1982). Williams (2009) suggest the lower finer grained unit is rapidly deposited early in the storm surge from suspended load. The second phase of storm surge deposition drapes coarser particles from traction load. These distinct units within overwash deposits may be helpful in distinguishing historic storm layers, but it must be recognized that the overwash strata will be variable in nature. Therefore, the identification of the deposit depends not only on the environment where deposited (e.g. over preexisting marsh, barrier sand, sound, etc.) but also the nature of the depositional conditions. These will vary depending on storm conditions, initial geomorphology and sediment availablity.

Although minimal reworking was apparent in the Isabel deposits on Ocracoke, it must be noted that overwash layers are subject to biological and physical (waves, wind) reworking (Grand Pre, 2011; Hippensteel, 2011), making their recorded signature potentially complex. Furthermore, as seen in the LiDAR analysis, human activities may play a huge role in altering the sedimentary record. The other consideration is that barrier islands are dynamic and potentially ephemeral features. The average residence time of storm deposit preservation can be estimated by dividing the approximate average island width by long-term average island narrowing rates . Using this approach, a preservation period of ~100-500 years can be inferred for the majority of Ocracoke (and much of the Outer Banks), excluding the historically accreting sections around the village. Additional disturbance to layer preservation that must be considered includes historic inlet migration and subsequent storm sedimentation. Ultimately, due to this residence time, a dynamic environment like Ocracoke can only be used for short time period storm reconstruction.

Several cores were collected in this study to evaluate the preserved sedimentary record and the contribution of storms to elevation growth. The Chris's Hole (C6) core at site B, located in a narrow portion of the northeastern side of the island has experienced overwash previously and been heavily impacted by storms as shown by historic aerial imagery (Figure 3). Based on stratigraphic analysis, the site contains four storm deposits, the most identified among the study (Fig. 7). Event layers are believed to be associated with the Great Atlantic Hurricane (1944), Hurricane Hazel (1955), the Ash Wednesday Storm (1962) and Hurricane Isabel (2003). Higher mud content in the top of the Ash Wednesday layer may be due to flood tidal-delta or intertidal conditions after deposition from soundside flooding (Hennessy and Zarillo, 1987).

With a back-barrier island elevation of only ~1 m, the overwash layers identified within cores show the important contribution of storm sedimentation to the structure of the island. Stacked storm deposits also reveal the regions most dominated by recent decadal storm events. Back-barrier storm-driven sedimentation coupled with the observed long-term oceanside erosion reveals the ongoing process of barrier island rollover (Godfrey and Godfrey, 1976; Inman and Dolan, 1989). An interesting observation of this work is that, although Ocracoke, like many other barrier islands is long and linear, its process-controlled evolution and the resulting stratigraphic record is not a simple two-dimensional process as conceptual models have illustrated and implied by numerical models (GEOMBEST, Moore et al., 2007; XBEACH, Roelvink et al., 2009). Rather, there is substantial spatial and temporal variability in overwash deposition from different historic storms preserved in the geologic record (Fig. 7). While some areas of the island may experience local overwash and vertical elevation growth, others may not (Figs. 3, 8 and 11), resulting in non-uniform migration and alongshore variability. Therefore, while cross sectional models of barrier migration may be a useful starting point, the process is realistically much more complex and operates in three dimensions, as shown by preserved strata within these cores (Fig. 7).

6. CONCLUSIONS

This study provides insight into the barrier island dynamics of a moderately human-modified system. These findings provide analysis of past change that are useful in future maintenance of barrier islands subject to the impacts of sea level rise and storms.

Several specific conclusions are:

1) The island is narrowing in many areas but patterns are complex. The estuarine shoreline has eroded over the long-term (1949-2006) at an average rate of -0.11 m/yr. The oceanside shoreline has eroded at a rate of -1.84 m/yr over the same period. Some regions of the island have narrowed as much as 182 m in only 57 years. Both estuarine and ocean erosion rates have increased through time, and narrowing will likely continue with the effects of sea level rise and storms.

2) Ocracoke has been predominantly in a post-storm physiographic state through decadal time. Hurricane Isabel caused widespread but spatially variable and complex impacts. Prior decadal storms had greater impacts likely due to a closer succession of storms with less maintenance (i.e. dune building) in the earlier era.

3) The storm-impact scale was effective at identifying Isabel overwash areas, confirming how pre-existing dune conditions control spatial variability in storm impact. With the accessibility of LiDAR, coastal managers should use this methodology to identify areas most at risk to different magnitude storms.

4) Hurricane Isabel deposited a sedimentologically distinct, yet spatially variable, overwash layer covering 9% of Ocracoke Island. An estimated overwash volume of nearly 600,000 m^3 is considerable when assessing barrier island sediment budgets and may represent up to 26% of subaerial backbarrier volume. Moreover, Hurricane Isabel caused up to 40 m of soundward migration of the foredune and caused extensive oceanside erosion. These processes are critical componenets of barrier island evolution.

5) Overwash deposits from four storms dating back to 1944 are identifiable within the cores across the island. Some regions of the island are composed of four stacked overwash deposits

showing the overall importance of storm sedimentation in barrier island building. The preservation of spatially and temporally variable storm layers shows how barrier islands are not simple two-dimensional migrating systems as often modeled, but instead evolve in three dimensions.

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