Change in morphology and modern sediment thickness on the inner continental shelf offshore of Fire Island, New York between 2011 and 2014: Analysis of hurricane impact

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ABSTRACT

Seafloor mapping investigations conducted on the lower shoreface and inner continental shelf offshore of Fire Island, New York in 2011 and 2014, the period encompassing the impacts of Hurricanes Irene and Sandy, provide an unprecedented perspective regarding regional inner continental shelf sediment dynamics during large storm events. Analyses of these studies demonstrate that storm-induced erosion and sediment transport occurred throughout the study area in water depths up to 30 m. Acoustic backscatter patterns were observed to move from ~1 m to 450 m with a mean of 20 m and movement tended to decrease with increasing water depth. These patterns indicate that both of the primary inner continental shelf sedimentary features in the study area, linear sorted bedforms offshore of eastern Fire Island and shoreface-attached sand ridges offshore of central and western Fire Island, migrated alongshore to the southwest. The migration of the sorted bedforms represents the modification of an active ravinement surface and is thought to have liberated a significant volume of sediment. Comparison of isopach maps of sediment thickness show that the volume of modern sediment composing the lower shoreface and shoreface-attached sand ridges decreased by ~2.8 × 10⁶ m³ across the ~73 km² of common seafloor mapped in both surveys. However, a similar analysis for the relatively calmer 15-yr period prior to 2011 revealed significant accretion. This allows speculation that the shoreface-attached sand ridges are maintained over decadal timescales via sediment supplied through erosion of Pleistocene outwash and lower Holocene transgressive channel-fill deposits exposed on the inner continental shelf, but that the sand ridges also periodically erode and move to the southwest during large storm events. Analyses show that significant storm-induced erosion and sediment transport occurs far seaward of the 5 to 9 m depth of closure assumed for Fire Island, where it is thought that an onshore-directed sediment flux from the inner continental shelf to the littoral system is required to balance the coastal sediment budget. It is also thought that the morphology of the shoreface-attached sand ridges controls the persistent shape of the adjacent shoreline through modification of incident waves. Thus, we speculate that the sediment dynamics of the inner continental shelf and both storm-induced and anthropogenic modification of the field of shoreface-attached sand ridges be considered in future coastal resiliency planning.

1. Introduction

The formation of an erosional surface linked with marine transgression and the resultant development of transgressive sedimentary deposits are of keen interest to the scientific and engineering communities. Coastal sediment budgets and associated coastal evolution can be significantly influenced by the availability of nearshore transgressive sand deposits (Riggs et al., 1995; Thieler et al., 1995; Schwab et al., 2000, 2013; Gayes et al., 2003; Miselis and McNinch, 2006; Hapke et al., 2011; Denny et al., 2013; Twichell et al., 2013). In addition, these deposits are an important resource used for coastal erosion mitigation programs (e.g., Charlier, 2002; Drucker et al., 2004; http://www.nan.usace.army.mil/Missions/CivilWorks/ProjectsinNewYork/FireIslandtoMontaukPointReformulationStudy.aspx). As rates of sea level rise and the intensity and frequency of extreme storms are expected to increase in the immediate future due to climate change (e.g., Lozano et al., 2004; Sallenger et al., 2012; Church et al., 2013; Füssel, 2009), identification of additional offshore sand resources required for

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beach nourishment projects, assessment of potential coastal response to mining these nearshore deposits, and the modification of these deposits by oceanographic processes are research topics of growing importance (e.g., Maa et al., 2001; Cooper and Navas, 2004; Hayes and Nairn, 2004; Warner et al., 2014, 2017).

Large storms are known to be primary drivers of landward migration of barrier islands via shoreface erosion, overwash deposition, and island breaching and inlet processes (e.g., Brunn, 1962; Swift, 1968; Leatherman, 1985; Swift and Thorne, 1991) and are assumed to be primary drivers of shelf sediment transport on the inner continental shelf (e.g., Cacchione et al., 1987; Sternberg and Larsen, 1975; Wiberg and Smith, 1983; Wright et al., 1986, 1991, 1994; Warner et al., 2012). However, due to logistical difficulties involved in collecting the necessary pre- and post-storm regional geophysical mapping data, the impact of extreme storms on the morphology and sediment distribution of the submerged component of the coastal system (the shoreface and adjacent inner continental shelf) is relatively difficult to assess compared to the impact on subaerial areas. In fact, the thickness and distribution of mobile sediments are poorly documented in most inner continental shelf settings. Thus, along with the variability of storm events, it is not surprising that there are few high-resolution geophysical studies of large storm impacts on the coastal ocean seabed, especially those that include modern swath-mapping techniques and dense seismic-reflection data coverage before and after large storm events. We are not aware of any studies that provide a regional-scale perspective. Given these limitations, it is not surprising that interpretations from existing, site-specific studies have resulted in different conclusions concerning hurricane impacts ranging from accretion to erosion (e.g., Kraft and de Moustier, 2010; Goff et al., 2010, 2015a, 2015b; Trembanis et al., 2013).

Hurricane Sandy, the largest storm on historical record in the Atlantic basin (Blake et al., 2013), impacted the New York Bight coast in October 2012 causing breaching and erosion of the barrier-island chain along southern Long Island (Hapke et al., 2013; Schubert et al., 2015). Hurricane Sandy produced sustained winds of 25.1 m/s and significant wave heights of 9.7 m (http://www.ndbc.noaa.gov/station_page.php?station=44025), values ~25 and ~50% higher, respectively than most other large storms over the previous 17 yrs. (see Goff et al., 2015b, their Fig. 2). The single exception was Hurricane Irene, which impacted the area in August of 2011 and produced sustained winds of 19.2 m/s and significant wave heights of 7.9 m (http://www.ndbc.noaa.gov/station_page.php?station=44065).

Long before Hurricane Sandy impacted Long Island, in 1996 and 1997, the U.S. Geological Survey (USGS) conducted a series of high-resolution marine geophysical surveys along the inner continental shelf of southern Long Island to investigate the influence of the geologic framework on coastal evolution (Foster et al., 1999; Schwab et al., 2000). In May of 2011, the USGS resurveyed the lower shoreface and inner continental shelf seaward of the Fire Island barrier island system (Fig. 1) with a newer generation of marine geophysical instruments (including interferometric sonar and chirp seismic-reflection) to support further research focused on decadal to millennial scale coastal evolution and coastal processes modeling (Schwab et al., 2013, 2014c). Ultimately the 2011 survey served to document conditions on the seafloor offshore of Fire Island approximately 6 months before the passage of Hurricane Sandy. The USGS conducted two additional surveys offshore of Fire Island in 2014 to document post-storm seafloor conditions. In cooperation with the U.S. Army Corps of Engineers (USACE), the entire 2011 study area was re-surveyed in January and February 2014 (Fig. 1) using a high-resolution multibeam echosounder (Denny et al., 2015), and in October 2014 additional chirp seismic-reflection acquisition was focused on a series of shoreface-attached sand ridges offshore of western Fire Island (Denny et al., 2017). Objectives of the 2014 surveys were to determine the impact of Hurricane Sandy on the inner continental shelf and to broaden the baseline geospatial framework required for sediment transport and coastal change model development (Warner et al., 2014, 2017).

The comparison of the 2011 and 2014 mapping results presented in this paper allows an unprecedented opportunity to document regional-scale, hurricane-induced changes to seafloor morphology and modern sediment thickness on an inner continental shelf and lower shoreface setting. It also allows us to contrast these changes to those identified during the relatively calm period between 1996–1997 and 2011 reported in Schwab et al. (2014a, 2014b). These findings add to the scientific foundation used to manage sandy coastal systems and assess environmental changes caused by natural processes and human activities. We build upon similar observations reported by Goff et al. (2015b), who surveyed two small areas of the inner continental shelf

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**Fig. 1.** Map showing the 2011 (shaded dark gray area) and 2014 (multibeam echosounder survey outlined by dotted line and seismic-reflection survey outlined by dashed line) surveys offshore of Fire Island, New York. Inset map shows location of study area (outlined in black). Bathymetric contours are in meters below the North American Vertical Datum of 1988 (NAVD 88).
and shoreface offshore of Fire Island two months after Hurricane Sandy impacted the region. Although Hurricane Sandy was a more energetic event and likely had the greatest impact to the seafloor (Warner et al., 2017), Hurricane Irene could also have contributed to the changes to the seafloor revealed by the analyses presented in this paper.

2. Previous work

The south shore of Long Island west of Southampton (Fig. 1) consists of reworked glacial outwash associated with the Wisconsinan Laurentide glacial advance (Stone and Borns, 1986) and includes shallow back-barrier bays, marshes, and low-relief, sandy barrier islands (Leatherman, 1985). Located within this barrier-island chain is Fire Island, a 50-km-long barrier island that is bound by two tidal inlets managed as navigation channels, Moriches Inlet to the east and Fire Island Inlet to the west (Fig. 1). A natural tidal inlet, formed during Hurricane Sandy when a breach cut Fire Island at Old Inlet, remains open at the time of this writing.

For a full description of the major inner continental shelf sedimentary sequences offshore of Fire Island, see Schwab et al. (2014b) and references therein. Upper Cretaceous-age coastal plain strata south of Long Island are unconformably overlain by Pleistocene sediment with no preservation of Tertiary-age sedimentary units (Williams, 1976). This regional hiatus is referred to as the coastal plain unconformity and can be observed in seismic-reflection profiles on the inner continental shelf south of Long Island (Emery and Uchupi, 1972). Pleistocene glaciofluvial outwash deposited during the Middle and Late Wisconsinan glacial maximum composes the bulk of the sedimentary section above the coastal plain unconformity offshore of Fire Island (Williams, 1976; Foster et al., 1999). The Pleistocene outwash is either exposed at the seafloor over much of the study area east of Watch Hill and in the troughs between modern sand ridges west of Watch Hill (Fig. 2) or covered by a veneer of reworked modern sediment that is below the 20-cm resolution of the seismic-reflection systems used to map the region (Schwab et al., 2014b). The Pleistocene deposit is composed of poorly to very poorly sorted, medium-grained sand to
gravel. The upper surface of the Pleistocene deposit is incised by glaciofluvial paleochannels (Fig. 3A) that are filled with a transgressive sequence composed of reworked outwash and, in places, capped by lower Holocene muddy estuarine sediment (Schwab et al., 2000).

The present morphology of the Fire Island outer continental shelf is a consequence of the reworking of this Pleistocene glaciofluvial sedimentary deposit over the course of Holocene transgression. The eroded southeastern margin of the shallowest Pleistocene outwash lobe is morphologically expressed as a submerged headland offshore of central Fire Island (Schwab et al., 2014b, their Fig. 7) (Fig. 2A). A high-backscatter gravelly lag deposit identified on the southeast flank of the headland, in water depths from ~18 to 20 m (Fig. 4A), is thought to have originated from erosion of the shallow outwash lobe during marine transgression. The extent of the gravelly lag is suggested to approximate the original seaward extent of the lobe (Schwab et al., 2014b).

Schwab et al. (2013, 2014b) inferred that erosion of the outwash lobe offshore of central Fire Island yielded an abundant volume of fine to medium-grained sand, which, in turn, was a primary source of sediment for the development of a series of northwest-southeast-trending shoreface-attached sand ridges offshore of Fire Island west of Watch Hill (Figs. 2A and 4A). The ridges are spaced ~3 km apart and extend seaward at angles of ~20° to 40° to the shoreline offshore of central Fire Island, and increase to ~50° at the western limit of the study area (Duane et al., 1972; Schwab et al., 2000). East of the submerged headland, Pleistocene glaciofluvial and early Holocene channel-fill deposits are exposed over most of the inner continental shelf. Here the seafloor is typified by a series of < 2-m-deep sorted bedforms that are oriented ~60°–70° to the shoreline (Figs. 2A and 4A), and indicative of ongoing erosion and predominantly southwestward, shore-parallel sediment transport (Schwab et al., 2000, 2013).

The distribution of modern sand on the inner continental shelf south of Fire Island is discontinuous and variably thick (Williams, 1976; Foster et al., 1999; Schwab et al., 2014b). Where modern sandy deposits overlie the Pleistocene outwash and lower Holocene channel-fill units, they regionally define the Holocene marine transgressive unconformity (Fig. 3A). The modern sand deposit is fine- to medium-grained, moderately to well sorted, and thickest in the shoreface-attached ridges west of Watch Hill, which are up to ~5 m thick offshore of central Fire Island, but thin to < 1 m thick offshore of the western limit of the study area (Schwab et al., 2014b) (Fig. 2B). East of Watch Hill the modern sand deposit thins considerably seaward of the shoreface, presumably forming a veneer too thin (< 20 cm) to be reliably interpreted from the seismic-reflection data.

Modern sediment also forms the shoreface and subaerial beach system of Fire Island. The shoreface is defined as the narrow, relatively steeply sloping zone between the seaward limit of the shore at low water and the nearly horizontal inner continental shelf. In this paper, the geomorphic expression of the Fire Island shoreface is not meant to imply the width of a nearshore zone of active sediment transport, nor the seaward limit of processes forming a ravinement surface. The seaward limit, or toe of the modern shoreface is identified on seismic-reflection profiles lying unconformably above the Pleistocene glaciofluvial and early Holocene channel-fill deposits (Fig. 3B). In the study

Fig. 3. High-resolution chirp seismic-reflection profiles collected in 2014 illustrating the stratigraphic features and geometries discussed in this paper. Locations of the profiles are shown in Fig. 3C. Approximate water depth in meters was converted from two-way travel time assuming a seismic velocity of 1500 m/s.
area west of Watch Hill, it is difficult to define the toe of the shoreface based solely on seismic-reflection profiles because the sediment forming the lower shoreface and sand ridges attached to it tends to be acoustically indistinguishable. However, in places the shoreface-attached sand ridges are observed to onlap the relatively older, yet still modern sediment deposit forming the shoreface (Fig. 3C). Schwab et al. (2014b) mapped the toe of the shoreface using the swath bathymetry and seismic-reflection profiles collected in 2011 (Fig. 5). This interpretation indicates that the toe of the shoreface extends to a water depth of ~16 m west of Point O Woods and although highly variable, shoals to an average of ~13 m east of Point O Woods.

Schwab et al. (2013, 2014b) presented results of comparative analyses between the data collected over ~274 km² of common seafloor mapped during the 1996–1997 and 2011 surveys. The initial comparison of modern sediment thickness interpreted from the seismic-reflection datasets in Schwab et al. (2014b) indicated that modern sediment volume increased on the lower shoreface (~7.8 million m³) and decreased on the inner continental shelf (~3.1 million m³) over the 15-yr period. The changes were interpreted to suggest that the lower shoreface had gained volume by way of erosion of the shoreface-attached sand ridges and the inner continental shelf in general. However, this initial calculation was conducted in error because different seismic velocities (1630 m per second (m/s) for 1996–1997 and 1500 m/s for 2011) were used to convert the two-way travel times interpreted from the seismic-reflection data to thicknesses prior to generating the isopach maps. After converting the earlier interpretations using 1500 m/s, the re-calculated volumetric changes (Schwab et al., 2014a) indicated substantial accretion across both the lower shoreface (~10.2 million m³) and inner continental shelf (~10.0 million m³) offshore of Fire Island (Fig. 5).

Schwab et al. (2013, 2014b) suggest a predominantly southwest movement of the sand ridges and smaller subaerial dunes superimposed on them based on the following observations: accretion on the shoreface-attached sand ridges and the lower shoreface landward of the ridges between 1996-1997 and 2011 (Figs. 5 and 6A); erosion and accretion patterns observed from the comparison of modern sediment thickness for the same time period (Fig. 6A); comparison of sand ridge morphology with the morphology of the underlying Holocene transgressive surface; backscatter patterns over the sand ridges; and lateral movements of the boundaries between high- and low-backscatter zones detected in area of the ridges. Based on these findings, Schwab et al. (2013, 2014b) concluded that some portion of the net-southwestward alongshore sediment flux in the region is directed shoreward from the inner continental shelf to the shoreface, and that erosion of the Pleistocene outwash and lower Holocene channel-fill deposits exposed on the inner continental shelf is likely an important local source of sediment supplied to the observed accretion of the modern sand deposit and maintenance of the shoreface-attached sand ridges (Schwab et al., 2014a, 2014b).

3. Methods

3.1. Data acquisition and processing

The study area (Fig. 1) was surveyed in May 2011 aboard the motor vessel Scarlett Isabella using an interferometric sonar system to acquire bathymetric and acoustic backscatter data and a chirp seismic-reflection profiler to define the subsurface stratigraphy and structure. The survey area extends about 50 km alongshore and about 8 km offshore in water depths ranging from approximately 8 to 32 m, covering approximately 386 km². Data were acquired along ~2800 km of trackline spaced ~75-100 m apart in the shore-parallel direction with shore- perpendicular tie lines spaced ~2 km apart. A full description of the geophysical data acquisition and processing routines are described in Schwab et al. (2014c).

The study area was re-surveyed in January–February 2014 (Fig. 1) aboard the research vessel Shearwater using a multibeam echosounder to acquire bathymetric (Fig. 2A) and acoustic backscatter data (Fig. 4A). Details of the data acquisition and processing are described in Denny et al. (2015).

An ~86 km² area of prominent shoreface-attached sand ridges offshore of western Fire Island was re-surveyed in October 2014 (Fig. 1) using the same chirp seismic-reflection system used in the 2011 survey to reassess subsurface stratigraphy and structure (Denny et al., 2017). The methodology used for data collection, navigation and processing of seismic-reflection data was identical to that used in the 2011 survey as described in Schwab et al. (2014a). Survey line spacing varied from approximately 75 to 300 m in the shore-parallel direction with shore-perpendicular tie lines spaced ~2 km apart.

The geophysical data analyzed in this paper are stored and publicly available in the following references: 2011 interferometric sonar and seismic-reflection data (Schwab et al., 2014c); 2014 multibeam bathymetry (Denny et al., 2015); and 2014 seismic-reflection data (Denny et al., 2017).

3.2. Change analysis

The acoustic backscatter imagery from the 2011 (Schwab et al., 2014a) and 2014 surveys (Denny et al., 2015) were compared to assess morphologic and textural changes that occurred on the inner continental shelf over the stormy period encompassing Hurricanes Irene and Sandy. This analysis involved the comparison of 5-m/pixel acoustic backscatter imagery from each survey period to identify discrete seafloor features common to both data sets, but perhaps in different locations, and manually digitizing sharp transitions between areas of high and low backscatter along their margins (Figs. 4B, 7, and 8). The digitized transitions for each survey were stored within a geographic information system (GIS). Additional lines were then digitized between common feature boundaries at perpendicular angles and generally equal intervals along the lengths of the boundaries to measure the lateral offset between the pre- and post-storm locations. While the horizontal positional accuracies of the raw backscatter data are assumed to be within 2.0 m and 0.2 m for the 2011 and 2014 surveys (Schwab et al., 2014a; Denny et al., 2015), respectively, the positional accuracies of digitized transitions and lateral offsets measured between the 5-m/pixel acoustic backscatter imagery are undoubtedly less certain. Despite this, we are confident that the offset patterns observed in the comparison are meaningful, particularly when the measured offsets are 10 m or greater. Basic spatial and statistical methods were used to analyze the magnitude of boundary movement relative to water depth. The 2014 bathymetric data (Fig. 2A) were used to spatially query the lateral offset distance lines contained within four 5-m water depth intervals (10.0 to 14.9 m, 15.0 to 19.9 m, 20.0 to 24.9 m and 25.0 to 29.9 m). Minimum, maximum, mean, and standard deviation statistics were produced for the lateral offset distances in each depth interval (Fig. 4C).

Changes in modern sediment thickness on the inner continental shelf before and after the stormy period were evaluated by comparing isopachs produced from interpretations of the 2011 and 2014 seismic-reflection data. Sediment thicknesses were mapped following the methods described by Schwab et al. (2014c), in which along-track two-way travel times between the seafloor and the Holocene transgressive unconformity horizon were converted to thickness, assuming an average seismic velocity of 1500 m/s. These sediment thickness values were then interpolated using the natural neighbors algorithm of ArcGIS Spatial Analyst to create a 50-m/pixel isopach grid for each survey. The 2011 isopach (Fig. 2B) was then subtracted from the concurrent area of the 2014 isopach (Fig. 2C), yielding a 50-m/pixel difference grid to illustrate areal patterns of accretion and erosion over the 3-yr period (Fig. 6B). The horizontal positional accuracy of the raw seismic-reflection data is assumed to be within 10 m for both the 2011 and 2014 surveys (Schwab et al., 2014c; Denny et al., 2017), but we acknowledge
Fig. 4. Maps showing (A) acoustic backscatter data collected using a multibeam echosounder in 2014 and (B) backscatter transitions and measured distances between sharp backscatter transitions along the margins of common seafloor features digitized from 2011 and 2014 backscatter data. It is difficult to distinguish these changes at the regional scale, thus enlarged areas are shown on Figs. 7 and 8. (C) Graph illustrating the mean movement (in meters) of backscatter transitions within four depth intervals between 2011 and 2014. Vertical bars indicate one standard deviation of mean value. Regional bathymetric contours on (A) are in meters below the North American Vertical Datum of 1988 (NAVD 88).

Fig. 5. Map showing the change in modern sediment thickness in meters between 1996-1997 and 2011 offshore of Fire Island (modified from Schwab et al., 2014a). Green areas indicate accretion and red areas indicate erosion. This map is overlain on the sun-illuminated bathymetric surface derived from the bathymetry shown in Fig. 2A. Regional bathymetric contours are in meters below the North American Vertical Datum of 1988 (NAVD 88). A 50 cm conservative estimate of vertical resolution is assumed for the sediment volume calculation due to the resolution limits of the seismic-reflection system (Schwab et al., 2014a). However, the change in sediment thicknesses is displayed with a less conservative estimate of 10 cm to better illustrate the sediment flux patterns. The light blue line illustrates the 2011 toe of the shoreface position interpreted by Schwab et al. (2014b), and the dark blue and dashed black lines indicate the areas depicted in Fig. 6A and B, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
that gridding of the isopach data to 50-m/pixel for use in the change analyses contributes to increased horizontal and vertical uncertainty of the difference grid relative to the discrete along-track measurements. We assume a vertical resolution of 20 cm for the sediment volume calculations based on a conservative estimate of the vertical resolution limits of the subbottom profiling system used. However, Figs. 5 and 6 display a less conservative estimate of 10 cm to better illustrate the sediment flux patterns. The patterns of change indicated by the isopach calculations generally correlate spatially with the patterns observed in the backscatter analyses and comparison of generally coincident seismic-reflection profiles collected along the same planned tracklines from each survey period. Both indicate that the isopach difference grid accurately reflects the spatial patterns of change measured from the profile data.

Comparison of the 2011 and 2014 bathymetry also clearly identifies geomorphic changes in places (Fig. 9), but quantifying fine-scale change at the regional scale is not possible because of relatively poor bathymetric data quality primarily associated with the 2011 survey. Although the bathymetric data from the 2011 and 2014 surveys both show decreased signal-to-noise ratio in the far range, the 2011 interferometric sonar data required substantially greater editing due to multipath interference from the ship’s hull and insufficient sampling of water column sound velocities required to correct refraction artifacts. Because the 2011 survey was not designed to achieve seamless bathymetric coverage of the sea floor, the additional editing of the far-range data required interpolation over greater distances between adjacent swaths in the final bathymetric surface. Thus, the combination of artifacts related to slightly differing trackline orientations between the 2011 and 2014 surveys and greater interpolation in the 2011 bathymetric surface obscures the patterns of bathymetric change discernible in the computed difference grid.

4. Mapping results

Processing and interpretation of the 2014 geophysical survey data produced high-resolution maps of bathymetry (Fig. 2A), acoustic backscatter (Fig. 4A) and modern sediment thickness (Fig. 2C). These maps document regional seafloor conditions following the passage of Hurricanes Sandy and Irene. The same general seismic stratigraphic framework interpreted from previous surveys conducted in 1996–1997.
As previously recognized in the seabed mapping surveys of 1996–1997 (Foster et al., 1999; Schwab et al., 2000) and 2011 (Schwab et al., 2014b, 2014c), numerous, < 2-m deep sorted bedforms, distinguished by their high-backscatter troughs and eastward-facing flanks (Fig. 10), are the primary sedimentary feature on the inner continental shelf offshore of eastern Fire Island (Figs. 2A, 4A, and 8). Over most of this area, Pleistocene outwash and lower Holocene channel-fill deposits are exposed at the seafloor (Fig. 2B). The relatively young Pleistocene outwash lobe recognized in the 2011 survey (Schwab et al., 2013) is expressed as a submerged headland offshore of central Fire Island (Fig. 2A); its eroded southeast-facing flank identified as an area of high-backscatter gravelly lag (Fig. 4A). The field of shoreline-attached sand ridges offshore of western Fire Island continues to dominate the morphology of the inner continental shelf following the impacts of Hurricanes Irene and Sandy (Fig. 2C). The northeastern-facing flanks of these sand ridges display higher backscatter than the southwestern flanks (Fig. 11). The southwest-facing flanks of the larger sand ridges terminate in ~ 1-m high scarps in water depths ≤ 17 m. In places where the sand ridges attach to the lower shoreface, these scarps define the toe of the shoreface (Fig. 9).

Sharp transitions between areas of seafloor displaying high and low backscatter indicate minor variation in sediment texture and/or structure (e.g., subaqueous dunes, sorted bedforms, sand ridges). Comparative analysis of backscatter transitions identified in the 2011 and 2014 surveys detected predominantly southwestward movement of the transitions in water depths up to ~ 30 m during the 3-yr period (Fig. 4B). The measured movements range from ~ 1 to 450 m, with a mean of 20 m, indicating that the sorted bedforms east of Watch Hill (Fig. 8) and the subaqueous dunes observed on the sand ridges and ridge troughs west of Watch Hill (Fig. 7) all displayed southwest movement. In addition, the backscatter transitions in the sand ridge troughs, where modern sand pinches out on the outcropping Pleistocene outwash, also moved southwest (Fig. 7). Mean movements computed for changes that occurred within the four 5-m depth intervals indicate that change tended to decrease with increasing water depth (Fig. 4C).
The greatest change in backscatter transitions was detected offshore of Ocean Beach, in an area used periodically for sand mining since the early 1980s (Lentz et al., 2013). Here in water depths of about 15 m, comparison of backscatter imagery (Fig. 7), bathymetry (Fig. 9), and seismic-reflection data (Fig. 12) from the 2011 and 2014 surveys shows that the southwest-facing flank of a shoreface-attached sand ridge migrated up to ~450 m southwest. The comparison of the sediment thickness data from the same surveys shows that this ridge flank deflated up to ~1 m as did the adjacent sand ridge to the southwest (Fig. 13). However, the borrow pit offshore of Ocean Beach, last excavated in 2009 on this adjacent sand ridge, shows no indication of infilling (Fig. 13). In contrast, between ~20–70 cm of sediment was deposited in two borrow pits located on a sand ridge offshore of Fire Island Pines, also last excavated in 2009, while the remainder of the sand ridge crest eroded up to ~90 cm (Fig. 13).

Although the analysis of change in acoustic backscatter transitions between 2011 and 2014 indicates sediment mobility in the field of sand ridges west of Watch Hill, net movement of the sand ridges are better described via comparison of isopach maps of modern sediment thickness (Figs. 6B and 13). This comparison indicates a general erosion and accretion pattern that consists of erosion on the northeast-facing ridge flanks and crests of the sand ridges and deposition on the southwest-facing ridge flanks and in the troughs adjacent to the southwest-facing ridge flank. Although variable, the analysis also indicates that substantial net erosion occurred along the lower shoreface (Fig. 6B). This erosion of the lower shoreface is particularly apparent in the area west of Ocean Beach (Fig. 5), which was recognized by Schwab et al. (2014b) as an area of accretion between the 1996–1997 and 2011 surveys (Fig. 6A).

Modern sediment distribution was mapped over 73 km² of common seafloor in the 2011 and 2014 surveys (combined from each isopach, Figs. 2B, C). The difference grid computed between the isopachs (Fig. 6B) indicates that the modern sediment volume across this area of seafloor decreased by ~2.8 million m³, which equates to a mean sediment thickness change of ~0.04 m. Although well below the resolution limit of the seismic-reflection systems used for these surveys, calculation of this change in mean sediment thickness emphasizes that relatively minor changes in sediment thickness over a broad area can result in a significant volume of mobile sediment at the regional scale. In comparison, a similar analysis of modern sediment thickness over the 274 km² of common seafloor mapped in the 1996–1997 and 2011 surveys (Figs. 5 and 6A) showed that the modern sediment volume increased by ~20.2 million m³, with a mean sediment thickness change of +0.07 m (Schwab et al., 2014a).

5. Discussion

Comparison of regional mapping investigations conducted in 2011 and 2014 offshore of Fire Island allows a unique opportunity to analyze storm-induced changes to nearshore morphology and sediment distribution patterns on a regional scale. The analysis of storm impact presented here support previous hypotheses (Schwab et al., 2014b;
Warner et al., 2014 and references therein) that: (A) significant volumes of sediment are mobilized and transported on the inner continental shelf during severe storms in water depths far deeper than any previously assumed depth of closure and (B) shoreface-attached sand ridges periodically erode and move to the southwest during severe storms. Contrasting the results of this comparison to a similar analysis conducted in the same study area between 1996-1997 and 2011 (Schwab et al., 2014b, 2014c) allows observations related to the ongoing development of a ravinement surface and associated transgressive sand deposits, advances the understanding of processes responsible for the evolution of shoreface-attached sand ridges, and has implications for management of coastal resources in sandy barrier island settings.

5.1. Modern sediment flux – analysis of backscatter patterns

Comparative analyses of common acoustic backscatter transitions identified within the datasets before and after the 15-yr period prior to 2011 and the following stormy 3-yr period both indicate predominantly southwest movement of sediment distribution patterns, bedforms and sedimentary structures (Figs. 4, 7, and 8). Unfortunately, the somewhat lower quality imagery and less accurate navigation data collected using the towed sidescan sonar during the 1996–1997 survey allowed for the identification of relatively few acoustic backscatter transitions common to the 2011 survey data (Schwab et al., 2013, their Fig. 8). As a result, average acoustic backscatter transition movement statistics were not computed for the earlier 15-yr analysis period. However, Goff et al. (2015b) also presented results comparing the 2011 backscatter data with data from two smaller areas surveyed offshore of eastern and western Fire Island after Hurricane Sandy in January 2013 that agree well with our comparison of the 2011 and 2014 data, indicating predominantly westerly or southwesterly migration of backscatter transitions and a general decrease in the magnitude of change relative to water depth. The measured lateral offset distances of 40 to 75 m in 15-m water depth and 0 to 20 m in 20-m water depth reported in Goff et al. (2015b) are comparable to the values from our comparison of the 2011 and 2014 data over the larger survey area (Fig. 4C).

Schwab et al. (2000, 2013) interpreted the numerous sorted bedforms (Figs. 2A and 4A) and considerably limited modern sediment veneer (Fig. 2B) on the inner continental shelf offshore of eastern Fire Island as indications of efficient and ongoing erosion related to the continued formation of a ravinement surface associated with Holocene marine transgression. Where sorted bedforms have been mapped in high resolution in other inner continental shelf settings, their asymmetric morphologies, displaying coarser flanks facing up-current and opposite to the direction of dominant sediment transport, have been interpreted to indicate active erosion, although few studies have actually documented uniform, storm-induced movement of these features (Murray and Thieler, 2004; Goff et al., 2005 and references therein). The sorted bedforms offshore of eastern Fire Island fit this model, with their geometry and backscatter patterns indicating a net southwestward transport of the reworked sediment (Fig. 10).

The limited resolution and lower positional accuracy of the towed sidescan-sonar data collected in 1996–1997 generally precluded making observations regarding the migration of these sorted bedforms relative to the 2011 backscatter data. However, comparison of 2011
and 2014 backscatter data clearly illustrates migration of the sorted bedforms in a southwesterly direction with decreasing lateral offsets in deeper water (Fig. 8). Similar to the interpretation presented by Goff et al. (2015b), we attribute this southwest migration of sorted bedforms offshore of eastern Fire Island to the impact of Hurricanes Irene and Sandy. The decrease in lateral offsets of the sorted bedforms in deeper water is likely related to a reduction of storm wave energy with increasing distance offshore.

Although the sorted bedforms offshore of eastern Fire Island are < 2 m deep, movement of the east-facing erosional flanks by decimeters over such a broad area of the inner continental shelf indicates that erosion must have liberated a substantial volume of modern sediment from the underlying glaciofluvial deposits during this 3-yr time period and thus, represents modification of the Holocene ravine-ment surface. Quantifying the volume of sediment eroded or the change in modern sediment thickness at the regional scale was not possible due to vertical resolution limitations of the bathymetric and seismic-reflection data. It is unknown where the sediment mobilized by Hurricanes Irene and Sandy was ultimately deposited, however we speculate that it was transported in a general southwest direction and
5.2. Migration of shoreface-attached sand ridges – analysis of modern sediment thickness patterns

Similar sand ridges to those offshore of western Fire Island have been described in a number of investigations of inner continental shelf settings throughout the world (e.g., Duane et al., 1972; Swift et al., 1972, 1978; Swift and Freeland, 1978; Parker et al., 1982; Swift and Field, 1981; Figueiredo et al., 1982; Stubblefield et al., 1984; Hoogendoorn and Dalrymple, 1986; Van de Meene and Van Rijn, 2000). All of these sand ridges occur in settings where there are significant wind-driven currents and they are typically oriented at angles ~10° to 50° oblique to the shoreline and flow. Although it is beyond the scope of this paper to review in detail the processes proposed to form and maintain shoreface-attached sand ridges, a widely cited theory of origin and maintenance of shoreface-attached sand ridges is that of Trowbridge (1995), modified by Falques et al. (1998) Calvete et al. (2001a, 2001b), Vis-Star et al. (2007), Nnaife et al. (2014a, 2014b) and others who used stability analysis to show that sand ridges can be created, maintained, and enhanced during storm-driven alongshore-directed flow. Thus, the long-term maintenance of these ridges would be dictated by the long-term climate of the region.

Considerable offset observed between overlying sand ridges and underlying ridge-and-swale morphology on the Holocene marine transgressive unconformity offshore of western Fire Island led Schwab et al. (2014b) to conclude that the ridges have migrated southwestward since formation. The rate of migration is unknown, but models of shoreface-attached ridge migration have predicted rates of 1 to 10 m/yr for energy environments similar to southern Long Island (Trowbridge, 1995; Calvete et al., 2001a, 2001b; and Vis-Star et al., 2007), and similar rates of sand ridge movement have been recognized offshore of the Outer Banks, NC (Thieler et al., 2013). Preliminary analysis and modeling of wind and ocean currents offshore of Fire Island show that storm-generated winds from the northeast during the passage of tropical, subtropical and extratropical cyclones can generate strong southwest-directed alongshore currents and provide a mechanism to sustain the development, maintenance and southwestward migration of these sand ridges (Warner et al., 2014, 2017; Liste et al., 2016; Safak et al., 2016).

The observations made from modern sediment thickness change analyses offshore of Fire Island over the 15-yr period prior to 2011 (Schwab et al., 2014a, 2014b) and the 3-yr period between 2011 and 2014 provide new perspectives regarding dynamics of the shoreface-attached ridge systems. Analysis of the mapping data indicates that the
modern sediment deposit forming the sand ridges and the adjacent lower shoreface accreted over the 15-yr relatively calm period (Figs. 5 and 6A). On the basis of erosion and accretion patterns inferred from the backscatter data, Schwab et al. (2014a) suggested that the observed accretion was likely supplied by erosion of Pleistocene glaciofluvial and lower Holocene channel-fill deposits exposed at the seafloor offshore of eastern Fire Island and in the troughs between the sand ridges offshore of central and western Fire Island. Interpretation of seismic-reflection data indicates that the lower shoreface deposits lie above the Holocene transgressive unconformity (Fig. 3B). This stratigraphy is thought to be the result of southwest progradation of Fire Island since the formation of Fire Island Inlet in the late 1600s somewhere near Point ‘O Woods (Schwab et al., 2014b) (Fig. 2A). In addition, the shoreface-attached sand ridges are observed to onlap the relatively older shoreface deposit (Fig. 3C). This sand ridge evolution along with southwestern progradation of Fire Island imply that accretion of the lower shoreface offshore of western Fire Island (Fig. 6A) has been the norm on a centennial scale.

In contrast, the combined impacts of Hurricanes Irene and Sandy within the subsequent 3-yr period caused erosion of the lower shoreface and sand ridges offshore central and western Fire Island (Fig. 6B). Interestingly, erosion-accretion patterns from both analysis periods are indicative of net southwesterly migration of the larger sand ridges although the effect is more pronounced over the stormy 3-yr period between 2011 and 2014. This storm-induced migration is in agreement with the theoretical modeling results presented by Warner et al. (2014). In addition, an investigation of oceanographic conditions and changes to the seafloor offshore of Fire Island due to Hurricane Sandy using a coupled ocean-atmosphere-wave-sediment transport numerical modeling system (COAWST) (Warner et al., 2010), verified by observational analysis from oceanographic instrument deployments, showed similar sediment redistribution along the field of sand ridges, with southwest migration via erosion along ridge crests and sedimentation in the troughs (Warner et al., 2017).

The shoreward directed component of alongshore sediment transport that was assumed by Schwab et al. (2014a, 2014b) to drive accretion along the lower shoreface of western Fire Island over the 15-yr period prior to 2011 was apparently effectively subdued or absent during the stormy 3-yr period. This implies that sediment is more effectively liberated from the lower shoreface during relatively stormy periods of time, as might be expected. Surveys of the shoreface and subaerial components of Fire Island after Hurricane Sandy indicate that the eroded sediment was not transferred to the shoreface or adjacent barrier island (Hapke et al., 2013) and thus was transported out of the study area. Perhaps these sediments were distributed on the inner continental shelf in a veneer too thin to be resolved in the seismic-

![Bathymetry and Change in Modern Sediment Thickness](image-url)
reflection data (~20 cm) and/or deposited southwestward into the Fire Island Inlet system, which experienced high rates of sedimentation in the months following Hurricane Sandy (Steven Couch, USACE, personal communication). Approximately $1.8 \times 10^6$ m$^3$ of sediment was dredged from Fire Island Inlet to maintain navigational integrity between November 2013 and March 2014 (Aretxabaleta et al., 2017).

5.3. Implications for coastal management

Comparative analyses of geologic mapping data spanning two time periods (15 yr and 3 yr) indicate that oceanographic processes, especially large storms, actively modify the modern sediment distribution and morphology of the inner continental shelf offshore of Fire Island. These observations have implications to the development of coastal erosion mitigation strategies in many coastal settings, including the assumption of a definable depth of closure and potential impacts of nearshore sand mining on the evolution of the adjacent beach. In addition, these observations provide some insight on prioritization of research efforts in the development of predictive models required for the management of coastal resources under future climate scenarios.

An accurate coastal sediment budget is a critical component in the engineering design and implementation of a coastal erosion mitigation plan. Unfortunately, accurate sediment budgets are extremely difficult to establish because it is necessary to quantify the entire sediment volume along a segment of shoreline from storm overwash and flood-tidal shoal limits to the seaward limit of significant sediment transport over an extended period of time (e.g., Kana, 1995; Rosati et al., 1999; Thieler et al., 1995; Gayes et al., 2003; Rosati, 2005). Such data do not exist for most, if any, coastal areas. Thus, assumptions and generalizations must be made when formulating a coastal sediment budget. For example, the concept of depth of closure continues to be an important assumption applied to coastal erosion mitigation planning (e.g., Birkenmeier, 1985; Morang et al., 1999; Nicholls et al., 1998; Kana et al., 2011) where transport of sediment between the beach and lower shoreface/inner continental shelf is considered insignificant over timeframes applicable to coastal planning and management. Similarly, some publications assume that the seaward limit, or toe of the shoreface approximates the depth of storm wave base (limit of wave-induced sediment transport) and can be used as a minimum estimate for the depth of shoreface ravinement (e.g., Swift, 1968; Nummedal and Swift, 1987).

In contrast, the assumption of a definable depth of closure is widely considered to be erroneous in the geologic literature, in that it does not adequately describe or incorporate processes of decadal- to centennial-scale evolution of a barrier island beach (e.g., Wright, 1987; Gayes, 1991; Pilkey et al., 1993; Morton et al., 1995; Thieler et al., 1995, 2000; Cooper and Pilkey, 2004). In fact, a number of studies have identified inner continental shelf sediment transport as an essential component of coastal sediment budgets (e.g., Swift et al., 1985; Batton, 2003; Conley and Beach, 2003; Hinton and Nicholls, 2007; Park et al., 2009; Wright et al., 1991; Hequette and Aernouts, 2010; Denny et al., 2013).

The concept of depth of closure, estimated to range from ~5 to 9 m (Kana et al., 2011 and references therein), continues to be an important assumption applied to erosion mitigation planning efforts on Fire Island (http://www.nan.usace.army.mil/Missions/CivilWorks/ProjectsInNewYork/FireIslandToMontaukPointReformulationStudy.aspx). However, results presented here show that erosion of the inner continental shelf sedimentary deposits and transport of reworked sediment occurs in water depths up to 30 m during extreme storms (Figs. 4C and 6). These changes to the sediment distribution patterns and seabed morphology are well within the decadal timescale important to coastal planning and management and could potentially affect coastal evolution.

It is well documented that a primary component of sediment transport in the littoral system of Fire Island is alongshore from northeast to southwest, but discrepancies in coastal sediment budget calculations remain (Hapke et al., 2010 and references therein). It has been argued that a significant supply of sand moving onshore from the inner continental shelf is required to balance this coastal sediment budget and maintain the natural, long-term stability of the barrier island west of Watch Hill (Schwab et al., 2013 and references therein). Preliminary modeling results using the COAWST hydrodynamics-based modeling system to simulate the island-wide alongshore sediment transport show that the coastal evolution of Fire Island observed over the past ~80 yrs. cannot be explained by alongshore sediment transport gradients alone (List et al., 2016; Safak et al., 2016). These modeling results qualitatively support the hypothesized effect of onshore-directed sediment flux on the coastal stability of Fire Island west of Watch Hill. In addition, an oceanographic field study that included the deployment of nine instrumented tripods along the 10-m isobath from February to May 2014 offshore of western Fire Island observed a net southward alongshore sediment transport direction, with an onshore-directed component (Armstrong et al., 2015). Although the physical processes responsible for this onshore component of sediment flux are still under investigation (List et al., 2016; Warner et al., 2016), exchange of modern sediment between the inner continental shelf and the littoral system should be considered when developing coastal erosion mitigation plans. Quantifying these physical processes and advancing our understanding of how these processes may be affected by predicted increased rates of sea level rise and possible increases in the frequency and magnitude of storms due to climate change (Lozano et al., 2004; Sallenger et al., 2012; Church et al., 2013; Füssel, 2009) are research topics of growing importance to coastal management.

Analysis of shoreline positions from the past 80 years along Fire Island demonstrates a persistent undulating pattern of erosion and accretion west of Fire Island Pines, with cross-shore amplitudes of ~20–40 m and length scales of 3–4 km (Allen and LaBash, 1997; Hapke et al., 2011, 2016). Schwab et al. (2000) speculated that these persistent undulations in shoreline shape were due to wave shoaling over the adjacent shoreface-connected sand ridges and wave focusing on certain segments of the shoreline at an alongshore length scale related to sand ridge geometry. Safak et al. (2016) used the COAWST hydrodynamics-based modeling system, validated with field measurements (Armstrong et al., 2015), to simulate the waves and nearshore currents offshore of Fire Island. Preliminary results from these simulations support the hypothesis that the persistent shape of the shoreline is controlled by alongshore gradients of sediment transport induced by wave shoaling over the sand ridges.

Our results indicate that the morphology of the field of shoreface attached sand ridges offshore of Fire Island is actively modified, especially by large storm events (Figs. 4, 6B, 7, and 9). Similar to other coastal locations (Hayes and Naim, 2004 and references therein), this transgressive sand deposit has been mined in the past for use in beach nourishment projects (Lentz et al., 2013, their Fig. 2) and identified as an important resource required for ongoing and planned nourishment projects (http://www.nan.usace.army.mil/Missions/CivilWorks/Projects-in-NewYork/Fire-Island-to-Montauk-Point-Reformulation-Study/). Sites of past sand mining activities offshore of Fire Island from 1994 to 2009 remain clearly identifiable in the bathymetry (Fig. 13). A theoretical modeling investigation by Nnaie et al. (2014a) that examined the response of shoreface-attached sand ridges to sand extraction on the ridges themselves indicates that the ridges partially restore but never reach the same state as ridges that were not mined. The possibility that the sand ridges offshore of Fire Island or in other barrier island settings might migrate, deflate or disappear as a consequence of mining or increased storminess induced by climate change has serious implications for future coastal evolution. Therefore, the resulting changes in wave conditions along the adjacent shore due to natural or anthropogenic alteration of nearshore topography and the related change in longshore and cross-shore sediment flux are research topics of critical importance to coastal resiliency planning (Charlier, 2002; Hayes and Naim, 2004; Hommes et al., 2007).
6. Summary

The results of USGS-led coastal and marine studies along Fire Island, New York over the past two decades provide an unprecedented perspective regarding regional inner continental shelf sediment dynamics over time scales from large storm events to decadal and longer. Our comparative analyses between the marine geophysical data collected offshore of Fire Island in 2011 and 2014 document the changes in seabed morphology and modern sediment thickness that occurred on the lower shoreface and inner continental shelf during a 3-yr period encompassing the landfalls of Hurricanes Irene and Sandy, of which the later stands as the largest storm on historical record in the Atlantic Basin in terms of storm surge. The results demonstrate that storm-induced erosion and sediment transport occurred throughout the study area in water depths up to ~30 m, far seaward of the 5 to 9 m depth of closure assumed in current coastal erosion mitigation planning for this area in water depths up to ~30 m, far seaward of the 5 to 9 m depth of Basin in terms of storm surge. The results demonstrate that storm-in

Pleistocene outwash and lower Holocene transgressive deposits exposed

closure assumed in current coastal erosion mitigation planning for this

area in water depths up to ~30 m, far seaward of the 5 to 9 m depth of

Basin in terms of storm surge. The results demonstrate that storm-in


enceasing the landfalls of Hurricanes Irene and Sandy, of which the

seabed morphology and modern sediment thickness that occurred on

comparative analyses between the marine geophysical data collected

over time scales from large storm events to decadal and longer. Our

spective regarding regional inner continental shelf sediment dynamics

New York over the past two decades provide an unprecedented per-

ment of the sorted bedforms were historically significant con-

sidering the magnitude of Hurricane Sandy. The modern sediment

composing the lower shoreface and shoreface-attached sand ridges

offshore of central and western Fire Island were also significantly

eroded. Similar to the sorted bedforms, migration of the sand ridges was

driven by erosion along the southwest margins of the inter-ridge

troughs, the northeast ridge flanks, and the crests of the ridges, but

unlike the sorted bedforms, measurable accretion was detected along

the southwestern ridge flanks and the northeastern margins of the inter-

ridge troughs.

Similar comparative analyses between the marine geophysical data

collected in 1996–1997 and 2011 provided somewhat contrasting re-

sults to those of the subsequent 3-yr-long stormy period. Over the 15-yr

period prior to 2011, the shoreface-connected sand ridges and the ad-

jacent lower shoreface were observed to accrete, while little discernible

c change occurred in the sorted bedforms. Despite the primarily accre-

ional signal during this relatively calm period, erosion and accretion

patterns were similar to the 3-yr stormy period, albeit subdued, and

indicative of southwest migration of the shoreface-attached sand ridges.

The results of the two analysis periods provide a unique perspective to

consider that can be applied to the evolution of these common sedi-

mentary features; that the shoreface-attached sand ridges are main-

tained via erosion of the Pleistocene glaciofluvial deposit where it is

exposed on the seafloor, but are periodically eroded and move to the

southwest during large storm events.

An onshore-directed sediment flux from the inner continental shelf to

the littoral system is required to balance the coastal sediment budget for

Fire Island and the sand ridge morphology is thought to control the per-

sistent shape of the adjacent shoreline through modification of in-

cident waves. The intensity and frequency of storms are predicted to

increase due to climate change and the anthropogenic modification of

shoreface-attached sand ridges is expected to accelerate as they are

mined for beach nourishment projects. Thus, it would be advantageous

to consider both the sediment dynamics of the inner continental shelf

and natural and anthropogenic alterations of the nearshore morphology

during future coastal resiliency planning of Fire Island and similar

sandy coastal settings.

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