

INNER SHELF MORPHOLOGIC CONTROLS ON THE DYNAMICS OF THE BEACH AND BAR SYSTEM, FIRE ISLAND, NEW YORK

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Abstract: The mechanism of sediment exchange between offshore sand ridges and the beach at Fire Island, New York is largely unknown. However, recent evidence from repeat nearshore bathymetry surveys, coupled with the complex but consistent bar morphology and patterns of shoreline change demonstrate that there is a feedback occurring between the regional geologic framework and modern processes. Analysis of bathymetric survey data provides direct confirmation that the offshore ridges are connected to the shoreface and are spatially persistent. The fixed nature of the nearshore morphology is further supported by time series camera data that indicate persistent bars with breaks that re-form in the same locations. A long-term time series of shoreline change shows distinct zones of erosion and accretion that are pervasive over time scales greater than a half-century, and their length-scales are similar to the spacing of the offshore ridge-trough system. The first-order geologic framework is responsible for the existence and locations of the ridges and troughs, which then influence the morphodynamics of the beach and bar system.

Introduction

The inner shelf off Fire Island, New York has a well-defined ridge-and-trough morphology (Duane et al., 1972). The ridges consist of Holocene sand overlying a ravinement surface. Variable beach-dune morphology along the barrier island and imbalances in the regional sediment budget suggest that some material from the sand ridges likely supplies the beaches along western Fire Island (Schwab et al, 2000; Hapke et al, 2010a and references therein). Questions that remain unresolved include: (1) what impact does the ridge-trough morphology have on beach behavior over a variety of time scales, and (2) what are the active processes that result in cross-shore sediment flux? This paper is focused on addressing the first question - to explore how the inner shelf morphology impacts coastal change.

The late Holocene evolution of Fire Island has been well-documented by Leatherman (1985). East of Watch Hill (Figure 1) the island has migrated landward through inlet formation and marsh accretion on the bay-side. In comparison, west of Watch Hill to the Fire Island Lighthouse, the island has not migrated landward for

~800 yrs and the island has no historical inlets. The western-most segment of the barrier island from Fire Island Lighthouse to Democrat Point formed as a prograding spit that continued to migrate west until the Fire Island Inlet jetty was constructed in 1950.

Uncertainties and an unresolved deficit in the alongshore sediment budget have led some researchers to suggest that an inner-shelf sediment source supplies material to the upper shoreface, especially along western Fire Island (Schwab et al., 2000; Hapke et al., 2010a and references therein). The specific mechanism of exchange is uncertain because it is unknown whether the ridges are physically connected to the shoreface and because of a lack of detailed analyses of shoreline change patterns to assess any potential coupling between the ridge and shoreline behavior.

In this study, we present evidence from nearshore bathymetry, inner-shelf morphology, patterns of shoreline change and shoreline morphology that strengthens the argument for a linkage between the sand ridges and the shoreface, and suggests that an onshore component of sediment transport is likely more important along Fire Island than previously thought. Understanding the regional sediment budget and the processes that govern sediment movement are crucial for the effective management of Fire Island.

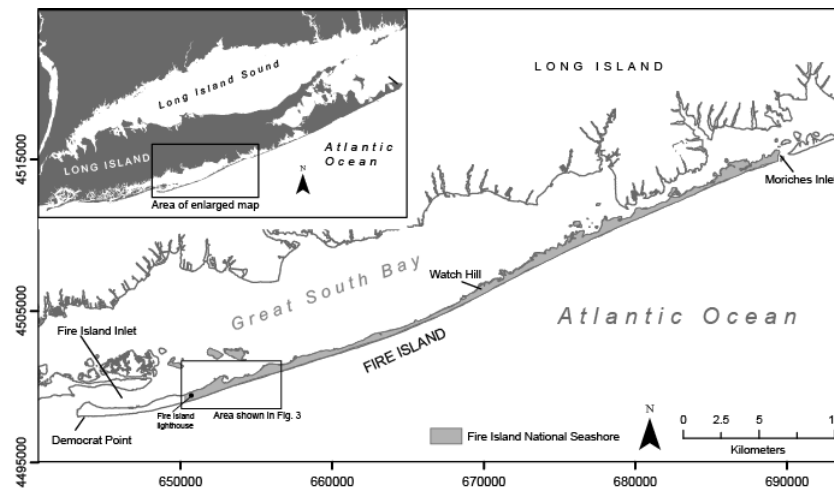


Figure 1: Location map of Fire Island, New York.

Data Collection and Analysis

New data in the form of high resolution, nearshore bathymetry, time-averaged imagery of the nearshore bar system, and a temporally dense dataset of historical and modern shorelines were collected and compiled for this study. The specifics of the data collection and analysis are described below.

Nearshore bathymetry

High-resolution single-beam bathymetric data were collected in the nearshore along western Fire Island in water depths ranging from 1 to the 12 m isobath approximately 1 km offshore. Initial data were collected in 2007 and provided the first high resolution surface of the nearshore. A repeat bathymetric survey was conducted in 2009. Single-beam data were collected aboard a rigid hull inflatable boat using a precision single-beam echosounder interfaced with a heave, pitch and roll sensor. Horizontal and vertical positions were acquired with real-time kinematic (RTK) GPS, with depths referenced to MLLW. Data were collected along a dense grid of along-shore and cross-shore tracklines spaced between 50-100 m parallel and 100 m perpendicular to the beach.

Swath bathymetric data were also collected along western Fire Island in 2009, extending from approximately 10 m to 25 m water depth, approximately 1 to 3 km from shore. Swath bathymetry data were collected using a dual head multibeam echosounder system. Sound velocity profiles of the water column were collected and used to correct for minor refraction errors. Two GPS antennas mounted along the vessel's centerline provided both accurate heading and RTK corrected GPS horizontal and vertical positions..

In addition to the bathymetry collected in 2007 and 2009 (described above), unpublished multibeam bathymetric data collected off Fire Island by the U.S. Geological Survey in collaboration with the Canadian Hydrographic Service, University of New Brunswick and NOAA in 1998 were included in the analysis to examine how the ridges may have changed over the decade between surveys.

Nearshore camera system

A video camera system including a camera, computer, and camera control software was installed on the upper deck of a two-story oceanfront home in western from January to April 2008. Images were averaged and variance computed by summing the pixel values and square of each value. After the pixel data were extracted, a time stack plot was created and time variance imagery was produced to monitor movement of the nearshore bar.

Shoreline change analysis

Twenty shorelines spanning 76 years (1933 to 2009) were acquired and incorporated into the shoreline change analysis (Table 1). Data are derived from a variety of sources including historical maps, aerial photography, field surveys and lidar data. The average uncertainty on the shoreline position ranges from 2.3 to 11.7 m (Hapke et al. 2010b), depending on the data source. In addition to exploring the 76-year patterns of shoreline change and morphologic behavior, a short-term subset of the data were also analyzed to investigate response to extreme storms and human activities over the most recent decade and a half (1993-2009). The temporal groupings for the long- and shorter-term analysis are included in Table 1.

All analyses are conducted on shore-normal transects spaced at 50-m intervals. For the linear regression time series analyses, temporal groupings were established using the available shorelines data. For the long-term (1933 – 2009) analysis, the data were subset into eleven groups, with a minimum of 4 and a maximum of 10 shorelines in each group. Data were grouped with the intention of having as similar a temporal distribution as possible from group to group. However, the paucity of historical data resulted in the oldest groupings covering a longer temporal span than the more recent groupings. For the shorter-term analysis (1993-2009), four temporally most proximal shorelines were grouped through time, resulting in 8 analysis groupings.

The linear regression time series steps for both the long- and shorter-term are calculated by determining the linear regression shoreline change rate for each group at each transect. A linear Delauney triangulation is used to interpolate between group data, creating a spatio-temporal Triangulated Irregular Network (TIN) which is then gridded using a cell size of 10 m (x-axis) by 36 days (y-axis). This gridding resolution provides a smoothed surface and uniform cell size given the spatial and temporal coverage of the data. The resulting time series grids, as well as the linear regression data from each time period, are assessed for spatial and temporal patterns.

Results and Discussion

The bathymetry data collected for this investigation indicate that there is continuity of the offshore ridge and trough morphology into the nearshore, extending to the seaward side of the nearshore bar system (Fig. 2). The morphologic features mapped by Schwab et al. (2000) were shown to extend to approximately 10 m water depth but the resolution of the data is coarse (30 m grid cell size) so details of the features are difficult to discern. The 2009 data show that the ridges tend to become narrower and more sinuous further landward on the shoreface and they bifurcate as

they approach the nearshore bar system. The troughs widen as they near the bar and they appear more as wide, shallow depressions, or swales, than sharper channel-like features. There are no well-defined central axes. However, the abrupt slope change at the ridge edge-trough floor intersection defines lateral axes which produce sharp lineations that are traceable to the seaward side of the nearshore bar ramp (Fig. 3). The topography of the bar system mimics the nearshore morphology wherein the lowest points on the irregular bar coincide with the lateral trough axes.

The features are remarkably persistent, even in shallow (~10-25 m) water depths. This is demonstrated in two adjacent surveys, one that was conducted by the USGS in 1998, and the more recent 2009 survey (Fig. 3). The ridge and trough features are continuous from one survey to another and, within the resolution limits of the data, show no evidence of having moved or migrated in the 11-year time span between surveys.

In the repeat single beam echosounder surveys from 2007 and 2009, the troughs and ridges extend to the seaward of the bar system and the positions of the lateral axes are persistent over the 2-yr period (Figs. 4 and 5), into water depths of less than 5 m. The effects of a large nourishment project in April of 2009 were captured in the September 2009 survey; the topography of the bar is muted and it has migrated landward. The lateral axes, however, are still distinctly present (Fig. 4), and the relief of the ridge-trough system changed little on the outer portion of the profile (9-12 m water depth; Fig. 5).

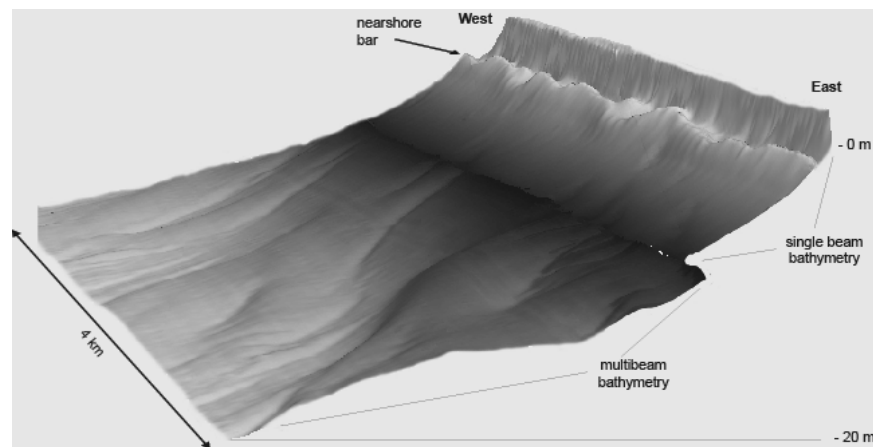


Figure 2. 3D rendering of nearshore bathymetry off western Fire Island from a multibeam echosounder survey (12 to 20 m water depth) and a single beam echosounder survey showing spatial persistence and continuity of ridge and trough features from the lower shoreface to the seaward side of the nearshore bar. The data extend to approximately 3 km offshore.

Table 1. Shoreline data and regression groupings used in shoreline change analyses

<i>Date of shoreline</i>	<i>Original data source</i>	<i>Long-term regression groupings</i>	<i>Short-term regression groupings</i>
1933	historical map	1933-1969	1993-1996
1938	aerial photography	1938-1979	1994-1997
1962	aerial photography	1962-1986	1995-1998
1969	aerial photography	1969-1988	1996-1999
1979	aerial photography	1979-1993	1997-2001
1983	aerial photography	1983-1994	2001-2006
1988	aerial photography	1988-1998	2002-2007
1993	field survey	1993-2005	2005-2009
1994	field survey	1994-2006	
1995	field survey	1995-2007	
1996	field survey	1996-2009	
1997	field survey		
1998	field survey		
1999	field survey		
2001	field survey		
2002	lidar survey		
2005	lidar survey		
2006	lidar survey		
2007	lidar survey		
2009	lidar survey		

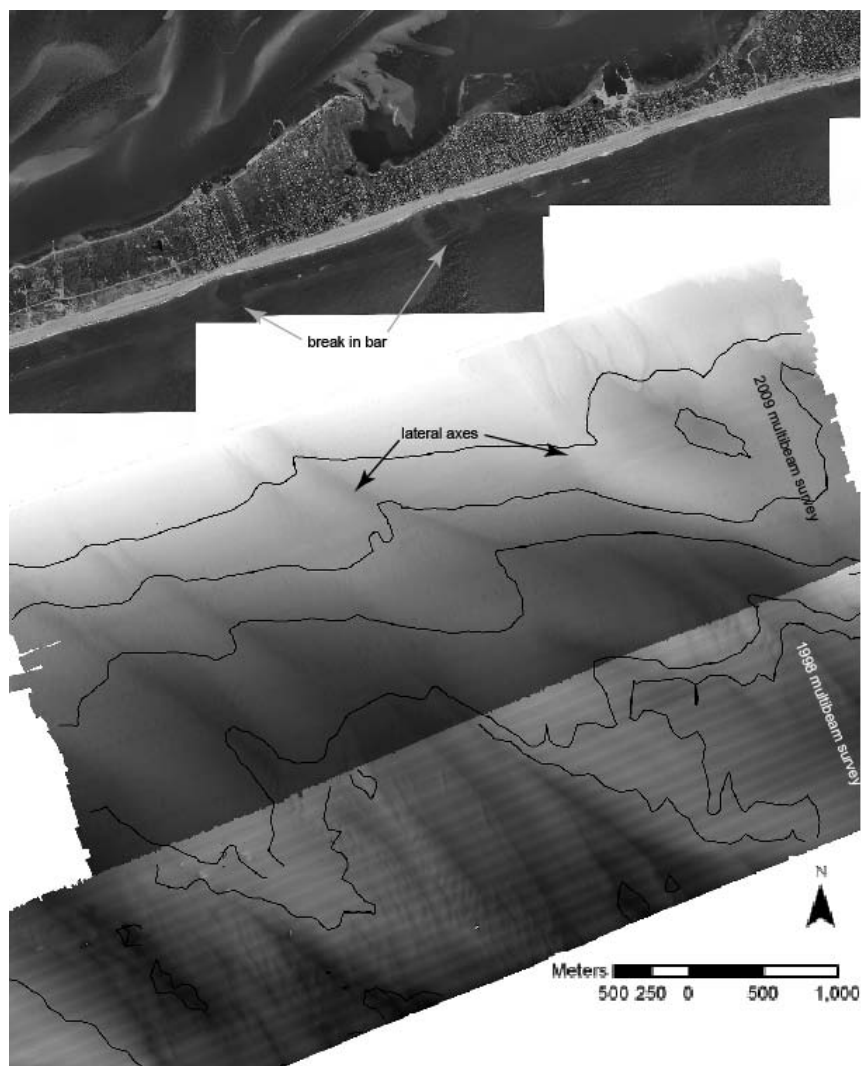


Fig. 3. Orthophotograph of a portion of western Fire Island (top) and multibeam bathymetry grids of the inner shelf (bottom). Ridges and swales are continuous from the 1998 (lower) survey to the 2009 (upper) survey. The 2009 bathymetry is the same as that shown in the 3D rendering in Fig. 2. The contours are discontinuous at the edges of the coverages.

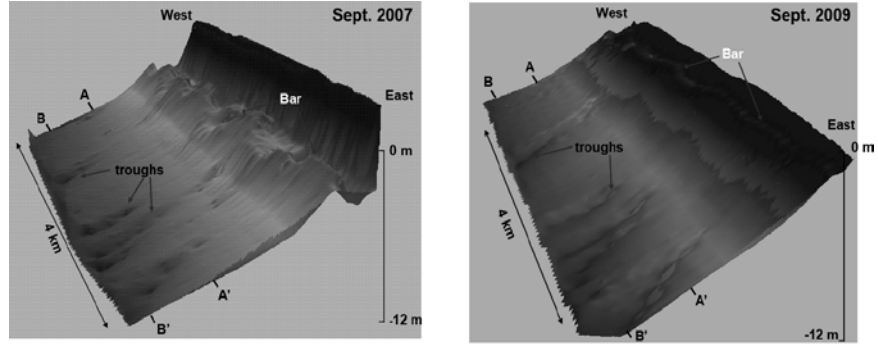


Fig. 4: 3D renderings of the nearshore single beam bathymetry from 2007 and 2009. Profiles A-A' and B-B' are shown in Fig. 5.

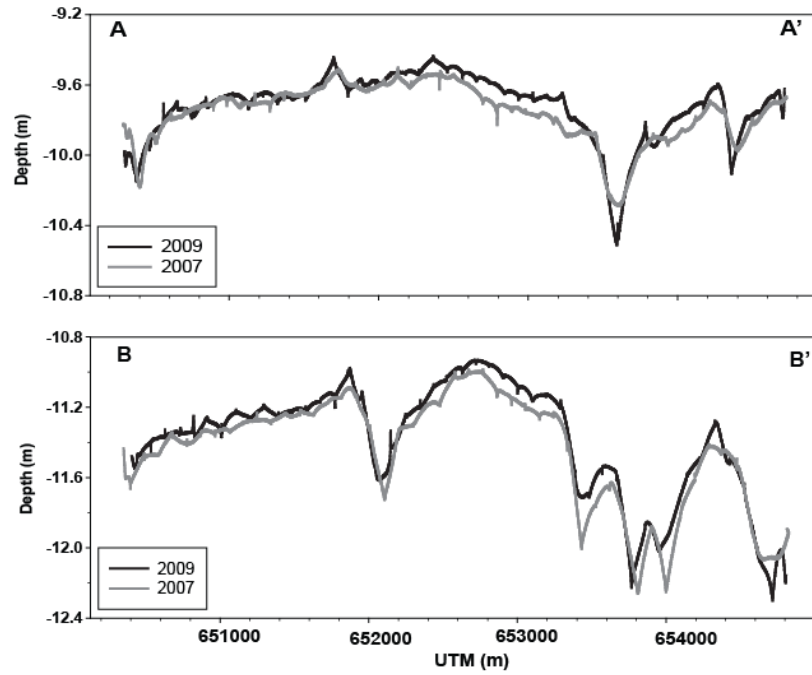


Fig. 5: Alongshore profiles from the BERM surveys. Locations of profiles are shown in Fig. 4.

The bathymetry data show a physical linkage between that sand ridges mapped on the inner continental shelf and the mid- to upper shoreface along western Fire Island, and that these ridges appear to maintain position over time-scales of years to decades. However, the morphologic continuity of the sand bodies does not provide information on the interplay of processes between the sand ridges, the nearshore bar and ultimately the short- and long-term behavior of the subaerial beach. Data from the remote camera system and an examination of patterns of shoreline change provide insight into the relationship between inner shelf morphology and morphodynamics of the beach and bar system.

The processed imagery from the remote camera documents a persistent trough and bar system. A large bar to the west of the primary trough remained stationary throughout the high energy winter months of 2008 while bars to the east were more intermittent (Fig. 6). The location of the primary trough is also spatially persistent and reforms in the same location after large wave events.

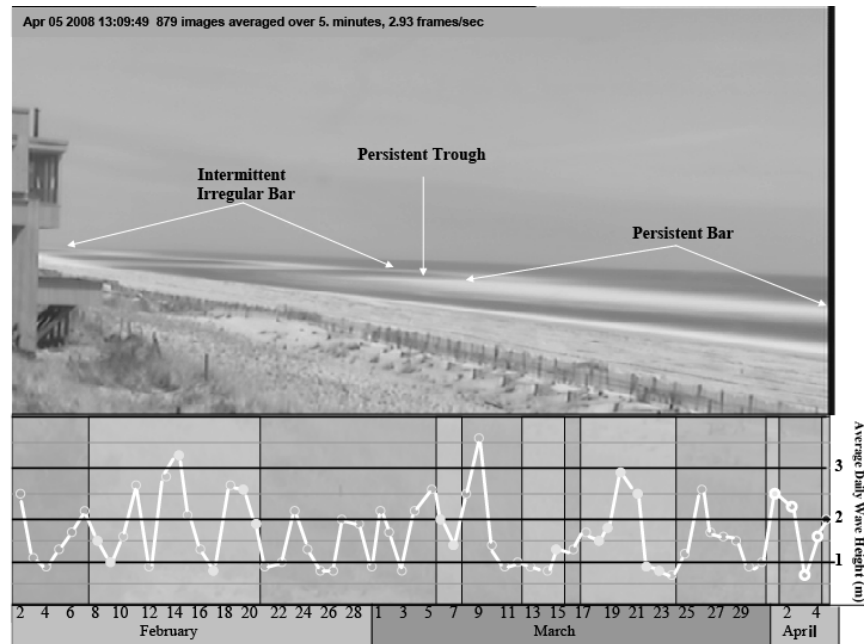


Fig. 6: Time averaged images of the nearshore bar system at western Fire Island collected during the winter of 2008. The image is looking southeast. The bar morphology remains consistent even during large wave events.

Breaks in the nearshore bars, as evidenced in 2004 orthophotography, appear to be spatially related to the lateral axes of the inner shelf sand ridges (Fig. 3). Although this relationship is difficult to firmly establish given the various dates of orthophotography, remote camera imagery, and bathymetry and the limited spatial coverage of the remote camera imagery, the stability of the sand ridges and the persistence of the breaks in the nearshore bar as documented with the remote camera system together suggest such a relationship may exist.

The locations of nearshore bars and gaps between bars appear to be influenced by the inner shelf ridge system which we suggest is linked to nearshore sediment dynamics. If this hypothesis is correct, the subaerial beach is expected to be linked as well, and shoreline behavior over a variety of time scales should exhibit a persistent pattern of change on spatial scales comparable to the inner shelf features discussed herein.

Previous analysis (Hapke et al 2010a; Schwab et al 2000) have shown that patterns of shoreline change are different along eastern and western Fire Island. Shoreline change to the east of Watch Hill (Fig. 1) is predominantly erosional whereas the beach has a more accretional trend to the west of Watch Hill. This general pattern also coincides with the inner shelf ridges, which are discontinuous (where they are present) and further offshore to the east of Watch Hill, and well-defined and shoreface-connected to the west of Watch Hill. The persistence of the dominantly accretional long-term shoreline change signal along western Fire Island may be related to the addition of material from the sand ridges to the beach over longer (decades to century) time scales, wave forcing associated with shoaling over the ridges, or both.

If the inner shelf morphology is exerting control on the morphologic evolution of the beach, as it appears to be the case with the nearshore bar system, it should be reflected in the temporal response of the shoreline. Long- and short-term (74 and 16 years, respectively) linear regression time series plots show well-defined and distinct zones of erosion and accretion along Fire Island (Figs. 7 and 8). In the long-term time series, periods of wide-spread erosion related to extreme storm occurrences (i.e. 1933-1969) are followed by more quiescent periods where the predominant signal is no change or accretion. However, throughout the record, there are distinct zones where erosion dominates the temporal signal and these persistent zones reform in the same locations, even after periods of accretion. The length scales of the erosional zones are similar to the ridge and trough morphology on the inner continental shelf (~1.5-2.0 km).

In the short-term time series the system appears to be in recovery from the severe storms of the early 1990s, with a dominantly accretional signal. However, the

distinct zones of erosion begin to reform in the mid-1990s and remain persistent until the most recent time period, which includes the severe nor'easters of 2007 and 2009. Based on the short-term time series plot the system undergoes rapid recovery following periods of storminess (some of which may be attributable to nourishment projects) shown in the wide-spread accretional trend. However, the persistent zones of erosion that are evident in the long-term record are also seen to reform and remain spatially static in the short-term time series. There are heterogeneities, but the overall trends are spatial consistent through time.

A variety of new data presented in this study provide direct evidence that the inner continental shelf geomorphology exerts some control on the nearshore bar system and behavior of the shoreline along western Fire Island. The coupling may be impacted by ongoing and proposed activities such as dredging of sand from the ridges for beach nourishment, which has the potential to alter the existing hydrodynamics. In addition to furthering the understanding of the geologic framework influence on beach and bar morphodynamics, the shoreline change assessment presented herein provides an analysis using one of the most temporally dense datasets to date. A solid and thorough understanding of past behavior of the coastal system will improve our ability to forecast future response.

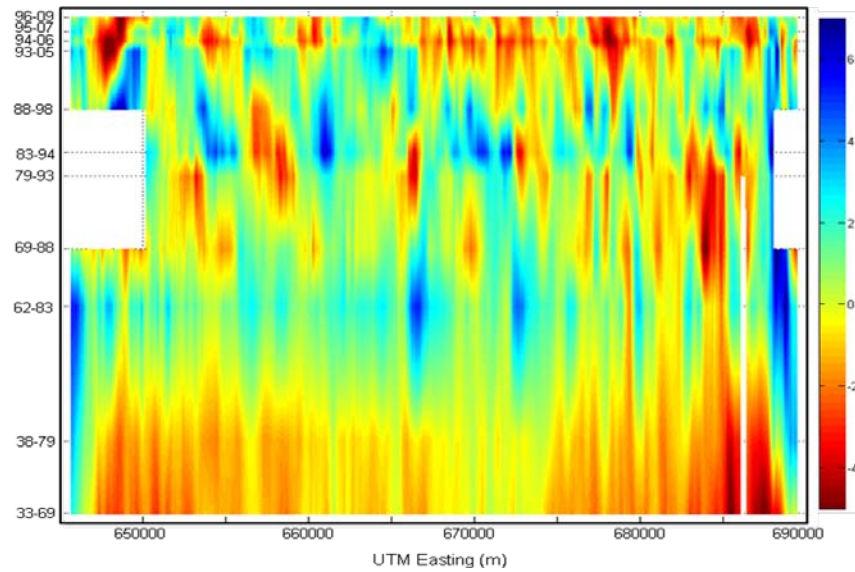


Fig. 7. Long-term linear regression time series from 1933- 2009. The time series is created using a gridded surface of linear regression shoreline change. The colors are change in meters.

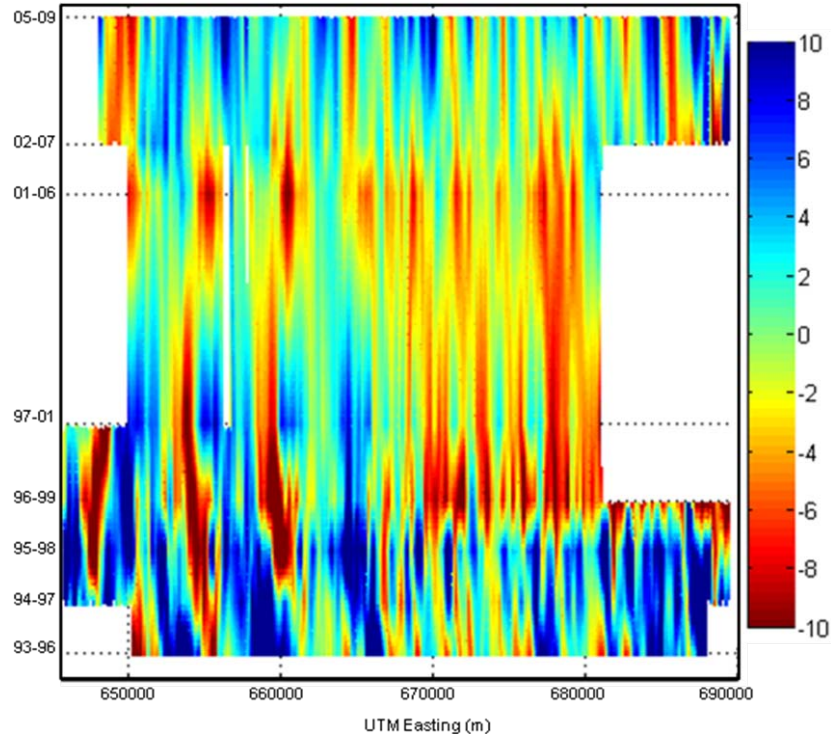


Fig. 8. Short-term linear regression time series from 1993- 2009. The time series is derived by creating a gridded surface of linear regression shoreline change. The colors are change in meters.

Conclusions

This study provides evidence that sand ridges present on the inner continental shelf along western Fire Island are physically connected to the upper shoreface and suggests that the morphology of the inner shelf influences the hydrodynamics of the system. The response of the beach and nearshore bar is detectible on a variety of time scales, from seasons to greater than a half-century.

Repeat high-resolution, nearshore bathymetry surveys, data from a remote camera system and a temporally dense shoreline change analysis demonstrate there is a connection between the inner shelf, the nearshore and the beach. The nearshore bathymetry shows that the inner shelf troughs and ridges appear to be fixed in place on time scales of years to a decade, and the axes of the features extend landward to the seaward side of the nearshore bar system in waters depths of less than 5 m. This

provides not only evidence of a physical connection, but also a possible sediment pathway between the ridges and troughs and the upper shoreface.

Analysis of images from a remote camera show that there is a persistent nearshore bar system that changes little even during large wave events, and alongshore breaks in the bars tend to reform in the same locations. Based on data collected during high wave-energy months, the gaps in the bar appear to be spatially correlated to the lateral axes of the offshore ridge-trough system, and the bars are more continuous and persistent onshore of locations where the inner shelf troughs are smooth and uninterrupted.

Long-term shoreline change analyses document a distinct behavioral difference between portions of the island where the inner shelf sand ridges are connected (western) versus where they are not (eastern). A time series of shoreline change over both long (74 years) and short (16 years) time scales highlights the temporal persistence of distinct zones of erosion and accretion, and the length-scaling of the zones correspond to the length-scaling of the inner shelf morphology.

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