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Sea level anomalies exacerbate beach erosion

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Abstract Sea level anomalies are intra-seasonal increases in water level forced by meteorological and oceanographic processes unrelated to storms. The effects of sea level anomalies on beach morphology are unknown but important to constrain because these events have been recognized over large stretches of continental margins. Here, we present beach erosion measurements along Onslow Beach, a barrier island on the U.S. East Coast, in response to a year with frequent sea level anomalies and no major storms. The anomalies enabled extensive erosion, which was similar and in most places greater than the erosion that occurred during a year with a hurricane. These results highlight the importance of sea level anomalies in facilitating coastal erosion and advocate for their inclusion in beach-erosion models and management plans. Sea level anomalies amplify the erosive effects of accelerated sea level rise and changes in storminess associated with global climate change.

Key Points:
- Beach erosion facilitated by frequent sea level anomalies is measured during a year
- Anomalies facilitate as much or greater erosion than a year with a hurricane
- Sea level anomalies should be included in beach-erosion models and management

Supporting Information:
- Readme
- Figure S1
- Figure S2

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1. Introduction

The morphologic responses of beaches to sea level rise over short (storm surge) and long (eustatic sea level change) time frames are well documented and generally include erosion, overwash and breaching during storms, and landward translation of the shoreline as ocean volume increases over centuries to millennia [e.g., *Zhang et al*., 2004; *Rodriguez and Meyer*, 2006; *Culver et al*., 2007; *Stockdon et al*., 2007; *Timmons et al*., 2010]. In addition, climate cycles such as El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) that operate at seasonal to multi-year time scales produce sea level highs that have been documented to enhance the magnitude of erosion and morphologic changes to beaches when they coincide with large storms [*Storlazzi and Griggs*, 2000; *Ruggiero et al*., 2001; *Dingler and Reiss*, 2002; *Keim et al*., 2004; *Allan and Komar*, 2006; *Eichler and Higgins*, 2006; *Vespremeanu-Stroe et al*., 2007]. Unlike sea level highs from climate cycles, intra-seasonal sea level changes (weeks to months), such as an increase in sea level along the U.S. East Coast resulting from a decrease in the strength of the Gulf Stream, do not always coincide with large storms [*Blaha*, 1984; *Ezer*, 2001; *Ezer et al*., 2013]. Those intra-seasonal highs, or coastal sea level anomalies, may influence beach morphology; however, assessments of their impacts are lacking. As a result, sea level anomalies are currently ignored in parameterizing shoreline-response models and beach management plans.

Coastal sea level anomalies arise from meteorological and oceanographic forcing mechanisms and have been observed globally [*Kolker and Hameed*, 2007] but may be more prominent and spatially uneven along the U.S. East Coast due to the influence of the Atlantic Meriodional Overturning Circulation (AMOC) and the Gulf Stream [*Sweet et al*., 2009; *Sallenger et al*., 2012; *Ezer*, 2013; *Ezer et al*., 2013]. Sea level anomalies impact coastal areas by changing the hydro-period of intertidal habitats [*Morris et al*., 1990] and result in beach morphologic change by shifting the zone of wave influence landward. Anomalies add to the erosive forces of storms and accelerated relative sea level rise [*Sweet and Zervas*, 2011]. Here, we explore morphologic changes to a barrier-island beach experiencing several sea level anomalies in a year. The objective is to compare the relative effectiveness of beach erosion due to typical wave conditions during sea level anomalies with that due to more extreme waves generated by Hurricane Irene during a time of non-anomalous sea level.

2. Study Area

Onslow Beach, North Carolina, USA, is a wave-dominated barrier island, located in Onslow Bay between Cape Fear and Cape Lookout (Figure 1). The island has a sinusoidal shape with a central headland flanked by embayments on either end of the island (Figure 1). Beach gradients are steeper along the headland than the adjacent embayments [*Rodriguez et al*., 2012]. The southwestern part of the barrier has a typical transgressive morphology, including narrow and discontinuous low-elevation dunes, multiple washover fans, a narrow

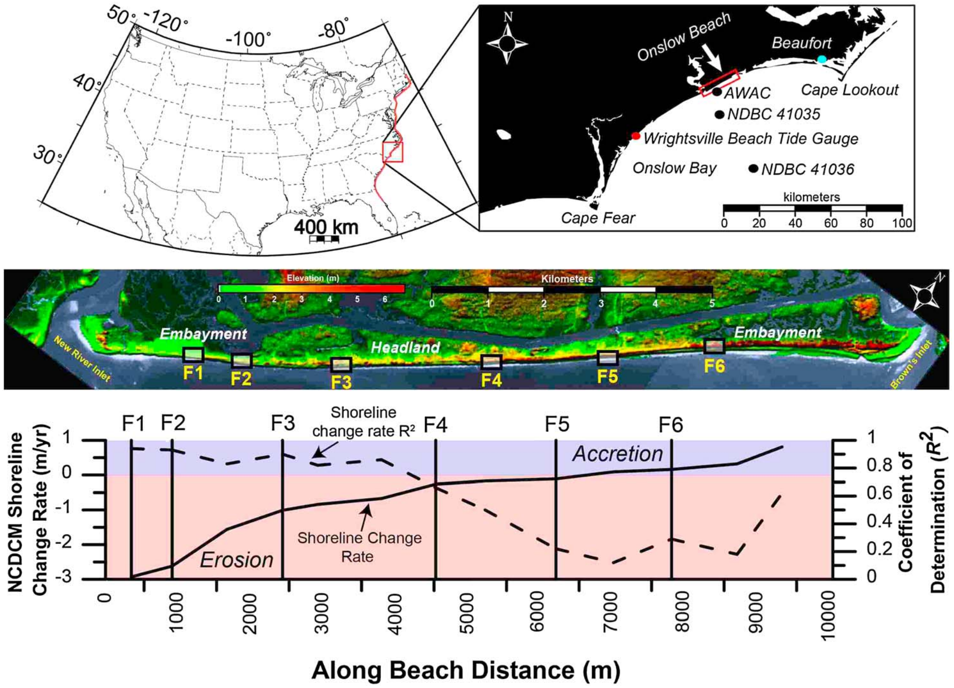

Figure 1. (Top) Study area map showing locations of the NOAA Wrightsville Beach (red dot) and Beaufort (blue dot) tide gauges, Acoustic Wave and Current profiler (AWAC), and NOAA data buoys. NOAA data buoys were used to fill wave-data gaps in the AWAC record. The geographic extent of the NOAA-reported 2009 sea level anomaly is shaded red. (Middle) Hill-shaded topographic map highlights the variable morphologies along Onslow Beach and the locations of the six focus sites. (Bottom) Decadal shoreline change rates for Onslow Beach [*Benton et al.*, 2004].

beach, and a shoreline that has been moving consistently landward over decadal time scales. The morphology of the northeastern part of the island is typical of an aggradational barrier, with continuous high-elevation dunes, a wide beach, and a shoreline that has been relatively stationary over decadal time scales. Onslow Beach enables exploration of the impacts from sea level anomalies on different beach morphologies and shoreline trajectories that are minimally confounded by spatial differences in hydrodynamic processes, making results from this study applicable to many other beaches. We selected six focus sites for data collection, each extending from the dune line to 0.0 m NAVD88 (North American Vertical Datum of 1988) and are 150 m wide in the along-beach direction. Three of the focus sites (F1, F2, and F3) are in the southwest transgressive section of the island, while the other three (F4, F5, and F6) are in the northeast aggradational section (Figure 1).

Waves predominantly approach Onslow Beach from the south, and the prevailing wind direction during the summer and winter is from the southwest and northeast, respectively [*Rodriguez et al.*, 2013]. Onslow Beach is impacted by tropical systems in the summer and fall and extratropical systems in the winter (nor'easters). Tidal variations at Onslow Beach are ~1 m. Long-term sea level rise in Onslow Bay is ~3.71 ± 0.64 mm/yr, as measured over 27 years at the NOAA tide gauge in Beaufort, NC [*Zervas*, 2001]. Water levels vary seasonally, as they do along the entire U.S. East Coast, in response to the steric cycle of oceanic heating and cooling. Specifically, there is a water level maximum along the U.S. East Coast in September and a minimum in March [*Hong et al.*, 2000; *Sweet et al.*, 2009].

While coastal erosion in response to accelerated sea level rise may be more prominent north of Cape Hatteras, erosion in response to sea level anomalies should affect areas south of Cape Hatteras as this region is strongly connected to changes in Gulf Stream transport [*Sallenger et al.*, 2012; *Ezer*, 2013]. Sea level anomalies along the U.S. East Coast, including Onslow Beach, are primarily forced by northeasterly winds and reductions in transport strength of the Florida Current, which becomes the Gulf Stream [*Sweet et al.*, 2009]. Northeasterly winds can raise coastal sea level through Ekman-driven onshore transport and by slowing the Florida Current [*Sweet et al.*, 2009]. The Florida Current transport and water surface gradient in the Gulf Stream are in geostrophic balance yielding a cross-stream water level gradient that increases as the transport increases and an inverse relationship between transport and coastal sea level along the U.S. East Coast. The connection between Florida Current transport and coastal sea level is most pronounced south of Cape Hatteras, which is ~175 km north of Onslow Beach. Sea level anomalies are often geographically extensive with one event extending over large stretches (>100's km) of coastline. *Sweet et al*. [2009] documented a sea level anomaly that occurred in June and July of 2009 across most of the U.S. East Coast from Massachusetts to Florida, which coincided with a perigean-spring tide to produce extensive coastal flooding.

3. Methods

Beach profiles are commonly used for evaluating volume changes to beaches; however, the results are sensitive to the hydrological and meteorological conditions around the sampling day, as well as where the profiles are located with respect to the beach morphology [*Robertson et al*., 2007; *Theuerkauf and Rodriguez*, 2012]. To minimize the contingency introduced by profiles, we assessed beach erosion by measuring the annual Maximum Depth of Erosion (MDOE) [*Rodriguez et al*., 2012]. In addition, the challenge of timing data collection before and after storms and sea level anomalies, which are difficult to forecast and plan around, is mitigated by measuring the MDOE.

The MDOE was measured using methods outlined in *Rodriguez et al*. [2012] and summarized below. Each February from 2009 to 2012 we sampled all six focus sites along Onslow Beach in one day during the 3 h before and after low tide to ensure similar hydrographic conditions during data collection. We collected six cores from each site each year using a jackhammer. Core locations and elevations were surveyed with an RTK-GPS. Two transects separated by ~40 m were occupied per site, and cores were collected at fixed locations along those transects based on the morphology of the beach in 2009 (mid intertidal, high intertidal, and backshore), resulting in 36 cores per year and 144 cores in total for the entire study. Beach profiles were collected using the RTK-GPS (0.25 m spacing between points) along each core transect from the dune toe to the lower intertidal part of the beach to calculate width and gradient (supporting information). Gradient was measured as rise over run along the profiles from the dune toe to the mean high water shoreline (0.36 m NAVD88) [*Weber et al*., 2005].

Prominent lithologic contacts and beds recognized at depth between pairs of successive cores (e.g., 2009 and 2010) were matched. The elevation offset or depth of bedding-pattern mismatch between the two time periods is the MDOE, which can also be interpreted as the lowest elevation of the beach at that coring location for the preceding time period [*Rodriguez et al*., 2012]. Error in the MDOE measurement is ~ ±2.5 cm, which is calculated as the sum of a ±1.5 cm average GPS error and a ±1 cm lithologic contact measurement error. Sediment compaction from the coring process was not measured. It is assumed to be constant among consecutive cores and, if present, would underestimate the true MDOE. The MDOE method integrates all erosion during a given period, caused by either one large erosive event (e.g., hurricane) or the sum of many smaller high-frequency erosive events. Cores were collected at approximately the same coordinates each year (~3 cm from the initial core location per subsequent year), making it unlikely that those small differences in core locations cause significant vertical displacement of bedding. At some sites the transgressing shoreline caused the beach zones to migrate landward. To account for this, if a beach zone shifted permanently landward over the adjacent core, the core was considered to be collected in the new zone for the MDOE calculation. For example, at Site F2, the backshore in 2009 shifted to high intertidal in 2010 and 2011; thus, those cores were labeled backshore for the MDOE from 2009 to 2010 but high intertidal for 2010 to 2011 with no backshore zone being sampled that year. Where the MDOE was deeper than we could sample, it was reported as a greater-than value.

Hourly water-level data relative to mean sea level (MSL) were analyzed to identify sea level anomalies (Figure 2). Water-level data from the Wrightsville Beach National Oceanic and Atmospheric Administration's (NOAA) tide gauge for the entire length of the record at this site (August 2004 through February 2012) were retrieved from the NOAA-Center for Operational Oceanographic Products and Services website [http://tidesandcurrents.noaa.gov]. The water level gauge is located at the end of the Johnny Mercer Pier (34° 12.8′ N, 77° 47.2′ W) in Wrightsville Beach, NC ~60 km southwest of Onslow Beach, and measurements are assumed to be relevant to the study area given their proximity within Onslow Bay (Figure 1). This assumption is supported by a strong correlation between water-level data from Wrightsville Beach and Beaufort, NC, which is located ~120 km away on the opposite end of Onslow Bay ($r = 0.964$). The residual

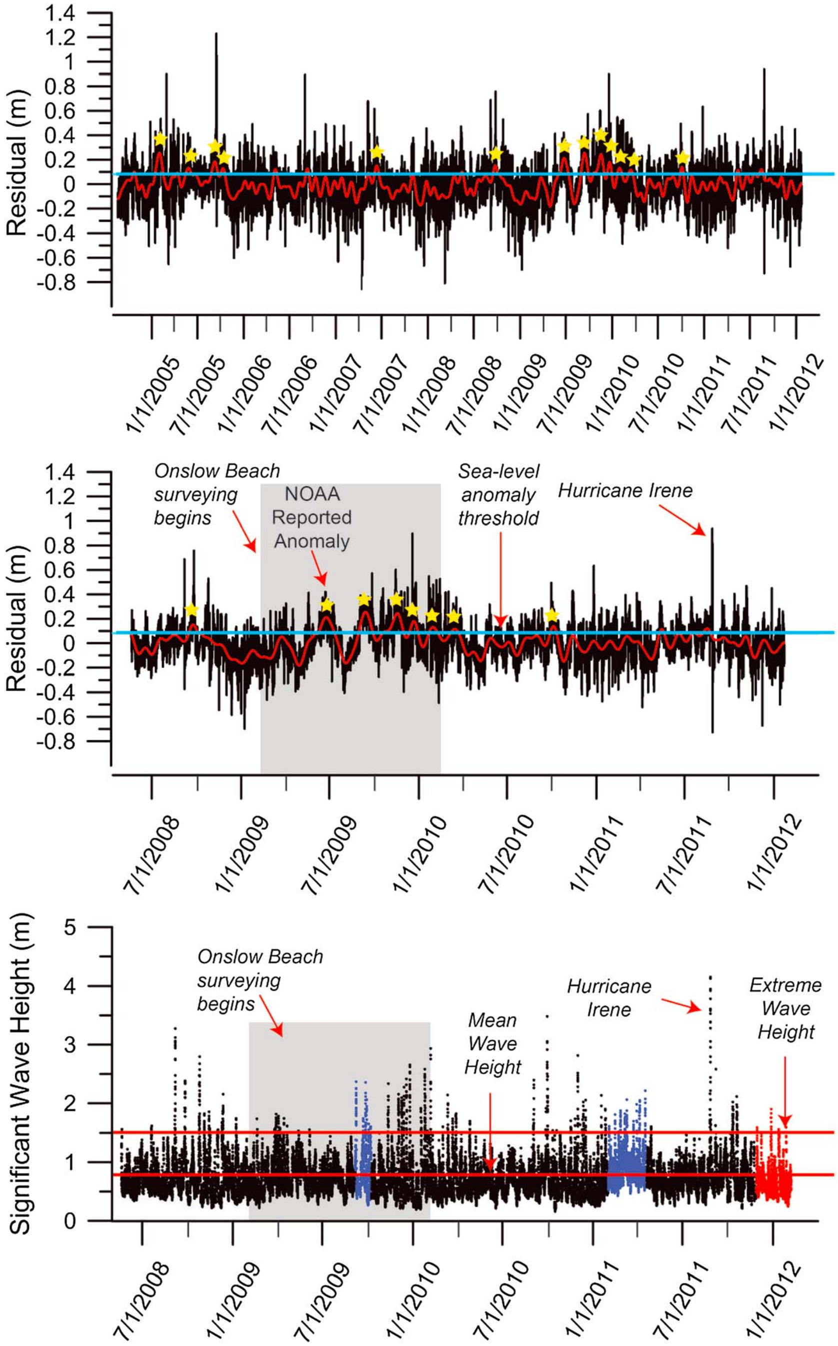

Figure 2. (Top) Residual between the observed and predicted water-level values for the entire record at Wrightsville Beach (August 2004 through February 2012). Unfiltered water-level data are in black, and the filtered data are in red. Sea level anomalies are annotated (stars) above the blue line marking one standard deviation above the average filtered residual water levels. (Middle) Water level data corresponding with beach surveys at Onslow Beach. (Bottom) Significant wave height data collected from an Acoustic Wave and Current profiler (AWAC) and two NOAA data buoys (NDBC 41035 and NDBC 41036). Black, blue, and red data points are from the AWAC, inner buoy, and outer buoy, respectively. Mean and extreme significant wave heights are denoted by the red lines. Hurricane Irene is annotated, and the interval with increased frequency of sea level anomalies is indicated by the gray box in panels 2 and 3. Details on the model used to transform the offshore NOAA-buoy data can be found in supporting information.

between observed and predicted water levels was detrended to remove longer term relative sea level rise and filtered using a 30 day low-pass filter (Figure 2). Those filtered residuals were used to identify sea level anomalies, which we define as occurring when the amplitude of the elevated water level residual is higher than 1 SD from the long-term mean (August 2004 through February 2012) over a period longer than a weather event (2 weeks) but shorter than a seasonal event (anomaly threshold = 0.0819 m relative to MSL; Figure 2). To compare these data with the MDOE sampling intervals (~1 year) the percentages of water-level observations identified as anomalies over those intervals were computed.

To quantify wave conditions, an Acoustic Wave and Current profiler (AWAC) was deployed offshore of Onslow Beach in ~7.5 m of water (Figure 1). The instrument provided a nearly continuous record of significant wave height (Hs) data from March 2008 through November 2011; however, since the instrument was taken offline several times for repairs and as our beach erosion data extends through February 2012, Hs data from adjacent NOAA National Data Buoy Center (NDBC) buoys (Onslow Bay Inner-41035; Onslow Bay Outer-41036; http://www.ndbc.noaa.gov) were utilized to fill in data gaps (Figure 2). Gaps (~14% of the total wave record) were filled using a Model II linear regression, which was required because the variables on both axes were measured with error [*Sokal and Rohlf*, 2012], between AWAC and buoy data (supporting information). For example, the AWAC data gap between February and April 2011 was filled by transforming Hs data from the inner buoy using an equation derived from regression analysis between contemporaneous AWAC and inner buoy data from February through April from other years in the study. Data gaps were preferentially filled with inner buoy data; however, when that buoy was offline, the same transformation method was used with the outer buoy. For analyses, the observations above the Hs mean (0.724 m) and above an extreme Hs threshold (1.56 m) were examined separately for each of the beach surveying time periods. The extreme Hs threshold was defined as those Hs values greater than the highest 2% of all Hs values, which is a commonly used extreme value cutoff [*Holman*, 1986].

4. Physical Forcing

The summer of 2009 through March of 2010 was a period of frequent sea level anomalies, with six events including three of the longest duration and highest amplitude in our record (Figure 2). During the first beach-sampling year (February 2009 through February 2010), 40% of the water-level observations were anomalies, which is greater than 2010–2011 (8.2%) and 2011–2012 (9.6%). The sea level anomaly in June and July of 2009, recognized by NOAA along most of the U.S. East Coast from Florida to Massachusetts [*Sweet et al.*, 2009], was recorded in Onslow Bay as the third highest and second longest duration in our study (Figure 2).

During the year with frequent sea level anomalies (2009–2010) no large storm events with Hs exceeding 3.0 m occurred at Onslow Beach (Figure 2). Only one sea level anomaly and one storm with a maximum Hs of ~3.0 m occurred at Onslow Beach from 2010 to 2011, which we label as a “low-events year.” The largest significant wave heights recorded during the study were associated with Hurricane Irene in August of 2011 (maximum Hs = 4.15 m), and we label the beach-sampling period from 2011 to 2012 as a “hurricane year.” Irene was a Category 1 hurricane when it made landfall near Cape Lookout, NC on August 27 and produced a storm surge of ~2 m above NAVD88 at a pier ~10 km south of Onslow Beach [*McCallum et al.*, 2012].

The percentage of wave observations greater than the mean Hs (2009–2010: 43.4%; 2010–2011: 36.1%; and 2011–2012: 47.3%) and greater than the extreme Hs (2009–2010: 2.5%; 2010–2011: 1.6%; and 2011–2012: 1.9%) does not vary greatly among these “event” periods. This suggests that waves were not consistently higher during any of the sampling periods. To test this more rigorously, we used one-way analysis of variance (ANOVA) to compare significant wave heights among each of the periods for just the mean to extreme Hs and, separately, for the extreme Hs. Preliminary examination of both data sets indicated significant autocorrelation of the Hs data. Consequently, we subsampled each data set (separately, $n = 1500$ for mean to extreme Hs and $n = 300$ for extreme Hs) and ln-transformed the subsets to remove autocorrelation, have normally distributed data, and meet assumptions of ANOVA. There were no significant differences among event periods in either data set (mean to extreme Hs, $P = 0.67$, and extreme Hs, $P = 0.85$). Overall, late autumn and winter have higher percentages of extreme waves than the other seasons due to the occurrence of nor’easters. Although there were several winter nor’easters in 2010, the higher number of extreme Hs observations during that winter (October 2009 to February 2010) did not, as indicated above, affect the mean Hs among the event periods.

5. Effects of Sea Level Anomalies on Onslow Beach

To relate the effects of the sea level anomalies and Hurricane Irene on beach morphology we assumed that the dominant event during a given sampling period is primarily responsible for the observed MDOE. This assumption is reasonable for the MDOE method because it is unaffected by accretion and records the maximum erosion that occurred during the period. Hs values were not significantly larger from 2009 to 2010 than the other sampling periods and there were no named storms; thus, the frequent sea level anomalies are assumed to be the main facilitator for erosion. The anomalies increased the duration and extent of wave energy impacting the beach, which resulted in erosion. From 2010 to 2011 there were no named storms and only one sea level anomaly. Erosion during that year resulted from the few wave events that impacted Onslow Beach, which were likely associated with nor'easters. Erosion measured from 2011 to 2012 is likely the result of Hurricane Irene because other than that storm, wave energy was relatively low and only two low-duration and low-magnitude sea level anomalies occurred. Although the highest storm surge would have occurred north of Onslow Beach, a post-storm field excursion revealed that washover terraces and fans formed along the southern and central potions of the island. Those features indicate that during the storm the island was heavily impacted by wave runup.

The average backshore, high intertidal, and mid-intertidal MDOE values during the year with frequent sea level anomalies were ~25, 50, and 55 cm, respectively (using minimum values when cores were not long enough to measure the MDOE). These average MDOE values are greater than those measured during the low-events year (~13, 29, and 32 cm) and similar to the storm year (~27, 49, and 40 cm; Figure 3). The average MDOE during the year with frequent anomalies includes 12 observations that were too high to measure (reported as minimum values), as compared to only one observation during the low-events year and four observations during the storm year. The true magnitude of the MDOE during the year with frequent anomalies is difficult to quantify because one third of the observations are minimum values; however, the MDOE was generally greater that year than what we measured during the subsequent 2 years. Comparing the MDOE at each beach zone between years illustrates how sea level anomalies and storms affect different areas of the sites, and how erosion varies with beach morphology.

Each year of this study, the MDOE roughly followed changes in the beach gradient, with the highest MDOE in the middle of the island along the headland where the beach gradient is steepest, and the lowest MDOE in the embayments where the gradients are lowest (supporting information and Figure 3). This was observed at Onslow Beach by *Rodriguez et al.* [2012] and was attributed to the higher wave energy that impacts steeper beaches (plunging breakers) than lower-gradient beaches (spilling breakers). The pattern is evident in all of the zones in the low-events year and is exacerbated during years with frequent sea level anomalies and a storm.

High backshore erosion occurred at the central Onslow Beach sites (F2–F4) in the year with frequent sea level anomalies (Figure 3). Morphologic changes at sites F2 and F4 were so dramatic that the backshore transitioned to high intertidal and the high intertidal transitioned to mid intertidal at these sites during that first year and remained in this configuration throughout the subsequent years (i.e., never recovered). The anomalies likely focused wave energy on the backshore and high intertidal of F2 and F4 given the steep and narrow morphology of the beach at these sites. The backshore at Site F1 accreted seaward during the year with sea level anomalies. That unique response was likely the result of short-term shifting of the ebb-tidal delta shoals associated with the New River Inlet because we observed seaward shoreline movement from Site F1 south to the inlet during 2007–2011. All sites (except F3) experienced similar or greater MDOE at the high-intertidal zone during the year with frequent sea level anomalies than the year with Hurricane Irene (Figure 3). The MDOE of the mid-intertidal zone was deeper during the year with frequent anomalies at all of the sites except F3 and F6 (Figure 3).

The relatively low MDOE measurements across all of the zones at Site F3 during the year with the frequent sea level anomalies and the high MDOE at that site during the hurricane year are inconsistent with adjacent sites. This is likely due to shallow muddy back-barrier deposits present below the foreshore that are resilient to erosion and occasionally crop out at that site [*Rodriguez et al.*, 2012]. Unlike sandier adjacent sites, erosion of the back-barrier unit at F3 requires a high-energy storm event, such as Hurricane Irene. The sea level anomalies coincided with lower wave-energy events; however, they persisted for much longer than a hurricane, which resulted in deep erosion at the sandy sites, but the more resistant back-barrier deposits at F3

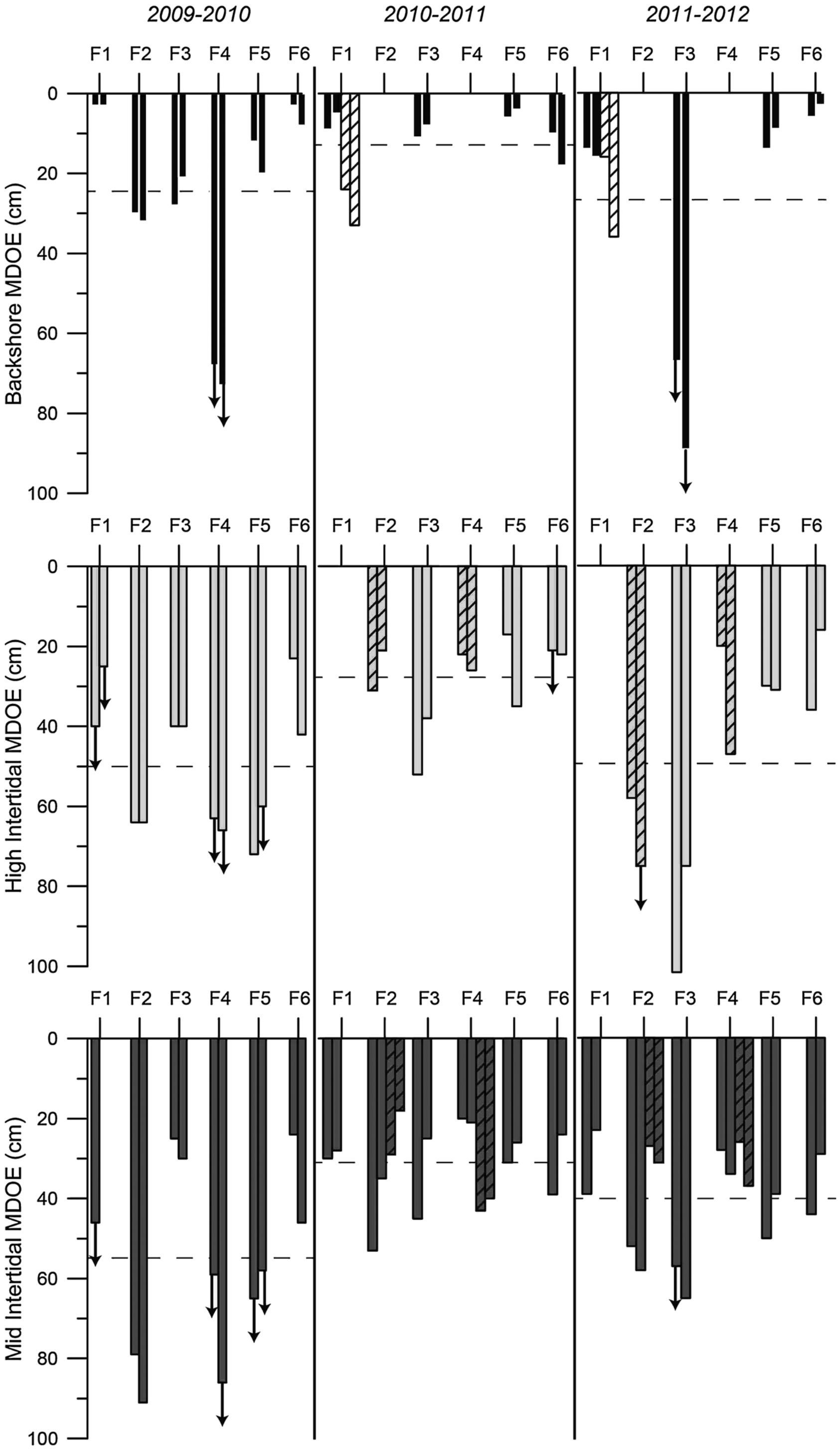

Figure 3. The annual Maximum Depth of Erosion (MDOE) at each beach zone and site for this 3 year study (2009–2010: frequent sea level anomalies; 2010–2011: low-event year; and 2011–2012: hurricane year). The dashed line shows the average annual MDOE at each beach zone. Downward pointing arrows indicate that the MDOE was greater than the core depth. Hatches are used to highlight an instance where beach morphology changed and the zone the core was collected in shifted; for example, the backshore at F2 transitioning to high intertidal after 2010.

were less affected. The MDOE at Site F6 was similar each year of the study and relatively low. Site F6 is not easily eroded by events such as storms and sea level anomalies because it is located in the aggradational section of the barrier where sediment supply is greater due to the landward transport of offshore sand deposits, which are absent south of F5 [*Riggs et al*., 1995].

6. Conclusion

Sea level anomalies are important facilitators of shoreline erosion but are not included in most models of shoreline response to climate change. Sea level anomalies are linked to the strength of the Gulf Stream [*Ezer et al*., 2013]; thus, variability in Gulf Stream transport induced by climate change [*Sallenger et al*., 2012; *Ezer*, 2013] may result in more frequent and/or higher magnitude anomalies. In addition, meteorological phenomena, such as variations in wind forcing and atmospheric pressure changes, can also result in sea level anomalies. Long-term coastal erosion is punctuated by week- to month-long sea level anomalies, which are shown in this study to enable a large amount of erosion despite not being associated with large storm events (Hs $>$ 3 m). At most sites, the erosion in the year with frequent anomalies was similar to or greater than the erosion in the year with Hurricane Irene. Periods with frequent anomalies are not uncommon; throughout the 8 year water-level record at Wrightsville Beach there was one additional period with frequent anomalies in 2005 with ~37% of the observations recorded as anomalies.

In addition to considering impacts from storms and eustatic sea level rise in projections of shoreline erosion, successful coastal management should include sea level anomalies in future planning, as well as how morphologic variations (e.g., beach gradient, and width) and underlying geology influence beach response. Higher gradient beaches, such as those in the center of Onslow Beach, are vulnerable to both storms and sea level anomalies because the wave energy and higher water levels are focused higher on the beach. Underlying geology controls, in part, the variable erosion of a site in response to anomalies because a beach that is underlain by clay at a shallow depth will not erode as easily as a beach where the entire shoreface is composed of unconsolidated sand.

Erosion that results directly from sea level anomalies can increase the vulnerability of a barrier island to overwash and storm erosion if the beach does not rapidly recover. Given that most of the sites at the morphologically variable Onslow Beach eroded during the year with frequent sea level anomalies, it is likely that anomalies influence erosion of sandy beaches worldwide, but the U.S. East Coast may be more prone to large anomalies than other regions due to the influence of the Gulf Stream [*Sweet et al*., 2009; *Ezer et al*., 2013; *Ezer*, 2013]. Sea level anomalies will exacerbate the effects of sea level rise and changes in storm intensity and frequency resulting in increased beach erosion, rates of shoreline transgression, increased demand for limited beach nourishment material, and associated impacts to coastal communities, economies, and infrastructure.

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