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Key Points:
- Intense storms import sediment into a system of bays in Virginia, USA
- Duration and magnitude of storm surge are among the most important factors in sediment import
- Intense storms may increase the stability of tidal bays by providing sediment necessary to counteract sea level rise

Supporting Information:
- Supporting Information S1

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Intense Storms Increase the Stability of Tidal Bays

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Abstract Coastal bays and, specifically, back-barrier tidal basins host productive ecosystems, coastal communities, and critical infrastructure. As sea level continues to rise and tropical cyclones increase in intensity, these coastal systems are increasingly at risk. Developing a sediment budget is imperative to understanding how storm events affect the system's resilience, where net import of sediment indicates growth and resilience against sea level rise, and net export of sediment indicates deterioration. Using high-resolution numerical simulations, we show that intense storms import sediment into a system of bays in Virginia, USA. Duration and magnitude of storm surge are among the most important factors in sediment import, suggesting that intense storms increase the stability of tidal bays by providing the sediment necessary to counteract sea level rise. Since climate models project that tropical cyclones will increase in intensity in coming decades, our results have significant implications for the resilience of tidal bays and the future of coastal communities worldwide.

Plain Language Summary In order to counteract rising sea levels, a coastal bay needs to increase its bottom elevation by trapping enough sediment in salt marshes and tidal flats. People believe that storms are deleterious to coastal bays, but this is not necessarily true. In many coastal settings, intense storms are the main mechanism providing coastal bays with the sediments necessary to offset sea level rise. Here we show that intense storms provide sediments to the bay and marsh systems of the Virginia coastal bays, USA, thereby increasing their long-term stability.

1. Introduction

Coastal bays and barrier island systems provide a variety of ecosystem services and play an integral role in protecting coastal communities from flooding and other destruction associated with coastal storms, including hurricanes and extratropical cyclones (Barbier et al., 2011). Communities are growing increasingly vulnerable to flooding from tropical cyclones and other storms due to increases in sea level rise (Woodruff et al., 2013), and continuing greenhouse gas-forced warming may augment tropical cyclone intensity and frequency (Sobel et al., 2016; Walsh et al., 2016). Coastal bays must trap sediments so that tidal flats and salt marshes can accrete and maintain the same elevation with respect to mean sea level, allowing the system to keep pace with sea level rise and avoid drowning (Fagherazzi et al., 2014). Though marshes have been shown to be resilient to periods of moderate sea level rise (Kirwan et al., 2010, 2016), accelerated sea level rise can cause marsh drowning and destruction (FitzGerald et al., 2008; Kirwan et al., 2010). Wave attack from intense storms has been shown to cause significant erosion (Barras, 2007; Howes et al., 2010; Morton & Barras, 2011; van de Koppel et al., 2005), but overwash and other deposition from intense storms have also been suggested as a major source of resilience-building sediment (Donnelly et al., 2001; Morton & Barras, 2011; Turner et al., 2006; D. C. Walters & Kirwan, 2016). Developing a sediment budget for these coastal bays is imperative to understanding how storm events in a regime of accelerated sea level rise affect the resilience of the system, where net import of sediment indicates growth and increasing stability of the system and net export of sediment indicates deterioration (Fagherazzi et al., 2014; Ganju et al., 2015).

In this study, we quantify the sediment fluxes into and out of coastal bays during storms to test the hypothesis that more frequent and intense storms will erode and deteriorate these valuable ecosystems. We focus this study on the Virginia Coast Reserve (VCR), a system of salt marshes and shallow back-barrier tidal bays

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along the Atlantic side of the Delmarva Peninsula (Figure 1a), because this reach is one of the longest expanses of undeveloped mixed-energy barrier islands worldwide (which controls for anthropogenic impacts) and experiences high rates of relative sea level rise (which provides an upper bound for expected marsh demise; Fenster et al., 2016). The VCR is composed of a system of shallow bays fringed by *Spartina alterniflora* marshes, which cover approximately 30% of the total surface area of the system (Fagherazzi & Wiberg, 2009; Oertel, 2001). The system has a mean tidal range of 1.2 m, and storms are a primary cause of short-term disturbance in the area (Fagherazzi & Wiberg, 2009; McLoughlin et al., 2015). The system lacks a significant riverine sediment source. Previous research in the VCR has included quantifying the main contributors to salt marsh erosion, a major threat to marsh ecosystem services. Though wave action is the main contributor to erosion (Fagherazzi & Wiberg, 2009; Mariotti & Fagherazzi, 2010; McLoughlin et al., 2015), vegetation changes and invertebrate burrowing also play a large role (Thomas & Blum, 2010). Previous geomorphic modeling in this location has focused on developing numerical models for marsh evolution (Fagherazzi et al., 2012; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010), detailing how waves shape marsh form and function (Leonardi & Fagherazzi, 2014, 2015), and quantifying how barrier islands and marshes interact (Deaton et al., 2016; Walters et al., 2014). Given the robust nature of previous research in the VCR, it is an ideal location to formulate a sediment budget to determine the supply of sediment to the tidal bays and their resilience in the face of sea level rise and increasing storminess.

2. Methods

2.1. Model Design

Hydrodynamic and sediment-transport simulations were conducted using the high-resolution, fluid dynamic model Delft3D-FLOW (Lesser et al., 2004) and the Delft3D-WAVE module, which is based on the SWAN (Simulating WAves Nearshore) wind wave generation and propagation model (Booij et al., 1999). This coupled system is suitable for simulating nonsteady flows, wave generation and propagation, sediment transport phenomena, and related morphological developments in shallow seas, coastal areas, estuaries, lagoons, rivers, and lakes.

The model used a nested grid system to simulate wave generation and propagation. The outer grid—a curvilinear, coarse-grid wave domain with cell sizes that decrease as depth decreases—extends up to the location of National Oceanic and Atmospheric Administration (NOAA) buoy 44014 or, if no data from 44014 is available, up to the location of NOAA buoy 44099 (Figure S2). The inner grid—a nested quadrangular grid—covers the area of the bays with a 250 m constant resolution over the whole domain (Figure S2). Details on the bathymetry and friction coefficients used for the inner grid can be found in Wiberg et al. (2015).

Water levels at the southern, northern, and seaward open boundaries of the second grid were set equal to the water level measured at NOAA station 8631044 (Wachapreague, VA), with a phase shift and an amplitude correction to account for tidal propagation and dissipation in the domain (Figure S3). Wind speeds were simulated in both grids, with the outer grid using data from the offshore buoys (44014 or 44099) and the inner grid using data from Wachapreague.

Wave heights were forced by offshore buoy data to allow the waves to propagate over a large distance before entering the inner grid. The wave heights were then calibrated to maximize agreement between simulated and measured wave height at the inshore NOAA buoy 44096 (Cape Charles, VA; Figure S4). For the purpose of analysis, maximum wave heights and wind speeds were determined using data from NOAA buoy 44096, which had no gaps in data during the study period.

2.2. Storm Identification

A total of 52 storm events from 2009 to 2015 were simulated (Table S1 and Figure S1). Storm events were identified when wind speed at NOAA station 8631044 (Wachapreague, VA) exceeded 11 m/s. The duration of each simulated storm was determined by the storm surge (difference between measured and predicted water levels) recorded at NOAA station 8638863 (Chesapeake Bay Bridge Tunnel, VA)—the starting and ending points of the storm were determined so that four complete tidal cycles during which the storm surge is below a threshold value of 0.2 m are included in the simulations before and after the peak wind speed (Figure S1). Threshold values of 11 m/s and 0.2 m were sufficient to identify all named tropical cyclones impacting the VCR in the given time frame. For storms where the wind speed exceeded the 11 m/s

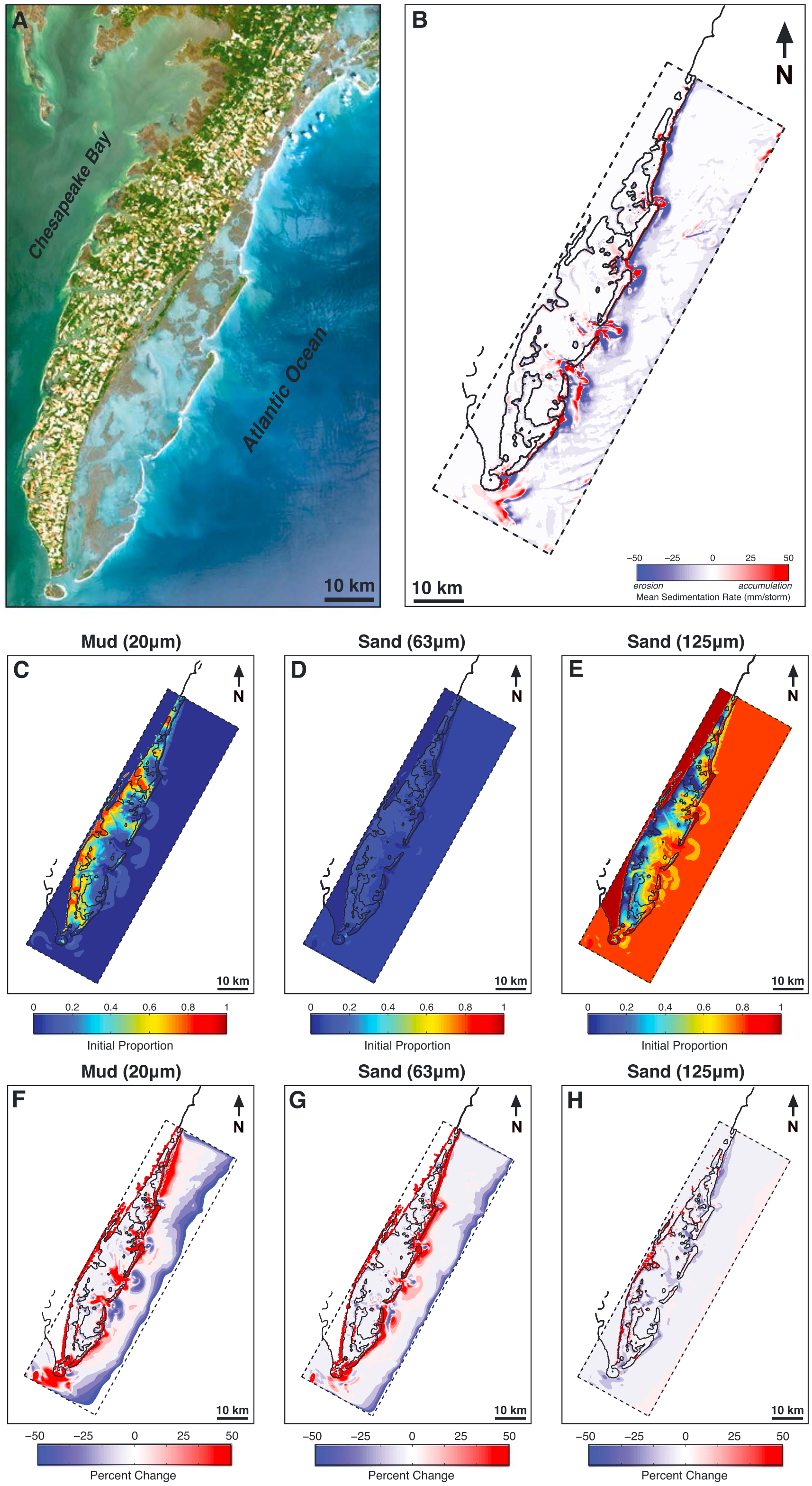

Figure 1. Bottom sediment distribution and change. (a) Aerial photograph of the Virginia Coast Reserve. (b) Mean cumulative elevation differences in the system for all 52 study storms. The blue areas indicate net erosion. The red areas indicate net accumulation. (c–e) Sediment bottom grain-size distribution. Scale is the proportion of the type of sediment, derived from Wiberg et al. (2015) and Fenster et al. (2016). (f–h) Average change in bottom sediment grain-size distribution after each storm, averaged for each type of sediment. Scale is percent change from initial to final bottom grain-size distribution.

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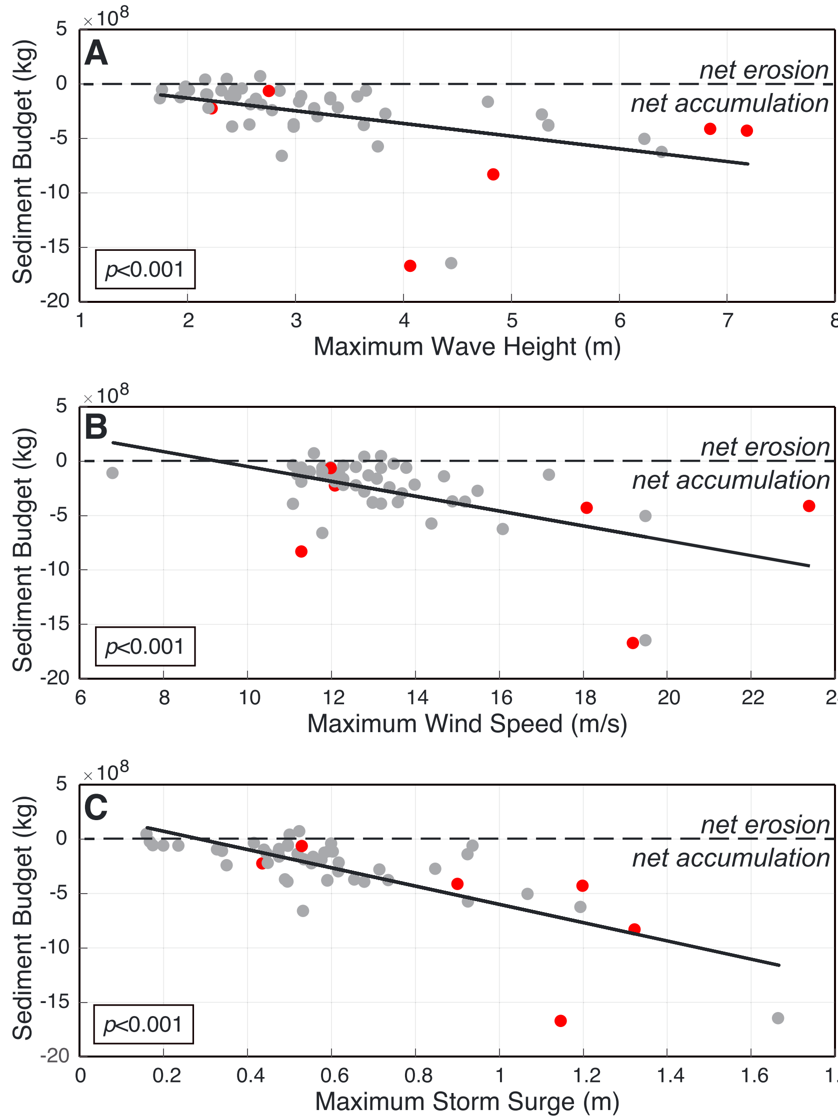

Figure 2. Sediment budget related to study parameters. Relationship between sediment budget and the maximum value per event of (a) wave height (R^2 = 0.30; $p < 0.001$), (b) wind speed (R^2 = 0.22; $p < 0.001$), and (c) storm surge (R^2 = 0.57; $p < 0.001$). There is a negative sediment budget (net accumulation of sediment into the system) as all study parameters increase in magnitude and duration. The red circles indicate named tropical cyclones.

threshold but did not produce surge above 0.2 m, the storm was defined as four complete tidal cycles before and after the peak in wind speed.

2.3. Sediment Budget and Flux

A sediment budget was constructed for each storm to determine resilience of the system (Ganju et al., 2015). Using high-resolution maps of bottom sediment size distributions within the bays of the VCR established by Wiberg et al. (2015), sediment resuspension and flux were modeled for each storm over a domain that included the full VCR and adjacent coastal ocean. Sediment size distributions for the adjacent coastal ocean were derived from grain-size distributions characterized by Fenster et al. (2016). The sediment budget into and out of the VCR (total cumulative sediment flux at the end of the model run for the series of basins) was modeled for three different particle sizes—20, 63, and 125 μm (Figures 1c–1e). At the start of each simulation, mud (20 μm) was primarily distributed closer to the mainland. Fine sand (125 μm) was primarily distributed closer to the inlets and the tidal flats. Very fine sand (63 μm) was relatively evenly distributed

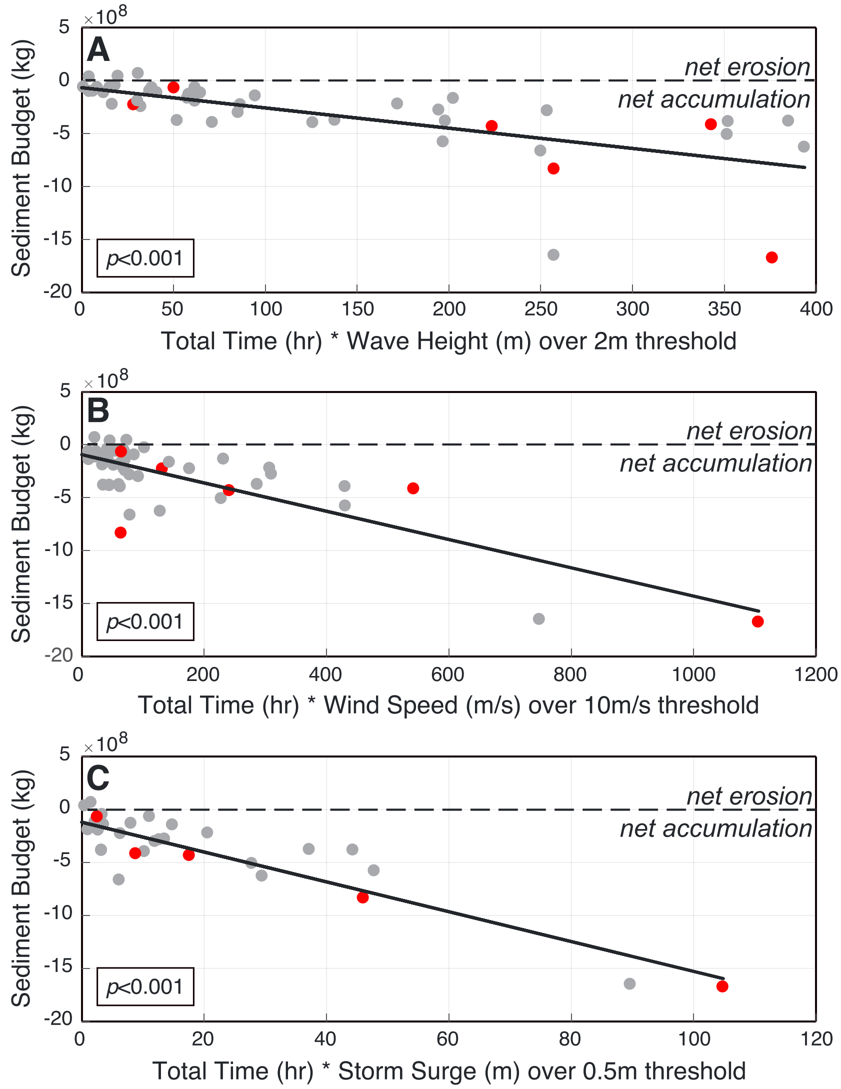

Figure 3. Sediment budget related to magnitude and duration of study parameter. Relationship between sediment budget and the product between magnitude and duration of (a) wave height above 2 m (R^2 = 0.47; $p < 0.001$), (b) wind speed above 10 m/s (R^2 = 0.63; $p < 0.001$), and (c) storm surge above 0.5 m (R^2 = 0.80; $p < 0.001$). There is a negative sediment budget (net accumulation of sediment into the system) as all study parameters increase in magnitude and duration. The red circles indicate named tropical cyclones.

throughout the system. Suspended sediment concentrations produced by the model were validated by Wiberg et al. (2015) over a three-week period in January 2003 (Figure S5). Though the model produces results in good accordance with measured data, there is the potential for spatial or temporal variation in the natural storm events that it may not capture.

Trends in cumulative sediment flux were analyzed for relationships with a variety of parameters including wind speed, wave height, storm surge, wind direction, and the time each storm remained above a given threshold of each parameter (Table S1). Wind direction was highly variable throughout each simulated storm and, as such, was not found to significantly influence sediment flux and was not included in the analysis.

3. Results

Using high-resolution bottom sediment distributions in the VCR (Fenster et al., 2016; Wiberg et al., 2015) in concert with hydrodynamic modeling, a sediment budget was developed to determine how this system

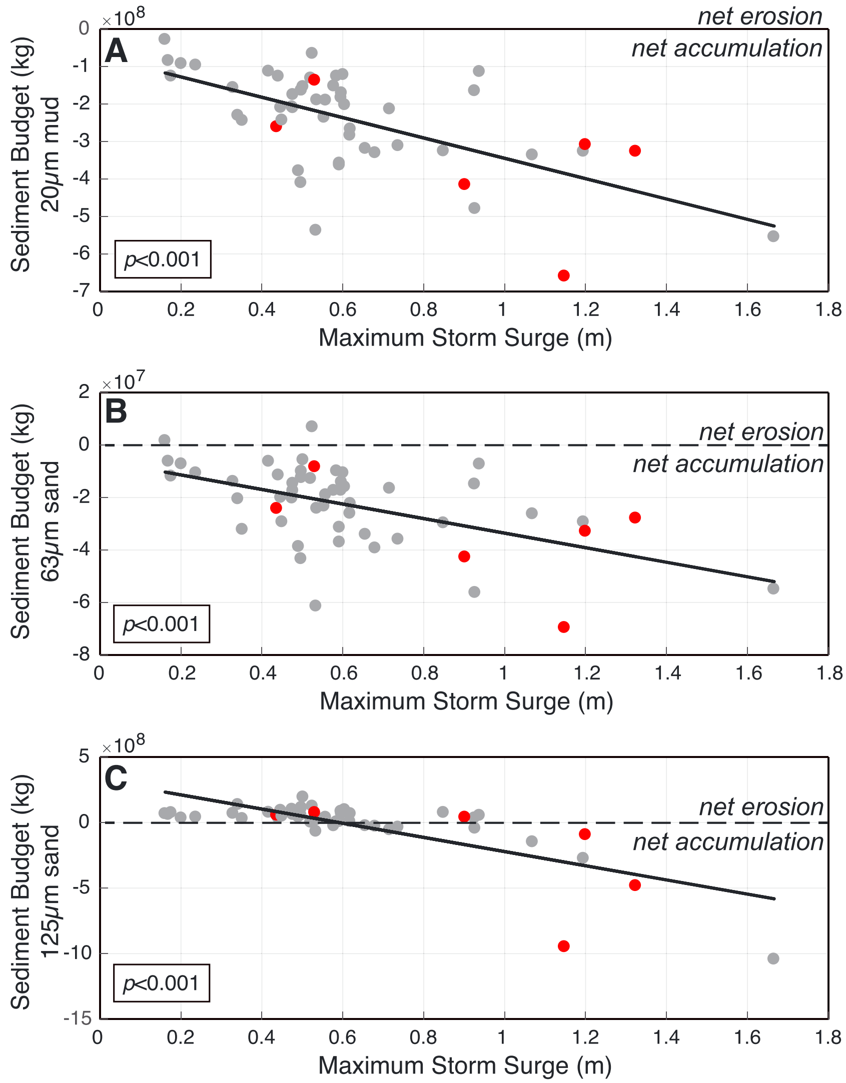

Figure 4. Sediment budget by grain size related to maximum storm surge. Relationship between maximum storm surge measured at NOAA stations 8631044 and 8638863 and total cumulative flux of (a) 20 μm mud ($R^2 = 0.39$; $p < 0.001$), (b) 63 μm very fine sand ($R^2 = 0.28$; $p < 0.001$), and (c) 125 μm fine sand ($R^2 = 0.57$; $p < 0.001$). There is a significant negative relationship between total cumulative flux and intensity of storm surge for mud (20 μm) and very fine sand (63 μm), indicating net accumulation. Though there is a negative relationship between total cumulative flux and storm surge for coarse sand (125 μm), total cumulative flux is predominantly greater than zero, indicating net erosion for most study storms. The red circles indicate named tropical cyclones.

responds to storm events. Averaging cumulative sediment flux spatially over all 52 storms, erosion is focused primarily along the ocean-side shorelines of the barrier islands, and sediment largely accumulated on the marshes, in the bays, and along the inlets (Figure 1b). Using values for bed porosity consistent with Wiberg et al. (2015), net accumulation of sediment within the domain from the modeled storms ranged from 2.0 to 5.3 mm/year.

Wind speed, wave height, and storm surge displayed statistically significant negative relationships with cumulative sediment flux (Figure 2 and Table S2). This suggests that there is increased sediment accumulation in the study region as each parameter increases in intensity. Cumulative sediment flux also displayed statistically significant negative relationships (net accumulation of sediment into the system) with the amount of time each parameter remained over the following thresholds: wave height > 2 m at Station 44096 or 44014 (dependent on data availability; Figure S2), wind speed >10 m/s, and storm surge >0.5 m. Relationships were determined using the product of the total time over the threshold and the magnitude of the corresponding variable for each storm. The product of magnitude (>0.5 m) and duration of storm surge alone explains most of the variance in cumulative sediment flux (Figure 3 and Table S2). A multiple regression analysis of the three variables indicates that, similarly, the storm surge threshold-time product contributes the most to the relationship ($p < 0.001$, $R^2 = 0.66$). As a result, the influence of storm surge, particularly its duration and magnitude, appears to control the sediment budget of the bays.

While the total cumulative flux indicates that more intense storms tend to result in net import of sediment to the study area, this result varies by sediment type. For all three study parameters, mud and very fine sand (20 and 63 μm, respectively) display the same significant negative relationship with cumulative flux, where increased storm intensity results in increased import of sediment to the back barrier basin (Figure 4 and Table S3). Fine sand (125 μm), however, tends to be exported from the tidal basin. Almost all storms (96%) exhibit net export of fine sand, regardless of intensity.

The spatial variation in percent changes in bottom sediment grain-size distributions provides insight into storm-induced sediment dynamics (Figure 1). Following a storm, back-barrier marshes accumulate medium-grained silt, herein defined as mud (20 μm), from the ocean side of the inlets. Back-barrier marshes experience erosion of mud (20 μm) and deposition of sand (63 and 125 μm) along their edges, enhancing vertical accretion in those locations. The bay side of the inlets accumulates mud (20 μm) and erode fine sand (125 μm), whereas the ocean side of the inlets generally erode mud (20 μm) and accumulate very fine sand (63 μm). The barrier islands experience deposition of very fine sand (63 μm) and erosion of fin e sand (125 μm) along their edges and offshore.

4. Discussion and Conclusions

Storm surge duration and magnitude have the most significant influence on cumulative storm sediment flux. The energy associated with a storm surge provides the shear stresses necessary for remobilization of sediment near the inlets and transport into the bay system. Storm surges have long been known to deposit sediment in marshes and bays during large storm events, on both historic and prehistoric timescales (Boldt et al., 2010; Donnelly et al., 2001; Hodge & Williams, 2016; Smith et al., 2015; Tweel & Turner, 2012).

Here we show that these storms transport mud and fine-grained sediment through the inlets and deposit them onto tidal flats and marshes proximal to the inlets (Figures 1f-1h). Tidal inlets serve as the conduit for funneling sediment from offshore to the bay. Storm-driven sediment transported through the inlets is then available for further remobilization by waves and tides, feeding additional interior flats and salt marshes (Wells, 1995). Without a net input of sediment through the inlets, in the absence of riverine inputs, the system would drown in place, unable to counteract sea level rise in the long run.

Our study suggests that a storm surge threshold of 0.5 m or greater is sufficient to cause a net import of mud to the back-barrier system, regardless of the amount of time that the surge is above that threshold, assuming a continued supply of fine-grained material. Furthermore, the fine-grained sediment accumulation rates in the tidal bay system of 2.0–5.3 mm/year have the potential to exceed the current sea level rise rates of approximately 4 mm/year (Wiberg et al., 2015). Indeed, recent work documenting marsh accumulation rates has suggested that marshes in the VCR may be accreting at rates great enough to avoid the threat of drowning from accelerated sea level rise (Kirwan et al., 2016; Walters & Kirwan, 2016). Other studies have supported sedimentation rates for large hurricanes ranging from 3 to 10 cm per storm event as sufficient for increased marsh production and growth (Baustian & Mendelssohn, 2015; McKee & Cherry, 2009). Since sea level rise rates in the VCR are relatively high and likely increasing (Mariotti et al., 2010; Sallenger et al., 2012), the resilience of these back-barrier tidal basins has significant implications for coastal bays worldwide, many of which have lower sea level rise rates.

The sediment budget of a given system is often considered a metric of coastal stability. Ganju et al. (2013) suggested that marsh systems with net export of sediment may be more unstable than marsh systems with net import of sediment. Though marsh stability can be influenced by a variety of factors, including net elevation change and suspended sediment source (Ganju et al., 2015), a marsh system's sediment budget has utility in predicting how the marsh will respond to rising sea levels over time, among other stressors. Our results suggest that storm events transport more sediment into tidal bays as they increase in intensity, thereby increasing their resilience in time.

Our results may also have implications for the fate of marshes globally. Lacking major rivers or other volumetrically important inputs of freshwater (Stanhope et al., 2009) or sediment (Morton & Donaldson, 1973) to the coastal bays, the major driver of sediment input to back-barrier marsh systems is likely storms. Marsh systems that have more sediment input from riverine sources may have an even greater long-term adaptability to sea level rise, which additional sediment input from storms will continue to augment. Indeed, meta-analysis of vertical accretion in salt marshes in both North America and Europe has shown that the majority of the 179 studied marshes have been accreting (Kirwan et al., 2016). Accumulation of sediment in tidal bay systems from storms, particularly intense storms, has been documented with Hurricanes Katrina, Rita, and Andrew in Louisiana (List et al., 2001; Morton & Barras, 2011), though documented impacts from storms are varied (Barras, 2007; List et al., 2001; Morton & Barras, 2011), and sediment budgets may vary between different tidal basins with different morphological characteristics (Pedersen & Bartholdy, 2006). Though some studies have suggested that erosion along the ocean side of barrier islands will increase as sea levels increase (Feagin et al., 2005; Leatherman et al., 2000), our study shows that input from storms alone may enable marsh accretion to keep pace with or counteract relatively high current rates of sea level rise (as previously suggested by Schuerch et al., 2013), provided the barrier islands remain relatively stable. As such, continued or increased storm activity may have positive implications for the resilience of marshes worldwide. This is particularly important as future projections indicate that rates of sea level rise will only continue to increase (Parris et al., 2012).

Many assessments agree that an increase in sea surface temperatures should result in an increase in the intensity of tropical cyclones (Holland & Webster, 2007; Sobel et al., 2016; Walsh et al., 2016), even with natural variability and confounding factors (Sobel et al., 2016). Our study identifies the mechanism by which increased storminess increases the resilience of coastal bays. In particular, storms provide the material necessary to counteract rising sea levels as storms entrain fine-grained material from the nearshore and transport the material into back-barrier tidal basins through the tidal inlets. These findings are particularly of interest for coastal protection schemes, since salt marshes and shallow tidal flats present a unique natural way to protect vulnerable communities from the effects of storm surge and flooding by dissipating energy, the effects of which will only increase as storminess increases. Sea level is rising in the VCR at fast rates (Mariotti et al., 2010), and, as such, our study provides a potential upper-bound example of the resilience of coastal bay systems in the face of increasing storminess. Increased storminess therefore may increase the long-term viability of marshes and coastal bays worldwide.

Acknowledgments
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