Storm Processes and Salt Marsh Dynamics

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Introduction

Marshes have long been considered useful for their ecosystem service of coastal protection. Their roles in protection from storms and floods are seen as necessary and important to many coastal communities (Barbier et al., 2011; Butchart et al., 2005; Costanza et al., 1997; Morgan et al., 2009). Understanding the impacts that storms have on coastal ecosystems and adjacent coastal communities is imperative to increasing coastal resilience in the face of future increases in coastal flooding and associated damage (Pielke et al., 2008; Mendelsohn et al., 2012). Salt marshes have been lauded as buffers to storm surges, wind-generated waves, and elevated water levels (French, 2006; Möller, 2012). The ecological restoration economy, which includes salt marsh restoration, in the United States alone generates $9.5 billion in annual economic output and employs an estimated 126,000 workers (BenDor et al., 2015). After Hurricane Sandy, the United States Fish and Wildlife Service spent more than $40 million on salt marsh restoration projects in response to this single event, including $11 million toward restoring a series of salt marshes along Long Island (US F&WS, 2017).

Recent research reviewed in this chapter explores the impacts of storms on salt marsh erosion and accumulation, with an eye toward the utility of salt marshes for coastal protection in the face of rising sea levels and increasing storminess. Our review is primarily focused to the East and Gulf Coast of the United States as well as Europe. This is in part due to the concentration of researchers and the prevalence of marsh systems in these regions, compared to mangrove wetlands that tend to dominate the tropics (Fig. 2.1). Our review highlights the processes that occur in marshes resulting from storms (Fig. 2.2), and provides insight into the future response of marshes to changes in storminess. The variability in storm impacts to marshes is largely based on both intensity and circumstance, with the potential for a spectrum of effects to be seen at a single marsh (Fig. 2.3; Cahoon, 2006; Morton & Barras, 2011). Though marshes may be generally resilient to coastal flooding on larger spatial and temporal scales, storms may have more subtle impacts, causing cascading effects on a variety of smaller scales. A single storm may result in overwash that provides sediment to build the marsh in some sections, while wave activity and higher channel velocities increases marsh-edge erosion/retreat in other sections due to scarping, undercutting, and slumping (Fig. 2.3). Given the prevalence of marshes worldwide and the likelihood of changes in storminess as climate changes (Walsh et al., 2016), it is important to understand the effectiveness of marshes in flood mitigation, as well as the role of storms in controlling marsh morphology. Our review begins with a discussion on the depositional record of storms in marshes, followed by an overview of modern storm impacts on marshes, and marsh attenuation of waves and storm surge.

Stratigraphic evidence of storms in marshes

Marsh stratigraphy and sediments provide both accretional and erosional evidence of paleo-storms. With respect to accretion, storm-induced overwash deposits in salt marshes have been used to augment our understanding of hurricane strikes (e.g., Boldt et al., 2010; Donnelly et al., 2001a, 2001b). Elevated water levels from storm surge and waves can be significant enough to overtop sandy barriers, transporting and depositing coarse sediment on top of salt marsh peat. During the years following the storm, organic material accumulates/grows over the associated overwash layer, thus preserving the storm event as a stratigraphically-distinct allochthonous layer. Donnelly et al. (2001b) described this sedimentary pattern in a salt marsh in southern Rhode Island (Fig. 2.4a). At this salt marsh, aerial photos after major hurricanes in 1938 and 1954 confirm overwash fans deposited by the events. These overwash fans, along with four older deposits, were confirmed in a series of 14 sediment cores, suggesting that several intense hurricanes had impacted the area since 1635. Other studies have also identified storm-induced deposits in marsh, including in the Gulf of Mexico (Williams, 2012), South Carolina (Hippensteel, 2008; Hippensteel & Martin, 1999), and Georgia (Kiage et al., 2011). For a complete database of paleo-storm reconstructions from marshes and other back-barrier environments please see recent reviews by Oliva et al. (2018) and Muller et al. (2017).

van de Plassche et al. (1999, 2004, 2006) proposed that intense storms (under a specific, yet unknown, combination of conditions) may be the cause of preserved stratigraphic evidence of widespread erosional events in a Connecticut salt marsh. At Pattagansett River Marsh, two distinct erosional events were discovered (van de Plassche et al., 2006), where the portion of the marsh that had been eroded appeared to have been quickly infilled with tidal mud, which then transitioned to low and then high marsh peat. This was interpreted to represent a small-scale complete transition from marsh to tidal creek/mudflat system then back to a low-to-high marsh again. Though storms have been shown to cause smaller, localized erosional events, the large-scale unconformities observed by van de Plassche et al. (on the order of >$100m^2$) were surprising. Erosion of this scale has not been documented in modern salt marshes, and did not appear to have deposited large blocks of excavated peat elsewhere. van de Plassche et al. (2006) found that the dates of their two identified erosional events corresponded with the age ranges of known hurricane deposits found at another salt marsh approximately 60 kilometers away (Donnelly et al., 2001a), including a hurricane in 1635, which is considered by many to be the most intense hurricane in the historical record to impact southern New England (Boose et al., 2001; Ludlum, 1963).

Nikitina et al. (2014) expanded on the van de Plassche et al. (2006) research with sedimentary evidence of potential storm erosion from more than 200 gouge cores along seven transects in a salt marsh in New Jersey. The authors documented similar depositional sequences as those seen by van de Plassche et al. (2006) across great swathes of marsh: in at least seven sequences, there were abrupt contacts between salt marsh peat and overlying intertidal mud, suggesting that the underlying peat was eroded and then rapidly infilled by tidal mud (Fig. 2.5f). Though the authors suggested several different processes that may produce these sequences, they developed a chronology that suggested that these events may have correlated with historic and prehistoric tropical cyclone events observed previously in the northeast (Donnelly et al., 2001b). The authors proposed that the most recent episodes of marsh erosion may correlate with tropical cyclones in 1903 AD, 1821/1788 AD, and 1635 AD.

Erosional features in marsh stratigraphy are attributed to storms largely through the discrediting of other potential mechanisms (Nikitina et al., 2014). Alternative explanations for the intertidal mud deposits overlying high marsh peat include an increase in tidal range (Long et al., 2006), gradual migration of tidal channels (Stumpf, 1983), background rates of marsh-cliff retreat (McLoughlin et al., 2015), marsh pond formation (Wilson et al., 2009), and changes in sea level (Schwimmer & Pizzuto, 2000). Migration of tidal channels was ruled out in the Nikitina et al (2014) study since tidal creeks are generally considered stable over long timescales (Redfield, 1972), and the process of tidal creek migration in the case of stabilizing vegetation loss is a slow time-transgressive process that would not result in the observed sharp contacts (Stumpf, 1983). Though many marshes have been extensively ditched for mosquito control since the 1800s and the erosive contacts may represent infilling of ditches, the authors suggest that would limit those contacts to post-1800, which is not observed in the record. Such erosive sequences would then also be common across many marshes—an observation also not seen as yet. Salt pans, which form either from marsh growing around a tidal depression or after significant vegetation disturbance (Wilson et al., 2009), have a similar stratigraphic signature to that seen by Nikitina et al. (2014) and van de Plassche et al. (2006). The authors assert, however, that the stratigraphic sequences seen in their study site appear to be laterally continuous across large areas of the marsh. This observation is more consistent with a major erosional event than a localized salt pan. Additionally, while most of these ruled-out processes occur over longer timescales, higher-energy events could also be responsible for more rapid changes in tidal range, channel geometry, or cliff erosion, among others.

It is important to consider why the Nikitina et al. (2014) and van de Plassche et al. (2006) studies observed evidence of wide-spread marsh erosion that they attribute to hurricanes when other marshes in the vicinity do not (e.g. Donnelly et al., 2001a; Donnelly, 2004; Miller et al., 2009). A variety of factors—including sampling biases, marsh geomorphology, marsh composition, storm track, and storm intensity—may play roles in observing eroding or depositing sediment in different locations or at different times. Indeed, sediment cores from marshes in New England suggest that a given location can experience both depositional and erosional events (Fig. 2.6). While the extensive erosion of marsh platforms by intense hurricanes remains an explanation for the features mapped in these marshes, the physical processes of erosion and the character and magnitude of the storms potentially responsible remains elusive. Smaller scale erosional processes have been observed historically and therefore the mechanisms responsible for them are better understood.

Analysis of paleorecords shows that salt marshes and intense storm events have coexisted for thousands of years. Boldt et al. (2010) identified 30 distinct storm events (including seven historical severe landfalling hurricanes) over the past 2,000 years in a sediment core collected from a salt marsh in Mattapoisett, MA (Fig. 2.7). Though there have been periods of increased hurricane activity and quiescence in the last two millennia (Donnelly et al., 2015), cores from Mattapoisett suggest continuous marsh development. Despite significant variability in both storminess and storm impact over the past millennia (Fig. 8a and 8c), sea levels have remained relatively stable (Fig. 2.8b and 2.8d), with the most notable increase in global sea levels occurring in the last 150 years (Donnelly et al., 2015; Kemp et al., 2014, 2015; Kopp et al., 2016; Lane et al., 2011; Fig. 2.8e). Tandem increases in sea levels and storminess may serve to multiply marsh vulnerability. The paleorecord shows that patterns of and mechanisms for erosion or deposition from intense storms are complex. These patterns and mechanisms will be explored in more detail in the following section on modern processes.

Modern storm impacts on marshes

To determine the modern impacts of storm events on marshes, one must first consider the factors that contribute to marsh stability (Fig. 2.9). Here, we provide an abbreviated review on the topic specific to storm impacts. A series of biological and physical feedbacks allow marshes to vertically keep pace with sea-level rise. Following Redfield's bi-directional model of salt marsh evolution (Redfield, 1965), as sea level rises and organic material and clastic sediment accumulates on the marsh, the marsh accretes vertically over basement material or mudflats (Fig. 2.2). Following the model described by Stumpf (1983), deposition of sediment on the marsh occurs predominantly with tidal flooding. As water from tidal currents floods the marsh surface, marsh vegetation slows the currents, trapping suspended sediment (Postma, 1961). In addition to regular tidal flooding, storms can be a major source of sediment for the marsh (Donnelly, 2004; Donnelly et al., 2001a; Turner et al., 2006; Walters et al., 2014; Walters & Kirwan, 2016; Fig. 2.4). Large storms can produce storm surge and wave heights significant enough to overtop sandy barriers, transporting and depositing coarse sediment on top of salt marsh peat. Highly turbid water from storms can also be carried into the marsh via creek networks along the back side of the marsh (Schuerch et al., 2013). Kolker et al. (2009) found a strong correlation between short-term sea-level change (e.g., storms) and increased accretion in marshes in Long Island, NY. Stumpf (1983) proposed that total sedimentation is from a combination of tidal and storm sources, with storms controlling sediment supply and movement on smaller time scales than daily tidal flooding, when considered over decades or centuries.

Though flooding during storms has documented impacts on marshes, in some cases very high storm surges over a marsh may actually help protect its surface from both erosion and accumulation of sediment. Elsey-Quirk (2016) measured the impacts of Hurricane Sandy (2012) on salt marshes in New Jersey, finding only localized and temporary marsh elevation changes and disturbances, despite Sandy making direct landfall. Similar conditions were seen after Hurricane Hugo (1989) in a salt marsh in South Carolina (Gardner et al., 1992). In both cases, the perpendicular coastal approach by both storms resulted in significant storm surges. The surge completely inundated the marsh, such that sediment associated with the surge was deposited more inland, being transported over and bypassing much of the marsh surface. Storm waves on top of the deep surge caused minimal erosion along the marsh surface or edge.

The marsh edge is subjected to constant stress from wind, waves, and currents. Field and model observations confirm that how a marsh edge erodes depends largely on the type of waves to which it is exposed. Leonardi and Fagherazzi (2014) found that, on small spatial scales, high storm wave energy conditions erode marsh boundaries uniformly, whereas low wave energy conditions result in a jagged erosion pattern—largely due to the influence of local marsh resistance. On larger, whole-marsh scales, boundaries of rapidly-eroding marshes are significantly smoother than those of sheltered or slowly-eroding marshes, though marshes experiencing low-wave energy conditions may be more susceptible to increased large, isolated failures (Leonardi et al., 2016; Priestas et al., 2015). There does not appear to be a threshold of wave power over which marsh erosion accelerates drastically. For example, Leonardi et al. (2016) identified a linear relationship between salt marsh erosion and wave power and determined that wind speeds associated with moderate storms (1.6-10.7 m/s) are associated with the greatest amounts of marsh deterioration due to their higher frequency of occurrence. In contrast, extreme wind speeds associated with rarer and more violent storms and hurricanes (>28.5 m/s) contribute less than 1% of long-term marsh deterioration along the lateral plane. Due to short observational periods, however, studies such as Leonardi et al. (2016) may miss more intense (e.g., > 50 m/s), relatively rare events.

Morton and Barras (2011) explored patterns of wetland erosion and deposition following major hurricanes in southern Louisiana. The authors determined—through analysis of aerial photography, satellite imagery, and on the ground mapping—several depositional features associated with major storms, including wrack zones, interior-marsh deposits, and shoreline deposits. If a storm does not deposit an extremely thick wrack or sediment layer, which would kill supportive vegetation, depositional events generally favor marsh resilience. Overwash fans associated with Hurricanes Audrey (1957), Andrew (1992), Lili (2002), Rita (2005), Gustav (2008), and Ike (2008) often exceeded 50 meters in width, with overwash terraces from Gustav as wide as 150 meters. These overwash deposits, however, were coupled with massive erosional signatures throughout the marshes, suggesting a more complicated relationship between marsh resilience and major storms. Following Hurricanes Audrey (1957), Hilda (1964), Andrew (1992), Katrina (2005), and Rita (2005), erosional features (including pond formation or expansion, marginal incised damage, braided channels, plucked or denuded marsh, floating-marsh redistribution, and shoreline erosion) were substantial. Hurricanes Katrina and Rita, for example, increased the water area in coastal Louisiana by 230 km^2 and 295 km^2, respectively (Barras, 2007). Most substantially, ponds expanded or created by hurricane erosion tended to become permanent features—increasing the open water area substantially across southern Louisiana. Contrary to the previously mentioned findings of Leonardi et al. (2016), Barras (2007) asserts that storm-related erosion is the primary natural process by which marshes in southern Louisiana degrade, especially since the self-healing capabilities of marsh systems using sediment and nutrients from the Mississippi delta system have been hindered since land development in the late 19th century. Barras (2007) suggests that increased wetland loss will increase overall vulnerability of southern Louisiana marshes to extreme storms, particularly in seasons with multiple storms, but the difficulty in predicting where and when extreme landfalls will occur makes it challenging to predict loss in specific areas at specific rates. Many of these marshes experiencing losses were fresh to brackish marshes, also emphasizing the importance of salinity for storm resilience (Howes et al., 2010).

Howes et al. (2010) determined that 2005 Hurricanes Katrina and Rita eroded more than 500 km^2 of wetlands within coastal Louisiana. Higher-salinity marshes were found to be more resilient to erosion than lower-salinity marshes, with lower-salinity marshes preferentially failing. Using field and lab measurements of soil strength, lower-salinity marshes were found to have a weak zone approximately 30 cm below the marsh surface (with shear strengths between 500 and 1450 Pa). Higher-salinity marshes had no documented weak zones, with shear strengths greater than 4500 Pa throughout the entire soil profile. Though controlled by a variety of factors, the difference is likely due to vegetation—*S. alterniflora* marshes are more tolerant to increased salinities, with more substantial, deeper root systems than less-saline marshes dominated by *S. patens*. The authors suggest that this research may have broader implications for current freshwater diversion plans. For example, the introduction of freshwater to marsh systems may decrease their resilience to large storms by creating weak zones within the marsh soil more susceptible to erosion.

As seen in the Howes (2010) study, variations in vegetation assemblage influence both sediment capture and platform stabilization, and such differences in vegetation are controlled by several factors that include salinity, tidal range, wave energy, and climatic setting (Frey and Basan, 1978). In addition to the findings of Howes et al. (2010), Snedden et al. (2014) found a negative relationship between the duration of flood inundation during an experimental mesocosm study of above- and below-ground *Spartina* biomass in the Mississippi deltaic plain, as did Watson et al. (2017) in southern New England marshes. Möller (2012) explored how individual plants can act as erosional agents, discovering that a stand of *Salicornia spp.* within a *Spartina* marsh may be responsible for large-scale bank failure in Tillingham, Essex, UK (Fig. 2.5b). These individual plants can interact with waves, causing small scale erosion at the plant scale, which, when extended to each individual plant within a stand, can lead to erosion on massive scales. Goodbred and Hine (1995) explored the impacts of the March 1993 "Storm of the Century" in a *J. roemerianus*-dominated marsh in west-central Florida, where despite storm surges nearing 3 m and deposition of up to 2 cm of sediment on the marsh, there was minimal marsh shoreline erosion. The authors attribute this to increased sediment stabilization from dense *J. roemeranius* root mats, as well as decreased surface erosion from a reduction in near-bed flow velocities by its canopy (L. A. Leonard et al., 1995). Tate and Battaglia (2013), however, found *J. roemaranius* to be vulnerable to storm surge and wrack deposition in an experimental set up in a marsh on the Florida panhandle.

Using a three-dimensional hydrodynamic and sediment transport model for a salt marsh in the Netherlands, Temmerman et al. (2005) found that vegetative impacts on flow velocity may influence marsh erosion. Erosion of sediment occurs as flow velocity increases over unvegetated portions of the marsh. Accumulation of sediment occurs as flow velocity decreases at the vegetation edge and sediment is trapped. The water level of the flow in relation to the height of the vegetation is also important—when the water level exceeds the vegetation height, flow shifts from a more regional deposition-erosion pattern to larger-scale, homogenous sheet flow. A certain threshold, however, may exist above which stabilizing vegetation cannot recover from destruction by wave action, as explored by a numerical model of salt marsh development by van de Koppel et al. (2005). Storm-induced disturbances, therefore, may trigger cascading vegetation loss and marsh collapse.

The positive feedback between vegetation growth and sediment accumulation, such as that described by Temmerman et al. (2005) among others, continues until the marsh reaches a critical state where marsh edge grows so steep that it is particularly vulnerable to erosion by storm waves. As the marsh collapses, it forms a scarp, which can retreat inland even in the absence of storm stress. The composition of the marsh sediment also plays a role in scarp retreat. Allen (1989) explored how sandy and muddy marsh scarp systems in west-coast British estuaries responded to wave attack. They found that muddy marsh systems in the Severn Estuary were more resilient to storm waves due to increased cohesion, often reach 5-10m in height, and only experience small cantilever failures after strong storms. Sandier marsh systems in Solway Firth and Morecambe Bay more frequently experience toppling and cantilever failures, with much of the soil strength limited to the first 10-20 cm of root-dominated sediment.

Baustian and Mendelssohn (2015) analyzed the recovery rate of plant cover in coastal Louisiana salt marshes following Hurricanes Gustav and Ike (2008). To determine marsh resilience in the absence of stabilizing vegetation, the study followed control and experimentally-disturbed plots (treated with herbicide), and quarterly monitored rate of recovery—both prior to and after the impact of the 2008 hurricanes. The authors found that hurricane-induced sedimentation was highly correlated with above ground primary vegetative production and increased recovery rates after the disturbance. The sedimentation from Hurricanes Gustav and Ike was found to increase the vigor of the vegetation in the experimental plots and, overall, increase marsh resilience. Though the authors acknowledge marsh destruction from the two hurricanes studied, they suggest that increased sedimentation may be beneficial in locally increasing marsh resilience to long-term sea-level rise and future storms.

A marsh requires sediment to accrete fast enough to ensure resilience to rising sea level. Walters and Kirwan (2016) suggest that overwash from hurricane waves actually may be responsible for increasing marsh resilience, citing an optimal thickness of deposit to maximize vegetation productivity, above which vegetation death begins to occur. Using a series of mesocosms to simulate a range of burial scenarios of *Spartina alterniflora* in a marsh in the Virginia Coast Reserve, the authors found that, though major overwash events (>10 cm) may cause marsh loss, smaller, more regular storm events (between 5-10 cm of overwash) contribute to the continued resilience of these marshes.

Turner et al. (2006) investigated the accumulation of inorganic sediment on coastal wetlands of Louisiana from Hurricanes Katrina and Rita and found that accumulation exceeded 131 x 10^6 metric tons over more than 38,500 km^2, with an average thickness of 5.18 cm. Sediment was not equally distributed throughout the marshes, with almost 5 m of storm surge depositing >10 cm of inorganic mud in some regions. Analyzing the spatial distribution and amount of sediment, the authors determine that major storm action is the dominant pathway by which offshore inorganic sediment moves inshore onto the coastal marshes of Louisiana. Burkett et al. (2007), however, suggest that this study fails to take into consideration the significant erosion that also occurred during these major storms, and did not adequately discern the true fluvial source of sediment sampled. Regardless, sedimentation from large storms in Louisiana (McKee & Cherry, 2009; Tweel & Turner, 2012) and elsewhere (Allison & Kepple, 2001; Hu et al., 2018) remains well documented and modeled, and attempts at developing a sediment budget of a marsh system over the course of a storm are necessary to understand the dynamics and impacts of major storms on these systems (Ganju et al., 2015).

Storm sediment dynamics play a large role in the elevation of a marsh, which ultimately determines its resilience. Marsh elevation is a controlling factor in several ecogeomorphic feedbacks, including vegetation establishment, growth, and survival (Cahoon, 2006). Cahoon (2006) reviewed major storm impacts on marsh elevations from Louisiana, Florida, North Carolina, Maryland, California, and the Honduras. Storm impacts on elevation vary based on both storm and marsh properties. Storms impacted marsh elevation positively in a variety of ways, including sediment deposition, root growth, soil swelling, and lateral folding of the root mat. Storms impacted marsh elevation negatively through sediment erosion, sediment compaction, soil shrinkage, and root decomposition.

Marsh attenuation of storm waves and surge

Salt marshes have recently been considered a critical resource in coastal protection (e.g. Gedan et al., 2011; Temmerman et al., 2013). Hurricanes Katrina and Rita both devastated southern Louisiana in 2005, but despite being of similar size and intensity, Hurricane Rita traveled over 30 to 50 km of wetland before reaching a main population center. In contrast, Hurricane Katrina traveled over a series of large lagoons, artificial channels, and highly-degraded wetlands before reaching a main population center. In the case of the Rita event, marshes were able to accommodate extra surge, reducing the impact when the storm reached populated areas, while the surge for Katrina was far less attenuated (Day et al., 2007). Though the marshes in both storm paths experienced significant destruction (Day et al., 2007; Tweel & Turner, 2012), the large extent of marshes in Hurricane Rita's path provided substantial protection. Wamsley et al. (2009) modeled the effects of Katrina and Rita on southern Louisiana marshes, finding similar results—increased restoration of marshes results in decreased storm surge and wave heights, though the amount of attenuation was highly variable among different marshes. Modeling results by Barbier et al. (2013) indicate that sea-to-land storm surge in Louisiana decreased as wetland continuity (i.e., presence of wetlands) and vegetation roughness (i.e., presence of vegetation in these wetlands) increased, and that a 10% increase in wetland continuity along a 6 km transect could save 3-5 homes/properties per storm. Some research has indicated that increased water depth associated with marsh erosion and conversion to a mudflat or open-water system may reduce storm surge levels (Loder et al., 2009). Decreased marsh continuity, however, is also associated with wetland loss increases storm surge levels and helps to highlight potential benefits of marsh restoration for coastal protection in many cases.

Stark et al. (2015) studied tidal and storm surge attenuation in a marsh along the Western Scheldt estuary, the Netherlands. The study site was a 4-km intertidal channel with a surrounding marsh platform of varying width. The authors found that maximum attenuation occurred along channels with wider marsh platforms. Interestingly, channels amplified smaller neap tides and attenuated larger spring tides. Optimal storm surge attenuation occurred when inundation heights were between 0.5-1 m. Inundation heights outside of this range were not attenuated as greatly, perhaps due to reduced bottom or vegetation friction. The authors propose that storm surge attenuation is both location- and event-specific, with storm surge reductions in the literature ranging from as much as 25 cm/km length of marsh, down to -2 cm/km where this negative value denotes actual amplification. This suggests that coastal management plans should consider the height and geometry of an individual marsh and the storm intensity threshold of interest on a case-by-case basis when considering their utility in mitigating storm surge.

Orton et al. (2015) ran hydrodynamic models for Jamaica Bay, New York City, to determine the utility of the site's marsh system for coastal protection. The Jamaica Bay marsh, though undergoing restoration beginning in 2006, has deep dredged channels throughout. Orton et al. (2015) found that the presence of these deep channels effectively short circuited the ability of the marsh to reduce storm surge, and that channel infilling would be far more beneficial for storm surge attenuation than the restoration of surrounding marshes, particularly for fast-moving events. Marsooli et al. (2016), however, showed that the Jamaica Bay marsh system did substantially reduce flow velocity of waves simulated for a tropical storm impacting the region in 2011 (Irene). Numerical modeling of morphological change caused by Hurricane Sandy (2012) found that the presence of marsh vegetation reduced erosion during coastal storms as well (Hu et al., 2018). Thus, though marshes may not be effective in all cases to mitigate storm surge, they may still prove to be highly effective as a means to attenuate storm waves.

Experimentally, lab-based research into the utility of marshes for attenuation of storm waves has involved the use of flume tanks or other in-lab procedures with natural or simulated marsh. Möller et al. (2014) used a 300-m flume tank to simulate a series of storm surge conditions on a transplanted natural marsh from the German Wadden Sea. The authors found that up to 60% of observed wave reduction in the marsh was due to the presence of vegetation. As the waves grew in intensity (heights up to 0.9 m in 2 m of water), the marsh continued to resist surface erosion, even as the waves began to flatten and break down vegetation. This suggests that wave attenuation by marsh vegetation is particularly important to continued resilience of marshes—especially since many field studies focus primarily on relatively low energy conditions. Möller et al. (2014) built on the meta-analysis of Shepard et al. (2011), which found that smaller, more frequent waves are easily attenuated by marsh vegetation. Across all 30 studies considered by Shepard et al. (2011), marsh vegetation was observed to play a significant role in shoreline stabilization. Although many studies focus on the utility of vegetation to attenuate high wave energy, a study by Feagin et al. (2009) suggests that soil type may be more influential than vegetation cover, with humic soils richer in fine-grained organics more resistant to erosion than soils rich in coarse-grained organics like roots or other plant debris. This is also consistent with the earlier mentioned study by Allen (1989), which showed a higher degree of stability for mud-dominated when compared to sand-dominated marshes. Vegetation, however, does play a major role in these soil parameters, so it is important to consider how marsh ecosystem maintenance, restoration, and creation can continue to develop sustainable and ecologically-sound coastal protection (Temmerman et al., 2013).

Regional setting

Storms are a natural component of most ecological systems. Though paleorecords show significant variability in both storminess and storm impact, coastal salt marshes have thrived since their development over the Holocene (Engelhart et al., 2009; Shennan & Horton, 2002). Intense storms have the capacity to dynamically impact marshes—particularly at meso- and microscales—but marshes also have the capacity to adapt and adjust to storm-induced changes, provided they have room to migrate. These dynamic impacts may be erosion of the marsh, accumulation of sediment on the marsh, or, more likely, a combination of both. Through the last several millennia, storm climate has varied considerably (Brandon et al., 2013; Donnelly et al., 2015), sea level has remained relatively stable (Kemp et al., 2014, 2015), and marshes have persisted (Figs. 2.7 and 2.8). Only in the last 150 years has sea-level risen at a significant rate (Fig. 2.8e), potentially leading marshes to become more vulnerable to storm impacts. Even so, a recent preliminary assessment of aerial photography before and after Hurricanes Michael (2018; category 4 landfall in Florida) and Florence (2018; category 1 landfall in North Carolina) shows only limited accumulation and erosion effects. This speaks to the ongoing resilience of salt marshes in the face of intense storms.

It is important to consider that marshes vary widely in terms of their geologic, geomorphic, geographic and climatic setting. *J. roemeranius* marshes, primarily located in the southeastern United States, are often more directly in the path of tropical cyclones. South-facing *Spartina*-dominated marshes in the northeastern United States may be more susceptible to tropical cyclones tracking up the east coast, whereas north-facing New England marshes may be more susceptible to damage from nor'easters. More protected marshes (e.g., those located up drowned river valleys) may be less susceptible to wave attack and surge associated with less intense storms, whereas coastal marshes are exposed to wave attack both daily and from storms of varying intensities. Storm impacts also are often highly variable on smaller scales, dependent on both storm characteristics (proximity to marsh, angle of approach, tide levels, rainfall levels, wind speeds, etc.; Resio & Westerink, 2008) and marsh properties (marsh health, soil strength, local bathymetry, groundwater levels, etc.; Cahoon, 2006). The interplay among all of these properties dictate the impact of a particular storm on a given marsh, and different impacts from the same storm may be seen at the same marsh or proximal marshes.

Summary

The appreciation of marshes for their storm protection and erosion control services continues to grow and is largely responsible for over an order of magnitude increase in the appraised value of tidal marshes in recent decades (e.g. from $14k to $194k /ha/yr between 1997 and 2014; Costanza et al., 2014). Critical to this increase in value is the perceived effectiveness of marshes in storm protection. Marsh sediments preserve evidence of storm-induced erosion and deposition that has and should continue to be utilized to gain more insight on both early historic and pre-historic storm events. This sedimentological evidence of past storm events also exhibits a high degree of spatial variability, both in terms of deposition and erosion. Studies of modern marsh processes confirm the spatial temporal variance in marsh response to storms. When depositional conditions occur, recent research indicates that storms can be a valuable mechanism for marsh resilience to sea-level rise. However, erosion primarily on the marsh edge causes systems in open water to be in a continued state of flux. Minor and moderate storms have been found to largely be responsible for most marsh edge erosion, although catastrophic loss from more intense events has the potential to significantly modify a marsh system. The diversity of responses and rates of erosion and accretion of different marshes during storms also highlight the importance that vegetative species and sediment composition play.

The effectiveness of marshes as a form of flood mitigation is an area of active research. It is clear that marshes provide an effective means of wave attenuation; however, the capacity of these systems to reduce storm surge varies significantly from site to site. As investments in ecosystem-defenses continue to grow, so should research on marsh-storm relationships. Of particular importance are the spatial and temporal factors that determine a marsh's effectiveness in storm flood mitigation, as it is likely that costs and benefits will vary widely depending on the specific setting.

Figures

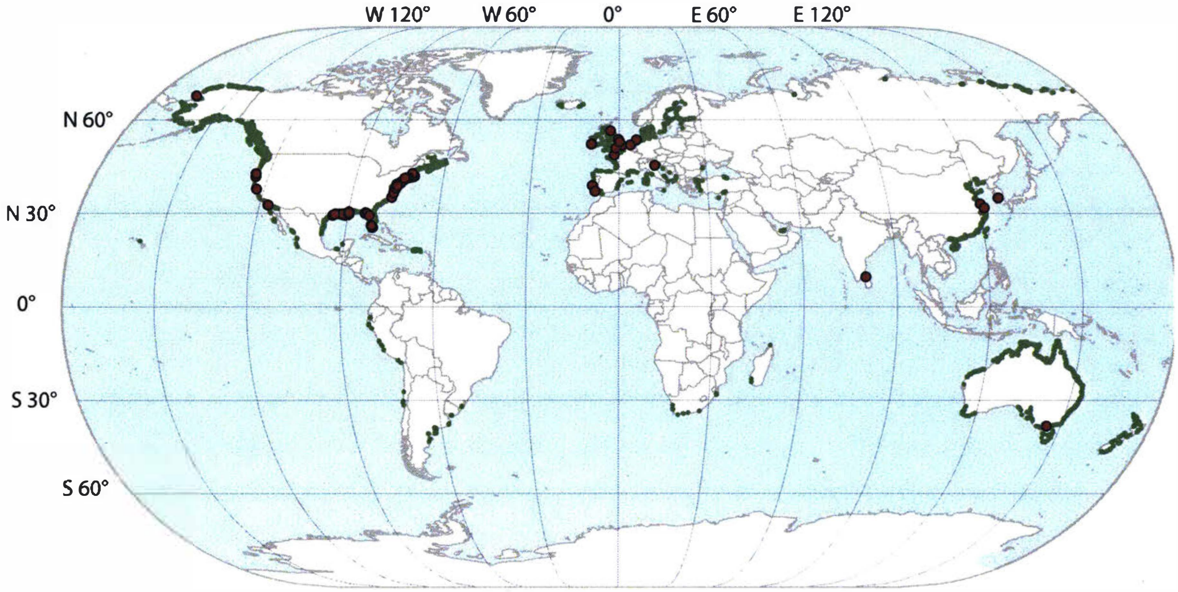

Figure 2.1 Locations of major research (red circles) on the effects of storms on salt marshes. Global marsh extent is indicated in green (Mcowen et al., 2017). For a full list of research locations, please see http://arcg.is/1CCuXj.

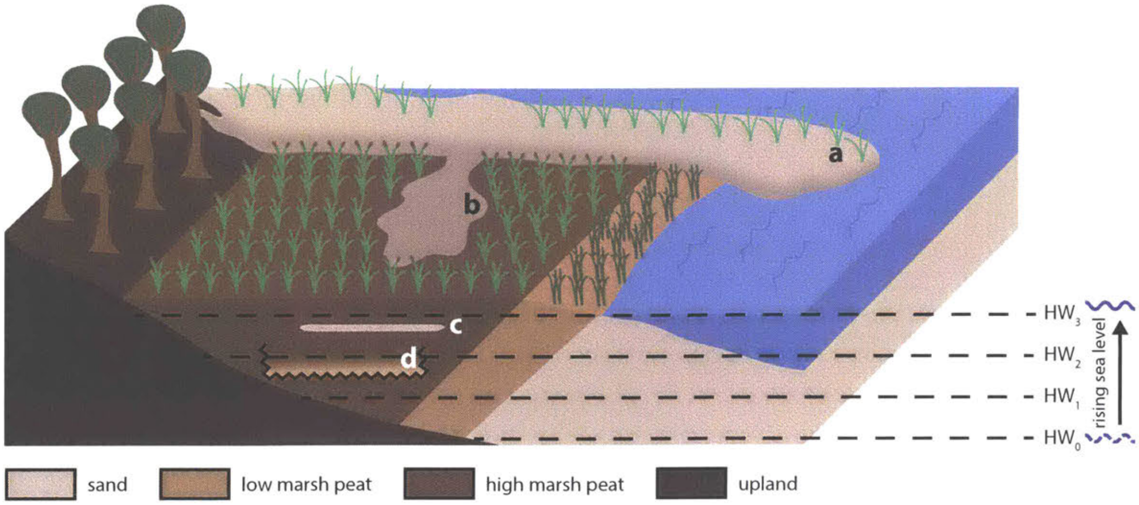

Figure 2.2 Theoretical structure of a salt marsh based on Redfield's bi-directional model of salt marsh evolution (Redfield, 1972), including a coastal barrier *(a)*. As sea level rises, the salt marsh spreads over both sand and upland through accumulation of sediment. Storm waves can overtop the barrier, leaving both present *(b)* and past *(c)* sandy overwash deposits in the marsh. Evidence of erosion *(d)* may also be seen.

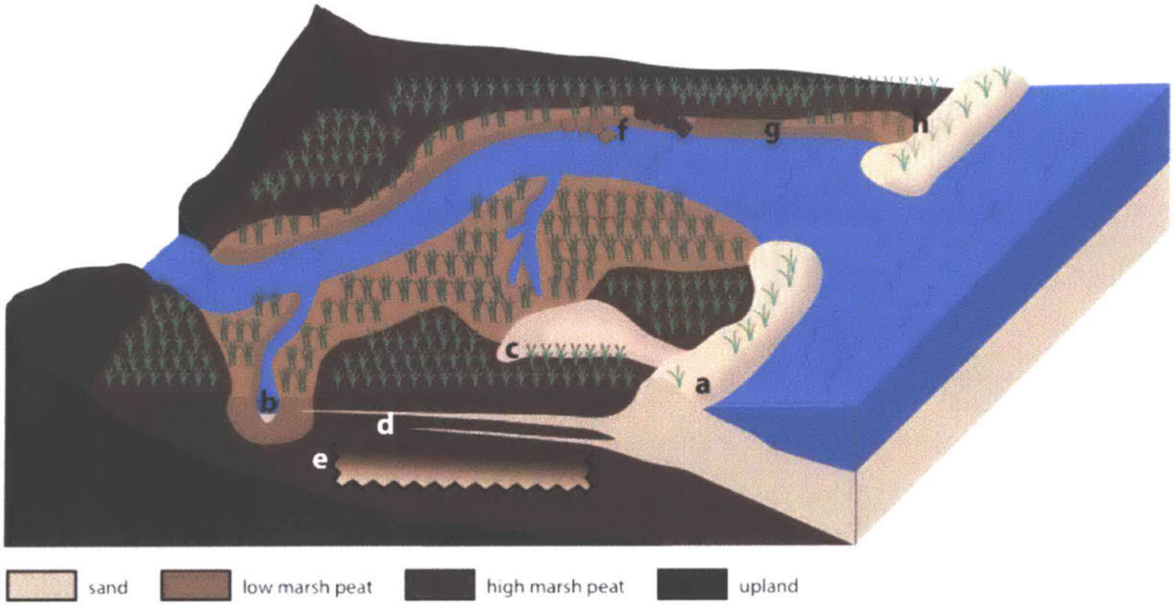

Figure 2.3 Theoretical structure of a salt marsh, including a coastal barrier (a) and channels (b). Impacts of storms on marshes exist along a spectrum based on a variety of factors, including intensity, circumstance, storm track, and marsh structure. Depositional features, such as present (c) and past (d) sandy overwash deposits, can occur concurrently with erosional features, such as stratigraphic evidence (e), edge erosion (f), slumping (g), and vegetation plucking (h).

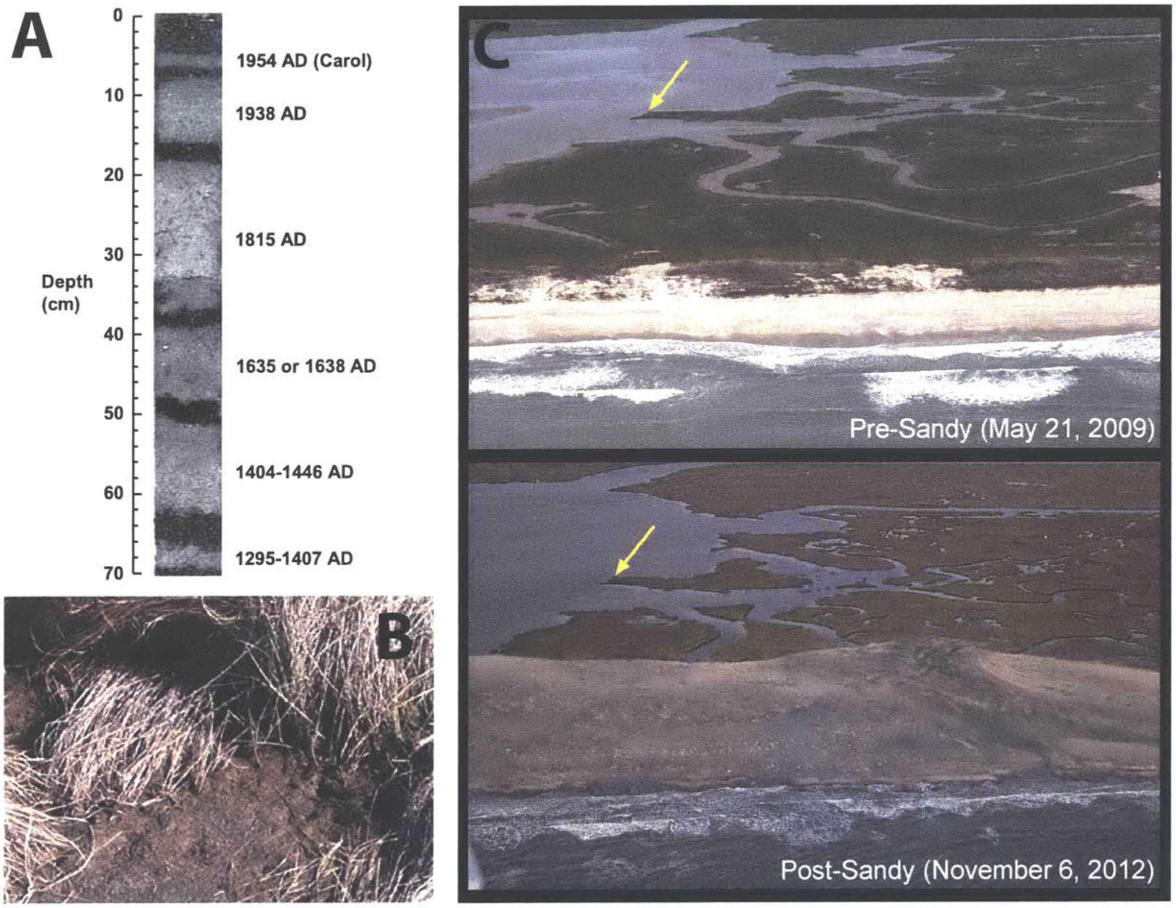

Figure 2.4 Field photos of various depositional impacts of storms on marshes. *A)* Storm-induced overwash deposits from Succotash Marsh, East Matunuck, RI (Cheung et al., 2007; Donnelly et al., 2001a). *B)* Example of sediment deposited on the marsh after Hurricanes Katrina and Rita (Turner et al., 2006). *C)* Aerial photos of overwash deposits left by Hurricane Sandy in Assateague Island, VA (Sopkin et al., 2014).

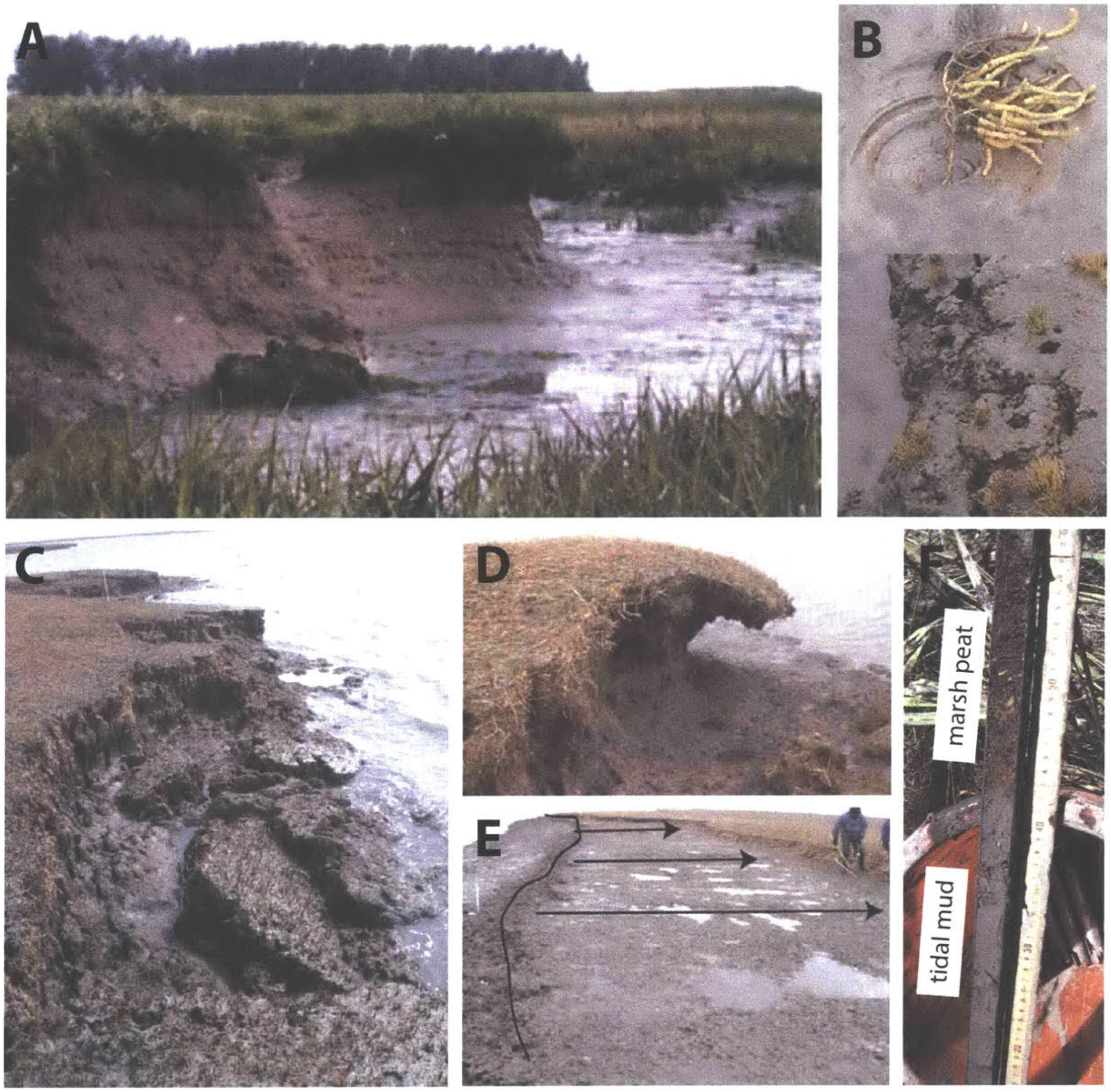

Figure 2.5 Field photos of various erosional impacts of storms on marshes. *A)* Eroding cliffs in the Westerschelde, the Netherlands (van de Koppel et al., 2005). *B)* Example of *Salicornia spp.* causing massive bank erosion in Tillingham, Essex, UK (Möller, 2012). *C-E)* Different kinds of marsh erosion (slumping, undercutting, and root scalping, respectively) in the Virginia Coast Reserve (Fagherazzi et al., 2014). *F)* Stratigraphic evidence of salt marsh peat overlain by tidal mud after a proposed erosional event in Sea Breeze Marsh, New Jersey (Nikitina et al., 2014).

Figure 2.6 Evidence of erosional (sharp contact with tidal mud and transition back to peat) and depositional (medium-grained sand overwash) features in the same core from Round Hill Beach, Dartmouth, MA.

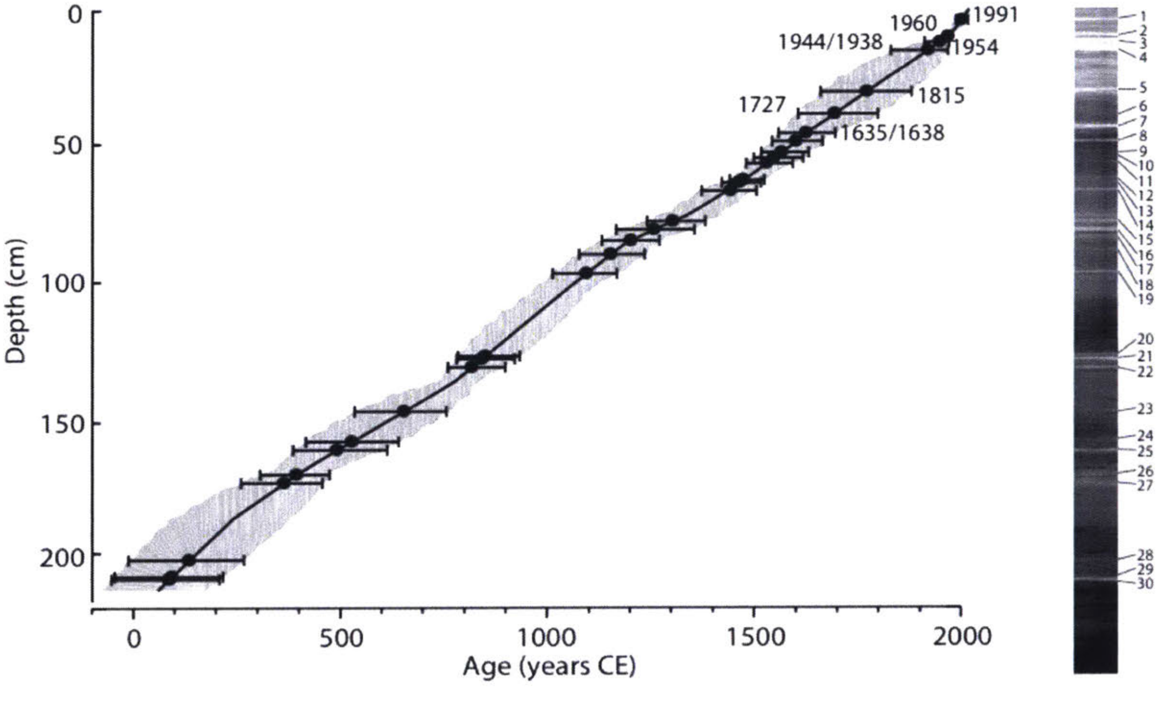

Figure 2.7 Evidence of continued storm activity and marsh persistence over the past 2,000 years from a salt marsh in Mattapoisett, MA (modified from Boldt et al., 2010). *Left,* radiocarbon-derived age model (gray) for 30 identified storm-induced overwash events (black circles, with uncertainties). *Right,* radiograph imagery identifying storm-induced overwash events.

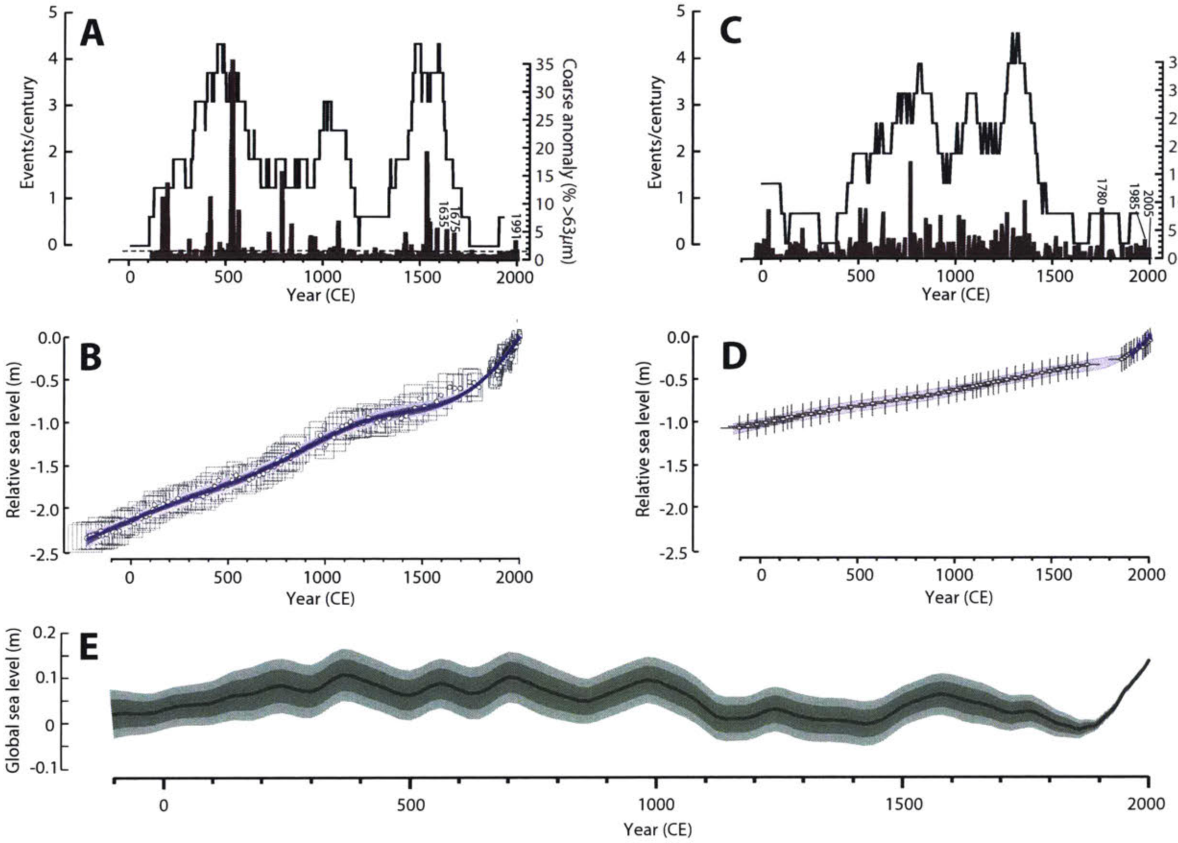

Figure 2.8 Though storminess has fluctuated over the past 2,000 years, sea level has remained relatively stable prior to the Industrial Revolution. *A)* Storm record for Salt Pond, Falmouth, MA, where peaks in coarse anomaly indicate a storm deposit (Donnelly et al., 2015). *B)* Relative sea-level reconstruction from East River Marsh, Guilford, CT, from salt marsh sediment dates and tide-gauge records (Kemp et al., 2015). *C)* Storm record for Mullet Pond, Apalachee Bay, FL (Lane et al., 2011). *D)* Relative sea-level reconstruction from Nassau Landing, FL, from salt marsh sediment dates and tide-gauge records (Kemp et al., 2014). *E)* Global sea-level curve for the past 2,000 years from statistical meta-analysis of proxy relative sea-level reconstructions and tide-gauge data (Kopp et al., 2016).

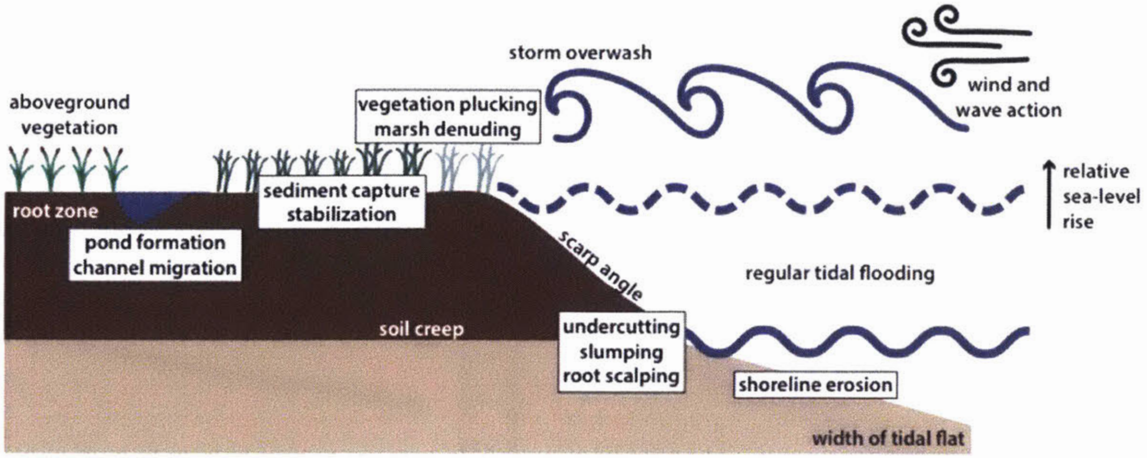

Figure 2.9 Diagram of different processes discussed in text related to storms that impact marsh stability.