Dynamic interactions between coastal storms and salt marshes: a review

Nicoletta Leonardi (a*), Iacopo Carnacina (b), Carmine Donatelli (a), Neil Kamal Ganju (c), Andrew James Plater (a), Mark Schuerch (d), Stijn Temmerman (e)

* Corresponding author nicleona@liverpool.ac.uk

(a) University of Liverpool, Department of Geography and Planning, 74 Bedford St S. Liverpool, UK

(b) Liverpool John Moores University, Department of Civil Engineering, Peter Jost Enterprise Centre, Byrom Street, Liverpool, L3 3AF

(c) U.S. Geological Survey, Woods Hole Coastal and Marine Science Center, MA 02543, USA

(d) Cambridge Coastal Research Unit (CCRU) Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, United Kingdom

(e) Ecosystem Management Research Group, University of Antwerp, Universiteitsplein 1, 2610 Wilrijk, Belgium

Abstract

The action of storms, and associated large waves and inundation depths, can strongly alter horizontal and vertical salt marsh dynamics in the immediate after-storm period, as well as in the longer term. This manuscript reviews the progresses made in the understanding of the dynamic interactions between coastal storms and salt marshes, including the dissipation of extreme water levels and wind waves across marsh surfaces, the geomorphic impact of storms on salt marshes, the preservation of hurricanes signals and deposits into the sedimentary records, and the importance of storms for the long term survival of salt marshes to sea level rise. Salt marshes are effective in dissipating wave energy, and storm surges, especially when

the marsh is highly elevated, continuous, and more than 10km wide. This buffering action, is very effective during moderate storms, but less efficient for long storms lasting more than one day; for this reason the use of hybrid approaches, combining continuous marshes with engineered defence structures is recommended for coastal protection. From a morphological point of view, our considerations highlight the necessity to focus on the indirect long term impact that large storms exerts on the whole marsh complex rather than on sole after-storm periods. Storms can cause tidal flats deepening which in turn promotes wave energy propagation, and exerts a long term detrimental effect for marsh boundaries even during calm weather. On the other hand, when a violent storm causes substantial erosion but sediments are redistributed across nearby areas, the long term impact might not be as severe as if sediments were permanently lost from the system, and the salt marsh could easily recover.

1. Introduction

1.1 Changing storm activity

Many areas are experiencing a change in both extreme and mean storm conditions as a consequence of a changing climate (e.g. Zhang et al., 2000; Webster et al., 2005; Bacmeister et al., 2016). For example, according to the Intergovernmental Panel on Climate Change (IPCC, e.g. Solom et al., 2007; Pachauri et al., 2014) it is virtually certain (99-100% probability) that the intensity of cyclone activity has increased in the North Atlantic since 1970, even if there is low confidence that the long term changes are robust. In terms of extremes, it is likely (66-100% probability) that extreme sea levels such as the ones experienced during storm surges have increased since 1970 on a global average. The latter trend has been mainly attributed to an increase in mean sea level even if more studies are necessary to fully separate the effect of global mean sea level rise from the effects of more local modifications to the coastal systems (e.g. Pachauri et al., 2014). Finally, it is also likely that there are more land regions where the number of heavy precipitation events has increased than where it has decreased.

Evaluations of future increases in storms and hurricanes activity are complex, and with large uncertainties. For example, a statistical correlation has been found between the power dissipation index of hurricanes (i.e. an index combining intensity, frequency and duration of hurricanes) and Atlantic Sea Surface Temperature (SST) (e.g. Vecchi et al., 2008). Based on this relationship and taking into account hurricanes activity since 1950, as well as future SST projection, there should be a 300% increase in hurricanes activity by the late 21st century. However, a statistical correlation has been also found between the power dissipation index and the Atlantic sea surface temperature relative to the Tropical mean sea temperature; if the latter relationship is considered, the projected change in hurricane activity by 2100 would be around 25%, which is modest with respect to the estimation above (Vecchi et al., 2008). Projections about the future of hurricanes activity might get even more complicated when looking at the longer term. Mean air temperature, Atlantic SST and the unadjusted hurricanes count all show a marked increase since the late 1800; however, when the raw hurricane count is adjusted for the storms which were not counted during the pre-satellite era due to technology, and ship track density limitations, no significant increase is observed (e.g. Vecchi et al., 2008).

Figure 1 illustrates model results in relation to the 21st century changes in Emmanuel's (1995) wind maximum potential intensity (MPI_V), the increase of which is generally associated with an increase in storms activity and intensity (Vecchi and Sobel, 2007). Results refer to the IPCC-AR4 Scenario A1B for the period from June-November. The MPIv index increases over most of the northern hemisphere and tropical zone of the southern hemisphere, but there are also large areas particularly in the southern hemisphere indicating decreases. The regions where the MPI_V decreases are associated with a relative minimum in SST (e.g. Sobel et al., 2002).

On a regional scale, for instance, by using a barotropic type surge model and global conditions representative of the IPCC A2 SRES scenarios between 1961-1990 and 2071-2100, it was shown that storm surge extremes may also significantly increase along most of the North Sea coast toward the end of this century (Woth et al., 2006). Recent results from ensemble simulation runs using Regional Climate Models for various locations in the United States (Jiang et al., 2016) also support the hypothesis of variations in future storm pattern; specifically, they predict shorter storm durations, longer inter-storms periods, and higher storms intensities.

In spite of the abundance of studies in relation to climatic projections and past trends, many challenges are still present, especially for the monitoring of coastal zones, due to limitations of some current modelling and field practice frameworks. For instance, the retrieval of waves and winds in the coastal areas is not yet as mature as sea level measurements, and the development of a wider applicability of altimetry techniques could be relevant for the simultaneous monitoring of wave height, wind speed and sea levels. In this context, Liu et al. (2012) showed the potential usefulness of the 1-Hz along-track altimetry data for the description of shelf areas, and Passaro et al., 2015 showed that estimations of wave height form ALES (Adaptive Leading Edge Sub-waveform retracker) were better correlated to buoy data than processed products. Such techniques could be coupled to standard modelling, and field data approach to build a more comprehensive and homogeneous database for the study of these coastal ecosystems

1.2. Pressures on salt marsh ecosystems

Salt marshes are important coastal ecosystems frequently fringing the interior of estuaries and bays, and establishing in low-energy inter-tidal zones. Due to their location and vegetated surfaces, salt marshes offer several ecosystem services. For example, their value for buffering against the impact of storms has been estimated up to 5 million USD per km^2 in the United States (e.g., Costanza et al., 2008), and 786 million GBP per year for UK marshes (UK

National Ecosystem assessment, 2011; Foster et al., 2013; Moller et al., 2014). Indeed, in recent years, salt marsh conservation and restoration projects are increasingly adopted as part of coastal and estuarine flood defence programs, based on the concept of "living shorelines" or "nature-based solutions" for flood defence (e.g., Temmerman et al., 2013; Fagherazzi, 2014).

Apart from flood protection, other salt marsh services include the storage of sediments, pollutants, nutrients, as well as of large amounts of carbon at a geological time scale (e.g. Mudd, et al., 2009; Kirwan and Mudd, 2012; Pendleton et al., 2012). They are also the natural habitat of many plants and animal communities, and offer a place for recreational and touristic activities (e.g. Barbier et al., 2011).

The long-term persistence of salt marshes appears related to the maintenance of a delicate balance between sediment and nutrient inputs, and external agents such as wave energy, storm surges, tidal inundation, and sea level rise (e.g. Spencer et al., 1998; Plater et al., 1999; van de Koppel et al., 2005; Deegan et al., 2012; Fagherazzi et al., 2012; Kirwan et al., 2016; Leonardi et al., 2016). Figure 2 represents a sketch of some of the main physical and ecological processes acting on a salt marsh. This includes, for instance, the exchange of sediments between the tidal flat and the marsh platform, biomass production and sediment deposition on the marsh platform promoting vertical accretion, and possible erosion/ progradation of the marsh edge. Ultimately, the survival of salt marshes has been related to a sediment budget problem (Ganju et al., 2017).

Salt marshes have been found to be extremely vulnerable, and large salt marsh losses have been documented worldwide. For instance, for areas in the south west of the Netherlands and the Wadden Sea, marsh edge erosion rates up to 4 m/yr have been observed, in spite of vertical accretion rates in balance with sea level rise (e.g., Bakker et al., 1993). In England and Wales salt marsh areal loss has been estimated to be around 83 ha yr^{-1} (Environment Agency, 2011; Foster et al., 2013), 105 ha yr^{-1} for the period in between 1993 and 2013 (Pye and French, 1993), and is projected to be 349 ha yr^{-1} for the period between 1998 and 2048 (Lee, 2001). In the Greater Thames area, the erosion was estimated to be around 25% of the total area present in 1973 (Cooper et al., 2009), while in the Solent (UK) 40% of the total salt marsh area present in 1971 was eroded between 1971 and 2001 (Cope et al., 2008). Erosion up to 80 cm/yr has been recently measured in the northern part of the Venice Lagoon (e.g., Bendoni et al., 2016). For the East Coast of the United States, in Plum Sound and the Virginia Coast Reserve, salt marsh boundary erosion rates ranged from a couple of cm up to 3 m/yr over a 7-year measuring period (Leonardi and Fagherazzi, 2014, 2015). In Barnegat Bay, New Jersey, USA, erosion rates from 1930 to 2007, and from 2007 to 2013, were similar, with around half of the marsh area that fringes the interior of the bay eroding less than 0.5 m/yr, the other half displaying erosion rates up to 2 m/yr, and only a 3 percent eroding faster than 2 m/yr (Leonardi et al., 2016b). A recent global analysis on salt marsh erosion and wave measurements by Leonardi et al., 2016a revealed that most of salt marsh deterioration is caused by moderate storms of a monthly frequency while intense hurricanes contribute to less than 1% to long term salt marsh erosion rates.

The action of storms and associated wind waves and storm surges can strongly alter both horizontal and vertical salt marsh dynamics in the immediate after-storm period, as well as in the long term, by affecting erosion/ deposition, and sediment import/ export in salt marshes and surrounding areas. Furthermore, storms generate serious flood risks in low-lying and highly populated coastal zones. For these reasons, and especially under a climate change perspective, it is important to understand the reciprocal interaction between storms and salt marshes. This manuscript aims to review progresses made in the understanding of salt marsh-storms interactions, and is organized as follows: we first review storm surges (section 2), and wind waves (section 3) attenuation across salt marshes. In section 4 we focus on the impact of storms on salt marshes morphology, and on the preservation of hurricanes signals into the sedimentary records. Section 5 focuses on the impact of storms on the marsh sediment budget. Section 7 discusses how the interplay between storms occurrence and sea level rise influences salt marsh survival. A set of discussions and conclusions is finally presented.

2. Storm surge attenuation by salt marsh

Vegetated coastal ecosystems, in particular salt marshes and mangroves, are increasingly valued for their protective function against storm surge flood risks. This is illustrated by the rapidly increasing number of scientific studies on storm surge attenuation by salt marshes and mangroves, and growing societal interest in so-called ecosystem-based or nature-based flood defence programs, i.e. marsh and mangrove restoration projects aiming to mitigate storm surge flood risks (e.g. Cheong et al., 2013; Sutton-Grier et al., 2015; Temmerman et al., 2013). The effectiveness of storm surge height reduction behind marshes is commonly quantified as the attenuation rate in cm of surge height reduction per km distance that the storm surge has propagated over marshes (e.g. Wamsley et al., 2010). However, mechanistic insights in the various factors that control this attenuation rate are rather fragmentary presented in recent literature, which may be one reason why real life implementations of nature-based flood defence are relatively scarce so far (Temmerman et al., 2013). Here in this section, we review the most recent scientific insights.

Although anecdotal evidence of storm surge protection behind large marshes is presented in early reports (e.g. Lovelace, 1994; USACE, 1963), systematic evidence and mechanistic studies only started to accumulate over the past 10 years. In particular major coastal flood disasters caused by the Indian Ocean tsunami in 2004 and hurricane Katrina along the US Gulf coast in 2005 boosted worldwide scientific and public awareness of the potentially important protective role of mangroves (Danielsen et al., 2005) and salt marshes (Day et al., 2007). A first important source of empirical evidence comes from studies that analysed the reduction of damage or human deaths as a function of marsh or mangrove width between coastal settlements and the open sea. For example, Costanza et al., 2008, performed an extensive analysis of 34 major hurricanes that hit the US Atlantic and Gulf coasts since 1980, demonstrating that damage to properties was significantly reduced behind marshes, and that a loss of 1 ha of marshes would increase average storm damages by 33000 USD. For mangroves, Das and Vincent, 2009, showed that villages that were hit by a tropical cyclone surge in India experienced significantly lower numbers of deaths when they had wider mangroves between them and the coast.

A second source of empirical evidence, are direct measurements of storm surge height reduction within and behind large marshes. Data reported in the literature are especially from the US Gulf coast (e.g. Lovelace, 1994; McGee et al., 2006; USACE, 1963), which is regularly hit by hurricane storm surges and where huge marshlands of several tens of kilometres wide exist in the Mississippi delta and in back-barrier tidal lagoons. A rule of thumb, derived from these reports, is that peak surge levels are reduced by on average 1 m for every 14.5 km that the surge has propagated over marshes (i.e. ~6.9 cm/km), with large variations between individual hurricane events as much as from 1 m surge reduction per 4 km of marshland (i.e. 25 cm/km) to only 1 m per 60 km (i.e. ~1.7 cm/km) (based on data compilation by Wamsley et al., 2010). This large variation in empirical data indicates that storm surge propagation and attenuation over marshes is complex and that the effectiveness of surge height reduction largely varies depending on specific storm characteristics, marsh ecosystem properties and larger-scale coastal landscape settings. For a macro-tidal estuarine marsh in the SW Netherlands, Stark et al., 2015, presented a large dataset ranging from regular tides to storm surges, showing that the magnitude of tidal and storm tide attenuation strongly depends on the marsh inundation depth and the dimensions of channels that dissect the marsh landscape. Maximum attenuation rates of up to 5 cm/km were measured over marsh transects with smaller channels and for marsh inundation depths of 0.5-1 m, while attenuation rates decreased for shallower and deeper inundation events, including storm surges. For mangroves in Southern Florida, hurricane surge attenuation rates of 9.4 cm/km have been measured over relatively continuous mangrove forests, and slightly lower rates for mangroves along a river corridor (Krauss et al., 2009).

Hydrodynamic modelling studies are a third line of evidence and important research tools to disentangle the various factors controlling the effectiveness of storm surge height reduction by wetlands. Comparing the rapidly growing number of publications in the past few years (see below), we can generally make a distinction between two main mechanisms that depend on the larger-scale landscape setting: (1) storm surge attenuation within and behind continuous marshes is basically due to *friction* exerted by the marsh vegetation and soil on the landward propagating storm surge (e.g. Sheng et al., 2012); and (2) storm surges propagating through an estuarine or deltaic channel or embayment can be attenuated due to lateral flooding and *water storage* on marshes adjacent to that channel (e.g. Smolders et al., 2015). The frictional effect (1) is called here *within-marsh attenuation* and the water storage effect (2) *along-channel attenuation*. Ultimately both take place in most real cases, as marshes and mangroves are typically dissected by networks of tidal channels, implying that surge propagation along these channels is affected by both frictional and lateral water storage effects (e.g. Stark et al., 2016).

Modelling studies, either for idealized marsh geometries (e.g. Loder et al., 2009; Sheng et al., 2012; Temmerman et al., 2012) or for specific more realistic landscape settings (e.g Resio and Westerink, 2008; Wamsley et al., 2010; Wamsley et al., 2009; Zhang et al., 2012), demonstrate that the effectiveness of storm surge attenuation depends on specific properties of (1) the storm forcing (such as storm intensity, duration, forward moving speed, storm track), (2) the marsh ecosystem (such as marsh size and soil elevation, vegetation density and continuity, within-marsh channel dimensions), and (3) larger-scale coastal landscape settings (such as off-shore bathymetry, shoreline shape, open coast, back-barrier, estuarine or deltaic setting, levees or dikes behind marshes, etc.).

In terms of effects of storm characteristics, attenuation rates are generally higher for shallow to moderate storm surge levels and decrease for more extreme storm surges that deeply submerge the marshes, as within-marsh frictional effects on the storm surge attenuation relatively decrease with increasing water depth on the marsh (Lawler et al., 2016; Resio and Westerink, 2008; Sheng et al., 2012; Wamsley et al., 2010). Similarly, marshes with a higher soil elevation are more effective in attenuating higher storm surges (Loder et al., 2009; Smolders et al., 2015; Stark et al., 2016), implying that marshes with a sediment accretion deficit and consequently decreasing surface elevation relative to rising sea level, lose their effectiveness for storm surge protection (Temmerman et al., 2012; Wamsley et al., 2009). The protective function also decreases for storms with a longer duration, as the surge has more time to propagate landward and to fill up the whole marsh area (Resio and Westerink, 2008; Wamsley et al., 2010). Similarly, storm surge attenuation behind wetlands is more effective for storms with a faster forward moving speed (Hu et al., 2015; Liu et al., 2013; Sheng et al., 2012; Zhang et al., 2012).

In terms of marsh ecosystem properties, obviously wider marshes, of at least 10 or more kilometres wide, are more effective, as well as marshes with a higher soil elevation, as explained above. Effectiveness of storm surge attenuation also markedly increases when marsh vegetation is simulated that exerts more friction (Hu et al., 2015; Loder et al., 2009; Sheng et al., 2012), and with higher ratios of marsh vegetation to open water (Temmerman et al., 2012; Zhang et al., 2012), implying that patchy patterns of gradual marsh degradation, which are observed in several marshes around the world (e.g. Schepers et al., 2017), lead to loss of their storm protection function (Temmerman et al., 2012). The dimensions of channels, which typically cut into marshes, play a major role: simulations with deeper or wider channels, show that landward flood propagation through the channels is facilitated leading to less storm surge height reduction (Stark et al., 2016; Temmerman et al., 2012). (Stark et al., 2016) showed for a marsh in the SW Netherlands that the effects of within-marsh channel dimensions, marsh platform elevation and storm surge height can be combined into one parameter predicting variations in attenuation rate from 0 to nearly 25 cm/km, i.e. as a function of the ratio between the water volume that is present at high tide above the marsh platform and the total water volume above the platform and in the channels (Figure 3).

Finally, the precise rates of storm surge attenuation by marshes depend on case-specific larger-scale landscape settings. For example, significant storm surge attenuation by wetlands is simulated for the several tens of kilometres wide marshes in the Mississippi deltaic area (Barbier et al., 2013; Hu et al., 2015; Resio and Westerink, 2008; Wamsley et al., 2010; Wamsley et al., 2009) and wide mangrove systems in Southern Florida (Liu et al., 2013; Zhang et al., 2012), while more moderate to limited contribution of marshes to storm surge protection are simulated for marshes along the Chesapeake Bay (Haddad et al., 2016), and back-barrier lagoon systems of Jamaica Bay, New York (Marsooli et al., 2016) and the Delmarva coast (Lawler et al., 2016). For the case of marshes occurring along the funnel shaped Scheldt estuary in the Netherlands and Belgium, simulations show that marshes of the same size but located more upstream are more effective in attenuating storm surges propagating upstream along the estuarine channel (Smolders et al., 2015). Man-made structures, in particular coastal defence structures such as levees and dikes behind marshes, may cause the setup of water levels against these structures and hence limit the storm surge attenuating effect of marshes in front of such structures, as shown for example in simulations for the 2005 hurricanes Katrina and Rita in the Mississippi delta (Wamsley et al., 2009). Similarly, for a marsh in the SW Netherlands, (Stark et al., 2016) showed blockage effects and setup of peak surge levels against dikes behind the marsh, and that the marsh width needs to be at least 6-10 km to avoid such blockage effects and to maximize the rate of storm surge attenuation.

Summarizing, we may say that empirical data and modelling studies demonstrate effective storm surge height reduction behind large (at least 10 km wide), high-elevated and continuous marshes with few or small channels, and by marshes located more inland along funnel-shaped estuarine and deltaic channels, especially during moderate storm surges, but less effectively during extreme storms that continue for more than a day. The latter implies that solely relying on nature-based flood defence in populated low-lying coastal and estuarine areas is commonly not advised. Instead so-called hybrid approaches, combining conservation and restoration of continuous marshes with engineered defence structures, are increasingly developed and implemented worldwide (Sutton-Grier et al., 2015; Temmerman and Kirwan, 2015; Van Wesenbeeck et al., 2014), e.g. on large scales in the Mississippi delta (CPRA, 2012) and Scheldt estuary in Belgium (Meire et al., 2014). An important argument for such hybrid approaches, is that they are more cost-effective as they do not only provide flood risk mitigation but also other valuable ecosystem services, and marshes and mangroves build up land with rising sea levels, making them self-adaptive defences in face of global change (Temmerman et al., 2013).

3. Wave energy dissipation by salt marsh

Salt marshes are natural wave energy dampers (e.g. Moeller, 2006; Moeller et al., 2014; Spencer et al., 2016). For shallow water, the dissipation of wave energy is related to the viscous boundary layer friction, permeability, and viscous layer of the seabed (e.g. Le Hir et al., 2000). Over a salt marsh the bed-roughness might be considered as the result of two contributions, i.e., vegetation induced friction, and topographic variations over the marsh surface (Hartnall, 1984; Dijkema, 1987; Pethick, 1992). It is also recognized that wave attenuation is affected by plant characteristics such as geometry, stem density, spatial coverage, and stiffness, and that hydrodynamic conditions such as water depth, wave period, and wave height are relevant.

The pioneer work conducted in relation to the interaction between wave oscillatory motion and vegetation has been mainly aimed at quantifying wave attenuation within vegetation (e.g. Fonseca and Cahalan, 1992; Kobayashi et al., 1993). Standard approaches for the prediction of wave energy attenuation by vegetation, are based on the equation for the conservation of energy where the local flow field is estimated using linear wave theory. This approach, while reasonable, might be compromised if the vegetation substantially modifies the flow field. An alternative approach was proposed by Kobayashi et al., 1993, for the submerged vegetation case, for which the problem was formulated by using the continuity and linearized momentum equations for the regions over and within the vegetation canopy. By considering the effect of vegetation in terms of drag coefficient, introducing an unknown damping coefficient, and linearizing the friction term, they obtained an analytical solution for small monochromatic waves whose amplitude has been found to decay exponentially in the propagation direction. Koch and Gust, 1999, suggested that the periodic motion of seagrass blades also promotes mass transfer between the meadow, and the overlying water column. Luhar et al., 2010, demonstrated that even when the motion is driven by a purely oscillatory flow, a mean current in the direction of wave propagation is generated within the meadow. This current is forced by non-zero wave stress similar to the streaming observed in wave boundary layers, and the current is approximately four times the one predicted by the laminar boundary layer theory.

Among others, the dissipation of wind waves has been found to increase with increasing relative wave height, i.e. the ratio between wave height and water depth (e.g. Le Hir et al., 2000). Field measurements in England support this relationship, and show that for the analyzed field sites the relationship was mainly valid for relative wave height ratios above a critical lower limit and below 0.55; when the ratio is below the lower limit, waves become too small (or water depth to high) to have an effective vegetation-wave interaction; however, when the relative wave height is > 0.55, the relationship between wave dissipation and relative wave height becomes invalid because the maximum dissipation capacity of vegetation has been reached (Moeller, 2006).

Field measurements of wind waves over sand flat to salt marsh cross-shore transects, also suggest that wave energy dissipation over salt marshes is significantly higher (up to 82% of the energy is dissipated) then on sand flats (29% dissipation) (Moeller, 1999, Figure 4). While part of the wave damping effect is attributable to the reduction in water depth on the higher elevated marsh platform (relative to the lower elevated tidal flat), the energy dissipation over salt marshes is up to 50 % stronger even under similar water depth conditions, which proves the important role of vegetation in the dissipation process.

Another parameter controlling the rate of energy dissipation is the ratio between water depth and plants height (submergence ratio, i.e. Yang et al., 2012): the smaller this ratio, the larger the wave attenuation rate (Augustin et al., 2009; Paul et al., 2012). Wave damping is also strictly related to the relative motion between fluid and plants, which depends on plants stems flexibility, stems diameter, and stems length. Stems with relatively high stiffness tend to follow an oscillatory swaying movement throughout the wave cycle, while more flexible stems tend to bend in the dominant direction of the orbital flow with a high angle which results in canopy flattening, and loss of flow resistance (whip-like movement) (i.e. Luhar and Nepf, 2016; Mullarney and Henderson, 2010; Paul et al., 2016). The movement can switch from swaying to whip-like as the wave energy increases (for example during storm periods) (e.g. Luhar and Nepf, 2016). Increasing plant flexibility reduces the damping of waves as stems tend to move with the surrounding water (Bouma et al., 2005; Elwany et al., 1995; Riffe et al., 2011), however stiff plants can break if hydrodynamic loads are higher than a critical value (Heuner et al., 2015; Puijalon et al., 2011; Silinski et al., 2015). The dissipative contribution given by flexible plants is low, but their deformed configuration (flattening) under high orbital velocities ($\geq$ 74 cm s^{-1}) helps to stabilize surface sediments (Neumeier and Ciavola, 2004; Peralta et al., 2008). In contrast, more rigid plants can reach breakage (from medium orbital velocities), increase turbulence and sediment scouring around the stems (reference) and cause more erosion due to increased shear stress values (Spencer et al., 2016).

During extreme storms and associated storm surges, waves and water levels are the highest, and hence it can be questioned whether, under these conditions, salt marshes still play a considerable role in wave attenuation. Large scale laboratory experiments (Moeller et al., 2014) confirm that, even under extreme conditions, wave energy dissipation by salt marshes is very high, and up to 60% of this wave energy reduction is attributed to the presence of vegetation. As the storm progresses, vegetation stems are gradually flattened and the wave dissipation decreases, but as suggested by previous work (e.g. Neumeier and Ciavola, 2004; Peralta et al., 2008), the flattening of vegetation promotes the stability of the substrate. Paul et al., 2016 tested different artificial vegetation elements to measure drag forces on vegetation under different wave loading. They found that stiffness and dynamic frontal areas (e.g. frontal area resulting from bending) are the main factors determining drag forces, while the still frontal area of plants dominate the force-velocity relationship only for low orbital velocities. Rupprecht et al., 2015 presented biophysical properties of species commonly found in NW European salt marshes, and compared the performance of two methods for the non-destructive assessment of aboveground biomass during storms, i.e. measurements of light availability within vegetation canopy, and side-on photography vegetation, with the latter being found more accurate. In the same experiments as reported by Moeller et al. 2014, Rupprecht et al., 2017, tested the effectiveness of two typical NW European salt marsh grasses (Puccinellia maritima, and Elymus athericus) under simulated storms an no-storms conditions. They found that under high water levels and long wave periods, within the flexible Puccinellia canopy the orbital velocity was reduced by 35%, while for the more rigid stems of Elymus, no significant changes in orbital velocity were found. Differently, under low water levels, and short wave periods, Elymus reduced near bed velocity more than Puccinellia. As expected, more flexible stems of Puccinellia were able to more easily survive the more severe conditions, while the more stiff Elymus plants were subject to structural damage.

4. Storms impact on salt marsh morphology

In comparison to other wetlands, and from a morphological point of view, salt marshes have been found to be more resistant to the impact of storms; this has been mainly attributed to the increased shear strength conferred to the soil by the presence of root systems which are deeper than in other coastal areas such as freshwater wetlands, and floating marshes (e.g. Morton and Barras, 2011). Nevertheless, the impact of storms on salt marshes can significantly vary depending on both storms and ecosystem properties, and can translate into various geomorphic signatures. Some of these signatures have contrasting effects in relation to the long term resilience of the ecosystem. Apart from erosion and deposition processes, affecting marsh platform, marsh shoreline, as well as surrounding tidal flats, storms can also deform the marsh surface trough subsurface processes, and incision (e.g. Morton and Barras, 2011). This section presents a summary of some of the main geomorphic impacts of storms on salt marsh ecosystems (Figure 5).

4.1 Incision

For salt marshes, ponds generated during storms are generally much smaller and less frequent with respect to brackish and freshwater marsh ponds; they also maintain a more amorphous shape (with no preferential direction) in comparison to the more elongated ponds frequently found in freshwater marshes (e.g. Barras, 2011). These ponds are more easily formed where the terrain is already lower, and strong wind driven currents can erode surface sediments (e.g. Morton et al., 2011). Ponds can then enlarge in time due to subsequent storms, and can also deepen leading to a loss of sediments from the marsh (e.g. Mariotti, 2016). In fact, once the ponds are formed, these can expand even if the rest of the marsh platform is able to keep pace with sea level, and wave action; enlarged ponds can eventually connect to tidal channels (e.g. Mariotti and Fagherazzi, 2013; Schepers et al., 2017).

When a pond is connected to channels, it can recover if its bed is higher than the limit for vegetation growth, or if the deposition rate is larger than the rate of sea level rise. When these conditions are not satisfied, the pond enlarges, becomes susceptible to edge erosion due to internally generated wind waves, and the eroded sediments can get lost through tidal channels (Mariotti and Fagherazzi, 2013). Therefore, depending on the action of biological processes, and sedimentation rates, the formation and enlargement of ponds can be irreversible, or reversible with ponds eventually recovering back to the surrounding marsh platform elevation (e.g. Mariotti and Carr, 2014; Mariotti, 2016).

Plucked marsh features (e.g. Barras et al., 2007) are erosional signatures consisting of irregular scours ranging from around 2 to 20 m which can be found in saline as well as intermediate or freshwater marshes when the mineral matter represents a high percentage of the substrate. Plucked marsh features can occur independently from the elevation with respect to mean sea level, as long as the shear stress is sufficient to incise the areas (e.g. Barras et al., 2007).

4.2 Erosion – surface erosion, and lateral erosion

The denudation of the marsh from the vegetation cover (also referred to as root scalping, e.g. Priestas et al., 2015) can affect areas of the order of kilometres, and occurs when currents and waves induced shear stress strip vegetated surfaces. The depth of denudation determines the chances and the rate of recovery of the affected areas. If the eroded areas remain above the permanent submerged location, and the root system is not completely destroyed, the denudated zones can recover during the following growing seasons, otherwise the denuded areas might convert to pond or bare tidal flats (e.g. Hendrickson, 1997). The erosion depth of the marsh platform can range from a few to several centimetres. For instance, Hendrickson, 1997, reported erosion rates of 6 cm after the occurrence of Hurricane Erin, and Opal, 1995 for salt marshes in St. Marks River, Florida. However, the erosion of the marsh surface doesn’t necessarily correspond to an elevation change as the deformation of the marsh platform trough subsurface processes, like compaction or soil swelling, can play an important role as well.

As a consequence of waves generated shear stress, the tidal flats in front of the marsh can deepen which indirectly impacts salt marsh survival, because of an increased depth in front of the marsh can increase wave energy and promote lateral erosion (e.g. Fagherazzi et al., 2006).

The lateral erosion of marsh shorelines has been found to be mainly dictated by the action of wind waves (e.g. Schwimmer, 2001; Marani et al., 2011; Leonardi et al., 2016a, b). For freshwater marshes, the lateral erosion during hurricanes can be up to 100s m; for salt marshes, while wave-induced lateral erosion is in the long term one of the main causes of deterioration, the lateral retreat occurring during hurricanes is relatively low due to the short, and impulsive nature of these events (e.g. Leonardi et al 2016a, b; Figure 6a). Based on a global dataset of salt marsh lateral erosion, and wave data it was found that the yearly retreat rate of marsh shorelines linearly increases with wave energy and a critical threshold in wave energy above which salt marsh erosion drastically accelerates is absent. Such critical threshold is instead more commonly found in sandy environments where erosion drastically increases once the sand dunes are over-washed. While the impact of hurricanes on salt marshes can be very strong, their low frequency and short duration lead to a relatively small effect and they contribute to only 1% of the erosion in the long term. On the contrary, moderate and frequently occurring storms with a monthly reoccurrence are the most dangerous for salt marsh survival (Leonardi et al., 2016a). It is then reasonable to assume that a storm impacting a stretch of shoreline at 90 degrees has a potential to erode salt marshes which is higher than a storm whose waves are parallel to the shore (e.g. Tonelli et al., 2010).

Finally, in regard to lateral shorelines dynamics, the intensity of wind waves has been found to also modify the shape of marsh boundaries; Leonardi and Fagherazzi, 2014, 2015 showed that the interplay between waves intensity and the spatial variability in marsh resistance determines the shape of marsh shorelines, as well as erosion rates predictability. The variability in erosional resistance is due to the presence of natural heterogeneities caused by different soil resistance and by the variety of ecological, and biological processes interesting different marsh portions. In case of low wave energy conditions, the presence of a variability in erosional resistance might lead to the unpredictable failure of large marsh portions with respect to average erosion rates, and to rough, and jagged marsh boundary profiles displaying high sinuosity values (e.g. Figure 6b, top panel). High-wave-energy conditions, while overall leading to a faster marsh deterioration, cause a constant and predictable erosion, and a smooth marsh boundary profile. A high occurrence of extreme events significantly smooths the marsh boundary, even if it doesn't strongly alter average erosion rates (Figure 6b). Finally, salt marshes subject to weak wave energy conditions are the most susceptible to variations in the frequency of extreme events (Leonardi et al., 2014, 2015).

4.3 Deposition

The occurrence of storms and hurricanes can be accompanied by the deposition of large amount of sediments. As an example, Hurricane Rita generated 4-5 m of storm surge, which resulted in a deposit 0.5m thick, and extending 500 m inland (e.g. Williams, 2009). Cahoon, 2003, 2006 presented a comprehensive set of measurements in regard to elevation changes following the impact of hurricanes at ten sites in the United States; he found deposition rates ranging from a few cm (e.g. 3 cm after Hurricane Emily, 1993, and Gordon, 1994 for salt marshes in North Carolina), up to around 30 cm (e.g. 28, and 20 cm after Hurricane Andrew, 1992, for salt marshes in Bayou Chitigue, and Old Oyster, Louisiana).

Depending on the net direction of sediment transport, deposits may be laid down over the salt marsh surface or translated seaward. Storms may not, therefore, necessarily leave behind distinct depositional units but instead increase the increment of tidal deposition through elevated suspended sediment concentrations and/or flow velocities (Stumpf, 1983), thus enhancing the usual mechanisms of settling during inundations or over-bank spilling in close proximity to creeks or the point of tidal ingress. Indeed, Turner et al. (2006) suggest that large storms increase the supply of mineral matter from offshore via tidal creeks, and have shown that, for Mississippi River salt marshes, the density of minerogenic sediments in salt marsh cores increases in concert with the occurrence of major hurricanes (Turner et al., 2007).

Deposition during storms is readily evidenced where breaching and flooding of the supratidal coastline occurs, e.g. washover deposits or fans. For example, Scileppi and Donnelly (2007) found that washover deposits on the Long Island coast correlate with landfalls of the most intense documented hurricanes, and that periods of increased and decreased landfall incidence can be evidenced in the back-barrier sediment record (cf. Liu and Fearn, 2000; Donnelly et al., 2001; 2004). Barrier overwashing during storms can also deposit lobes of sand and intermixed shells over back-barrier salt marshes, where shell beds may then be preserved in the sediment record as an archive of storm washover (Ehlers et al., 1993). Extensive washover deposits resulting from storms have also been found in a back-barrier setting along the Chenier Plain of Louisiana where the intensity of recent hurricanes influences the extent and grain size of the deposits (Williams, 2011).

It is less common for salt marshes to preserve depositional evidence of storms, or at least deposits that can readily be distinguished from the usual background of regular tidal deposition or, indeed, other extreme events such as tsunami (cf. Goff et al., 2004; Morton et al., 2007). Goodbred and Hine (1993) recorded the deposition of a tan to grey unit of clays, silt to very fine sand, and marine biogenic matter across Waccasassa Bay salt marshes in Florida following a 3 m storm surge. The deposit was made up of sedimentary material similar to that of the underlying marsh sediments, indicating a local origin. Proximity to tidal ingress had a significant influence on the thickness of the deposit, increasing from a few cm on the salt marsh surface to as much as 12 cm along creek margins. Generally, severe storms have the potential to deposit distinctive sand units that thin and fine in a landward direction over 100s of meters, that have a sharp basal contact with the underlying salt marsh deposits, and that contain marine microfossils (e.g. Morton and Sallenger, 2003; Turner et al., 2006; Williams, 2009). Such anomalous deposits are characterized using several criteria such as the extent of inundation, landward-thinning and/or landward-fining of the deposit, single or multiple particle size grading, and contained microfossil assemblage (Hawkes and Horton, 2012).

Similar, unconformable sand deposits can be found within the salt marsh sediment record of back-barrier estuaries along the Central Coast of California (e.g. Clarke et al., 2014) where their incidence is connected to barrier breaching and inundation during storms. In this case, high frequency variability in the particle size of such deposits in the back-barrier stratigraphy can be associated with ENSO-driven storms, but where the barrier breaching is most likely due to high river flow as opposed to coastal erosion during storms (Clarke et al., 2017).

Drawing on examples from the longer Holocene sediment record, Haggart (1988) examined the stratigraphic and sedimentary evidence of a tidal surge deposit in two open estuary settings in north-eastern Scotland. This micaceous, silty sand was deposited across pre-existing inter-tidal to perimarine environments, which then returned immediately following its deposition. The stratigraphic evidence is therefore indicative of a high energy environment affecting a wide range of coastal environments simultaneously, with a vertical range of 3.5-5.0 m. Detailed dating, particle size, and paleoecological data reveal this deposit to be marine in origin and virtually instantaneous in its deposition. Similar deposits of this kind are found in a number of estuarine and back-barrier settings in north-east Scotland (Smith et al., 2004) for which the timing, rarity, and run-up (as much as 25 m) are indicative of a tsunami rather than a storm surge. Information on storm-related sediment redistribution across the salt marsh surface can equally come from evidence other than stratigraphic, grain size or palaeoecological data. For example, Rahman et al. (2013) explored down-core trends in radioactive pollution to determine patterns of sedimentation in north-west England. A secondary increase in both ^{241}Am and ^{137}Cs activity in the upper 5-10 cm of salt marsh cores from the Dee was interpreted as the re-deposition of sediments eroded from the salt marsh edge, linked to a severe storm in 1990. In principle, the erosion and redistribution of historical pollutants in industrialized estuaries can also be revealed by the analysis of heavy metals or persistent organic pollutants.

In summary, storm deposits are more readily apparent in back-barrier salt marshes where coastal breaching and overwashing enable the landward penetration of coarse sediment lobes that then appear anomalous against the background of tidal mud deposition. Such deposits also have the potential to be found in more open estuary settings where the storm surge results in the landward transport of coarse marine sediment or increases the potential for the redistribution of eroded material onto the salt marsh surface. Identifying such deposits requires a multi-proxy approach to evidence not only the nature and dynamics of the depositional environment but also the age and origin of the sediments, particularly for reconstructing periods of increased and decreased storminess.

4.4 Deformation

Apart from surface processes of erosion, deposition, and incision, subsurface processes induced by soil compaction or groundwater flow are also an important consequence of storms and storm surges occurrence, and can lead to substantial deformation or changes in marsh elevation.

Soil compaction due to storm surge water is quite common; for instance, after hurricane Andrew, 1992, and for salt marshes in Bayou Chitigue, Louisiana, in spite of a 28 cm thick deposit, the total change in elevation was -5cm due to soil compaction (Cahoon, 2006). Similarly, for salt marshes in Cedar Island, North Carolina, the surface erosion due to Hurricane Felix, and Jerry was only -1cm, but the change in elevation due to soil compaction reached -18cm (Cahoon et al., 1999; Cahoon, 2006). Soil shrinkage or swell can be also caused by an alteration of water fluxes mainly induced by storm surge events. According to Hendrickson, 1997, soil shrinkage caused a 13 cm, and 8 cm lowering of the marsh platform for salt marshes in Florida after Hurricane Opal, 1995 and Erin, 1995 respectively. On the contrary, during Hurricane Alberto, 1994, soil swelling caused by the storm surge increase in water content, caused an increase in elevation of 13 cm for the salt marshes in Florida, (Cahoon, 2006).

5. Storms impact on salt marsh sediment budget

A salt marsh is defined not only through the vegetated marsh plain, but by the entire geomorphic complex. This complex includes the adjacent estuarine/marine seabed, tidal marsh channels, intertidal flats, marsh scarps, the marsh plain, and pools within the marsh plain. Though the salt marsh plain can accrete vertically through organic and inorganic sediment accretion, the geomorphic evolution of the other components is influenced by the inorganic sediment budget (e.g. Ganju et al., 2017).

Sources of sediment for coastal salt marshes are diverse, but can broadly be categorized into external sources, from the erosion of neighbouring coasts or seafloor and from riverine sediment discharge, as well as internal sources from sediment resuspension on intertidal mudflats adjacent to the salt marshes or erosion of the marsh edges and tidal channels (Schuerch et al., 2014). All sources can be highly variable in time and space and are often driven by highly energetic events, such as storms causing severe precipitation, storm surges and/or wave setup (Ma et al., 2014; Schuerch et al., 2016).

The transport of sediments to the salt marsh occurs on multiple timescales. Wind-waves, due to diurnal or stronger episodic winds, can mobilize estuarine and intertidal flat sediments, erode marsh scarps, and increase sediment concentrations in the water column (Fagherazzi and Priestas, 2010; Ganju et al. 2013).

Over large and small spatio-temporal scales, the net sediment budget will govern whether the complex is trending towards expansion or contraction. For example, a sediment transport deficit that results in a deepening of the estuary will allow for greater propagation of wave energy towards the marsh scarp, leading to increased thrust and erosion of the scarp. The sediment liberated from the marsh scarp may then deposit elsewhere in the complex, or it may be exported from the entire system through hydrodynamic processes. Inorganic sediment supply is also important for vertical accretion on marsh plains (Reed 1989), though in some environments marshes can subsist entirely on organic production (Turner et al. 2002). Furthermore, where the marsh plain meets the marsh scarp, there is a more delicate balance that is dependent on sediment supply, and morphological features as well; for instance, Redfield (1972) identifies the tendency for slumped blocks of peat to trap sediment, and reconstitute marsh plain through recolonization by vegetation, thereby leading to no net loss of marsh plain.

Storms can have varying effects on sediment supply: in some cases they lead to massive sediment export from the system (Ganju et al. 2013), substantial sediment import (Rosencranz et al. 2016), significant marsh plain deposition (Goodbred and Hine, 1995), or negligible marsh plain deposition (Elsey-Quirk 2106).

Ganju et al. (2013) identified disparate sediment sources and transport mechanisms at two Chesapeake Bay marsh complexes (one stable, one degraded), i.e., tidal processes delivered sediment to the stable marsh while fall and winter storms exported sediment from the degraded marsh. Conversely, Rosencranz et al. (2016) found that a single 3 day storm delivered enough sediment to counteract two months of tidally driven sediment export within a Pacific coast marsh complex.

For a degraded marsh complex in Blackwater, MD, USA, tidal resuspension and advection did not provide sediments, while sustained northwest wind events with a 2-wk return interval were able to both mobilize sediment from open-water areas and export sediments (Ganju et al., 2013, Figure 7b); the orientation of the open-water area was aligned along the northwest-southeast axis, thereby allowing for greater fetch and wind-wave exposure during northwest winds. The ensuing wind-waves both mobilized subaqueous sediments and eroded marsh edges; export was then caused by a regional hydrodynamic response which led to net water export. However, a nearby stable complex (Fishing Bay, MD, USA, Figure 7a) imported sediment due to tidal resuspension/advection and proximity to an estuarine sediment source. There was minimal sediment export during the same aforementioned wind-wave events, due to a lack of open-water area.

In Barnegat Bay, New Jersey (USA) a strong south-to-north gradient in shoreline type and sediment availability leads to a variable response to storm events. Dinner Creek, in the southern portion of the bay, is bordered by undeveloped marsh shoreline and shoals consisting of fine sediment (Miselis et al. 2016; Ganju et al. 2014), while Reedy Creek is surrounded by hardened shorelines and coarse-sediment dominated shoals. Ganju et al. (2017) reported a net sediment import for Dinner Creek and negligible sediment transport in Reedy Creek; cumulative fluxes in response to wind events indicate a direction-dependent response (Figure 7c, d). Both sites export sediment during periods with northwest winds and import sediment during southerly winds, but Dinner Creek imports sediment during easterly winds while Reedy Creek remains neutral (Figure 7c, d). This differential response is likely due to the availability of sediment in the estuary. These results show that the location of a salt marsh plays a strong role in the sediment dynamics during storm events, with varied directional responses. Tidal asymmetry affects the net import/ export of sediments as well. The distortion of the tidal wave may significantly change under storm conditions, hence converting a system which would normally import sediments into a system which export sediments (Schuerch et al., 2014).

Finally, Ganju et al. (2017) synthesized sediment budgets of eight microtidal salt marsh complexes, and demonstrated a relationship between the sediment budget and the unvegetated-vegetated marsh ratio, indicating that sediment deficits are linked to conversion of vegetated marsh portions to open water. Both observational and modelling efforts provide insight into the influence of storms and extreme events on sediment transport to and from salt marshes.

Storms impact on sea level rise resilience

Accelerated sea level rise is challenging the survival of coastal salt marshes, which may decrease in elevation within the tidal frame and eventually be inundated too frequently to support the growth of salt marsh vegetation (Kearney et al., 1988; Day et al., 2000; Schepers et al., 2017). With increasing rates of sea level rise, coastal salt marshes rely on a higher sediment supply in order to vertically adapt to the rising sea level (French, 1993; Kirwan et al., 2010a; D'Alpaos et al., 2011). Ma et al. (2014), for example, show a decrease in marsh sedimentation rates in the Oosterschelde estuary (NL) after the construction of a storm surge barrier, which markedly reduced the (external) marine sediment delivery, but also show that sedimentation rates are still keeping up with sea level rise due to sediment resuspension on the adjacent intertidal mudflat during storm events.

Although estimates of critical rates of sea level rise for coastal salt marshes around the world indicate a relatively high resilience for many salt marsh sites (Kirwan et al., 2016), all assessments also highlight that the available sediment supply is a key factor for marsh resilience to sea level rise (French, 2006; Kirwan et al., 2010a; D'Alpaos et al., 2011; Schuerch et al., 2013). Furthermore, salt marshes in microtidal regimes were identified as particularly sensitive to a drop in sediment supply under increasing rates of sea level rise, whereas salt marshes in macrotidal regimes are more resilient to high rates of sea level rise and/or reduced sediment supply (Spencer et al., 2016; Kirwan et al., 2010b). While being more susceptible to drowning as a consequence of sea level rise, sedimentation rates on microtidal marshes were also shown to be more responsive to changes in storm activity due to an increase in sediment supply through intertidal sediment resuspension with respect to macrotidal marshes. Kolker et al. (2009), for example, found clear storm signals in the sedimentation records of their microtidal and wave exposed study sites within the Long Island Sound (USA), but a much reduced signal in the neighbouring macrotidal sites.

In this context, elongated periods (decades) of increased storm activity appear as the main driver for sedimentation in excess of local sea level rise rates as shown for a mesotidal salt marsh in the German North Sea (Figure 8; Schuerch et al., 2012). This excess sedimentation significantly contributes to the resilience of the marsh with respect to its vertical performance and its ability to adapt the future SLR (Schuerch et al., 2013). In the Mississippi Delta, extreme events such as the hurricanes Katrina and Rita in 2005 were reported to contribute sediment layers of 9-13 and 7 cm, respectively, which is a manifold of the regular annual sedimentation (Horton et al., 2009). Meanwhile, Tweel and Turner (2014) argue that the strongest 2% of extreme events contribute 15% of the sedimentation to the marshes of the Mississippi Delta, whereas the majority of the sedimentation (78%) can be attributed to moderate hurricanes with a landfall barometric pressure between 930 and 960 mb (Tweel and Turner, 2014). In addition to sediment deposition, subsurface processes may, however, dominate the elevation response to storm events in many marshes of the Mississippi Delta (Cahoon, 2006; McKee and Cherry, 2009). Subsurface processes are primarily related to soil organic matter, hence are most relevant in organogenic marshes and less so in minerognic marshes.

Moderate storm events also appear to be responsible for the majority of marsh sedimentation on the Danish peninsula of Skallingen (Bartholdy et al., 2004), where extreme storm events were shown to increase suspended sediment concentrations within the adjacent tidal basin by a factor of up to 20 due to sediment resuspension on the intertidal mudflats. There, a single extreme event could contribute 7.5% to the annual sediment deposition, whereas a single regularly occurring gale already contributes 71% of this (Bartholdy and Aagard, 2001). The high importance of frequently inundating gale events is in accordance with the modelling study of Schuerch et al. (2013), who suggest that the frequency of storm events is more important for inorganic marsh accretion than their intensity. The explanation for this behaviour is that the frequency distribution of high and extreme water levels decreases exponentially with increasing high water levels (Bartholdy et al., 2004; Schuerch et al., 2013), whereas the sediment resuspension on the intertidal mudflat appears to follow a linear relationship with increasing high water level (Temmerman et al., 2003) or significant wave heights (Fagherazzi and Pristas, 2010). Therefore extreme sediment resuspension events are too rare to make a significant impact. Furthermore, the impact of wave-induced sediment resuspension decreases with increasing water depths during high inundation events (Fagherazzi and Wiberg, 2009; Christiansen et al., 2006).

However, sediment resuspension within the intertidal zone is a highly variable process (Carniello et al., 2016), as it also relies on the sediment composition of the seabed and the presence of benthic biology determining the erosion thresholds and the stability of the seabed (Le Hir et al., 2007; Grabowski et al., 2011). In particular the benthic biological activity (e.g. vegetated seabeds, diatom biofilms, and benthic macrofauna) has the potential to introduce significant spatial and temporal variations in sediment resuspension (Andersen et al., 2001). Locally, and depending on biological activity, the impact of storm events on the sediment supply of coastal salt marshes may therefore be subject to considerable seasonal variations, often with a stronger impact of storm events on sediment supply during the winter months (Temmerman et al., 2003).

During elongated periods of increased storm activity, which appear to be most effective in increasing sedimentation rates on salt marshes (Figure 8; Schuerch et al., 2012), intertidal sediment resuspension may cause a lowering of the mudflat elevation and potentially conversion to a subtidal flat. In combination with an enhanced vertical growth of the vegetated marsh platform this may lead to an increased mudflat-salt marsh elevation gradient (Le Hir et al., 2007; Mariotti and Fagherazzi, 2010). Incoming waves, therefore, have an increased erosive impact on the steeper marsh edge, hence increasing the marsh's vulnerability to lateral erosion (e.g. Van de Koppel et al., 2005)). A reduction of the intertidal mudflat area due to storm erosion also reduces the sediment resuspension and therefore the sediment supply for the vertical growth of the salt marsh. Both marsh edge erosion and the vertical performance of coastal salt marshes are therefore critically dependent on external sediment supply, which in fact is often enhanced by storm events as well (Mariotti and Carr, 2014).

The sediment import into the tidal basins of the Wadden Sea (South-eastern North Sea), for example, increases during storm events and the sediment composition shifts into the coarser spectrum as increased erosion takes place along the beaches of the adjacent barrier islands and the ebb-tidal delta (Schuerch et al., 2014). Similarly, increased suspended sediment concentrations are observed along the UK East coast as a consequence of the erosion of soft cliffs, particularly during the winter season and intensified storm periods (McCave, 1987; Nicholls et al., 2000; Dyer and Moffat, 1998). Storm events are also often associated with increased precipitation in the catchments of the rivers draining into the coastal zone. The increased river runoff often increases the sediment delivery into the coastal zone and hence the "external" sediment supply for coastal salt marshes (Schuerch et al., 2016). The relationship between river runoff and sediment delivery is, however, not necessarily a straightforward one as it is subject to intense anthropogenic modifications, such as river damming or land use change in the river catchment (Syvitski et al., 2005).

Despite the abundant field evidence and the well-developed knowledge on the importance of sediment supply for coastal salt marshes, current estimations of future salt marsh development largely neglects the processes and feedbacks involved in storm-related sedimentation by neglecting the temporal variations in sediment supply and assuming a constant sediment supply throughout the coming century (e.g. Kirwan et al., 2010; D'Alpaos et al., 2011; Mariotti and Carr, 2014). Accounting for the storm-induced variability in sediment supply for coastal salt marshes in future models is particularly important as storm activity is known to be subject to significant decadal variability (e.g. driven by the North-Atlantic Oscillation) and may prevent or facilitate the collapse of coastal salt marshes, when conventional modelling under the assumption of constant sediment supply and storm activity would predict differently.

Discussion and Conclusions

In face of climate change, the continued delivery of salt marsh ecosystem services, such as mitigation of flood risks and shoreline erosion risks, and carbon sequestration, is increasingly important.

Under storm conditions salt marshes are able to effectively dissipate both high water levels and wave energy even under extreme water level conditions such as during storm surges, and even if the wave-bottom interaction, and energy dissipation decreases with increasing water level. Empirical data and modelling studies demonstrate effective storm surge height reduction behind large (at least 10 km wide) and continuous marshes during moderate storm surges, but also point at limitations in the storm surge protection value, when marshes are smaller, intersected by large channels or open water areas, and during extreme storm surges. This implies that storm surge protection schemes should ideally rely on a combination of conservation and restoration of large continuous marsh areas, where space is available, and engineered flood defences, where necessary (Temmerman et al. 2013).

Under storm surge conditions, up to 60% of the wave attenuation is attributable to the sole presence of vegetation, rather than to the decrease in water depth on the marsh platform relative to the surrounding tidal flat (e.g. Moeller et al., 2014). Vegetation properties largely influence this dissipation process; while the more flexible stems tend to flatten during powerful storms (with a reduction in dissipation potential), they are also the more resilient to structural damage, and their flattening helps to protect the marsh substrate against erosion. On the other hand, with increasing wave energy, high vegetation stiffness can enhance the turbulence and surface erosion around plant stems (Silinski et al., 2016; Rupprecht et al., 2017).

Storm action can have various impacts on the geomorphological evolution of salt marshes, and different implications for their long term survival to sea level rise, and climate change in general. Storms impact potentially causes erosion of marsh boundaries, marsh platforms, and surrounding tidal flats, but it might also deliver substantial amount of sediments to the marsh platform.

Under the assumption of an increase in magnitude, and reduced frequency of extreme events it can be argued that the after-storm impact on marsh boundaries is expected to be only slightly affected by such changes; this is because it has been shown that the lateral erosion of salt marshes is mostly dictated by average weather conditions rather than by extreme events. The biggest impact that storms could have in relation to lateral salt marsh dynamics could instead be connected to the deepening of tidal flats which promote higher wave energy at the marsh boundary, and reduces wave energy dissipation by bottom friction, causing therefore an increase in the erosion potential during inter-storms period, i.e. under normal weather conditions.

The impact on the vertical salt marsh dynamic is complicated because, even if more intense storms have the potential to deposit more sediments, there are evidences about the fact that storms frequency is more important than intensity for the long term inorganic accretion of salt marshes. The explanation for this behaviour is that the frequency distribution of high and extreme water levels decreases exponentially with increasing high water levels (Schuerch et al., 2013, 2014).

The occurrence of storms might then directly or indirectly impact the sediment budget of the coastline. In particular, the direction of storm events can determine whether there is a direct import or export from a coastal embayment. Furthermore, the occurrence of storms is generally connected to precipitation events and surface runoff which might increase the transport of sediments from the catchment to the coastline (e.g. Ganju et al., 2013)

The latter considerations highlight the necessity to focus on the indirect impact that large storms might exert on salt marshes not only in the immediate after storm period, but also in the longer term, and on how their morphological consequences influence the response of the system to normal weather conditions during inter-storm periods. Some of the challenges highlighted from the complexity of the problem also include the necessity to consider salt marsh systems as a whole by adopting an integrated approach, taking into account the marsh tidal flat continuum and by accounting for various sediment sources.

Figures

Figure 1

Percentage changes in Emmanuel's (1995) wind maximum potential intensity (MPI_V) per degree increase in global surface air temperature. Large values of MPIv values are generally associate to enhanced tropical storms activity, and intensity (adapted from Vecchi and Soden, 2007).

Figure 2

Sketch of mechanisms and sediment fluxes possibly responsible for salt marsh vertical and horizontal dynamics. Black dashed box represents an hypothetical control volume for the evaluation of the sediment budget.

Figure 3

Relationship between the attenuation rate of High Water Levels (dHWL/dx) at least 0.4m above the marsh platform, and α_V, i.e. ratio between the over-marsh water volume (Vpl) and the total water volume (Vpl+Vc, i.e. over-marsh water volume + water volume within channels) (adapted from Stark et al., 2016).

Figure 4

Reduction of total Energy [J m-2] between sand flat, marsh edge and marsh interior for ten representative measurements 'bursts' (adapted from Moeller, 1999).

Figure 5

Diagram representative for some of the major morphologic impacts of storms on salt marshes, their spatial scale, and useful literature references. Morton and Barras, 2011; b) Mariotti and Carr, 2014; c) Mariotti, 2016; d) Fan et al., 2006; e) Scileppi and Donnelly, 2007; f) Williams, 2009; g) Leonardi et al., 2016a,b; h) Leonardi et al., 2014, 2015; i) Barras, 2007, l) Cahoon, 2006; m) Cahoon, 2003; These impact are mainly categorized into the following: Deformation, Erosion, Deposition, and Incision.

Figure 6

A) Contribution of different wind categories to salt marsh erosion (from Leonardi et al., 2016). B) Impact of increasing extreme events frequency on the shape of marsh shorelines (adapted from Leonardi et al., 2014, 2015). Increasing the occurrence of extreme events smooths the marsh shoreline.

Figure 7

Sediment flux response to wind forcing at four wetland complexes, as a function of wind direction (radial position) and speed (outward position). The wind direction indicates direction the wind is coming from. Fishing Bay and Blackwater (Maryland, USA), are adjacent to Chesapeake Bay, but their respective locations relative to sediment sources and external forcing result in disparate sediment transport responses to wind events. Northwest winds export sediment from both sites, but southerly winds allow for sediment import at Fishing Bay due to proximity to a southern sediment source (Ganju et al., 2013). Dinner and Reedy Creeks, in southern and northern Barnegat Bay (New Jersey, USA), respectively, both export sediment during westerly winds, but Dinner Creek imports sediment during strong easterly winds. This is likely due to increased fine sediment availability and undeveloped shoreline in the southern portion of Barnegat Bay, as opposed to coarser sediments and hardened shoreline in northern Barnegat Bay.

Figure 8

(a) Historic marsh elevations in comparison to the development of the mean high water level (MHW) and the mean sea level (MSL) for three cores (S1: high marsh; S2: low marsh; S3: pioneer marsh) from a salt marsh on the German island of Sylt (in the South-eastern North Sea). Deposition dates were derived from ^{210}Pb and ^{137}Cs data (open diamonds). The green shaded area indicates the periods of excess sedimentation during periods of increased storm activity. (b) Comparison of sedimentation rates (stars) at core location S2 with storm frequency (open circles), defined as the number of water levels exceeding 2.4 m above the long-term mean sea level (NN: German ordnance datum). Modified after Schuerch et al. (2012).

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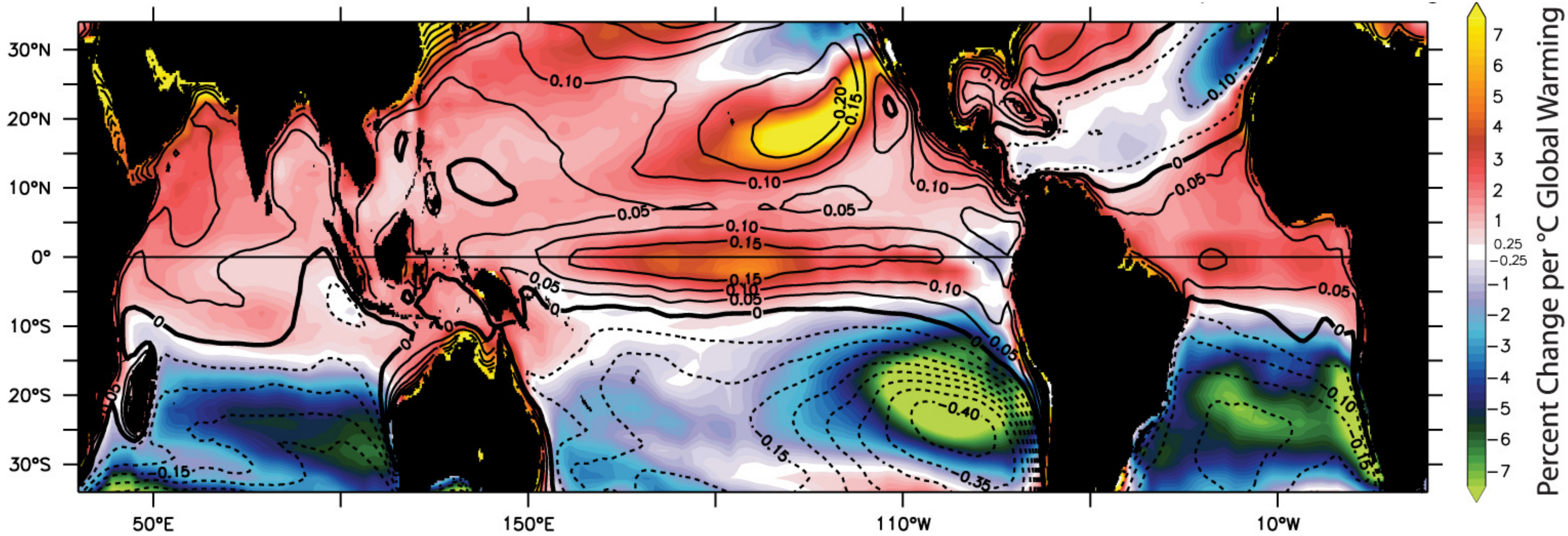
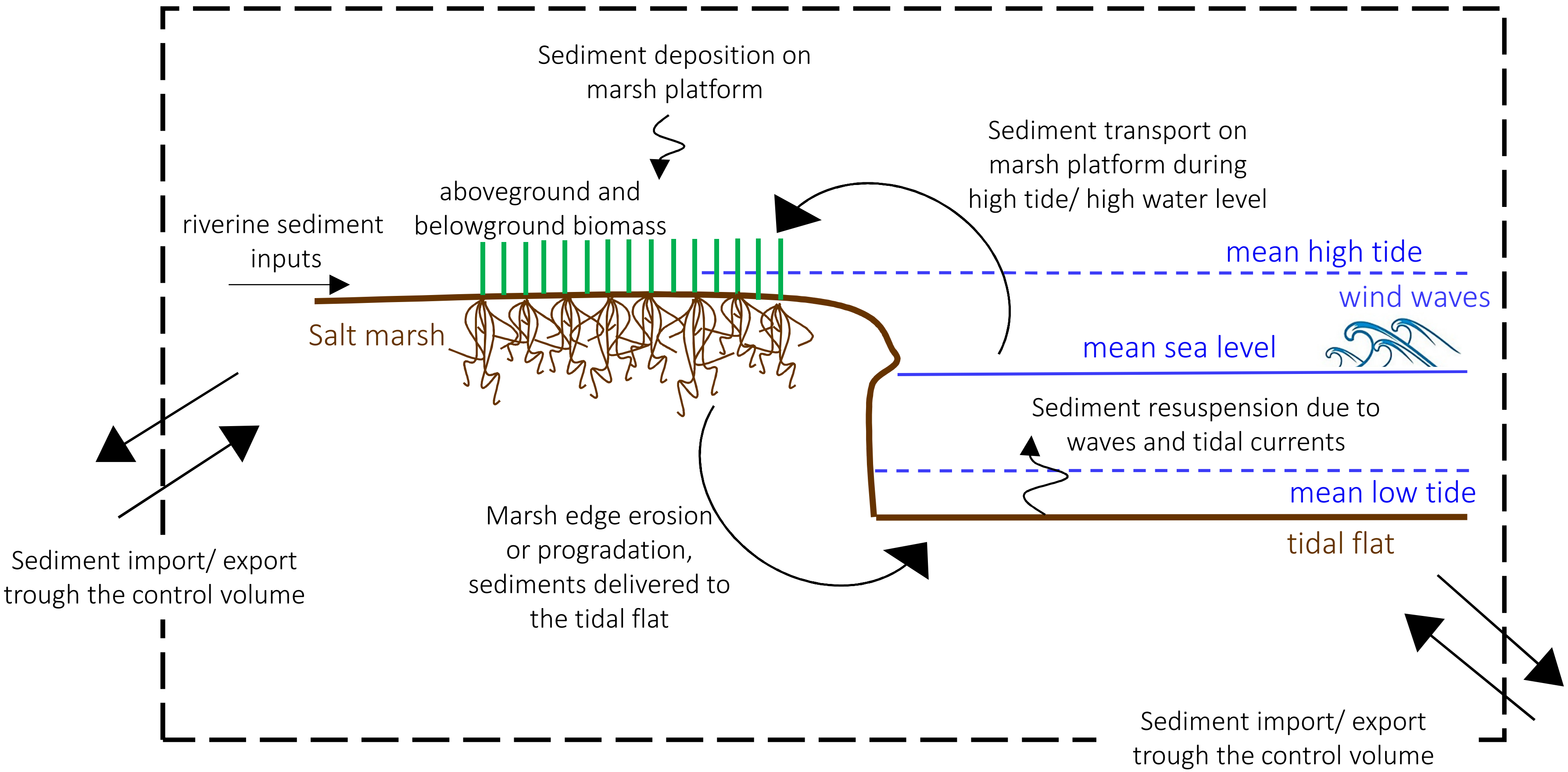
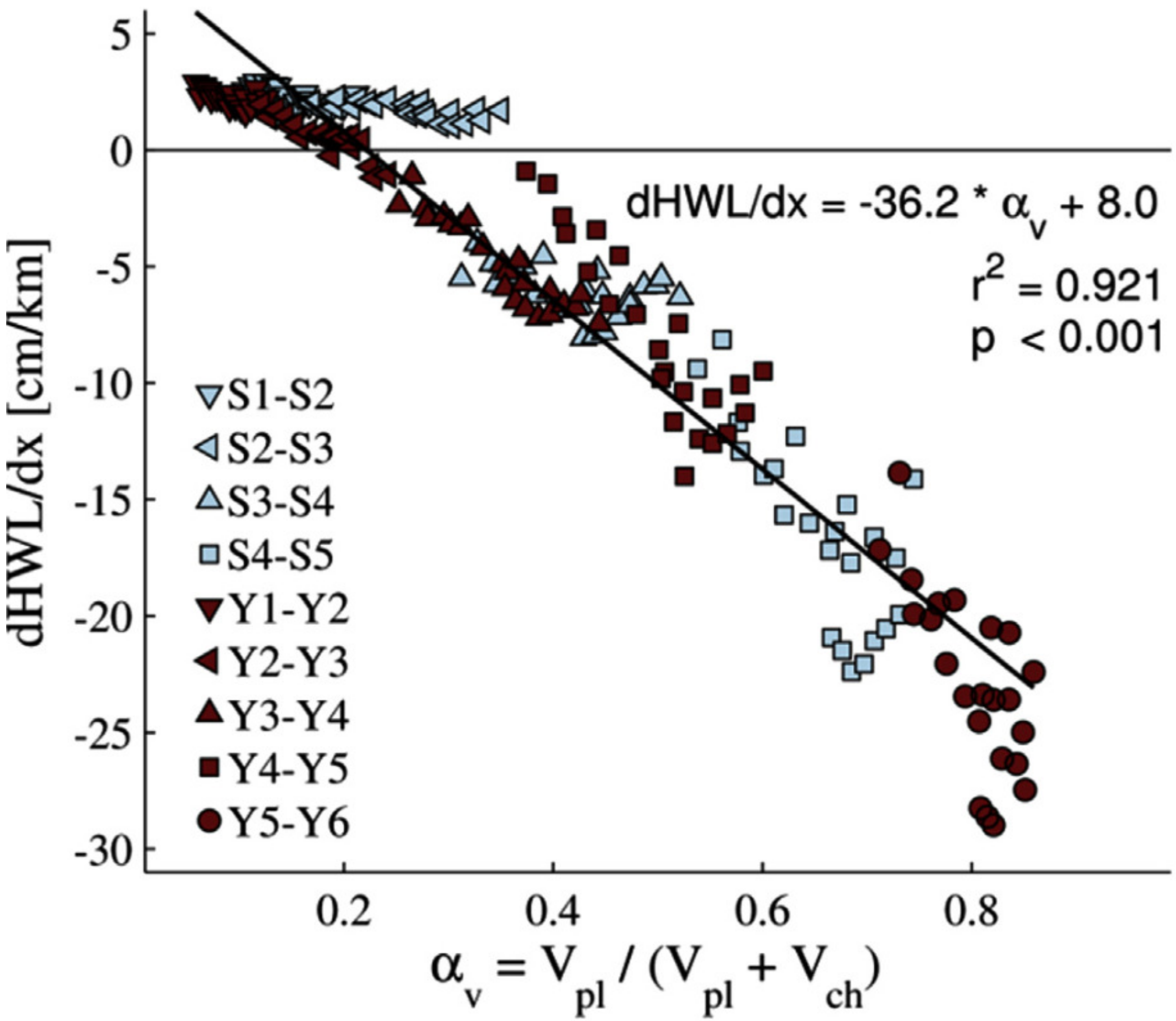
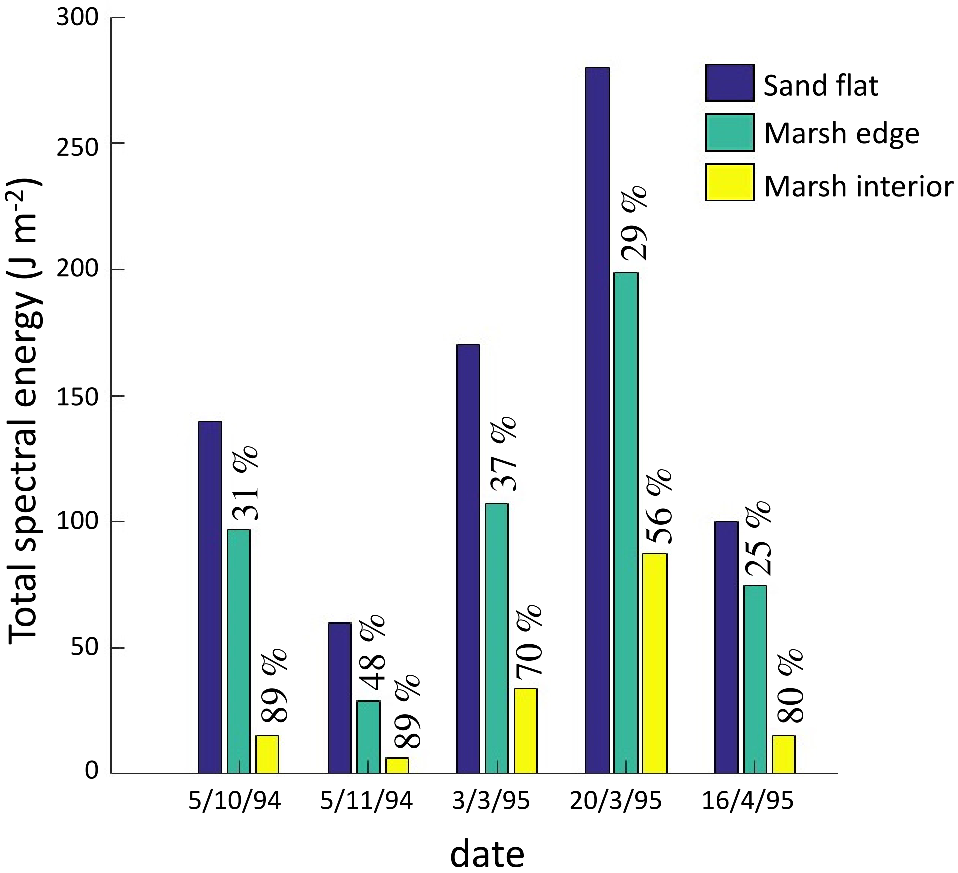


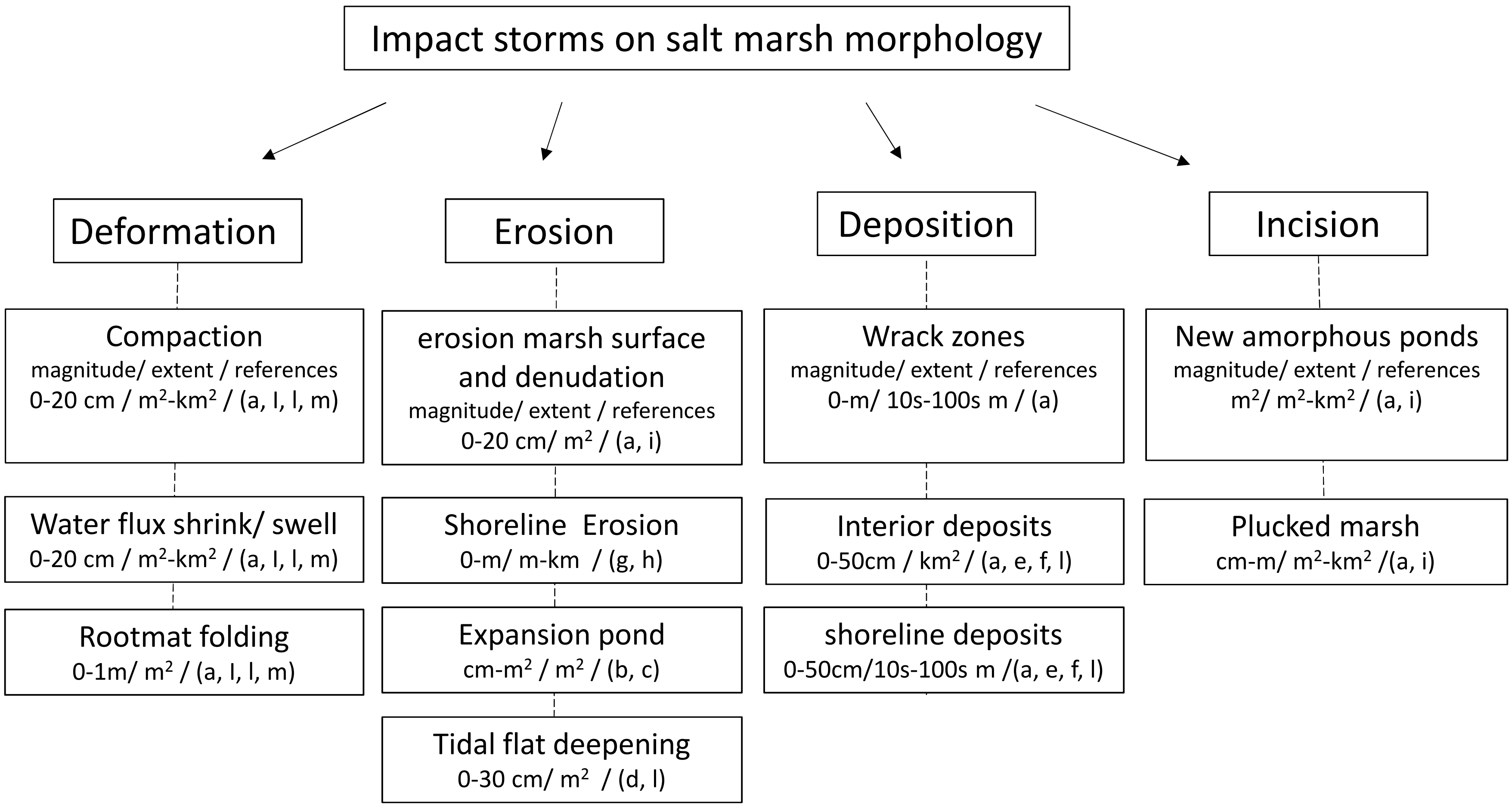
30°N
20°N
10°N
0°
10°S
20°S
30°S
50°E
150°E
110°W
10°W
Percent Change per °C Global Warming
7
6
5
4
3
2
1
0.25
−0.25
−1
−2
−3
−4
−5
−6
−7



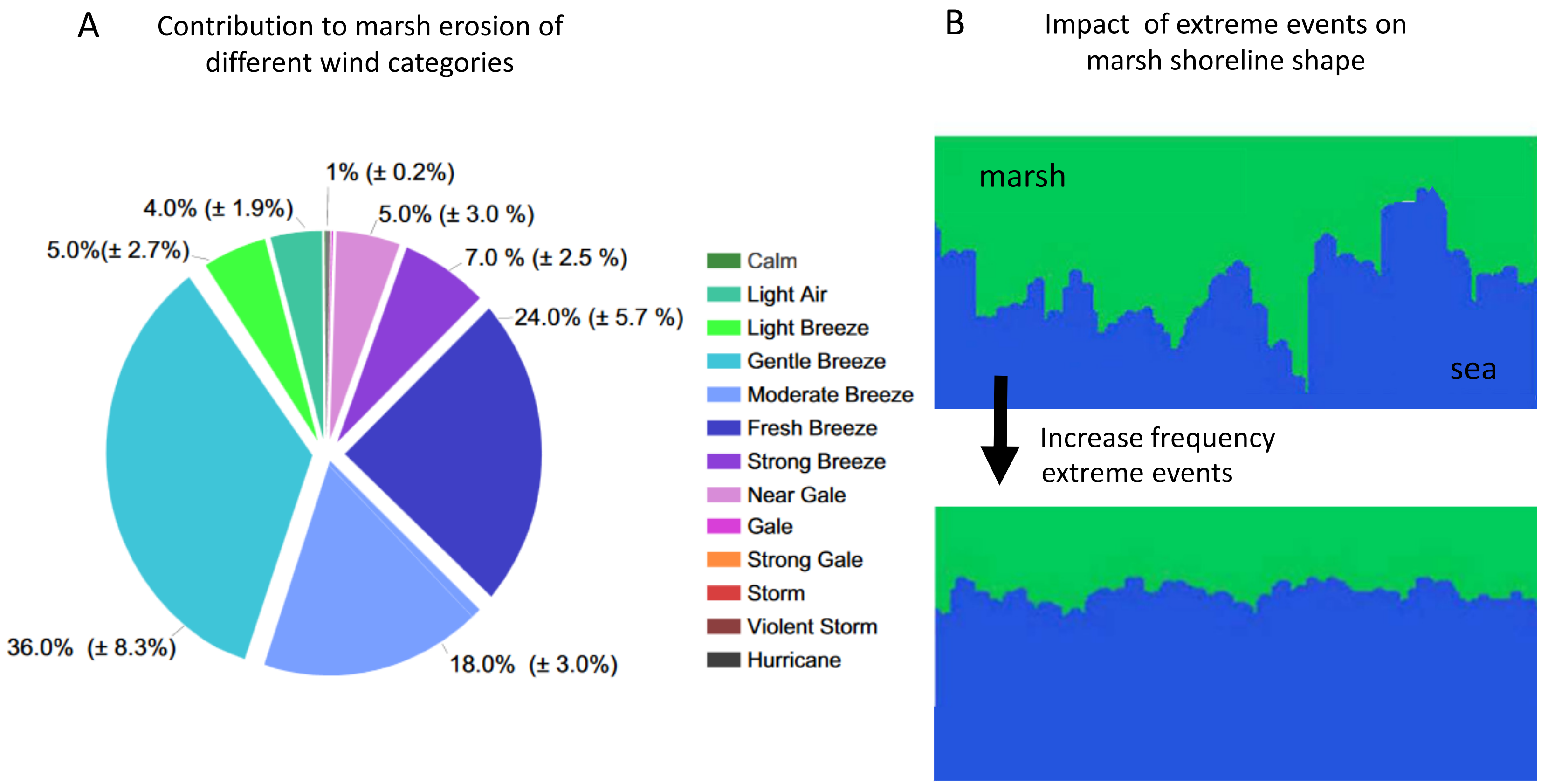
Sediment deposition on
marsh platform
Sediment transport on
marsh platform during
high tide/ high water level
aboveground and
belowground biomass
riverine sediment
inputs
Salt marsh
mean high tide
wind waves
mean sea level
Sediment resuspension due to
waves and tidal currents
mean low tide
tidal flat
Marsh edge erosion
or progradation,
sediments delivered to
the tidal flat
Sediment import/ export
trough the control volume
Sediment import/ export
trough the control volume


dHWL/dx = -36.2 * α_v + 8.0
r^2 = 0.921
p < 0.001
S1-S2
S2-S3
S3-S4
S4-S5
Y1-Y2
Y2-Y3
Y3-Y4
Y4-Y5
Y5-Y6
dHWL/dx [cm/km]
5
0
-5
-10
-15
-20
-25
-30
0.2
0.4
0.6
0.8
$\alpha_v = V_{pl} / (V_{pl} + V_{ch})$

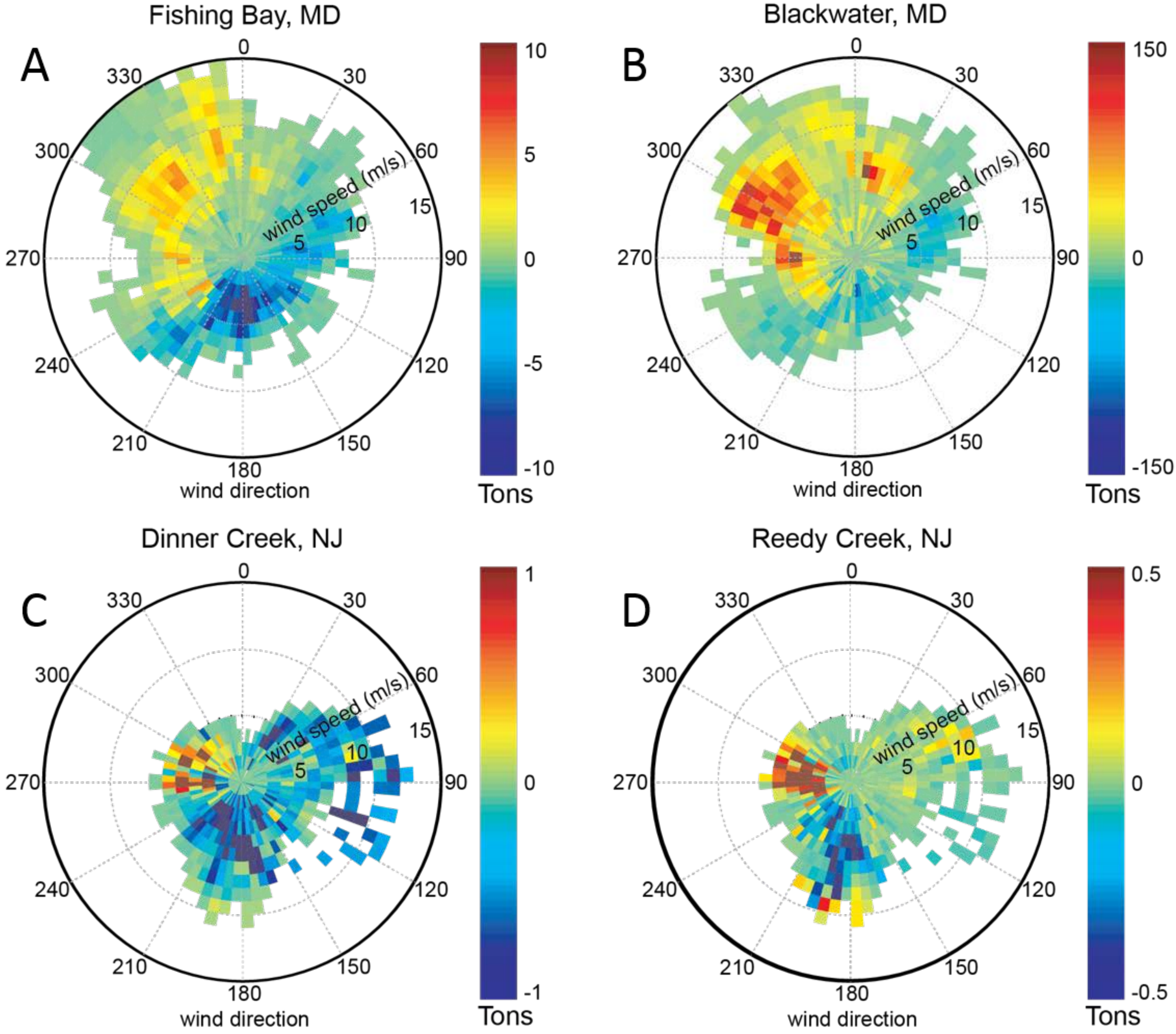

300
250
200
150
100
50
0
Total spectral energy (J m-2)
Sand flat
Marsh edge
Marsh interior
31 %
89 %
48 %
89 %
37 %
70 %
29 %
56 %
25 %
80 %
5/10/94
5/11/94
3/3/95
20/3/95
16/4/95
date



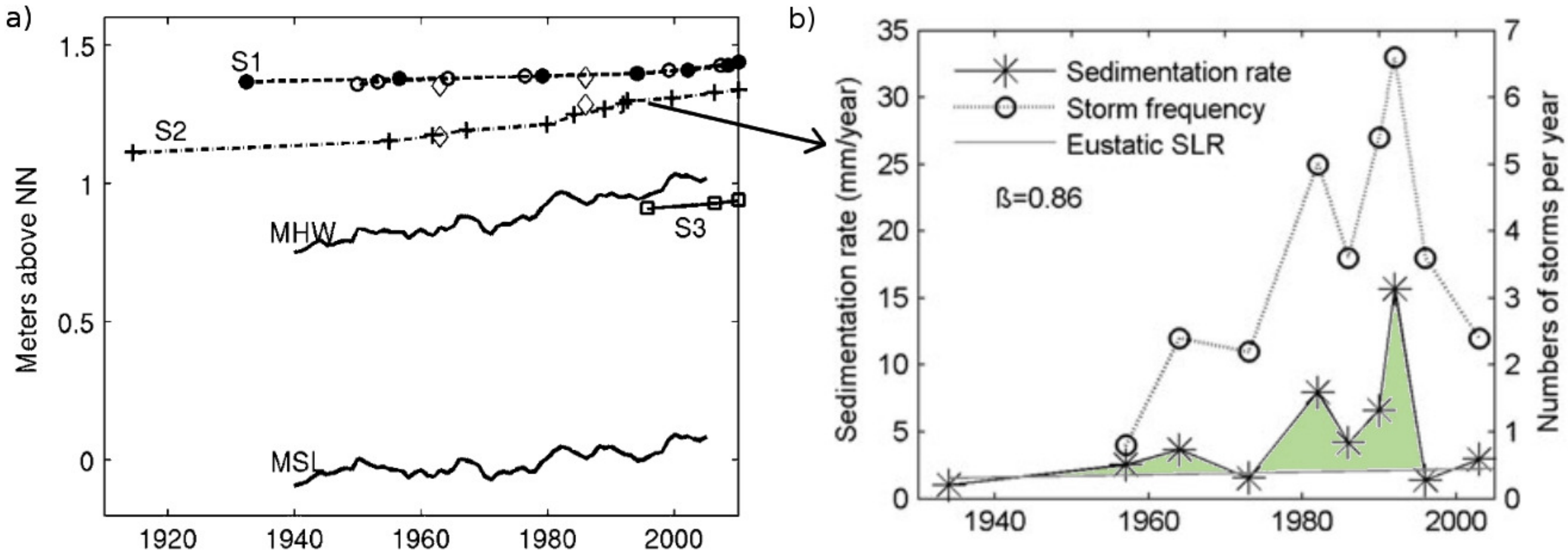
Impact storms on salt marsh morphology
Deformation
Erosion
Deposition
Incision
Compaction
magnitude/ extent / references
0-20 cm / m²-km² / (a, I, l, m)
Water flux shrink/ swell
0-20 cm / m²-km² / (a, I, l, m)
Rootmat folding
0-1m/ m² / (a, I, l, m)
erosion marsh surface and denudation
magnitude/ extent / references
0-20 cm/ m² / (a, i)
Shoreline Erosion
0-m/ m-km / (g, h)
Expansion pond
cm-m² / m² / (b, c)
Tidal flat deepening
0-30 cm/ m² / (d, l)
Wrack zones
magnitude/ extent / references
0-m/ 10s-100s m / (a)
Interior deposits
0-50cm / km² / (a, e, f, l)
shoreline deposits
0-50cm/10s-100s m /(a, e, f, l)
New amorphous ponds
magnitude/ extent / references
m²/ m²-km² / (a, i)
Plucked marsh
cm-m/ m²-km² /(a, i)



A
Contribution to marsh erosion of different wind categories
1% (± 0.2%)
4.0% (± 1.9%)
5.0% (± 3.0 %)
5.0%(± 2.7%)
7.0 % (± 2.5 %)
24.0% (± 5.7 %)
36.0% (± 8.3%)
18.0% (± 3.0%)
Calm
Light Air
Light Breeze
Gentle Breeze
Moderate Breeze
Fresh Breeze
Strong Breeze
Near Gale
Gale
Strong Gale
Storm
Violent Storm
Hurricane
B
Impact of extreme events on marsh shoreline shape
marsh
sea
Increase frequency extreme events



Fishing Bay, MD
A
0
30
60
90
120
150
180
210
240
270
300
330
wind speed (m/s)
5
10
15
wind direction
10
5
0
-5
-10
Tons
Blackwater, MD
B
0
30
60
90
120
150
180
210
240
270
300
330
wind speed (m/s)
5
10
15
wind direction
150
0
-150
Tons
Dinner Creek, NJ
C
0
30
60
90
120
150
180
210
240
270
300
330
wind speed (m/s)
5
10
15
wind direction
1
0
-1
Tons
Reedy Creek, NJ
D
0
30
60
90
120
150
180
210
240
270
300
330
wind speed (m/s)
5
10
15
wind direction
0.5
0
-0.5
Tons



a)
b)
1.5
1
0.5
0
Meters above NN
S1
S2
MHW
S3
MSL
1920
1940
1960
1980
2000
35
30
25
20
15
10
5
0
7
6
5
4
3
2
1
0
Sedimentation rate (mm/year)
Numbers of storms per year
Sedimentation rate
Storm frequency
Eustatic SLR
ß=0.86
1940
1960
1980
2000