ANNUAL REVIEWS

Annual Review of Marine Science

Improving Predictions of Salt Marsh Evolution Through Better Integration of Data and Models

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Annu. Rev. Mar. Sci. 2020. 12:389–413

First published as a Review in Advance on July 5, 2019

The *Annual Review of Marine Science* is online at marine.annualreviews.org

https://doi.org/10.1146/annurev-marine-010419-010610

Keywords

marsh accretion, morphodynamic modeling, sea level rise, storm surge, sediment budget, marsh-edge erosion

Abstract

Salt marshes are recognized as valuable resources that are threatened by climate change and human activities. Better management and planning for these ecosystems will depend on understanding which marshes are most vulnerable, what is driving their change, and what their future trajectory is likely to be. Both observations and models have provided inconsistent answers to these questions, likely in part because of comparisons among sites and/or models that differ significantly in their characteristics and processes. Some of these differences almost certainly arise from processes that are not fully accounted for in marsh morphodynamic models. Here, we review distinguishing properties of marshes, important processes missing from many morphodynamic models, and key measurements missing from many observational studies. We then suggest some comparisons between models and observations that will provide critical tests and insights to improve our ability to forecast future change in these coastal landscapes.

1. INTRODUCTION

Awareness of the value and vulnerability of salt marshes has increased dramatically over the past few decades (Costanza et al. 1989). Once commonly viewed as land to be reclaimed, attention has shifted to how to preserve and restore these coastal ecosystems, which are increasingly threatened by human activities and climate change. Informed decisions require both an understanding of the mechanisms controlling the form and function of salt marshes (Ganju 2019) and the ability to anticipate how these systems will change in response to disturbance, whether natural or anthropogenic (Day et al. 2007, Silliman et al. 2015). Models and field-based attempts to forecast these changes have developed largely independently, and sometimes with conflicting results (Fagherazzi et al. 2012, Kirwan et al. 2016b, FitzGerald & Hughes 2019). Therefore, integrating measurements and models is now essential for understanding marsh vulnerability.

Research over the last 50 years has led to many insights into the ecomorphodynamics of salt marshes (e.g., Fagherazzi et al. 2004). Strong feedbacks among marsh vegetation, tidal inundation, and sediment deposition exert a primary control on marsh elevation and morphology. In undisturbed systems, these feedbacks have typically maintained vegetated marshes in the intertidal zone for thousands of years (Kirwan & Megonigal 2013, FitzGerald & Hughes 2019). However, recent assessments also point to extensive wetland loss: Global wetlands have declined in area by 87% over the last 300 years and 54% since 1900 (IPBES 2018). Although human activities have been primarily responsible for historic marsh loss (Gedan et al. 2009, IPBES 2018), the potential for climate change–driven losses is likely to increase in the future. Assessments of marsh vulnerability to sea level rise (SLR) have diverged markedly in their predictions of future loss (e.g., Crosby et al. 2016, Kirwan et al. 2016b). Predictions of the impact of changes in storm frequency and intensity on salt marshes also differ, ranging from beneficial (e.g., Smith et al. 2015, Castagno et al. 2018) to harmful (e.g., Howes et al. 2010).

Several factors contribute to the lack of clarity regarding the future trajectory of salt marshes under changing climate conditions. Differences in marsh setting and anthropogenic history can significantly affect marsh response to changes in environmental drivers such as SLR and storminess (Howes et al. 2010, Weston 2014). Some differences are widely recognized (e.g., tidal range, vegetation type, and extent of ditches) but not consistently factored into comparisons or meta-analyses of marsh accretion rates. Other differences may also be important but are less frequently accounted for in comparisons (e.g., geomorphic setting, microtopography, exposure to waves and currents, sources of sediment, seasonal variations in vegetation cover, and ice and periglacial processes).

Differences in the temporal and spatial scales associated with measurements of marsh vulnerability are another complicating factor. Comparisons of measured marsh accretion rates based on radiometric dating of core samples (timescales of decades or longer) with measurements of accretion and elevation change based on short-term point measurements [e.g., surface elevation tables (SETs)] are particularly problematic (Breithaupt et al. 2018). Short-term estimates of marsh accretion are generally higher than long-term estimates because long-term records are more likely to include periods of nondeposition or erosion (Sadler 1981, Sommerfield 2006), integrate over periods of slow SLR (Kirwan et al. 2017), and more fully reflect sediment compaction and organic matter decomposition (Breithaupt et al. 2018). Point-based measures of wetland accretion also miss potentially important lateral processes, such as the erosion of marsh edges (Mariotti & Fagherazzi 2013) and the migration of marshes into uplands (Kirwan et al. 2016a, Fagherazzi et al. 2019). For example, measured sediment budgets suggest that point-based approaches underestimate vulnerability because marshes often diminish in size even as they accrete vertically (Fagherazzi et al. 2013, Ganju et al. 2017). Finally, the relatively short duration of SET data sets and sediment budgets relative to interannual variability in marsh sediment accumulation rates presents challenges for identifying longer-term trends and extrapolating into the future.

Model-based assessments of future marsh loss provide an alternative approach to those based on measured accretion rates. Models are able to provide a more complete spatial perspective on marsh morphodynamics, including horizontal and vertical change. Furthermore, some sort of model, whether statistical or process based, is necessary for making predictions because linear extrapolation of historical trends is unlikely to be appropriate in the face of accelerating rates of SLR and other trends in forcing conditions. Models, however, suffer from their own set of limitations. For example, commonly used simplifications (e.g., a planar marsh surface, a constant supply of sediment, astronomical tidal inundation, simplified wind conditions, domination by one vegetation species, and constant vegetation parameters) are likely to miss some of the processes and feedbacks working in real ecosystems. In general, the degree of model simplification increases with the temporal and spatial scales considered (Fagherazzi et al. 2012), so that large-scale predictions of marsh change rely on the simplest models. Model resolution also varies with temporal and spatial scale owing to computational limitations; however, the majority of observational data (other than remote sensing) cannot readily be adjusted to match the scale of a model. In fact, marsh models can easily reach a resolution of several to tens of meters, while field measurements are rarely so dense. Only remote sensing data provide sufficient resolution to inform spatially explicit models of salt marsh evolution.

For the first time, a variety of numerical models are capable of simulating the response of salt marshes to SLR (Fagherazzi et al. 2012). These models differ in purpose (from general morphodynamic understanding to site-specific prediction), complexity (from bathtub-style inundation to physics-based hydrodynamics), and spatial scale (from site specific to global). But they also differ in important assumptions, such as how accretion responds to changes in inundation, and the inclusion or exclusion of marsh erosion and migration. Unsurprisingly, these models lead to fundamentally different predictions, ranging from widespread marsh submergence (Thorne et al. 2018) to global marsh expansion (Schuerch et al. 2018). However, the extent to which divergent model outcomes should be attributed to site differences, the quality of field-based model parameterization, or inherent model assumptions remains unclear.

Ideally, measurements and models would be used in combination to achieve the best possible understanding of the processes and evolution of salt marsh environments. The most common way observations and models are combined is to use measurements to set values of model parameters (e.g., Morris et al. 2002, Mudd et al. 2004, Mariotti & Fagherazzi 2010). Model results have also been compared, qualitatively or quantitatively, to measurements of various marsh characteristics to test how well a model is able to reproduce observed behavior (e.g., D'Alpaos et al. 2007a, Schwarz et al. 2018, Sullivan et al. 2019). While this approach is appropriate for site-specific models, many morphodynamic models start from idealized transects (e.g., Mariotti & Fagherazzi 2010, Mariotti & Carr 2014, Kirwan et al. 2016a, Lorenzo-Trueba & Mariotti 2017) or hypothetical marsh surfaces (e.g., D'Alpaos et al. 2007b, Kirwan & Murray 2007, Mariotti & Canestrelli 2018) and require a more general comparison with observations.

An obvious goal for future work is to use process-based modeling to hindcast marsh change at a particular site where historic rates of vertical accretion and lateral boundary change are well characterized and then forecast future change for a range of scenarios of sea level and storminess. Such a study would face several challenges. A limited number of marshes have well-characterized rates of vertical and horizontal change. For shorter-term hindcasts, it may be possible to reconstruct forcing conditions (winds, tides, and sediment supply) from available data sets, but this is almost impossible for long-term hindcasts. The same is true for the boundary conditions needed to initialize a model (e.g., the initial morphology of tidal channels, flats, and marsh platforms, including sediment and vegetation characteristics). While it might be most straightforward to do such a comparison over short timescales, natural variability in real systems may obscure the type of longer-term trends that models are often best suited to predicting.

This review focuses on the questions and challenges associated with comparing observations and models of salt marsh morphodynamics, with a focus on physical processes. While some of the challenges could be addressed by careful choice of site and model, it remains unclear what criteria should be used to match sites and models. What processes are critical to represent when modeling a particular salt marsh? What parameters are most important to measure? How are these considerations affected by timescale and spatial setting? How generalizable are non-site-specific model results? In sum, what do we need to know about a site and what do we need to represent in a morphodynamic model to make the results comparable enough to be useful for hindcasting past change and forecasting future change?

2. DISTINGUISHING CHARACTERISTICS OF MARSHES

This review focuses on intertidal salt marshes. While there are commonalities among wetlands of all types, such as the primary importance of feedbacks among vegetation, inundation, and sedimentation, the halophytic vegetation and tidal inundation that define salt marshes produce a distinct landform found in many coastal and estuarine settings. Salt marsh vegetation is typically dominated by a few plant types: *Spartina*, *Distichlis*, *Juncus*, and *Salicornia* are common in Europe and the United States (e.g., Adams 1963), while *Phragmites*, *Suaeda*, and *Scirpus* are typically found in Asia (Zhao et al. 2011). These plants vary in their tolerance for salt and inundation time. Regularly flooded parts of the marsh (the low marsh) are often dominated by a single species, such as the marsh cordgrass *Spartina alterniflora* in the United States and Europe. The maximum productivity of *S. alterniflora* is found in the elevation range between mean sea level and mean high water (Morris et al. 2002), coincident with the range of water levels usually used to define the low marsh.

Intertidal salt marshes fringe shallow and deep coastal bays, including mainland borders (mainland marshes), marsh islands, and marshes fringing barrier islands or spits. Differences in depth and circulation in larger estuaries compared with shallow coastal bays, as well as differences in tidal range, can lead to differences in sediment supply to fringing marshes even when the systems have similar forcing and vegetation (Boyd et al. 2017). Marshes in different locations within a bay can also differ in sediment characteristics and in the frequency and intensity of sediment resuspension. For example, in many shallow coastal bays, there is a gradient from sandier sediment near inlets and barrier islands to muddier sediment near the mainland (Wiberg et al. 2015). As a result, the tidal flats that supply sediment to backbarrier marshes tend to be coarser grained than are tidal flats adjacent to mainland marshes.

The dynamics of high and low marshes differ in important ways, with organic matter accretion accounting for most of the change in marsh surface elevation in high marshes (generally above mean high water), whereas inorganic sediment accretion is the largest contributor to elevation change in low marshes (Roner et al. 2016). The higher elevation limit of a marsh generally borders upland forest or fields (grassland or agricultural fields), though they may also abut roads, lawns, parking lots, and other developed land. The lower limit of a marsh generally borders estuarine waters (shallow or deeper bays) or large tidal creeks. The elevation gradient from tidal flats or creeks to uplands strongly affects the extent of low and high marsh and their response to SLR (Brinson et al. 1995).

The frequency, duration, and depth of tidal inundation are defining characteristics of intertidal salt marshes. Greater frequency, duration, and depth of tidal inundation allow for greater amounts of sediment deposition, provided that the frequency and duration of inundation are not so great as to limit plant productivity (Friedrichs & Perry 2001, Morris et al. 2002, Kirwan & Megonigal 2013). Traditional descriptions of hydrodynamics in coastal environments recognize three classes of tidal range: microtidal (0–2 m), mesotidal (2–4 m), and macrotidal (>4 m). Tides in the open ocean have ranges of 0–2 m (Haigh 2017), but coastal and estuarine bathymetry and morphology locally amplify or diminish tidal range (**Supplemental Figure 1**, **Supplemental Table 1**). Smaller tidal ranges increase marsh vulnerability to drowning in the face of SLR (Kirwan et al. 2010).

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In addition to astronomical tidal range, meteorological effects can further increase or decrease water levels. Storm-related increases or decreases in water levels are related to wind conditions (speed, duration, and direction) and atmospheric pressure. For example, along the US Atlantic coast, moderate to strong winds (>6 m/s) from the northeast are associated with storm surge in shallow coastal bays (Fagherazzi et al. 2010). As a result, the highest measured tides can be much higher than mean high water or the highest astronomical tides (**Figure 1*a***, **Supplemental Table 1**). This difference is most obviously important for the high marsh, which is flooded only during the highest astronomical tides and storm surges. Storm surge, however, is also critically important for the low marsh because of the associated increase in deposition potential, as discussed in Section 3.1.

Whereas increases in storm frequency or intensity directly affect marsh inundation and thereby deposition, the effect of SLR is subtler. Increases in sea level increase the baseline on top of which tides and storm surges act. However, on timescales from several days to a decade, water level variability due to storms, seasonal temperature variations, and other large-scale effects (e.g., related to variations in ocean circulation) greatly exceeds the variation due to SLR in many coastal environments (**Figure 2**). In addition, marshes that increase in elevation at a rate commensurate

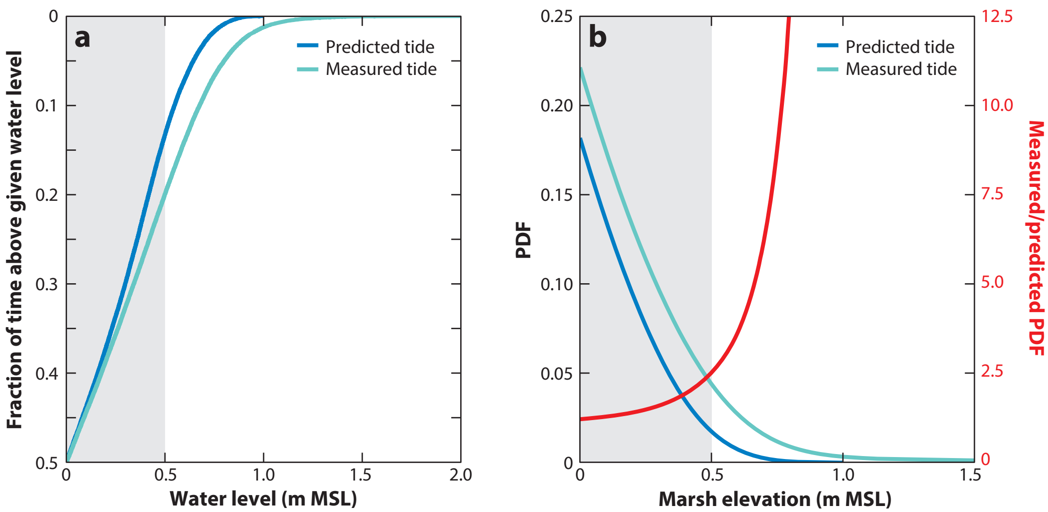

Figure 1

(*a*) Fraction of time when water levels were above indicated values based on 10-year record (2009–2018) of measured and predicted water levels at a NOAA tidal gauge station in a coastal bay at Wachapreague, Virginia (**https://tidesandcurrents.noaa.gov**; **Supplemental Table 1**). The gray shaded region indicates a 0.5-m-high marsh, which measured water levels indicate would be inundated 20% of the time, while astronomical tides alone would inundate the marsh just 12% of the time. (*b*) Potential deposition factor (PDF) calculated as the integral over time of water depth above a given marsh elevation (area above curves in panel *a*) to account for the combined role of depth and inundation time on potential deposition. The ratio of the PDFs for measured and predicted water levels (*right axis*) indicates that a 0.5-m-high marsh could receive 2.5 times the deposition associated with astronomical tides alone for the same suspended sediment concentration. Additional abbreviation: MSL, mean sea level.

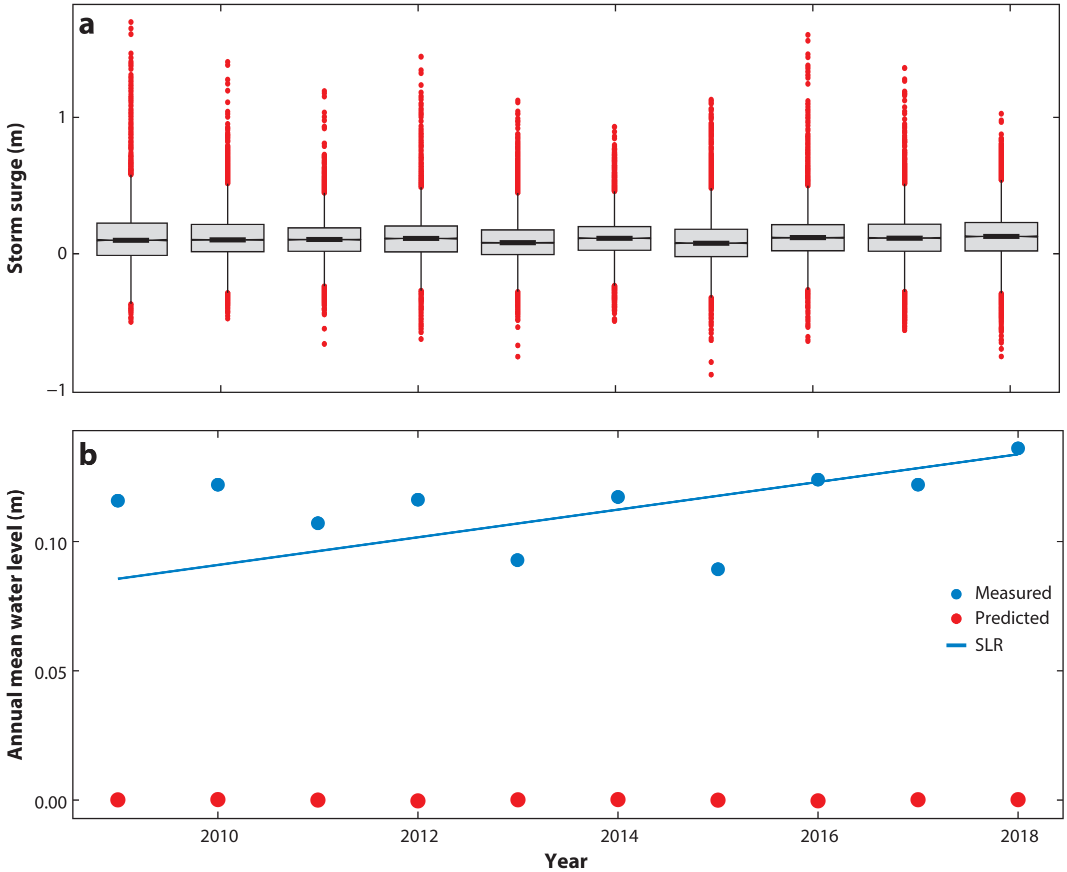

Figure 2

(*a*) Annual statistics of the difference between measured and predicted water levels (storm surge) at a NOAA tidal gauge station in a coastal bay at Wachapreague, Virginia (**http://tidesandcurrents.noaa.gov**; **Supplemental Table 1**), showing that the majority of the time measured water levels are close to predicted values (*gray boxes* include the upper and lower quartiles) but that every year there are extreme high and low water levels that are far outside the bounds of astronomical tides (tidal range 1.2 m). Positive storm surge increases peak annual marsh inundation depths by more than 1.0 m on average. (*b*) Measured (*blue*) and predicted (*red*) annual mean water level at Wachapreague, Virginia. The predicted annual mean water level is set at zero; the long-term trend in measured water levels [sea level rise (SLR)] is shown by the line with an origin in 1993. During this 10-year period, the variability of the measured annual mean water level is large enough to obscure the long-term trend, with as much year-to-year variability as there is SLR over this decade. The difference between measured and predicted water levels accounts for the offset of the median difference from zero in panel *a*.

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with the rate of SLR maintain a constant hydroperiod and tidal prism. If marshes maintain their elevation with respect to mean sea level while flats or channels become deeper, then changes in hydrodynamics and resuspension will affect rates of marsh accretion, at least in the short term (Silvestri et al. 2018). If rates of SLR persistently exceed rates of marsh accretion (e.g., conditions of accelerating rates of SLR or a reduction in sediment supply), a variety of responses are possible, including expansion of the channel network (D'Alpaos et al. 2007b, Hughes et al. 2009), inland transgression of the high marsh (Kirwan et al. 2016a, Fagherazzi et al. 2019), and possible drowning of the low marsh (Schepers et al. 2017).

As this inventory of marsh characteristics makes clear, intertidal salt marshes reside in a multidimensional framework that includes geomorphic setting (sediment, exposure, and shallow or deep bay), morphology (elevation, vegetation, and tidal channel network), inundation frequency (tidal range, storm surge, and SLR), and different degrees of human impact. These dimensions must be taken into consideration in marsh modeling and in intersite comparisons. Impacted or pristine, marshes are conspicuous coastal landforms, a majority of which are found in microtidal environments (Kearney & Turner 2016). In this review, we focus on low-marsh environments in coastal bays with smaller tidal ranges (<2 m) and in settings that have not been significantly affected by human activities. Such marshes are more vulnerable than those in settings with larger tidal ranges, have relatively simple vegetation, and experience locally controlled forcing (tidal circulation and waves), with vertical accretion rates controlled primarily by physical processes (tides, winds, and inorganic sediment). This combination of characteristics makes them particularly well suited to process-based modeling. While understanding morphodynamics and future change of human-impacted marshes is obviously important, addressing the complexity and variety of anthropogenic modifications is extremely difficult without a strong understanding of the morphodynamics of pristine environments.

3. IMPORTANT MARSH PROCESSES THAT ARE OFTEN ABSENT IN MORPHODYNAMIC MODELS

Current models of salt marsh morphodynamics capture many key processes controlling the evolution of these landforms. Resuspension of sediment caused by waves and currents in tidal flats bordering a marsh can be simulated by high-resolution models with relatively good results (Mariotti et al. 2010, Donatelli et al. 2018, Zhang et al. 2019), even for vegetated tidal flats (Nardin et al. 2018). For marshes dominated by only one plant species, extensive data sets quantify the relationship between marsh elevation and biomass, thus allowing the derivation of friction, particle sediment capturing, and belowground organic production, which strongly depend on vegetation biomass (Morris et al. 2002, Mudd et al. 2010). Several studies have focused on the formation of tidal channels in a marsh complex (D'Alpaos et al. 2005, 2006; Kirwan & Murray 2007). Current models can produce channels with statistical properties similar to those of real ones, including width and depth (D'Alpaos et al. 2010). Gradients in sediment deposition on the marsh platform as a function of distance from tidal channels are easily implemented in marsh models and can be successfully calibrated with limited data sets (Christiansen et al. 2000, Temmerman et al. 2003, D'Alpaos et al. 2007b).

There are a variety of processes that are often not included in models but may be important for improving estimates of marsh sedimentation and geomorphic change. These include contributions of high-water (storm surge) events to marsh deposition; marsh-edge retreat and bay or channel bottom erosion as a source of sediment for marsh accretion; postdepositional changes to the marsh surface, including shallow subsidence or compaction, bioturbation, and herbivory; and, at high latitudes, the impact of freezing and ice on marsh morphology.

3.1. The Effects of Wind-Driven Variability in Water Levels and Suspended Sediment Concentration on Marsh Deposition

Tides provide the hydrodynamic context within which intertidal salt marshes exist. Tidal water level variations ensure regular flooding of intertidal low marshes and modulate the suspended sediment concentration (SSC) in the network of tidal channels that distribute water throughout the low marshes (Leonard et al. 1995, D'Alpaos et al. 2007b). In general, longer and deeper marsh inundation increases the mass of suspended sediment in the water over the marsh (even if SSC is unchanged) and the time available for that sediment to deposit (**Figure 1*b***). Storm-driven high

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water levels (storm surge) can far exceed water levels associated with the highest astronomical tides, particularly for microtidal marshes (**Figure 1*a***, **Supplemental Table 1**). Meteorological effects increase or depress water levels (negative storm surge), depending on wind direction (**Figure 2*a***). Therefore, it is not simply wind speed or atmospheric pressure but the particular combination of wind speed, direction, duration, atmospheric pressure, and coastal morphology that produces the storm surge observed at a given location.

Storms accompanied by large surges have the potential to dramatically increase marsh deposition (Cahoon 2006). For example, Goodbred & Hine (1995) documented the extensive deposit left on a bay-fronting marsh in west-central Florida by a very large extratropical storm in March 1993 that produced several meters of storm surge. That single event deposited approximately 10 times the average annual deposition on the marsh. Reed (1989) found that more typical winter storms also significantly increased marsh deposition on tidal creek marshes in coastal Louisiana but did so only when winds blew from the south, a result of increased inundation coupled with wind-wave-driven sediment resuspension in a nearby bay. Averaged across the Louisiana Gulf coast, storms are thought to account for more than half of all inorganic sediment deposition on marshes (Turner et al. 2006, Tweel & Turner 2014). High-frequency, low-magnitude storms account for approximately 80% of storm-induced deposition (Tweel & Turner 2014). However, storms can also lead to erosion and subsidence of marshes (Cahoon 2006, Howes et al. 2010).

Wind-driven wave resuspension is the dominant control on SSC over tidal flats (Lawson et al. 2007, Callaghan et al. 2010). However, SSC will remain low close to the marshes fringing tidal flats, even if winds speeds are high, when winds blow from the back-marsh direction due to limited fetch (McLoughlin et al. 2015). Fringing marshes oriented into the direction of large fetch and surge-producing winds (e.g., facing northeast along the US Atlantic coast) experience high water and high SSC (**Figure 3*a*,*b***), whereas winds from the opposite direction can have a small or negligible effect (**Figure 3*c*,*d***). By contrast, fringing marshes oriented away from surge-producing winds will experience high water levels but low SSC during surges, and high SSC but low water levels when high winds come from the opposite direction (Duvall et al. 2019). When high water and high SSC co-occur on the tidal flats bordering a marsh, suspended sediment is effectively transported across the marsh edge and promotes higher rates of deposition on the marsh platform (Duvall et al. 2019).

Wind-driven effects on water level and SSC affect tidal creeks as well as marsh boundaries. Storm-driven high water levels and SSC on tidal flats increase flood-tide sediment fluxes at the mouths of tidal creeks and result in higher water levels and SSC throughout the tidal network (Reed 1989, Leonard et al. 1995) and net import of sediment to the marsh system (Ganju et al. 2017, Fagherazzi & Priestas 2010). For example, Christiansen (1998) found that high-tide water levels in a large tidal creek (tidal range 1.2 m) departed from astronomically predicted values only when winds were from the northeast. Under those conditions, which were associated with positive storm surges in the adjacent bay, tidal water elevations increased by close to 0.5 m and SSC increased by up to a factor of five (Christiansen 1998, Christiansen et al. 2000). Northeasterly winds producing these conditions occurred 11% of the time but accounted for an estimated 27% of marsh deposition (Christiansen 1998). Negative storm surge can also be important. Fagherazzi & Priestas (2010) measured a large export of sediment from a marsh in Louisiana during an extreme low tide driven by landward winds. This sediment flux was likely triggered by the scouring of tidal channels and not by the erosion of the marsh surface.

Most models of marsh evolution focus exclusively on tidally driven flows despite the observations that accretion is dominated by episodic events (Tweel & Turner 2014). In these models, the SSC in waters flooding the marsh is often specified as a tidally averaged value (e.g., Kirwan et al. 2010). Some marsh models allow SSC to vary along the channel (D'Alpaos et al. 2007b)

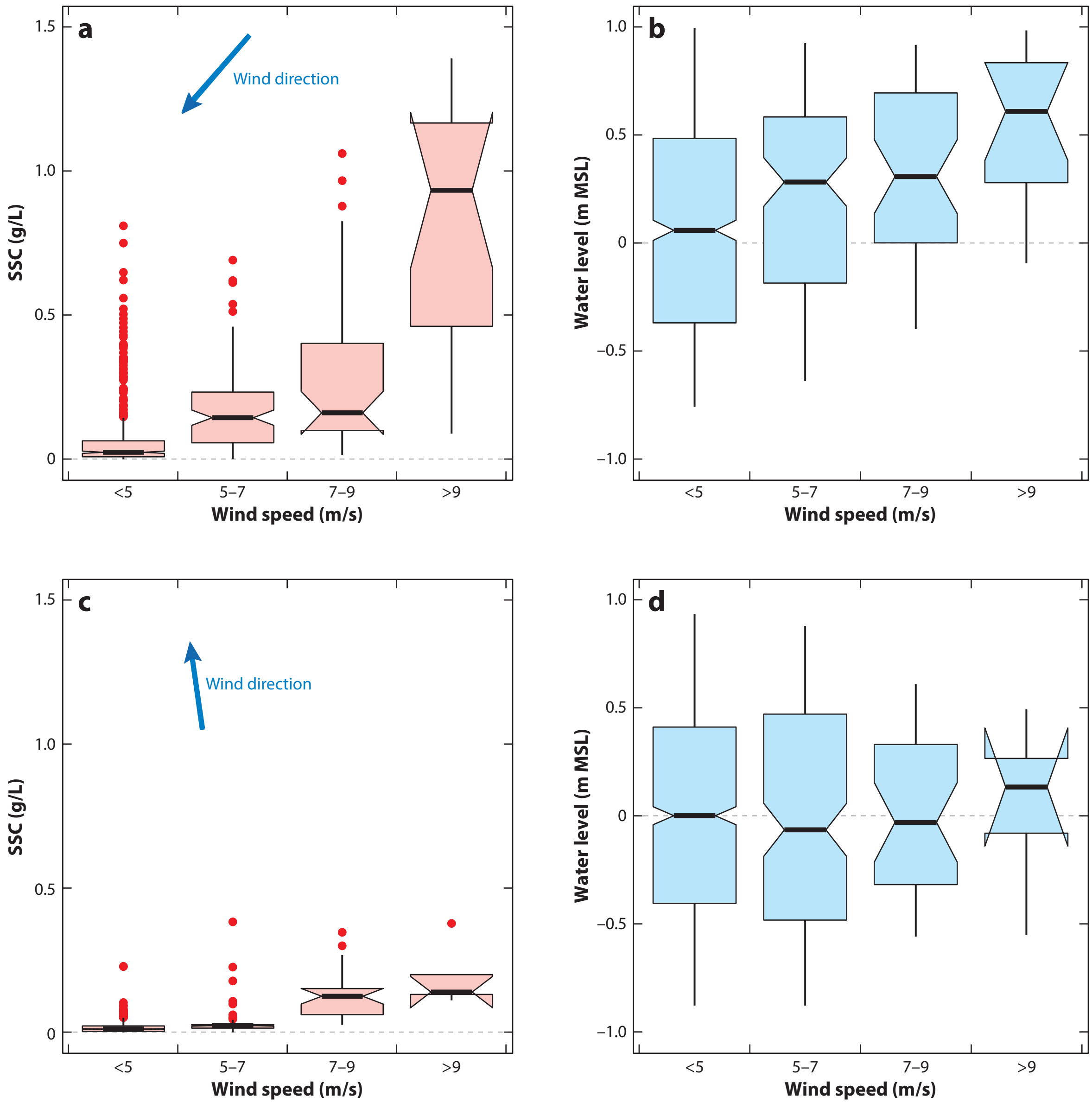

Figure 3

(*a*,*b*) Relationships between wind speed and suspended sediment concentration (SSC) (panel *a*) and between wind speed and water depth (panel *b*) during a 20-day period marked by two northeasterly wind events (maximum speed 11 m/s), showing a strong response of SSC and water depth to high wind from this direction. (*c*,*d*) Relationships between wind speed and SSC (panel *c*) and wind speed and water depth (panel *d*) during a 20-day period marked by southerly winds (maximum speed 10 m/s), showing a more moderate increase in SSC and no significant difference in water levels for winds from this direction. Both sets of measurements are from a westward-facing bay-fronting marsh in a Virginia coastal bay. The blue arrows indicate the dominant direction of high winds during these time periods. Additional abbreviation: MSL, mean sea level.

and in the shallow bays bordering the marsh (e.g., Mariotti & Canestrelli 2018). Attributing the distribution and deposition of suspended sediment to regular tidal flooding will not capture the additional effect of storm-enhanced inundation depths and durations and will inevitably lead to underestimation of sediment deposition rates on the low marsh (**Figure 1*b***). Indeed, one of the few models that incorporate storm frequency suggests that increased storminess in the future may increase the resilience of marshes to SLR (Schuerch et al. 2013).

3.2. Coupling of Horizontal and Vertical Marsh Dynamics and Sediment Budgets

Marshes that are unable to increase in elevation fast enough to stay above mean sea level are susceptible to large-scale conversion to open water, as observed at the Blackwater National Wildlife Refuge (Maryland, USA) (Schepers et al. 2017). For marshes that are able to maintain their elevation with respect to SLR, a more persistent cause of deterioration is lateral retreat. Marsh-edge retreat is a common feature of microtidal marshes fringing coastal bays (Leonardi et al. 2016b) (**Figure 4**). In a transgressive system, marsh area may be maintained by a gain due to landward migration of high marsh into adjacent uplands. This gain sometimes equals the loss due to lateral erosion (Brinson et al. 1995, Kirwan et al. 2016a, Raabe & Stumpf 2016, Schieder et al. 2018), but marsh-edge retreat does not require rising sea levels, so it is present even without transgression (Mariotti & Fagherazzi 2013).

Waves drive erosion of the marsh edge. Waves encountering a marsh-edge scarp dissipate their energy on the scarp face, dislodging sediment from the scarp and blocks of root mat from the marsh

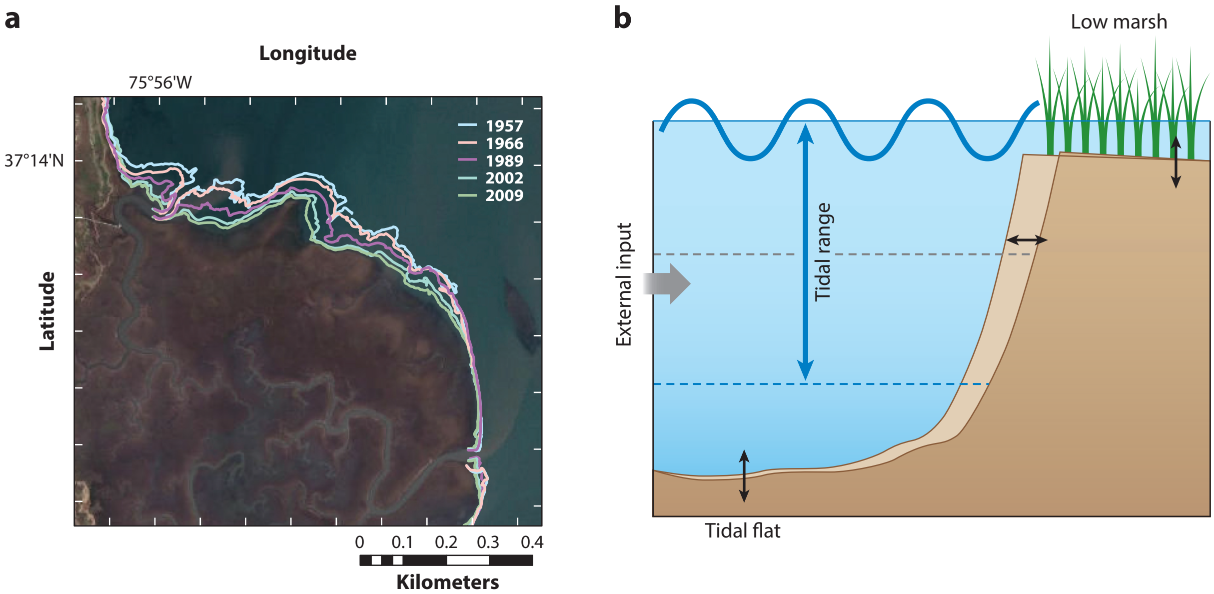

Figure 4

(*a*) Shoreline change, based on aerial photo analysis, at a mainland marsh site in a Virginia coastal bay (Marion Scott Cove), with maximum rates in excess of 2.0 m/y (McLoughlin et al. 2013). (*b*) Schematic of marsh–tidal flat boundary. Black arrows indicate potential for erosion or deposition of the marsh platform, marsh edge, and tidal flat. The mass stored or released by changes in the positions of these boundaries, in addition to external inputs from rivers or through tidal inlets, defines the sediment budget for the system. Sediment released by edge erosion contributes to deposition on the flat and/or marsh, but both the flat and marsh cannot increase in elevation at the rate of sea level rise in the absence of external sediment sources.

surface (Fagherazzi et al. 2013, Bendoni et al. 2016). Maximum wave thrust on a marsh-edge scarp occurs when water surface elevations are close to the top of the scarp (Tonelli et al. 2010), while higher water levels allow waves to propagate across the marsh edge, where they dissipate their energy to marsh vegetation (Möller et al. 1996, 2014). As a result, smaller, more frequent storms have a greater impact on marsh-edge retreat than do extreme events (Leonardi et al. 2016b). Rates of marsh-edge erosion, which exceed 1 m/y in many locations (Fagherazzi 2013), are linearly related to wave power on the marsh boundary (Marani et al. 2011, Leonardi et al. 2016b) and seem less sensitive to specific mechanisms of edge erosion, such as root scalping, block detachment, and undercutting (McLoughlin et al. 2015, Bendoni et al. 2016).

Erosion of the marsh edge releases a substantial amount of sediment onto tidal flats bordering the marsh (**Figure 4**). This sediment can then be transported back to the marsh surface in subsequent tides. For marsh systems lacking significant external sediment sources (e.g., river inflow), edge erosion can be a large part of the sediment budget. A recent analysis of sediment sources in the Plum Island Sound estuary (Massachusetts, USA) concluded that erosion of the marsh shoreline can generate 23–76% of the sediment mass required to maintain marsh elevation relative to mean sea level in the lower river and sound (Hopkinson et al. 2018). However, sediment eroded from the marsh edge is not constrained to redeposit on the marsh surface. It can also be transported offshore, where it can contribute to net deposition on bay bottoms, or alongshore, where it may help to supply sediment to the mouths of tidal channels. Only allochthonous sediment imported to a system from rivers or from the ocean can allow both bay bottoms and marshes to accrete at the rate of SLR (**Figure 4**).

A few models have been developed to explore the detailed dynamics of marsh-edge erosion (Leonardi & Fagherazzi 2014, Leonardi et al. 2016a) and the coupled evolution of marshes and tidal flats along a transect (Mariotti & Fagherazzi 2010, Mariotti & Carr 2014). For example, Mariotti & Carr (2014) used an empirical linear relationship between wave power at the marsh boundary and the rate of marsh-edge erosion to quantify retreat rates under different wind and fetch scenarios. They found that conditions favoring high rates of marsh-edge retreat (strong winds, large fetch, and high erodibility) also promoted high rates of vertical accretion on the marsh surface, whereas conditions resulting in more stable marsh edges (weak winds, small fetch, and low erodibility) promoted marsh drowning by reducing sediment supply to the marsh surface. Which of these scenarios is the greater threat to long-term marsh survival depends on rates of SLR and the availability of upland area into which marshes can expand (Mariotti & Carr 2014, Kirwan et al. 2016a).

Marsh-edge erosion has not been incorporated into most landscape-scale models of marsh evolution because these models tend to focus exclusively on the vertical balance between accretion and SLR (Schile et al. 2014, Alizad et al. 2016, Thorne et al. 2018). This approach may suffice in places where the amount of exposed marsh edge is small relative to the total size of a marsh or under conditions in which SLR leads to wholesale drowning of the marsh platform, like in the subsiding Mississippi Delta. However, the field observations and morphodynamic models discussed above suggest that vertical accretion and lateral erosion are fundamentally linked and that erosion may still have important indirect effects on marsh accretion through its influence on SSC. Observations suggest that wave conditions and rates of marsh-edge erosion are linearly related (Leonardi et al. 2016b), making it relatively straightforward to incorporate this source of marsh loss into landscape-scale marsh models (e.g., Kirwan & Murray 2008, Mariotti & Canestrelli 2018).

Processes related to the morphodynamics of adjacent bays have also not been incorporated into local models of marsh evolution. Modeled accretion rates are very sensitive to SSC (Kirwan et al. 2010) and the bay-centric processes that influence sediment availability and SSC. The survival of extensive marsh platforms at high rates of SLR depends on the continued availability of sediment, but most landscape models do not discern where that sediment comes from. Distinguishing the sediment source is important since terrestrial sediment sources are declining (Fagherazzi & Priestas 2010, Weston 2014, Castagno et al. 2018, Hopkinson et al. 2018), and sediment budgets suggest that most microtidal marshes are contracting despite continued marsh accretion (Ganju et al. 2017). Landscape models that neglect lateral processes and related sediment sources or sinks may therefore incorrectly predict changes in salt marsh area through time. By contrast, models that include lateral processes can track the fate of sediment released by edge retreat, thereby quantifying its contribution to deposition on marsh and tidal flats, something that is challenging to measure in the field.

3.3. Postdepositional Change to the Marsh Surface

The dendritic channel network that dissects salt marshes (**Figure 5**) conveys water, nutrients and sediments to the marsh platform. Both marsh models and field data show that the tidal signal first propagates up the channels, after which water flows from the channels to the marsh platform

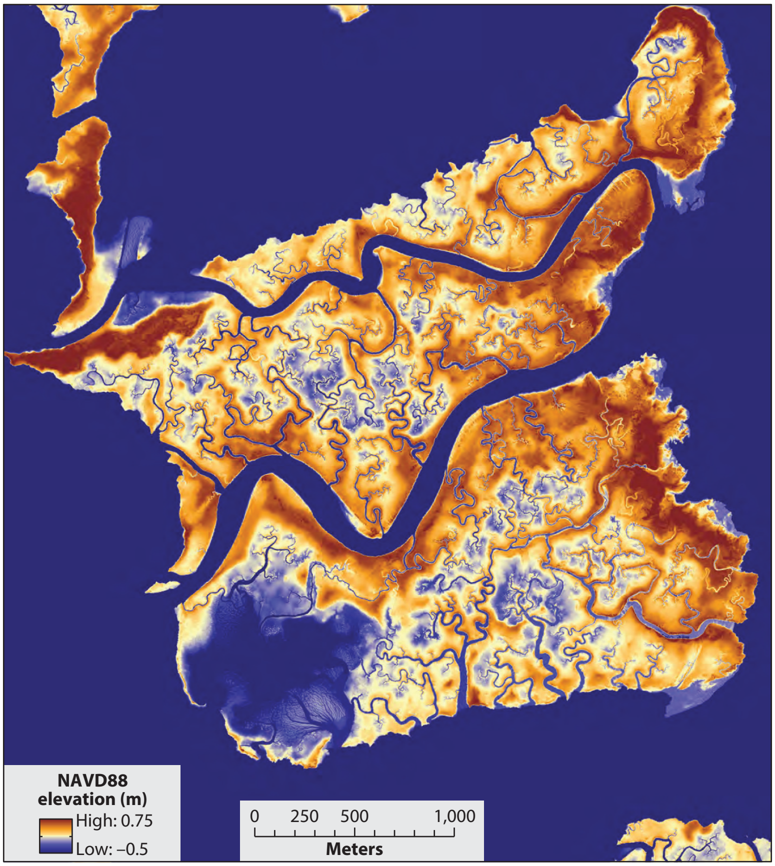

Figure 5

Lidar-derived topography of a marsh island (Chimney Pole Marsh) in a Virginia coastal bay, revealing considerable small-scale variability in the elevation of the marsh surface, largely related to the tidal channel network. The two largest tidal channels are almost unchanged from those shown in an 1871 map (US Coast Surv. 1871), though the island itself has lost area due to erosion at its edges. Abbreviation: NAVD88, North American Vertical Datum of 1988. Image courtesy of John H. Porter.

(Temmerman et al. 2003, Fagherazzi et al. 2008). Only when the entire marsh is flooded with more than several decimeters of water (e.g., during storm surge conditions on microtidal marshes) do the channels lose importance, allowing a direct connection between bays and the interior of the low-marsh platform (Temmerman et al. 2003, Mariotti et al. 2010).

Morphodynamic models are able to simulate the flux of sediment from channels to the marsh, giving rise to enhanced deposition near marsh boundaries and the formation of natural levees similar to those observed along tidal channels (Temmerman et al. 2003, D'Alpaos et al. 2007b) (**Figure 5**). Because typical tidal flooding is shallow and the flow is slowed by vegetation, this deposition does not extend far into the marsh interior. Astronomical tidal deposition is limited primarily to a zone on the order of a few tens of meters (microtidal marshes; Moskalski & Sommerfield 2012) to 100 m (mesotidal marshes; Temmerman et al. 2003, Zhang et al. 2019) from the creek banks, leaving portions of the marsh interior with little tidal deposition and therefore susceptible to ponding (Wilson et al. 2014, Schepers et al. 2017, Zhang et al. 2019). A set of poorly defined processes is likely responsible for the low rates of deposition observed in the marsh interior, including deposition of fine sediment from diffuse tidal flooding of these low-lying regions, infrequent storm surge that provides a more direct connection from tidal flats and channels to the marsh interior, redistribution of sediment across the marsh surface by processes such as rainfall runoff (Mwamba & Torres 2002) and ice cover (see below), and a higher fraction of organic matter accumulation (Reed 1989, Moskalski & Sommerfield 2012).

Lack of regular tidal deposition makes interior portions of the low marsh vulnerable to ponding (Zhang et al. 2019). Ponding is a striking morphodynamic feature of marshes, one that is prone to self-reinforcing feedbacks that accelerate lateral erosion, and a primary process by which marshes are lost to SLR (Kearney & Turner 2016, Ortiz et al. 2017, Schepers et al. 2017). Yet the formation and evolution of ponds have rarely been explored with numerical models (Kirwan & Guntenspergen 2010, Mariotti 2016).

Because vegetation plays a fundamental role in marsh evolution, anthropogenic and naturally occurring disturbance events often lead to rapid loss of marsh elevation, the creation of ponds, and erosion of marsh edges. For example, mortality of roots and rhizomes associated with storms, oil spills, and other events has led to vertical peat collapse (Cahoon et al. 2003, Baustian et al. 2012) and more rapid lateral erosion (Silliman et al. 2012, Coleman & Kirwan 2019). Herbivory and bioturbation by animals have led to the formation of tidal channels, accelerated wave erosion, and reduced mineral accretion (Escapa et al. 2007, Kirwan et al. 2008, Hughes et al. 2009, Wilson et al. 2012, Smith & Green 2015, Vu et al. 2017). Field observations suggest that temporary disturbance to vegetation can result in permanent loss of vegetated marsh (Kirwan et al. 2008, Silliman et al. 2012). At best, these processes are modeled as stochastic drivers of vegetation-mediated marsh evolution (Kirwan et al. 2008, Mariotti 2016). Therefore, future models should consider vegetation disturbance more explicitly, including the interaction of plants with higher trophic levels.

On a marsh platform, measured accretion rates are often higher than rates of elevation change because of a group of postdepositional processes, collectively termed shallow subsidence, that lead to decreases in soil volume through time (Cahoon et al. 1995). These processes include dewatering, compaction, and organic matter decomposition. Shallow subsidence tends to be greatest in locations with rapid mineral sedimentation and where inorganic sediment deposition on the marsh surface compresses organic-rich material at depth (Törnqvist et al. 2008). In these situations, shallow subsidence rates can exceed 5 mm/y and negate approximately half of total accretion (Jankowski et al. 2017). Postdepositional compaction of sediment is also important for marsh erosion. More consolidated sediment is more difficult to erode (Wiberg et al. 2013), suggesting that marsh age and underlying stratigraphy influence salt marsh morphology and vulnerability (Fagherazzi & Furbish 2001, Feagin et al. 2009). Nevertheless, models rarely consider the influence of stratigraphy and postdepositional changes to the soil profile (Mudd et al. 2009, Kirwan & Mudd 2012). Instead, models treat compaction implicitly by assuming a steady-state bulk density (Kirwan et al. 2016a, Morris et al. 2016) or parameterizing with long-term accretion rates that implicitly incorporate some compaction (e.g., Thorne et al. 2018).

At high latitudes, ice and periglacial processes can also act as powerful geomorphic agents on marsh landscapes. These processes are rarely accounted for in salt marsh models. Ice rafting can redistribute sediments within a marsh. Rafts that form in tidal flats and ponds at low tide can be mobilized at high tide together with a surficial layer of sediments. The rafts are then moved to the marsh platform, and after melting they deliver the sediment trapped within them to the marsh surface (Argow et al. 2011). Ice cover in tidal flats and marsh creeks can lead to tidal damping (Georgas 2012), altering tidal modulation and therefore reducing currents and fluxes of water on the marsh platform. The mobilization of the ice cover can also scour and erode the vegetation mat below (Richard 1978). Permafrost thawing and other periglacial processes likely affect Arctic salt marshes, yet no studies are available on the geomorphology of these wetlands, and only a handful focus on their vegetation and ecology (e.g., Taylor 1981). This is a staggering lack of information, given the extent of shoreline at high latitudes and the fact that global warming increases coastal erosion in the Arctic (Mars & Houseknecht 2007).

4. KEY MEASUREMENTS AND PARAMETERS NEEDED IN MORPHODYNAMIC MODELS OF SALT MARSHES

Characterization of geomorphic setting and forcing conditions is necessary for initializing morphodynamic models, comparing models and data, and interpreting and generalizing observational data. Most observational studies of marshes focus on rates of accretion at several locations within a study area and document some subset of other marsh characteristics. Because few observational studies were conceived with the intent that they would be integrated with models, they may not have collected all the data necessary for model parameterization and testing. Here, we highlight aspects of marsh morphology and forcing that are likely to be important when linking observational and modeling studies of the morphodynamics of low marshes.

Proper characterization of tidal propagation and related flooding regimes requires a high-resolution digital elevation model (DEM) that includes the tidal channel network as well as the topographic variations that are linked to the channel network, such as channel-bank levees (Sullivan et al. 2019) (**Figure 5**). Larger-scale planform characteristics like third- and fourth-order tidal channels can be obtained from aerial imagery, but the kind of vertical resolution required for morphodynamic modeling is best provided by detailed topographic surveys, lidar-based elevation measurements, or high-resolution photography coupled with structure-from-motion analysis (James et al. 2017). Repeated high-resolution topographic surveys offer the potential to spatially map rates and patterns of marsh erosion and deposition (Zhao et al. 2017, Goodwin et al. 2018), providing both insight into these processes and a challenging test of model predictions.

Modeling marsh systems affected by SSC in adjacent bays requires knowing not only the marsh platform and tidal network morphology but also the morphology of the adjoining tidal flat and basin. Because of the importance of water depth to local wave generation, tidal circulation, and bed shear stresses in bays, poor resolution of bay bathymetry can potentially lead to substantial errors in calculated SSC on the tidal flats bordering marshes and channel mouths. Subtidal processes are less sensitive to microtopography than are those acting on intertidal marsh platforms, but the larger-scale patterns of subtidal channels and shoals are an important—though not always well resolved—control on sediment resuspension and transport in shallow coastal bays.

Rates of sediment resuspension and deposition depend on sediment properties such as grain size, erodibility, and settling velocity, but these can be challenging to map over a marsh system.

The relatively high density of vegetation over most of the marsh platform slows tidal flows over the marsh to the point where shear stresses are too low to entrain sediment from the marsh surface (Leonard & Luther 1995, Christiansen et al. 2000). As a result, the sediment properties of the tidal flats or channels that supply sediment to the marsh (e.g., Wiberg et al. 2015) are generally more important for morphodynamic processes than the properties of the sediment on the marsh surface. Direct freshwater inflow, along with the sediment it carries, is also important in fluvial-dominated systems (e.g., Khan et al. 2013, Ensign et al. 2014).

While the marsh surface is generally depositional, the marsh edge is most often erosional (Mariotti & Fagherazzi 2013), and characterizing the physical properties of the marsh edge (e.g., soil strength, root strength, and the depth and density of invertebrate burrows) is a challenge, particularly because the position of the edge is not static but progresses through the marsh as the edge erodes. Few models of lateral marsh retreat represent the processes at the marsh edge at this level of detail (Bendoni et al. 2016). Even the use of a simple linear relationship between wave power (or another wave parameter) and rates of marsh-edge erosion requires local calibration (e.g., Marani et al. 2011, McLoughlin et al. 2015).

Tides and winds provide the primary forcing for flow and sediment transport in shallow coastal bays and marshes. Astronomical tides are straightforward to calculate and predict from tidal constituents available for much of the world's coastline (e.g., Hamlington et al. 2016), whereas temporal variations in winds and storm surge are more difficult to characterize. For many US coastal sites, 30–40-year records of meteorological data are available from coastal stations or from reanalysis products, such as the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR). Care must be taken when choosing a site to be representative of wind conditions in coastal bays. A recent analysis by Mariotti et al. (2018) showed that land-based meteorological data can underestimate wind speed and modify wind direction relative to offshore or bay stations, primarily owing to effects of high land roughness.

In many shallow bays, waves are a much more important driver of high SSC than are tides (Lawson et al. 2007, Callaghan et al. 2010). Few coastal bays have long-term monitoring of waves, and wave fields can exhibit strong spatial variations owing to differences in fetch, water depth, and bottom roughness. As a result, it is often necessary to compute the wave field in coastal bays using models such as the Simulating Waves Nearshore (SWAN) numerical wave model (Booij et al. 1999) or the Young & Verhagen (1996) parametric wave model developed for shallow water bodies. Storm surge (positive and negative) can be quantified as the difference between measured and predicted tides at a site (e.g., Castagno et al. 2018). Forecasting storm surge is challenging and is best approached statistically or using specific storm scenarios combined with a storm surge model (Garzon & Ferreira 2016).

Testing of marsh morphodynamic models is limited by a lack of sediment transport measurements from the marsh itself. SSC and sediment fluxes are typically measured in tidal channels via high-frequency optical backscatter sensors (Fagherazzi & Priestas 2010, Ganju et al. 2017). Suspended sediment measurements on the marsh platform are frequently limited to a few points on the marsh surface (Christiansen et al. 2000, Leonard & Luther 1995). This approach makes it difficult to determine how conditions in tidal channels relate to conditions on marshes and largely precludes understanding how nontidal drivers (e.g., storms and seasonal vegetation growth) influence the distribution of sediment across marsh platforms.

Quantifying rates of marsh accretion is the goal of a majority of observational and modeling studies of marshes, but calculations of marsh deposition rates should be made within the context of the broader sediment budget of the system. Morphodynamic models, by definition, are mass conserving and therefore track sediment in and out of every grid cell in the model as well as any sediment added at a boundary (e.g., fluvial input). That does not guarantee, however, that mass is eroded and deposited in the correct amounts in the correct locations. Observational data are essential to constrain how much sediment is entering and leaving the system (Ganju et al. 2017, Hopkinson et al. 2018) and document patterns of marsh deposition (e.g., van Proosdij et al. 2006, Moskalski & Sommerfield 2012) and edge erosion (e.g., McLoughlin et al. 2015, Goodwin et al. 2018). Geochemical measurements may help to distinguish among terrestrial, marine, and estuarine sources. For example, organic matter deposited on marshes is often old and isotopically different from estuarine sediment sources, suggesting that continued marsh accretion takes place at the expense of existing marshes (Hopkinson et al. 2018, Van de Broek et al. 2018).

5. CRITICAL QUESTIONS AND DATA FOR COMPARING MODELS AND OBSERVATIONS

The previous sections have highlighted often overlooked processes that are critical to represent when modeling the morphodynamics of intertidal low marshes in settings with a small to moderate tidal range, as well as a set of site characteristics that we may need to know to make observations and model results comparable enough to be useful for hindcasting past change and forecasting future marsh change. This section considers how to better integrate models and observations. We focus largely on using field observations to parameterize and test numerical models, but model–data integration also allows interpretation of field measurements in the context of long-term ecomorphodynamic feedbacks that are difficult to observe with point-based or short-term measurements.

How to proceed with model–data comparisons depends on the spatial and temporal scales of interest and the nature of the models being considered. Idealized morphodynamic models are designed for improving general understanding, not making site-specific predictions. Therefore, the general outcomes should be qualitatively compared with behaviors from a diverse set of marshes rather than quantitatively compared at one particular site. Idealized morphodynamic models also pair well with field experiments as a test of our understanding of specific marsh processes. For example, early models with vegetation–sedimentation feedbacks (Morris et al. 2002, D'Alpaos et al. 2007b, Kirwan & Murray 2007, Temmerman et al. 2007) were instrumental in establishing the role of vegetation in marsh stability, which has now been tested in multiple manipulative and natural field experiments (Langley et al. 2009, Baustian et al. 2012, Silliman et al. 2012, Möller et al. 2014, Coleman & Kirwan 2019).

Landscape-scale (regional) models make actual predictions for specific sites, sea level scenarios, and time frames (Schile et al. 2014, Alizad et al. 2016, Thorne et al. 2018). These models inform management decisions but have rarely been tested (Mogensen & Rogers 2018). Hindcasting is difficult because model behavior depends so strongly on the initial elevation of the marsh (Wu et al. 2015, Gesch 2018). High-resolution lidar-based DEMs are available for only the last decade or two and have a vertical error of approximately 10–20 cm (Gesch 2009, Hladik & Alber 2012). Therefore, the amount of error in measured elevations is potentially greater than the amount of elevation change that could be predicted by the models. Hindcasting over longer timescales precludes the use of high-resolution elevation data but allows comparisons based on vegetation change, which can be reconstructed over the multidecadal timescales that landscape models are designed to simulate. Mogensen & Rogers (2018) suggested beginning with a modern DEM and then using the model itself to hindcast the amount of elevation and vegetation change that would have occurred in historical time steps. Nevertheless, hindcasts involve assumptions about how other environmental factors (e.g., SSC) have changed through time.

An alternative approach to testing model performance is determining how well models predict current spatial gradients in accretion rates, biomass, and organic content (e.g., Hu et al. 2018). This approach only requires information on current environmental drivers, such as elevation and distance from channels, and does not require assumptions about changing historical conditions. Elevation change rates based on SETs are the best source of accretion rates for this test because they reflect current (i.e., the last 5–20 years) rather than historical conditions. A third approach uses the multiple marsh accretion models now available, each with a different set of assumptions and simplifications. Although they have not yet been used to simulate a common location, comparing an ensemble of models, as is often used in climate studies, may help evaluate model uncertainty and provide more robust results (e.g., Kirwan et al. 2010).

Global models also need better integration with field data. There is only one global marsh model, the Dynamic Interactive Vulnerability Assessment (DIVA), and it is calibrated using marsh accretion data from just 18 locations (Schuerch et al. 2018). While the model can predict neutral, positive, or negative accretion balances (i.e., accretion rate minus SLR rate) in these locations, a more proper test would be how well it predicts what regions of the world are currently experiencing marsh loss, and their rates. Such a test would be difficult. There are no global compilations of marsh loss extent, much less rates of marsh loss. Global models also remain constrained by the availability of data sets for model parameterization. Satellite-derived global sediment data have a resolution of approximately 5 km (1/24°), which precludes knowledge of SSC in most of the tidal channels and coastal bays that directly supply marshes (Barrot et al. 2007). Global DEMs are not adequate for modeling coastal vulnerability to increments of SLR less than 1 m or for planning horizons less than 100 years (Gesch 2018). Finally, it is not possible to evaluate model performance with an ensemble approach, as in global climate models, because there are no other global marsh models to compare.

Spatially distributed models of salt marsh evolution require spatially distributed data sets for calibration and validation. However, salt marsh evolution and vulnerability are typically evaluated with point measurements of accretion such as sediment cores and SETs (Crosby et al. 2016, Kirwan et al. 2016b, Jankowski et al. 2017), and hydrodynamic and sediment transport processes are typically compared with point measurements taken with just a few instruments, such as pressure sensors for water elevation and waves, velocimeters for water flow, and turbidity sensors for SSC (Fagherazzi & Priestas 2010, Ganju et al. 2017, Duvall et al. 2019).

Remote sensing represents an alternative, and potentially powerful, approach for developing data sets to test and validate models of salt marsh evolution (Moffett et al. 2015). The spatial scale of remote sensing data, from meters to hundreds of meters, often matches the resolution of marsh models. Historically, aerial photograph analysis has been used to test the ability of models to reproduce spatial patterns such as the planform geometry of tidal channels (D'Alpaos et al. 2005, 2007b), migration of marshes into forests (Kirwan et al. 2016a), and erosion of marsh edges (McLoughlin et al. 2015, Leonardi et al. 2016a). Landsat imagery has been used to determine vegetation dynamics in salt marshes (O'Donnell & Schalles 2016, Sun et al. 2018), showing how marsh vegetation is changing in time because of SLR and increased flooding (**Figure 6**). Hyperspectral and multispectral sensors can be used to infer the spatial distributions of SSC and other compounds in the water column and their variations in time (Volpe et al. 2011, Newcomer et al. 2014). Finally, lidar-derived DEMs corrected for vegetation height based on hyperspectral imagery and/or real-time kinematic surveys may lead to DEMs that are accurate enough to parameterize and test numerical models over large spatial scales (Hladik & Alber 2012, Hladik et al. 2013, Garzon & Ferreira 2016, Wagner et al. 2017). These remote sensing applications will only improve as unmanned aerial vehicles facilitate data acquisition (Gray et al. 2018).

In the near future, novel airborne and satellite sensors will provide high-resolution data sets that can be used to validate models of marsh flooding, tidal channel hydrodynamics, and sediment transport. The Surface Water and Ocean Topography (SWOT) mission can provide spatially distributed measurements of water slopes in tidal channels, thus unlocking the detailed mechanisms

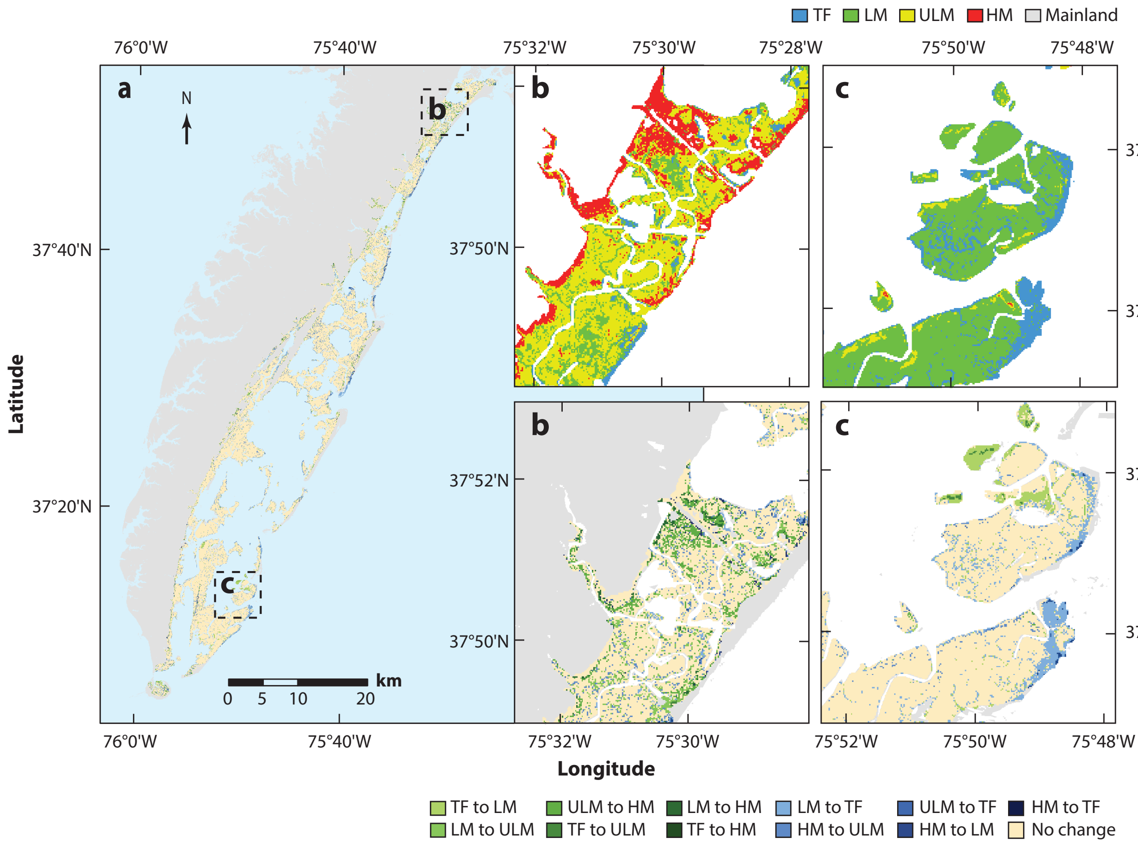

Figure 6

Classification and conversion maps of salt marsh vegetation communities at two sites in the Virginia Coast Reserve (VCR) based on Landsat images. (*a*) Map of the VCR showing the site locations. (*b*,*c*, *top*) Detailed classification maps of two sites within the VCR in 2011. (*b*,*c*, *bottom*) Conversion maps for each pair of salt marsh vegetation communities for the period 1984–2011. Darker colors indicate more dramatic changes in relative elevation. Abbreviations: TF, tidal flat; LM, low marsh; ULM, upper low marsh; HM, high marsh. Figure adapted from Sun et al. (2018) with permission.

of marsh plumbing (Altenau et al. 2019). The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) can measure variations of water levels under vegetated canopies (Shaw et al. 2016), thus allowing the calibration of vegetation modules in salt marshes. The richness of these data sets makes it possible to capture spatial gradients in water surface elevation and SSC, constraining the supply of sediment to the marsh platform and providing detailed observations for model–data comparison.

6. CONCLUSIONS

Marshes exist in a multidimensional framework that includes their geomorphic, hydrodynamic, climatological, and ecological settings and their histories (at both the geologic and human timescales). Because every marsh is different, intercomparisons and meta-analyses must be done with care so that variability in characteristics among sites does not obscure broad trends.

Better predictions require models that account for all important processes, but the particular set of key processes varies depending on the location and model purpose. One example of a broadly applicable but underrepresented process in models is the effect of storms (winds, waves, and storm surge) on water levels, SSC, and depositional volumes and patterns. Marshes are also often tightly coupled with processes in adjacent bays, particularly through marsh-edge erosion and sediment fluxes. This coupling controls changes in bay width and depth and variations of marsh elevation relative to mean sea level. As a result, the sediment budget of the entire intertidal landscape must be correctly captured by models of marsh evolution.

Model parameterization and testing remain limited by spatial and temporal observations of marsh change. New observational techniques, particularly remote sensing, offer the possibility of measuring landscape change at scales comparable to model hindcasts and forecasts, thereby providing more robust and informative tests of model skill.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

Primary support for this work was provided by the National Science Foundation through awards 1237733 and 1832221 (P.L.W., S.F., and M.L.K.), 1427282 (P.L.W.), 1426981 (M.L.K.), and 1637630 (S.F.). Further support for the preparation of this review was provided by a Sesquicentennial Associateship from the University of Virginia (P.L.W.).

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