

Influence of tidal range on the stability of coastal marshland

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[1] Early comparisons between rates of vertical accretion and sea level rise across marshes in different tidal ranges inspired a paradigm that marshes in high tidal range environments are more resilient to sea level rise than marshes in low tidal range environments. We use field-based observations to propose a relationship between vegetation growth and tidal range and to adapt two numerical models of marsh evolution to explicitly consider the effect of tidal range on the response of the marsh platform channel network system to accelerating rates of sea level rise. We find that the stability of both the channel network and vegetated platform increases with increasing tidal range. Our results support earlier hypotheses that suggest enhanced stability can be directly attributable to a vegetation growth range that expands with tidal range. Accretion rates equilibrate to the rate of sea level rise in all experiments regardless of tidal range, suggesting that comparisons between accretion rate and tidal range will not likely produce a significant relationship. Therefore, our model results offer an explanation to widely inconsistent field-based attempts to quantify this relationship while still supporting the long-held paradigm that high tidal range marshes are indeed more stable.

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1. Introduction

[2] Due to their ecological and economical value, understanding how tidal wetlands will respond to global sea level acceleration has been identified as a scientific priority [Intergovernmental Panel on Climate Change, 2007]. Analyses of tide gauges and biostratigraphic indicators worldwide suggest the rate of sea level rise has doubled or tripled since the late 19th century, and will continue to accelerate throughout the 21st century [Donnelly *et al.*, 2004; Church and White, 2006; Rahmstorf, 2007; Gehrels *et al.*, 2008]. Although coastal marshes have generally maintained their morphology and position within the intertidal zone under historic rates of sea level rise [e.g., Redfield, 1972], concerns about their ability to survive more rapid rates of sea level rise have been expressed for more than 20 years [Orson *et al.*, 1985; Stevenson *et al.*, 1985; Reed, 1995].

[3] The ability of marshes to maintain their position within the intertidal zone depends on complex interactions between biological and physical sediment transport processes and their dependence on sea level [Allen, 2000; Friedrichs and Perry, 2001; Torres *et al.*, 2006]. At the most basic level, field measurements indicate that rates of mineral sediment deposition increase with the frequency and duration of tidal inundation, suggesting that marshes have some ability to

adapt to changing rates of sea level rise [Pethick, 1981; Bricker-Urso and Nixon, 1989; Pasternack *et al.*, 2000]. Increasing inundation may also stimulate vegetation growth, promoting inorganic sediment trapping and in situ organic accretion [Morris *et al.*, 2002; Mudd *et al.*, 2009]. Furthermore, ecomorphodynamic feedbacks between the marsh platform and channel network influence the elevation of a marsh relative to sea level since channels deliver sediment to the marsh platform, and interactions between vegetation growth and tidal prism volume control channel network evolution [D'Alpaos *et al.*, 2007b; Kirwan and Murray, 2007; Kirwan *et al.*, 2008]. Numerical modeling suggests that these feedbacks allow marshes to persist in the intertidal zone under a wide range of sea level rise rates and suspended sediment concentrations [e.g., Morris *et al.*, 2002; D'Alpaos *et al.*, 2007b; Kirwan and Murray, 2007; Kirwan and Temmerman, 2009]. Indeed, many marshes worldwide have accreted vertically at roughly the same rate as sea level rise over time scales ranging from a few years to a century [Friedrichs and Perry, 2001; Cahoon *et al.*, 2006; French, 2006].

[4] While vertical accretion rates are often high enough to compensate for rates of sea level rise, marshes in some regions are losing elevation relative to sea level or showing other signs of submergence [e.g., Day *et al.*, 1995; Reed, 1995; Donnelly and Bertness, 2001; Kearney *et al.*, 2002; Van der Wal and Pye, 2004; Hughes *et al.*, 2009]. Early compilations of measured accretion rates in marshes from a variety of tidal ranges demonstrate a tendency for accretion deficits (sea level rise rate minus accretion rate) to decrease with increasing tidal range [Harrison and Bloom, 1977; Stevenson *et al.*, 1986]. Consequently, several authors have

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hypothesized that tidal range exerts a strong control on the stability of coastal marshes, where macrotidal marshes (tidal range > 4 m) can survive faster rates of sea level rise than mesotidal (tidal range 2–4 m) or microtidal marshes (tidal range < 2 m) [Harrison and Bloom, 1977; Stevenson *et al.*, 1986; Day *et al.*, 1995; Friedrichs and Perry, 2001]. A variety of conceptual explanations have been proposed, although most focus on the expanded range of elevations that vegetation can occupy and the ability of tidal channels to deliver more sediment in high tidal range environments (see Friedrichs and Perry [2001] and discussion below). These observations inspire simple attempts to relate global wetland vulnerability and projections of future sea level induced marsh loss to tidal range. For example, the ratio between tidal range and sea level rise rate defines the vulnerability index used to project global wetland losses on the order of 20–50% in the next century [Nicholls *et al.*, 1999; Nicholls, 2004; McFadden *et al.*, 2007].

[5] Despite the widespread assumption that tidal range significantly enhances marsh stability, more recent and comprehensive compilations of accretion rate measurements have not confirmed early observations. One compilation from macrotidal marshes in Canada suggests a negative relationship between accretion rate and tidal range [Chmura and Hung, 2004]. Large data sets centered in North America [Cahoon *et al.*, 2006] and Europe [French, 2006] imply no clear relationship between tidal range and accretion rate or accretionary deficit. These contrasting scenarios (increased stability at higher tidal range, decreased stability at higher tidal ranges, and no effect of tidal range on marsh stability), illustrate a need to more thoroughly examine a potential relationship between tidal range and marsh stability.

[6] Predicting the vulnerability of coastal marshes to sea level rise is vital for effective management, and discerning a mechanistic relationship between tidal range and marsh stability represents a potentially important scientific contribution. In this work, we incorporate empirical relationships between vegetation growth and tidal range into two existing models of biologically influenced marsh evolution to explore how tidal range influences the elevation, biological productivity, and platform stability of salt marshes responding to sea level change.

2. Model Approach

[7] We explore the influence of tidal range on the stability of coastal marshes by modeling the response of marshes to sea level change under a variety of tidal ranges. We focus on incorporating relationships between tidal range and vegetation growth since previous modeling work suggests vegetation plays a crucial role in determining the evolution of intertidal surfaces [Kirwan and Murray, 2007; Marani *et al.*, 2007], and a connection between tidal range and the range of elevations that vegetation can occupy has been hypothesized to explain patterns of marsh stability [Day *et al.*, 1995]. Our first modeling approach considers the zero dimensional, vertical evolution of a point within the vegetated marsh platform [Morris *et al.*, 2002]. Such an approach assumes to a certain degree that a single point can represent the marsh platform as a whole, and is most applicable to portions of a marsh far away from the influence of channels. In an effort to

consider how important interactions between the channel network and the marsh platform influence the stability of marshes under various tidal ranges, we have also incorporated tidal range effects into a previously described, spatially explicit model [Kirwan and Murray, 2007]. Both of these models include feedbacks between inundation, sediment deposition, and vegetation growth that allow marshes to adjust to changes in rates of sea level rise, and generally maintain an equilibrium position within the intertidal zone under moderate rates of sea level rise.

3. Vertical (0-D) Evolution of the Marsh Platform

3.1. Sediment Deposition

[8] For a marsh surface inundated by tidal waters containing fine sediment, deposition rates are generally proportional to the depth of water inundating the marsh platform, a proxy for the duration of flooding [e.g., Allen, 2000]. Following Morris *et al.* [2002], bed surfaces accrete at rates proportional to the depth of water at high tide (D):

$$\text{Accretion rate} = (q + k_1 B)D \quad (1)$$

where B represents the local vegetation biomass. The coefficients q and k describe the relationship between deposition and inundation in the presence and absence of vegetation, respectively, as quantified for *Spartina alterniflora* salt marshes at North Inlet, South Carolina [Morris *et al.*, 2002]. The value of q is dependent on sediment availability, and k_1 accounts for sediment trapping by vegetation [Morris *et al.*, 2002]. Vegetation biomass is also related to inundation depth at high tide:

$$B = aD + bD^2 + c \quad (2)$$

where a , b , and c are empirical coefficients that determine the upper and lower depth limits, and magnitude of B . These coefficient values were measured in a single South Carolina salt marsh, and are likely to vary at other individual marshes, and as a function of tidal range [Morris *et al.*, 2002; Morris, 2006]. Nevertheless, the qualitative pattern that an increase in inundation depth stimulates vegetation growth up to an optimal depth, beyond which it reduces growth, is consistent with ecological theory postulating that an optimum exists for any factor (i.e., stressor) which governs the range and abundance of an organism [Shelford, 1931].

3.2. Influence of Tidal Range on Vegetation

[9] Marsh vegetation generally occupies bed surfaces within the intertidal zone, and the range of suitable elevations has been widely observed to increase with tidal range [e.g., McKee and Patrick, 1988]. Although *Spartina alterniflora* can grow at elevations slightly above mean high tide, for simplicity and consistency with previous modeling efforts, we assume in the model that its upper elevation limit is mean high tide. (This assumption will not likely effect model behavior since *S. alterniflora* productivity typically has low productivity at elevations above mean high tide [Morris *et al.*, 2002], and marsh stability is more importantly

related to the lower bound of vegetation growth.) Based on a compilation of the growth ranges of *S. alterniflora* at 24 marshes in the United States [McKee and Patrick, 1988] the minimum elevation (relative to high tide) that can support vegetation growth can be written as

$$z_{\min} = 0.7167t_r - 0.0483 \quad (3)$$

where t_r is the tidal range in meters.

[10] While tidal range clearly affects the growth range of marsh vegetation, we assume that it does not directly influence the productivity or standing biomass of vegetation for a given inundation depth in our model. We base this assumption on an analysis of *S. alterniflora* productivity measurements for 51 marshes along the Gulf and Atlantic coasts of North America [Kirwan *et al.*, 2009]. Here, we compare estimates of productivity compiled by Kirwan *et al.* [2009] to mean tidal ranges for each site. After removing latitudinal trends, the residual productivity estimates show only a weak relationship with tidal range (Figure 1).

[11] Following Morris *et al.* [2002], we assume that the relationship between elevation and productivity can be expressed as a quadratic function (equation (2)) where the maximum productivity exists at an elevation halfway between the lower and upper limits of its growth range. Given that the biomass at the upper and lower bounds is equal to zero and that it reaches a maximum at a known elevation, we use these three constraints to solve equation (2) for a , b , c for each tidal range considered. In this manner, we use equation (3) to essentially expand or contract the original productivity curve to address productivity under different tidal ranges without modifying the shape or maximum productivity that it predicts. Figure 2 depicts the modeled biomass productivity for a given inundation depth and tidal range. An important characteristic is that while tidal range does not directly influence the maximum productivity, the productivity for a given inundation depth strongly depends on the tidal range. For example, the model predicts that the productivity of a surface 20 cm below high tide would be $\sim 1700 \text{ g m}^{-2} \text{ yr}^{-1}$ under a 1 m tidal range or $\sim 1100 \text{ g m}^{-2} \text{ yr}^{-1}$ under a 2 m tidal range.

[12] Preliminary experiments designed to measure the relationship between productivity and inundation depth across sites with different tidal ranges confirm that a quadratic form productivity curve expands or contracts under different tidal ranges, suggesting our approach is reasonable (J. T. Morris, unpublished data, 2009). Nevertheless, we also consider alternative scenarios in which maximum productivity slightly increases or decreases with tidal range, and scenarios with a stronger or weaker relationship between tidal range and vegetation growth range. Variations in the range of elevations suitable for vegetation growth directly influence the productivity at a given inundation depth, and its relationship with tidal range (see Text S1 and Figures S1 and S3 of the auxiliary material).¹

3.3. Response of Marsh Platform to Sea Level Change

[13] For the equilibrium condition where the rate of sea level rise equals the rate of platform accretion, equation (1)

predicts equilibrium depths that are dependent on the relative rate of sea level rise (R), the sediment supply (q), and the biomass productivity:

$$D = R/(q + k_1B) \quad (4)$$

Therefore, for a given sediment supply and rate of sea level rise, the equilibrium depth is dependent on biomass productivity, which is in turn influenced by the tidal range. Together, equilibrium depths on vegetated surfaces increase slightly with tidal range if the rate of sea level rise is relatively slow (Figure 3a). Since the marsh surface equilibrates to generally similar elevations relative to high tide under a variety of tidal ranges, an expanding tidal range results in marsh elevations that are higher within the entire tidal frame (i.e., marsh elevations are always somewhere near high tide, but become much higher than low tide under large tidal ranges). Similarly, the biomass productivity on a marsh surface at equilibrium with the rate of sea level rise decreases with increasing tidal range since the platform's overall position in the tidal frame becomes more shallow (Figure 3b). Although the exact equilibrium depth and biomass productivity of a specific marsh would be a function of many factors (including sediment supply and the rate of relative sea level rise), their general relationship with tidal range is not strongly sensitive to alternative vegetation treatments (see Text S1 and Figures S2 and S4 of the auxiliary material).

[14] Under moderate and large tidal ranges, the model predicts equilibrium platform depths that are shallow enough to maintain vegetation growth, even at rapid rates of sea level rise (Figure 3). Under low tidal ranges and high rates of sea level rise, however, inundation depths may exceed those capable of supporting vegetation. Without vegetation, the depths required to balance sea level rise rates are very high, and the only stable configuration is a subtidal surface.

4. Coupled Channel Network and Marsh Platform Evolution

4.1. Model Approach and Construction

[15] Morphodynamics in the intertidal zone and the stability of marshes responding to sea level change are not governed exclusively by depositional processes on the marsh platform, but also by key interactions between the platform and channel network [D'Alpaos *et al.*, 2007b; Kirwan and Murray, 2007]. Channels supply sediment to the marsh platform, and platform characteristics influence the size and path of the tidal prism, strongly influencing how channel networks evolve. To capture these effects, we utilize an existing, spatially explicit model of marsh evolution [Kirwan and Murray, 2007]. The accretion and vegetation treatments are identical to the point based (0-D) model described above (including our tidal range modifications), except that we incorporate a sediment supply term that decreases with distance away from the nearest channel, and do not allow vegetation growth in eroding cells. Following Kirwan and Murray [2008a], the suspended sediment concentration decreases exponentially with distance (x) away from the nearest channel:

$$q(x) = q(0)e^{-rx} \quad (5)$$

¹Auxiliary materials are available in the HTML. doi:10.1029/2009JF001400.

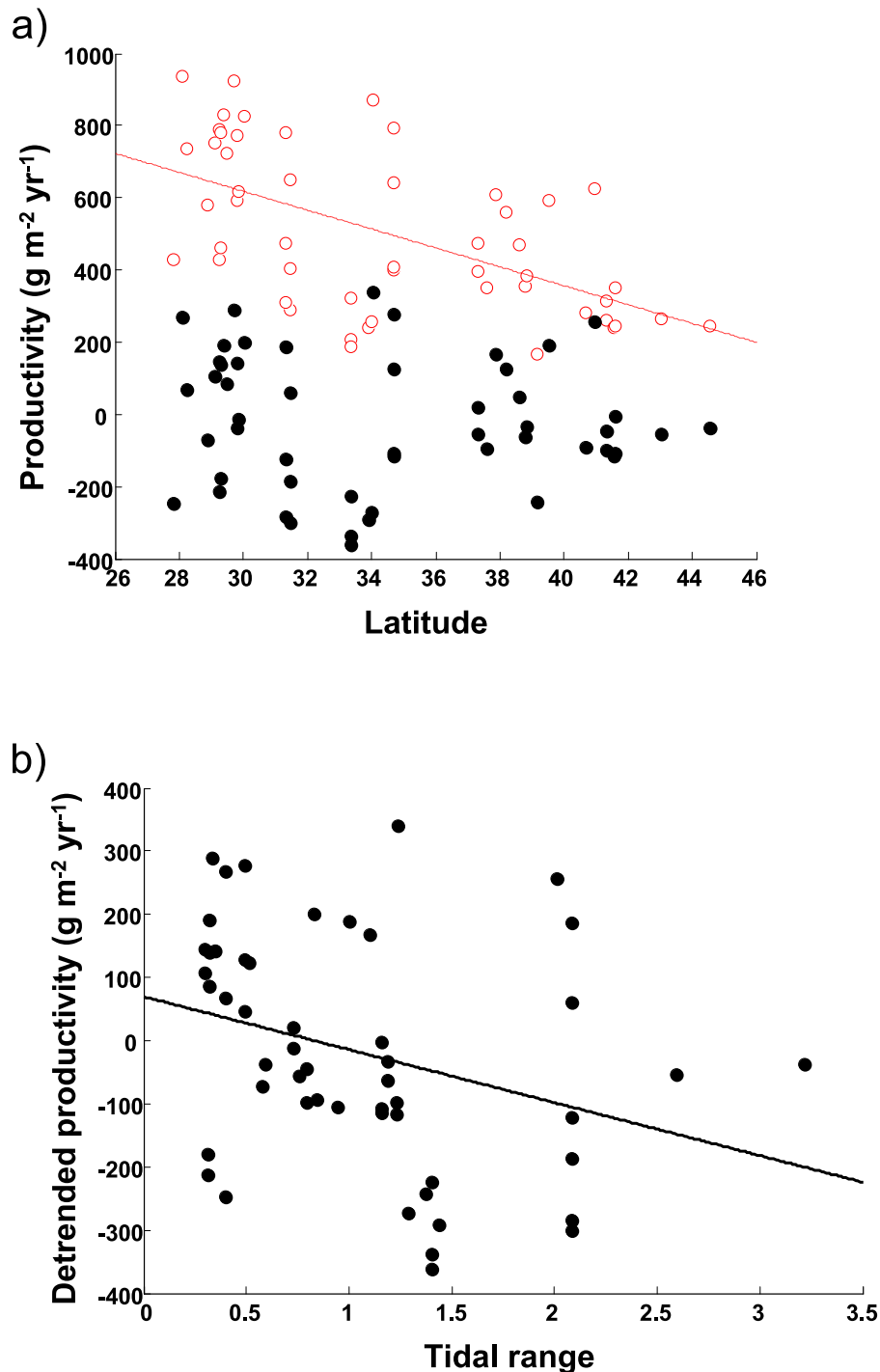


Figure 1. The effect of tidal range on *Spartina alterniflora* annual productivity. (a) Productivity across a latitudinal gradient in U.S. salt marshes, determined by end-of-season biomass measurements as compiled by Kirwan *et al.* [2009] (red open circles). Since tidal range generally increases with latitude in this data set, we have detrended the productivity measurements by latitude (black circles). (b) Detrended productivity measurements decrease slightly with increasing tidal range but the relationship is weak ($r = -0.32$, $p = 0.02$).

[16] Although the value of the decay coefficient (r) would be site-dependent, we choose $r = -0.031$ based on measurements in a Virginia salt marsh by Christiansen *et al.* [2000], and scale $q(0)$ to produce spatially averaged plat-

form accretion rates that are similar to previous modeling efforts [Morris *et al.*, 2002; Kirwan and Murray, 2007].

[17] Additionally, we represent minor and temporary vegetation disturbance by setting $B = 0$ in a small number of

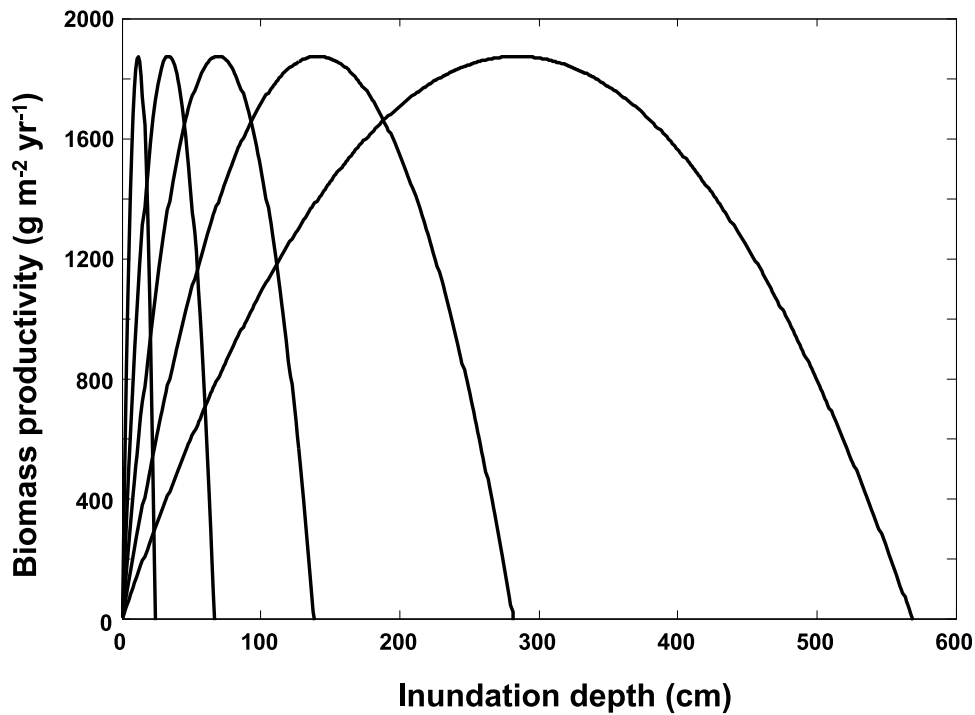


Figure 2. Relationship between biomass productivity and inundation depth for various tidal ranges. In the model experiments, increasing the tidal range causes an increase in the range of depths suitable for vegetation growth, but does not affect the maximum productivity. (left to right) Tide range = 40 cm, 100 cm, 200 cm, 400 cm, 800 cm.

randomly selected platform cells during each model iteration [Kirwan *et al.*, 2008]. In these experiments, each disturbed area covers at least one cell (5×5 m) and remains unvegetated for 1 year (six iterations). New disturbances replace formerly disturbed areas stochastically, so that the number of disturbed cells always oscillates around 5% of the total number of platform cells.

[18] As described previously [Kirwan and Murray, 2007], the model routes water across the marsh platform and through the channel network during each tidal cycle according to a simplified flow routing scheme proposed by Rinaldo *et al.* [1999]. The volume (V) of water flowing through each cell is a function of sea level at high tide (s) and the bed elevations (z) of every cell within its watershed (w):

$$V = \int_w [s - z(x, y)] dx dy \quad (6)$$

[19] We set the maximum value of $(s-z)$ to the tidal range since surfaces with elevations below low tide do not drain completely. We convert the volume of water passing through each cell into discharge and shear stress as described by Kirwan and Murray [2007]. Channels erode when bed shear stresses exceed the shear strength of cohesive sediment. A gravity-driven transport function moves sediment in the downslope direction and tends to widen channels as they deepen in an attempt to represent processes such as creek bank slumping. The gravity-driven sediment flux leaving each model cell is inversely proportional to the local biomass

of vegetation, reflecting the stabilizing effect of plant roots [Kirwan and Murray, 2007].

[20] In addition to ecomorphodynamic couplings between vegetation growth, platform accretion, and channel widening, the model captures two important feedbacks between the marsh platform and channel network. First, the elevation of the marsh platform relative to sea level influences the total volume of water flowing through channels (i.e., the tidal prism volume). Second, the accretion rate of the marsh platform is determined by sediment concentrations that decrease with distance away from channels. Therefore, the channel network will tend to expand with increasing submergence of the platform, but channel expansion will lead to enhanced platform accretion. Previous simulations demonstrate that water depths on the platform tend to deepen and channels expand slightly in response to an increase in sea level rise rate until vegetation productivity and accretion rates increase enough to accommodate the rate of sea level rise, establishing an equilibrium morphology [Morris *et al.*, 2002; Kirwan and Murray, 2007; Kirwan *et al.*, 2008].

4.2. Model Experiments

[21] We start each experiment with a gently sloping subtidal bed surface and allow the surface to develop into a distinct vegetated marsh platform and channel network under a constant 1 mm yr^{-1} rate of sea level rise [e.g., Kirwan and Murray, 2007]. When the surface reaches dynamic equilibrium (i.e., accretion everywhere equals the rate of sea level rise, and the morphology remains constant), we increase the rate of sea level rise to 3 mm yr^{-1} and then to 10 mm yr^{-1}

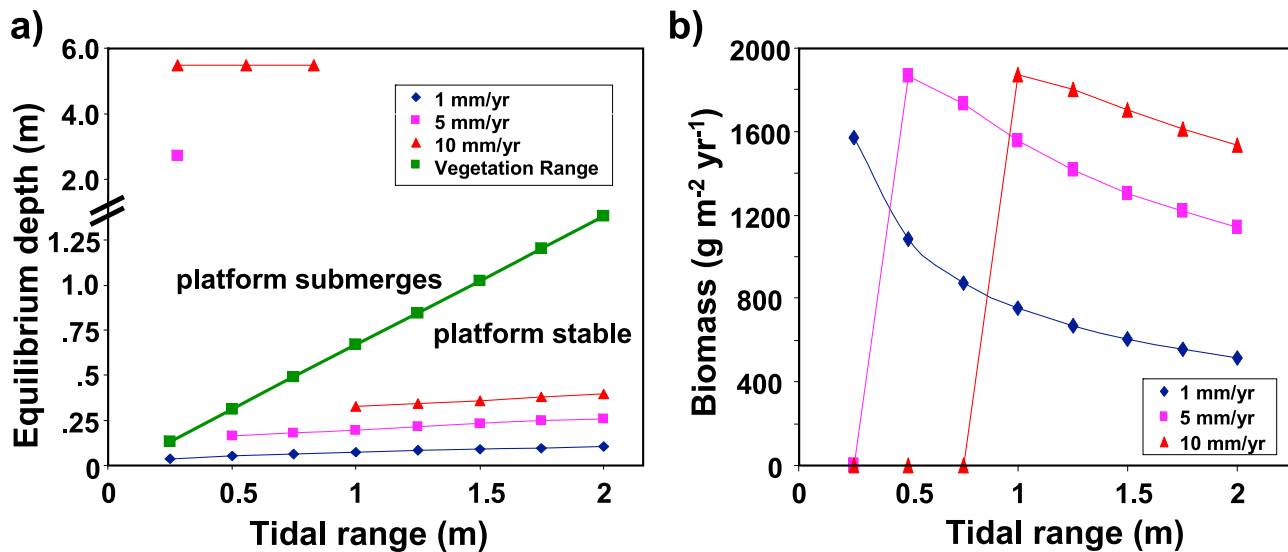


Figure 3. (a) Modeled equilibrium depth (m below MHT) of the marsh platform as a function of tide range under a variety of sea level rise rates. Green squares denote the maximum depths capable of supporting vegetation, so points above the solid green line indicate conditions where the platform will become too deep for vegetation growth and points below the line indicate conditions where the platform will remain vegetated. (b) Biomass productivity as a function of tidal range for marshes at equilibrium with various rates of sea level rise (where equilibrium depths correspond to Figure 3a). Biomass is zero when equilibrium depths are too great for vegetation growth.

and allow the morphology to equilibrate after each step. In separate experiments, we consider the morphologic response to sea level acceleration under a 0.4 m, 1 m, and 4 m tidal range.

[22] Marsh surfaces deepened in response to sea level acceleration in all experiments (Figure 4). Like the 0-D model experiments, platform elevations maintained an intertidal position except for the lowest tidal range experiment (40 cm), where elevations across the entire platform submerged to depths incapable of supporting vegetation under a rapid rate of sea level rise (10 mm yr⁻¹). In the coupled 2-D model experiments, however, the vertical position of the marsh within the tidal frame influences the extent and stability of the channel network. In all experiments, an increase in inundation depth led to an increase in the tidal prism volume, and a tendency for channels to expand (Figure 5). The channel network deepened, lengthened and widened significantly in response to sea level acceleration under the 0.4 m and 1 m tidal range experiments, but was relatively stable in the 4 m tidal range experiment.

[23] Different patterns of tidal prism enlargement explain the observation that channels were more stable at higher tidal ranges. Under low rates of sea level rise, both the 0-D and 2-D models predict that the marsh platform sits high in the tidal frame, and at relatively similar elevations for various tidal ranges. Channel networks, however, are deeper, more expansive, and experience greater tidal fluctuations in high tidal range environments than channel networks in low tidal range environments. Therefore, the contribution of water from the channel network itself likely explains the initially large tidal prism volumes under large tidal ranges and the initially small tidal prism volumes under small tidal ranges

(Figure 5). The maximum amount of water a point within the channel network can contribute toward the tidal prism volume is limited by the tidal range since channels deeper than low tide drain only to low tide levels. Our 2-D model experiments indicate that even at low rates of sea level rise, large portions of the channel network have bed elevations below low tide, and therefore do not increase their contribution to the tidal prism volume with an increase in the rate of sea level rise. Since the contribution of tidal prism volume from the channels themselves is unlikely to change dramatically, increases in tidal prism volume due to sea level acceleration must come from changes on the marsh platform. Given that platform inundation depths increase similarly for all tidal ranges, and that channel contributions are small for low tidal range environments, prism volumes expand disproportionately under low tidal ranges (Figure 5). In these experiments, small changes in platform depth lead to a five-fold increase in tidal prism volume under a 1 m tidal range, but contribute relatively little water to the tidal prism at higher tidal ranges.

[24] The peculiar oscillations in tidal prism volume and channelized area in the 4 m tidal range experiment (Figure 5) reflect complex interactions between the platform and channel network, and between biological and physical processes. This behavior follows an increase in the rate of sea level rise to 10 mm yr⁻¹, and captures the migration and reorganization of a dominant tidal channel network (Figure 4). Since sediment concentrations decrease exponentially with distance from the nearest channel, new channels bring extra sediment to the marsh platform. This tends to increase the elevation of the platform and reduce tidal prism volumes in the model. Platform shallowing, in turn, causes vegetation productivity

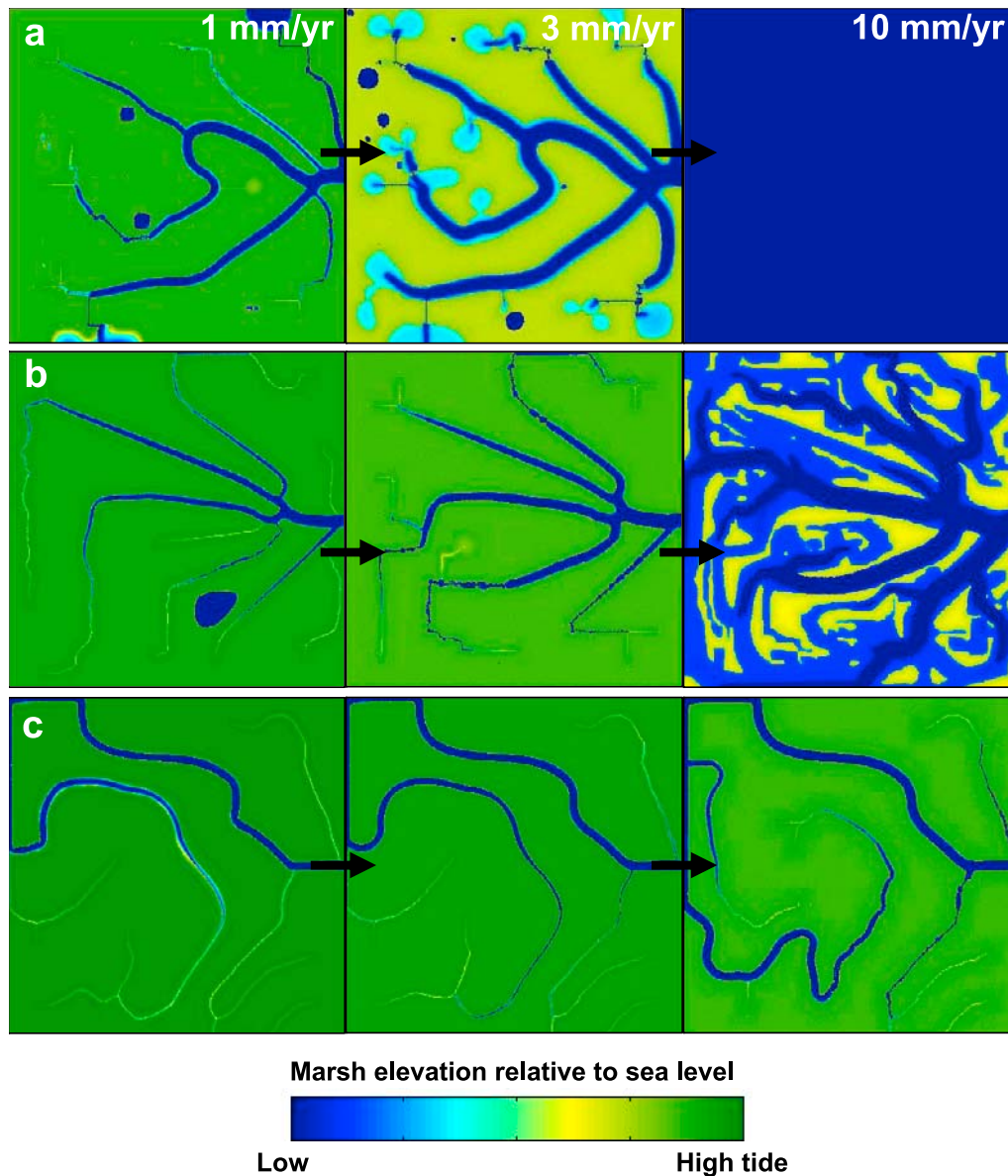


Figure 4. Planform response of marshes to sea level change. (left to right) Equilibrium morphology at 1 mm yr^{-1} , 3 mm yr^{-1} , and 10 mm yr^{-1} sea level rise rate. Figure 4a is with 40 cm tidal range; Figure 4b is 1 m tidal range; Figure 4c is 4 m tidal range. Dark blue colors indicate bed elevations near mean low tide; dark green colors indicate bed elevations near mean high tide.

to decrease which leads to network expansion, and an increase in tidal prism. The opposite scenario would occur during channel abandonment. Figure 5a shows tidal prism volumes that are initially very high after the abrupt sea level acceleration at year 3333. Through time, both the amplitude and magnitude of the tidal prism fluctuations decrease, reflecting an overall adjustment of the platform and network toward the new rate of sea level rise, though it is statistically similar to the initial equilibrium configuration. While this transient behavior illustrates important processes occurring in the model, applying it to natural systems seems inappropriate since sea level rise rates seldom increase according to abrupt step changes, and tidal channel network organization has long been observed to be remarkably stable

[e.g., Goldthwait, 1937; Redfield, 1972; Gabet, 1998; Marani *et al.*, 2003].

5. Discussion

[25] In this initial attempt to explore how tidal range and vegetation growth interact to govern the stability of marshes responding to sea level change, we represent a number of complex processes in simple ways in our model approach (e.g., water routing, vegetation treatment, shear stress calculations). Some of these treatments have been discussed previously and subjected to sensitivity analyses [e.g., Kirwan and Murray, 2007, 2008b]. Our simplified flow routing scheme, for example, does not consider hydro-

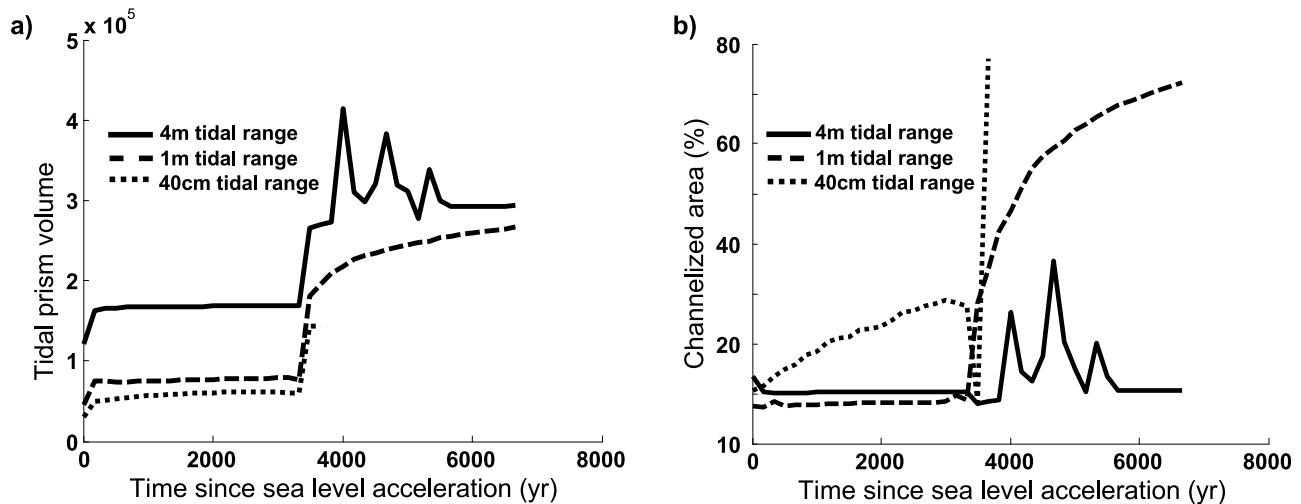


Figure 5. Response of (a) tidal prism volume and (b) channel network extent to accelerations in the rate of sea level rise under various tidal ranges. In these experiments, which correspond to Figure 4, sea level rise rates increase from 1 mm yr^{-1} to 3 mm yr^{-1} at year zero, and from 3 mm yr^{-1} to 10 mm yr^{-1} at year 3333. Solid line denotes 4 m tidal range, dashed line denotes 1 m tidal range, and dotted line denotes 40 cm tidal range. Experiment under 40 cm tidal range ends shortly after bed surface becomes completely subtidal. Tidal prism volume, defined as the total volume of water passing through the channel network during a single ebb flow, expands disproportionately at low tide ranges (Figure 5a). The channelized area, defined as the percent of the model domain occupied by channels, expands more under low tidal ranges than high tidal ranges (Figure 5b). (Our method for extracting the channel network cannot discern between channel cells and shallow ponds connected to the channel network. Therefore, it tends to slightly overestimate channelized area for the 0.4 m tidal range case and mask an initial condition where channelized area increases with tidal range. Short-term fluctuations in tidal prism volume and channelized area after year 3333 in the 4 m tidal range experiment reflect the migration and reorganization of a dominant tidal channel, as described in the text.)

dynamic intricacies that could influence channel erosion and its effect on sediment deposition. Although this hydrodynamic treatment is widely used in spatial models of tidal channel network evolution [Rinaldo *et al.*, 1999; Fagherazzi and Sun, 2004; D'Alpaos *et al.*, 2005, 2007b], tidal asymmetry and the maximum rate at which water drains from the platform edge to the channel would likely change with tidal range. Moreover, since we focus on describing the direct effects of tidal range on vegetation growth, and its impact on marsh stability, we assume that many site-specific parameters do not vary with tidal range. Certain model parameters (e.g., q , k , r) are based on empirical observations in microtidal environments and would likely change in unknown ways for marshes at other tidal ranges. For simplicity and clarity of results, we assume these parameters remain constant. Therefore, we caution that our results should be interpreted as an initial exploration into the key ecomorphodynamic interactions that govern the basic responses of marshes to sea level rise, rather than as a detailed and quantitatively accurate prediction [Murray, 2003, 2007].

[26] We further caution that our model approach does not attempt to address two processes that are important contributors to vertical accretion in marshes in low tidal range environments. First, deposition of sediment during storms can be a large source of mineral sediment in low tidal range environments [e.g., Day *et al.*, 1995; Leonard *et al.*, 1995; Cahoon, 2006; Turner *et al.*, 2007]. Accretion from this

process might not be directly related to inundation depth as our model suggests, but could still be proportional to aboveground biomass. Second, the in situ accumulation of organic matter from below ground root production dominates vertical accretion in microtidal marshes of Maryland, North Carolina and Louisiana [e.g., Kearney *et al.*, 1988; Brinson, 1991; Craft *et al.*, 1993; Turner *et al.*, 2000; Nyman *et al.*, 2006]. A lack of a mechanistic understanding of the relationship between inundation depth and organic accretion, and how it would vary with tidal range, precludes its treatment in the model. However, a significant and consistent correlation between above and below ground biomass measured in *S. alterniflora* marshes with a variety of tidal ranges along the Atlantic coast of North America [Gross *et al.*, 1991] might suggest our treatment (i.e., accretion proportional to aboveground biomass) is at least adequate for exploring general responses.

[27] Despite these simplifications, similar modeling approaches have generally led to patterns of marsh behavior and morphology that are similar to those observed in nature. Patterns of channel network formation, and resulting channel morphologies are similar to those observed in Venice Lagoon [D'Alpaos *et al.*, 2007a, 2007b]. Vegetation-accretion interactions can largely explain relationships between inundation depth and accretion in South Carolina [Morris *et al.*, 2002], the elevation profiles of some Fraser River delta marshes [Kirwan and Murray, 2008a], and patterns of disturbance induced marsh loss in a variety of marshes worldwide [Kirwan

et al., 2008]. Nevertheless, our simplifying assumptions make the model more appropriate for exploring general relationships between tidal range and marsh stability rather than making quantitative predictions.

[28] In the absence of suitable field-based studies to compare with our model results, we highlight two modeling derived observations that might easily be examined in the field to determine whether our model adequately captures fundamental processes related to tidal range. First, extensive ponds develop in the low tidal range experiments, but not in the high tidal range experiments. In these experiments, pond formation occurs where a combination of low sediment concentrations and disturbed vegetation prevents marsh accretion from keeping up with the rate of sea level rise. Therefore, ponds develop more quickly and are more likely to become permanent features under low tidal ranges where the suitable growth range of vegetation is small. In nature, microtidal environments do appear to be particularly susceptible to pond formation and expansion. Marsh loss in the Chesapeake Bay and Coastal Louisiana regions, for example, is dominated by pond expansion [Kearney *et al.*, 1988; Turner and Rao, 1990]. Marshes in higher tidal range environments (e.g., Barnstable, Massachusetts) also have ponds but these marshes appear relatively stable [Redfield, 1972]. Second, our model predicts that for a given inundation depth, biomass productivity should be greatest in low tidal range environments, and that the productivity of marshes in equilibrium with similar rates of sea level rise should be slightly higher in low tidal range environments. While the relationship between inundation depth and biomass productivity could be easily examined, our compilation of biomass productivity measurements across the Gulf and Atlantic coasts of North America seems to support the model observation that biomass productivity decreases slightly with tidal range (Figure 1).

[29] Our model results suggest that marshes in low tidal range environments are fundamentally more unstable than marshes in high tidal range environments, despite a tendency toward higher biomass productivity. Our results demonstrate that two mechanisms are responsible for the reduced stability under low tidal ranges: (1) increases in inundation that are generally similar for various tidal ranges are not as easily accommodated by a small growth range of vegetation and (2) tidal prism expansion is disproportionately large, leading to rapid channel expansion.

[30] The idea that marshes in high tidal range environments can more easily accommodate high rates of sea level rise has been widely proposed, but explained only in general terms. For example, Stevenson *et al.* [1986] noted that the accretion deficit (sea level rise rate minus accretion rate) measured in 15 marshes along the U.S. Atlantic coast was greater in low tidal range marshes than in high tidal range marshes. Although a variety of explanations have been proposed, Day *et al.* [1995] and Friedrichs and Perry [2001] concluded that microtidal marshes are most sensitive to changes in sea level rise rates since adjustments to marsh elevation can only occur over a limited growth range of vegetation. Our modeling results support this hypothesis, and demonstrate mechanistically that the vertical stability is directly tied to the growth range of vegetation.

[31] Our results also suggest that comparisons between accretion rate (or accretion deficit) and tidal range are not likely to provide direct and clear information describing the

stability of marshes. In all our experiments, marsh or mudflat elevations equilibrate to a step change in the rate of sea level rise regardless of tidal range. Conceptually, this must be true over long time scales whenever accretion rates are positively related to inundation depth [Kirwan and Murray, 2008b]. Results that suggest otherwise are likely transient. For example, the model observation that accommodation space and accretion rate increases with tidal range and tends to exceed the rate of sea level rise [French, 2006] is unsustainable over long time scales. Based on the rules of that model, if accretion rates exceed the rate of sea level rise at high tidal ranges, then accommodation space and accretion rates would necessarily decrease through time, until a new equilibrium condition develops. This feedback ensures that marsh accretion rates should be near the rate of sea level rise regardless of the tidal range, a conclusion supported by French's [2006] compilation of measured marsh accretion rates. Not surprisingly, syntheses of field data that do compare accretion deficits to tidal range are widely inconsistent. Various compilations for marshes in different regions suggest that accretion deficits decrease with tidal range [Stevenson *et al.*, 1986], increase with tidal range [Chmura and Hung, 2004], or have no significant relationship [Wood *et al.*, 1989; French, 2006; Cahoon *et al.*, 2006].

[32] In these model experiments, we allow the marsh surface ample time to equilibrate to step changes in the rate of sea level rise. Because the adjustment process is not instantaneous (the platform must deepen before accretion rates increase), a marsh surface will not reach equilibrium with an oscillating or continuously accelerating rate of sea level rise [Kirwan and Murray, 2008b; Kirwan and Temmerman, 2009]. If tidal range were to influence the rate at which marshes adjust to sea level change, then careful comparisons between tidal range and marsh accretion during these transient periods could offer insight into the role tidal range plays in marsh stability. However, we note that despite a 20th century acceleration in the rate of sea level rise [Church and White, 2006] and significant multidecadal oscillations [Jevrejeva *et al.*, 2008], the most extensive data sets comparing accretion to tidal range show no clear relationship [Cahoon *et al.*, 2006; French, 2006]. This suggests that marshes from different tidal range environments adjust to sea level change at similar rates, have platform accretion rates that have nearly adjusted to modern sea level rise rates, or that there are simply too many variables involved in natural marshes to easily observe a relationship between tidal range and marsh accretion.

[33] Perhaps more interesting than the vertical stability of marshes under different tidal ranges is the counterintuitive result that tidal channel networks were most stable to sea level acceleration under high tidal ranges. This is particularly surprising given that the vegetation biomass decreased with increasing tidal range. Since previous experiments demonstrate that vegetation strongly limits channel widening and lengthening [Kirwan *et al.*, 2008], these results suggest that the effect of physical processes (i.e., disproportionate tidal prism expansion) exceeded the effects of ecomorphodynamic feedbacks in these experiments.

[34] Friedrichs and Perry [2001] hypothesize that the stability of marshes at high tidal ranges could be due to the sediment transport capacity of tidal channels in these high energy environments. Indeed, water velocities and suspended sediment concentrations in salt marsh creeks typically increase

with tidal range [Ward, 1981; Friedrichs, 1995; Leonard et al., 1995; Temmerman et al., 2003]. Our observations of channel network stability at high tidal ranges may offer some insight into the source of this sediment. Although water velocities are higher in the larger tidal range experiments, channel incision and widening are less prominent. This suggests that the source of sediment observed to increase with tidal range may be from outside the marsh channel network portion of the estuary, rather than from increased internal erosion of the marsh platform and channel bottoms. Since many factors influence the amount and vertical distribution of suspended sediment concentrations in tidal channels, we have assumed for simplicity that they do not increase with tidal range in these experiments. Incorporating a relationship where sediment concentrations increase with tidal range would reinforce our observations of marsh stability increasing with tidal range.

[35] Additional mechanisms may complement those discussed here. For example, Stevenson et al. [1986] hypothesize that a connection between marsh submergence and tidal range might be related to vegetation stress due to water logging, where microtidal marshes may be more poorly drained than macrotidal marshes. Friedrichs and Perry [2001] suggest that high tidal range environments tend to be more flood dominated, promoting the net import of sediment into the estuary, while low tidal range marshes tend to be ebb dominated which might promote the efflux of sediment out of the estuary. Although these mechanisms may be important in some marshes, we do not consider them in our model approach. This suggests that field observations of enhanced stability with increasing tidal range could be explained by an expanding vegetation growth range alone, rather than requiring more detailed explanations involving tidal asymmetry, marsh drainage, and/or sediment availability.

[36] Finally, our model results suggest that for a moderate sediment supply, the marsh platform is relatively stable in the vertical dimension to most reasonable combinations of tidal range and sea level rise rate; platform sensitivity to the growth range of vegetation is only important under more extreme scenarios (e.g., 10 mm yr^{-1} rate of sea level rise, 0.4 m tidal range). These model results would be sensitive to specific sediment supply conditions, but generally suggest that marsh stability as a function of tidal range is more importantly related to channel processes and pond development. Existing projections of global wetland loss depend on a direct and strong hypothesized link between tidal range and vertical accretion [Nicholls, 2004]. Our modeling efforts offer a mechanistic explanation for this relationship, but suggest that other processes may be more important for relating marsh stability to tidal range under most combinations of sea level rise rate and tidal range.

6. Conclusions

[37] In this contribution we use highly simplified numerical modeling in an attempt to offer mechanistic explanations for the long-held paradigm that marsh stability is positively related to tidal range. In our model experiments, sea level acceleration causes marsh surfaces to become deeper in the tidal frame, an effect that is amplified at low tidal ranges. In addition, disproportionate tidal prism enlargement leads to the erosion of the marsh platform by an expanding channel

network in experiments conducted under relatively low tidal ranges. Accretion rates equilibrate to the rate of sea level rise in all experiments, suggesting that comparisons between rates of sea level rise and rates of accretion are not likely to show a significant relationship with tidal range. Therefore, our model results offer an explanation to widely inconsistent field-based attempts to quantify this relationship, while still supporting the long-held paradigm that marshes in high tidal range environments are indeed more stable.

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