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LETTER

Bifurcate responses of tidal range to sea-level rise in estuaries with marsh evolution

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Scientific Significance Statement

Tidal marshes are among the most valuable ecosystems and face degradation under the rising sea levels. How marshes will respond to sea-level rise (SLR) is being hotly debated. Recently, much discussion has been focused on whether the marshes are as vulnerable as conventional thought. Our study provides new insight into this debate from a different but important perspective. Tidal range, besides sediment supply, is the other critical factor that determines marsh's resilience to SLR. In general, the larger the tidal range, the more resilient the marsh to SLR. Although the importance of tidal range has been recognized, a synthesis of the responses of tidal range to SLR with different marsh evolutions is still lacking. Here, we investigated the responses of the tidal range to SLR in tidal marshes. We demonstrate the existence of bifurcate tidal responses: tidal range can either increase or decrease, depending critically on the marsh evolution. The result is then incorporated into the current framework of studying marsh resilience to SLR, indicating that the bifurcate tidal responses may help resilient marshes become more resilient while causing vulnerable marshes to become more vulnerable to SLR. Our finding suggests that the varying tidal range should be always considered in future studies.

Abstract

The response of tidal range in tidal marshes under sea-level rise (SLR) is essential to the marsh resilience, but how tidal ranges respond to different marsh evolutions remains unclear. Here, we show the existence of bifurcate responses of tidal range to SLR using both numerical model and theoretical analyses. The tidal range tends to increase if marsh accretion keeps pace with SLR; otherwise, the tidal range tends to decrease. As tidal range plays the key role in marsh evolution, the interactions between changing tidal range and marsh evolution lead to positive feedback on marsh resilience. If the marsh accretion can keep up with the SLR, the increase in the tidal range can enhance marsh resilience to SLR. If the marsh cannot keep up, the decrease in the tidal range may further threaten the marsh resilience or even lead to marsh retreat.

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Author Contribution Statement: XC proposed the concept and designed the research. QQ and JS provided conceptual advice on the design of the scenario experiments. QQ developed the mathematic equations of the conceptual model. XC conducted the model experiments and performed the analysis. YJZ provided advice on numerical model computation. X.C. drafted the initial manuscripts with contributions from all authors. All authors contributed to the interpretation of the results and the manuscript revisions.

Data Availability Statement: Data and metadata are available in the Github repository at https://github.com/nicolecx122/SLR_TidalRange_OLLetters

Additional Supporting Information may be found in the online version of this article.

Worldwide sea-level rise (SLR), which is reported to be about 3.2 mm yr^{-1} on average between 1993 and 2010, is accelerating over the recent decades under climate change (Boon 2012; IPCC 2014). And SLR has been recognized as a major driver for tidal marsh evolutions (Friedrichs and Perry 2001; Morris et al. 2002). Affected by multiple abiotic and biotic factors (sediment supply, plant growth, salinity, and tide), it is suggested that a threshold exists that determines whether the vertical accretion can keep up with the rate of rising sea level (Kirwan et al. 2010). Tidal marshes were generally able to adapt to SLR before the 18th century (Jevrejeva et al. 2010) when the SLR rate was relatively small (< 1 mm yr^{-1}). The vertical accretions are supported by the prolonged and more frequent inundation that promotes more sedimentation over marshes (Reed 1990; Friedrichs and Perry 2001). Observations have also suggested the increased tidal inundation enhances productivity and organic matter accumulation under SLR (Morris et al. 2002; Mudd et al. 2009). Under the accelerating SLR rate presently, however, some marshes are degrading since the SLR rates exceed their thresholds, with low marshes being converted to open waters, channel network expanding, marsh platform elevation decreasing, and high marshes being replaced with low marshes (Reed 1995; Donnelly and Bertness 2001; Kearney et al. 2002; Morris et al. 2005; Hughes et al. 2009; Mitchell et al. 2017).

The tidal range is one key factor affecting coastal inundation and shoreline resilience. In tidal marshes, the tidal range is demonstrated to determine the threshold rates of SLR for marsh survival and resilience (Kirwan et al. 2010; Townend et al. 2011; Fagherazzi et al. 2012). A larger tidal range leads to enhanced sediment deposition and organic matter accumulation, which in return enhances the marsh resilience (Reed 1990; Friedrichs and Perry 2001; Morris et al. 2002; Kirwan and Guntenspergen 2010). On the other hand, SLR also alters the tidal range, and the response is nonlinear and heterogeneous in different settings of estuaries (Flick et al. 2003; Araújo et al. 2008; Picado et al. 2010; Hall et al. 2013; Holleman and Stacey 2014; Lee et al. 2017; Ross et al. 2017; Du et al. 2018; Khojasteh et al. 2020; Talke and Jay 2020). If the shoreline consists of hardened walls, the tidal range will increase under SLR; if the shoreline allows for inundation (e.g., with living shoreline), the tidal range may decrease under SLR. This prediction is consistent with the predictions in the San Francisco Bay by Holleman and Stacey (2014), and the predictions in the Chesapeake Bay and Delaware Bay by Lee et al. (2017). Du et al. (2018) further emphasized the importance of estuary type on the response of tidal range to SLR—estuaries with a narrow channel and large low-lying shallow areas are predicted to decrease tidal range under SLR, while tidal ranges in the estuaries without low-lying shallow areas are predicted to increase. Palmer et al. (2019) further illustrated the nonlinear interactions among SLR, tides, and geomorphic change, which were simplified as estuary infill. Clearly, tidal range changes under SLR in tidal marshes, and this change is affected by the marsh evolution that shapes the shoreline condition, which in turn will affect the tidal range locally. However, so far, the change in tidal range with marsh evaluation and its associated feedback have not been evaluated thoroughly. In ecogeomorphic models estimating the migration of the marshes, a fixed tidal range is usually prescribed (Kirwan and Murray 2007; Kirwan et al. 2010; Kirwan and Guntenspergen 2010; Fagherazzi et al. 2012). In more sophisticated models that couple hydrodynamics and morphology, the tidal range is responsive to the feedback among SLR, hydrodynamics, and marsh evolution (Alizad et al. 2016, 2018; Passeri et al. 2016). But a synthesis of the responses of tidal range to SLR at different marsh evolution stages is still lacking.

A better understanding of the response of tidal range to SLR in tidal marshes under different marsh evolution scenarios is warranted. Two extreme patterns of marsh evolutions in response to SLR, the "keep-up" and the "give-up," are considered explicitly here (Fig. 1). The "keep-up" refers to the equilibrium where marsh accretion is equal to the SLR if the SLR rate is below the threshold (Kirwan and Murray 2007; Kirwan et al. 2010). The "give-up" refers to the condition of marsh degradation, where enhanced inundation stress prohibits the vegetation growth if the SLR rate exceeds the threshold (i.e., more than 10 mm yr^{-1}) (Morris et al. 2002; Kirwan et al. 2010). The variations of the SLR rate, the supply of allochthonous sediments, and the vegetation growth rate all drive marsh evolutions in natural systems (Friedrichs and Perry 2001; Morris et al. 2002; Kirwan et al. 2016); however, the variations can be considered as different combinations of these two basic patterns. In this study, we used a conceptual model to analyze the factors determining the tidal range and demonstrated the existence of bifurcate responses of the tidal range to SLR in tidal marshes when accounting for marsh evolutions. A realistic case was presented using a 3D numerical model, and idealized scenarios based on the realistic case were conducted to examine the tidal range change with multiple combinations of marsh evolution and SLR scenarios. Finally, we proposed a feedback mechanism between marsh evolution and changing tidal range under SLR, for consideration in the current framework of studying marsh resilience to SLR.

Conceptual model of tidal response

Consider tides propagating along an estuary, the tidal range (H) at any location x can be described as (see the detailed derivations in Supporting Information):

$$H(x) = H_0\sqrt{\frac{C_0 b_0}{C(x)b(x)}}\sqrt{1-\frac{F(x)}{E_0 C_0 b_0}}, \tag{1}$$

where H_0 is tidal range at the mouth ($x = 0$), $C = \sqrt{gh}$ is tidal phase velocity, h is the *effective* water depth accounting for

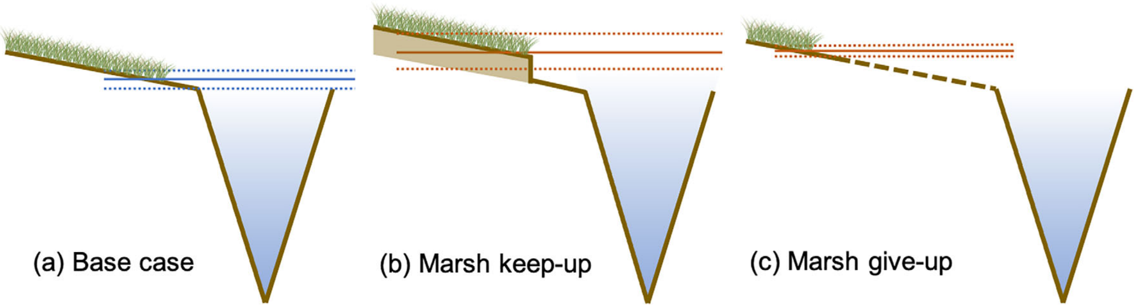

Fig. 1. Two basic responses of marsh evolution under SLR. The solid line represents mean sea-level, which roughly coincides with the lower limit of the marsh. The upper/lower dashed lines represent the mean high/low tides. **(a)** The Base case represents the present condition. (**B**) The "keep-up" refers to the equilibrium where marsh accretion is equal to the SLR, without considering the horizontal migration towards the channel. (**c**) The "give-up" refers to the condition of marsh degradation.

cross-sectional variations, b is estuary width including the marsh, and E_0, C_0, and b_0 are the tidal energy, phase velocity, and width at the mouth, respectively. F is the integration of cross-sectionally integrated energy dissipation from the mouth to the location x, and $\left(\frac{F}{E_0 C_0 b_0}\right)$ is the ratio of F to the energy flux at the mouth. The tidal shoaling effect on the tidal range is represented by the product of C and b (i.e., $Cb = b\sqrt{gh}$): with a narrower and shallower estuary toward the head, a smaller Cb tends to increase tidal range. Setting the non-dimensional parameters $\varepsilon_1 = \sqrt{1 - \left(\frac{F}{E_0 C_0 b_0}\right)}$ and $\varepsilon_2 = \sqrt{\frac{Cb}{C_0 b_0}}$, we can rewrite Eq. 1 as $H = H_0 \frac{\varepsilon_1}{\varepsilon_2}$. If $\varepsilon_1 > \varepsilon_2$, $H > H_0$, vice versa.

Under SLR, the ratio of the changed tidal range (H') to the original tidal range is

$$\frac{H'}{H} = \left(\frac{H_0{}'}{H_0}\right)\left(\frac{\varepsilon_1{}'}{\varepsilon_1}\right)/\left(\frac{\varepsilon_2{}'}{\varepsilon_2}\right) \text{ or denoted as } \frac{H'}{H} = \left(\frac{H_0{}'}{H_0}\right)\frac{\Delta\text{Friction}}{\Delta\text{Shoaling}}, \tag{2}$$

where the prime denotes the changed parameters after SLR, $\Delta\text{Shoaling} = (\varepsilon_1{}'/\varepsilon_1)$ and $\Delta\text{Friction} = (\varepsilon_2{}'/\varepsilon_2)$ denote the impact of the change in shoaling effect and bottom frictional dissipation on tidal range, respectively. Thus, the change of tidal range under SLR is determined by the change in incoming tidal range at the mouth $(H_0{}'/H_0)$, ΔFriction, and ΔShoaling. $\Delta\text{Friction} > 1$ and $\Delta\text{Shoaling} > 1$ indicate reduced frictional dissipation and weakened tidal shoaling effect, respectively.

Marsh evolution can greatly change the geometry of tidal marshes, which can then alter tidal range through the changes in bottom frictional dissipation and tidal shoaling (Fig. 1). For the marsh "keep-up" case, the changes in the estuarine geomorphology indicate that width b changes little after SLR, and therefore the weakened shoaling effect on the tidal range may be mainly through the increases in water depth and C, which results in a limited increase in ΔShoaling. b may even decrease in some cases if the marshes migrate toward the channel and this leads to an even smaller increase in ΔShoaling, against the impact of increased h in reducing the shoaling effect. With water depth increase under SLR, the ratio of energy dissipated by bottom friction $\left(\frac{F}{E_0 C_0 b_0}\right)$ generally decreases in shallow estuaries; this leads to $\Delta\text{Friction} > 1$ and tends to increase the tidal range. The impact of reduced frictional dissipation becomes dominant ($\Delta\text{Friction} > \Delta\text{Shoaling}$), and so the tidal range may increase under SLR if $H_0{}' \approx H_0$. In more complex reality, it is plausible to conceive rare scenarios where the converse is true, but we suspect that the tidal range will mostly increase under SLR in this case.

For the marsh "give-up" case, width b increases after SLR due to an increase in laterally inundated area, and the changes in the shoaling effect and bottom frictional dissipation are more complex. Clearly, an increase in b is small if the marsh extent is limited and it becomes larger with wide marshes, and the impact of the weakened shoaling effect can play a greater role than in the "keep-up" case. However, the change in shoaling effect may be limited in some systems where the mouth width also becomes significantly larger. The ratio of energy dissipated by bottom friction $\left(\frac{F}{E_0 C_0 b_0}\right)$ in the "give-up" case may either decrease or increase. Although SLR tends to decrease friction in the deep channel, the tidal energy may experience larger frictional dissipation when propagating over the marsh with much larger shallow inundation areas created by marsh retreats. As a result, the shoaling effect can dominate the impact of reduced frictional dissipation ($\Delta\text{Friction} < \Delta\text{Shoaling}$), resulting in a tidal range decrease under SLR.

A realistic case

We applied an unstructured-grid numerical model SCHISM (schism.wiki; Zhang et al. 2016) to the York–Pamunkey–

Mattaponi Estuary, a tributary of the Chesapeake Bay, USA, where several tidal marshes exist, and studied the response of tidal range in a realistic case (Fig. 2). Tidal harmonics results show that M2 tide is the dominant constituent in the system (Supporting Information Fig. S4). The validated model setup was shown as the Base case. The tidal range generally increases toward upstream (Fig. 3). We then conducted SLR scenarios by adding 0.5, 1, and 1.5 m to the sea surface height at the ocean boundary of the Base case, respectively, using the two scenarios of marsh evolution (Supporting Information Table S1). Data from model scenarios are available in Cai et al. (2022).

In the "marsh keep-up" case, a full marsh accretion was assumed, and the bottom elevation of the marsh region increased corresponding to each SLR scenario. The possible horizontal migration of marsh toward the channel was not accounted for. For the York River, the mean width increases by about 17% and the mean depth increases by 0.33 m after SLR of 1.0 m, and the mean width of the Pamunkey section changes little while its mean depth increases by 0.80 m (Supporting Information Table S2). For the transect along the main channel of the estuary, the tidal range increases for each SLR scenario (Fig. 3), consistent with the prediction by the conceptual model. The increase in tidal range is more pronounced toward upstream from the mouth of the York River and gradually becomes "linear" after passing the Sweet Hall. The increase in mean tidal range is 4.4, 17.2, and 13.2 cm in the York, Pamunkey, and Mattaponi, respectively, when SLR is 1.5 m (Supporting Information Table S1). After a 1.0 m SLR, the range of the incoming tide into the Pamunkey River increases from 0.852 to 0.954 m, resulting in (H_0'/H_0) equal to 1.120; ΔFriction is calculated to be 1.055 and Δ*Shoaling* to be 1.023 (Supporting Information Table S3). This indicates that the increases in the tidal range are due to increased incoming tidal range as well as significant reductions in frictional dissipation with smaller changes in shoaling effect.

In the "marsh give-up" case, the marsh retreats from the original location, and the bottom elevation remains the same as the Base case. For simplicity, we assumed that shoreline erosion does not occur, so the inundation area increases in low-lying areas under SLR and is determined by the lateral slope. In the York River with little or no marshes, the changes in sectionally averaged width and depth are similar to that in "marsh keep-up" case. The mean width of the Pamunkey section with extensive marshes increases about 111% (from 540 to 1140 m) and the mean depth also decreases largely (Supporting Information Table S2). The mean tidal range is

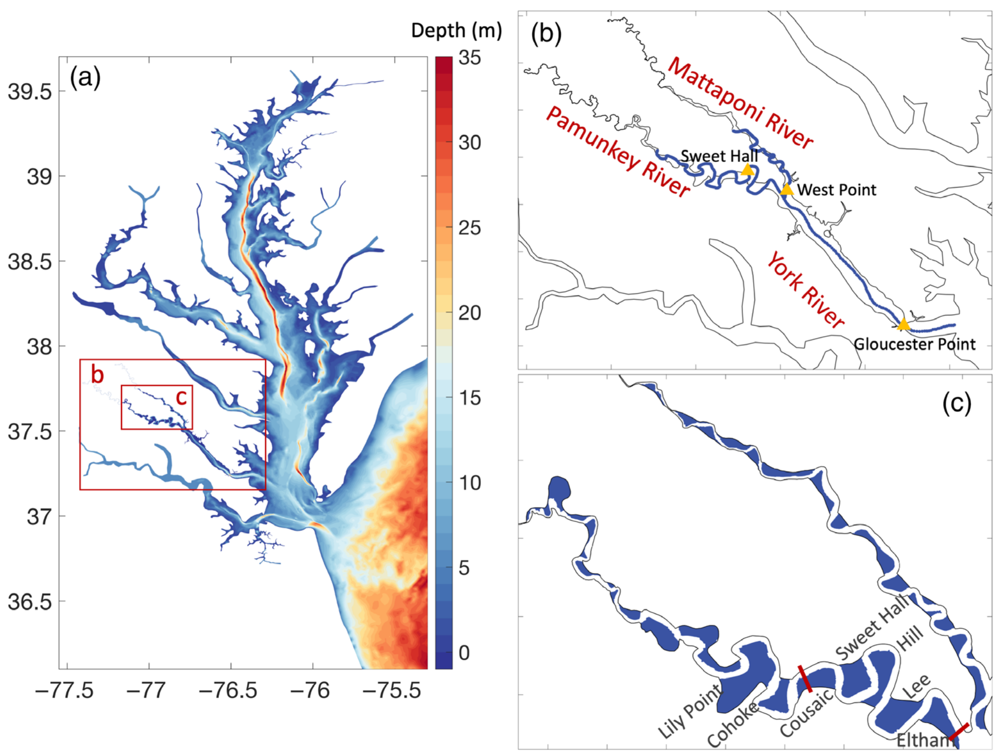

Fig. 2. (**a**) The Chesapeake Bay model grid domain. (**b**) Zoom-in of the York–Pamunkey–Mattaponi Estuary. The blue line in (**b**) denotes the center axis of the York River, the Pamunkey River, and the Mattaponi River. The yellow triangles denote the major stations. **(c)** Extensive and fringing marshes in the Pamunkey–Mattaponi River system. The blue polygons mark the marshes along the Pamunkey River and the Mattaponi River based on the United States Geological Survey (USGS) topography map. Red lines denote the start and end locations of the analytical analysis.

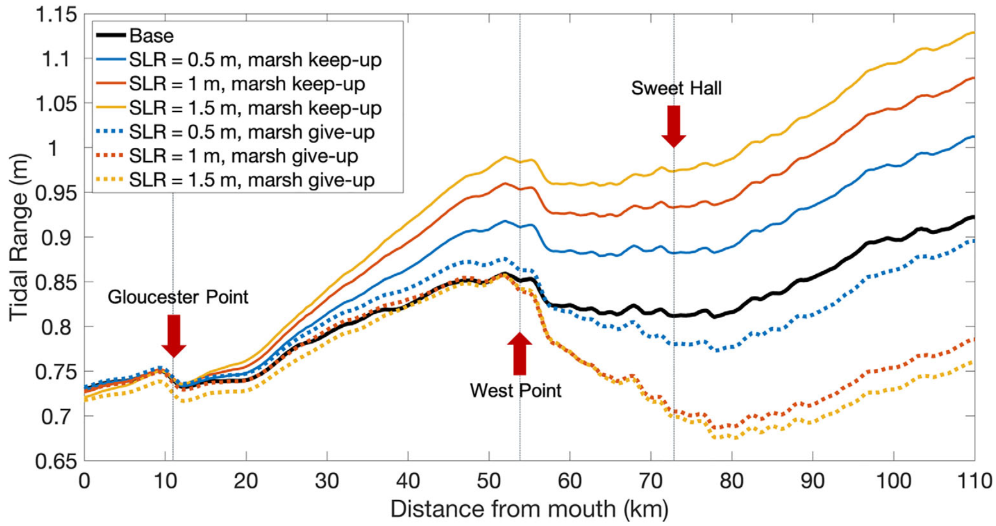

Fig. 3. Response of tidal range to SLR with scenarios of full marsh accretion or total marsh retreat in the York and Pamunkey River.

negatively correlated with SLR in the York–Pamunkey–Mattaponi Estuary. The tidal range generally changes relatively small (less than 1 cm) in the York River (Fig. 3; Supporting Information Table S1). By contrast, the tidal range decreases significantly in the Pamunkey (Fig. 3) and the Mattaponi (not shown), except for the lower river close to the West Point when SLR is relatively small (0.5 m). For a 1.5 m of SLR, the metidal range decreases −12.0 cm in the Pamunkey and −4.2 cm in the Mattaponi (Table S1). In the York River where the reduction of the tidal shoaling effect is limited with little or no marshes, the impact of friction reduction dominates the change of tidal range which results in an increased tidal range. In the Pamunkey and the Mattaponi where the existing marshes are retreated, the largely increased shallow area plays a key role in causing the decrease in tidal range. In the case of a 1.0 m SLR, (H_0'/H_0) equals 0.985 in the Pamunkey River, and ΔFriction is calculated to be 0.847 and ΔShoaling to be 0.990 (Supporting Information Table S3). This indicates that the decreased tidal range in the Pamunkey marsh for the give-up case is mainly due to the increased frictional energy dissipation. The shoaling effect does not change much even the width of the marsh increases largely because the mouth of the Pamunkey River also becomes wider.

The above scenarios are designed with idealized SLR-driven marsh evolutions: marsh is elevated to the SLR in the keep-up scenarios and marsh is fully retreated in the give-up scenarios. In nature, marsh evolution can be somewhere in between, depending on the supplies of sediments or the shift in the local marsh community (Reed 1990; Reed 1995; Mitchell et al. 2017). It is therefore interesting to examine those "middle cases." This was examined by conducting additional numerical scenarios: three "slow catch-up" scenarios with different catch-up rates and a "partial catch-up" scenario (Fig. 4). For the three "slow catch-up" scenarios, the bottom elevation of the marsh region increased by 0.25, 0.5, and 1 m, respectively, while SLR was set to be 1.5 m. For the "partial catch-up" scenario, it is assumed that the marsh near the waterfront retreated by about 200 m to reduce about half of the total marsh area while the marsh immediately behind the front had the same vertical accretion as the rising sea level, which makes the total marsh area decreased by about 47% in the system.

In the slow catch-up scenarios, relatively small vertical accretions (e.g., 0.25 and 0.5 m) lead to decreases in tidal range while relatively large marsh vertical accretions (e.g., 1 and 1.5 m) correspond to increased tidal range (Fig. 4), dependent on the competition of the changes in frictional dissipation and shoaling effect. In the partial catch-up scenario, the combined effects of marsh accretion and retreat lead to a relatively small change of the tidal range in the Pamunkey (Fig. 4). The mean differences of tidal ranges are less than 1.8 and 3.3 cm in the Pamunkey and Mattaponi, respectively (Supporting Information Table S1). These additional scenarios suggest that the changes of the tidal range corresponding to the "middle case" fall in somewhere between the changes in the full keep-up and give-up cases.

Proposed feedback on marsh resilience

SLR drives the change in tidal range and marsh evolution, and the two processes also interact with each other in tidal marshes. Previous studies have suggested that tidal range is one of the key factors regulating the marsh evolution under SLR, and the tidal range is suggested to be positively correlated with marsh resilience, that is, a larger tidal range leads to a higher threshold rate (Kirwan et al. 2010; Kirwan et al. 2016). Thus, the coupling between tidal range change and marsh evolution, in turn, impacts the marsh resilience to SLR. This

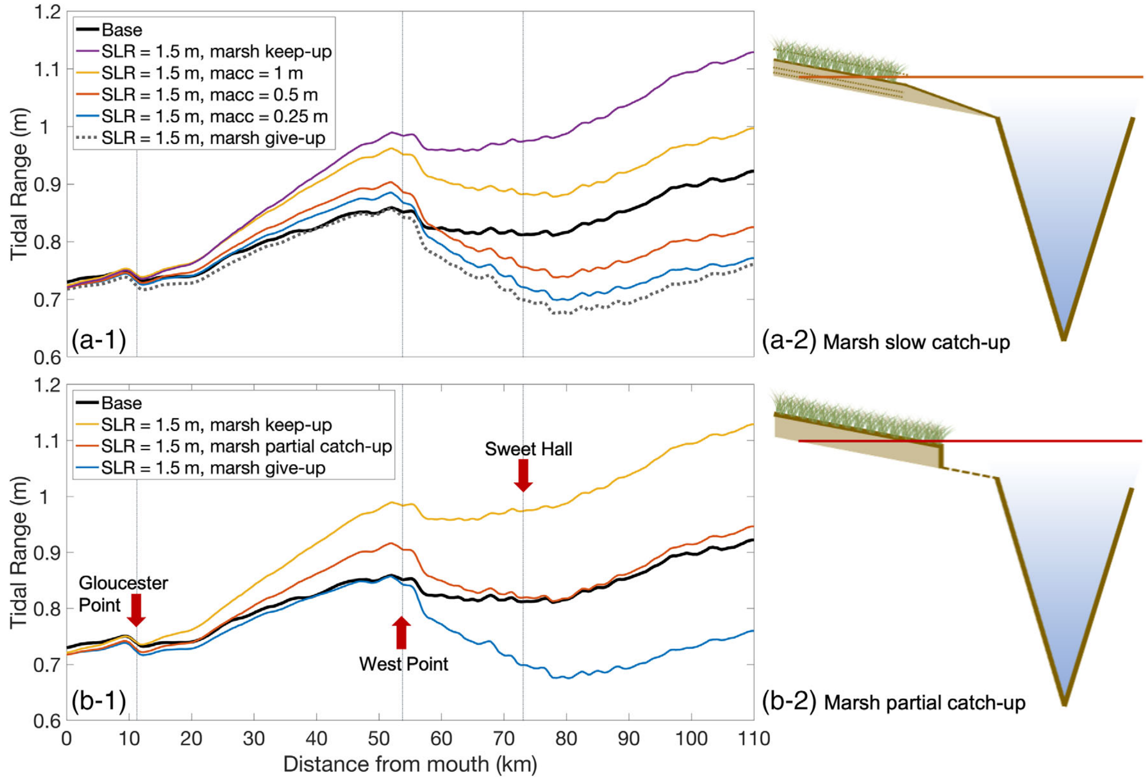

Fig. 4. (**a-1**) Response of tidal range to SLR along with different levels of marsh accretion (“macc”) in the York and Pamunkey River. (**a-2**) Diagram of "macc". (**b-1**) Response of tidal range to SLR with both marsh accretion and retreat (“partial catch-up”) in the York and Pamunkey River. (**b-2**) Diagram of "partial catch-up".

study showed that tidal range can either increase or decrease depending on marsh resilience. It is interesting to evaluate how the revealed bifurcate responses of tidal range, coupling with marsh evolution, dynamically alter the marsh resilience. Here, we hypothesize positive feedback exists (Fig. 5).

Vertical accretion is driven by increased inundation that favors more sedimentation and enhanced marsh growth. If the SLR rate is below a threshold rate, the vertical accretion tends to keep up with the rising sea level (“keep-up”). If the SLR rate exceeds the threshold rate, the marsh in the front edge retreats until a new equilibrium between the marsh and the tidal environments is reached (“give-up”). For the marsh keep-up case where the marsh gains sufficient accretion, the tidal range tends to increase under SLR. The distance between mean high-water level to the elevated marsh platform increases along with the increasing tidal range. As a result, this feedback further may increase sedimentation and enhance marsh resilience. For the marsh give-up case where the vertical accretion is not rapid enough, the tidal range tends to decrease. The decreased tidal range may contribute to an even slower accretion by reducing the inundation and sedimentation. The slower accretion further threatens marsh survival and favors marsh retreat. In summary, the bifurcate tidal responses may help resilient marshes become more resilient but cause vulnerable marshes to become more vulnerable to SLR.

The positive feedback driven by the tidal range may contribute to the diversity of marsh evolution observed in different marsh systems. The feedback may not always be important compared with other controls (i.e., the increased inundation directly induced by the rising mean sea level and the supply of sediments). Nevertheless, the recorded historical

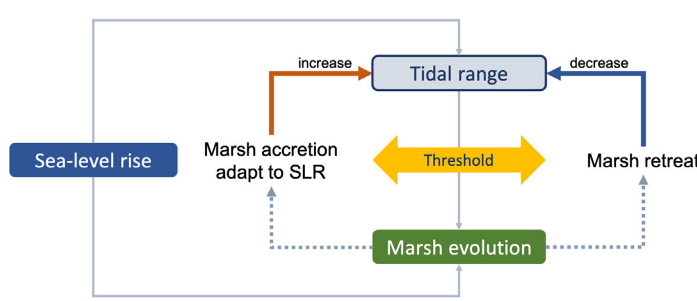

Fig. 5. Concept framework of the interactions among tidal range, SLR, and marsh evolution, with the proposed feedback.

change of tidal range and its impact on marsh evolution have been found to be great in some systems. For example, the increase of tidal range is 35% from a tidal range of 1.02 m from 1935 to 1999, at a rate of 542 mm per century in Wilmington, North Carolina, USA (Flick et al. 2003). The significant change of local tidal range increases the threshold of the marsh by about 50% based on the estimation in Kirwan et al. (2010) with identical sediment supplies. Under the accelerated SLR, the predicted change of tidal range can be even larger, which highlights the importance of considering the feedback as one critical component of marsh resilience.

Note that tidal asymmetry is another factor of tides besides its range to affect sedimentation and hence marsh evolution under SLR (Passeri et al. 2016). As we focus on the changing tidal range, the possible impact of altered tidal asymmetry is omitted in the proposed feedback. Also, we used a simplified modeling approach with analytical analysis to test the hypothesis and diagnose the underlying physical processes. As more advanced model approach with directly coupling of hydrodynamics-morphological-marsh become available (Alizad et al. 2016), this feedback mechanism can be further investigated under more sophisticated conditions for different marshes.

Simplifications in the conceptual model of tidal response

In this study, we focused on the role of marsh evolution on the response of tidal range to SLR using a simplified approach. For example, the seasonality of marsh biomass or stem density was not considered. Different types of tidal marshes, such as a salt marsh or freshwater marsh, with different seasonal patterns of productivity, may induce variance in the impacts of marshland on the tidal range. Because tidal range change due to SLR depends on the length, depth, and channel convergence (Du et al. 2018), the magnitude of change in the tidal range in other systems may differ from the York–Pamunkey–Mattaponi Estuary. Nevertheless, our study here provides the first example of showing the bifurcate responses of tidal range to SLR and suggests that the proposed feedback mechanism should be considered in future ecomorphology studies to accurately investigate the dynamic marsh evolution under future climate changes.

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