LETTER

Coastal wetland adaptability to sea level rise: The neglected role of semi-diurnal vs. diurnal tides

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Scientific Significance Statement

Sea level rise (SLR) is causing loss of valuable coastal wetlands (tidal marshes and mangroves) in certain places around the world, while wetlands can adapt to SLR in other places. Studies have attempted to understand this global variability in wetland adaptability to SLR, but never considered global variations in the tidal pattern, that is the number of high and low tides per day, varying from one cycle of high and low waters in about half a day (semi-diurnal tides), to one cycle in a full day (diurnal tides). Here, we analyze global data and perform model simulations of wetland adaptation to SLR to show that coastal wetlands experiencing diurnal tides are more likely to be vulnerable to SLR. Hence, our results suggest that the tidal pattern is a relevant—but previously neglected—factor contributing to global wetland adaptability to SLR, and call for further research.

Abstract

Tidal marshes and mangroves are threatened by relative sea level rise (RSLR) in certain regions on Earth. Elsewhere, these coastal wetlands can adapt through sediment accretion and resulting surface elevation gain. Studies identifying drivers of the global variability in coastal wetland adaptability to RSLR ignored the role of the tidal pattern, varying from semi-diurnal to diurnal globally. Here, we present a meta-analysis, including 394 marsh and mangrove sites worldwide, and demonstrate that the tidal pattern explains $\sim 25\%$ of the variability in wetland elevation response to RSLR. Using a numerical model, we illustrate that less frequent, diurnal tides trigger lower sediment accretion rates, hence higher wetland vulnerability to RSLR, for various values of

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

RSLR rates, tidal range and sediment supply. Our findings reveal a previously overlooked but relevant driver of coastal wetland adaptability to RSLR and call for new research as tidal patterns may affect other wetland ecosystem functions and services.

Coastal wetlands including tidal marshes and mangroves are among the most valuable ecosystems on Earth, providing extensive ecosystem services (Barbier et al. 2011). At the same time, they are particularly vulnerable to submergence driven by relative sea level rise (RSLR) and human impacts (Kirwan and Megonigal 2013). Marsh conversion to open water has been observed in the Mississippi delta (Day et al. 2007), Chesapeake Bay (Kearney et al. 2002), and Venice Lagoon (Carniello et al. 2009); many mangrove forests throughout the Indo-Pacific region are showing signs of submergence (Lovelock et al. 2015). Conversely, along the North Sea basin (French 1993; van Wijnen and Bakker 2001; Temmerman et al. 2004) and the Yangtze delta (Yang et al. 2020), coastal wetlands are building up elevation through sediment accretion at rates equal to or exceeding the rate of RSLR.

Identifying the factors that control the global variability in coastal wetland adaptabilty to RSLR is a major scientific and societal challenge. Regional- to global-scale meta-analyses of observed rates of sediment accretion and surface elevation change from marshes and mangroves suggest widespread but variable patterns of wetland submergence (Lovelock et al. 2015; Crosby et al. 2016; Kirwan et al. 2016; Jankowski et al. 2017; Liu et al. 2021; Coleman et al. 2022), with rates of RSLR, suspended sediment concentration (SSC) and tidal range (TR) identified as key drivers of this variability. Numerical models reveal that threshold RSLR rates for marsh submergence (i.e., above which marshes convert to bare tidal flats or open water) decrease with reduced TR and SSC (Kirwan et al. 2010). Based on these relations, regional- to global-scale model projections of wetland loss in response to 21st century RSLR scenarios have been proposed (Lovelock et al. 2015; Kirwan et al. 2016; Schuerch et al. 2018).

All previous assessments of coastal wetland adaptability to RSLR overlook the fact that marshes and mangroves do not only occur under semi-diurnal tides, characterized by two high and two low waters per lunar day (i.e., 24.84 h). Certain coastal wetlands on Earth experience diurnal tides ($\sim$ 10% of global wetland surface area; Fig. 1), with only one high and one low water per lunar day, or mixed tides, characterized by periodic alternations but with a predominance of either diurnal or semi-diurnal pattern ($\sim$ 9% and $\sim$ 40% of global wetland surface area, respectively). Locations featuring semidiurnal, mixed or diurnal tides are primarily determined by ocean dimensions and continental boundaries, but diurnal tides are mostly expected to be found around the Tropics of Cancer and Capricorn, at locations under maximum lunar declination of $\pm$ 28° latitude (Pugh and Woodworth 2014),

while semi-diurnal tides are predominantly found at the equator and high latitudes (*see* Fig. 1).

Tidal inundation regime (duration, depth, and frequency) affects sediment accretion through a dynamic feedback whereby, under adequate sediment availability, increased tidal inundation associated with RSLR promotes more frequent and longer periods of supply and settling of suspended sediments, resulting in increased sediment accretion rates (French 1993; Morris et al. 2002; Temmerman et al. 2004). This fundamental tidal inundation–sediment accretion feedback, to which plants participate by trapping sediments and adding organic matter accretion, eventually allows the wetland to adjust its elevation to RSLR, up to a certain threshold RSLR rate (Kirwan et al. 2016). Coastal wetlands forced by diurnal vs. semi-diurnal tides are thus likely to exhibit distinct sediment accretion and elevation responses to RSLR, given their apparent differences in inundation duration and frequency. But surprisingly, until now no studies have assessed the effects of tidal patterns on coastal wetland adataptibility to RSLR.

Here, we first explore the relative influence of tidal patterns among previously identified, key environmental drivers, on globally observed rates of wetland elevation change in comparison with local RSLR rates. Second, using a model of tidally driven sediment accretion in marshes, we simulate the distinct effects of diurnal vs. semi-diurnal tides on sediment accretion and on the threshold conditions leading to wetland submergence. Both field data and modeling show that tidal patterns exert a significant control on the sediment accretion and elevation responses to RSLR, whereby coastal wetlands experiencing diurnal tides are consistently less resilient to RSLR. Although our model results are representative for minerogenic marshes, we also discuss on potential impacts of tidal patterns on organic matter accretion in coastal wetlands. Our findings offer new perspectives on coastal wetland adaptability to RSLR.

Influence of tidal patterns on observed wetland responses to SLR

We compiled data on observed contemporary rates of surface elevation change across 394 wetland sites from published meta-datasets of tidal marshes and mangroves (Lovelock et al. 2015; Crosby et al. 2016; Kirwan et al. 2016; Jankowski et al. 2017) and from several individual studies (*see* Supporting Information S1, Supporting Dataset and locations in Fig. 1). These data were measured using surface elevation tables (SET; Cahoon et al. 2002), a method that is a standard to monitor wetland elevation changes in response to RSLR (Webb et al. 2013). Boosted regression tree (BRT) models were applied to investigate the relative influence of several environmental variables on the rates of wetland elevation change in
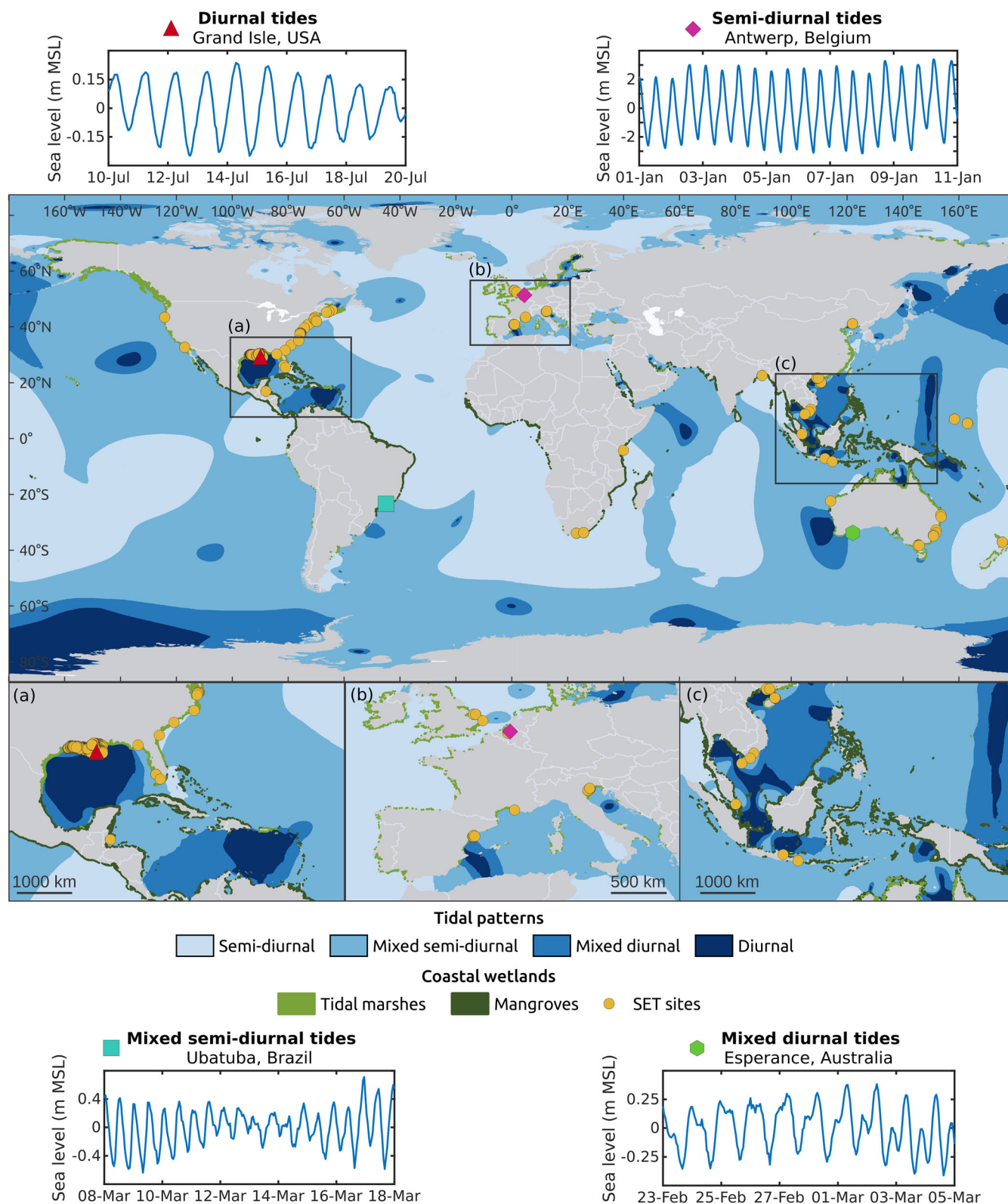
Fig. 1. Global distribution map of the tidal pattern, further illustrated by tide gauge records selected over 10 days in 2015 at different locations. Global distribution of tidal marshes and mangroves, and surface elevation tables (SET) sites measuring rates of surface elevation change, used in our data analysis. Insets show "zoom-ins" on regions with complex spatial distributions of tidal patterns, combined with high density of SET sites.

comparison to local RSLR rates (Supporting Information S2). These included previously identified major drivers of the variability in rates of wetland elevation change: the rate of local RSLR, SSC in nearby waters, and TR (Lovelock et al. 2015; Crosby et al. 2016; Kirwan et al. 2016). In addition, we included here the newly-investigated tidal pattern, quantified by the form factor (*see* Supporting Information S1).

We find, after 100 runs of the BRT model, that the tidal pattern explains $\sim 19\%$ of the variation in observed rates of surface elevation change (Fig. 2a). Comparatively, SSC explains a somewhat higher proportion (with a relative importance of $\sim 23\%$), while TR and the rate of RSLR are the most influential predictors, both explaining $\sim 28\%$ of the observed rates of surface elevation changes (with relative influences being not significantly different). The BRT model performance is characterized by R-squared (R^2) values ranging between 0.38

and 0.44, but with low RMSE and MAE values that suggest high predictive accuracy (Table S1). In the context of wetland resilience to RSLR, we conducted a second set of BRT model runs to assess the relative influence of these environmental variables on the wetland elevation balance with RSLR, defined as the rate of surface elevation change minus the local rate of RSLR (Fig. 2b). The tidal pattern ranks as the third most influential predictor, higher than the rate of RSLR, and with a relative influence ($\sim 24\%$), nearly close to that of SSC ($\sim 26\%$). TR is the strongest influential predictor, explaining $\sim 38\%$ of the total variability. However, evaluation measures show a somewhat slower model performance (Table S1).

To assess which tidal pattern(s) coincides with increased wetland vulnerability, we calculated the percentage of SET sites with a wetland elevation deficit (i.e., with rates of elevation gain lower than the local RSLR rate) relative to all SET sites per class
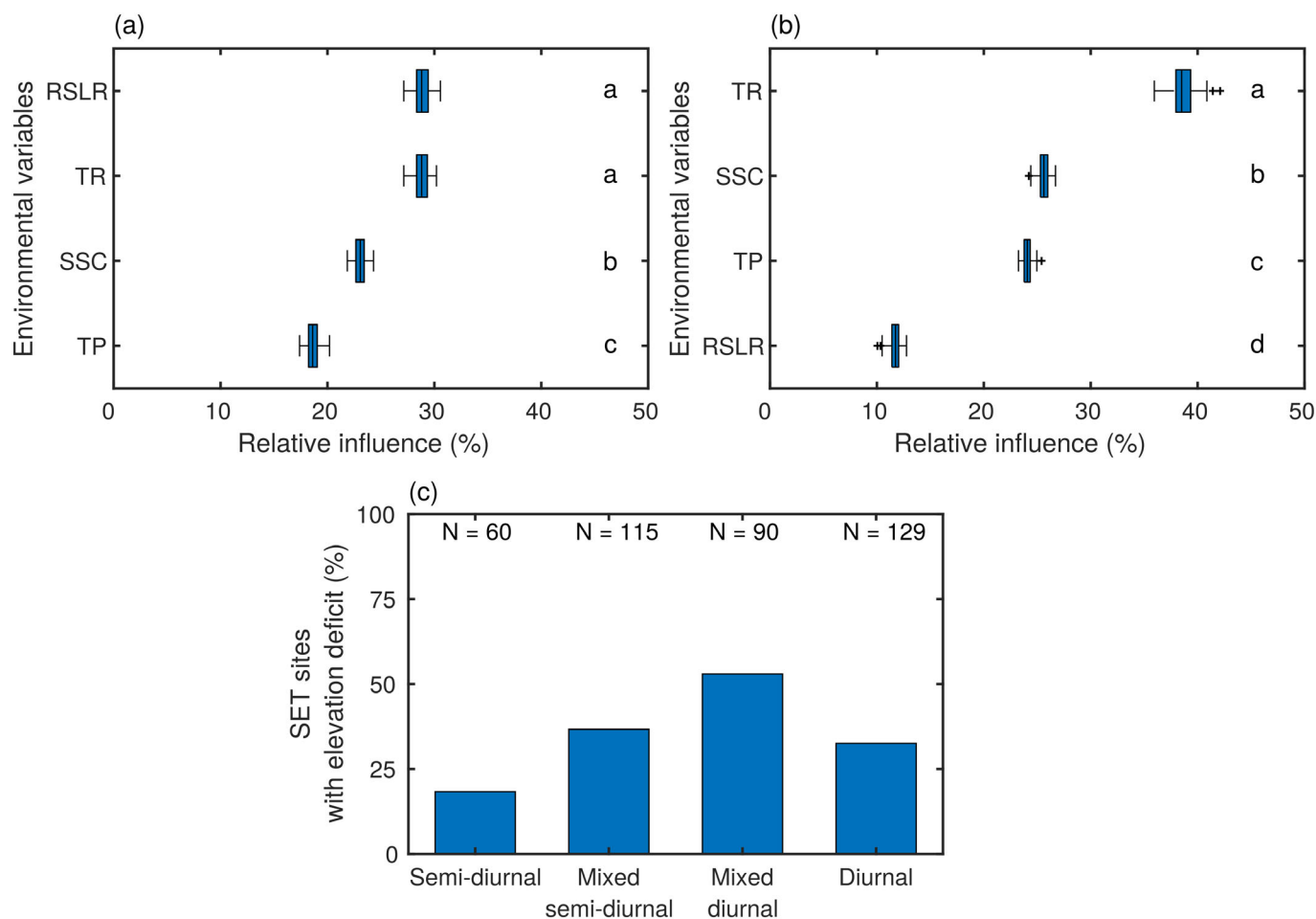

Fig. 2. (**a**, **b**) Boxplots of relative influence (in percentage) of the environmental variables, determined from 100 runs of the BRT model applied to (**a**) rates of wetland elevation change and (**b**) elevation balance with RSLR, measured at the SET sites. The investigated environmental variables are: Rates of relative sea level rise (RSLR), tidal pattern (TP), tidal range (TR) and suspended sediment concentration (SSC). Variables that share the same letter are statistically not significantly different from each other (after running one-way ANOVA test followed by multiple pairwise comparisons). (**c**) Percentage of SET sites with surface elevation deficit (i.e., sites experiencing rates of surface elevation gain lower than the local RSLR rate) relative to all sites per tidal pattern category, with site counts (N) indicated.

of tidal patterns, which are classified by the form factor: semi-diurnal, mixed semi-diurnal, mixed diurnal, and diurnal tides (Fig. 2c). We find that coastal wetlands that experience predominantly diurnal tides are more subject to elevation deficits relative to RSLR. Indeed, we observe that 52% and 33% of all sites that occur under mixed diurnal tides and diurnal tides have an elevation deficit, respectively. While sites that occur under mixed semi-diurnal tides have comparable elevation deficits (35%), this elevation deficit greatly reduces to 18% for all sites that occur under semi-diurnal tides.

Influence of tidal patterns on modeled wetland responses to future accelerating SLR

We performed a modeling study to assess how various tidal patterns cause distinct wetland sediment accretion and elevation trajectories, ultimately leading to wetland resilience/vulnerability to future RSLR. We focused on modeling mineral suspended sediment accretion, as its response to different tidal patterns can be assessed by models simulating suspended sediment deposition driven by tidal inundation (*see* Fagherazzi et al. 2012). We used a

wetland elevation numerical model (Temmerman et al. 2003) that simulates the spatially-averaged sediment accretion and surface elevation change for a given site from decades to centuries (Supporting Information S3). The model notably simulates the supply and settling of mineral suspended sediments with a certain concentration in the water that floods the marsh platform during single tidal inundation cycles in timesteps of 5 min. Accordingly, this model explicitly simulates the fundamental tidal inundation–sediment accretion feedback at the timescale of single tidal cycles and is suitable to explore the direct effects of tidal inundation regimes, induced by different tidal patterns, on the rates of mineral sediment accretion and surface elevation change.

In a first model experiment, we explore the sediment accretion and elevation responses of a tidal marsh in the Scheldt estuary (Belgium and the Netherlands) forced by semi-diurnal tides (reference situation) vs. diurnal tides and adjusting to various accelerating SLR scenarios for the 21st century, using IPCC projections (Oppenheimer et al. 2019; Supporting Information S4).

The simulated marsh forced by diurnal tides is consistently decreasing in elevation relative to the local mean sea level,
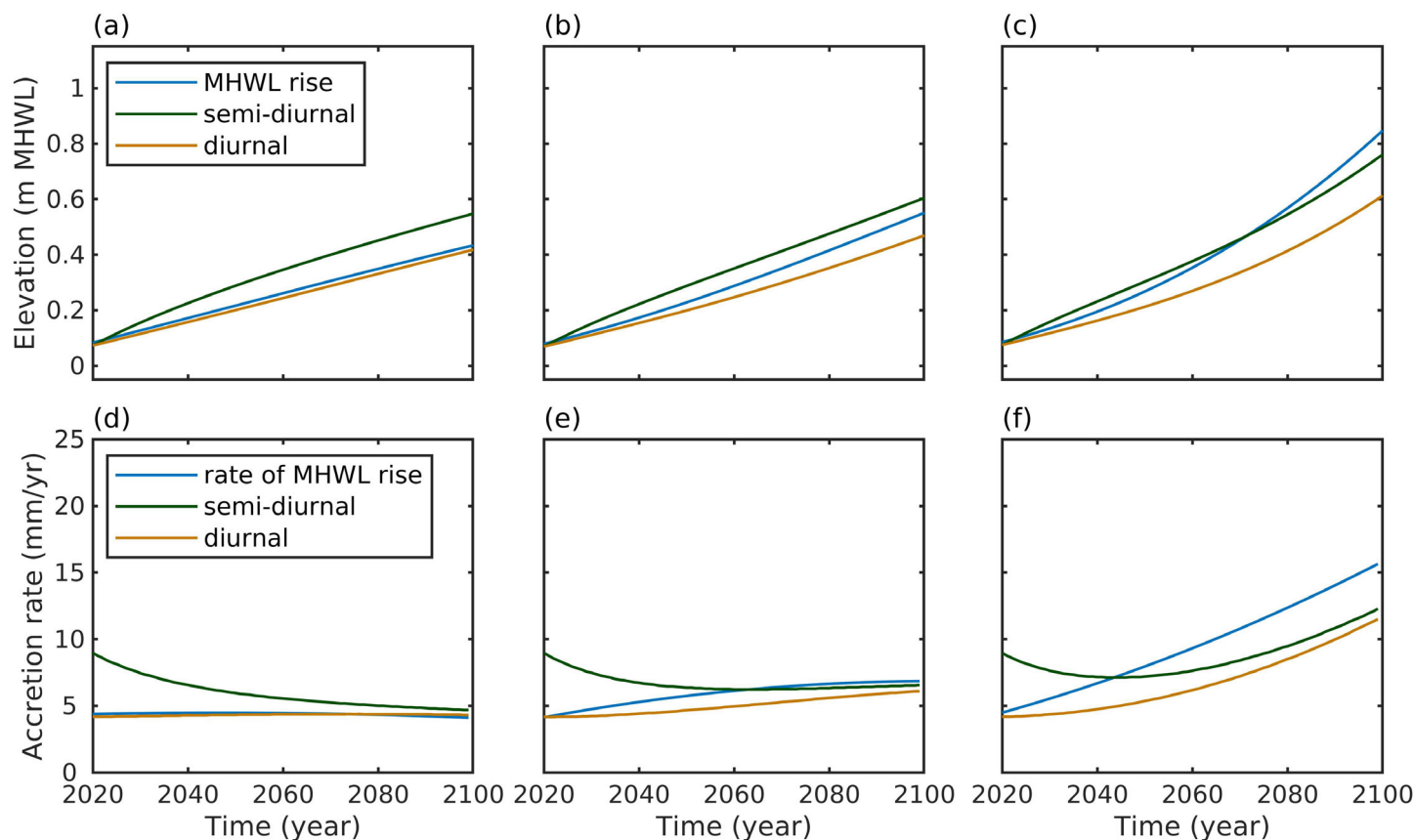

Fig. 3. Modeled marsh elevation (**a–c**) and accretion rate (**d–f**) responses to a low (RCP2.6; **a, d**), medium (RCP4.5; **b, e**), and high (RCP8.5; **c, f**) scenario of projected SLR during the 21st century for a reference marsh in the Scheldt estuary (Netherlands). These projected median sea levels, illustrated by the dark blue lines, are represented here as mean high water level (MHWL). The green and brown lines represent the elevation (**a–c**) and accretion rate (**d–f**) responses to the sea level projections, for the marsh forced by semi-diurnal tides (reference situation) and diurnal tides, respectively.

regardless of the RSLR scenario (Fig. 3a–c). This corroborates accretion rates that are initially always higher under the semi-diurnal than diurnal tides, while accretion rates evolve towards similar values by the end of the 21st century, as a balance is approaching between tidal inundation and accretion rates (Fig. 3d–f). For the low RSLR scenario, the accretion rates under both tidal patterns are evolving towards values equal to the constant RSLR rate (Fig. 3d), implying that the marsh elevation is keeping up with RSLR, although the marsh forced by semi-diurnal tides is able to maintain a higher elevation (Fig. 3a). In contrast, accretion rates become lower than the accelerating RSLR rate for the high RSLR scenario in both situations (Fig. 3f), implying that marsh submergence will become inevitable if simulations would continue over longer periods of accelerating RSLR. This moment of marsh submergence will be reached earlier under diurnal tides, as in this case the marsh evolves faster to lower accretion rates and lower elevations relative to the local mean sea level.

Influence of tidal patterns on the limits of wetland survival

A second set of model simulations builds directly upon the experiment conducted by Kirwan et al. (2010) that utilized an ensemble of five marsh elevation models, including the model used here, to quantify the threshold rate of RSLR for which marshes are evolving to elevations that are no more able to sustain vegetation growth and hence are expected to convert to bare tidal flats or open water. In particular, Kirwan et al. (2010) produced linear relationships between this threshold RSLR rate for marsh submergence and incoming SSC for different TRs. These relations agree with similar empirical relationships found from a meta-analysis (Coleman et al. 2022) and are used in a widely cited global-scale projection of coastal wetland responses to future RSLR scenarios (Schuerch et al. 2018). This emphasizes the relevance to test the additional effects of semi-diurnal vs. diurnal tides on the threshold RSLR rates, which we address here using the current model.

We find that the predicted threshold RSLR rate for marsh submergence is consistently lower for marshes forced by diurnal tides, for all SSC and TR scenarios tested (Fig. 4). The threshold RSLR rates are linearly related to SSC and TR for the two tidal patterns (*see* lines in Fig. 4), similar to Kirwan et al. (2010) and Coleman et al. (2022). These linear relationships show that for a given TR scenario, the larger the amount of tidally-supplied sediment to the marsh, the larger the discrepancy becomes between threshold RSLR rates under diurnal vs. semi-diurnal tides.

Synthesis and future research

Despite important recent advances on global-scale empirical assessments and model projections of coastal wetland responses to RSLR (Lovelock et al. 2015; Kirwan et al. 2016; Schuerch et al. 2018; Saintilan et al. 2020), until now the potential role of the tidal pattern, varying around the globe from semi-diurnal to diurnal tides, on determining wetland
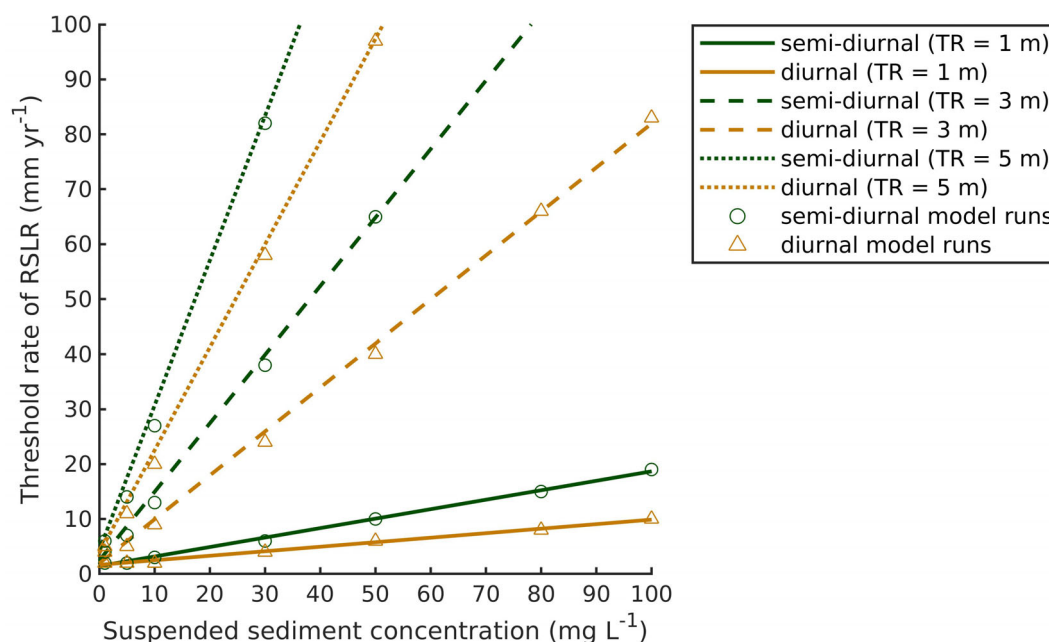

Fig. 4. Predicted threshold rates of RSLR, for which marshes start drowning, forced by semi-diurnal (green lines and circles) and diurnal (brown lines and triangles) tides. These predicted threshold rates of RSLR result from marshes simulated under a range of SSC and TR, the latter with values ranging from 1 m (microtidal; solid lines), 3 m (mesotidal; dashed lines) and 5 m (macrotidal; dotted lines). Symbols represent results of individual model simulations forced by semi-diurnal (circles) and diurnal (triangles) tides and lines are linear regression fits for the respective scenarios of tidal pattern.

adaptability to RSLR has never been addressed. Our study, for the first time, unveils its significant role, in addition to the well-known role of SSC, TR and the rate of RSLR itself.

The multivariate analysis applied to the observed rates of wetland elevation change and their balance with RSLR reveals that the tidal pattern is a relevant determinant at the global scale (*see* Fig. 2). More specifically, coastal wetlands experiencing predominantly diurnal tides are more subject to elevation deficits relative to RSLR (*see* Fig. 2c). With the selected set of predictors, the BRT models explained 41% and 33% of the total variability in surface elevation change and its balance with RSLR, respectively. This suggests that there are additional environmental controls on wetland resilience to RSLR that were not considered here. These may include the wetland surface elevation relative to the tidal frame, sediment bulk density, geomorphic setting, distance to sediment sources, etc. Yet, we opted to focus here on assessing the importance of the tidal pattern against the main drivers of coastal wetland adaptability to RSLR, as widely identified by previous regional- (Lovelock et al. 2015) and global-scale (Crosby et al. 2016; Kirwan et al. 2016; Schuerch et al. 2018) field assessments as well as modeling studies (Kirwan et al. 2010).

We acknowledge that the relatively unbalanced geographic coverage of the SET sites, that centers on marshes situated in mid to higher latitude regions, represents a limitation (*see* Fig. 1). In our dataset, ~ 60% of SET data come from the US Gulf coast alone, in particular the marshes of coastal Louisiana (Jankowski et al. 2017), which also concentrates the majority of sites that occur under (mixed) diurnal tides. Outside coastal Louisiana, the compiled (mixed) diurnal SET sites only occur in four different locations. Hence, results need to be interpreted with caution. Therefore, we support calls for expanding the geographic distribution of surface elevation change monitoring, especially in tropical regions (Webb et al. 2013). In order to cope with this over-representation of SET data from coastal Louisiana, we conducted additional BRT runs considering random subsamples taken from the original dataset, so that remaining SET data from coastal Louisiana only covered 10% of the resampled dataset. We show that results are consistently similar for the different resampled datasets, that is, showing the tidal pattern as an important variable, particularly to explain variations in wetland elevation balance with RSLR (Fig. S1).
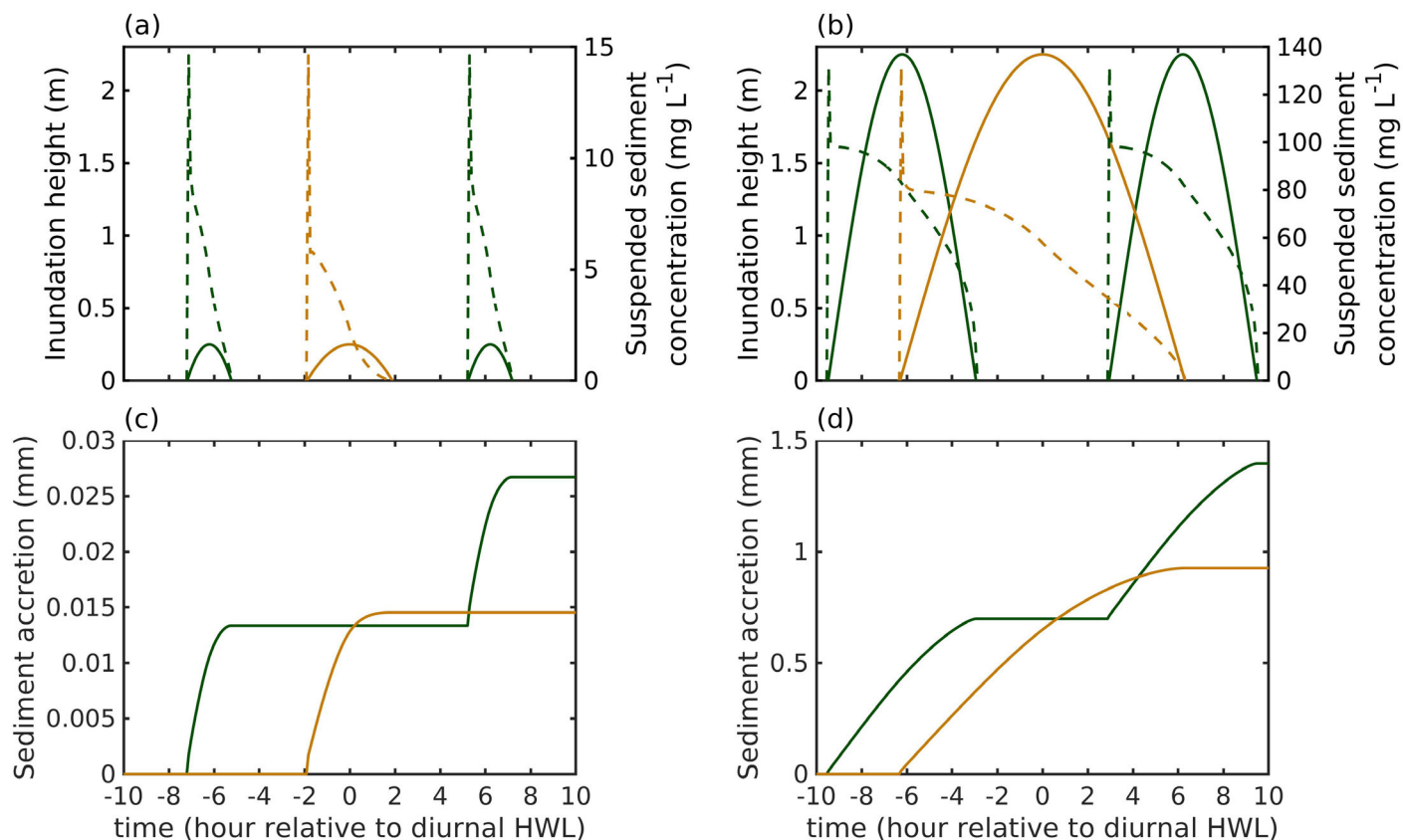

Fig. 5. (**a**, **b**) Temporal variation of marsh inundation height (solid lines) and SSC (dashed lines) during two semi-diurnal (green lines) and one diurnal (brown lines) tidal inundation cycle(s) and (**c**, **d**) corresponding rate of mineral sediment accretion integrated over the duration of a lunar day. These tidal inundation cycles correspond to a marsh inundation height at high tide of (**a**, **c**) 0.25 m and (**b**, **d**) 2.25 m.

Our model simulations indicate that marshes under diurnal tides are less resilient to future RSLR, a finding consistent through a range of 21st century accelerating SLR projections (*see* Fig. 3), and combinations of SSC and TR values (*see* Fig. 4). Comparing simulated sediment dynamics during one lunar day provides additional insights into the underlying mechanisms (Fig. 5). Essentially, two semi-diurnal tides as compared to one diurnal tide occurring during the same period, lead to two vs. one inundation event(s), respectively. Since each inundation event introduces initially high SSC values that subsequently decrease during the tidal inundation through sediment settling (Fig. 5a,b), the two semi-diurnal tides result in a higher net elevation gain (Fig. 5c,d), as compared to the single diurnal tide, although the latter has a longer inundation duration (i.e., hydroperiod). In other words, this demonstrates that inundation frequency is more important here than hydroperiod in driving sediment accretion. Note however that with higher marsh inundation heights (Fig. 5b,d), the importance of hydroperiod increases relative to the inundation frequency, although the latter still remains dominant. As mixed tides are characterized by a periodic alternations between semi-diurnal and diurnal tides, but with a predominance of one pattern onto the other, semi-diurnal and diurnal tides can be thus seen as the two end-members of a spectrum of patterns that tides exhibit on a global scale, with mixed tides falling in the middle of that spectrum. Therefore, in line with the results of our model assessment that focusses on comparing the effects of semi-diurnal vs. diurnal tides on sediment accretion and resulting elevation changes, results suggest that coastal wetlands that occur under mixed tides are expected to experience intermediate rates of sediment accretion and elevation change, and hence would be more resilient than marshes under diurnal tides but less than those under semi-diurnal tides.

Our model was originally designed to study the response of tidal marshes to RSLR through the feedback between tidal inundation and mineral suspended sediment accretion. Although this model has not been tested yet explicitly for mangroves, we expect that results are qualitatively relevant to mangroves dominated by tidal supply and deposition of mineral sediments, where such inundation–accretion feedback prevails similarly (Krauss et al. 2014).

The model does not explicitly simulate the mechanisms of organic matter accretion resulting from vegetation biomass productivity and organic matter decomposition. Instead we assume here a constant organic matter accretion rate, derived from field measurements in our reference marsh in the Scheldt estuary (Temmerman et al. 2004). We acknowledge this is a simplification and as such, our model assessment may be only representative of minerogenic marshes. Yet, we opted here for this simplification, because at present, we lack empirical insights into how rates of marsh vegetation productivity and organic matter decomposition differ under various tidal patterns. Despite this, we may expect impacts of tidal patterns

on organic matter accretion in coastal wetlands. Indeed, perturbation theories in ecology, such as the "subsidy-stress gradient" hypothesis (Odum et al. 1979), suggest that small disturbances to an ecosystem can stimulate its productivity and ecological functioning. Studies notably show that regular tidal inundation pulses of medium energy (Odum et al. 1995) and sediment deposition disturbances (Tang et al. 2020) enhance marsh vegetation productivity. Accordingly, various tidal patterns that are differentiated by inundation durations and frequencies, and which result in distinct sediment deposition rates, may induce different responses in plant biomass productivity, and consequently on organic matter accretion.

The previously ignored role of the tidal pattern in coastal wetland adaptability to RSLR brings new perspectives on observations of wetland vulnerability to RSLR in regions like the Mississippi delta, the surrounding US Gulf coast, the Caribbean, and parts of South-East Asia and Oceania, which experience (mixed) diurnal tides. These regional hotspots identified here fairly agree with regions of wetland vulnerability previously identified (Webb et al. 2013; Goldberg et al. 2020). In this regard, increasing the spatial distribution of SET sites can also help to further constrain these regional hotspots or identify new ones. Modeling studies also project that climate change and SLR will contribute to future changes in the global spatial distribution of the amplitudes of semi-diurnal and diurnal tidal constituents (*see* Haigh et al. 2020). Therefore, some regions will likely experience future changes in tidal patterns, with implications on coastal wetland adaptability to RSLR.

Our findings imply that the specific tidal pattern may not be ignored when analyzing data and conducting model projections on coastal wetland responses to RSLR. While many studies on the bio-geomorphology of coastal wetlands exist from sites under different tidal patterns, their distinctive role is mostly ignored. Therefore, new insights on this role of tidal patterns may be gained by revisiting empirical studies across sites under different tidal patterns and by dedicated experiments on bio-geomorphic processes such as vegetation productivity, sediment trapping, and organic matter deposition, including carbon sequestration, in order to support further advances on the understanding and projection of coastal wetland responses to future RSLR.

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