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A one-dimensional biomorphodynamic model of tidal flats: Sediment sorting, marsh distribution, and carbon accumulation under sea level rise

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ABSTRACT

We develop a biomorphodynamic model to investigate sediment and vegetation dynamics on a schematic intertidal flat characterized by an initially well-mixed sand-mud mixture. Major interactions between tides, wind waves, salt marshes, sediment transport and sea level rise (SLR) are taken into account. For a bare flat under only tidal action, the model predicts a convex cross-shore profile with the surficial distribution of mud and sand on the upper and lower part of the intertidal flat, respectively. When wind waves are strong, the intertidal flat is highly eroded resulting in a concave profile near the high water mark. This behavior is pronouncedly altered when the intertidal flat is vegetated with the presence of salt marshes. Numerical results suggest that a considerable amount of mud can still remain in the vegetated region even when wave action is strong. A steeper transition zone forms at the boundary between salt marshes and bare flats because of the differential sediment deposition in the two neighboring regions. The inclusion of wind waves is found to considerably enhance the size of the marsh-edge transition zone. For the numerical experiments designed in this study, the profile shape and sediment sorting behavior of tidal flats are not significantly modified by a gradual rising sea level. However, the impacts of SLR on vegetated tidal flats are still manifold: (a) driving the landward migration of intertidal zone and salt marshes; (b) enhancing sediment erosion on intertidal flats; and (c) drowning salt marshes under limited sediment supply with the constrain of seawalls. Finally, model results suggest that organic carbon accumulation on marshlands may be enhanced with an increasing SLR rate provided that salt marshes are not drowned.

1. Introduction

Tidal flats are observed in a variety of sheltered or exposed coastal and estuarine environments, such as back-barrier basins, estuaries, deltas and coastal plains [18,19,23]. Tidal flats are vitally important for their ecological and socio-economic values as they provide extensive ecosystem services, serve as a natural buffer against coastal storms and accommodate commercially important fisheries [6]. The dimension and morphology of tidal flats vary considerably worldwide depending on several major factors including tidal range, wave climate, sediment supply, biological context and landscape setting [5,20]. Large tidal range and strong wave action tend to favour the accretion and erosion of tidal flats, respectively [21,56]. Abundant sediment supply, either from a marine or a fluvial source, leads to the growth and seaward advance of tidal flats [30,40,71]. Recent studies (e.g., [11,32]) also highlight that biophysical feedbacks between ecology and geomorphology tend to stabilize tidal flats and wetlands and improve their resilience and adaptability to environmental change and sea level rise (hereafter referred to as “SLR”).

Although differing remarkably in size and shape, tidal flats generally display a typical zonation from the low water to high water marks as shown in Fig. 1. Salt marshes (or vegetated tidal flats) usually occupy a higher elevation than the mean sea level (MSL), and are (partially-) flooded during high tides [12]. The non-vegetated bare flats lie below the MSL and hence are exposed mainly during low tides. Depending on the local sedimentological history of the estuarine setting, bare flats may consist of sand-mud mixtures displaying a seaward coarsening trend in grain size [2,20,34]. The boundary of salt marshes and bare flats is usually characterized by the presence of a vertical scarp (or termed as “cliff”) ranging from a few decimetres to several metres [1]. Finally, the local heterogeneity of tidal flats (presence of depressions or vegetation) may lead to the initiation and formation of tidal creeks which are essential for the wetlands to exchange water, biotic and abiotic matter and nutrients with the adjacent open water [8,57,73].

Using a morphodynamic model, Zhou et al. [72] explored the sorting dynamics of cohesive and non-cohesive sediments on bare

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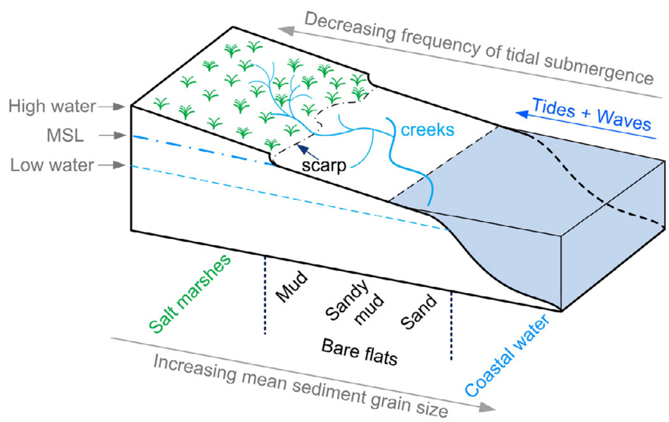

Fig. 1. A schematic view of the zonation and geomorphic features on a tidal flat from low water to high water levels.

intertidal flats. They found large tidal ranges and strong wind waves favour the accretion and erosion of intertidal flats, respectively. Consistent with field observations, the simulated sediment grain size shows a "seaward coarsening" characteristic: mud tends to distribute on the upper tidal flat while sand on the middle or lower flat. This sorting behavior appeared to be particularly sensitive to wind wave climate and sediment properties. Under strong wind waves, mud was highly eroded and could hardly remain on the surface of intertidal flats. Nevertheless, one may argue that mud is also widely observed on the upper intertidal flat at some natural sites where wind waves are not necessarily minor and even some occasional storms are present. This is because, on the one hand, mud with a higher critical shear stress for erosion and a larger settling velocity than the one assumed in numerical simulations can survive stronger wave activities. On the other hand, the presence of salt marshes on the upper tidal flat plays a crucial role to prevent sediment erosion and enhance deposition, which was not considered in [72].

During the last decade, the evolution of shallow vegetated basins has been studied by many authors from different perspectives, highlighting the importance of biomorphodynamic feedbacks between hydrodynamics, sediment dynamics, topographic change and vegetation processes (see, e.g., [51] and [15] for a review). Field measurements indicate that salt marshes effectively reduce the flow velocity and dissipate wave energy through the dense vegetation canopy and the roots of salt marshes can enhance the resistance of substrate against erosion [15,59]. Furthermore, salt marsh stems can directly capture sediments accounting for up to 70% of sedimentation [48]. On the other hand, variations in environmental conditions can also affect the growth and death of salt marshes. Morris et al. [47] suggested that salt marshes regulate their elevation within a narrow portion of the intertidal zone and their survival or drowning is primarily determined by the competition between sediment accretion rate and SLR rate (see also [26]). Recent studies also highlight the considerable impact of wave-induced lateral erosion on marsh deterioration, which can be further exacerbated by SLR [16,42,44]. These biophysical interactions affect the sediment budget and vegetation condition, and subsequently modify the ability of coastal and marine vegetation in carbon sequestration which contributes to nearly half of the carbon burial in the coastal and global ocean [14]. Numerical experiments in [50] indicate that the carbon burial in salt marshes is nonlinearly dependent on both inorganic sediment supply and the SLR rate. They suggest that there exists a critical SLR rate below which carbon accumulation increases with SLR, while above which marshes may drown and carbon accumulation is halted. Extending the biophysical model of Mudd et al. [50], Kirwan and Mudd [32] examined the relative importance between direct impact of global warming and warming-driven SLR, suggesting the former has a more subtle effect on carbon accumulation.

Although remarkable progress has been made, the discipline of biomorphodynamics is still in its infancy and our understanding of the intertwined biophysical interactions on tidal flats remains inadequate. In this contribution, we present a biomorphodynamic model extending the work of Zhou et al. [72], aiming to shed light on the long-term morphological evolution of tidal flats in the presence of salt marshes under the combined effect of tides, wind waves and SLR. The biomorphodynamic model treats all vegetation-related processes using existing formations on the basis of biomass production so as to build a consistent modeling framework [15,43,49]. The specific research questions we try to address are: (1) How do salt marshes affect sediment sorting on tidal flats? (2) What is the role of SLR on the distribution of salt marshes? and (3) How do carbon accumulation and sediment sorting change under SLR? Understanding these questions can provide in-depth insights on various biophysical feedbacks under SLR, and hence assist to make long-term sustainable management strategies for tidal flats and wetlands.

2. Model description

Based on the framework of an open-source morphodynamic model (Delft3D), a wind wave module and a vegetation module are developed following existing literature [43,48,69,70]. Since the morphodynamic model has been well documented elsewhere (e.g., [39,62]), it will be only briefly introduced in this section while the emphasis is given to the wind wave module and the vegetation module which have been developed specifically for this study. Assuming the alongshore uniformity as previous studies (e.g., [40,55,56]), a one-dimensional (1D) cross-shore profile model is considered to reduce model complexity and computational time. The use of a 1D model is mostly valid for relatively long and straight stretches of tidal flats.

2.1. The morphodynamic model

Based on the assumption of long-shore uniformity, the 1D mode of Delft3D model is considered by using only one grid cell in the long-shore direction. The model consists of several key modules simulating, e.g., flow motion, sediment transport, bed stratigraphy and morphological change. The non-linear shallow water equations are solved to obtain the flow field (i.e., velocities and water levels), which in 1D form read:

$$\frac{\partial \eta}{\partial t} + \frac{\partial (hu)}{\partial x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} + \nu\frac{\partial^2 u}{\partial x^2} - g\frac{u|u|}{C_z^2 h}, \tag{2}$$

where u is the depth-averaged velocity in the x direction (m/s); t is time (s); h is the water depth (m); η is the water level with respect to datum (e.g., MSL) (m); ν is the horizontal eddy viscosity coefficient (m^2/s); C_z is the Chézy friction coefficient ($m^{1/2}/s$) and g is the gravitational constant (m/s^2). In this study, the values of ν, C_z and g are set to 1 m^2/s, 65 $m^{1/2}/s$ and 9.81 m/s^2, respectively.

A spring-neap tidal cycle boundary condition is imposed at the offshore by the superposition of tidal constituents M_2 and S_2. Wind waves are described by the formulation of [69,70] which is introduced in the following subsection. The combined maximum bed shear stress of tides and waves is considered to be responsible for the mobilization and transport of bed sediments following [58], which has been also used by other researchers for shallow tidal basins and flats (e.g., [4,43]):

$$\tau_{max} = \tau_w + \tau_c\left[1 + 1.2\left(\frac{\tau_w}{\tau_c + \tau_w}\right)^{3.2}\right], \tag{3}$$