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Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows

D.P. Callaghan [a,*], T.J. Bouma [b], P. Klaassen [b], D. van der Wal [b], M.J.F. Stive [c], P.M.J. Herman [b]

[a] School of Civil Engineering, The University of Queensland, Brisbane, Australia
[b] Netherlands Institute of Ecology (NIOO), The Netherlands
[c] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

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ABSTRACT

To unravel the relation between hydrodynamic forcing and the dynamics of the tidal flat–salt-marsh ecosystem, we compared hydrodynamic forcing in terms of proxies relevant to bed sediment motion for four tidal flat–salt-marsh ecosystems that were contrasting in terms of wind exposure (sheltered vs. exposed) and lateral development (shrinking vs. expanding). Wave and current field measurements on these four contrasting tidal flat and salt-marsh ecosystems indicated that the hydrodynamic forcing on the bottom sediment (bed shear stress) was strongly influenced by wind-generated waves, more so than by tidal- or wind-drive currents. The measurements further showed that the hydrodynamic forcing decreased considerably landward of the marsh cliff, highlighting a transition from vigorous (tidal flat and pioneer zone) to sluggish (mature marsh) fluid forcing. Spatial wave modeling using measured wind, revealed that the time-integrated wave forcing on the intertidal mudflat in front of the marsh (i.e., the potential bed sediment pickup) was a factor two higher for salt marshes that are laterally shrinking than for laterally expanding marshes, regardless of whether these marshes were exposed to or sheltered from the wind. The same result could not be obtained from a straightforward wind speed and fetch length approach for estimating wave forcing. This confirmed that wave force estimates required spatial modeling to be consistent with the sites trends of shrinking or expanding marshes and wind exposure is not enough to characterize the wave forcing at these sites.

Seasonal changes in wave forcing identified from wind measurements potentially provide an alternative mechanism for marsh cliff formation. During the calm summer, fine sediments switches from the water column to the bed. During the following winter, fine sediment is retained within the vegetated regions while being returned to the water column from the bare tidal flats. The continuous slow upward growth of vegetated areas combined with the seasonal cyclic tidal flat elevations, could, during winter, cause a discontinuity at the bare/vegetated boundary. If this discontinuity grows large enough for plant die-off to occur, then a small cliff will form.

1. Introduction

Estuarine tidal flats and salt marshes are important ecosystems providing, for example, nursery functions for various organisms and coastal protection in the form of reduced hydrodynamic energy that engineered defenses need to resist. Economic development has placed ever greater demands on estuaries, coastal regions and on tidal flat and salt-marsh ecosystems (e.g., estuary dredging and coastal squeeze). The establishment and lateral extension of salt marshes on tidal flats under constant tidal forcing (i.e., no sea-level rise) with constrained landward boundaries is predominantly the result of bio-physical interactions between vegetation and hydrodynamically governed sediment transport (Kirwan and Murray, 2007; Temmerman et al., 2007). Conceptual models indicate that storm events may induce cliff formation on maturating marshes, thereby causing lateral erosion which after time is followed by re-establishment of pioneer species in front of the cliff, resulting in cyclic marsh dynamics (van de Koppel et al., 2005). The marsh cliff being formed consists of vertical elevation changes from a few centimeters to over 1 m, over a horizontal distance up to several meters. The cliff line usually separates the mature-marsh vegetation from the pioneer grass species. Despite the clear importance of hydrodynamics in all aspects of salt marsh dynamics, there is still a lack of understanding about the physical processes that are important drivers of tidal flat and salt marsh dynamics.

* Corresponding author.
E-mail address: dave.callaghan@uq.edu.au (D.P. Callaghan).

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Previous field measurements and modeling of hydrodynamics on tidal flats and salt marshes can be divided into groups addressing specific topics. The first group focused on the relation between hydrostatic currents and biogeomorphological development, particularly channel formation and the role of over-marsh vs. creek flows for net sediment transport. The approaches used in these studies ranges from measurements based (Bayliss-Smith et al., 1979; Reed et al., 1985; Reed, 1988; Stoddart et al., 1989; French and Stoddart, 1992; Wang et al., 1993; Leonard and Luther, 1995; Christiansen et al., 2000; Bouma et al., 2005, 2009; Temmerman et al., 2005a,b) to more modeling based (Kirwan and Murray, 2007; Temmerman et al., 2007). The second group of studies focuses on the coastal defense value of coastal vegetations like salt marshes by studying wave attenuation from vegetation and one dimensional wave generation and propagation (Wayne, 1976; Dalrymple et al., 1984; Brampton, 1992; Kobayashi et al., 1993; Moller et al., 1999; Moller and Spencer, 2002; Mendez and Losada, 2004; Moller, 2006; Fagherazzi et al., 2006, 2007; Fagherazzi and Wiberg, 2009). The third group investigated seasonal changes in bed elevation and sediment properties that occurred on the tidal flats, without looking at the salt marsh (O'Brien et al., 2000; Moller and Spencer, 2002; Carniello et al., 2005; Widdows et al., 2008). The fourth group involved conceptual modeling to understand the long-term dynamics of the tidal flat–salt-marsh ecosystems (e.g., van de Koppel et al., 2005; Fagherazzi et al., 2006).

Most of the aforementioned studies are site specific or, in case of some models, for one idealised site, thereby ignoring that tidal flats–salt-marsh ecosystems may occur in areas that strongly differ in wind fetch (van der Wal et al., 2008) and that there may be a large difference in the relative importance of forcing from hydrostatics flow (e.g., tidal- and wind-driven current) and non-hydrostatic oscillatory flow (short-period waves) between sites. As a result, it is still poorly understood how hydrodynamic forcing relates to the dynamics of the tidal flat–salt-marsh ecosystems. In this study, we aim at elucidating the latter by comparing hydrodynamic forcing between four contrasting tidal flat–salt-marsh ecosystems. Of these four sites, two were exposed to and two were sheltered from the prevailing southwesterly winds. For both the two exposed and the two sheltered sites, one site had a laterally expanding salt marsh (i.e., an expanding pioneer vegetation in front of a stationary marsh cliff) while the other site had a laterally shrinking marsh (i.e., a landward moving marsh cliff). That is, shrinking and expanding salt-marsh behaviors thus occurred at locations with similar wind exposure and fetch length.

Wave forcing is known to vary strongly with wave direction, wave period, wave height and tidal phase or water depth (Nielsen, 2009), while current forcing varies hourly with the tidal phase and the tidal range varies fortnightly with the spring/neap cycle (Bouma et al., 2005). Hence, to investigate possible links between hydrodynamic forcing and the observed contrasting lateral salt-marsh behavior, ideally require hydrodynamic field measurements at extensive spatial and temporal scales to cover different weather conditions at all sites. As our field measurements of currents and waves were limited to a subset of the full spectrum of weather conditions, we used two-dimensional in the horizontal plane wave modeling to extrapolate wave forces for a wider range of conditions. In this approach, our field measurements were useful for qualitative comparisons between calm and stormy weather along the measurement transects and for validating the model. To unravel the relation between hydrodynamic forcing and the dynamics of the tidal flat–salt-marsh ecosystem, we translated hydrodynamic data in proxies relevant to bed sediment motion: bed shear stress and potential bottom sediment pickup rate. These proxies we preferred over hydrodynamic data (e.g., fluid velocity) for one major reason: at short time scales (min to h) one forcing is steady and the other is unsteady and oscillatory (positive and negative velocities). The nature of the fluid boundary layer which establishes the fluid forces on the bottom sediment are very different for steady and oscillatory flow regimes (Nielsen, 1992). That is, the steady flow boundary exists the entire time (albeit changing slowly) where the oscillatory boundary layer starts from zero, grows to a maximum thickness before breaking up twice every wave period. A sediment forcing proxy consequently requires boundary layer physics in their formulation. These details are not available directly from measured flow velocities as the complexities of the boundary layer physics results in different (depending on flow type) non-linear relationships between velocity and fluid force on bottom sediments.

Summarizing, we address how hydrodynamic forcing relates to the dynamics of the tidal flat–salt-marsh ecosystems by comparing hydrodynamic forcing in terms of proxies relevant to bed sediment motion for four contrasting tidal flat–salt-marsh ecosystems. We specifically test the hypotheses that: (1) at all sites and in all seasons, waves exert greater hydrodynamic force on tidal flat and mature marsh bottom sediments then tidal currents, (2) wave forcing decreases across the tidal flat and mature marsh and tidal flat sediments experience more hydrodynamic forcing than their mature marsh counterparts, (3) hydrodynamic forces in terms of bed sediment motion is higher at sites with shrinking marshes than sites with expanding marshes, regardless of wind exposure.

2. Methods

The hydrodynamic force on bottom sediments from currents and waves (Section 2.3) was determined from processed field measurements during calm and stormy weather (Section 2.2) obtained from four sites located within the Westerschelde estuary (Section 2.1). The seasonal analysis involved modeling waves over large spatial (tidal flat) and temporal (i.e., 20 years hindcasting) scales (Section 2.4.1). Wave forces on the bottom sediments across the seasons (Section 2.4.2) were estimated from the hindcast wave predictions.

2.1. Field site

The Westerschelde (Fig. 1) is a meso to macrotidal estuary with tidal flats and shoals interrupted by evasive meandering ebb and straight flood channels (Fig. 3; Swinkels et al., 2009). Both natural processes (e.g., sea-level rise, subsidence) and anthropogenic influences have influenced the morphological evolution of the Westerschelde estuary. For a long time, anthropogenic influences consisted of reclamation of silted up intertidal areas. During the last 50 years, sand extraction and dredging of the shipping lanes have become the dominant influences, with a deepening of the shipping lane by 2–3 m in the seventies and 1–1.5 m in 1997/1998 (Jeuken and Wang, 2010). As a result of all these processes, the tidal amplitude has gradually increased over time resulting in the maximum tidal ranging increasing from 4.3 m in 1895 to 5.2 m in 2005 at Antwerpen (Meire et al., 2005). The mean tidal range at the field sites (Fig. 1) was *ca* 4.1 m (1987–2008). The tidal flats fronting the salt marshes were 'dry' at low tide and submerged at high tide (water depths between 1 m and 3 m). The mature marsh inundation depths varied between 0.2 m and 0.6 m.

The Westerschelde estuary has freshwater inflow from the Schelde, which is a typical rain-fed lowland river, with an average discharge of 104 m^3/s at Schelle (Meire et al., 2005), which strongly fluctuates over the seasons from 50 m^3/s in summer and up to 400 m^3/s in winter (Temmerman et al., 2003; van Damme et al., 2005). The river inflows causes seasonal variability in the salinity