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The role of flow asymmetry and mud properties on tidal flat sedimentation

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ABSTRACT

It is well known that landward transport of fine sediments on tidal flats is caused by lag effects, of which the scour lag and the settling lag are the best known. These lag effects result from a combination of sediment properties and hydrodynamic asymmetries. However, it is not well-understood how, in a quantitative way, these lag effects depend on the sediment properties and the hydrodynamic forcing, and what the relative importance of these sediment properties and hydrodynamics is. As a result, it is not known which lag effect is more important under which conditions. We therefore set out to explore the relative importance of hydrodynamics and sediment properties on tidal-flat sedimentation using a schematized 2DV cross-shore profile model with a tidal range of 6 m and an intertidal width of ~5 km. The effect of hydrodynamics is parameterized through a varying offshore tidal asymmetry and four different cross-shore profiles (a horizontal, convex, linear and concave profile). The effect of sediment properties is examined by evaluating a range of settling velocities w_s and critical bed shear stresses for erosion τ_{cr}. The main findings of this work are that (1) conditions of maximum sediment deposition rates exist for w_s ~0.5 mm/s and τ_{cr} ~0.1 Pa, (2) deposition rates due to slack tide asymmetry are comparable to symmetric tides, while peak flow asymmetry produces the greatest deposition rates, (3) tidal flat deposition rates are greatest for concave profiles and least for convex profiles mainly due to the horizontal velocity gradient, and (4) the type of lag effect dominating landward transport varies spatially.

1. Introduction

Many tidal embayments and estuaries harbor extensive tidal flats where fine-grained sediments accumulate. These tidal flats play an important role in the ecological functioning of such marine systems, and in protecting the low-lying hinterland against flooding. However, mudshores are still poorly understood compared to their sandy equivalents, partly because of the complexity of behavior of cohesive sediments, which is influenced by chemical, physical, and biological processes (e.g., Pethick, 1996; Kirby, 2000; Widdows et al., 2004; Friedrichs, 2012). The transport of fine-grained sediments towards these flats has therefore been extensively studied in the past, starting with the pioneering work of Van Straaten and Kuenen (1957, 1958) and Postma (1954, 1961, 1967). Over long timescales, tidal flats generally keep pace with rising sealevel owing to a variety of landward sediment transport processes related to lag effects (notably the settling lag introduced by Postma (1954), and the scour lag introduced by van Straaten and Kuenen (1957)).

Bartholdy (2000) concluded that lag effects are most important for coarse silt and fine sand, while Ridderinkhof and Eisma (in Eisma et al., 1998) state that settling and scour lag are only pronounced when suspended sediment concentrations are high, as then flocculation processes become important. Hence, the response of tidal flats to a change in sediment supply and grain size is strongly non-linear. This response may become even more complicated because of differences in Eulerian tidal asymmetries (slack tide asymmetry and peak flow asymmetry) and Lagrangian asymmetries in flow velocity or water depth. Due to the interaction between sediment properties, sediment concentration, hydrodynamics and bathymetry, the various contributions of these processes to tidal-flat sedimentation are not easily determined.

Previous analyses of tidal-flat transport processes using analytical (Friedrichs and Aubrey, 1996; Pritchard and Hogg, 2003) and numerical models (Roberts et al., 2000; Pritchard et al., 2002; Le Hir et al., 2000) of cross-shore profile evolution have lead to improved understanding of the long-term behavior of tidal flats. Roberts et al. (2000) and Pritchard et al. (2002) determined equilibrium bed profiles for tidal flats with a variation in tidal range, sediment supply and tidal asymmetry. An increase in tidal

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range and a decrease in sediment concentration both lead to a steeper tidal-flat profile. An asymmetrical tide with greater peak flood currents leads to accretion, while ebb-dominance leads to erosion; the bed profile shaped by ebb-dominant tidal asymmetry is steeper than for flood-dominant tidal asymmetry. Inclusion of wave effects by Roberts et al. (2000) leads to a transition from convex to concave equilibrium profiles, in agreement with observations (i.e., Kirby, 2000). Pritchard and Hogg (2003) compute the equilibrium state of tidal flats under constant forcing conditions by applying an analytical model. They concluded that the gross morphological evolution of tidal flats (erosion/accretion rates as well as shape) depends on the offshore sediment supply. Although tidal asymmetries were related to equilibrium tidal-flat morphology, the actual transport rates and processes were not analyzed in detail.

A fundamental aspect not covered by previous modeling studies on tidal-flat sedimentation is the relation between sediment characteristics (settling velocity, critical shear stress for erosion), tidal asymmetry, and settling lag. The relative contribution of lag effects and tidal asymmetry on residual transport has mainly been explored on larger scales, e.g., for bays (Pritchard, 2005) or estuaries (Chernetsky et al., 2010). Only recently Hsu et al. (2013) developed a detailed intertidal flat model simulating the effect of tides and thereby the settling lag on residual fine sediment transport. Therefore, the aim of this paper is to analyze and quantify the effects of tidal asymmetry and sediment characteristics on transport rates and mechanisms for various tidal-flat geometries using a numerical model. The structure of this paper is as follows. First, we review tidally-driven fine sediment accumulation processes in intertidal areas. This is followed by a model description and model results. These are further interpreted in the discussion, followed by conclusions.

2. Net fine sediment transport by oscillating tidal currents

Net transport of (fine) sediments is always related to asymmetries in the hydro-sedimentological conditions. Basically, two types of asymmetries can be distinguished, which often occur simultaneously: (1) asymmetries in the water movement, and (2) asymmetries in the sediment properties/behavior. Therefore we will discuss the relevant hydrodynamic and sedimentary processes, limited to abiotic processes of tidal origin.

2.1. Asymmetries in the sediment properties/behavior

The energy required to mobilize fine cohesive sediment particles from the bed is much greater than the energy to keep/bring these particles into suspension. Also, because cohesive sediment particles (flocs) are very small (with settling velocities between ~0.1 mm/s and ~1 mm/s), the time scale to mix the particles over the water column is much smaller (~minutes) than the settling time (~hours or more). These asymmetries in mobilization, vertical mixing and settling can contribute to processes known as settling lag and scour lag. The term settling lag was introduced by Postma (1954), and further elaborated by van Straaten and Kuenen (1957, 1958), and Postma (1961, 1967). The settling lag is the period or distance a particle can travel when the flow velocity has fallen below the critical shear stress for erosion, before settling on the bed. Combined with a spatial asymmetry in the water depth or flow velocity and a certain critical shear stress for erosion, this leads to transport in a preferential (usually landward) direction. The term scour lag was introduced by Van Straaten and Kuenen (1957), describing another form of landward sediment transport. They defined scour lag as the net transport arising from the greater critical shear stress needed for erosion than for maintaining particles in suspension. Combined with an asymmetry in the flow, this may lead to a net transport of sediment. Physical mechanisms for this increase in critical shear stress with time are self-weight consolidation, bed strengthening by diatom mats, and/or drying of intertidal areas. Nicholls (1986) and Dyer (1994) defined scour lag as the time required to vertically disperse sediment, thereby focusing on processes in the water column rather than at the water–bed interface. They defined the net transport arising from an increase of shear stress within the bed (comparable to van Straaten and Kuenen's scour lag) as erosion lag. We will use both the Dyer and van Straaten and Kuenen terminology, defining scour lag as the net transport of sediment resulting from time-lags associated with the vertical mixing of sediment and the mobilisation of sediment from the bed.

2.2. Asymmetries in the water movement

Asymmetries in water movement may occur over time, over horizontal space, and/or over the water column.

2.2.1. Time asymmetries

In semi-diurnal tidal regimes, tidal asymmetry results from the generation of the M_4 overtide, and asymmetry is often measured in terms of phase differences between the M_2 and M_4 tidal component. In mixed tidal regimes, other components may play a role as well (Hoitink et al., 2003; Niedziko, 2010; Song et al., 2011; van Maren and Gerritsen, 2012). For instance, when $0^\circ < (2\phi_{M2} - \phi_{M4}) < 180^\circ$ (where ϕ_{M2} and ϕ_{M4} are the phase angle of the M_2 and the M_4 component, respectively) peak flood velocities exceed peak ebb velocities, resulting in a net flood-directed sediment transport (as the sediment transport rate generally scales with the flow velocity to the power n, with $n > 1$). This process has been extensively elaborated in the literature for granular sandy material (e.g., Friedrichs and Aubrey, 1988; Van de Kreeke and Robaczewska, 1993), but it is relevant for alluvial systems of fine sediment as well (Dronkers, 1986). Asymmetry in the slack tidal period is defined as the difference between ebb and flood slack tide period at which the flow velocity is below a critical velocity threshold. Landward transport prevails if the duration of HWS (high water slack) exceeds the duration of LWS (low water slack): this occurs for $90^\circ < (2\phi_{M2} - \phi_{M4}) < 270^\circ$. In general, coarser sediment is more sensitive to local asymmetries in maximum velocity, while fine sediment is more sensitive to local asymmetries in the duration of slack (Friedrichs, 2012), as long as suspended sediment concentrations are fairly low.

2.2.2. Vertical asymmetries

Asymmetry in vertical mixing (often referred to as internal asymmetry; Jay and Musiak, 1994), results from asymmetries in peak flow velocities (with vertical mixing scaling non-linearly with flow velocity). If vertical mixing during floodis more intense than during ebb, particles will travel longer distances during flood owing to the larger flow velocities higher in the water column. Tidal asymmetries in vertical velocity distribution are associated with accelerating and/or decelerating flows, and density currents. Combined with the vertical distribution in suspended–sediment concentration, an asymmetry in the flow velocity profile may induce net sediment transport by differential advection. However, the asymmetries in vertical suspended concentration often occur in conjunction with asymmetries in vertical mixing, in particular in the case of gravitational circulation (e.g., Dyer, 1994).