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Dynamic equilibrium behaviour observed on two contrasting tidal flats from daily monitoring of bed-level changes

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ABSTRACT

Dynamic equilibrium theory (DET) has been applied to tidal flats to systematically explain intertidal morphological responses to various distributions of bed shear stress (BSS). However, it is difficult to verify this theory with field observations because of the discrepancy between the idealized conceptions of theory and the complex reality of intertidal dynamics. The core relation between intertidal morphodynamics and BSS distribution can be easily masked by noise in complex datasets, leading to conclusions of insufficient field evidence to support DET. In the current study, hydrodynamic and morphodynamic data were monitored daily for one year on two tidal flats with contrasting wave exposures. BSS distribution was obtained by validated numerical models. Tidal flat dynamic equilibrium behaviour and BSS were linked via Empirical Orthogonal Function (EOF) analysis. We show that the principal morphodynamic modes corresponded well with the respective modes of BSS found at both sites. Tide-induced BSS was the dominant force at both sites, regardless of the level of wave exposure. The overall erosional and steepening trend found at the two flats can be attributed to the prevailing action of tidal forcing and reduced sediment supply. Hence, EOF analysis confirmed that tidal flat morphodynamics are consistent with DET, providing both field and model evidence to support this theory.

1. Introduction

Tidal flat morphology is continuously shaped by diverse physical and biological processes, e.g. tidal currents, wind waves, variability in sediment supply and bioturbation/bioaggregation (Le Hir et al., 2000, 2007; Friedrichs, 2011; Green and Coco, 2007; Talke and Stacey, 2008; Stanev et al., 2009; Green and Coco, 2014; Hunt et al., 2016; Duran-Matute et al., 2016). The long-term dynamics of bare tidal flats is widely recognized as being important in the overall sustainability of coastal ecosystems, such as saltmarshes and mangroves (Fagherazzi et al., 2006; van der van der Wal et al., 2008; Mariotti and Fagherazzi, 2010, 2013). Recent studies have also identified the short-term dynamics of bed level as a major physical disturbance constraining the establishment of intertidal biotas (Bouma et al., 2001, 2016; Nambu et al., 2012; Balke et al., 2013, 2014, 2015). Thus, understanding intertidal morphodynamics is key to preserving ecosystems and their various services (Barbier et al., 2008; Arkema et al., 2015).

Dynamic equilibrium theory (DET) has been proposed to systematically explain the morphological responses of intertidal systems to tidal and wave-induced forcing over various timescales (Friedrichs and Aubrey, 1996; Friedrichs, 2011) (Fig. 1). DET assumes that tidal flat morphological equilibrium is achieved when the maximum bed shear stress (BSS) is uniform over space, ensuring zero net sediment transport (Friedrichs and Aubrey, 1996; Friedrichs, 2011). Based on this assumption, tidal-dominated (convex) or wave-dominated (concave) profiles of tidal flat equilibrium can be predicted from corresponding BSS distributions. DET further illustrates that under varying BSS, the actual tidal flat profile approximates a dynamic equilibrium over long timescales, situated somewhere between the purely tide-dominated and wave-dominated extremes. Over shorter timescales, tidal-flat morphology may be attracted to one or the other extreme depending on BSS variability (Fig. 1). DET can potentially function as a unifying concept in that it systematically illustrates the relation between prevailing mode of hydrodynamic forcing (in the form of BSS) and intertidal morphodynamics. Other drivers are also included in the DET framework, such as external sediment supply, bioturbation/bioaggregation, and human interference (Friedrichs, 2011).

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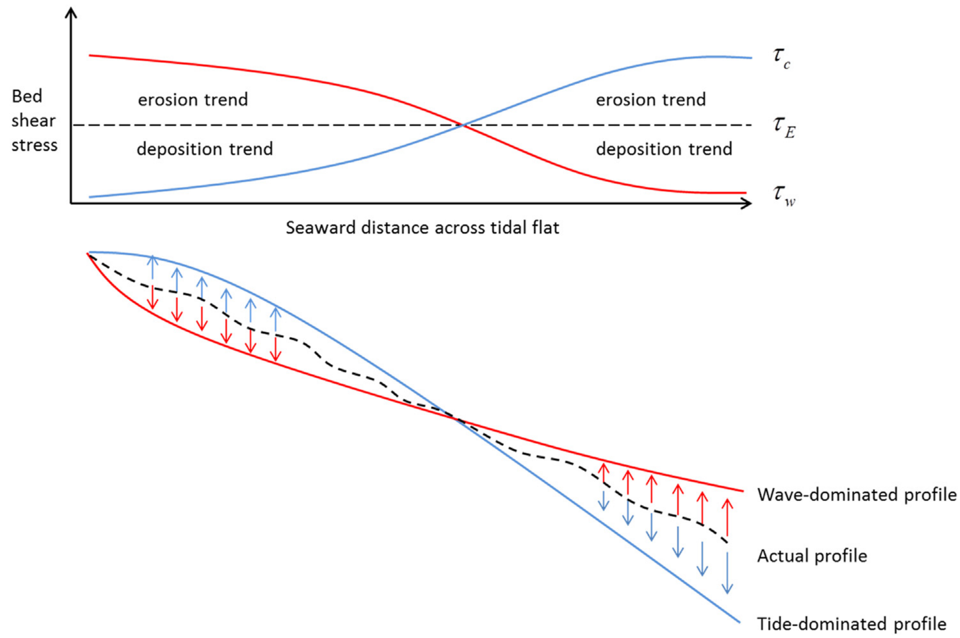

Fig. 1. Conceptual diagram of the dynamic equilibrium theory (DET) of tidal flats, as proposed by Friedrichs (2011). The patterns in bed shear stress (BSS) induced by tidal currents (τ_c) and waves (τ_w) result in contrasting spatial distributions of sediment across flats. Where bed shear stress is higher than the uniform BSS associated with tidal flat equilibrium (τ_E), erosion tends to occur. Where BSS is lower than τ_E, deposition tends to occur. The sediment distributions resulting from tidal and wave forcing lead to corresponding tide-dominated (convex) and wave-dominated (concave) profile shapes. With constantly changing BSS, an actual tidal flat typically lies somewhere between tide-dominated and wave-dominated profiles, and is driven towards one or the other extreme depending on the prevailing mode of hydrodynamic forcing.

As such, DET is an important theory in understanding and predicting intertidal morphodynamics. However, it is usually difficult to link or test DET with field observations because of the clear discrepancies between theoretical schematization and the complex reality of intertidal morphodynamics. As a result, most of the evidence used to support DET are based on numerical modelling, which involves intrinsic abstraction of intertidal sediment dynamics (Liu et al., 2011; Pritchard et al., 2002; van der Wegen and Jaffe, 2014; Hu et al., 2015a; Maan et al., 2015), while there is much less direct field evidence supporting DET (Wang et al., 1999; Yang et al., 2003; Bearman et al., 2010; Ni et al., 2014). The reason that fewer field studies have addressed this topic may be attributed to the difficulties in obtaining data sets taken over a sufficient length of time and with adequate spatiotemporal resolution, as well as the difficulty in analyzing these complex data sets. In the few field studies supporting DET, intertidal profile shape and morphodynamic behaviours were examined in detail with extensive observations (Yang et al., 2003; Bearman et al., 2010). However, the driving force, i.e. BSS, was not quantified in concert with intertidal morphological evolution in these studies; thus, the correlation between BSS distribution and intertidal bed-level evolution, which sits at the core of DET, remains unverified.

In this study, we aim to provide combined field and modelling evidence for DET by quantitatively linking tidal flat dynamic equilibrium behaviour to BSS distribution. Hydrodynamic and bed-level monitoring was conducted daily for a year (20-Nov-2013 to 20-Nov-2014) on two tidal flats with contrasting wave exposure in the Westerschelde Estuary, the Netherlands (Fig. 2). Newly-developed SED-sensors (Surface Elevation Dynamic sensors) were installed at 12 stations to obtain high-frequency data on bed-level dynamics (Hu et al., 2015b). Wave and tidal current data were measured simultaneously and used to quantify BSS. The main components of BSS were identified, as well as the relative importance of tidal and wave forcing at these two sites, using Empirical Orthogonal Function (EOF) analysis. In order to demonstrate the underlying dynamic equilibrium behaviour, the main components of bed-level dynamics were also identified via EOF and analysed in parallel with BSS. Finally, the effect of lower sediment supply on the overall morphological trend at these two tidal flats is discussed.

2. Materials and methods

2.1. Field measurements

The two studied tidal flats in the Westerschelde Estuary have relatively fine sediment, with a median sediment grain size (D50) of 72.1 μm at Zuidgors and 26.8 μm at Baarland. The instrument set-up to measure bed level is shown in Fig. 2. This year-long daily bed-level monitoring was realized by SED-sensors (Surface Elevation Dynamics sensor), recently developed by the Royal Netherlands Institute for Sea Research (NIOZ) (Hu et al., 2015b). The precision of the SED-sensor is ±2 mm and was compared with a precise manual measurement method (sedimentation erosion bars) in an earlier study, with excellent agreement between these two measurements (Hu et al., 2015b). SED-sensors rely on daylight and do not work when submerged by turbid water. The measuring windows of SED-sensors thus occur during "dry" periods under daylight conditions. In the current study, these sensors generally had 1–2 measuring windows per day, depending on the tide level. In each window, one valid data point was recorded to track the bed-level. When there were no bed-level data due to sensor failure, we substituted Differential GPS data obtained at monthly intervals. The DGPS measurement was surveyed manually on these two studied tidal flats. Even though the precision of the DGPS data is lower than for SED-sensors, typically in the range of 5–10 mm (Nolte et al., 2013), we used them as the only other option during SED-sensor failure.

Besides bed-level measurements, pressure sensors (OSSI-010-003C; Ocean Sensor Systems, Inc.) were used to simultaneously obtain tidal level and wave height data at the measuring frequency of 5 Hz. The measuring interval and the measuring period for each interval were 15 min and 7 min, respectively. In a measurement interval, time-averaged water depth and bulk wave parameters (peak wave period and significant wave height) were derived by a MATLAB routine based on