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Wind influence on tidal flat sediment dynamics: Field investigations in the Ho Bugt, Danish Wadden Sea

Christian Christiansen [a,*], Gunnild Vølund [b], Lars C. Lund-Hansen [c], Jesper Bartholdy [a]

[a] *Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K., Denmark*
[b] *Kystdirektoratet, Højbovej 1, 7620 Lemvig, Denmark*
[c] *Department of Marine Ecology, University of Aarhus, Finlandsgade 14, 8200 Aarhus C., Denmark*

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Abstract

Sediment dynamics on a mixed microtidal flat in a sheltered backbarrier position are shown to vary strongly on short term, tidal, and monthly timescales. Bed level changes were ±1 mm per tidal period in the absence of winds. Erosion of 10 to 20 mm within a few hours was possible during high combined current and wave shear stress. Mean grain size in the upper 1 cm bed sediment varied from 34 to 155 μm and was consistently coarser than the mean size of trapped suspended matter (7–10 μm). Threshold for resuspension was low at 0.03 N m^{-2}. No clear correlation was found between resuspension activity and suspended matter concentrations as these concentrations also depend on current induced advection. Due to tidal asymmetry, the net suspended sediment flux was flood directed. On average it was 14 kg m^{-2} per tidal period in the summer and 3 times higher during November when wave activity generally was stronger. Bed micro topography, was followed on digital photos taken every 1.5 h during the two month study period, showed that (1) ripples started to develop when wave shear stress exceeded 0.15 N m^{-2}, and (2) their wavelength varied with shear stress.
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1. Introduction

Many estuaries are semi-enclosed or protected by barriers, such that wave activity is sufficiently diminished to allow the development of harbours, recreational facilities, and sheltered environments that are suitable for aquaculture. Nevertheless, the estuaries may be very energetic environments and dynamic processes can influence biota, morphology, and civil works projects on both short and long-term timescales (Perillo, 1995). As a result, research on estuarine sediment transport processes has received widespread and increasing attention in recent years (e.g. Bartholdy and Anthony, 1998; Christie et al., 1999; Andersen, 2001; Bartholdy and Aagaard, 2001; Grabemann and Krause, 2001; McAnally and Mehta, 2001; Lee et al., 2004).

In the estuarine environment, suspended sediment concentrations are high, and the particles are fine, cohesive and organic-rich. High concentrations are a

* Corresponding author. Tel.: +45 35322510; fax: +45 35322501.
E-mail addresses: cc@geogr.ku.dk (C. Christiansen), guv@kyst.dk (G. Vølund), lund-hansen@biology.au.dk (L.C. Lund-Hansen), jb@geogr.ku.dk (J. Bartholdy).

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result of estuarine processes that continuously concentrate the sediment inside the estuary, and an overall net transport direction, especially of fine-grained sediment, that is generally towards the estuary head. Among the processes that cause the high concentrations are (1) Settling and scourlag (Van Straaten and Kuenen, 1958; Postma, 1967; Pejrup, 1988a), (2) Deformation of the shoaling tidal wave causing an asymmetric distribution of the velocity and sediment concentration, known as tidal pumping (Dyer, 1995), and (3) Flocculation processes that cause aggregation of the cohesive particles and settling velocities high enough for settling when current velocities are low at or near high slack water (e.g. Pejrup, 1988b).

Generally there is an accretion of sediment on the tidal flats and in inner parts of tidally influenced estuaries where low energy conditions prevail. Such areas are, for example, found in the inner parts of the Wadden Sea and hence also in the northern part of the Grådyb tidal area where large amounts of fine-grained sediment accumulate (Pedersen and Bartholdy, 2006-this volume). Because mudflats (both quantitatively and qualitatively) are sinks for fine-grained material, a thorough understanding of the processes that govern deposition and erosion in these environments is important. Detailed investigations of suspended sediment transport on intertidal mudflats were undertaken by Pejrup (1988a), Christie et al. (1999), O'Brien et al. (2000), Bassoullet et al. (2000), Le Hir et al. (2000), and Whitehouse et al. (2000). Nutrients, heavy metals, pesticides and herbicides tend to adhere to fine-grained material and knowledge of the transport pathways and the potential for erosion and deposition of the material will consequently give information on the fate of these toxic and potentially harmful substances.

Local hydrodynamics are helpful in describing the system, with tidal forcing and wave activity often determining the physical and biological characteristics of tidal flats. Such studies were carried out by Janssen-Stelder (2000), Le Hir et al. (2000), Christie et al. (2001), and Lee et al. (2004). Other authors focused on bed level changes in relation to suspended sediment concentrations on intertidal mudflats (Christie et al., 1999; Andersen and Pejrup, 2001), on the nutrient and trace metal exchange between the bed and the water column (Pratska and Jickells, 1995; Mortimer et al., 1998; Laima et al., 2002; Christiansen et al., 2004), or on the formation of bedforms and their influence on flow and sediment transport (Whitehouse et al., 2000). However, bedform development in cohesive sediment in areas that are influenced by both tidal currents and waves has received little attention, and is thus neither well described nor adequately understood.

The main objective of this study was to identify and quantify sediment and morphodynamics of an intertidal flat in Ho Bugt in the northern part of the Danish Wadden Sea. Field monitoring of hydrodynamics, suspended sediment concentrations and bed level variations was undertaken and will be examined and discussed in the following sections of this paper. In addition, grain-size distributions of sediment from the surface and in a sediment trap were examined and incorporated into the findings. Finally, time-series of digital images of the tidal flat surface are presented. Microtopography is identified from the images and the formation of small-scale ripples on the study site is discussed.

2. Study area

The study area is a mixed tidal flat (Sørensen et al., 2006-this volume) situated in the northernmost part of European Wadden Sea in shelter of the Skallingen barrier spit (Fig. 1). The area is micro-tidal with a tidal range of 1.5 m. However, sea-level may reach +4 m during storm surges. Wind energy has increased from the late 1970s and the prevailing wind direction has changed from northwest to west and even to west-southwest. These changes may explain the magnitude of extreme water levels and storm surges at Esbjerg in recent years (Christiansen et al., 2001). In this part of Denmark, a sea level of more than +3 m Danish Ordnance Datum (DNN) is defined as a storm surge. Waves are generally small in the back-barrier area. Significant wave heights range from 0.1 m during quiet meteorological conditions to 0.4 m during storms, and wave periods range from 1.5 s to 3.6 s on the tidal flats (Bartholdy and Aagaard, 2001). Background suspended matter concentrations in the bay are 10 to 30 mg l^{-1} increasing to a maximum of about 1000 to 1500 mg l^{-1} in periods of high wind velocities in the northern end of Ho Bugt (Pejrup et al., 1993). About 60% of the fine-grained sediments deposited in the backbarrier tidal area are estimated to be imported from the North Sea (Pedersen and Bartholdy, 2006-this volume), and fine-grained deposition on the backbarrier salt marsh is significantly correlated to the North Atlantic Oscillation (Bartholdy et al., 2004). Import of material from the North Sea to the Wadden Sea is hypothesized to take place during storm surges (Jakobsen, 1961). Bartholdy and Anthony (1998) suggested an alternative mechanism where strong import mainly takes place during windy periods following long periods of low energy conditions in the North Sea. During such low energy periods, fine-grained material may settle to the bottom on the shelf and thereby act as a reservoir for import to the Wadden Sea area when resuspended during high energy conditions.

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