FERRY OBSERVATIONS OF CURRENTS AND BEDFORMS

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Since 1998, currents and water depths have been recorded in the Marsdiep tidal inlet with an acoustic Doppler current profiler (ADCP) mounted under the ferry 'Schulpengat'. The objective of this project is to gain insight in the effects of tides, storms, and density differences on the currents, and to determine long-term sediment transport pathways. The measurements indicate that along-channel currents and bedload transport are governed by tides, while cross-channel currents are governed by density differences and bathymetry. The observations also reveal the existence of large bedforms that migrate floodward. The strong seasonal variability in bedform height and migration speed in the northern half of the inlet may be attributed to the tides or to a temperature-related fluctuation in fall velocity.

Introduction

In cooperation with the ferry company 'Texels Eigen Stoomboot Onderneming' (TESO), we conduct ferry-mounted ADCP measurements in the Marsdiep tidal inlet since 1998 (Fig. 1). The ADCP, mounted at 4.3 m below the water level, measures current speeds, acoustic backscatter (ABS), and water depths. The ferry crosses the inlet twice per hour at a speed of about 17 km h^{-1}, up to 32 times per day, 7 days per week, about 300 days per year.

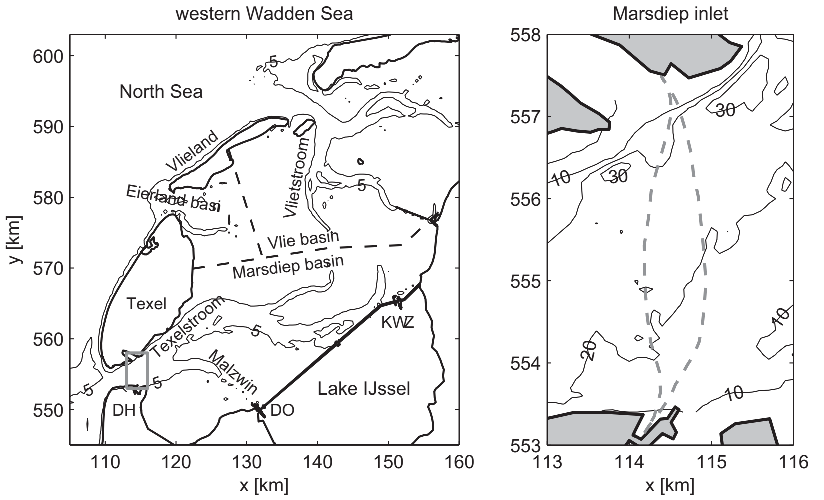

Fig. 1. Study area showing the western Wadden Sea (left panel) and the Marsdiep inlet (right panel). In the left panel, the Marsdiep inlet is marked by the grey box and watersheds by black dashed lines. In the right panel, the envelope of ferry crossings is marked by the grey dashed lines. Contourlines are contoured in meters relative to mean-sea level.

Tidal water transport and currents.

We analyzed the instantaneous water transport and (depth-averaged) currents to study the contribution of the tides. The water transport was computed by integrating all eastward current velocities *u* along the ferry transect and over the water depth. With 144 tidal constituents, maximally 98% (50%) of the variance in water transport and along-channel currents (cross-channel currents) is explained by the tides. The most important constituent is the semi-diurnal lunar M_2 constituent, which is modulated by the second-largest solar S_2 constituent (about 27% of M_2). Compound and overtides, such as $2MS_2$, $2MN_2$, M_4, and M_6, are important in the inlet. The currents are strongly rectilinear and they are sheared vertically and horizontally, with the highest currents at the surface above the deepest part of the inlet (maximally 1.8 m s^{-1}).

Subtidal water transport

An analytical model of the subtidal water transport between the Vlie and Marsdiep tidal basins was used to study the influence of wind. The model results and observa-

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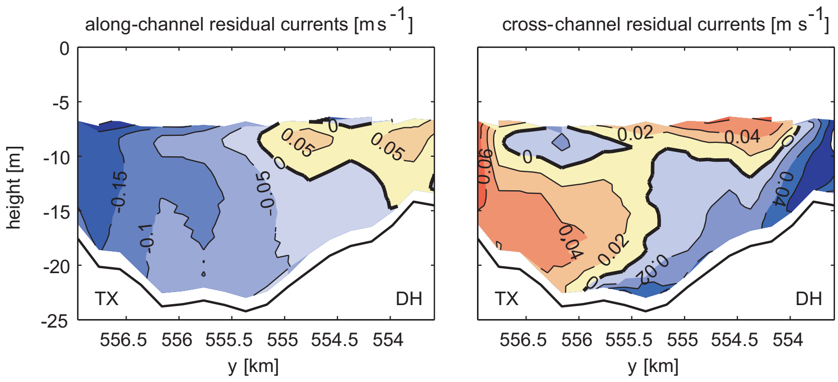

Fig. 2. Mean currents in the Marsdiep inlet for the period 2000-2001. Warm (cold) colours in the left panel indicate floodward (ebbward) flow. Warm (cold) colours in the right panel indicate northward (southward) flow. View is in the flood direction. The *y*-axis increases northward. TX (DH) refers to the Texel (Den Helder) side of inlet.

tions reveal a constant throughflow of about 1000 m^3 s^{-1} from the Vlie to the Marsdiep basin, which is due to the influence of tidal stresses. In agreement with data, the model shows that variability in subtidal water transport is mainly governed by wind stress. In particular, southwesterly winds force a throughflow from the Marsdiep to the Vlie basin, whereas northwesterly winds force a smaller mean water transport in the opposite direction. The contribution of remote sea-level change to the water transport has been found to be much smaller than the contribution of local wind stress.

Mean currents

The mean along-channel currents are directed into the basin in the shallower channel to the south and out of the basin in the deeper channel to the north (Fig. 2, left panel). These mean currents result from a fairly uniform inflow during flood and asymmetric outflow during ebb, with highest current velocities in the deeper channel along the Texel shoreline.

The mean cross-channel currents in the right panel of Fig. 2 are northward (southward) near the surface (bottom) in the southern half of the inlet and vice versa in the northern half. The counterclockwise circulation in the southern half is due to the inflow of fresher water from the Malzwin channel (Fig. 1) into the inlet channel during ebb. This fresher water flows northward over the heavier

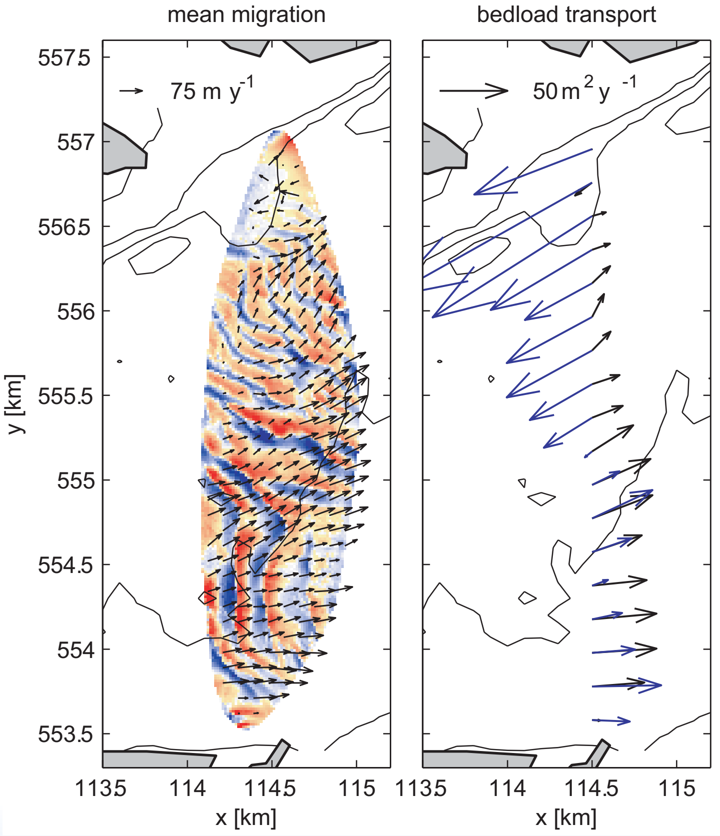

Fig. 3. Bedform migration and bedload transport. The left panel shows the mean bedform migration vectors for the period 1998-2004. Background is a digital terrain model showing the variance around the mean water depth. Warm (cold) colours indicate crests (troughs) of the bedforms. The right panel shows the mean bedload transport inferred from the bedforms (black) and currents (blue) for 1999-2002.

saltier water. In the northern half, the clockwise circulation is due to the curvature of the streamlines and density differences. During flood, a body of heavy salt water spreads out northward near the bottom, contributing to the clockwise circulation.

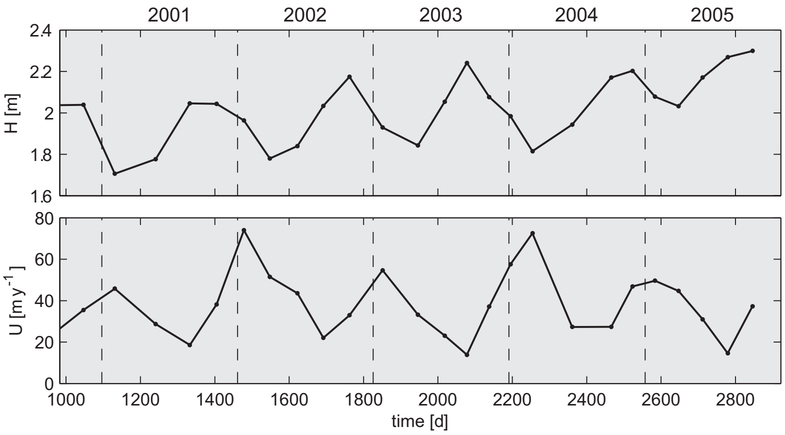

Fig. 4. Time series of area-mean sand-wave height H and migration speed U for sand waves in the northern half of the Marsdiep inlet. Vertical dashed lines indicate the beginning of a new year. Years are indicated above the top panel.

Bedforms

ADCP-depth measurements were compiled into digital terrain models (DTMs; Fig. 3, left panel). These DTMs reveal the existence of large asymmetric bedforms, i.e. sand waves, with lengths of order 100 m and heights of about 1 m. The sand waves migrate in the flood direction with rates up to 90 m y^{-1} (Fig. 3, left panel). The height and migration speed portray a strong seasonal variability in the northern half of the inlet (Fig. 4). The area-mean height is about 0.5 m higher in fall than in spring and the area-mean migration rate is about 40 m y^{-1} higher in winter than in summer.

The ADCP-current measurements were used to explain the sand-wave observations. ‘Measured’ bedload transport was inferred from sand-wave dimensions and migration speed and this was compared with ‘predicted’ bedload transport based on currents and bedload transport formulas (Fig. 3, right panel). In the flood-dominated southern half of the inlet, predicted bedload transport agrees in direction, magnitude, and trends with measured bedload transport. However, in the ebb-dominated northern part of the inlet the predicted bedload transport is opposite to the sand-wave migration. It is hypothesized that in the northern half suspension transport dominates over bedload transport in driving the sand-wave migration. The dominance of suspension transport also explains why sand waves are smaller, more three-dimensional and more rounded here. The seasonal variability in height and migration may be attributed to the tides and/or temperature-related seasonal fluctuation in fall velocity. The fall velocity depends on kinematic viscosity, which is temperature dependent. In winter, stronger tides and/or a lower fall velocity enhance sediment transport, increasing sand-wave migration and decreasing sand-wave height. Storms and estuarine circulation do not appear to be important for the sand-wave variability.

Ferry Schulpengat.