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Vertical circulation in shallow tidal inlets and back-barrier basins

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Abstract

In this paper, we analyse the contribution of tidally induced drift in the surface layer to the overall dynamics of well-mixed tidal basins undergoing drying and flooding. The study area covers the East Frisian Wadden Sea (German Bight, Southern North Sea), which consists of seven tidal basins. The major interest is focused on the tidal basin behind the islands of Langeoog and Spiekeroog and the inlet connecting it with the North Sea. The comparison between theoretical concepts, results from direct observations, and simulations with a numerical model helps to understand the underlying physics controlling the tidal response. The data were collected during the period 1995–1998 and consist of cross-channel ADCP transects. The identification of the dominant spatial patterns and their temporal variability is facilitated by applying an EOF analysis to the data. The numerical simulations are based on the 3-D primitive equation General Estuarine Transport Model (GETM) with a horizontal resolution of 200 m and terrain-following vertical coordinates. We find distinct differences between the temporal variability of the transports near the surface and those in deeper layers of the tidal inlets. The near surface transport is dominated by the tidally induced drift (similar to the Stokes drift), whereas the deeper layer transport is dominated by asymmetries caused by the hypsometric properties of the intertidal basins. These transports, when averaged over a tidal period, have opposite directions and compensate each other. This explains the establishment of a vertical overturning cell: landward motion in the upper layers and seaward motion in the deeper parts of the tidal channels. This vertical circulation cell is also observable in our numerical simulations and shows a clear dependency of the temporal asymmetry in the transport patterns on the local depth. In deep tidal channels, the overall properties of the tidal signal show a clear ebb dominance, whereas in the shallow extensions of the channels the transports during flood are larger than during ebb. Although, our research area can be characterized as a well mixed estuary, baroclinicity associated with the fresh water flux from the coast can substantially affect vertical overturning.

Keywords: Wadden Sea; Tidally induced Stokes transport; ADCP measurements; EOF analysis; Numerical modelling; Tidal asymmetry

1. Introduction

The ratio δ between tidal range and depth, which is known as the external Froude number (Jay and Smith, 1988), controls the shallow water dynamics.

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This control becomes very pronounced when the local depth is comparable to the tidal range (Ianniello, 1977), i.e. when δ tends to unity.

In the case of the tidal basins of the East Frisian Wadden Sea (Fig. 1), the mean depth can be even smaller than the tidal range and large areas of the basins undergo drying during part of the tidal cycle. This very specific dynamics necessitates a more detailed analysis because earlier studies have addressed mostly weakly non-linear systems in which the external Froude number is much smaller than unity (e.g. Ianniello, 1977). Effects associated with drying and flooding also need more attention.

In this paper, we will illustrate some important effects resulting from the shallow depth of the Wadden Sea using data from observations and numerical modelling, and analyse the consistency of observations and numerical simulations with theory. The considerations above are reminiscent of the classical problem of surface gravity waves where variations of sea level over time induce a Stokes drift. This issue has been the subject of a number of studies (Longuet-Higgins, 1969; Ianniello, 1977; Ianniello, 1979; Jay and Smith, 1988; Jay, 1990).

We can present the transport, vertically integrated from the bottom $-H$ to the ocean surface ζ and averaged over a full tidal cycle T, as

$$\langle U \rangle = \left\langle \int_{-H}^{\zeta} u \, \mathrm{d}z \right\rangle, \tag{1}$$

where

$$\langle \chi \rangle = \frac{1}{T} \int_{0}^{T} \chi \, \mathrm{d}t. \tag{2}$$

This transport can be decomposed into two parts (see e.g. LeBlond and Mysak, 1978):

$$\langle U \rangle = \int_{-H}^{0} \langle u \rangle \, \mathrm{d}z + \left\langle \int_{0}^{\zeta} u \, \mathrm{d}z \right\rangle. \tag{3}$$

In the simplest case of linear waves

$$\zeta = a \cos(kx - \omega t) \tag{4}$$

the velocity components $\vec{v} = (u, v, w)$ being given by

$$u = \frac{gak}{\omega} \frac{\cosh[k(z+H)]}{\cosh kH} \cos(kx - \omega t), \tag{5}$$

$$v = 0, \tag{6}$$

$$w = \frac{gak}{\omega} \frac{\sinh[k(z+H)]}{\cosh kH} \sin(kx - \omega t), \tag{7}$$

where a, k and ω are the amplitude, wave number and frequency, respectively, the time-averaged velocity is zero, and the first integral in Eq. (3) vanishes. However, the second integral which measures the contribution of the interval between the troughs and the crests of the waves to the total transport of momentum is not zero, but proportional to a^2. This results in a forward (in the direction of wave propagation) transport of mean momentum, which is concentrated at the surface (Fig. 2). Thus, at any level above $z = -a$ there is more transport forward than backward, which leads to a non-zero second-order drift. Lagrangian and Eulerian mean velocities can differ considerably (Longuet-Higgins, 1969), the difference between them is the Stokes drift measured by the correlation between surface velocity and sea level. Furthermore, velocities associated with the Stokes drift can exceed

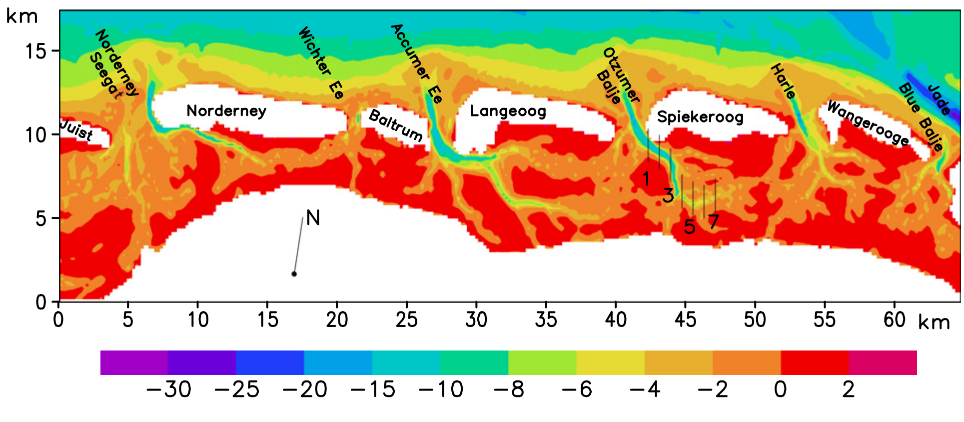

Fig. 1. The East Frisian Wadden Sea. The plot displays the model topography (see also Section 4.1) and the locations of observations and model samples discussed in the text. The depths are represented as negative numbers (m) below the mean sea level. The thin meridional sections in the extension of Otzumer Balje in the tidal basin of Spiekeroog Island are sections sampled every 5 min from the model simulations. ADCP measurements were taken along Section 1.