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Intra- and inter-tidal variability of the vertical current structure in the Marsdiep basin

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ABSTRACT

The vertical structure of the along-stream current in the main channel of the periodically-stratified estuarine Marsdiep basin is investigated by combining velocity measurements collected during three different seasons with a one-dimensional water column model. The observed vertical shears in the lowest part of the water column are greater during ebb than during flood due to an asymmetry in drag coefficient (i.e. bed friction), which is most likely determined by the surrounding complex bathymetry. This asymmetry is usually not incorporated in models. Furthermore, a mid-depth velocity maximum is observed and simulated during early and late flood which is generated by along-stream and cross-stream tidal straining, respectively. Negative shears are present in the upper part of the water column during flood, which correlate well with the along-stream salinity gradient. The mid-depth velocity maximum during late flood results in an early current reversal in the upper part of the water column. The elevated vertical shears during ebb are able to reduce vertical stratification induced by along-stream tidal straining, whereas cross-stream tidal straining during late flood promotes the generation of vertical stratification. The simulations suggest that these processes are most important during spring tide conditions. This study has demonstrated that an asymmetry in bed friction and the presence of density gradients both have a strong impact on the vertical structure of along-stream velocity in the Marsdiep basin.

1. Introduction

Currents in estuaries and coastal seas are the main transport agents of suspended matter. The net transport patterns of plankton, larvae, nutrients, pollutants and suspended sediment are partly determined by the residual current. The vertical distribution of suspended matter varies in the water column and therefore for understanding the vertical and horizontal exchange patterns in an estuary, it is important to also take the vertical profile of the current and salinity into account.

In estuaries, the shape of the vertical profile of along-stream velocity is determined by the interaction of the barotropic and baroclinic pressure gradients, which creates a difference in the shape of the vertical profiles between ebb and flood (Simpson et al., 1990; Jay and Musiak, 1996; Seim et al., 2002; MacCready and Geyer, 2010; Geyer and MacCready, 2013 and references therein). During flood, the direction of the baroclinic force in the near-bottom layer coincides with the direction of the barotropic force, which in the absence of bed friction and vertical mixing would result in the strongest velocities near the seabed (Valle-levinson and Wilson, 1994). However, the seabed imposes a frictional drag on the tidal currents, which, in combination with the strong near-bed velocities during flood, results in greater near-bed shears, potentially generating a well-mixed water column (e.g. Jay and Musiak, 1996). During ebb, the baroclinic and barotropic forces oppose each other near the bottom, generating smaller shears at the bottom and greater shears in the upper part of the water column. Furthermore, fresher water higher up in the water column is advected over saltier water during ebb which generates vertical stratification, a process called tidal straining (van Aken, 1986; Simpson et al., 1990). Classical tidal straining only generates vertical stratification during ebb, because advection of salty water over less salty water during flood results in unstable stratification, which generates vertical mixing.

The steady baroclinic pressure gradient (Pritchard, 1956; Hansen and Rattray, 1966) and the strain-induced periodic stratification (Simpson et al., 1990; Jay and Musiak, 1996) modify the shape of the vertical profile in estuaries. Burchard and Hetland (2010) demonstrated with model simulations that tidal straining contributed approximately two-thirds to the residual circulation, whereas the baroclinic tide itself contributed only one-third in periodically-stratified estuaries. Both mechanisms are able to

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modify the shape of the vertical profile of along-stream velocity and thereby determine the vertical profile of residual circulation.

Commonly, the difference in shape of the vertical profiles between ebb and flood results in the classical residual estuarine circulation with inflow at the bottom and outflow at the surface (e.g. Geyer et al., 2000; Stacey et al., 2001, 2008; Seim et al., 2002; Murphy and Valle-Levinson, 2008). There also exist inverse estuaries, where the baroclinic force near the bottom is directed in the opposite direction (towards the sea), e.g. by strong evaporation within the estuary, which has an inverse effect on the vertical profile of ebb and flood and produces an inverse estuarine circulation cell with the near-bed and near-surface residual currents directed down- and up-estuary, respectively (e.g. Winant and Gutierrez de Velosco, 2003).

Additionally, the shape of the vertical profiles is strongly influenced by the impact of bed friction on the current. Generally, the drag coefficient is taken as a measure for bed friction and is in the order of $1-3\times10^{-3}$ (e.g. Geyer et al., 2000; Seim et al., 2002; Li et al., 2004). However, greater values have also been observed up to 1×10^{-2} (Cudaback and Jay, 2001; Fong et al., 2009). In addition, the drag coefficient has been observed to vary from neap to spring tide, and from ebb to flood (Geyer et al., 2000; Li et al., 2004; Fong et al., 2009). The drag imposed on the currents by the seabed is only transferred up in the water column to a certain height, called the bottom boundary layer. Stacey and Ralston (2005) demonstrated that the bottom boundary layer does not cover the entire water column during the entire tidal cycle in the northern San Francisco Bay, which was also found in the Marsdiep basin (De Vries et al., 2014). Also, several studies have shown that form drag is another important mechanism which is able to dissipate tidal energy (Chriss and Caldwell, 1982; Moum and Nash, 2000; Warner et al., 2013). Form drag is the drag imposed on the fluid by pressure differences generated by currents traversing non-uniform bathymetry, which may be up to 10–50 times greater than drag generated by bed friction (Edwards et al., 2004; Warner et al., 2013). Furthermore, Warner et al. (2013) showed that the presence of form drag produces elevated values of C_D, when it is estimated from the depth-averaged along-stream momentum balance.

In literature, less attention has been paid to understanding the shape of the vertical profiles of horizontal velocity during the remaining phases of the tide (namely during early and late ebb and flood). An interesting feature, described for several estuaries, is the occurrence of a mid-depth velocity maximum during flood (e.g. Jay and Smith, 1990; Lacy and Monismith, 2001; Warner, 2005; Chant et al., 2007), which has also been observed in a modeling study of the Chesapeake Bay (Li and Zhong, 2009). This velocity maximum occurs at the upper boundary of the bottom boundary layer (Chant et al., 2007). Cudaback and Jay (2001) explained the occurrence of a mid-depth velocity maximum during early flood in the Colombia inlet, which is a strongly-stratified estuary, using a simple three-layer model based on the barotropic and baroclinic pressure gradient and bed friction. They concluded that bed friction and a strongly-stratified water column are crucial in driving a mid-depth jet. Similar observations in the stratified North Sea were explained by Maas and van Haren (1987) using a comparable model.

To complicate matters further, the shape of the vertical profiles of instantaneous and residual currents varies spatially due to bathymetric and nonlinear effects, as e.g. tidal asymmetry (Aubrey and Speer, 1985; Speer and Aubrey, 1985; Dronkers, 1986; Friedrichs and Aubrey, 1988). Li and O'Donnell (1997) demonstrated that a lateral water depth gradient produces a tidally-driven horizontally-sheared exchange pattern, whereas Li and O'Donnell (2005) showed that the length of an estuary determines the inflow and outflow patterns at the channel and shoals. Scully and Friedrichs (2007) observed lateral asymmetries in current magnitude and concluded that spatial asymmetries in mixing modify the duration of the ebb phase and change the residual circulation. In the Marsdiep basin, the tidal asymmetry is great and is spatially variable. Zimmerman (1976b), Ridderinkhof (1988) and Buijsman and Ridderinkhof (2007a) observed stronger flood currents and inflow at the shallower south side of the Marsdiep tidal inlet and stronger ebb currents and outflow at the deeper north side.

In the Dutch, German and Danish Wadden Sea, the mechanisms that contribute to the residual circulation are still a matter of debate (Zimmerman, 1986; Ridderinkhof, 1988; Buijsman and Ridderinkhof, 2007a; Burchard and Hetland, 2010; Becherer et al., 2011; Flöser et al., 2011). The first three studies argue that tide-topography interaction is the major forcing of residual currents in the Wadden Sea, whereas the latter three argue that tidal straining, and the presence of an estuarine circulation, is the major forcing. Since the shape and variability of the vertical profiles of along-stream velocity are essential for estuarine dynamics, the aim of this paper is to explain the structure (and variability) of the vertical profile of the horizontal velocity in the main channel of the Marsdiep basin. This study shows that the shape of the vertical profiles in the Marsdiep deviates in several ways from the standard estuarine profiles.

Three deployments of a bottom frame in the Marsdiep basin, equipped with an upward-looking Acoustic Doppler Current Profiler (ADCP) and temperature, conductivity and depth sensors (microCAT), resulted in over 100 days of current data during 3 different seasons. This dataset, in combination with simulations with the General Ocean Turbulence Model (GOTM) provides a better understanding of the factors that determine the shape of the vertical profiles of along-stream velocity in the Marsdiep. Hereby, we focus on the combined effects of bed friction and density-related processes, e.g. the baroclinic pressure gradients and vertical stratification, on the vertical profile of along-stream velocity over the tidal cycle. In addition, the mechanism behind the occurrence of a mid-depth along-stream velocity maximum during late flood is investigated. This phenomenon is related to the occurrence of vertical stratification during late flood, which is generated by cross-stream tidal straining and which the small currents are not able to destroy during this phase of the tide. We hypothesize that vertical stratification inhibits the vertical momentum exchange in upward and downward direction, thereby producing the greatest current around the pycnocline: vertical stratification restricts bed-generated turbulence to the lower part of the water column limiting seabed-induced vertical mixing of momentum, whereas the superimposed effect of the barotropic and baroclinic components of the tide limits the increase in current speed with depth, as described earlier, to the part of the water column above the pycnocline.

The paper is structured as follows. In Section 2, more detailed information on the study area, the data handling as well as the model settings is presented. Sections 3 and 4 describe the observations and model simulations, respectively. In Section 5, typical characteristics of the vertical current structure at the study site are discussed in more detail, and in Section 6 the main findings of this study are summarized.

2. Study site, material and methods

2.1. Study site description

The study site is located in one of the main channels of the Western Dutch Wadden Sea, the Texelstroom channel (Fig. 1b). The Western Dutch Wadden Sea is comprised of the Marsdiep and Vlie basins (Fig. 1a) and there is only limited exchange between both basins (Zimmerman, 1976a, 1976b; Buijsman and