Continental Shelf Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

An exploratory study of the variability of currents and density in the Marsdiep

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ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form
10 February 2014
Accepted 3 May 2014

Keywords:
Tidal currents
Spatial variability
Estuaries
Wadden Sea
Vertical stratification
Q3 Tidal straining
Bottom boundary layer

ABSTRACT

Observational data of tidal currents and vertical stratification in a periodically-stratified estuarine basin are presented in this study. The data were collected between 2010 and 2012 during multiple surveys in the Marsdiep basin, which is part of the Western Dutch Wadden Sea. The aim of this study is to better understand the spatial variability of the tidal currents and the occurrence of vertical stratification in the Marsdiep basin. A harmonic analysis is applied to the depth-averaged velocity to obtain estimates of the tidal ellipse parameters of the M_2 tidal constituent along the surveys. The spatial variation in magnitude of the tidal currents is complex but seems mainly related to water depth. This relationship varies in time on a daily to fortnightly timescale, which result in a variation of the lateral velocity shears over time. Furthermore, the lateral density gradient is the same order of magnitude as the longitudinal density gradient, which implies that cross-stream processes are important in the Marsdiep basin. At some locations, vertical stratification is only observed during the flood phase which seems mainly driven by lateral processes. This pattern is inconsistent with the classical alongstream tidal straining mechanism, where vertical stratification develops during ebb and diminishes during flood. It is hypothesized that vertical stratification during flood increases from neap to spring tidal conditions due to increased differential advection. The strength and timing of vertical stratification is shown to be highly spatially variable in the Marsdiep basin, which might have implications for the residual circulation patterns.

1. Introduction

Tides contain a copious source of kinetic energy and are therefore a dominant factor in advecting salt, heat, nutrients, pollutants, fish eggs, larvae, plankton and suspended particles in shelf seas and estuaries. In addition, buoyancy and wind forcing are other important factors, where their relative contribution depends on local conditions. Recently, tides are considered as a potential source of renewable energy, which resulted in a growing interest in the small-scale ($\sim$0.1–1 km) spatial variability of tidal currents. In the Marsdiep basin, a floating test tidal energy plant with a size of 100×30 m^2 is planned to be moored. Tidal energy production is related to flow speed cubed. It is therefore important to obtain a thorough understanding of the spatial variation in the currents in order to find an optimal location for such a platform for optimizing tidal energy production.

In estuaries like the Marsdiep basin, the currents are influenced by bathymetry, by the wind and by density gradients originating from freshwater inflow. Much research has already been conducted on the large-scale spatial variability of currents and on the residual circulation at the inlet of and in estuaries, e.g. the Chesapeake Bay (Valle-Levinson et al., 1998), Colombia River Estuary (Jay and Smith, 1990a, 1990b, 1990c), the Marsdiep inlet (Buijsman and Ridderinkhof, 2007). The variation of tidal flow on a smaller spatial scale ($\sim$0.1–1 km) has been another area of research. Murphy and Valle-Levinson (2008) investigated the spatial and temporal variability of currents on a smaller scale in the shallow ($h < 15$ m), microtidal and subtropical Saint Andrew Bay system, Florida USA. Li (2002) covered the spatial variability at an axial convergence front system, whereas Li et al. (2006), Li (2006) and Li et al. (2008) investigated the small-scale variability of geometry-driven residual currents and eddies using observations and model simulations. In the Marsdiep basin, large depth variations are present on a small spatial scale, which makes it worthwhile to investigate the spatial variability of tidal currents. Furthermore, the temporal modulation of the spatial variability in currents has not yet been investigated in the Marsdiep basin.

Variations in currents are important since the associated lateral shears are essential for horizontal mixing (Zimmerman, 1986) and the formation of fronts (Li, 2002). In addition, they generate complicated flow patterns around complex bathymetry (Geyer, 1993). Lateral velocity shears originating from differential advection have also been observed to drive secondary currents in a channel and to modify the density distribution (Nunes and Simpson, 1985).

The currents in the Marsdiep inlet itself are well described by Buijsman and Ridderinkhof (2007) using measurements from the

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http://dx.doi.org/10.1016/j.csr.2014.05.003
0278-4343/

Den Helder–Texel ferry. However, less is known about the current field in the inner part of the Marsdiep basin. Groeskamp and Maas (2012) investigated the spatial variation in the Marsdiep basin in a small part of a tidal channel, the Malzwin channel, which has water depths between 5 and 15 m. At that location, they found a linear increase in flow strength with depth. They discussed two simple, but contradictory theories that predict tidal amplitude as a function of local water depth (inversely proportional) or as a function of friction (linearly/parabolically proportional) and they demonstrated that the latter was applicable to their research area. However, they did not cover the entire range of water depths in the Marsdiep which varies between 0 and 40 m. Furthermore, measurements were acquired during one single tidal cycle.

A fundamental characteristic of estuaries is the presence of longitudinal, lateral and vertical density gradients due to the (varying) influence of freshwater (Hansen and Rattray, 1966; Simpson et al., 1990; MacCready and Geyer, 2010 and references therein). The spatial density field in the Marsdiep basin has only been studied marginally (Zimmerman, 1976a, 1976b; Buijsman and Ridderinkhof, 2008b), even though visible signs of their importance are a common feature in the Marsdiep basin such as frontal features, e.g. axial density lines which indicate the boundary of different water masses, and internal wave signatures (Groeskamp et al., 2011). Generally, it is assumed that the gravitational estuarine circulation as well as tidal straining dominates the longitudinal exchange in narrow estuaries with inflow at the bottom and outflow at the surface. In wide estuaries however, rotational effects become more important. Valle-Levinson (2008) was able to semi-analytically express the density-driven exchange flow in terms of the Ekman and Kelvin number. Basdurak and Valle-Levinson (2012) demonstrated the great temporal variation in estuarine exchange patterns, i.e. horizontally versus vertically sheared, in a microtidal estuary. Recent studies have shown that lateral processes may influence the longitudinal exchange. Several model studies have shown that lateral advection is able to modify longitudinal exchange (Geyer et al., 2000; Lerczak and Geyer, 2004; Cheng and Valle-Levinson, 2009; Scully et al., 2009; Burchard and Schuttelaars, 2012), which has also been confirmed by an observational study in the microtidal James River Estuary (Basdurak and Valle-Levinson, 2012). In the Marsdiep, Postma (1954), Zimmerman (1976a, 1976b) and Ridderinkhof (1988, 1989) assumed the water column to be well-mixed as a result of the strong currents (up to 2 m/s). However, recent studies have shown that the Marsdiep is periodically stratified during the flood and ebb phase (Buijsman and Ridderinkhof, 2008b; Groeskamp et al., 2011; De Vries et al., 2012). Despite the observations in recent studies, the dynamics of the spatial density field and their effect on the residual circulation have not yet been investigated in detail in the Marsdiep basin.

Furthermore, the existence of an estuarine circulation in the Wadden Sea is still a topic of debate. Floser et al. (2011) found indications of an estuarine circulation in the German Wadden Sea, in the Hornum Deep near Sylt, by analyzing the vertical profile of the horizontal velocity during peak ebb and flood. However, Buijsman and Ridderinkhof (2007) found contradictory vertical profiles of horizontal velocity in the Marsdiep inlet. They concluded that the horizontal residual circulation pattern was determined by the advection of vorticity as described by Ridderinkhof (1989), which is determined by the complex bathymetry of the western Dutch Wadden Sea, but they did not analyze the vertical residual circulation. Floser et al. (2013) presented suggestive indications of an estuarine residual circulation based on the vertical profiles of the horizontal velocity but they did not relate them to the strength of the longitudinal density gradients or any other baroclinic forcing. Therefore, the importance of tidal straining in the Wadden Sea is still a topic of debate.

Becherer et al. (2011) related the occurrence of vertical stratification in the German Wadden Sea during specific tidal phases to tidal straining and thereby indirectly suggested the presence of an estuarine circulation. The mechanism of tidal straining, first described by Van Aken (1986) in a shelf sea and Simpson et al. (1990) in an estuary, explains the asymmetry in vertical stratification, in estuaries between ebb and flood, as a result of the interaction between tidal currents and the longitudinal density gradient. During the flood (ebb) phase of the tide, the longitudinal baroclinic pressure gradient opposes (enhances) the barotropic pressure gradient which diminishes (increases) vertical stratification. Such a mechanism results in the strongest stratification during ebb and strongest mixing during flood. In this study, observations of vertical stratification are presented that deviate from those observed under the tidal straining mechanism. These patterns correspond to observations in other estuaries by Lacy et al. (2003), Scully and Friedrichs (2007), Scully and Geyer (2012) and Basdurak et al. (2013) and they illustrate that the formation of vertical stratification in the Marsdiep is not merely a one-dimensional process. Furthermore, the spatial variability in vertical stratification, presented in this study, may be large depending on the phase of the tide, which corresponds to other studies (Scully and Friedrichs, 2007; Cheng et al., 2009).

The aim of the research presented in this paper is two-fold. Firstly, one aim is to obtain a better understanding of the variation of currents over a wide range of water depths. Secondly, due to its importance in estuarine dynamics, the spatial variability in occurrence and strength of vertical stratification in the Marsdiep is investigated. In Section 2, the study site and material and methods are discussed. In Section 3, the results are treated. In Section 4, the results are discussed and in Section 5 concluding remarks are given.

2. Study site, material and methods

2.1. Study site

The Marsdiep inlet forms the connection between the North Sea and the meso-tidal Marsdiep basin. The Marsdiep basin is the westernmost tidal basin of the Dutch Wadden Sea and the largest tidal inlet of the Netherlands (600 km^2, Fig. 1a), almost twice as large as the Western and Eastern Scheldt (300 and 350 km^2, respectively). At the inlet, the Marsdiep consists of one channel. At the eastern, inner part of the inlet, the Marsdiep channel splits up into the Texelstroom channel (northern branch) and the smaller Malzwin channel (southern branch) which are separated by an intertidal shoal, named Lutjeswaard. The bathymetry of the Marsdiep basin varies strongly on different spatial scales. The intertidal flats and the channels are distinct morphological units with the channel being much deeper than the intertidal flats. Also within the channels, large depth variations are present. On larger spatial scales of O (10 km), the channels become shallower further into the Wadden Sea. However, over small-scale of O (1 km) depth variations in the main channels are in the order of 10–20 m, and are common at the seaward side of the basin, in the vicinity of the inlet, in along- and cross-stream direction. On a very small spatial scale (100–200 m), the depth in the main channels may vary by 2–3.5 m as a result of the occurrence of sandwaves. These have been observed in the tidal inlet using depth observations from a ferry-mounted ADCP (Buijsman and Ridderinkhof, 2008a).

The main sources of freshwater are located at Den Oever (DO) and Kornwerderzand (KWZ) which are the outlet sluices of the freshwater lake IJsselmeer into the Marsdiep basin (Fig. 1a). The sluices discharge only during low tide. The daily mean discharge at the DO and KWZ sluices for the period 1998–2004 is 333 m^3/s and

Please cite this article as: de Vries, J.J., et al., An exploratory study of the variability of currents and density in the Marsdiep. Continental Shelf Research (2014), http://dx.doi.org/10.1016/j.csr.2014.05.003