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Estimation of the bottom stress and bottom drag coefficient in a highly asymmetric tidal bay using three independent methods

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A R T I C L E I N F O

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A B S T R A C T

Three independent methods, the dynamical balance (DB) method, the turbulence parameter (TP) method, and the log-layer fit (LF) method, are commonly employed to estimate the bottom stress and bottom drag coefficient in strong tidal systems. However, their results usually differ from each other and the differences are attributed to form drag. Alternatively, some researchers argued that the differences are caused by overestimates in some methods. Aiming to measure the performances of the three independent methods, they were simultaneously constructed in a bay with highly asymmetric tides. The results of the DB and TP methods are consistent with each other in not only the magnitude but also time variation patterns. The consistency of results of the two methods indicates that skin friction is dominant in the bay. The results of the DB and TP methods reveal obvious flood-dominant asymmetry caused by tidal straining. This flood-dominant asymmetry is enhanced during the transition period from spring to neap tide. When the original log-layer fit is employed, the results are much larger than those of the DB and TP methods, and these differences cannot be attributed to form drag since skin friction is dominant in the bay. Moreover, the results of the original log-layer fit reveal an obvious ebb-dominant asymmetry, which is contradictory to the results of the DB and TP methods. Therefore, the results of the original fit are just overestimates and lack physical meaning. By considering the effect of stratification on the mixing length, the modified log-layer fit achieves results with magnitudes that are close to those of the DB and TP methods, indicating that the modified log-layer fit is more representative of the bottom stress than the original log-layer fit in terms of physical meaning. However, the results of the modified log-layer fit still exhibit an ebb-dominant asymmetry in contrast to that of the DB and TP methods, implying that the empirical formula of the mixing length in stratified water is not universally applicable and should be further improved.

1. Introduction

Bottom stress plays an important role in tidal dynamics. According to the results of Munk and Wunsch (1998), bottom stress is responsible for the dissipation of over 70% of the global tidal energy in shallow seas. Moreover, the bottom stress plays an important role in sediment resuspention and transport (Churchill et al., 2004; Stanev et al., 2008). The bottom stress can be parameterized in tide models as a product of the bottom drag coefficient and the square of depth-averaged tidal currents based on the quadratic law (Mofjeld, 1988). As an important numerical factor in the parameterization of bottom stress, the bottom drag coefficient can exert direct influence on the simulation results (e.g., Spitz and Klinck, 1998). Therefore, the accurate estimation of the bottom stress and bottom drag coefficient has been an important subject of oceanographic research, especially in shallow seas.

With the development of observational instruments and skills, three main independent methods of estimating bottom stress and the related bottom drag coefficient have been proposed and constructed in numerous marginal seas. One method is based on tide dynamical balance equations, which are derived from Newton's second law of motion, while the other two are based on the boundary layer theory. The bottom stress can be estimated using tide dynamical balance equations with other terms quantified by observational data except for bottom stress (DB method hereafter) (Campbell et al., 1998; Rippeth et al., 2002). Usually, the bottom stress and pressure gradient terms are regarded as dominant terms in shallow-sea tidal equations (Friedrichs and Madsen, 1992; Friedrichs and Aubrey, 1994), and the nonlinear advective term is neglected (Huntley et al., 1993; Campbell et al., 1998). However, numerical results have revealed that nonlinear advection can also be significant in certain regions (Hench and

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Luettich, 2003). Therefore, to obtain accurate estimations of bottom stress, nonlinear advection should not be neglected. By assuming that the measurements were made in the bottom boundary layer (BBL), bottom stress can be converted from the in situ estimated turbulence parameters (TP method hereafter) or estimated by fitting the observed tidal currents to the log-layer (LF method hereafter) (e.g., Lueck and Lu, 1997; Trowbridge et al., 1999; Kim et al., 2000; Rippeth et al., 2002). The TP method includes the so-called “variance”, “eddy correlation”, and “dissipation” methods (e.g., Kim et al., 2000; Rippeth et al., 2002; Perlin et al., 2005b), but they are not independent of each other (Perlin et al., 2005b). The key to estimating bottom stress with the LF method is to identify the log layer. Two log layers can be identified in the BBL, and the friction estimated from the upper log layer is larger than that from the lower log layer by a factor of ~3 (Sanford and Lien, 1999). Some researchers have argued that the discontinuity between the upper and lower log-layers is the result of an inappropriate mixing length scale that just includes the influence of the bottom boundary. Therefore, a modified log layer that considers the mixing length affected by both stratification and boundaries has been proposed. The lower and upper log layers can be unified in this modified log layer (Perlin et al., 2005b).

However, the results from the three independent methods usually differ, even in the same region. These differences are usually attributed to that each method investigates friction associated with different mechanisms (e.g., Trowbridge et al., 1999; Rippeth et al., 2002). Frictional effects are caused by two mechanisms when tidal currents flow past objects. One is skin friction, which is the tangential stress at the bottom boundary, and the other is form drag, which is caused by flow separation or baroclinic (internal) wave generation (MacCready and Pawlak, 2001; Edwards et al., 2003; Warner and MacCready, 2009). Based on the relative magnitudes of the results and the spatial scale of the observation data, the bottom stresses estimated using each method are thought to correspond to the skin friction and the total bottom stress including skin friction and form drag (e.g., Trowbridge et al., 1999). The DB method employs spatial gradients of pressure and tidal currents, and the results are usually regarded as the total bottom stress (Campbell et al., 1998; Rippeth et al., 2002). The results of TP method are considered to represent skin friction because the turbulence data used in the calculations are local (e.g., Trowbridge et al., 1999). The bottom stress estimated from the lower log layer is skin friction while that obtained with the upper log layer includes form drag because the latter is significantly larger than the former (Chriss and Caldwell, 1982; Perlin et al., 2005b). The results of the modified log layer are believed to be skin friction because of the similar magnitude as that obtained from the lower log layer (Perlin et al., 2005b).

As more and more applications of the three independent methods, it has been realized that just attributing the differences between the results of the methods to form drag is not very convincing. The results of some methods could just be overestimations or underestimations that lack physical meaning, such as the results obtained from the upper log-layer, as argued by some researchers (Kim et al., 2000; Perlin et al., 2005b). Therefore, it is necessary to apply all the three independent methods to the same region simultaneously to measure their performance. To accomplish this, an in situ experiment in a bay with highly asymmetric tides was constructed. This paper is organized as follows. The experimental site and observations are introduced in Section 2, the data analysis method is described in Section 3, and the results are presented in Section 4. The discussion and conclusion follow in 5 and 6 sections.

2. Experimental sites and observations

The observations were performed in the inner reaches of Xiangshan Bay, which is an elongated, energetic tidal bay located on the western coast of the East China Sea (Fig. 1). The bay is ~70 km long and ~10 km wide, and has an average depth of ~10 m. Xiangshan Bay is characterized by large mudflats, which account for approximately 1/3 of the total area of the bay (Xu et al., 2016).

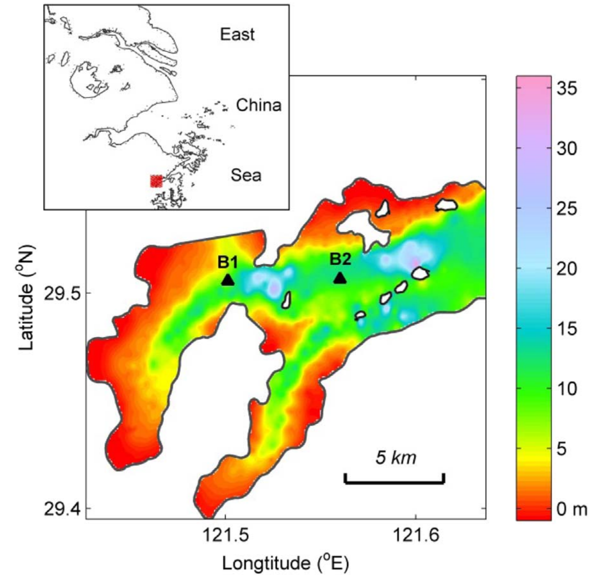

Fig. 1. Experimental sites in the inner portion of Xiangshan Bay. The colors in the figure represent the bathymetry, with red color marking the large area of mudflats. Sta. B1 and Sta. B2, which collected tidal elevation and currents data, are located along the main channel of Xiangshan Bay. The small panel indicates the location of Xiangshan Bay in the East China Sea, and the red square box indicates the study area.

Because Xiangshan Bay is surrounded by low mountains and hills, the input of fresh water into the bay is limited and wind and waves are weak (Gao et al., 1990). In contrast, the tides in the bay are energetic and have an average tidal amplitude of over 3 m. A persistent horizontal salinity gradient exists in the bay, and the energetic tides play an important role in vertical mixing (Dong and Su, 2000). The tides are standing waves due to the reflection of the bay head. The tidal currents in the inner portion of the bay, which are constrained by the bay banks, are rectilinear. The tides are dominated by an M_2 frequency and are highly asymmetric because of the superimposition of M_4 tides generated by the strong nonlinear effects of the tidal currents and topography. The M_4 amplitude increases from 0.02 m to 0.36 m along the bay according to observational results (Dong and Su, 1999a, 1999b; Dong and Su, 2000). The flood tides in the inner Xiangshan Bay can persist for up to 2 h longer than the ebb tides (Xu et al., 2014).

Two bottom-mounted quadrapods equipped with an RDI 600 kHz Workhorse acoustic Doppler current profiler (ADCP) and an RBR XR420 CTD, were deployed at the stations B1 and B2 in inner Xiangshan Bay (Fig. 1) over two periods. The first period lasted for 2 days in the winter of 2010 and occurred during the spring tide (Fig. 2). The quadrapod at Sta. B1 tipped over on the first day, but this was rectified on the second day. The second period lasted for 1 day in the winter of 2012 and occurred during a transition period from spring to neap tides (S-N tide hereafter). The distance between Sta. B1 and Sta. B2 was ~5 km, and the average water depth of the two stations were both approximately 12 m. In each case, the ADCPs were set up to record the along-beam velocities with a ping rate of 2 Hz. For both spring and S-N deployments, the bin size was set to 0.5 m and the data were ensemble-averaged over 2 s. The ADCPs were deployed in the standard RDI mode 1, in which the noise characteristics can be assumed to be independent of the measured velocities (RDI, 2000). The CTDs were set to continuously collect sea surface elevation data at 1 Hz. Based on data collected by CTDs, no significant waves were