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The relative importance of the wind-driven and tidal circulations in Malacca Strait

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ABSTRACT

The Malacca Strait is traditionally treated as a typical tidally-driven channel with the wind-driven and other components considered negligible. However, the strait is frequently affected by intense tropical weather events distorting the background monsoon winds. The variable winds can create large wind-stress curl at the surface level. To answer the question of how significant the wind-driven circulation is to the total circulation, numerical simulations are carried out by isolating or superimposing the different driving mechanisms. Comparison of the time series at selected points reveals that the winds significantly affect the tidal currents in different ways in the northern and southern strait. In the northern wide strait, the tidal current is enhanced while in the southern narrow channel it is weakened. Experiments with uniform water depth confirm that the weakening is mainly due to the interaction among tidal current, wind-driven current and bathymetry in the southern strait. Spectral analysis of the currents in the whole MS quantifies that the wind-driven current energy is more significant in the northern channel than in the southern one. Furthermore, winds with high intensity and large wind-stress curl can produce an eddy as large as the northern channel width which significantly distorts the tidal circulation especially during the neap tide. Vorticity analysis shows that the eddy in the northern Malacca Strait is purely wind-driven. Our study highlights that the wind stress, which has been ignored in previous studies in this region, is an important driver of the circulation in the Malacca Strait even when tidal forcing is strong.

1. Introduction

The Malacca Strait (MS) is strategically located between the east coast of Sumatra Island and the west coast of the Malay Peninsula. It links the Indian Ocean via the Andaman Sea, to the South China Sea (SCS) and the Pacific Ocean via the Singapore Strait (Fig. 1). As an international shipping route, MS is among the busiest and most important waterways in the world. It is also home to extensive capture fisheries, providing an employment to more than 200,000 fishermen (Thia-Eng et al., 2000). The strait is approximately 980 km long and its width gradually narrows from 445 km in the north to 52 km in the south. Its water depth increases from about 25 m in the south to about 200 m in the north with an abrupt change around 3°N (Fig. 1).

With regard to the atmospheric conditions over the MS, the strait has a tropical climate and is under the influence of the monsoon winds (Rizal and Sundermann, 1994). The northeast (NE) monsoon blows from November to March, reaching maximum strength and steadiness in January, while the southwest (SW) monsoon blows from May to September, reaching maximum strength and steadiness in July and August (Joo and Samahand, 2004). The background monsoon winds are modulated by the intraseasonal Madden–Julian oscillation (MJO) (Madden and Julian, 1972), and synoptic weather of the deep convection (Chang et al., 2005; Salahuddin and Curtis, 2011). Furthermore, strong diurnal land–sea breezes driven by land–sea temperature contrast (Simpson, 1994) exist on both sides of the strait (Joseph et al., 2008; Teo et al., 2011). Although typhoons are absent from such equatorial latitudes, mesoscale convective systems and line squalls known locally as “Sumatras” are common in MS particularly between April and November. The accompanying winds may reach force 7 or 8. Overall, the multi-scale atmospheric activity in this region induces

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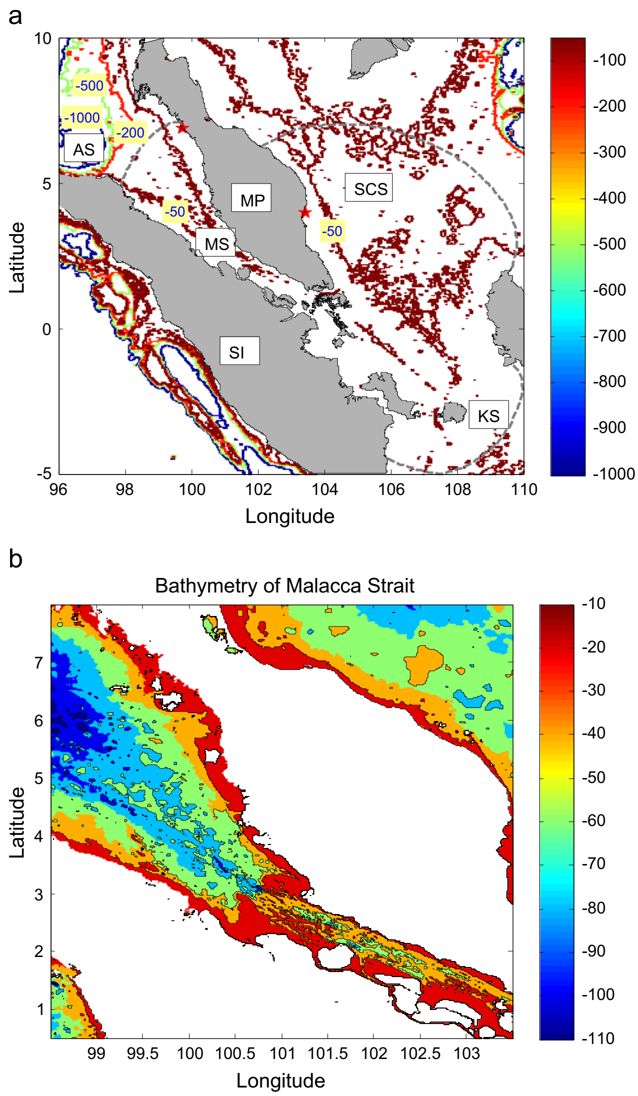

Fig. 1. (a) Contour lines (50 m, 200 m, 500 m and 1000 m) of water depth of Malacca Strait and its surrounding area. (b) Zoomed-in bathymetry of Malacca Strait. The bold dashed gray lines are boundaries of computational domain in the study. SCS, AS, MP, MS, SI, and KS stand for South China Sea, Andaman Sea, Malay Peninsula, Strait of Malacca, Sumatra Island, and Karimata Strait, respectively. The red star in northern MS indicates the location of Langkawi tidal station, while the red star facing the SCS is for Kuantan tidal station. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

complex and variable winds especially during the inter-monsoon months when the seasonal background winds are weakened.

With regard to the circulation in the MS, the basic and general properties were first comprehensively summarized by Wyrtki (1961). A mean current from southeast to northwest toward the Andaman Sea exists throughout the year because of the sea level difference between the two ends of the strait, with a downward slope toward the Andaman Sea (Wyrtki, 1961; Thia-Eng et al., 2000; Namba and Saadon, 2001). However, in the strait, tidal currents are strong and affect transport and mixing processes (Wyrtki, 1961; Rizal and Sundermann, 1994; Rizal, 1997; Hatayama et al., 1996; Sannasiraj et al., 2004). The most important tide in the MS is the semi-diurnal M_2. In the main fairway the tidal currents are about 0.5 m/s, but may reach 1 m/s in the more restricted channels and inshore waters (NGA, 2010). The tides are mainly controlled by the northern Indian Ocean and modulated by the tides from the Pacific Ocean and the complex topography (Thia-Eng et al., 2000; Siegel et al., 2009; Kurniawan et al., 2011).

Many other areas of the world ocean are dominated by the M_2 tide similarly to the MS, such as the Gibraltar and Tsugaru Strait and the English Channel, among others. The most important difference is that the MS is located very near the equator 3°N and the others are in mid-latitude. The characteristics of semi-diurnal tides (M_2, S_2) in the MS have been numerically studied in a series of papers by Rizal (Rizal and Sundermann, 1994; Rizal, 1997, 2000). In particular Rizal (2000) carried out an important study on the MS solving for it the Taylor problem in low geographical latitudes. He concluded that the MS has a virtual amphidromic point fully analogous to the one of the English Channel and that the distinction between mid-latitude and equatorial locations is not relevant to the forcings controlling the circulation. In all the above, and many other, straits/channels and coastal areas the dominant current is the M_2 tidal one. Hence the question we ask, i.e. how important is the wind-driven circulation in the MS, is broadly relevant.

Finally, in two recent reports Rizal et al. (2010, 2012) investigate the effect of wind on the MS circulation but only for two mean seasonal NE and SW monsoons. We on the other side focus on the inter-monsoon period when the local winds are more effective due to the weakened monsoon strength.

We ask the following questions which are both scientifically and economically important: How important are the wind-driven currents in the MS? On which time scale are the wind-driven currents more energetic? Can they be ignored for the practical prediction of current patterns? Chen et al. (2010) showed that in the Singapore Strait which is at the southern end of the MS, the wind-driven currents can be of the same order of magnitude as the tidal currents during neap tide. Given the much greater extension, both in length and width, of the MS compared to the Singapore Strait, it is plausible to hypothesize that the strong seasonal monsoons, the intense synoptic winds and land–sea breezes drive the currents that could modify or even dominate the circulation especially during neap tides. Unfortunately, we cannot investigate this hypothesis observationally because there are very few instrumental measurements in the MS. Coastal ocean models are therefore necessary to simulate and reproduce not only the tidal currents (Rizal, 1997; Kurniawan et al., 2011; Sannasiraj et al., 2004) but also the superimposed wind effects (Chen et al., 2012) to confirm or refuse this hypothesis.

This paper is organized as follows. The setups of ocean and meteorological models are described in Section 2. The wind effects on the tidal currents are investigated through numerical simulations in Section 3. A final discussion is given in Section 4.

2. Ocean model and atmospheric model

2.1. Ocean model and its configuration

Numerical simulations are carried out with an unstructured-grid, free-surface, 3D primitive equation Finite Volume Coastal Ocean Model (FVCOM). In FVCOM, the horizontal grid comprises unstructured triangular cells (Fig. 2) and the realistic topography is represented using terrain-following coordinates. The equations of motion are solved numerically by a discrete flux calculation that is second-order accurate in the integral form of the equations (Chen et al., 2003). More details of FVCOM can be found in Chen et al. (2006).

As shown in Fig. 1, the computational domain covers not only the MS but also the Karimata Strait and part of the SCS. This boundary configuration avoids cutting across dozens of islands around the Singapore Strait and includes a region significantly large for the tides from the SCS and the Java Sea to penetrate into the MS and interact with these islands. The northwest boundary is set in the region with a gentle bottom slope, avoiding the very steep slope between the Andaman Sea and the MS. We have