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Volume transport through the Taiwan Strait and the effect of synoptic events

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ABSTRACT

Volume transport through the Taiwan Strait during 2005–2008 was simulated using a shallow water model forced by high spatio-temporal resolution meteorological data. On average, simulated monthly mean transports ranged from a southward maximum of 0.38 Sv in December to a northward maximum of 2.02 Sv in June, with an annual mean northward transport of 0.78 Sv. These estimates are in agreement with the published results based on bottom-mounted ADCP observations. Several sensitivity experiments were conducted to separately examine possible influence of ignoring air pressure or applying time-averaged wind forcing on the transport estimate. We found that excluding the air pressure component in the model gave rise to an insignificant difference (0.01 Sv) in the mean transport estimate. Using multi-year-averaged monthly mean wind, however, provided markedly different results; it brought about a magnitude change of up to 0.65 Sv for the monthly mean transport and 0.34 Sv for the annual mean transport. The nonlinear parameterization of wind stress was mainly responsible for the distortion. In addition, we found that typhoons, as one kind of synoptic events, had an accumulative influence not only on the monthly mean transport during the typhoon season but also on the annual mean transport. The effect of typhoons reduced the monthly mean transport by up to 0.45 Sv and the annual mean transport by 0.09 Sv (more than 10%). Therefore, high temporal resolution wind data with synoptic scale variability are required to accurately estimate the monthly mean and annual mean transports when using a model.

1. Introduction

The Taiwan Strait is a wide (average 180 km) and long (about 350 km) channel oriented along the southwest-northeast direction. It connects two large marginal seas in the western North Pacific—the South China Sea to the south and the East China Sea to the north (Fig. 1). It is a unique, direct passage for water exchange, energy transfer and nutrient flux between the two seas (Liu et al., 2000; Chung et al., 2001). Since an accurate estimate of volume transport through the strait is a prerequisite for clarifying material exchange, many investigations have been conducted intermittently since the 1960s (e.g., Wyrtki, 1961; Fu et al., 1991; Chai et al., 2001; Jan et al., 2006; Wang et al., 2009).

Based on the sea level measurements at an imperfect pair of stations located on both sides of the Taiwan Strait and the geostrophic assumption in the cross-strait direction, Wyrtki (1961) reckoned that the transport through the strait is less than 1 Sv (positive for northward and negative for southward, similarly hereinafter) even in July and December when the currents in the strait are strong, and that the transport direction is northward in summer but southward in winter. The results calculated directly from limited current observations taken by survey ships indicated that the transport is always northward, and its magnitude is 3.32 Sv in summer and 1.74 Sv in winter (Fu et al., 1991). Using more current observations by anchored moorings from ships and moored current meters at a few sites in the strait, Fang et al. (1991) obtained similar results of 3.1 Sv in summer and 1.0 Sv in winter, with an annual mean transport of 2 Sv. From the current measurements by shipboard Acoustic Doppler Current Profiler (sb-ADCP) during two survey periods of 23–25 May and 13–14 August 1999, Chung et al. (2001) estimated that the transports in May and August are 2.0 and 2.2 Sv, respectively. Later on, more cruise data

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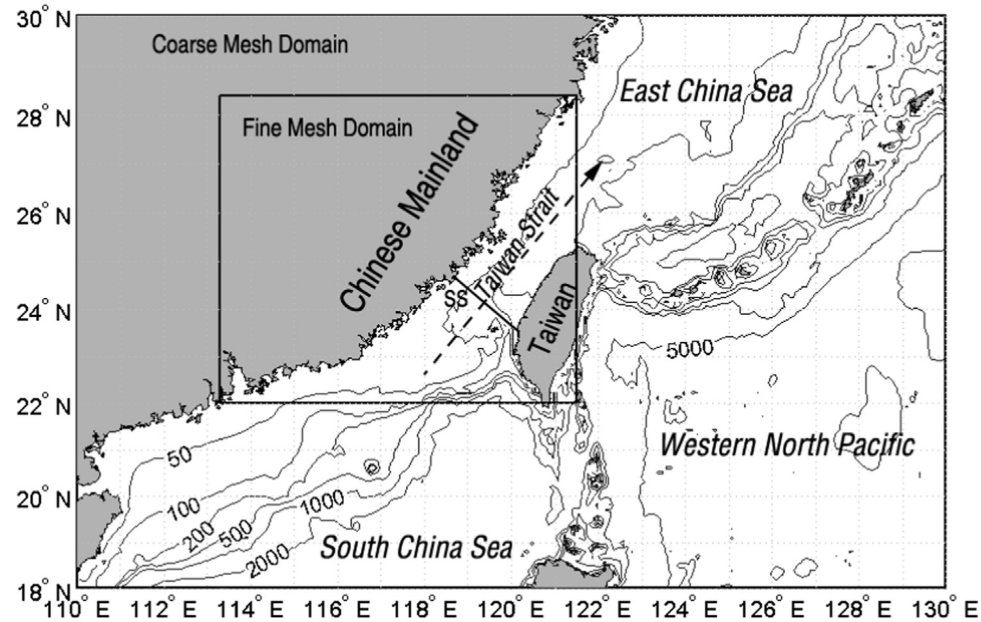

Fig. 1. The geographic map and model domains for the coarse and fine meshes. Gray contours are isobaths in meters. The dashed line with an arrow marks the direction of the Taiwan Strait, which is 40°clockwise from the north. SS denotes the section across the strait, which is perpendicular to the dashed line.

became available in estimating the transport. Wang et al. (2003) analyzed the sb-ADCP data collected between 1999 and 2001 and pointed out that the transport varies from 2.7 Sv in summer to 0.9 Sv in winter, with an annual mean of 1.8 Sv. Four bottom-mounted Acoustic Doppler Current Profilers (bm-ADCP) were deployed across the strait during October–December 1999, and their measurements were used to estimate the transport through the strait (Teague et al., 2003; Lin et al., 2005). Three-month mean transport was 0.14 Sv with a standard deviation of 1.3 Sv, and expected error in the transport estimate was about 0.33 Sv at any time (Teague et al., 2003). The instantaneous transport was between −5 and 2 Sv, with a mean value of 0.12 Sv during the synchronous observation period from 28 September to 14 December 1999 according to the four profilers (Lin et al., 2005). Jan et al. (2006) presented more detailed information about the monthly mean transport which varies from 1.87 to 2.34 Sv in June–August (based on sb-ADCP observations) and from −0.26 to −0.07 Sv in December–February (based on bm-ADCP records). Their results are evidently different from most of the early estimates, not only in terms of transport magnitude during summer but also in terms of transport direction during winter; however, their results support Wyrtki's (1961) result in winter.

Since numerical models can provide, with some degree of accuracy, the spatio-temporal state of the ocean, to supplement sparse, short-term observations, they have been extensively employed in estimating the transport through the Taiwan Strait. All estimated monthly mean transports for summer in previous research are universally northward (e.g., Fig. 2), but their magnitudes range from below 1.0 Sv to over 3.0 Sv. Wang and Yuan (1997) set up a three-dimensional (3D) nonlinear model for the Taiwan Strait, which was used to diagnostically calculate currents with hydrographic data collected during August 1984 and 1–6 September 1988; then, they obtained a transport of only 0.83 Sv through the strait. Cai and Wang (1997) used a barotropic model forced by monthly mean wind stress to estimate the transport in summer, but their estimate was as large as 3.39 Sv. Most other estimates are in between the two estimates mentioned above (e.g., Isobe, 1999; Liu et al., 2002; Wang et al., 2009). The transport estimate for winter varies even more widely, in terms of both magnitude and direction. In winter, non-wind-driven flow in the Taiwan Strait is against the northeasterly monsoon wind. Most simulated results concluded that the mean transport in winter is relatively weak and northward (e.g., Bao et al., 2002; Cai et al., 2002; Wang et al., 2009). A diagnostic analysis performed by Guo et al. (2005) derived a similar result, which used altimeter sea surface height anomaly data from the Archiving, Validation and Interpretation of Satellites Oceanographic data (AVISO) and wind field from the Reanalysis II by the National Centers for Environmental Prediction (NCEP). These results seem to be supported by current observations from survey ships (e.g., Fu et al., 1991; Wang et al., 2003). However, they have been challenged by bm-ADCP measurements (Jan et al., 2006) and by a few numerical simulations (Fang et al., 2003; Wu and Hsin, 2005), which demonstrated the mean transport in winter should be southward by the northeasterly monsoon wind. Meanwhile, the annual mean transport estimates cover a large range of 0.4–2.3 Sv. Notwithstanding such differences and contradictions, none of them paid attention to their sources. In this study, we examine the transport through the Taiwan Strait using a shallow water model and high resolution spatio-temporal forcing, and more importantly we address the influence of external forcing on the monthly mean and annual mean transport estimates. The results show that the monthly mean transports can be greatly distorted if wind stress is calculated using monthly mean wind. Additionally, we investigate the effect of synoptic events on the monthly mean and annual mean transports.

2. Model and driving force

The Taiwan Strait is located over a wide, shallow continental shelf with an average depth of only about 60 m, where both tides and winds are strong because of channel effects. As a result, vertical stratification is very weak due to energetic tidal mixing and strong wind mixing (Wyrtki, 1961; Zhu et al., 2013). In this area, baroclinic effect is negligible and easily overcome by atmospheric forcing (Chuang, 1985). The aspect ratio between horizontal and vertical dimensions for the transport through the strait is on the order of 10^{-4}, indicating its shallow-water characteristics. The vertical structures of currents are not considered in view of the depth-integrated concept of volume transport. Thus, a two-dimensional (2D) barotropic numerical model,