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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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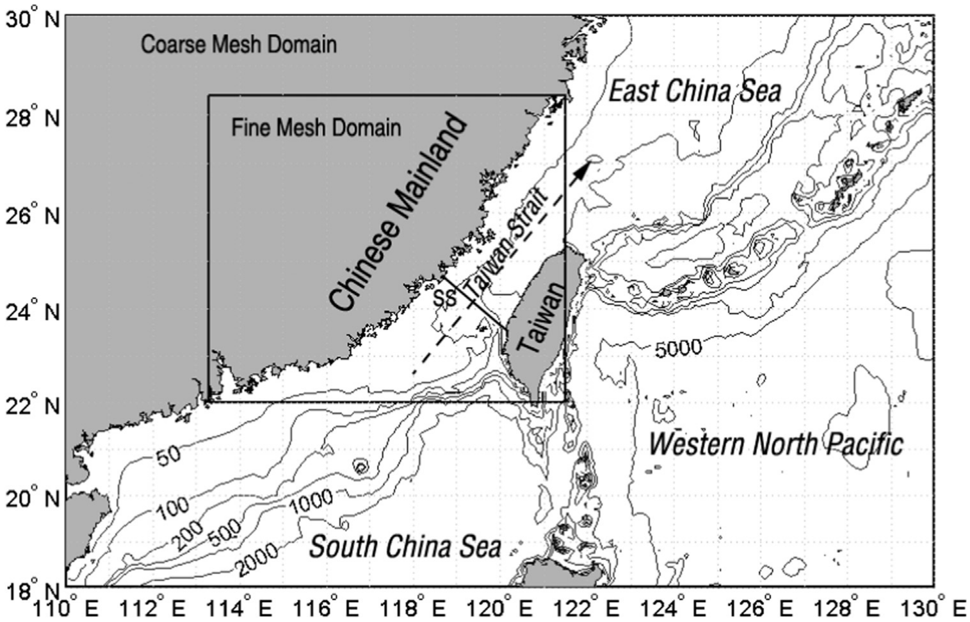

Fig. 1. The geographic map and model domains for the coarse and fine meshes. Gray contours are isobaths in meters. The dashed line with an arrow marks the direction of the Taiwan Strait, which is 40°clockwise from the north. SS denotes the section across the strait, which is perpendicular to the dashed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

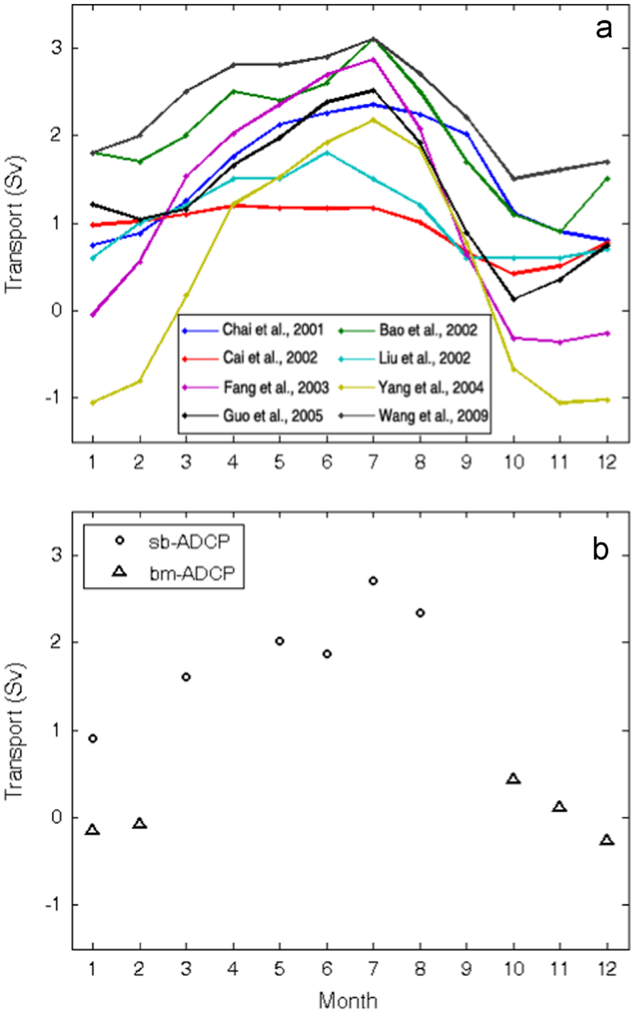

Fig. 2. (a) Previous model estimates of monthly mean transports (Sv) through the Taiwan Strait. (b) Monthly mean transports (Sv) based on shipboard ADCP (sb-ADCP) and bottom-mounted ADCP (bm-ADCP) measurements are taken from Wang et al. (2003) and Jan et al. (2006). The sb-ADCP measurements were collected during repeated cross-strait cruises under calm weather conditions, whereas the bm-ADCP observations were obtained with fixed time interval by four (October–December 1999) or three (January and February 2001) moored current meters (RDI Workhorse 300 kHz ADCPs) deployed along the same section as the cruises.

developed and validated by Zhang et al. (2007, 2009), is used in this study. Briefly, it is a shallow water model based on nonlinear shallow water equations in the spherical coordinates. A shallow water model can depict important processes of oceanic motion and avoid the complex thermodynamics related to stratification and baroclinicity (Pedlosky, 1987). Because of its simplicity, a fine resolution is easily achieved with higher efficiency than a 3D model, which makes it possible to better describe the complicated local bathymetry and curving coastline in the model domain.

The model has two grid meshes: a coarse mesh (110–130°E, 18–30°N) with a resolution of 1/10° in longitude and latitude, and a fine one (113.3–121.5°E, 22.0–28.4°N) with a resolution of 1/30° (see Fig. 1). They interact at every time step via a two-way nesting technique (Zhang et al., 2007). The output from the fine mesh is used to calculate the transport through the Taiwan Strait.

Wind stress ($\boldsymbol{\tau}_s$) is parameterized via a commonly used bulk formula as follows,

$$\boldsymbol{\tau}_s = \rho_a C_d |\mathbf{W}|\mathbf{W} \tag{1}$$

where C_d is the drag coefficient, ρ_a air density (kg m^{-3}), and $\mathbf{W}$ the wind vector (m s^{-1}) at a height of 10 m above the sea surface. C_d is determined from the equation (Zhang et al., 2007):

$$C_d \times 10^3 = \begin{cases} 1.052, & |\mathbf{W}| \le 6 \ \ m/s \\ 0.638 + 0.069|\mathbf{W}|, & 6 < |\mathbf{W}| < 30 \ \ m/s \\ 2.708, & |\mathbf{W}| \ge 30 \ \ m/s \ . \end{cases} \tag{2}$$

Bottom friction ($\boldsymbol{\tau}_b$) is calculated using a quadratic law:

$$\boldsymbol{\tau}_b = \rho g c^{-2} |\mathbf{q}|\mathbf{q} \tag{3}$$

where $\mathbf{q}$ is the depth-averaged current vector (m s^{-1}), ρ the density of sea water (kg m^{-3}), and g the gravitational acceleration (m s^{-2}). $c{=}H^{1/6}/n$ is the Chezy coefficient in which H is the total water depth (m) and n, the Manning coefficient, is set to 0.0295 m$^{-1/3}$ s. This formula has been extensively adopted in shallow water models (e.g., Zhang and Li, 1996; Kang et al., 1998). Along coastal boundaries, the normal component of current is set to zero. For open boundaries, a radiation condition developed from Flather's (1976) is applied (Zhang et al., 2007), which prevents artificial reflection of the disturbances generated within the model domain.

Meteorological data, including surface wind at 10 m above the sea surface and surface air pressure, and ocean currents at the open boundaries of the coarse mesh, are required to drive the model. The wind field is a blended product of the operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) and near real-time remotely sensed measurements by the Quick Scatterometer (QuikSCAT) and the Defense Meteorological Satellite Program (DMSP) satellites (referred to as the blended wind hereafter). It has a high spatial resolution of 0.25° in both zonal and meridional directions, and a temporal resolution of 6 h. This blended wind data set was downloaded from the Centre ERS d'Archivage et de Traitement (CERSAT) at the French Research Institute for Exploitation of the Sea (IFREMER) (Bentamy et al., 2007), which covers the period from 1 April 2004 to 22 November 2009 before the failure of the QuikSCAT satellite. It is a state-of-the-art surface wind product over global oceans, comparing well with off-line remotely sensed measurements and buoy observations (Bentamy et al., 2009; Zhang et al., 2009). The surface air pressure field, taken from the global mean sea level pressure data set of the ERA Interim Reanalysis (Dee et al., 2011), has a spatial resolution of 0.75 × 0.75° and a temporal resolution of 6 h. The ERA Interim is the latest reanalysis product by the ECMWF and has substantial improvements in some aspects over ERA-40 (Dee et al., 2011). Obtained from the pentad ocean reanalysis data set of the NCEP Global Ocean Data Assimilation System (Behringer and Xue, 2004), the ocean currents at the resolution of 0.33° (latitude) by 1.00° (longitude) and 40 levels in the vertical direction were used to calculate depth-averaged currents. These depth-averaged currents were then interpolated to model grids at the open boundaries and used as input for the radiation boundary condition. Since previous studies of volume transport through the Taiwan Strait did not take into account the influence of tides due to their periodicity, tides are not considered in this work for comparability, although the model is capable of simulating them well (Zhang et al., 2007). More detail about the model and its validation can be found in Zhang et al. (2007, 2009).

The spin up and running processes of the model are the same as described in Zhang et al. (2013). It was spun up for six months using monthly mean atmospheric and current data of April 2004 and then forced by the above-described data sets from 1 May 2004 to 22 November 2009. Estimated monthly mean transport through the Taiwan Strait will be compared with the results calculated from ADCP observations in Section 3.1.

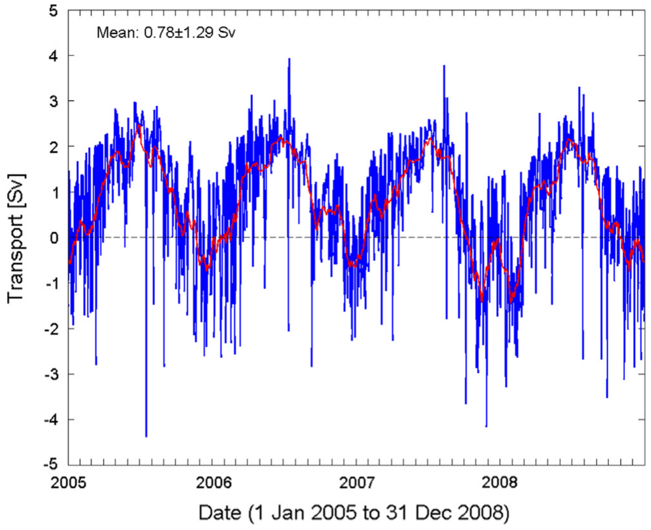

Fig. 3. Time series of simulated transport (blue) through the Taiwan Strait during 2005–2008. The red curve denotes 30-day moving average.

3. Results and discussion

3.1. Transport

Along-strait transport in the Taiwan Strait is not sensitive to the location of a section across the strait (Zhang et al., 2009); therefore, the transport through the section located in the southern part of the strait (see the line SS in Fig. 1) is used. The modelled transport during 2005–2008 is shown in Fig. 3 after a 25-h filtering via a nonlinear second power function fit method to remove high frequency noises. The transport varies in the range of −4.38 to 3.94 Sv, with a mean of 0.78 Sv and the standard deviation of 1.29 Sv. It displays a significant seasonal variation and drastic fluctuation at the synoptic time scale, which is similar to the results of Wu and Hsin (2005). Its 30-day moving average clearly shows that the transport tends to be northward in summer and southward in winter. This seasonal variation is closely related to the alternation between the southwesterly monsoon in summer and the northeasterly monsoon in winter (Wu and Hsin, 2005; Jan et al., 2006). The short-time drastic fluctuation is induced by strong weather events, such as typhoons (including tropical storms, severe tropical storms, typhoons, severe typhoons, and super typhoons) and winter wind bursts (Ko et al., 2003; Zhang et al., 2009). The standard deviation of the transport after removing its 30-day moving average is 0.89 Sv, indicating that the short-time fluctuation accounts for about 48% of the total variance, slightly less than longer time scale (≥ 30 days) variation.

Annual mean transports during 2005–2008 were between 0.60 Sv and 0.92 Sv, with an average of 0.78 Sv. These results are smaller than most estimates in the literature, but larger than that of Yang et al. (2004). The time series is too short to adequately exhibit its inter-annual variability, which is not our focus in this paper.

Spectrum analysis using the weighted overlapping segment averaging Fourier transform (FT) with a segment length of 180 days (4320 hourly data, 50% overlapping), following Harris (1978), demonstrates that the seasonal variation dominated at the time scales up to four years (Fig. 4). The largest, predominant peak is located at the frequency of 0.0029 cycle per day (about 345 days). The FT method is based on the assumption that the time series analyzed is linear and stationary. The dominant, strong signal in the seasonal band indicates that the seasonal variation is more or less repetitive. Because the synoptic time scale fluctuations caused by severe weather events are intermittent and non-stationary, their signals spread to a wide band from several days to dozens of days. This is the reason why no prominent peak appears in the synoptic band in Fig. 4b.

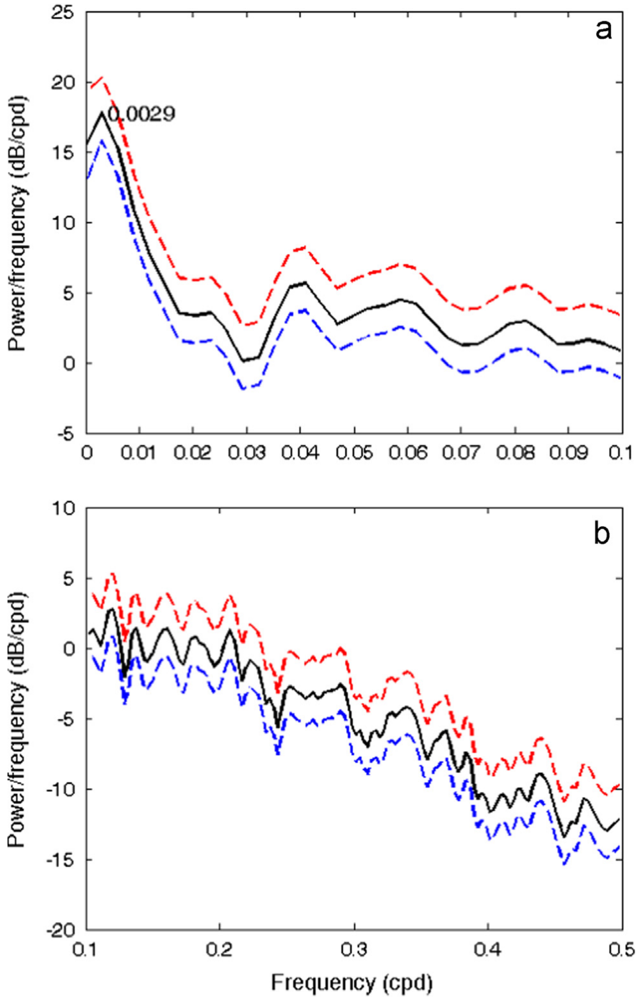

Fig. 4. Power spectral density distribution (solid curve) of the transport through the Taiwan Strait for a 4-year time series from 2005 to 2008 (after removing its mean value), using the Welch's method. The frequency spans a range (a) from 0 to 0.1 cpd (cycles per day) and (b) from 0.1 to 0.5 cpd with upper (red dashed curve) and lower (blue dashed curve) 95%-confidence bounds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Multi-year-averaged monthly mean transport ranges from −0.38 Sv in December to 2.02 Sv in June (see Table 1 and Fig. 5). The mean transports in spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) are 1.22, 1.91, 0.22, and −0.24 Sv, respectively. Although the seasonal variation in terms of monthly mean estimates is apparently similar to the results in the literature, there is a notable difference in transport magnitude during summer and in transport direction during winter. In most published results, the transport magnitudes during summer are larger than 2 Sv, some may even be larger than 3 Sv, and the transport directions during winter are still northward as described earlier. Note that our model estimate for winter transport is southward, consistent with the result based on bm-ADCP data (Jan et al., 2006). The southward monthly mean transport starts in November and ends in February (Fig. 5).

The simulated monthly mean transport is obviously smaller than the estimate based on the sb-ADCP observations except in June (which will be addressed later), but it is in good agreement with the estimate based on the bm-ADCP observations (Fig. 5).

Table 1
The monthly mean and annual mean transports (Sv) through the Taiwan Strait. Standard results (SR) are the results simulated with full forcing; no air pressure (NAP) and monthly mean wind forcing (MMF) are two sensitivity experiments. NT means the results calculated from the SR after removing typhoons' influence.

	Monthly mean transports (Sv)												Mean (Sv)
	1	2	3	4	5	6	7	8	9	10	11	12	
SR	−0.31	−0.02	0.84	1.30	1.53	2.02	1.95	1.76	0.72	0.16	−0.23	−0.38	0.78
NAP	−0.31	−0.02	0.84	1.29	1.52	2.01	1.94	1.75	0.72	0.16	−0.23	−0.38	0.77
MMF	0.11	0.63	1.38	1.69	1.84	1.85	1.87	1.73	1.35	0.68	0.31	0.03	1.12
NT	−0.31	−0.02	0.84	1.31	1.69	2.02	2.17	1.83	1.17	0.26	−0.09	−0.38	0.87

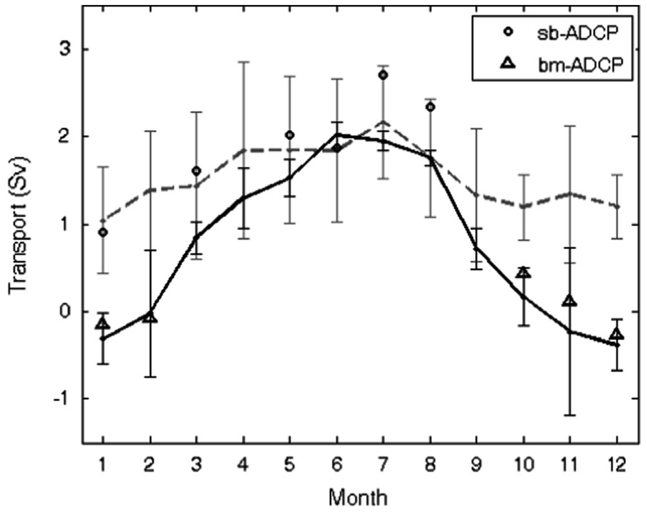

Fig. 5. Comparison between simulated monthly mean transports (solid curve) with corresponding error bars (two standard deviations) and the results based on shipboard ADCP (sb-ADCP) and bottom-mounted ADCP (bm-ADCP) observations, which are the same as those in Fig. 2b. Dashed curve denotes the median results of all months with their variation ranges, based on sub-sampled modelled transport under calm wind weather conditions.

The absolute errors of the simulated results with respect to the sb-ADCP-based results are between 0.15 and 1.21 Sv, while those to the bm-ADCP-based results are only 0.05–0.35 Sv.

Under the influence of northerly wind bursts in winter or typhoons in summer, northward transport through the Taiwan Strait is often reversed momentarily (Ko et al., 2003; Zhang et al., 2009). Note that both sb-ADCP and bm-ADCP observations used for transport estimate were sparse in space. Although there were many stations during a cruise, very few were designed to obtain current profiles for a period longer than one day. Since survey ships generally stayed away from severe weather events, monthly mean transport was easily overestimated based on the sb-ADCP observations because of systematic bias in sampling times. In order to explain this, we extracted the simulated transports during the days when spatially averaged wind speed was less than 8 m s^{-1} in the Taiwan Strait, excluding the influence periods of typhoons when all ships were forced to stay in harbors for safety. This cutoff wind condition is close to the requirement of most research vessels for field surveys in the strait. Fig. 5 shows the median transport of every month with maximum variation range based on such sub-sampled data. We can see that the transports in calm wind weather conditions are definitely northward and basically larger than the original monthly mean results, particularly in winter. As anticipated, they are in agreement with the sb-ADCP observations.

In contrast, the estimate based on the bm-ADCP observations, which were almost evenly spaced in time, was less biased in this respect. This means the monthly mean transport estimated from the bm-ADCP data is more accurate than that from the sb-ADCP data. For example, a monthly mean transport of 0.9 Sv for January was estimated by Wang et al. (2003) based on the sb-ADCP observations during 1999–2001, but the estimate obtained by Jan et al. (2006) from the current profiles of three bm-ADCPs deployed across the Taiwan Strait from November 2000 to February 2001 was −0.15 Sv (see Fig. 5). The latter is more reasonable for winter.

Since direct current observations were sparse during 2005–2008, the estimates based on historical observations are used in the above comparisons. This does not take into account the difference caused by inter-annual variation, which would introduce some uncertainty. Although the inter-annual variation of the transport is not yet accurately determined, its magnitude is limited and small compared to the seasonal variation. This is because the largest difference in the annual mean transport (0.32 Sv) during 2005–2008 was much smaller than that in the monthly mean transport (2.40 Sv). For the same reason, many previous investigations did not consider the inter-annual difference when comparing their results with the estimates based on in situ measurements (e.g., Bao et al., 2002; Fang et al., 2003; Wang et al., 2009).

In view of the discussion above, our simulated transport is reasonable and credible. The results from that simulation will be referred to as the "standard results", namely, as a reference for other estimates in the following sensitivity experiments and analyses.

3.2. Influence on transport estimate

The model itself and its configuration are undoubtedly important for numerical simulation of the ocean state. Since the model used here, along with its configuration, has been validated and shown to work well in the Taiwan Strait by Zhang et al. (2007, 2009), no change has been made to the model itself. In addition to the model used, external driving forces are also important for the accuracy of transport estimate, which will be investigated next.

3.2.1. Influence of surface air pressure

Driving forces for the model include surface air pressure gradient, but most studies do not take it into account. Although a few models included air pressure component, the effect of air pressure on monthly mean and annual mean transports through the Taiwan Strait was not illustrated explicitly. This seems to mean that air pressure gradient is dispensable when numerically estimating these transports. However, Lin et al. (2010) argued that air pressure gradient predominantly contributed to the transport during Typhoon Krosa (2007). Our question is how significant air pressure is for the monthly mean and annual mean transports. In order to answer this question, an experiment without air pressure term (referred to as NAP) is conducted.

The results demonstrate that excluding air pressure produces little difference (0.01 Sv at most) in both monthly mean and annual mean transport estimates (see Table 1). The scaling analysis of along-strait momentum equation, which controls the change of along-strait current with time, shows that atmospheric pressure gradient term is smaller by at least one order than wind stress, sea level gradient, bottom friction, and Coriolis force terms. The sea level instantaneously responds to any uneven distribution of air pressure via inverted barometer effect. Although this response takes place dynamically and can be sensed by the model, air pressure gradient is mostly balanced by the adjusted sea level gradient, and the horizontal movement of sea water induced purely by air pressure is weak and insignificant in the Taiwan Strait, at least at the monthly time scale or longer.

3.2.2. *Influence of using monthly mean forcing data*

Multi-year-averaged monthly mean wind or wind stress data were extensively used as driving force in numerical models to estimate monthly mean and annual mean transports through the Taiwan Strait (e.g., Chai et al., 2001; Bao et al., 2002; Fang et al., 2003). These data can generally describe basic seasonal variations of atmospheric motion and momentum flux into the ocean; however, inter-annual differences are averaged out and short-term disturbances due to synoptic events, such as typhoons and winter storms, are smoothed out by time averaging as well. What influence do such monthly mean data have on the estimate of actual monthly mean transports? A numerical experiment using multi-year-averaged monthly mean data to drive the model (referred to as MMF) is carried out to answer this question. For consistency and comparability, monthly mean winds averaged during 2005–2008 are used in this sensitivity experiment.

Fig. 6 shows the difference between the test results and the standard results in terms of monthly mean transports. The largest difference, 0.65 Sv, appears in February and the second, 0.63 Sv, in September (Table 1). Compared with the standard results, the test results slightly underestimate the transport in summer and significantly overestimate it in other seasons. As a result, the range of monthly mean transports is reduced to 0.03–1.87 Sv (Table 1). All monthly mean transports are northward in the whole year and the maximum value appears in July, which is similar to most studies mentioned earlier. Additionally, annual mean transport is overestimated by 0.34 Sv, or about 44% (1.12 Sv in the test vs 0.78 Sv in the standard results).

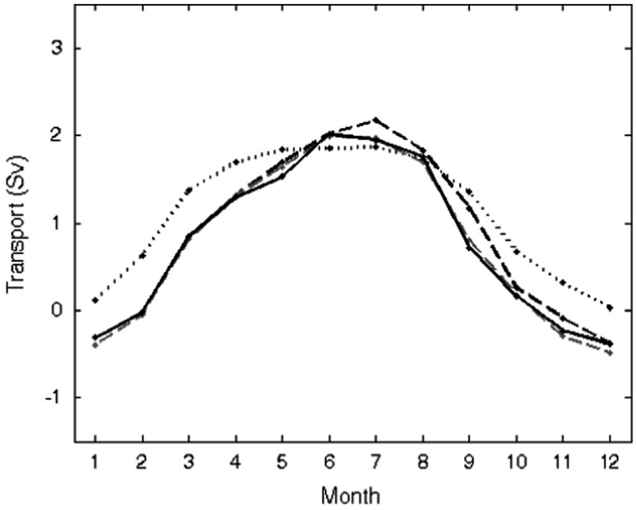

Fig. 6. Comparison between simulated monthly mean transports. Solid curve shows the standard results and black dashed curve denotes the results after removing the influence of typhoons. Dotted and gray dashed curves indicate simulated results using monthly mean wind stress calculated from monthly mean wind and using monthly mean wind stress averaged from 6-hourly wind stress, respectively.

An important question is what causes these differences. Two kinds of nonlinear processes may result in these differences: the first is the parameterization of wind stress; the second is the nonlinear response of the model ocean to wind stress. Monthly mean wind stress may be underestimated if it is calculated directly from monthly mean wind using Eq. (1), compared with that averaged from high temporal resolution wind stress (Thompson et al., 1983). Fig. 7 shows the multi-year-averaged monthly mean wind stress fields and the corresponding differences of these two methods in January (mid-winter) and July (mid-summer). It is clear that the wind stress field averaged directly from 6-hourly wind stress is stronger, in both January (Fig. 7a and c) and July (Fig. 7b and d), than that calculated from monthly mean wind, although they both are based on the same parameterization equation. Their difference is southward and unfavorable for the northward transport through the Taiwan Strait in January, while their difference is northward and favorable for the northward transport in July. In other words, the monthly mean wind stress obtained using monthly mean wind underestimates both southward wind stress in winter and northward wind stress in summer. This must be the main reason why the simulated transport in winter is changed to northward while the northward transport in summer becomes weaker in the experiment with respect to the standard results. In order to further illustrate this point and examine the influence of the nonlinear response of the model ocean to wind stress, we conduct an additional experiment using the monthly mean wind stress averaged from 6-hourly wind stress instead of that calculated from multi-year-averaged monthly mean wind. The results are almost consistent with the standard results (see Fig. 6). Thus, it is mainly the nonlinear parameterization using multi-year-averaged monthly mean wind to derive its corresponding wind stress, rather than the nonlinear response of the model ocean to wind stress, that distorted the transport estimate. On the other hand, monthly mean wind stress is acceptable for forcing a model that is used to estimate monthly mean transports if the stress is averaged from high temporal resolution wind stress, not calculated directly from monthly mean wind.

3.3. *Effect of synoptic events on mean transports*

Since extreme synoptic events, such as typhoons and northerly winter wind bursts, can reduce and even reverse instantaneous northward transport through the Taiwan Strait temporarily (Ko et al., 2003; Zhang et al., 2009), we need to know whether their influence on monthly mean and annual mean transports is of importance. As an example, typhoons will be the focus here. This is not only because typhoons frequently affect the Taiwan Strait but also because they are more fickle than northerly winter wind bursts. Strong northerly winter winds definitely tend to reduce, if not reverse, the northward transport. Although many typhoons tended to impede the northward transport, a few typhoons actually enhanced the northward transport (Zhang et al., 2013). Additionally, typhoons mostly appear in summer when the northward transport is the strongest in the Taiwan Strait.

During the four-year period considered in this work, there were 94 typhoons formed in the western North Pacific, among which 35 affected the transport through the Taiwan Strait. Zhang et al. (2013) demonstrated that 30 typhoons had negative effects (meaning reducing the northward transport), three had positive effects, and the other two had no net effect on the instantaneous northward transport. However, the authors did not address the influence of these typhoons on the monthly mean and annual mean transports, which will be examined next.

The transport during the influence of each typhoon is removed from the transport time series, in order to obtain the transport estimate without typhoons. The influence period of a typhoon is

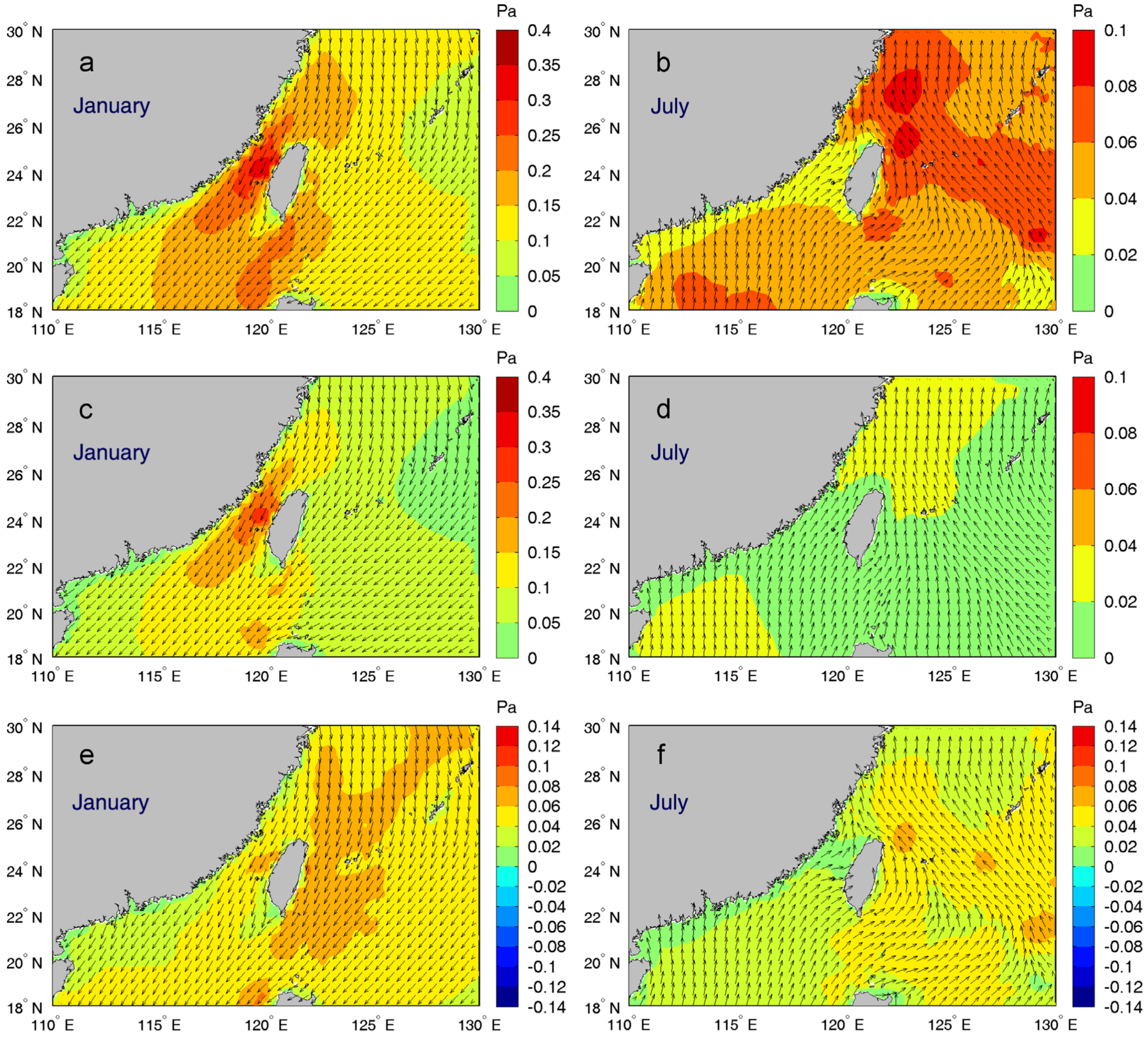

Fig. 7. Multi-year-averaged monthly mean wind stress fields during 2005–2008: (a and b) averaged from 6-hourly wind stress fields; (c and d) calculated from multi-year-averaged monthly mean wind fields; and (e and f) their corresponding differences (the former minus the latter). The arrow denotes the wind stress direction only, and the color shows its magnitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

defined as the period from the beginning to the end of abnormal transport induced by the typhoon, i.e., surpassing one standard deviation from the running average, and amended according to the distance between the typhoon center and the Taiwan Strait if necessary (Zhang et al., 2013). Based on the "de-typhooned" data, multi-year-averaged monthly mean and annual mean transports are calculated again (Table 1). Fig. 6 shows that the monthly mean transport in the typhoon prevailing season becomes larger when the influence of typhoons is removed. During the time period from May to November, the monthly mean transport increases as much as 0.45 Sv without the influence of typhoons. The largest increase of 0.45 Sv appears in September, and the second largest of 0.22 Sv, in July. There is no difference in June because no typhoon affected the Taiwan Strait in this month during 2005–2008. Interestingly, June is the only month during which simulated monthly mean transport is very close to that estimated from the sb-ADCP observations. The observations were obtained in June 2000 (Jan et al., 2006) when no typhoon appeared in the western North Pacific. This may be coincidental, but it is consistent with the fact that the sb-ADCP data described the flow in the absence of typhoons. The annual mean transport also increases by approximately 11% (0.87 Sv without the influence of typhoons vs. 0.78 Sv in the standard results) after removing the influence of typhoons. It should be noted that although the transport during the influence periods of typhoons could be removed, the inertial oscillation induced by typhoons could not be eliminated from the rest of the transport estimate, which supposedly has little contribution to the net transport due to its periodicity. These results reveal that the accumulative effect of typhoons on the monthly mean, and even annual mean, transports is considerable and should not be neglected.

4. Summary and conclusion

Volume transport through the Taiwan Strait during 2005–2008 was estimated using a 2D barotropic model and high spatio-temporal resolution meteorological data. The estimated transport was between −4.38 and 3.94 Sv, with a 4-year mean of 0.78 Sv. The transport had a significant seasonal variation, namely, northward in summer and southward in winter, which was due to the alternation between southwesterly and northeasterly monsoons. Superposed on its seasonal variation, the short-time scale fluctuations were usually caused by synoptic events, such as typhoons. On average, estimated multi-year-averaged monthly mean transports ranged from −0.38 to 2.02 Sv, with an annual mean of 0.78 Sv.

The sensitivity experiment NAP demonstrated that excluding the air pressure component in the model gave rise to an insignificant difference in terms of monthly mean and annual mean transport estimates. The second sensitivity experiment MMF using wind stress derived from monthly mean wind data produced markedly different monthly mean and annual mean transports from the standard results. It underestimated the transport in summer, and obviously overestimated the transport in other seasons. The annual mean transport was increased by 44%. However, using monthly mean wind stress averaged from 6-hourly wind stress, an additional experiment produced almost the same monthly mean transports as the standard results. The nonlinear parameterization from monthly mean wind to its corresponding wind stress underestimated the air-sea momentum flux, causing distorted transports in the experiment MMF.

Typhoons, as one kind of synoptic events affecting the Taiwan Strait, had an evident influence on the monthly mean transports in the typhoon season, even on the annual mean transport. The monthly mean and annual mean transports may be falsely overestimated without considering the occurrence of typhoons, by as much as the estimate based solely on the sb-ADCP observations that were obtained in calm, no-typhoon conditions. The seasonal variation of the transport is mainly determined by large-scale monsoon transitions, however, it is not fully independent of synoptic events, but partially accumulates their effects.

Extreme synoptic events usually exhibit strong and variable winds, which make time-averaged wind field quite different from original wind snapshots. If monthly mean wind stress is used to force a model, it should be averaged from sufficiently high resolution wind stress (say 6 h), not parameterized directly from monthly mean wind. Doing so, the resulting monthly mean wind stress integrates influence from synoptic events and is closer to real monthly mean momentum flux into the ocean. If so doing, simulated monthly mean transports would not be distorted seriously.

In conclusion, the seasonal transport through the Taiwan Strait tends to be northward in summer and southward in winter, not only by southwesterly and northeasterly monsoons but also by accumulative effect of synoptic events. Since the reliability of wind stress ultimately depends on the temporal resolution of the adopted wind fields, high-resolution wind data resolving synoptic scale events are required for a numerical model to accurately estimate monthly mean and annual mean transports in the strait. Such data distinguish the alternation between the southwesterly and northeasterly monsoons and more precisely describe the synoptic events as well. The error in open boundary forcing and the simplicity of the numerical model used may affect the estimated transport somewhat, but they should not impair the perspective and discussion presented in this paper.

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