Transports and tidal current estimates in the Taiwan Strait from shipboard ADCP observations (1999–2001)

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Abstract

Tidal and mean flows in the Taiwan Strait are obtained from analysis of 2.5 years (1999–2001) of shipboard ADCP data using a spatial least-squares technique. The average tidal current amplitude is 0.46 ms−1, the maximum amplitude is 0.80 ms−1 at the north-east and southeast entrances and the minimum amplitude is 0.20 ms−1 in the middle of the Strait. The tidal current ellipses derived from the shipboard ADCP data compare well with the predictions of a high-resolution regional tidal model. For the mean currents, the average velocity is about 0.40 ms−1. The mean transport through the Strait is northward (into the East China Sea) at 1.8 Sv. The transport is related to the along Strait wind by a simple regression, transport (Sv)=2.42 + 0.12 wind (ms−1). Using this empirical formula, the maximum seasonal transport is in summer, about 2.7 Sv, the minimum transport is in winter, at 0.9 Sv, and the mean transport is 1.8 Sv. For comparison, this result indicates that the seasonal amplitude is almost identical to the classical estimate by Wyrtki (Physical oceanography of the southeast Asian waters, scientific results of marine investigations of the South China Sea and Gulf of Thailand, 1959–1961. Naga Report 2, Scripps Institute of Oceanography, 195 pp.) based on the mass balance in the South China Sea, while the mean is close to the recent estimate by Isobe [Continental Shelf Research 19 (1999) 195] based on the mass balance in the East China Sea.

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1. Introduction

The Taiwan Strait is a relatively shallow channel connecting the East and South China Seas (Fig. 1). It plays a major role in material transport in and out of the East China Sea (ECS). Huh and Su (1999) suggest that the Taiwan Strait contributes 2.6 × 108 tons of sediment, about one-third of the total annual input, to the ECS. Chen and Wang (1999) estimate that the Taiwan Strait contributes 36 and 11% of the total nutrients in the ECS in summer and winter, respectively. Using the combined hydrographic and ADCP measurements, Liu, Tang, Gong, Chen, and Shiah (2000) point out drastic changes in the nutrient flux between summer and winter. The nutrient flux from the Taiwan Strait is less than half of the slope water input in summer, but is more than twice the slope water input in winter. They, however, caution that the flux estimate is based on a single transect and more direct transport measurements are necessary.

The original estimate of the seasonal transport through the Taiwan Strait was provided by Wyrtki (1961) in an effort to balance the total transports in and out of the South China Sea (SCS). His value varies from 0.8 Sv (1 Sv=106 m3 s−1) in summer (out of the SCS) to −0.9 Sv in winter. More recently, there have been several attempts to revise this estimate. Qu (2000) finds that the mean transport through the Luzon Strait is about −3 Sv (into the SCS), the maximum is in winter, at −5.3 Sv and the minimum is in summer at −0.2 Sv. Presumably, the Taiwan Strait would respond to changes in the Luzon Strait. Isobe (1999) suggests that
the flow out of the Taiwan Strait stays in the ECS and exits into the Tsushima/Korea (T/K) Strait. Using the observed transports through the T/K Strait, the Taiwan Strait transports are estimated to be about 1.6 Sv in spring, 2 Sv in summer and winter, and 0.8 Sv in fall. Both studies were based on indirect methods using hydrographic data.

Very few direct current measurements have been made in the Taiwan Strait due to the difficulty of maintaining moorings against heavy fishing. Based on several moored current meters, Chuang (1985, 1986) and Wang and Chern (1988) found that the mean currents are northward with occasional flow reversals. Their studies, however, cannot be used to determine the total transport and their record lengths are too short to establish a meaningful seasonal pattern. In this study, the Taiwan Strait transports are calculated using the shipboard ADCP observations collected between 1999 and 2001. While most of the cruises were not designed specifically to map the transport, the large amount of data permits quantitative estimate of the total transport. An attempt was also made to determine the seasonal transport variation through regression with the seasonal along Strait wind.

2. Material and methods

The data used in this study are based on the shipboard ADCP profiles routinely collected in the Taiwan Strait onboard three research vessels, OR-1, -2 and -3, between 1999 and 2001. There were over 40 cruises during the study period. About half of the cruises had durations of 3–5 days and the other half lasted 1–2 days. All three ships are equipped with a hull-mounted RDI ADCP mounted at approximately 4 m below the sea surface. The bin depth is 4–8 m and the average time interval is 1–4 min. The data are screened to remove outliers. The criteria are set such that the acceptable data are characterized by the percentage good being greater than

Fig. 1. The dotted lines indicate the composite cruise tracks of the shipboard ADCP observations in Taiwan Strait from 1999 to 2001. The nodes are marked in circles. Inserted are location map (upper left) and simplify bathymetry of Taiwan Strait. Peng Hu is near 23.5°N and 119.5°E.
85%, error velocity and vertical velocity less than 0.15 ms$^{-1}$, ship speed at 0.5–6 ms$^{-1}$, and change in heading less than 2 min$^{-1}$. The useful data are calibrated using the method described in Joyce (1989). There are over 4000 half-hourly data points. Fig. 1 shows the composite 2.5 years cruise tracks.

The depth-averaged shipboard ADCP data are spatially interpolated to derive tidal and residual currents, following the method of Candela, Beardsley, and Limeburner (1992) and Munchow (2000),

$$u(r, t) = u_1(r) + \sum_{i=1}^{N} [A_i(r) \cos(\omega_it) + B_i(r) \sin(\omega_it)]$$

+ $u_2(r, t)$

where $r$ is the position vector, $u_1$ is the mean (over the entire 2.5 years period), $u_2$ is the residual, and $N$ is the number of tidal constituents used in the analysis. In the Taiwan Strait, the semidiurnal $M_2$ (period = 12.42 h) tide is dominant. Because the duration of each individual cruise is relatively short, it is difficult to separate the individual harmonics. Hence, only the $M_2$ is included in the expansion ($N = 1$). The spatial functions $A(r)$, $B(r)$ and $u_1(r)$ can be expanded in terms of a set of spatial base functions. For example, $A(r)$ can be written as

$$A(r) = \sum_{k=1}^{M} z_k G(|r - r_k|)$$

where $M$ is the number of nodes (where the base functions chosen to span the spatial variability), $r_k$ is the nodal location, $G$ is the base function, and $z_k$’s are the expansion coefficients. $B(r)$ and $u_1(r)$ can be expanded likewise using the same base function but with different coefficients. The choice of the spatial base function is somewhat arbitrary. The polynomial and biharmonic functions have been used in the past. The polynomial function is difficult to use in a large domain, and the biharmonic function can be sensitive to the choice of nodes (Munchow, 2000). In this study, the Gaussian function is implemented,

$$G(|r - r_k|) = \exp\left(-|r - r_k|^2/2L^2\right).$$

The expansion includes nine uniformly spaced nodes ($M = 9$) and $L = 110$ km. Use of a larger $M$ and/or a smaller $L$ increases the spatial resolution, but at the expense of having too few data points in each estimate. The design here is to achieve robust results that are relatively insensitive to changes in the number of nodes and the length scale. After detiding, the residual velocities are fitted to obtain transport stream function using multivariate optimum interpolation (Bretherton, Davis, & Faunery, 1976). A MATLAB program library, SDA-TA, which includes the detiding, multivariate optimum interpolation and sample examples can be retrieved from ftp://pro.msrs.sunysb.edu/sdata.

### 3. Results

Fig. 2 shows the $M_2$ tidal ellipses, together with those calculated from a limited-area barotropic tidal model (Jan, Wang, Ghao, & Wang, 2001). The regional tidal model is driven by the sea level elevations specified at the two open ends; the open-boundary conditions are adjusted using an inverse (adjoint) method to best fit (within several centimeters) model results with respect to a set of coastal and isle sea level observations. The agreements between the ADCP and model results are remarkable. The spatially tidal averaged principal-axis currents are 0.49 ms$^{-1}$ and 0.45 ms$^{-1}$, respectively, from the observation and model results. (The observation result is expected to bias upward as it does not resolve all the semidiurnal tidal components.) The correlation between the two results is 0.85 and the standard deviation is 0.10 ms$^{-1}$. Obviously, the detiding is quite successful, which can be attributed to the use of a very large data set. It is noted that in several places the observation and model ellipse orientations are not properly aligned, which is caused by the model not resolving the local geometry.

The $M_2$ tidal ellipses vary significantly along and across the Strait. Tidal currents are strong near the two ends of the Strait and diminish towards the center, and are generally larger on the Taiwan coast than on the mainland coast. The maximum tidal current amplitudes are about 0.80 ms$^{-1}$ and the minimum amplitudes are about 0.20 ms$^{-1}$. The tidal eccentricity generally follows the change of tidal current amplitudes. The strong tidal currents tend to move alongshore, whereas the weak tidal currents exhibit significant rotary motion. The complex tidal velocity structure is mainly caused by the diffraction of tidal waves around the island of Taiwan. The semidiurnal tide is maintained by the tidal energy flux coming from the ECS and the Luzon Strait (Fang et al., 1999). As the tidal waves enter the Strait, sea levels pile up in the middle of the Strait. The location of the maximum sea level coincides with that of the minimum current, indicating a basic standing wave structure. Also, the Strait length is approximately one-half of the semidiurnal tidal wavelength, which may explain the anomalous amplification of the tidal amplitude (Lin, Juang, & Tsay, 2001). Jan et al. (2001) note that the semidiurnal tide is Kelvin-wave like along the mainland coast.

Fig. 3 shows mean (over the entire 2.5 years record) flows and the standard deviation. A strong jet of about 0.40 ms$^{-1}$, enters the Strait through the Penghu Channel. The jet is deflected by the shallow sand ridge but stays on the right hand side of the Strait. As the flow exits over the deeper northeast end of the Strait, its magnitude drops to about one-half of the upstream value. The stability of the mean flow can be examined by comparing its value with the standard deviation. In Eq. (1)
the un-fitted residual \( u_2 \) contains the analysis error as well as the (actual) time-varying non-tidal flow; hence, the rms of \( u_2 \) is a conservative estimate of the actual non-tidal variability. The standard deviation typically is much smaller than the mean (Fig. 3), indicating that the mean flow is persistent and the analysis error is small. However, on the mainland coast and near the northeast exit the two become comparable.

Fig. 2. The semidiurnal tidal ellipses derived from the shipboard ADCP data (thin line), together with the tidal ellipses calculated from a limited-area barotropic tidal model (gray line).

Fig. 3. The mean flows (arrows) and the standard deviations (ellipse).
Fig. 4 shows mean transport streamfunction, calculated from the multivariate optimum interpolation of the mean flow field (Bretherton et al., 1976). Since there is no evidence for transport recirculation, every streamline that enters from the south should exit through the north. This is indeed the case in the lower three-fourths of the Strait, and the estimated total transport is 1.8 Sv. About half of the inflow is through the deep Penghu Channel, and the other half is over the shallow Taiwan Bank. On the other hand, the transport decreases noticeably in the upper quarter of the Strait. In the northeast sector, the tidal currents are strong; yet, the observations are limited. Most likely, the mean flow estimate is contaminated by errors in the tidal analysis, as suggested by the presence of proportionally large standard deviations (Fig. 3). The transport on the upper quarter sector therefore is ignored.

The Taiwan Strait is subject to strong monsoon forcing. The southwest monsoon prevails from May to September, and the northeast monsoon dominates the rest of the year. Conceivably, there could be a significant seasonal variation in the mean flow. To estimate the effect of wind forcing, mean transports through the middle section of the Strait (marked in Fig. 4) are calculated for ten individual cruises. The corresponding surface wind for each cruise is calculated from the weather data at Pehgntu, after removing the short-term (less than 1 week) fluctuations. Fig. 5 compares the transport with the along-Strait wind. (The wind is predominantly in the along-Strait direction.) A simple regression \( \beta = 0.74 \) gives the relationship,

\[
\text{transport (Sv)} = 2.42 + 0.12 \times \text{wind (ms}^{-1})\]

(4)

From the climatology of wind field, the mean is \(-5.2\,\text{ms}^{-1}\) (towards the south) and the annual amplitude is \(7.4\,\text{ms}^{-1}\). Applying the mean wind to Eq. (4) gives a mean transport of 1.8 Sv, which agrees exactly with the mean transport derived earlier. Applying the
annual wind amplitude gives the transport amplitude of 0.9 Sv, with the maximum transport (2.7 Sv) in July and the minimum (0.9 Sv) in January. It may be more appealing, theoretically, to relate the transport to the wind stress, which results in a mean transport of 1.6 Sv and a seasonal amplitude of 1.1 Sv. This result is not significantly different from the estimate using the wind. Use of Eq. (4), on the other hand, is more straightforward, as the wind is measured directly.

4. Discussion

Based on the 2.5 years of shipboard ADCP data, the estimated transports in the Taiwan Strait vary from 2.7 Sv in summer (JJA) to 0.9 Sv in winter (DJF), with a mean of 1.8 Sv. In Wyrtki (1961), the summer and winter transports are 0.8 Sv and −0.9 Sv, respectively. His mean transport value (of about 0) is different from ours, but the seasonal amplitude of 1.7 Sv is remarkably close to the present estimate. In Wyrtki (1961), the Taiwan Strait transport is balanced by the transports through the Luzon and Gaspar–Karimata Straits. His estimated Luzon Strait transports are 2.8 Sv in summer (out of SCS) and −3.5 Sv in winter (into SCS). Corrected for the bias in the Taiwan Strait, the Luzon Strait transports would become 0.9 Sv in summer and −5.4 Sv in winter. For comparison, Qu (2000) obtained the Luzon Strait transports of −0.2 Sv in summer and −5.3 Sv in winter. It is again quite extraordinary that these two studies agree (at least for the winter transport). It is also quite intriguing to note that seasonal transports between the Taiwan and Luzon Straits are 180° out of phase. The inflow through the Luzon Strait is at a maximum in winter when the outflow through the Taiwan Strait is at a minimum.

According to Isobe (1999), the Taiwan Strait transport remains relatively constant, at 2 Sv. His conclusion (small amplitude) obviously is different from ours. There are two potential sources of error in his calculation. His Taiwan Strait transport was derived indirectly from the transport through the T/K Strait. However, the two Straits may not be directly coupled. Alternatively, his T/K Strait transport values are bias. Recently, the moored ADCP measurements in the T/K Strait found a summer transport of 2.9 Sv (Jacobs et al., 2001), which is significantly higher than that estimated by Isobe (1999), but closer to our estimate of 2.7 Sv. There has not yet been any published winter transport measurement for the T/K Strait.

Near the northeast exit of the Taiwan Strait, the standard deviation is comparable with the mean flow (Fig. 3). This indicates that the analysis result appears to be contaminated by the tidal current. It remains a challenge to obtain transport measurements near the northern exit, especially in winter season extreme sea states. Also in this study, most data that are used in deriving the empirical relation are from the summer season (Fig. 5). To improve the empirical formula, more winter data are needed. The meaning of the empirical relation, on the other hand, is not clear. Since a northward transport of 2.4 Sv is present in the absence of wind, an up-channel sea surface slope is required. Whether this surface slope is maintained by the adjustment of the ECS and SCS to the large-scale monsoon forcing, or whether it is a consequence of the intrusion of the Kuroshio onto the SCS, needs to be tested.

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