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Deepwater overflow observed by three bottom-anchored moorings in the Bashi Channel

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ABSTRACT

Three moorings equipped with 10 current meters and 7 CTDs were deployed in the Bashi Channel, the main deep connection between the northwestern Pacific Ocean and the South China Sea, from August 2010 to April 2011 to investigate the deepwater overflow of the North Pacific Deep Water through it. Results from these observations provide, for the first time, valuable information on the spatial structure of the deep current and allow us to estimate the overflow transport with greater accuracy. The observed current is coherent both vertically and horizontally but exhibits a much stronger velocity in the central area compared to near the edges of the channel. The core of the overflow is found near 2600 m, with mean velocity, potential temperature, and salinity of 22.5 cm s^{-1}, 1.79 °C, and 34.64 psu, respectively. The current is approximately geostrophic, with isopycnals sloping upward to the right-hand side of the flow. The local Froude number is found much less than 1, implying that the deep flow in the Bashi Channel could not be hydraulically controlled. The observations yield an 8-month mean transport of 0.78 Sv with an rms error of 0.18 Sv. The transport time series exhibits significant intraseasonal variabilities, including variability on time scale close to the resonance period of the deep channel in the Luzon Strait (~30 days). Higher transports are connected with a higher velocity and a thicker overflow layer, allowing colder and saltier (thus denser) North Pacific Deep Water to flow into the South China Sea.
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1. Introduction

The South China Sea (SCS), with an area of approximately 3.5×10^6 km^2 and a depth exceeding 4000 m in the central basin, is the largest marginal sea in the Southeast Asian Waters (Wyrtki, 1961). Connections between the SCS and the surrounding waters are mostly shallow: the Taiwan Strait to the East China Sea in the north, the Karimata Strait to the Java Sea in the south, and the Mindoro Strait to the Sulu Sea in the southeast. The 355 km wide Luzon Strait between the Taiwan and Luzon island (Fig. 1), with a sill depth of ~2400 m, is the only deep connection between the SCS and the surrounding waters. Through a deepwater overflow driven by the baroclinic pressure gradient between the Pacific Ocean and the SCS in the Luzon Strait, the North Pacific Deep Water (NPDW) spills into the SCS and generates a basin-scale cyclonic deep circulation (Qu et al., 2006a; Wang et al., 2011; Lan et al., 2013; Shu et al., 2014). The deep water in the SCS interior then upwells as a result of enhanced mixing (~10^{-3} m^2 s^{-1}, Tian et al., 2009), eventually exiting the SCS either in the intermediate layer through the Luzon Strait back to the Pacific Ocean (Chao et al., 1996; Chen and Huang, 1996; Qu et al., 2000; Tian et al., 2006; Zhang et al., 2015) or in the upper layer through shallow straits to the Java and Sulu Seas (Qu et al., 2009; Yaremchuk et al., 2009). This three-dimensional circulation constitutes a portion of the SCS throughflow and acts as a heat and freshwater conveyor that is believed to impact climate, both regionally and globally (Qu et al. 2006b).

A number of studies using different approaches have estimated the magnitude of the deepwater overflow through the Luzon Strait into the SCS (Tian and Qu, 2012). Indirect estimates on the basis of one-dimensional advective-diffusive heat balance (Wang, 1986) and hydraulic theory (Qu et al., 2006a) yielded a transport of 0.7 and 2.5 Sv, respectively; note the latter number represents the maximum hydraulically controlled transport through a rectangular channel narrower than the Rossby Radius (Whitehead, 1998). Later ship surveys of the current and hydrographic fields yielded estimates with a smaller range of 1 to 2 Sv (Tian et al., 2006; Yang et al., 2010; 2011). Based on repeated conductivity-temperature-depth (CTD) and lowered acoustic Doppler current profiler (LADCP) surveys, Zhao et al. (2014) yielded a transport of 1.4 Sv in the Luzon Strait and 1.1 Sv in the Bashi Channel. Direct estimates

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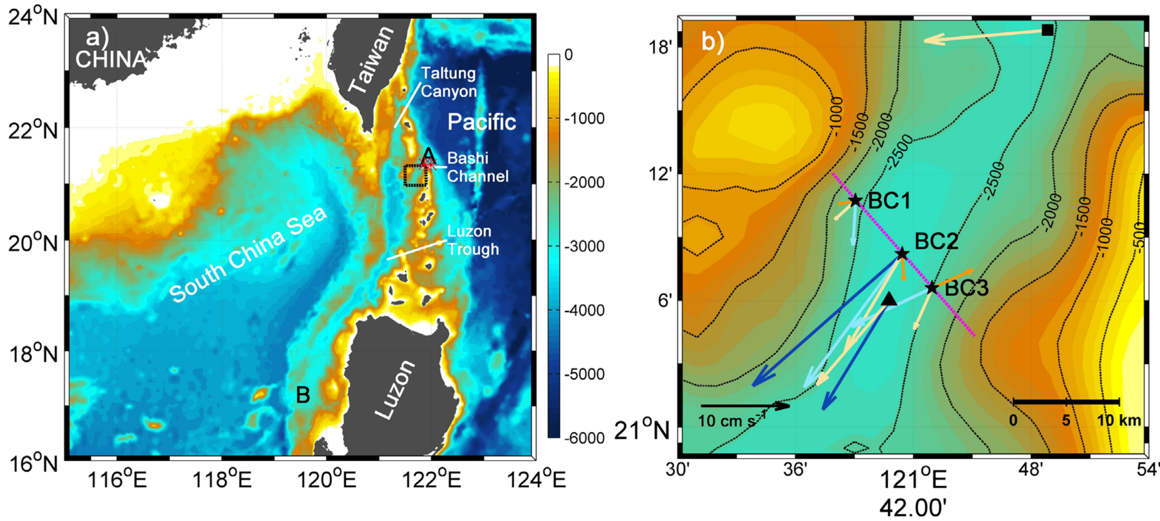

Fig. 1. Bottom topography in (a) the northeast part of the South China Sea and (b) the Bashi Channel based on version 15.1 of Smith and Sandwell (1997). Note the Luzon Trough extends approximately from 21°N to 17°N in the deep Luzon Strait. The red asterisks in (a) denote the locations of CTD profiles (used in Fig. 9). The black square, triangle, and stars in (b) denote the mooring locations in Liu and Liu (1988), Chang et al. (2010), and in this paper, respectively, with arrows representing the observed mean velocities. The pink dashed line indicates the section shown in Fig. 2. (For interpretation of the reference to color in this figure legend, the reader is reffered to the web version of this article.)

based on moored current meter data have also been made. Liu and Liu (1988) estimated a transport of ~1.2 Sv based on an 82-day current meter record in the Bashi Channel. Chang et al. (2010) estimated a similar mean transport value (1.06 Sv) from two nearly 10-month observation periods, which exhibit significant intraseasonal variations on time scales ranging from 30 to 60 days. The authors also deployed one mooring in the Taltung Canyon (the other channel in the Luzon Strait that is deeper than 2000 m, see Fig. 1) at the same time and found very weak mean flow there, confirming that the majority of the deep water enters the SCS through the Bashi Channel. More recently, Zhou et al. (2014) estimated a mean transport of 0.83 Sv in the Bashi Channel and 0.88 Sv further downstream in the Luzon Trough (which includes contribution from the Taltung Canyon) from a 3.5-year long mooring deployed at each location. Their transport time series also exhibited a significant seasonal variability (with a higher/lower transport in the late fall/spring, respectively), corresponding well with the seasonal variation of the density difference between the SCS and the Pacific Ocean close to the sill depth.

It is important to recognize that, although the transport values are generally comparable between Chang et al. (2010) and Zhou et al. (2014), there is one notable difference. With only a single mooring available, one has to make an inevitable assumption on the spatial, especially horizontal, structure of the flow. Chang et al. (2010) assumed a two-layer flow (separated by the mid-depth between the two instruments) that is homogenous horizontally across the channel, whereas Zhou et al. (2014) interpolated the velocity in cubic spline by assuming zero velocity at the two sidewalls. Although the channel is narrower than the Rossby Radius (~20 km), one wonders if the deepwater overflow exhibits a significant spatial structure that impacts the transport estimates. Also, although hydraulic theory has been previously used to estimate the upper limit of the transport (Qu et al., 2006a; Zhao et al., 2014), it remains unknown whether the flow is actually hydraulically controlled. To address these questions, two additional moorings were deployed in the Bashi Channel on both sides of the central mooring used by Zhou et al. (2014) from August 2010 to April 2011. Results from all three moorings are discussed in this paper. We found that.

a) The deepwater overflow exhibits a much stronger current in the middle than near the sides of the Bashi Channel. The isotherms, isohalines and isopycnals all bank upward to the right-hand side of the flow. The 8-month averaged transport is 0.78 Sv based on the three moorings (10 current meters) with an estimate of the total rms error of 0.18 Sv.
b) The Froude number at the Bashi Channel is much less than 1 and the signals propagate against the main stream of the overflow, both implying that the deep flow in the Bashi Channel could not be hydraulically controlled.
c) The overflow transport exhibits significant intraseasonal variabilities on a near 30 days time scale, which is close to the resonance period of the deep channel in the Luzon Strait. The higher transport is associated with a high velocity as well as an upward displacement of the upper interface of the overflow, allowing slightly colder, saltier (thus denser) NPDW to flow into the SCS.

2. Data

As part of the SCS deep circulation experiment, three bottom-anchored moorings were deployed in the Bashi Channel from August 2010 to April 2011 (see Fig. 1 for locations). 10 Aanderaa Instruments RCM Seaguard current meters and 7 SBE 37-SM CTDs were used to measure the current and hydrographic characteristics of the deepwater overflow (see Table 1 and Fig. 2 for the detailed instrument configurations). The instruments covered the entire depth below 2000 m, which is estimated to be the upper limit of the overflow based on the results from Zhao et al. (2014). With multiple deployments during a 3.5-year period, the central mooring BC2 collected significantly more data and the results have been discussed in Zhou et al. (2014). Only the data collected from August 2010 to April 2011 are used for the present study. All but one of the instruments (the CTD at 2406 m on BC2) returned high-quality data at hourly sampling intervals. As stated by the manufacturers, the measurement accuracies are: ~0.15 cm s^{-1} for velocity, 0.002 °C for temperature, 0.003 mS cm^{-1} for conductivity, and 0.1% of full scale range for pressure (or ~7 m for the CTDs). The vertical excursion of the instruments is relatively small as well

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