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Deep water characteristics and circulation in the South China Sea

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the deep circulation in the South China Sea (SCS) using oceanographic observations combined with results from a bottom layer reduced gravity model. The SCS water, 2000 m below the surface, is quite different from that in the adjacent Pacific Ocean, and it is characterized by its low dissolved oxygen (DO), high temperature and low salinity. The horizontal distribution of deep water properties indicates a basin-scale cyclonic circulation driven by the Luzon overflow. The results of the bottom layer reduced gravity model are consistent with the existence of the cyclonic circulation in the deep SCS. The circulation is stronger at the northern/western boundary. After overflowing the sill of the Luzon Strait, the deep water moves broadly southwestward, constrained by the 3500 m isobath. The broadening of the southward flow is induced by the downwelling velocity in the interior of the deep basin. The main deep circulation bifurcates into two branches after the Zhongsha Islands. The southward branch continues flowing along the 3500 m isobath, and the eastward branch forms the sub-basin scale cyclonic circulation around the seamounts in the central deep SCS. The returning flow along the east boundary is fairly weak. The numerical experiments of the bottom layer reduced gravity model reveal the important roles of topography, bottom friction, and the upwelling/downwelling pattern in controlling the spatial structure, particularly the strong, deep western boundary current.

1. Introduction

The South China Sea (SCS) is the largest deep marginal sea in the waters of southeastern Asia and plays an important role in connecting the tropical Pacific with the Indian Ocean (Wyrtki, 1961; Nitani, 1972; Qu et al., 2005; Qu et al., 2009). The circulation of the SCS is closely linked to changes in global climate, energy balance, and the uptake of anthropogenic CO_2. A recent review suggests that deep circulation is one of the key research directions of ocean dynamics in the SCS (Huang and Du, 2015). The maximum depth of the SCS basin is approximately 4700 m within a bowl-shaped trench (Fig. 1; Chu and Li, 2000). Below the deepest sill of 2400 m in the Luzon Strait (LS; Qu et al., 2006), the SCS is a completely isolated basin. Over the range of 2000–2400 m, the SCS is connected to the Pacific through two channels: the Taltung Canyon and the Bashi Channel (Fig. 1b). The Bashi Channel is the main deep connection between the Pacific and the SCS (Chang et al., 2010). On the other hand, the Taltung Canyon in the north is very restricted below 2000 m and thus is not a major deep exchange conduit.

Water properties in the deep SCS is relatively homogenous and is very similar to that of the Pacific at depths around 2000 m (Nitani, 1972; Gong et al., 1992; He and Guan, 1984). Below 2000 m, water in the Pacific becomes denser than that in the SCS, providing a persistent, baroclinic pressure gradient across the Luzon Strait (Liu and Liu, 1988; Qu et al., 2006; Tian et al., 2009). This pressure gradient drives flow from the Pacific into the SCS, i.e. the deep water overflow. Assuming a simple advective-diffusive heat balance, Wang (1986) estimated the deep water overflow transport through the LS below 1500 m to be 0.7 Sv. Field measurements estimate the volume transport in the deep ($>$ 1500 m) layer to be 2 Sv (Tian et al., 2006). Similarly, during the observation period in late August 2008, Yang et al. (2011) estimated approximately 1.9 Sv of overflow transport entering the SCS below 1740 m depth. Chang et al. (2010) observed the transport of Bashi Channel below 2000 m was 1.06 $\pm$ 0.44 Sv. With current meter moorings' 3.5 yr measurements, Zhou et al. (2014) estimated the deep water overflow of 0.83 $\pm$ 0.46 Sv below about 2000 m at the Bashi Channel. Combining observations with numerical experiments, Zhao et al. (2014) estimated the Luzon Strait overflow transport to be below the 36.82 kg/m^3 isopycnal surface at approximately 1.5 Sv. More recently, Zhao et al. (2016) observed the averaged transport is 0.78 Sv based on three moorings. With very weak mean flow of ~0.05 Sv

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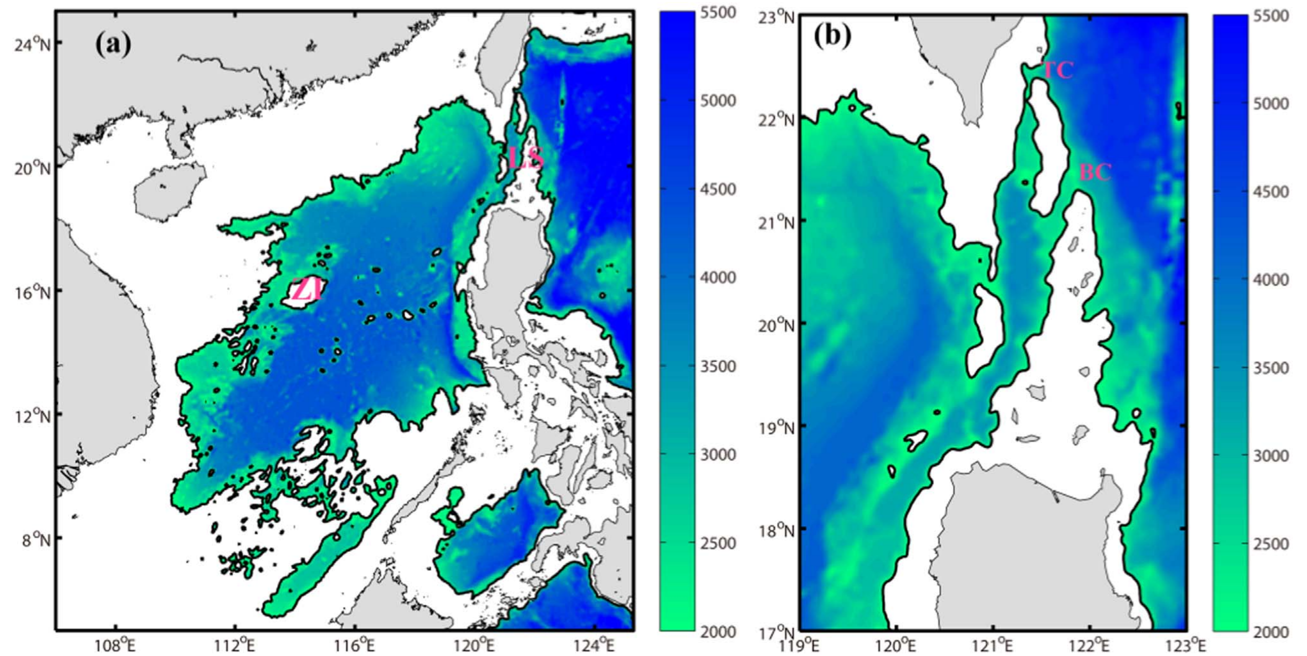

Fig. 1. The bottom topography of (a) the South China Sea and (b) the Luzon Strait. The thick solid black lines indicate the 2000 m isobath. The ZI and LS represent the Zhongsha Islands and the Luzon Strait in (a). The TC and BC represent the Taltung Canyon and the Bashi Channel in (b).

through the TC, the majority of the deep water enters the SCS through the BC (0.83 Sv) (Zhou et al., 2014). Thus, there is approximately 0.7–2 Sv of Luzon Strait overflow entering the SCS.

Once crossing the LS, the deep water in the SCS joins a basin-scale cyclonic deep circulation (Qu et al., 2006; Wang et al., 2011). A few studies using different approaches have analyzed the deep circulation in the SCS. Yuan (2002) found that the basin circulation of the SCS is cyclonic in the abyss based on the GFDL MOM and the model is driven by specified Philippine Sea currents and by surface heat and salt flux conditions. With potential density, potential vorticity (PV), dissolved oxygen, and sediment distributions, the deep circulation at depths below 2000 m reveal a basin-scale cyclonic circulation (Li and Qu, 2006; Qu et al., 2006; Wang et al., 2011). Lan et al. (2013) gave a good description of the SCS deep circulation using the Hybrid Coordinate Ocean Model. The results reveal the deep circulation is basin-scale cyclonic and is controlled by the Luzon Strait overflow. Lan et al. (2015) examined the deep circulation seasonal variability that it is strong in summer season and weak in winter.

Along its path, the overflow water gradually mixes with the ambient water and upwelling occurs to compensate the surface buoyancy flux (Nitani, 1972; Qu and Lindstrom, 2004; Lüdmann et al., 2005). Diapycnal mixing is non-uniform in the basin and thus the strength of upwelling is regionally dependent. The diapycnal mixing increases from approximately $10^{-3} m^2 s^{-1}$, at 1000 m depth, to $10^{-3} \sim 10^{-2}$ $m^2 s^{-1}$ near the seafloor in the northern SCS (Tian et al., 2009). In comparison, it is only 10^{-5} $m^2 s^{-1}$ in the open ocean in Pacific (Tian et al., 2009). Field observations and model results indicate that the diapycnal mixing is enhanced near the rough topography, such as steep slopes and abrupt ridges (Ledwell et al., 2000; Wang et al., 2016). Enhanced diapycnal mixing, from strong turbulence generated by the dissipation of internal tides (Tian et al., 2009), drives the LS overflow as well as the cyclonic circulation and controls the residence time of the deep water in the deep SCS (Tian et al., 2009; Wang et al., 2017). Nevertheless, some important issues regarding the impact of the sense and pattern of the diapycnal mixing on the deep circulation features in the SCS remain open to discussion.

Due to the complicated bottom topography and lack of observations, exploring deep water properties and its dynamics in the SCS remains a challenge, especially the dynamical mechanism of the deep circulation remains poorly understood. In this study, we attempt to describe the deep water properties and to investigate the deep circulation in the SCS with historical measurements and a bottom layer reduced gravity model. Sensitivity experiments are designed to focus on the influence of topography, upwelling and friction dissipation on the deep circulation. The remainder of the paper is organized as follows. The historical measurements and the bottom layer reduced gravity model are described in Section 2. Then, the SCS deep water properties are discussed in Section 3. Section 4 presents the model experiments and analyses the results. The role of the topography, upwelling and friction dissipation in the pattern of the deep circulation is examined. A brief summary and discussion are given in Section 5.

2. Data and numerical ocean model

2.1. Data

This study uses all dissolved oxygen concentration (DOC) profiles at the standard levels from the World Ocean Database 2013 (WOD13). The DOC data are organized by year and stored in 5 data sets. Each data set represents a group of similar oceanographic instruments: Ocean Station Data (OSD); Profiling Float (PFL); Undulating Oceanographic Recorder (UOR); Drifting Buoy (DRB); and High-resolution Conductivity-Temperature-Depth (CTD). More information can be found at http://www.nodc.noaa.gov/OC5/WOD/. We first eliminated the profiles that were flagged as “bad” or did not pass the monthly, seasonal, and annual standard deviation checks, as well as the profiles shallower than 2000 m. In addition, we removed the profiles with obviously erroneous records, including those with a vertical DOC difference between two continuous standard levels larger than 0.8 ml L^{-1}. The final data set for this study consist of 37 oxygen profiles in the SCS below 2000 m depth.

2.2. Bottom layer reduced gravity model

For the circulation in the deep basin, flow near the bottom is much faster than flow above, so we assume that the pressure gradient in the water above can be neglected. Thus a 1.5 layer, reduced gravity model can be formulated, as represented in Fig. 2. Such a simplified theory