On the dynamics of the South China Sea deep circulation

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[1] In the South China Sea (SCS), the deep water is confined to a bowel-type trench, and the maximum depth is approximately 4700 m. The Luzon Strait is the only deep connection between the SCS and the Pacific Ocean, with the deepest sill at about 2400 m in the Bashi Channel. Using the Hybrid Coordinate Ocean Model, this study gives a good description of the SCS deep circulation. The most obvious features are basin-scale cyclonic gyre and western intensification. The gyre is elliptical shaped, and its major axis is northeast-southwest. A numerical experiment is designed to investigate what could be possibly responsible for the SCS deep circulation. The results reveal that the deepwater overflow through the Luzon Strait controls over the basin-scale circulation structure in the deep SCS basin. The driving mechanism is elucidated based on the potential vorticity (PV) integral constraint, which means the PV inflow across the boundary is balanced by the net PV dissipation along the boundary.


1. Introduction

[2] The South China Sea (SCS) is a large marginal sea with a total area of 3.5 × 10^5 km^2 and an average depth of over 2000 m, located to the southwest of the North Pacific Ocean (Figure 1). The deepest water is confined to a bowel-type trench, and the maximum depth is approximately 4700 m [Chu and Li, 2000]. The SCS is a partly enclosed ocean basin surrounded by Asian landmass to the north and the west, Philippine Islands to the east, and Kalimantan to the south, with connections to the surrounding oceans through straits [Chu et al., 1999; Fang et al., 2009]. The Luzon Strait between Taiwan Island and Luzon Island is the only deep connection between the SCS and the Pacific Ocean, with the deepest sill at about 2400 m in the Bashi Channel [Qu et al., 2006]. Below the sill, the SCS is a completely isolated basin with no direct water exchange to the surrounding oceans.

[3] Since Wyrski [1961] provided the first picture of the SCS upper layer circulation based on early hydrographic observations, sea level records, and ship drifts, great efforts have been devoted to the study. Corresponding to the winter and summer monsoon, the basin-scale upper layer circulation in the SCS exhibits a dramatic seasonal variability, e.g., generally, cyclonic in the winter, reversing to largely anticyclonic in the summer [Wyrski, 1961; Chu et al., 1999; Shaw and Fu, 1999; Chu and Li, 2000; Qu, 2000; Liu et al., 2001; Yue et al., 2004; Fang et al., 2009].

[4] Though investigations on the SCS upper layer circulation have been made previously, the present study will focus on the SCS deep circulation. Fewer studies reported the deep circulation. The analysis of water property distributions in the deep South China Sea reveals a basin-scale cyclonic circulation at depths below 2000 m, which allows Pacific characteristics to spread southwestward along the continental margin off southeast China and east Vietnam before being mixed away in the basin interior. The distributions of potential density, potential vorticity (PV), dissolved oxygen, and sediment distributions in the deep SCS are consistent with the existence of the cyclonic circulation [Li and Qu, 2006; Qu et al., 2006; Wang et al., 2011]. Li and Qu [2006] proposed a four-cell conceptual model for the SCS thermohaline circulation, which consists of an abyssal replenishment cell in the deep and a cyclonic recirculation cell in the interior basin. Based on an updated monthly climatology of observed temperature and salinity from the U.S. Navy Generalized Digital Environment Model, Wang et al. [2011] provided the quantitative description of the deep SCS circulation and its concomitant boundary current system. The boundary current transport of the cyclonic circulation is around 3.0 Sv.

[5] In this paper, the SCS deep circulation is simulated by an OGCM (Ocean Circulation General Model), and its pattern is examined in detail. Numerical experiment is designed to investigate what could be possibly responsible for the SCS deep circulation. Our numerical results show that the SCS deep circulation is cyclonic. The mechanism is elucidated based on the potential vorticity integral constraint. The rest of the paper is organized as follows. The OGCM and the numerical experiment are introduced in section 2. The climatology of the SCS deep circulation is described in section 3. The results of the numerical experiment are analyzed in section 4. The driving mechanism of cyclonic deep circulation is discussed in section 5. A brief summary will be given in section 6.
2. Numerical Ocean Model

The OGCM used in this study is the Hybrid Coordinate Ocean Model (HYCOM). This is a primitive equation ocean general circulation model. It has a hybrid vertical coordinate that is isopycnal in the open, stratified ocean; a terrain-following coordinate in shallow coastal regions; and z coordinate in the mixed layer and unstratified seas [Bleck, 2002].

The model domain is from 78°S to 66°N and from 180°W to 180°E, covering the global ocean except Arctic Ocean. The model has a horizontal resolution of 0.5° × 0.5 cosθ (θ denotes latitude) and 33 levels in vertical with a finer resolution in the upper ocean. The bottom topography is obtained from the ETOPO5 with a 5 min resolution. Nonslip conditions are applied along continental boundaries. The K-profile parameterization is used for the vertical mixing scheme [Large et al., 1994, 1997]. The wind forcing, the net shortwave and longwave radiation, precipitation, air relative humidity, and air temperature fields used to force the model are from the monthly National Centers for Environmental Prediction/National Center for Atmospheric Research climatology.

For our control run, the HYCOM is integrated for 50 years with all three components of velocity initially to zero and with temperature and salinity specified by Levitus annual mean climatology. The sensitivity run uses the same equations and forcings as the control run but closes the Luzon Strait to prevent deepwater overflow.

3. Climatology of SCS Deep Circulations

The control run gives a good description of the SCS surface circulation on annual mean (Figure 2) in reasonable agreement with the previous studies [Wyrtki, 1961; Chu et al., 1999; Shaw and Fu, 1999; Chu and Li, 2000; Qu, 2000; Liu et al., 2001; Xue et al., 2004; Fang et al., 2009]. During the winter monsoon period, the northeasterly wind is stronger with a maximum wind stress of nearly 0.3 N m⁻². During the summer monsoon period, the southwesterly wind is weaker with a wind stress of over 0.1 N m⁻² [Chu et al., 1999]. On the annual mean, the field of wind stress over SCS is similar to the field during the winter monsoon period. Thus, the major feature of the SCS surface circulation pattern on the annual mean is prominently cyclonic, similar to that in the winter. The western boundary current (WBC) flows southward along the Vietnam coast. The Natuna eddy, which locates at 5°N, 110°E, is another major feature. The results show that our model is capable of realistic simulations in the SCS circulations.

Figure 1. Geography and isobaths showing the bathymetry (m) of the South China Sea.

Figure 2. Annual mean surface circulation for control run (Luzon Strait open).

Figure 3. Annual mean velocity vector fields for control run (Luzon Strait open), vertically averaged from 2000 m to the bottom. The gray shading indicates water depths shallower than 2000 m.
to the bottom. The most obvious features are basin-scale cyclonic gyre and western intensification, consistent with earlier descriptions [Li and Qu, 2006; Qu et al., 2006; Wang et al., 2011]. The gyre is elliptical shaped, and its major axis is northeast-southwest. A current, originating from the west of the Luzon Strait, flows westward in the northern SCS basin to the Asian continental margins. The current is strong and follows closely the Asian continental margins southwestward. Thus, the western boundary current (WBC) is formed. The strong and narrow WBC flows across the narrow passage between the Xisha Islands and the Zhongsha Islands into the southern SCS basin, and a very weak southwestward branch exists in the east of the Zhongsha Islands. The maximum speed of the WBC is found around 1.0 cm/s.

[11] The current continues to move into the southern end of the SCS basin and then turns northeastward through the interior basin and along continental margins. The current becomes broad and weak. South of 15°N, the current bifurcates into two branches. One branch turns northward and rejoins the westward current in the northern SCS basin. Another branch turns eastward and moves to the western coast of the Philippine Islands. Thus, a cyclonic gyre is formed.

[12] Wang et al. [2011] also reported the deep cyclonic gyre, calculated from hydrographic data using the thermal wind relation. Their studies show that the cyclonic gyre is confined in the northern and interior basin and does not extend to the southwestern basin, where there seems to exist a separate weak cyclonic gyre. This feature is somewhat different from our result that the deep cyclonic gyre almost occupies the whole deep basin.

4. The Role of Deepwater Overflow Through the Luzon Strait

[13] As in early descriptions, the SCS is a completely isolated basin under 2400 m with no direct water exchange to the surrounding oceans [Qu et al., 2006]. However, its deep water appears to have the same characteristics as the Pacific water at about 2000 m [Naitani, 1972; Broecker et al., 1986; Qu, 2002]. This has been interpreted as evidence for the existence of a deepwater overflow from the Pacific passing over the Luzon Strait into the deep SCS. The modeled meridional overturning structure with an opening of the northern SCS supports the sinking of the Pacific water through the Luzon Strait [Wang et al., 2004; Liu et al., 2008]. On the basis of the comparison of density profiles on both sides of the Luzon Strait, Qu et al. [2006] revealed that, below 1489 m, water in the Pacific becomes denser than that in the SCS, providing a baroclinic pressure gradient driving the deepwater overflow into the SCS.

[14] Based on our numerical simulation (control run), the zonal volume transport along 121°E through the Luzon Strait is estimated (Table 1). On the annual mean, the net volume transport is 1.76 Sv (negative) in the upper layer (<500 m). The negative value indicates westward transport, which means that water flows into the SCS. From 500 to 1500 m, the net volume transport is eastward with the value of 1.40 Sv (positive), and the water flows out of the SCS. In the deep layer (1500–2500 m), the net volume transport is westward, the same direction as the upper layer. The value is around 1.70 Sv, which represents the deepwater overflow transport through the Luzon Strait. Our numerical simulation shows that Luzon Strait transport (LST) is characterized as an alternant direction. This confirms the hypothesis that the LST has a sandwiched vertical structure [Wang, 1986; Liu and Liu, 1988; Qu et al., 2006; Tian et al., 2006].

[15] Several papers have done research work on the estimation of deepwater overflow transport based on different observations and model results. In order to establish a stable thermocline, Wang [1986] argued that about 0.7 Sv of cold water must upwell from below (>1500 m). This provided a quantitative, albeit indirect, transport estimate of the deepwater overflow through the Luzon Strait into the South China Sea. From a single 82 day current meter time series near the bottom of the Bashi Channel, Liu and Liu [1988] derived an upward transport of 1.2 Sv. Using collected current and hydrographic data, Tian et al. [2006] provided a high-resolution picture of the subinertial flow and estimated the volume transport through the Luzon Strait. The net westward volume transport in the deep (>1500 m) layer of the Luzon Strait reaches 2.0 Sv. Applying hydraulic theory with assumptions of zero potential vorticity and flat bottom to the Luzon Strait yields a deepwater overflow transport estimate of 2.5 Sv, based on all available hydrographic data [Qu et al., 2006]. Our estimation of the deepwater overflow transport (1.7 Sv) is comparable with these previous estimations.

[16] Water properties in the deep South China Sea are heavily influenced by the deepwater overflow through the Luzon Strait [Qu et al., 2006]. Along the continental margin off southeast China, water has an elevated oxygen level, confirming its Pacific sources. Oxygen concentration drops southeastward, approaching its minimum around the southeastern corner of the basin [Qu, 2002]. Another important evidence of the intrusion comes from sediment measurements. This sediment distribution is most likely a direct consequence of deepwater overflow from the Pacific [Lüdmann et al., 2005; Kienast et al., 2005]. The result of Wang et al. [2011] shows that the boundary current transport of the SCS deep circulation is around 3.0 Sv, which is fairly close to the estimate (2.5 Sv) of the Luzon deepwater overflow [Qu et al., 2006]. These facts support the speculation that the deepwater overflow may provide a source for the basin-scale SCS deep cyclonic gyre.

[17] In order to explore the impact of deepwater overflow on the SCS deep circulation, a numerical experiment (sensitivity run) is designed by closing the Luzon Strait. This means deepwater overflow from the Pacific into SCS via the Luzon Strait is removed in the sensitivity run. The SCS deep circulations vertically averaged from 2000 m to the bottom (Figure 4) for the sensitivity run illustrate a prominent difference in structure from the control run results (Figure 3). With no deepwater overflow, the deep cyclonic gyre disappears, and the deep circulation pattern seems anticyclonic. The difference between sensitivity and control runs reveals that the deepwater overflow through the Luzon Strait controls over the basin-scale circulation structure in the deep SCS basin.

Table 1. Volume Transports at Different Depth Ranges of the Luzon Straita

<table>
<thead>
<tr>
<th>Depth Range</th>
<th>Net Volume Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;500 m</td>
<td>-1.76</td>
</tr>
<tr>
<td>500–1500 m</td>
<td>1.40</td>
</tr>
<tr>
<td>1500–2500 m</td>
<td>-1.70</td>
</tr>
<tr>
<td>Whole Depth</td>
<td>-2.06</td>
</tr>
</tbody>
</table>

aUnits are Sv. Positive values indicate eastward transport.
5. Driving Mechanism

[18] In the upper layer, the ocean circulation is forced primarily by surface wind stress. Below the thermocline layer, the circulation can be driven primarily by other processes, such as lateral inflows and outflows, and is not forced directly by wind stress [Yang, 2005]. The results from the two experiments (control and sensitivity runs) show that the deepwater overflow (lateral inflow) through the Luzon Strait provides a source for the basin-scale SCS deep cyclonic gyre. The dynamic process in the formation of the SCS deep cyclonic gyre is related to the potential vorticity (PV) flux by the deepwater overflow.

[19] As shown in Yang and Price [2000] and Yang [2005], the area integral of the PV equation in the form of line integral along the side boundary C

\[
\oint \nabla \cdot \mathbf{u} + \nabla \cdot \mathbf{F} \int_{-C} \mathbf{D} \cdot ds + \oint \oint \mathbf{n} \cdot \mathbf{F} \cdot ds = 0
\]

where \( \mathbf{n} \) and \( \mathbf{l} \) are the unit vectors perpendicular and parallel to the lateral boundary \( C \), respectively; \( \mathbf{H} \) is the layer thickness; \( \mathbf{U} = H \mathbf{u} \) is the transport velocity vector; \( \mathbf{u} \) is the horizontal velocity vector; \( f \) is the Coriolis parameter; \( \mathbf{u} = \mathbf{v} - \mathbf{w} \) is the relative vorticity; \( \mathbf{D} \) is the PV dissipation term; and \( \mathbf{F} \) is the surface stress.

[20] In the SCS deep basin, the left term in equation (1) denotes PV transport by the deepwater overflow through the Luzon Strait. In practice, the relative vorticity \( \mathbf{u} \) is usually much smaller than \( f \), so the transport of PV would be dominated by the planetary one [Yang, 2005]. In this case, the PV transport can be simplified to

\[
\oint \frac{Q_{\text{Luzon}}}{H_{\text{Luzon}}} \int_{-C} ds = \oint \oint \mathbf{n} \cdot \mathbf{F} \cdot ds
\]

where \( Q_{\text{Luzon}} \) is the volume transport of the deepwater overflow through the Luzon Strait, and \( H_{\text{Luzon}} \) is the thickness of the deepwater overflow in the Luzon Strait. According to Qu et al. [2006], the deepwater overflow occupies the range from 1489 m depth to the sill depth (around 2400 m). Below 1489 m, water in the Pacific becomes denser than that in the South China Sea, the deepwater overflow being driven into the South China Sea. Below the sill depth, the SCS is a completely isolated basin with no direct water exchange to the surrounding oceans.

[21] The first term on the right side in equation (1) indicates PV dissipation, which is generated by the frictional process due to the SCS deep circulation. If a Rayleigh friction is applied, the PV dissipation would become

\[
-\lambda \oint \oint \mathbf{F} \cdot ds
\]

where \( \lambda \) is the Rayleigh friction coefficient. In this case, \( C \) is the lateral boundary of the SCS deep basin, and \( \mathbf{u} \) is the basin-scale SCS deep circulation.

[22] There is no wind forcing considered, so the second term on the right side in equation (1) is zero. Thus, equation (1) can be rewritten as

\[
\oint \frac{Q_{\text{Luzon}}}{H_{\text{Luzon}}} \int_{-C} ds = -\lambda \oint \oint \mathbf{F} \cdot ds.
\]

[23] Equation (4) is the PV integral constraint, which indicates that the PV integral over the whole basin yields a balance between the net lateral PV inflow and the PV dissipation by the Rayleigh friction. For the semienclosed SCS deep basin, when there is a positive PV transport into the basin by the deepwater overflow through the Luzon Strait, the SCS deep circulation becomes cyclonic so that friction can generate a flux of negative PV to satisfy the integral balance. Thus, the SCS deep cyclonic gyre over the whole deep basin is developed.

6. Conclusion and Discussion

[24] The goal of this study is to investigate the general pattern of the SCS deep circulation and explore its driving mechanism. On the basis of the Hybrid Coordinate Ocean Model (HYCOM), the SCS deep circulation is well presented. The most obvious features are basin-scale cyclonic gyre and western intensification, consistent with earlier descriptions [Li and Qu, 2006; Qu et al., 2006; Wang et al., 2011]. The gyre is elliptical shaped, and its major axis is northeast-southwest. The studies of Wang et al. [2011] show that the cyclonic gyre is confined in the northern and interior basin and does not extend to the southwestern basin, where there seems to exist a separate weak cyclonic gyre. This feature is somewhat different from our result that the deep cyclonic gyre almost occupies the whole deep basin.

[25] Based on the results of our numerical simulation, the deepwater overflow transport through the Luzon Strait is calculated. The flow is westward with the maximum speed exceeding 4.5 cm/s. The estimate of the annual mean deepwater overflow transport is around 1.7 Sv, comparable with the values of previous estimation based on different observations and model results. A numerical experiment is designed by closing the Luzon Strait to explore the impact of deepwater overflow transport on the SCS deep circulation.
overflow on the SCS deep circulation. The results reveal that the deepwater overflow through the Luzon Strait controls over the basin-scale circulation structure in the deep SCS basin.

[26] The dynamic process in the formation of the SCS deep cyclonic gyre is elucidated based on the potential vorticity (PV) integral constraint, which means the PV inflow across the boundary is balanced by the net PV dissipation along the boundary. For the semiclosed SCS deep basin, when there is a positive PV transport into the basin by the deepwater overflow through the Luzon Strait, the SCS deep circulation becomes cyclonic so that friction can generate a flux of negative PV to satisfy the integral balance.

[27] Our numerical simulations need improved due to the coarse grid resolution. A perfect simulation of the SCS deep circulation, the Luzon Strait transport, and its vertical distribution depends on the fine vertical and horizontal grid resolution, bathymetry precision, and correct value of the turbulence mixing coefficient. Some numerical experiments have proved that the sandwiched vertical structure is very sensitive to the SCS mixing coefficient. [28] Our numerical experiment need improved also.

Closing the Luzon Strait means that the deepwater overflow from the Pacific into the South China Sea is removed. At the same time, it also removes the water exchange in the upper and intermediate layers. Our numerical simulation cannot clarify that the differences between control and sensitivity runs are due to the removal of deepwater overflow and not due to the removal of upper and intermediate layer exchange. In general, the crossing-isopycnal-surface impact of water exchange is weaker, especially with the existence of thermocline. However, a more complicated numerical experiment should be designed to clarify this issue.

[29] Our numerical simulation (control run) shows that the SCS deep circulation is prominently cyclonic on the annual mean (Figure 3) with slightly seasonal variability (figure not shown). The wind-driven upper layer circulation in the SCS is also cyclonic on the annual mean with strong seasonal variability [Wyrtki, 1961; Chu et al., 1999; Shaw and Fu, 1999; Chu and Li, 2000; Qu, 2000; Liu et al., 2001; Xue et al., 2004; Fang et al., 2009]. Although the deepwater overflow through the Luzon Strait controls over the SCS deep circulation, the effect of the wind-driven upper layer circulation on the deep circulation should be considered in further studies.

[30] Due to the rough topography in the SCS and the Luzon Strait, tidal dissipation in the deep ocean can be substantially enhanced, and a large amount of barotropic tidal energy is converted into internal tides, internal waves break, and diapycnal mixing enhance [Wang et al., 2012]. The enhanced diapycnal diffusivity in the SCS and the Luzon Strait is elevated by 2 orders of magnitude over that of the smooth bathymetry in the North Pacific, reaching $O(10^{-3} \text{ m}^2 \text{ s}^{-1})$ [Tian et al., 2009]. The diapycnal mixing could be a vital mechanism controlling the density distribution in the SCS and could maintain pressure gradient between the SCS and the adjoining Pacific Ocean. Thus, the overflow through the Luzon Strait is driven from the Pacific Ocean into the SCS. The influence of mixing/tides on the overflow is of high scientific interest and needs further study.

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