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# Layered model and insights into the vertical coupling of the South China Sea circulation in the upper and middle layers

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ABSTRACT

By changing the calculation of the pressure gradient, we convert a 3.5-layer model to a 3-layer model that includes entrainment and detrainment as well as interfacial friction between layers. In comparison with the reanalysis and satellite altimetry data, the model can well reproduce the circulation and reveal the primary dynamics in the South China Sea. We then use the 3-layer model to investigate the vertical coupling of the South China Sea circulation in the upper and middle layers. It is found that the horizontal pressure gradient, which reflects the depth-integrated effect of the thickness variation across all layers, plays a key role in the dynamical link between layers. Perturbations induced by changing the monsoonal wind or the Kuroshio in two comparative experiments are able to excite cyclonically propagating, slope-trapped waves and the westward planetary Rossby waves to modulate the basin wide circulation in all layers, indicating the dynamically similar adjustments throughout the water column in the SCS in both experiments. Even though the interface frictional dissipation and the entrainment/detrainment induced momentum exchange are small, analysis suggests that the exchange velocity between layers, which varies as the waves pass by, contributes considerably to the redistribution of the layer thickness hence the pressure gradient field in each layer to regulate the variability of the SCS circulation.

## 1. Introduction

As the largest marginal sea in the western Pacific Ocean, the South China Sea (SCS) has a deep, semi-enclosed basin surrounded by a steep slope and links to the adjacent seas via several straits (Fig. 1). Dominated by the East Asian monsoon and the Kuroshio intrusion (Xue et al., 2004; Gan et al., 2006; Chen and Xue, 2014; Quan et al., 2016), the SCS not only shows some dynamical similarities with the open oceans (e.g., the westward intensification of the circulation), but also has the unique and complicated dynamics as a regional sea (Gan et al., 2016). Currently, more and more studies suggest that there is a sandwich-like circulation in the SCS, which is cyclonic in the upper and deep layers but anticyclonic in the middle layer (Wang et al., 2011; Shu et al., 2014; Lan et al., 2015; Gan et al., 2016). Closely related to the SCS throughflow, the SCS circulation not only plays a key role in the mass, energy and heat balances in the interior SCS, but also contributes to the fluxes between the Pacific Ocean and the Indian Ocean, which has a significant effect on the regional climate (Qu et al., 2006a, 2009; Gordon et al., 2012; Wei et al., 2016).

Different from the circulation in the open oceans, the SCS circulation shows a prominent seasonality in the pattern and intensity, especially for that in the upper 200 m, which was firstly revealed by Dale (1956) and Wyrtki (1961). To date, there have been many insightful and review studies on the circulation in the upper layer of the SCS, revealing its spatial structures, temporary variations and the corresponding dynamical mechanisms (e.g., Xu et al., 1982; Fang et al., 1998; Hu et al., 2000; Su et al., 2004). The general features of the middle and deep layers have been examined by the numerical models and the diagnoses based on the hydrological data (Wang et al., 2011; Shu et al., 2014; Lan et al., 2015; Gan et al., 2016). However, more investigations are still needed to form a comprehensive understanding of the three-dimensional SCS circulation.

The previous researches tried to explore the role of the vertical motion in linking the wind-driven circulation to the thermohaline circulation, and it was found that the mean upwelling rate below the main thermocline in the open ocean is so weak that it cannot become a

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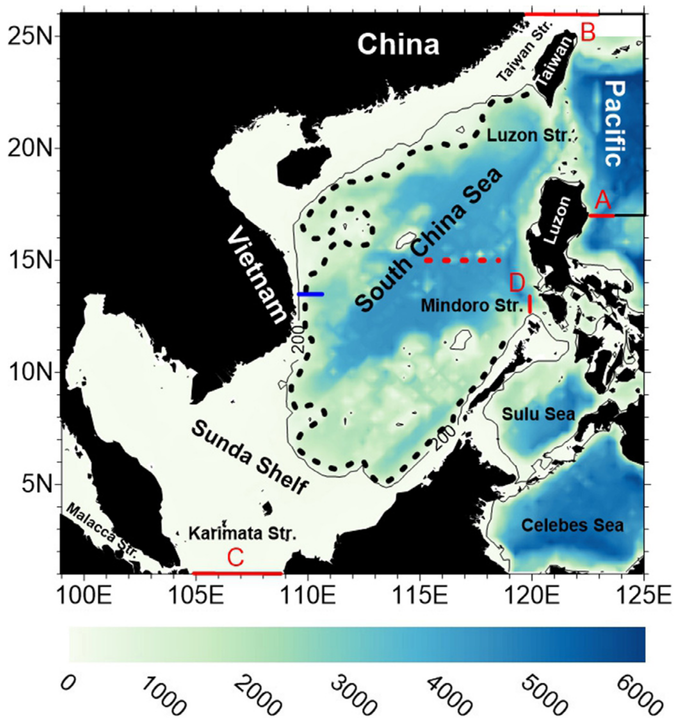


**Fig. 1.** Topography (m) of the South China Sea (SCS). The black solid line is the 200-m isobath. The red solid lines with A, B, C, and D refer to the open boundaries in the model. The blue solid line denotes the transect at 13.5°N, 109.6–110.6°E. The red dashed line represents the transect in the central basin, and the black dashed line is the connection of the model grids along the 1000-m isobath, both of which are used to track the signal propagation in Fig. 17. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

material contributor to the vertical coupling of the two circulations (e.g., Luyten and Stommel, 1986; Hautala and Riser, 1989; Huang, 1993). However, in the SCS, where the mixing is very strong over the rough topography, the mean upwelling rate is found to be on the order of $10^{-6}$ m·s$^{-1}$ (Qu et al., 2006b; Zhu et al., 2016), which is comparable to the magnitude of the Ekman pumping. Therefore, the vortex squashing due to the upwelling from the abyssal SCS may induce an anticyclonic circulation component to significantly affect the wind-driven circulation in the upper layer (Wang et al., 2012). Moreover, Shu et al. (2014) used the HYCOM global reanalysis data GLBa0.08 to show that there are three layers of the meridional overturning cells in the SCS, which appear to link the sandwich-like horizontal circulations in the vertical. Unfortunately, due to the exiguous observations, the detailed process of how the vertical motion could modulate the horizontal circulation is still not well understood. Answering this question will help us advance the dynamical understanding of the SCS circulation and even provide a reference to the dynamics of the multi-layer circulation in other marginal seas and open oceans.

Different from the three-dimensional models, with a simplified framework, the layered models can elucidate the concerned dynamics of the oceans by excluding the impacts from other processes. Therefore, they become very useful tools to study the dynamical mechanism of the SCS circulation (Wang et al., 2006; Cai et al., 2007; Yaremchuk et al., 2009; Yang et al., 2015). Unfortunately, most of the existing layered models for the SCS came short in meeting our goals in this study. For example, the models with all layers active were usually exclusive of the vertical exchange process that occurs in the slope region of the SCS (e.g., Cai et al., 2007; Yang et al., 2015). On the other hand, the models with an infinitely deep layer did not adapt to the variable topography (e.g., Yu et al., 2007; Yaremchuk et al., 2009). To overcome the defects of the two types of models, we modified a 3.5-layer model (McCreary and Kundu, 1988, 1989; McCreay et al., 1993) into a 3-layer one by maintaining its original vertical exchange module but changing the calculation of the pressure gradient to allow the inclusion of the continental slope as well as the shelf circulation in the SCS. Moreover, we also introduced the interface friction into the model to enhance the interactions between layers.

The 3-layer model results suggest that the pressure gradient (PG) is the key factor that transmits the influence from the monsoonal wind and the Kuroshio through the water column. It is also found in two comparative experiments that the perturbations induced by altering the monsoonal wind or the Kuroshio propagate as the cyclonically moving, slope-trapped waves and the westward planetary Rossby waves to modulate the basin-wide circulation. Moreover, the exchange velocity between layers (hereafter EV), which varies as the waves pass by and leads to the redistribution of the thickness in each layer, can affect the PG field to facilitate the vertical coupling.

## 2. Ocean model

In this study, a 3-layer ocean model including entrainment and detrainment as well as the interface friction between layers is modified from the 3.5-layer one by McCreary and Kundu (1988; 1989) and McCreary et al. (1993) to explore the vertical coupling of the SCS circulation.

### 2.1. Model equations

The model consists of three active isopycnal layers and the thermodynamic process was excluded for simplification. The equations of motion are as follows

$$\left(h_1\vec{v}_1\right)_t + \nabla\cdot\left(\vec{v}_1 h_1\vec{v}_1\right) + f\vec{k}\times h_1\vec{v}_1 + h_1 < \nabla P_1 > = \vec{\tau}_{wind} - \vec{\tau}_{12} + \upsilon\nabla^2\left(h_1\vec{v}_1\right) + \vec{v}_2 w_{12}\theta(w_{12}) + \vec{v}_1 w_{12}\theta(-w_{12}), \tag{1}$$

$$\left(h_2\vec{v}_2\right)_t + \nabla\cdot\left(\vec{v}_2 h_2\vec{v}_2\right) + f\vec{k}\times h_2\vec{v}_2 + h_2 < \nabla P_2 > = \vec{\tau}_{12} - \vec{\tau}_{23} + \upsilon\nabla^2\left(h_2\vec{v}_2\right) - \vec{v}_2 w_{12}\theta(w_{12}) - \vec{v}_1 w_{12}\theta(-w_{12}) + \vec{v}_3 w_{23}\theta(w_{23}) + \vec{v}_2 w_{23}\theta(-w_{23}), \tag{2}$$

$$\left(h_3\vec{v}_3\right)_t + \nabla\cdot\left(\vec{v}_3 h_3\vec{v}_3\right) + f\vec{k}\times h_3\vec{v}_3 + h_3 < \nabla P_3 > = \vec{\tau}_{23} - \vec{\tau}_{bottom} + \upsilon\nabla^2\left(h_3\vec{v}_3\right) - \vec{v}_3 w_{23}\theta(w_{23}) - \vec{v}_2 w_{23}\theta(-w_{23}), \tag{3}$$

where $h_i$ and $\vec{v}_i$ are the instantaneous values of the layer thickness and horizontal velocity, respectively, and the subscript $i$ ($i$ = 1, 2, 3) is the layer index, $f$ is the Coriolis parameter varying linearly with the latitude, $\upsilon = 5\times10^3$ m$^2$·s$^{-1}$ is the coefficient of eddy viscosity, $w_{12}$ ($w_{23}$) is the EV between the 1st (2nd) and 2nd (3rd) layers, and θ is the heaviside step function defined as $\theta(x) = 1$ if $x > 0$ and $\theta(x) = 0$ if $x < 0$.

In Eqs. (1)–(3), the terms, from left to right, are the acceleration (ACC), advection (ADV), Coriolis force (COR), pressure gradient (PG), wind stress (WS; only for the 1st layer), interface friction (IF; for the water boundary between layers) or bottom friction (BF; if the layer bottom is sea floor), horizontal diffusion (HD) and entrainment/detrainment-induced momentum exchange between layers (EDIME).

The pressure gradient term in each layer is as follows

$$< \nabla P_1 > = g\nabla\zeta_1, \tag{4}$$

$$< \nabla P_2 > = g\nabla\zeta_1 + g_1'\nabla\zeta_2, \tag{5}$$

$$< \nabla P_3 > = g\nabla\zeta_1 + g_1'\nabla\zeta_2 + g_2'\nabla\zeta_3, \tag{6}$$

where $\zeta_i$ is the surface/interface elevation and is given by the following

$$\zeta_1 = h_1 + h_2 + h_3 + H, \tag{7}$$