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Seasonal features of the Sverdrup circulation in the South China Sea*

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Abstract Based on the Sverdrup relation, using climatological wind stress data, the basin scale Sverdrup transport in the South China Sea(SCS) is calculated and the basic seasonal features of the Sverdrup circulation are obtained. A comparison of these calculated features with observations proves that the wind-driven circulation in the SCS is very important for the formation of the SCS upper oceanic circulation in winter, summer and fall. It is shown that the non-uniform sea surface wind is one of the causes to form multi circulation centers in the basin of the SCS. The westward current at 18°N is caused by the local wind, which is stronger in fall and winter. The seasonal variation of circulation in the southern SCS is much more remarkable than that in the north. The wind in spring is helpful to the seasonal reversal of the circulation in the central SCS. The northward transport of the cyclonic circulation reaches the maximum in fall.

Keywords: Sverdrup relation, the South China Sea, Seasonal variation.

The Sverdrup balance is the primary balance in the oceanic circulation[1]. Based on the Sverdrup relation, the Sverdrup transports in the Pacific and the Atlantic were calculated by many researchers[2~4]. These calculations were consistent with both the observations and the results by numerical models. However, the Sverdrup relation has not been applied to the SCS. In this paper, the adaptation of the Sverdrup relation in the SCS is analyzed under climatological mean, and then the seasonal mean Sverdrup transport is calculated. The importance of the wind-driven circulation in the internal region of the SCS has been determined and some general features of the SCS circulation have been found. The similarity and difference of the circulation patterns between the Sverdrup circulation and the observations are elucidated here.

1 Sverdrup relation and its applicability for the South China Sea

Based on the analysis of the observation data, there are always 1 ~ 2 gyres with the horizontal spatial scale L of about 1000 km and velocity scale U of $10^{-1}\mathrm{ms}^{-1}$ in the SCS. If the longitudinal gradient of the Coriolis parameter $\beta = 2\times10^{-11}\mathrm{m}^{-1}\mathrm{s}^{-1}$ and the horizontal turbulent coefficient $A_1 = 1000\ \mathrm{m}^2\mathrm{s}^{-1}$, the Rossby number and Ekman number are much smaller than 1, which is a necessary condition for the validation of Sverdrup balance[5]. In addition, the advection of relative vorticity is much less than that of the planetary vorticity (the ratio is about 0.005) in the SCS. Therefore, the Sverdrup relation is

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always valid for the SCS.

Meanwhile, multi-eddy is also a feature of the SCS circulation. Due to many factors, such as wind, the bottom topography and the nonlinear effect, usually there are some strong eddies ($U \approx 1$ ms^{-1} and $L \approx 100$ km) with synoptic scale. For these eddies the Rossby number and Ekman number are still much smaller than 1, but the advection of relative vorticity is almost equivalent to that of the planetary vorticity. Therefore, for synoptic scale eddies, the Sverdrup balance is not valid any more. However, compared with the climatological mean mass transport by large scale circulation, the transport by synoptic scale eddies can be neglected. Since the velocity scale of the eddies (U_{eddy}) is 10^{-1} ms^{-1}, the ratio of the advection effect of the eddy vorticity to the planetary vorticity $U_{\mathrm{eddy}}/(\beta L L_{\mathrm{eddy}})$ is about 0.05. Then, even if there are strong and small eddies in the basin scale gyre, the Sverdrup relation is still applicable. For example, in the North Pacific Subtropical Gyre where there are always strong synoptic scale eddies, we still use the Sverdrup relation to discuss mean mass transport.

When the bottom topographic effect is neglected, the Sverdrup balance equation is[5]

$$\beta V_{\mathrm{S}} \equiv \beta \int_{-H}^{0} v \mathrm{d}z = \mathrm{curl}\left(\frac{\tau}{\rho_0}\right), \tag{1}$$

where V_{S} is the vertical averaged velocity for the whole fluid column, H the depth of the ocean, τ the wind stress, ρ_0 the density of sea water, v the longitudinal velocity, and curl the operator of rotation.

Since the horizontal scale of the SCS is about 1000 km, which is about one tenth of the Pacific ocean, the Rossby wave spends less time crossing the SCS than crossing the Pacific at the same latitude, meaning that the adjustment of the SCS circulation to external forcing would be very fast. Therefore, at the time scale of a month, the Sverdrup relation is applicable

$$\beta(\mathrm{d}\psi/\mathrm{d}x) = \mathrm{curl}\left(\frac{\tau}{\rho_0}\right). \tag{2}$$

Here ψ is the stream function and x is zonal coordinate. By integrating Eq. (2) along latitude from east to west, the stream function ψ of the Sverdrup transport in the interior SCS can be evaluated. The wind stress data are from the climatological seasonal mean COADS/UWM with a horizontal resolution of 1° × 1° Lat./Lon. Here the solid boundary is used, in which $\psi = 0$.

2 Results and discussions

Based on the historical data of temperature and salinity of 6000 stations in the SCS during 1921 ~ 1970, the seasonal mean surface geostrophic current was evaluated by Xu[7]. The basic patterns of the seasonal mean wind stress and the Sverdrup transport in the interior SCS are shown in Fig. 1 (the west boundary and shallow shelf are not included). In winter (Dec. ~ Feb.), there is the northeast monsoon over the SCS, the wind stress curl is positive except for the northwest and the southeast of the SCS. Except for north of 20°N, the Sverdrup transport is always northward (dashed line in Fig. 1) in the interior SCS, and there is a strong westward current (the contour line is very dense in Fig. 1) at 18°N. The circulation corresponding to the Sverdrup transport has the following features: there is a basin scale cyclonic circulation in the south of 20°N, in which two regional high value centers exist in the west of Luzon Island and in the southwest of the Nan-Sha Islands respectively. This implies that in these places the wind stress curl is advantageous to the formation of local cyclonic circulation in winter. This feature of Sverdrup circulation is consistent with the observational research of Xu[7].

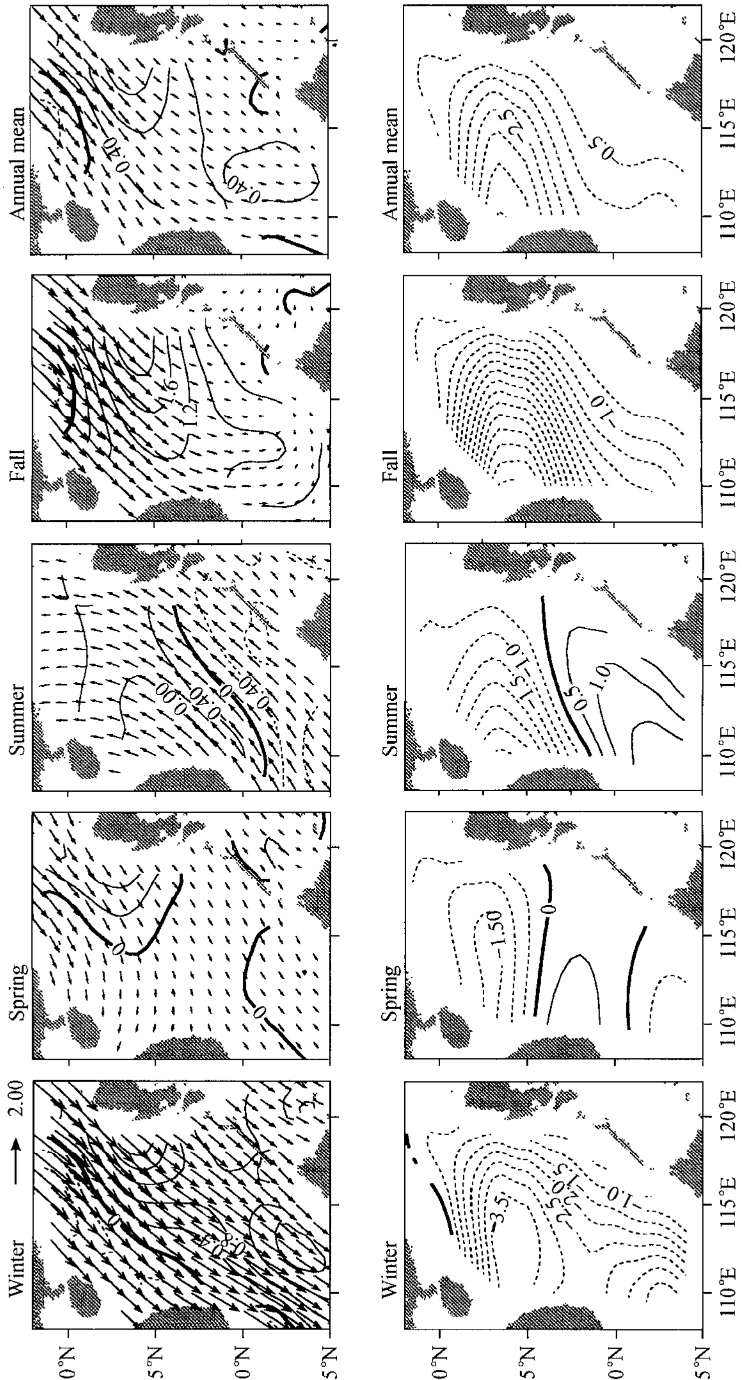

Fig. 1. Upper panel: COADS Wind-stress τ/ρ_0(vectors, $10^{-5}m^2/s^2$) and wind-stress curl (CI $= 0.4\times10^{-10}$ m/s^2) in seasonal mean and annual mean. Lower panel: barotropic transport stream function(CI $= 0.5\times10^6$ m^3/s) in seasonal mean and annual mean.

In spring (March ~ May), both the wind stress and its curl are very weak, and a negative wind stress curl appears in the central SCS (10° ~ 15°N), which produces a weak anticyclonic circulation and the southwards transport. This anticyclonic circulation is advantageous to the increase of sea surface temperature[8]. In other region, the circulation pattern in the north and south of the SCS is similar to that in winter, but the intensity of the current is weaker than that in winter and the latitudinal transport is very weak. At 18°N there is still a westward current, but the contour line is sparser than that in winter. In spring, the wind stress curl is very weaker, but the heat flux, especially the radiation heat flux, is larger[8]. Then the Sverdrup circulation pattern is different from the observations by Xu[7]: there are anticyclonic Sverdrup circulations in the central SCS and cyclonic circulations in other region. But according to Xu's result, there are two small cyclonies in the central SCS. This shows that the wind is advantageous to the reversal from winter circulation to summer circulation in the central SCS. This result is similar to that of the numerical research using the 2.5 layer model[9].

In summer (June ~ August), there is the stable southwest monsoon in the SCS. The wind curls are opposite to each other in the northern and southern SCS. The division of the circulation patterns in the SCS is 14°N: there is a cyclonic gyre, the seawater transports northward in the north of 14°N, while there are an anticyclonic gyre and the southward transport in the south of 14°N. There is still westward current at 18°N. Those features are similar to the surface geostrophic current observed by Xu[7], but the upwelling by Ekman pumping near the coast of Vietnam is not shown in the Sverdrup circulation.

In fall (September ~ November), the wind stress curls are positive in the whole area. The corresponding Sverdrup circulation is cyclonic and the total transport is northward. A strong westward current appears again at 18°N. From fall to winter, there is an abrupt process for the circulation: in the southern SCS the southward transport quickly changes into northward and in the north the cyclonic is increased. The intensity of cyclonic gyre and the corresponding northward transport reach the maxima of a year. In fall the feature of Sverdrup circulation is similar to the surface geostrophic current observed by Xu[7].

Based on the above analyses, the following conclusion can be reached: the Sverdrup circulation pattern is similar to Xu's surface geostrophic current pattern, except for the part of the central SCS in spring. This means that in the SCS the wind-driven current dominates the surface current in winter, summer and fall. However, in spring, the wind-driven current does not dominate in surface current, especially in the central SCS. Why is the pattern of the Sverdrup circulation similar to the pattern of the geostrophic current given by Xu in winter, summer and fall? The physical mechanism will be given in another paper. In short, the first baroclinic Rossby wave crosses the SCS in 1 ~ 3 months, then, in terms of the seasonal mean, the dynamic field of two-layer baroclinic model meet quasi-steady vorticity balance, which corresponds with the barotropic current field. When the wind force is considered only, the current of baroclinic or barotropic satisfies the Sverdroup relation. Thus in winter, summer and fall the pattern of the Sverdrup circulation is similar to that of the geostrophic current observed by Xu[7].

3 Summary

In this paper the applicability of the Sverdrup relation for climate mean with basin scale has been discussed, and the seasonal variation in the mass transport has been diagnosed in the SCS when the bottom topography was neglected. The Sverdrup relation gave the basic circulation pattern, namely the wind-driven circulation in the SCS. Some interesting features are revealed as follows. (i) In winter, because of non-uniformity of wind curl, there are two cyclonic circulations in the SCS. (ii) In the northern SCS, between 15°N and 20°N there is always a basin scale cyclonic gyre; the transport in the interior is always northward, which implies the western boundary current is always southward in all seasons. (iii) At 18°N there is a strong westward current throughout the year, even if the boundary condition is closed in the Luzon Strait. This westward current is stronger in winter and fall but weaker in spring and summer, which is forced by local wind and its formation is not related to bottom topography and the incidence of the Kuroshio. The westward current is almost from west and southwest of the Luzon Island, and the incidence of the Kuroshio is not a necessary condition of the westward current formation. (iv) In spring, the wind is advantageous to the advent of anticyclonic gyre in the central SCS. The seasonal variation of the circulations is very obvious in the southern SCS while the circulation in the north is more stable. (v) In fall the intensity of cyclonic gyre reaches the maximum of a year.

Although the calculations show that the wind stress curl would dominate the circulation in interior SCS, let it be noted that from the Sverdrup relation only the net vertical mean transport caused by wind stress curl can be calculated, and the vertical mean transport caused by other factors is negligible. In fact, even through the baroclinic effect can be neglected, the interaction between topography and current could obviously affect the vertical mean transport, and even change the direction of transport. In the SCS, the interaction could be more important, because there is very complex topography. Moreover the buoyancy flux cannot be neglected in the study of the circulation in the SCS.

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