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On the mechanism of the cyclonic circulation in the Gulf of Tonkin in the summer

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[1] The circulation in the Gulf of Tonkin had been traditionally considered to be anticyclonic in the summer. This view was challenged recently by results from reanalyzing observational data, which clearly revealed that the circulation is cyclonic in all seasons. The surface wind stress is monsoonal, southwesterly in the summer and reversed in the winter. It remains unexplained why the circulation is always cyclonic, while the surface forcing reverses seasonally. In this study, we hypothesize that the inflow through Qiongzhou Strait, a shallow and narrow channel between Hainan Island and the Chinese mainland, is responsible for maintaining the cyclonic circulation in the summer. Besides the requirements of mass conservation and bathymetry constraint, this flow, even with a rather small transport, carries a considerable amount of potential vorticity (PV) into the gulf, and the integral constraint of PV requires the presence of a frictional torque to be associated with a cyclonic circulation. Several numerical experiments with a three-dimensional model have been conducted to test this hypothesis. When the westward flow through Qiongzhou Strait is blocked, the model simulates an anticyclonic circulation in the summer. When the westward flow through Qiongzhou Strait is allowed, the circulation changes to a cyclonic one, consistent with our hypothesis.

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1. Introduction

[2] The Gulf of Tonkin is located in the northwest of the South China Sea (SCS), which is the biggest marginal sea in the Northwestern Pacific Ocean. Bounded by China and Vietnam to the north and west, the Gulf of Tonkin connects to the northwestern shelf of the SCS through the Qiongzhou Strait. The bathymetry deepens gradually to the south (Figure 1). Due to the unsettled territorial claims between China and Vietnam, large-scale and coherent observations, especially direct measurements of the flow field, have been extremely scarce. The flow pattern was derived largely from numerical simulations. In the region, the prevailing wind, influenced by the East Asian Monsoon, is dominated by the northeasterly wind in winter and southwesterly wind during the summer.

[3] All previous studies of the regional circulation in the Gulf of Tonkin have shown that the northeasterly wind in winter forces a southward flow in the upper layer along the Vietnamese coast which is compensated by the northward return flow in the interior and along Hainan's coast, resulting in a gulf-wide cyclonic gyre [*Xu et al.*, 1980; *Zhuang et al.*, 1981; *Yu and Liu*, 1993; *Yuan and Deng*, 1999]. The flow pattern in the summer, however, is much less clear. The summer circulation is usually weaker than in the winter, and thus it is more difficult to separate the geostrophic flow from the tidal and Ekman flow, especially in the shallower region. Numerical simulations typically showed that the circulation reversed from the winter to the summer, because of the monsoonal forcing [*Yuan and Deng*, 1999; *Manh and Yanagi*, 2000; *Sun et al.*, 2001]. Figure 2 shows the earlier, traditional current pattern in the northern Gulf of Tonkin in summer [*Yu and Liu*, 1993]. Others, such as Xu et al., Zhuang et al., *Xia et al.* [2001], and *Bao et al.* [2005], dissented and argued that the circulation pattern remain cyclonic in the summer.

[4] In addition to the direct wind-stress forcing, the Gulf of Tonkin interacts with surrounding seas through water-mass exchanges. Chief among them is the broad-scale southward flow which is compensated by an inflow into the gulf through the Qiongzhou Strait. On the basis of the analysis of tidal station data and some direct current measurements in the past 40 years, *Shi et al.* [2002] and *Yang and Bao* [2003] concluded that the flow along the Qiongzhou Strait should be westward toward the Gulf of Tonkin in all seasons.

[5] We hypothesize in this paper that the perennial westward current in the Qiongzhou Strait is associated with the summer cyclonic circulation in the Gulf of Tonkin. The mass conservation in the gulf requires a southward flow along the bathymetry. Furthermore, this inflow advects a considerably greater amount of potential vorticity (PV), i.e., the inflow through Qiongzhou Strait occurs in a higher

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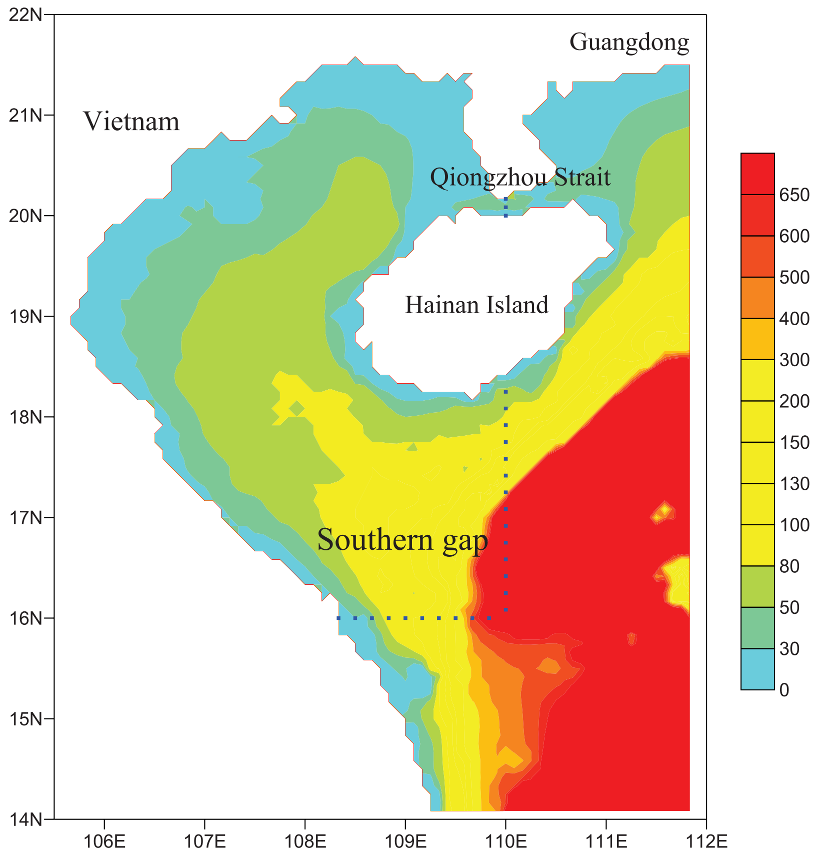

Figure 1. The bathymetry of the Gulf of Tonkin (meter). The blue dots show the position of open boundary.

latitude and over a shallower bathymetry, than that of the exit flow in the south. The integral constraint of PV requires the existence of a frictional torque associated with a cyclonic gyre [*Yang and Price*, 2000; *Yang*, 2005]. We have conducted several numerical simulations, using a three-dimensional model to test this hypothesis.

[6] This paper is organized in the following manner. The model is introduced and the simulation results are presented in the next section. This will be followed, in section 3, by the discussion of PV integral constraint and its application to the circulation in the Gulf of Tonkin. More discussion and a summary are included in section 4.

2. Model and Results

[7] We use the three-dimensional Estuarine and Coastal Ocean Model with a Semi-implicit Scheme (ECOMSI)

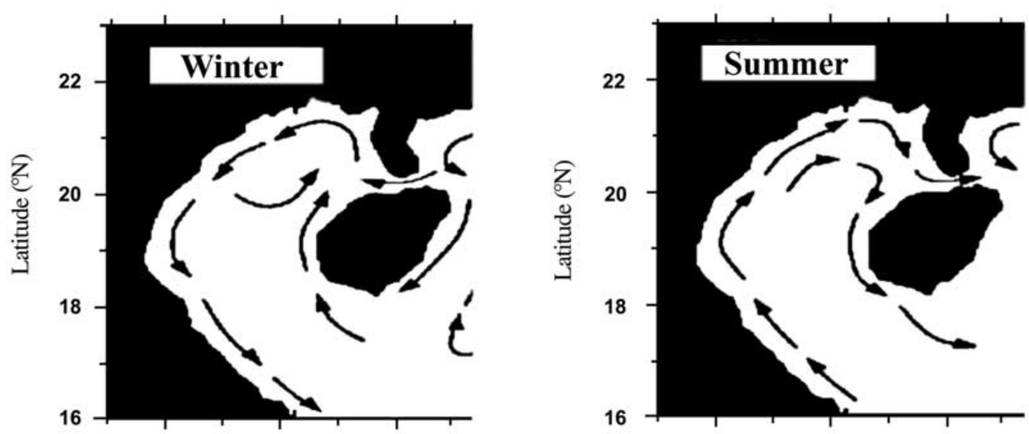

Figure 2. The traditional view of the seasonal circulation on the Gulf of Tonkin. Note that the circulation was anticyclonic in the summer. This pattern was challenged by the more recent analyses of observations.

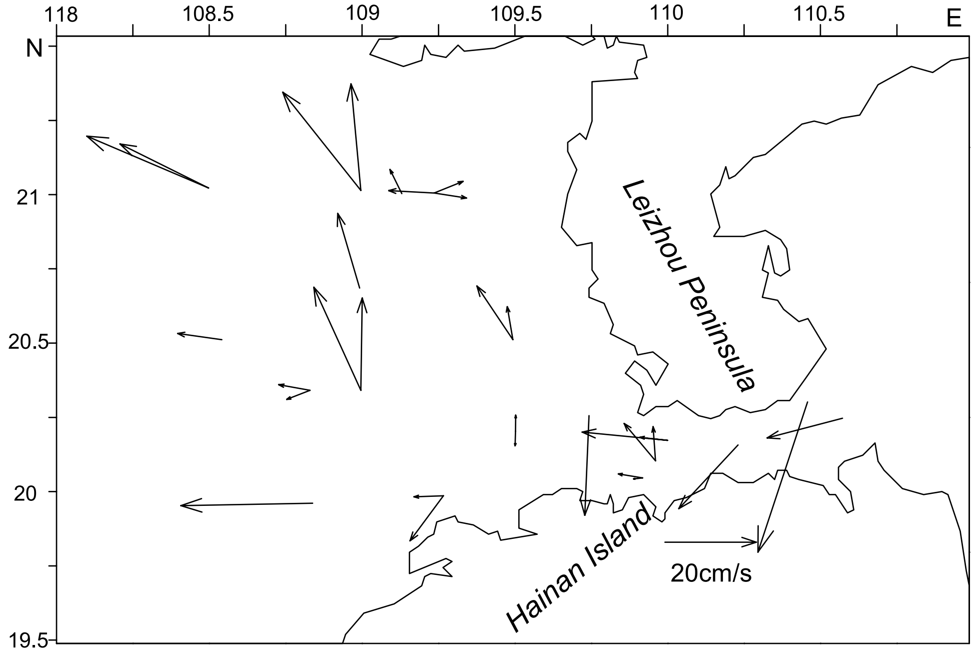

Figure 3. The summer flow pattern derived from drifting bottles and current measurements. The velocity contains both Ekman and geostrophic components. Since the pattern shown here is actually against the monsoonal wind, one would suspect that the geostrophic current, evidently, is even more cyclonic.

which incorporates the Mellor & Yamada level 2.5 turbulent closure model [*Mellor and Yamada*, 1982; *Casulli*, 1990; *Casulli and Cheng*, 1992; *Wang and Ikeda*, 1995]. This model has been used successfully in simulating the hydrodynamic process of coastal ocean, estuaries and bays in China [e.g., *Zhang and Sun*, 2001; *Zhu et al.*, 2002].

[8] For our purpose of investigating the summer circulation in the Gulf of Tonkin, we have configured a regional model domain which extends from 16°N to 22°N meridionally and from 105.5°E to 110°E zonally. The horizontal grid uses rectilinear coordinates and the horizontal resolution is 5'. We set six Sigma layers in the vertical direction (0.00, −0.05, −0.20, −0.50, −0.80, −1.00) with a finer resolution for the upper layers. The transport through the Qiongzhou Strait is prescribed in the second and third sets of experiments in three grid points as the open boundary condition. A corresponding flow of the equal transport is specified with uniform velocity along the southern and eastern boundaries so that the mass conservation is satisfied. The 4-year (2000–2003) averaged July wind stress derived from observations made by NASA satellite scatterometers http://www.ssmi.com) is used here. The wind stress data have a resolution of 1/4 degree in both longitude and latitude, and thus, are linearly interpolated into the model grids. Because the Gulf of Tonkin is dominated by the typical diurnal tide, the k1 tidal current is used as the boundary condition to represent the tidal forcing. The tidal harmonic constant is computed from a basin-scale tidal model. The water depth in the Gulf of Tokin is usually less than 80m (Figure 1), so we only consider the barotropic circulation and the model is integrated from an initial condition with summer averaged temperature (22°C) and salinity (33.5) derived from WOA (World Ocean Atlas) 01

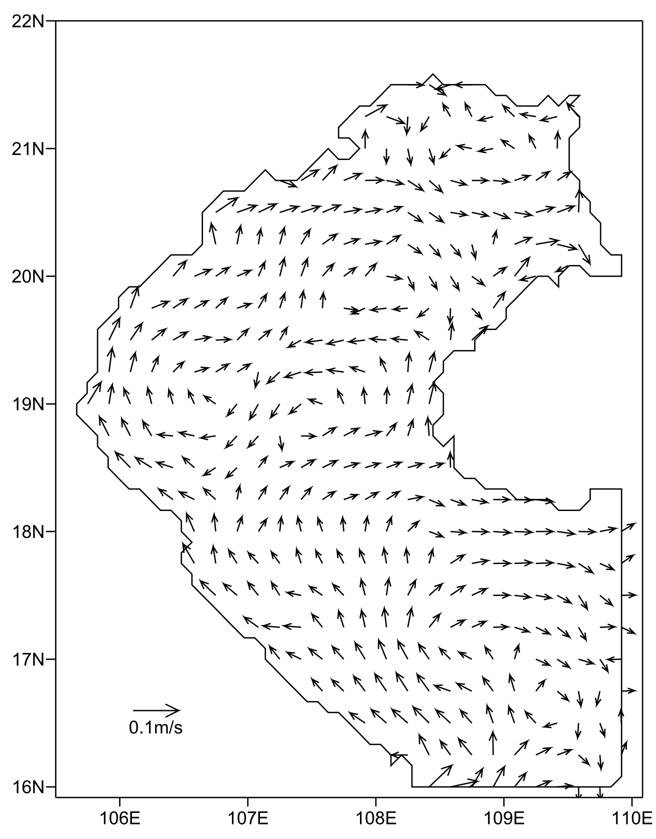

Figure 4. The depth-averaged velocity from the EXP1a in which the model is forced by both tide and wind stress. Without the inflow through the Qiongzhou Strait, the flow consists of an anticyclonic circulation.

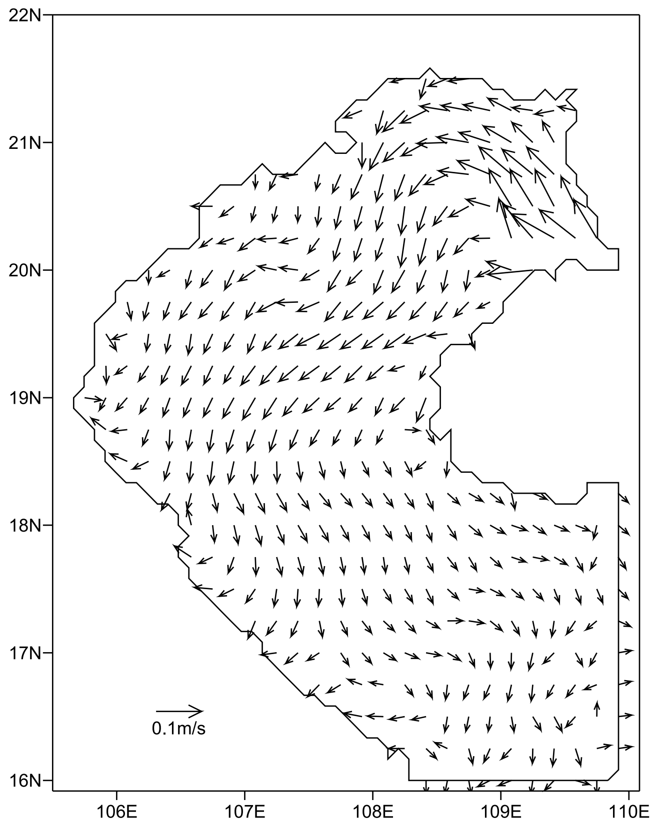

Figure 5. The depth-averaged velocity from the EXP2a. The same as the EXP1a except that an inflow of 0.15 Sv is specified a priori at the Qiongzhou Strait. The exit flow is prescribed uniformly across the southern and eastern boundaries. Note the existence of a cyclonic circulation in the northern Gulf of Tonkin.

data [*Conkright et al.*, 2002]. We also use the real temperature and salinity from WOA 01 data set as the initial condition to evaluate the baroclinic effect of summer stratification on the circulation pattern. The results (not shown here) show that in depth averaged velocity, the current pattern is similar to that of the barotropic one, so the conclusions drawn from the barotropic model are robust.

[9] Results from three sets of experiments will be shown to elucidate the roles of different forcing mechanisms for the circulation in the Gulf of Tonkin. The winter circulation from each experiment is cyclonic, a well-established consensus, and our model, indeed, simulated one that is consistent with this well-accepted pattern. Our discussion, therefore, will be concentrated on the contentious circulation in the summer. In every experiment, we integrate for more than 6 months and take the last month output for analysis. Considering the relative small scale for the Gulf of Tokin, 6 months is sufficiently long for the model to reach the equilibration state with the adjustment of barotropic process. In the first set of experiments, we only take account the forces of tide and wind stress. In the second set of experiments, we add the Qiongzhou Strait inflow and the outflow that exits the southern and eastern boundaries. In the third set of experiments, we reverse the direction of the inflow and outflow or modify the bathymetry in the open boundaries so that the PV budget impact can be better highlighted.

2.1. The Observed Summer Flow Patterns in the Gulf of Tonkin and Along Qiongzhou Strait

[10] Before the model results are shown, we would like to present some observational evidence for supporting the cyclonic pattern of the summer circulation. The data set consists of trajectories of approximately 4,000 drifting bottles, released in the northern region of SCS from 1964–1972, continuous current measurements in some stations, and ADCP data collected along the western coast of Guangdong (WCG). The residual velocity, shown in Figure 3, shows that the flow along the Qiongzhou Strait is westward toward the Gulf of Tonkin in the summer and the current in the northern Gulf of Tonkin is cyclonic with speed more than 10cm/s, both consistent with the more recent analyses [e.g., *Shi et al.*, 2002].

2.2. The First Set of Experiments: Tidal and Wind-Stress Forcing

[11] In the first set of experiments, the perennial westward flow of the Qiongzhou Strait isn't taken into account. The k1 tidal current and the wind stress are used as the open boundary condition and the upper boundary condition, respectively. There is no net transport in the open boundary. We conduct three experiments in the first set of experiments (named by EXP1a, EXP1b and EXP1c). In EXP1a, the model is forced by both the tide and wind stress. In EXP1b and EXP1c, the model is forced by tide and wind stress individually. The results of EXP1b and EXP1c, not shown here, that use either tidal or wind forcing show that the wind-forced flow of about 5–10cm/s is considerably stronger than the tide-induced one of about 0.5–2cm/s even though the southwest monsoon in summer is relatively weak. This is consistent with the study of *Zu* [2005] who estimated that the ratio of the speed of tide-induced residual current is a factor of 3.5 weaker than that induced by wind stress.

[12] Figure 4 is the depth-averaged velocity from the EXP1a. The flow field is rather complex because of variations of bathymetry and wind stress on various scales. The depth-average velocity ranges typically within 5–10cm/s. Regardless of small-scale features, the overall circulation pattern from this experiment is anticyclonic, consistent with the traditional view depicted in Figure 2, but opposite to the new pattern revealed by the analyses of observations [*Xu et al.*, 1980; *Zhuang et al.*, 1981; *Xia et al.*, 2001; *Bao et al.*, 2005].

[13] We do not wish to emphasize in this study whether and how the Qiongzhou inflow can be westward in a general circulation model like ours. Such a task would probably involve the model's numerical details that are beyond the scope of this study. Rather, we would like to concentrate on exploring the impact of the Qiongzhou inflow on the broad scale circulation in the gulf. To do so we decided to conduct additional experiments in which this inflow is specified according to observations.

2.3. The Second Set of Experiments: The Role of the Qiongzhou Strait Flow

[14] In the second set of experiments, the inflow through the Qiongzhou Strait is specified a priori. These experi-

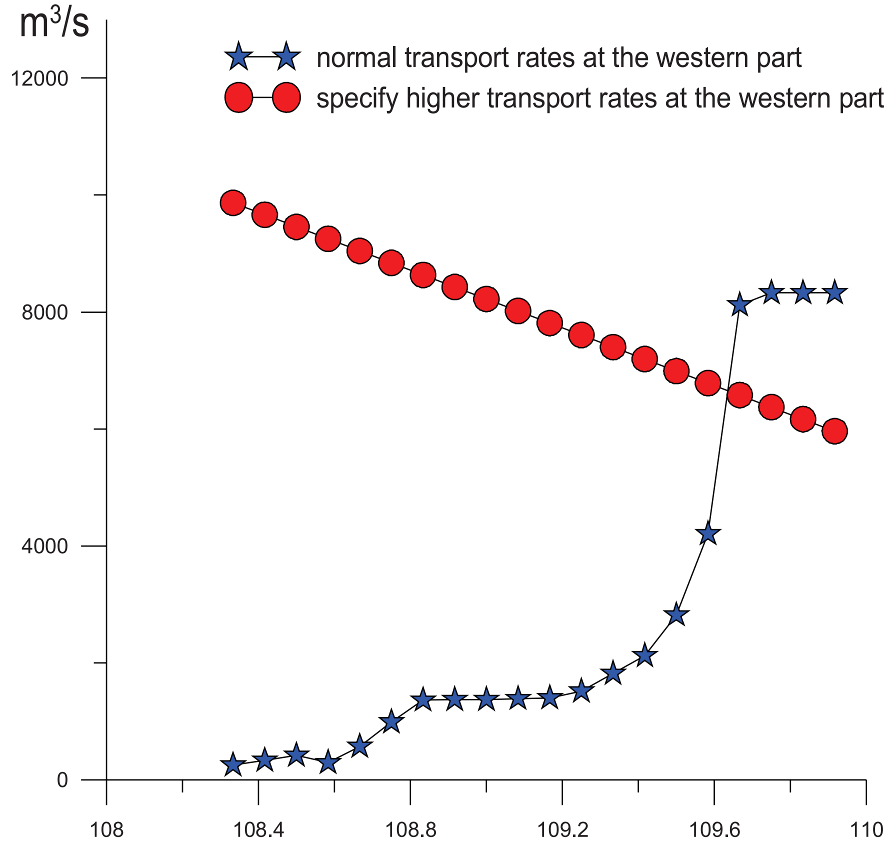

Figure 6. The transport (circular line, EXP2c) at the southern boundary when we specify higher transport rates at the western part as open boundary condition. The line labeled by the five-pointed star represents the transport of the EXP2a in the southern boundary.

ments can be considered as a fully forced one with tide, wind stress, and lateral inflow/outflow. *Shi et al.* [2002] estimated that the water-mass transport Q through the strait is about 0.1–0.2 Sv and is directed westward toward the Gulf of Tonkin. In the model, we chose 0.15 Sv so that the impact from a normal transport can be demonstrated (the impact is proportionally larger for a greater inflow transport). We conduct three experiments in the second set of experiments (named by EXP2a, EXP2b and EXP2c). In the EXP2a, we set the uniform velocity both horizontally and vertically as the open boundary condition. Figure 6 shows the transport along the southern boundary (labeled by five-pointed star). The depth-averaged velocity, shown in Figure 5, is remarkably different from the previous experiment with only tidal and wind-stress forcing (Figure 4, EXP1a). The Qiongzhou Strait inflow feeds a cyclonic gyre in the Gulf of Tonkin, and together with an outflow condition along the southern and eastern boundaries, forces a broad southward flow in the interior. The circulation, in a broad sense, is cyclonic, especially in the northern model domain. It is noted that the western boundary current to the south of 19°N is similar in these two cases with and without Qiongzhou inflow. A plausible reason is that the exit flow speed is specified uniformly both in horizontal and vertical across the southern and eastern boundaries, and thus more transport occurs in the deeper interior region. The exit flow would more likely be along the western boundary if it were not specified a priori. In such a scenario, the whole western boundary current would be likely dominated by a southward flow and the cyclonic pattern would be more evident. To evaluate the effects of different open boundary conditions on the circulation pattern, we conduct two other experiments with radiation open-boundary condition (EXP2b) and higher transport rates specified in the western part of southern boundary (EXP2c), respectively. We still keep 0.15 Sv transport in the Qiongzhou Strait in these two experiments as we used in the EXP2a. Figure 6 shows the transport in the southern boundary when we specify higher transport rates in the western part (EXP2c, labeled by a circular line). The depth-averaged velocity under the above boundary conditions, Figure 7 (EXP2b) and Figure 8 (EXP2c), show a more obviously cyclonic circulation as we expected. However, the circulation structures are basically consistent with the result of the EXP2a. The different boundary conditions may affect the current field in some area however the cyclonic circulation in summer is robust and is rather insensitive to the boundary condition. Without sufficient observational guidance, we have to choose an open boundary condition rather arbitrarily. However, in all the scenarios that we experimented, the introduction of the Qiongzhou Strait inflow always leads to the formation of a cyclonic gyre.

2.4. The Third Set of Experiments: The PV Budget Effect on the Circulation Pattern

[15] The previous two sets of experiments have demonstrated quite clearly that a cyclonic circulation in the Gulf of Tonkin is associated with the westward transport through

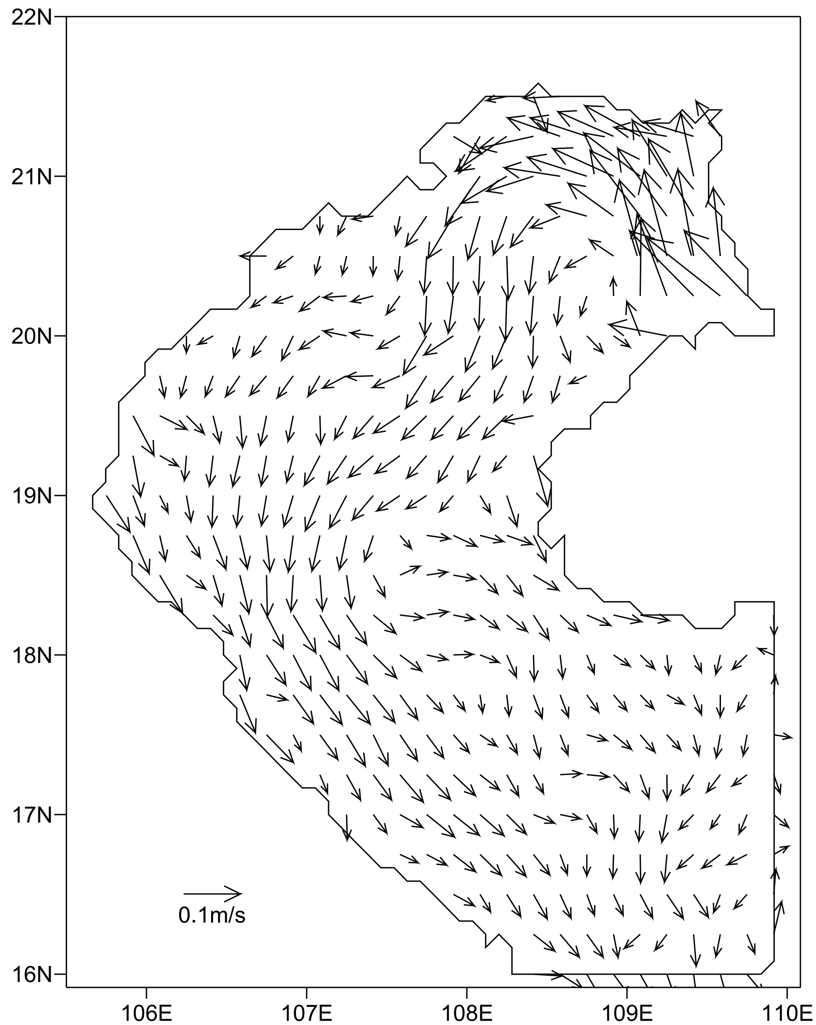

Figure 7. The same as the EXP2a (Figure 5) except that the radiation condition is used for the open boundary in the southern gap (EXP2b). The exit flow is southward along the western boundary and the cyclonic circulation is more obvious. However, the circulation structure does not change much compared with the EXP2a.

the Qiongzhou Strait. One may wonder what would happen if this transport in the Qingzhou Strait were reversed to be eastward in the summer as shown in the traditional view (Figure 2) so that it is in the same direction as the southwesterly wind. In the first experiment in this set of experiments (EXP3a), the transports through the Qiongzhou Strait and the southern and eastern boundaries are reversed while the tidal and wind-stress forcing remain unchanged. As shown in Figure 9, the circulation becomes much stronger than in any of the previous cases. The circulation over the whole model domain, including the western boundary current, is clearly anticyclonic. As discussed earlier, the southwest monsoon would tend to force an anticyclonic circulation, while the lateral inflow/outflow would drive an opposite one. The combination of this forcing would result in a cyclonic flow. If the inflow/outflow were reversed, as in the present case, both wind stress and the Qiongzhou Strait inflow promote a cyclonic circulation and thus a stronger gyre would be formed. We would like to note here that due to the mass conservation, the inflow (outflow) from the Qingzhou Strait usually leads to a southward (northward) circulation along the bathymetry and western boundary. So one may naturally conclude that the flow pattern is set merely by the direction of mass flux through the Qiongzhou Strait and thus the PV integral is of little relevance here. Can we reverse the integral PV budget without changing the mass flux? In the next experiment (EXP3b), we modify the three lines of model bathymetry in every open boundary and keep the inflow from the Qingzhou Strait and outflow in the southern and eastern boundaries. This experiment is similar in design to those conducted by *Yang* [2005] for the Arctic Ocean circulation. The water depth is more than 500m in the inflow area and less than 50m in the outflow area. We use the same radiation condition in the southern and eastern boundaries as EXP2b and all the other conditions remain unchanged. Figure 10 is the depth averaged velocity in EXP3b. From Figure 10 we can see that although the flow in the interior is basically southward as we expected from mass conservation, the boundary current, especially the western boundary current, is mainly northward. The only difference between the EXP3b and EXP2b is the bathymetry in the open boundary.

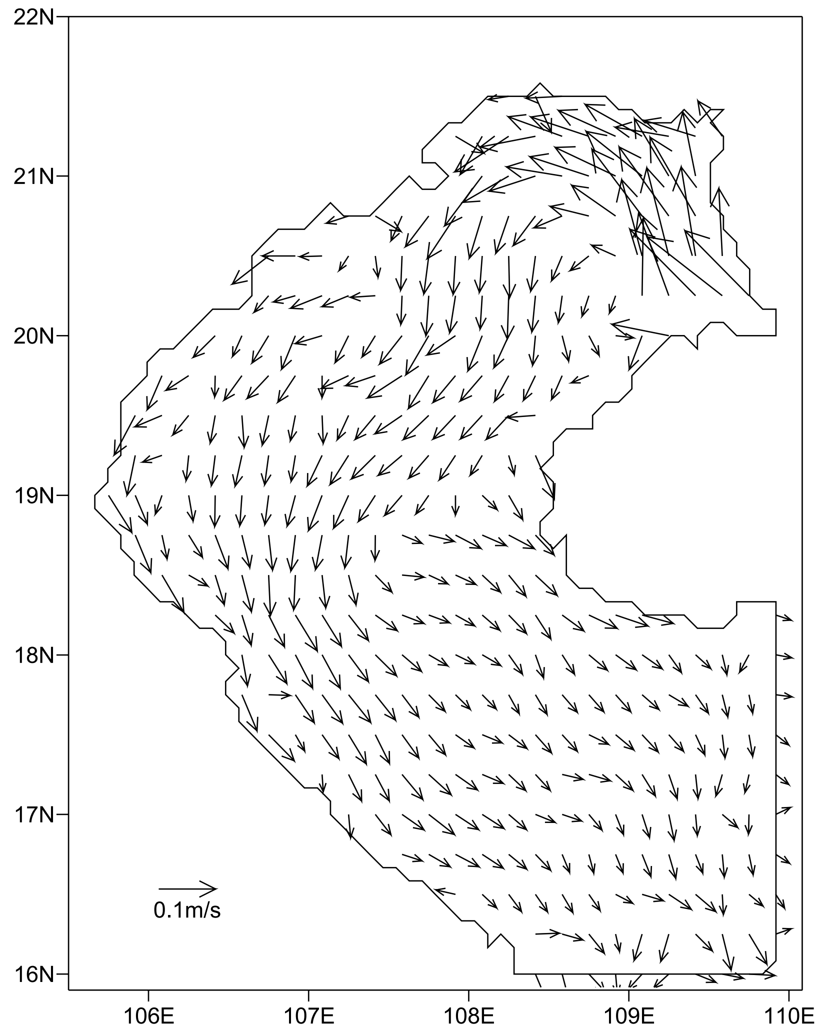

Figure 8. The same as the EXP2a (Figure 5) except that we specify a larger transport in the western part of the southern boundary (EXP2c) as shown in Figure 6. The exit flow is southward along the western boundary and the cyclonic circulation is also more obvious as Figure 7. However, the circulation structure does not change much compared with the EXP2a.

However, the boundary current in these two experiments are different with one cyclonic (Figure 7, EXP2b) and the other anticyclonic (Figure 10, EXP3b).

[16] How do we explain such a significant impact that a small transport through the Qiongzhou Strait or a small change in the bathymetry can exert on the whole circulation in the gulf? In the next section, we invoke the integral constraint of PV to elucidate a key mechanism that we believe to be responsible for setting the summer circulation pattern.

3. A Potential-Vorticity (PV) Integral Constraint

[17] *Yang and Price* [2000] considered a PV equation in an isopycnal layer, or over the whole water column (barotropic) in a semi-enclosed basin. They started with the following vorticity equation:

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot [\vec{u}(f + \zeta)] = F \quad (1)$$

where ζ is the relative vorticity, f is the planetary vorticity, u is the velocity vector, and F is the curl of the friction and external forcing (such as wind stress). We can derive the area integral of the PV equation in the form of line integral along C, the horizontal boundaries of the model domain:

$$\frac{\partial}{\partial t} \oint_C \left(\vec{u}_H \cdot \vec{l}\right) ds + \oint_C (H\vec{u}_H \cdot \vec{n}) \left(\frac{f + \zeta}{H}\right) ds = \iint_A F dxdy \quad (2)$$

where $\vec{l}$ and $\vec{n}$ are unit vectors tangential and perpendicular to the lateral boundary C respectively, and H is the total water column depth. The time scale of the flow to adjust to external forcing is short for a small domain like the Gulf of Tonkin. So one could assume a steady balance can be established soon after the flow through the strait switches its direction. In the model, we actually address the steady responses to the flow through the Strait. So the time-dependent term is neglected. Furthermore, although the southern gap is very wide, the velocity is small because of the greater depth. So the contribution to the circulation

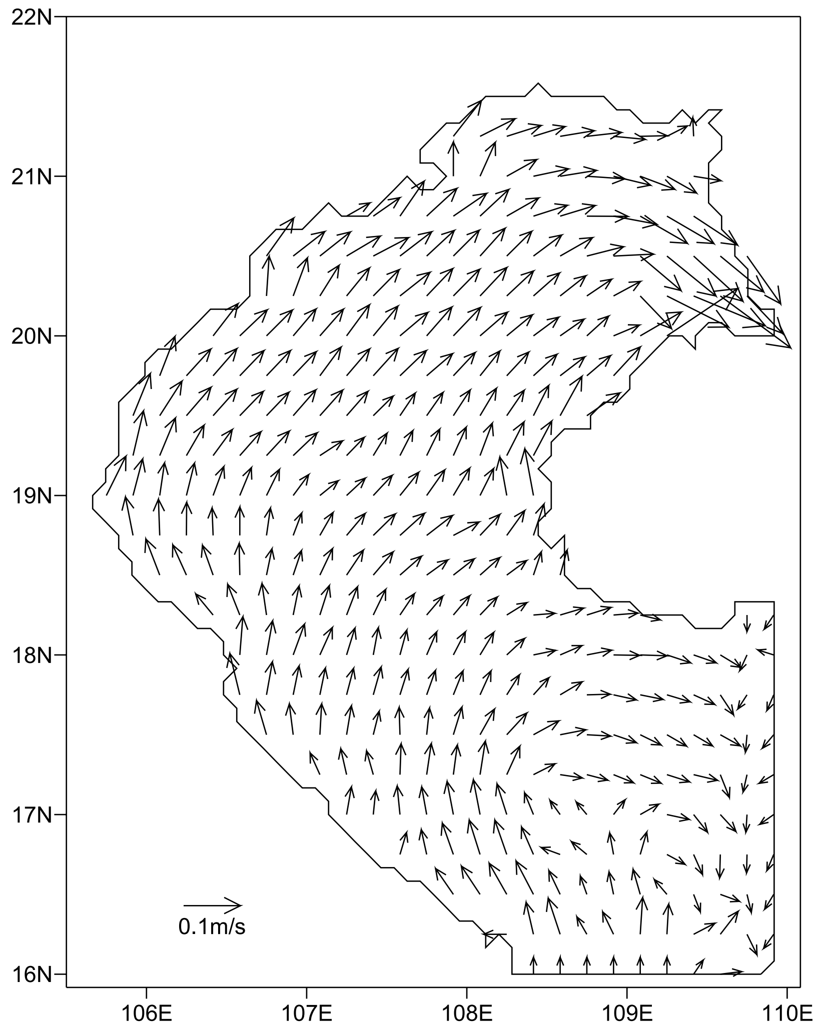

Figure 9. The depth-averaged velocity in the EXP3a in which the inflow and outflow are reversed. Consequently, an anticyclonic gyre emerges over the whole gulf. This further supports our hypothesis that the Qiongzhou inflow plays a leading role in setting the circulation in the Gulf of Tonkin.

integral in the Gulf of Tonkin is probably small even in a time-dependent model. To quantify the magnitude of the relative vorticity and the planetary vorticity in equation (2), a scaling argument is used. For the Rossby number

$$R = \frac{U}{fL},$$

in our research,

$$\begin{aligned} o(U) &= 0.1, f = 2w \sin \psi \\ &= 2 \times 7.292^{-5} \times \sin(19 \times 2 \times 3.14159/360) \\ &\approx 0.5 \times 10^{-5}, o(U) = 10^5. \end{aligned}$$

The value of Rossby number is $R = \frac{U}{fL} \approx 10^{-1}$. So, relative vorticity can be neglected relative to planetary vorticity in the second term. The integral of relative PV, associated with the inflow and outflow, also vanishes since the tangential component is small along the boundary [*Yang and Price*, 2000]. Consequently, (2) can be much simplified to:

$$\sum_{i=1}^{N} \frac{Q_i f_i}{H_i} = \iint F dx dy \quad (3)$$

where Q_i is the volume transport out of the basin across the i-th opening, and f_i/H_i is the potential vorticity at the i-th opening.

[18] We further assume here that the integral of the wind-stress along the boundary is smaller (the wind in the summer is weak in the region and the southwest monsoonal wind is cyclonic along Hainan's coast and anticyclonic along the Vietnamese coast, and thus they tend to cancel each other in the integral). In such case, F in equation (3) represents a frictional torque. The integral (3) indicates that in a steady state, the net PV inflow across the horizontal boundaries into a density layer must be balanced by the net PV frictional torque within this layer. Thus the inflow/outflow and associated PV flux can exert a powerful control on the basin circulation, especially the large-scale pattern of

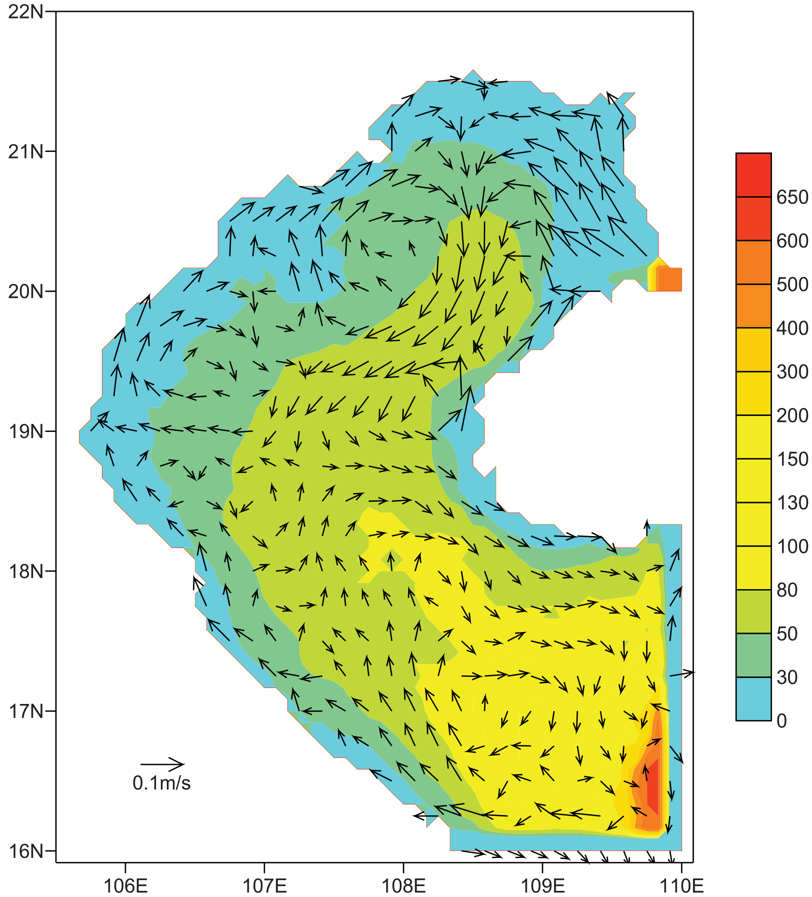

Figure 10. The depth-averaged velocity in the EXP3b in which the bathymetry is modified in the three lines in the open boundary. It is clearly to see an anticyclonic boundary current when we change the sign of PV budget in the experiment.

the boundary currents that generate most of the frictional torque.

[19] For our application here in the Gulf of Tonkin, equation (3) can be written as:

$$f\left(\frac{Q_{Qiongzhou}}{H_{Qiongzhou}}+\frac{Q_{Southern-gap}}{H_{Southern-gap}}\right)=\iint Fdxdy \quad (4)$$

where, $Q_{Qiongzhou}$ and $Q_{Southern\text{-}gap}$ are the water-mass transports at the Qiongzhou Strait and the channel in the south of the Gulf of Tonkin (both are 0.15 Sv, but $Q_{Southern\text{-}gap}$ is negative because of the outflow), $H_{Qiongzhou}$ and $H_{Southern\text{-}gap}$ are the corresponding water layer thickness. We roughly estimate the term value in the both side of the equation (4). According to *Yang* [2005], the term on the right-hand side can be written as:

$$\iint Fdxdy=\oint_{c}\frac{A_H}{H}\vec{n}\cdot\nabla(H\zeta)ds \quad (5)$$

where, A_H is the horizontal viscosity. On the basis of the result of second experiment, we calculate all the terms in the equation (4). The advection PV flux $f\,\frac{Q_{Qiongzhou}}{H_{Qiongzhou}}$ is 0.455 m^2 s^{-2}, $f\frac{Q_{Southern-gap}}{H_{Southern-gap}}$ is -0.02 m^2 s^{-2}, and the frictional torque $\iint Fdxdy$ is 0.41 m^2 s^{-2}. The terms in both sides of the equation (4) are approximately equivalent. Therefore the equilibrium given in equation (4) is achievable in the Gulf of Tonkin.

[20] The PV transport into the gulf through the Qiongzhou Strait is much greater, because of both shallower H and larger f, than that out of the gulf through the southern and eastern boundaries. So there is a net positive inflow of PV into the gulf, and the integral constraint (4) requires a negative frictional torque to balance it. So a cyclonic circulation must be formed. If we change the sign of PV budget in the gulf such as EXP3b, the boundary current will reverse to an anticyclonic one.

4. Discussion and Summary

[21] In this paper, we have investigated the summer circulation in the Gulf of Tonkin, located in the northwestern South China Sea. Recent analyses of observations revealed that the circulation there remains cyclonic in the summer despite the monsoonal forcing that tends to drive an anticyclonic one. This is in contrary to the traditional view that circulation in the Gulf of Tonkin reverses from winter to summer with the change from the northeast to southwest monsoon. Observations also indicated that the flow along the Qiongzhou Strait is directed westward, against the wind, in the summer. We hypothesize here that this inflow, albeit its small transport, is with the key factor for the cyclonic circulation pattern in the gulf. Besides the mass conserva-

tion, the mechanism involves the integral balance of the potential vorticity which requires that the lateral advection of PV into the gulf be balanced by frictional torque [*Yang and Price*, 2000]. Since the Qiongzhou Strait is shallow and located in higher latitude, the inflow water has a much higher planetary PV (f/H) than that of the exit flow across the southern boundary. This results in a net positive PV advection into the gulf and therefore requires a negative frictional torque to maintain PV balance.

[22] We must point out here that we did not investigate why the flow along the Qiongzhou Strait is westward against the southwest monsoon. The mechanism for driving this flow is probably non-local. Without any remote forcing, one would expect that the wind stress be balanced by bottom friction along a narrow and shallow channel like the Qiongzhou Strait. In such a scenario, the flow would be in the same direction as the prevailing wind. However, remote forcing, either resulting from wind-stress forcing in upstream shelves or from deep-basin influence, may set up a pressure gradient along the channel that could counter the direct forcing from local wind stress. This is an interesting topic but beyond the scope of the present study.

[23] **Acknowledgments.** The authors would like to thank Zu Tingting for her advice during this study. We also thank three anonymous reviewers for their helpful comments. This study is supported by the National Basic Research Program of China under contract 2005CB422302 and 2007CB411804, the key project of the International Science and Technology Cooperation program of China under contract 2006DFB21250, and the 111 project under contract B07036.

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