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# Summer circulation structure and formation mechanism in the Beibu Gulf

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Due to limited *in situ* data and diagnostic numerical models, the summer circulation structure and formation mechanism in the Beibu Gulf have always been in controversy in the past 50 years. Therefore, a new three-dimensional hindcast model was built within the northwestern South China Sea (SCS), forced with the daily averaged wind, heat flux, lateral flux, as well as tidal harmonic and eight major rivers discharges. And the east boundary was set up far away off the Qiongzhou Strait (QS). Lastly, the model results were consistent with not only the synchronous observation data from the project 908 but also the historical observed data. As a result, the summer circulation structure was revealed that the southern Gulf was occupied by an anticyclonic eddy whereas the northern Gulf was dominated by a cyclonic gyre. Although the circulation major structure was stable, its area and strength had yearly and monthly oscillation. The other three sensitive experiments indicated that the circulations in the southern and northern Gulf were driven by the SCS circulation and monsoon wind, respectively. After the theoretical analysis of the potential vorticity budget, it was further revealed the circulation in the northern Gulf was driven by the positive wind stress curl in summer. Besides, the river discharge was also significant as the vertical circulation had two layer structures outside the mouth of the Red River. Generally, this work calls for the further research on other subjects, such as ocean biogeochemical or marine fisheries.

**Beibu Gulf, summer circulation, numerical model (POM), mechanism**

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The Beibu Gulf, located in the northwestern South China Sea (SCS), has an area of 130000 km$^2$. Its water depth is usually less than 100 m, with the mean depth of 50 m. In particular, it is rich in oil, gas, and biological resources. However, the summer circulation structure in the Beibu Gulf has been in controversy in the past decades, with three major views shown in Figure 1.

The first view suggested the summer circulation in the Gulf was anticyclonic (State Science and Technology Commission, 1964; Yu and Liu, 1993; Wang, 1998; Sun et al., 2001). Similar conclusions were derived by the first three papers (State Science and Technology Commission, 1964; Yu and Liu, 1993; Wang, 1998) that the Gulf was dominated by a gulf-scale anticyclonic gyre in summer, nested a small anticyclonic gyre in the southern gulf (Figure 1(a)). Verifying it by model and through observation, Wang (1998) pointed out the current off the northwestern coast of Hainan was northeastward (Figure 1(a)) whereas it was southwestward in the other two papers (State Science and Technology Commission, 1964; Yu and Liu, 1993), with the pink arrow shown in Figure 1(a). On the other hand, Sun et al. (2001) modeled a slightly different general circulation from above. But all the above studies suggested that the

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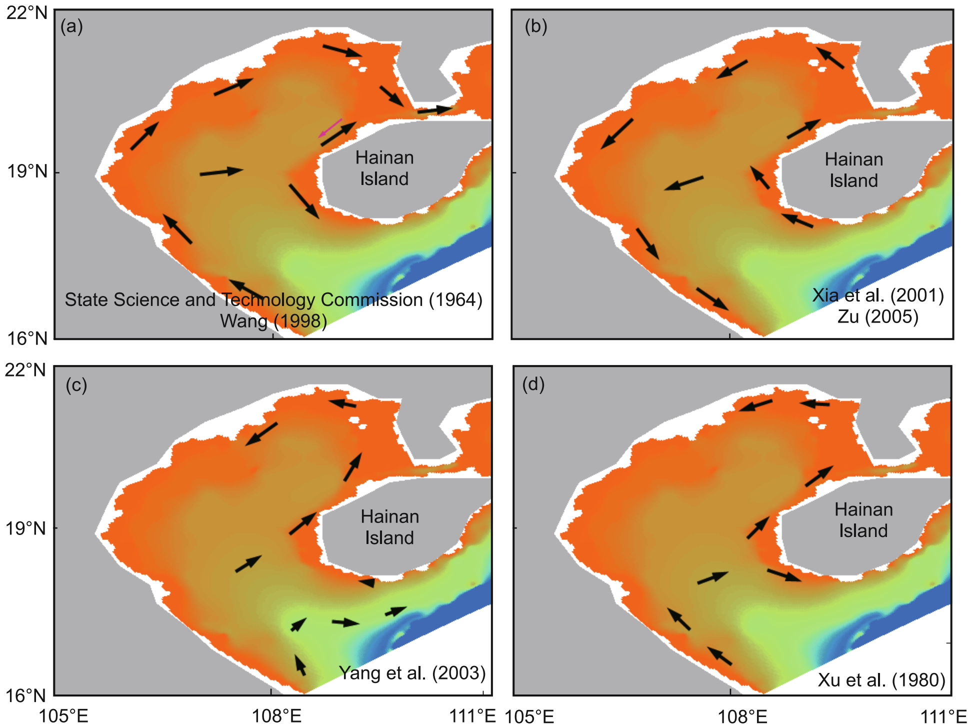


**Figure 1** The circulation diagram in the Beibu Gulf (only the arrow direction is meaningful). (a)–(d) Derived from the State Science and Technology Commission (1964) and Wang (1998), Xia et al. (2001) and Zu (2005), Yang et al. (2003), and Xu et al. (1980). Depths larger than 200 m are labeled in one color.

current off the Vietnamese coast was northward. In addition, Wang (1998) and Sun et al. (2001) suggested the summertime current off the northwestern coast of Hainan was northward by both model and observation results.

The second view (Figure 1(b)) pointed out the general summer circulation in the Gulf was cyclonic (Xia et al., 2001; Zu, 2005), that is, one branch of the current intruding into the Beibu Gulf off the southwestern coast of Hainan turned westward off the western coast of Hainan and then flew out of the Gulf off the Vietnamese coast to form a cyclonic gyre in the southern Gulf whereas another branch flew northward off the northwestern coast of Hainan, and then turned westward along the northern Gulf coast and finally flew southward off the Vietnamese coast to form a gulf-scale cyclonic gyre. Wu et al. (2008) revealed the circulation was gulf-scale cyclonic but the currents off the northwestern and southwestern coasts of Hainan were southwestward and southeastward, respectively. In general, both model and observation verified that the current along the northern coast of the Gulf was westward (Xia et al., 2001; Zu, 2005; Wu et al., 2008), indicating the northern Gulf was more likely occupied by a cyclonic gyre. On the contrary, using the numerical model, Yuan and Deng (1999) pointed out that the summer circulation was cyclonic and anticyclonic in the southern and northern Gulf, respectively. But their model results were not checked by observation data, so this circulation structure needs to be further examined.

With pure observation data, the third view was held by Yang et al. (2003) and Xu et al. (1980). They suggested the northern and the southern Gulf were occupied by a cyclonic and an anticyclonic gyre, respectively. Using drift bottles trajectories, current daily observation data, and temperature and salinity field observation data between 1962 and 1976, Yang et al. (2003) suggested that the summer circulation was cyclonic in the northern Gulf, with an anticyclonic gyre over the mouth of the Gulf (Figure 1(c)). Slightly different from Yang et al. (2003), Xu et al. (1980) revealed the northern and the southern Gulf were dominant by a cyclonic and an anticyclonic gyre (Figure 1(d)), respectively, through examining the geostrophic currents at surface and 500 m depth by observed data in almost 6000 stations between 1921 and 1970. Additionally, the observation stations utilized by Yang et al. (2003) were mostly located in the northern Gulf, and the historical observation data indicated the current off the Vietnamese coast was northward in the southern Gulf (State Science and Technology Commission, 1964; Wang, 1998; Sun et al., 2001). Therefore, the general circulation in the southern Gulf was more likely to be anticyclonic, similar to the conclusion of Xu et al. (1980). Why did the previous numerical models results differ from that of Xu et al. (1980)? Generally, it was mainly due to the incomplete driving forces in the previous models, such as lack of wind, heat flux or lateral flux. On the other hand, some scholars utilized temporally and spatially averaged wind. In this study, a new three-dimensional hindcast model was developed, with the daily averaged surface and lateral boundary fluxes as well as tidal harmonics and monthly climatological river discharges taken into account.

As with circulation structure, the formation mechanism was also controversial. With a theoretical model, Liu and Yu (1980) analyzed the circulation characteristics in the Beibu Gulf, and suggested that the circulation was related to the monsoon wind and geographical environment. Manh and Yanagi (2000) indicated the circulation in the Gulf was dominated by the monsoon wind. In other words, the current in the upper layer was essentially westward or southwestward during winter, whereas it was reversed during summer. Guo and Wang (1983), and Sun et al. (2001) concurred that the monsoon wind played the most important role in the Beibu Gulf circulation. However, Xia et al. (2001), and Zu (2005) thought density gradient was the key driving force of the Gulf circulation. On the other hand, Wang (1998) revealed the wind-driven current was the most critical in the Gulf and the SCS circulation was also important. Some scholars found that the westward transport or potential vorticity from the Qiongzhou Strait (QS) to the Beibu Gulf was significant to the circulation in the northern Gulf (Wu et al., 2008; Yang et al., 2003; Shi et al., 2002; Yang et al., 2006). Thus, the second purpose in this paper is to examine the formation mechanism of the summer circulation in the Beibu Gulf by sensitive experiments and theoretical analysis.

## 1 Model setup

In this study, the Princeton Ocean circulation model (Blumberg and Mellor, 1987) is utilized, which is a three-dimensional numerical model solving the primitive equations with free surface and 2.5 level turbulence closure (Mellor and Yamada, 1982). The model domain is shown in Figure 2, in which the horizontal grids are separated into 399×399 with orthogonal curvilinear coordinate, with horizontal resolution varying from 0.9 to 2 km. Vertically, there are 21 sigma layers. The depth data are extracted from ETOTO2v2. The maximum depth is 2129 m, located in the southeastern domain, whereas the minimum depth is set to 10 m.

In addition, daily averaged wind is obtained from http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html, which is a product merged from multiple satellite scatterometers and model analysis on a global 0.25° grid (Zhang et al., 2006). Daily averaged heat flux is extracted from OAFlux project (http://oaflux.whoi.edu/descriptionheatflux.html), which re-pre-sents the best possible estimate on a global 1° grid, synthesizing measurements from various sources (Yu et al., 2008). In this study, precipitation and evaporation are not considered.

And six principal tidal constituents ($K_1$, $O_1$, $P_1$, $M_2$, $S_2$, and $N_2$) are prescribed at the two open boundaries due to the strong tidal mixing in the domain (Shi et al., 2002; Hu et al., 2003; Lu et al., 2008). The tidal constants are obtained from the Oregon State University tidal model (http://volkov.oce.orst.edu/tides/YS.html), which has a horizontal resolution of 1/30° in the China Seas, with the root mean square (RMS) of $K_1$ and $M_2$ being 1.63 cm and 4.16 cm, respectively (Zu et al., 2008).

Derived from the global 1/12° HYCOM+NCODA analysis between December 1, 2005 and December 31, 2007,

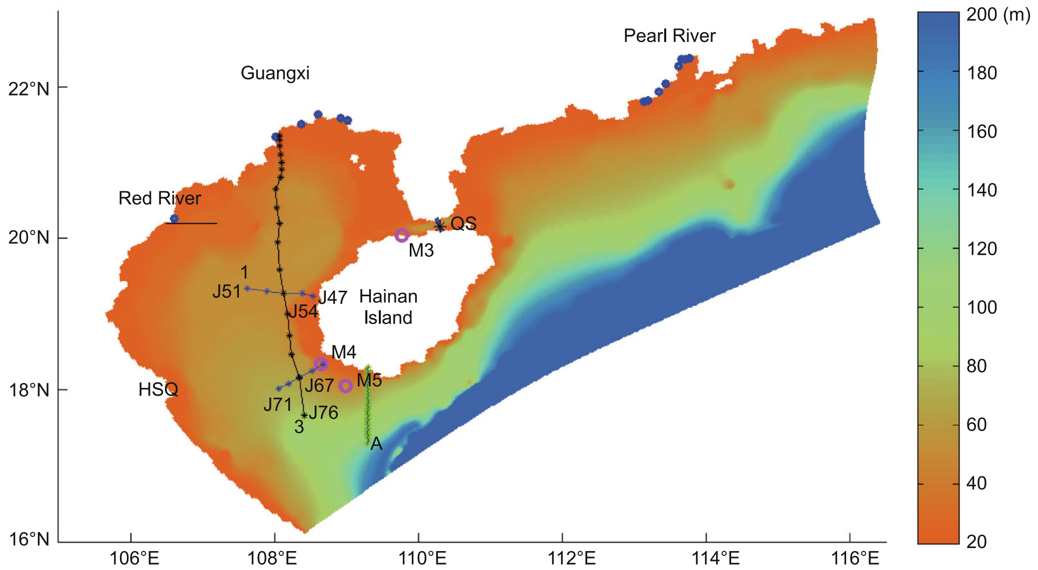


**Figure 2** Model domain and the bathymetry extracted from ETOPO2v2. To emphasize the depth characteristic in the Beibu Gulf, the depth larger than 200 m is shown as one color. The blue circles represent the river estuaries, and QS and HSQ represent the Qiongzhou Strait and the cape Hoanh Son Quan, respectively. Cross sections 1, 2, and 3 are utilized for the validation of temperature and salinity, as well as the current mooring stations M4 and M5 which are labeled as the pink circles. And cross section A is selected to compare the observed and modeled temperature and salinity in the transect off the southwestern coast of Hainan. Lastly cross section R is used to examine the vertical distribution of the circulation and salinity in the Red River plume.

daily averaged elevation, temperature, salinity, barotropic (vertically averaged), and baroclinic velocities are specified at the two open boundaries. Besides, the initial temperature and salinity are extracted from the global 1/12° HYCOM+ NCODA analysis on December 1, 2005. Flather (1976) boundary condition is adopted to relate the barotropic velocity and the elevation; gravity wave radiation combined with three-point smoothing is applied to the baroclinic velocity; and upwind advection is utilized for the temperature and salinity. To satisfy CFL condition, the time steps of internal (baroclinic) and external (barotropic) mode are set to 20 s and 1 s, respectively. Lastly, the daily averaged results are analyzed after the integration of three months (after March 1, 2006).

Although the Pearl River is at least 200 km far away from the Beibu Gulf, it still has an important effect of the hydrography in the northern South China Sea (Xue et al., 2004; Gan et al., 2009). Following Xue and Chai (2002) and Wong et al. (2003), here we divided the Pearl River into eight branches, which are shown in Figure 2. The discharges of them are 6.0%, 6.2%, 6.1%, 28.3%, 11.2%, 6.4%, 17.3%, and 18.5% from west to east, respectively. The Red River, located along the western coast of the Beibu Gulf, is the second largest river in the domain and its climatological monthly averaged discharges are derived from Van Maren and Hoekstra (2004). In addition, the climatological monthly averaged discharges of other six rivers around the northern Gulf coast are also considered (Table 1).

## 2 Model validation

In this study, *in situ* data between 2006 and 2007 were collected from the project 908, including current profiles, and temperature and salinity cross sections. Firstly, the current data from two moorings off the southwestern Hainan from April to May in 2007 were utilized (Wang et al., 2009), shown in Figure 3. Observation showed that the current at station M4 was basically westward except the bottom 5 m. At station M5, the current was southwestward in the upper 5 m, and rotated counterclockwise with the depth till the bottom boundary layer. These characteristics were reproduced in the model. On the other hand, the strong current in the upper boundary layer was simulated by the numerical model, but it was not presented by *in situ* data due to the limitation of observation instruments. Besides, the current rotation at station M5 in the model was not as strong as observation. In fact, the current rotation strength was proportional with water depth, so the upper and bottom boundary layers were more likely to be developed independently in deep zones (Durski et al., 2004). Therefore, the shallower water depth from ETOPO2v2 resulted in the weaker rotation at M5. Besides, the current rotation was related to the small-scale or localized processes, such as a topographic bump which might contribute to the stronger flows in the bottom boundary layer. Finally, the nearest grid to station M5 in the model was adopted for the current validation, so the offset grid will induce better validation.

In addition to the current validation, the temperature and salinity observation data during the spring of 2007 were also examined from the project 908. The observation results revealed that there were two cold water masses in spring in the Beibu Gulf, shown in Figure 4 (Huang et al., 2009). The northern water mass was cold and fresh (Figure 4(a) and (b)) whereas the southern one was cold and saline (Figure 4(c) and (d)). Besides, these two water masses were separated by the sea bridge at station J54 in the cross section 3 (Figure 4(e) and (f)). All these characteristics were available in the model, shown in Figure 5, including the northern fresh and cold water mass and southern saline and cold water mass. On the other hand, the model showed the northern shelf between B01 and B07 was seriously affected by the Beilun plume (Figure 5(e)), which was not shown in the observed results (Figure 4(e)). This difference was due to the fact that the observed temperature and salinity in the cross section 3 was obtained on April 29, 2007, but the river discharges adopted in the model were climatologically monthly averaged.

The temperature and salinity cross sections from the project 908 showed that there was an upwelling off the southwestern coast of Hainan in July of 2006 (Chen et al., 2009), presented in Figure 6. Due to the lack of the original data, the cross section of 109.3ºE was utilized to compare

**Table 1** Climatologically monthly discharges of the major rivers in the northwestern SCS

| | Monthly discharge ($10^8$ $m^3$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Pearl River | 94.5 | 91.3 | 110.8 | 228.2 | 453.1 | 446.6 | 560.7 | 469.4 | 299.9 | 218.4 | 157.3 | 127.1 |
| Nanliu River | 1.50 | 1.64 | 1.91 | 5.39 | 6.27 | 11.5 | 10.5 | 14.4 | 7.30 | 3.55 | 2.59 | 1.71 |
| Qinjiang River | 0.37 | 0.33 | 0.49 | 1.22 | 1.67 | 3.49 | 3.76 | 4.27 | 1.86 | 0.96 | 0.71 | 0.47 |
| Fangcheng River | 0.34 | 0.35 | 0.48 | 0.78 | 1.42 | 2.51 | 4.11 | 3.49 | 2.00 | 1.08 | 0.73 | 0.43 |
| Dafeng River | 0.22 | 0.20 | 0.28 | 1.06 | 1.43 | 3.42 | 3.93 | 4.46 | 1.79 | 0.75 | 0.48 | 0.28 |
| Maoling River | 1.06 | 0.90 | 1.10 | 2.31 | 2.65 | 3.53 | 4.43 | 4.93 | 4.06 | 2.23 | 1.04 | 0.78 |
| Beilun River | 0.62 | 0.62 | 1.00 | 1.66 | 3.32 | 4.48 | 6.54 | 5.12 | 2.82 | 1.78 | 0.83 | 0.54 |
| Red River | 6.53 | 6.53 | 6.53 | 6.53 | 7.62 | 16.3 | 32.6 | 49.0 | 42.5 | 30.0 | 19.1 | 11.4 |

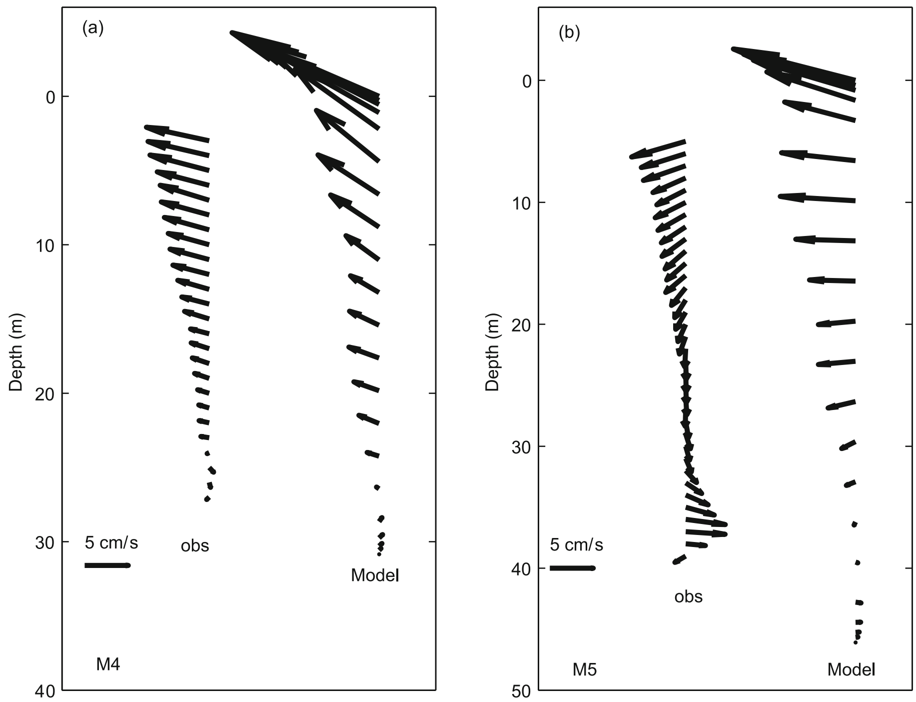


**Figure 3** The modeled and observed velocity profiles at stations M4 (a) and M5 (b), averaged from April 17 to May 17, 2007.

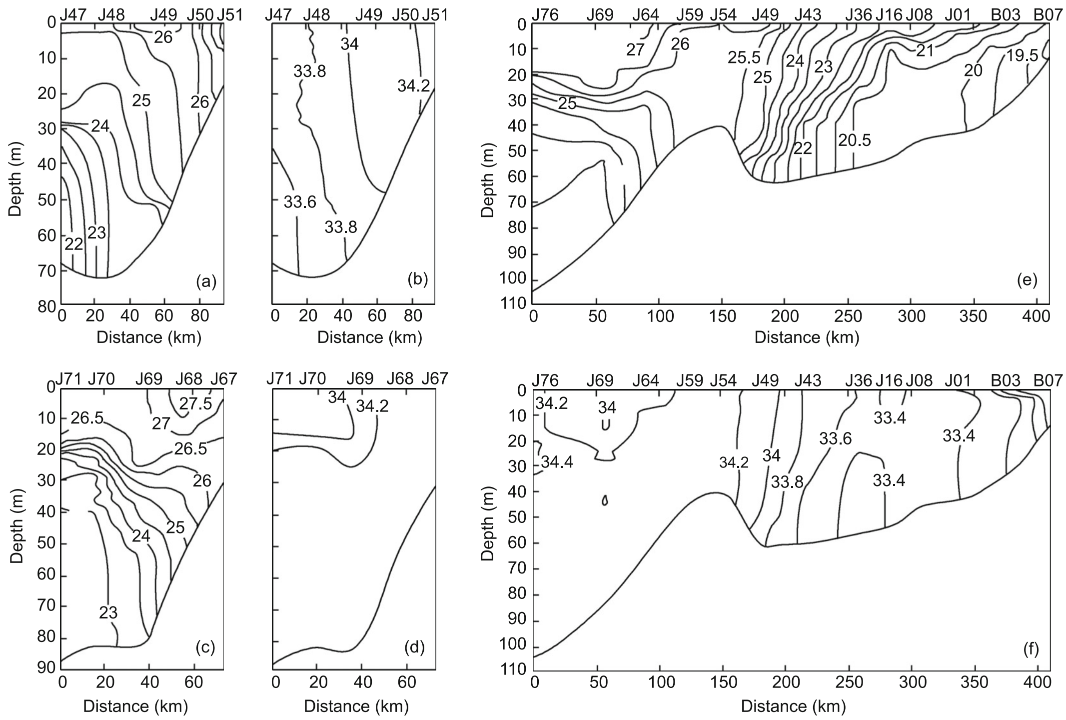


**Figure 4** The observed temperature ((a), (c), (e)) and salinity ((b), (d), (f)) from the project 908. (a) and (b), (c) and (d), and (e) and (f) represent the observed temperature and salinity in the cross section J47–J51 on April 26, 2007, the cross section J71–J67 on April 29, 2007, and the cross section J76–B07 on April 29, 2007, respectively. The pictures are derived from Huang et al. (2009).

the model and observation, shown in Figure 7. Both model and observation showed that the isohaline contours of 34 and 34.5 were dominant and isohaline contour of 34.5 curved upwards, with sparse isohaline contours in the cross sections. On the other hand, the upward curvature of the isotherm contours in the model was stronger than the observation, which was related to more stations contained in the cross section of 109.3°E of the model (Figures 2 and

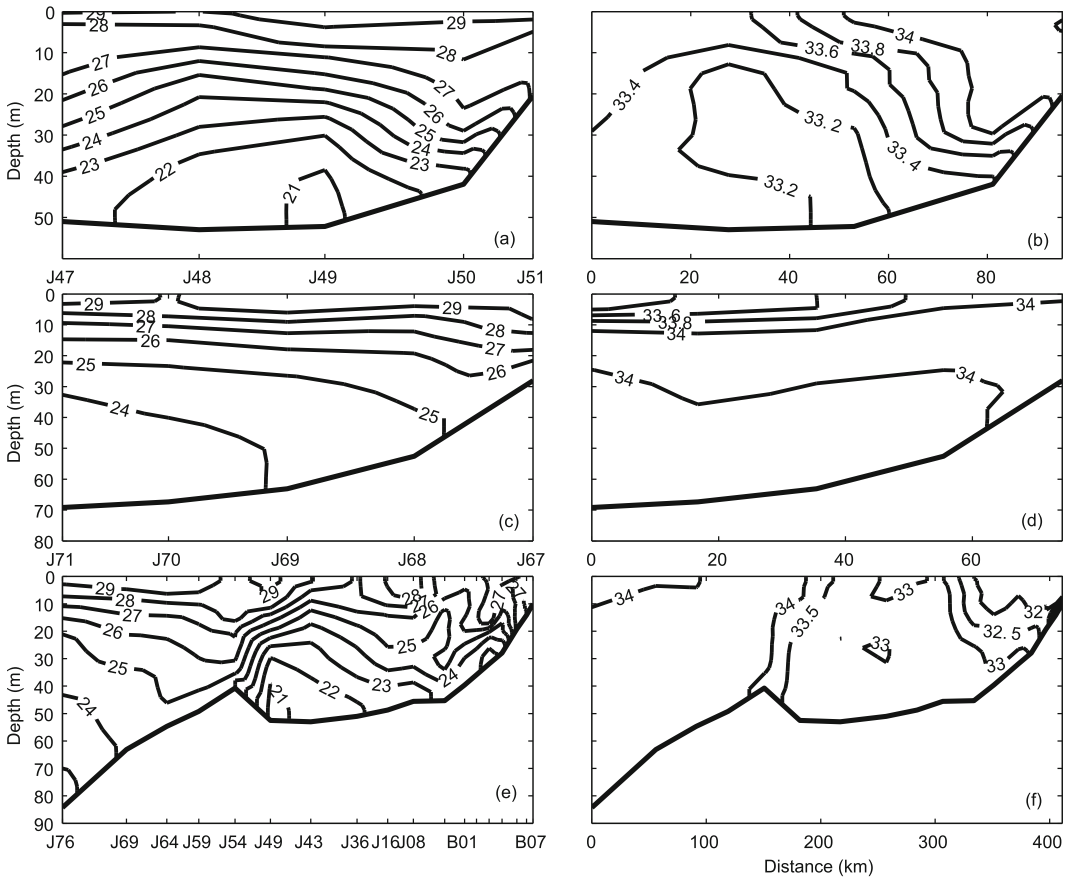


**Figure 5** The modeled temperature ((a), (c), (e)) and salinity ((b), (d), (f)) profiles. (a) and (b), (c) and (d), and (e) and (f) represent the modeled temperature and salinity in the cross section J47–J51 on April 26, 2007, the cross section J71–J67 on April 29, 2007, and the cross section J76–B07 on April 29, 2007, respectively.

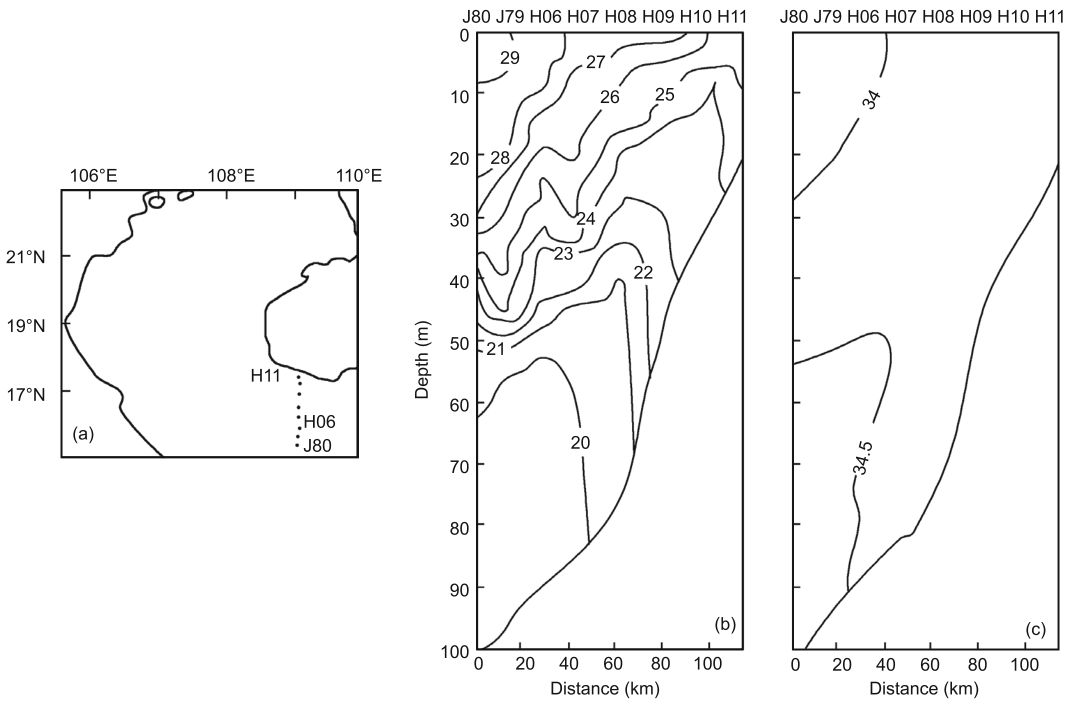


**Figure 6** The distribution of the observation stations off the southwestern coast of Hainan from July 15 to August 7, 2006 (a), and the corresponding vertical distribution of temperature (b) and salinity (c). The pictures are derived from Chen et al. (2009).

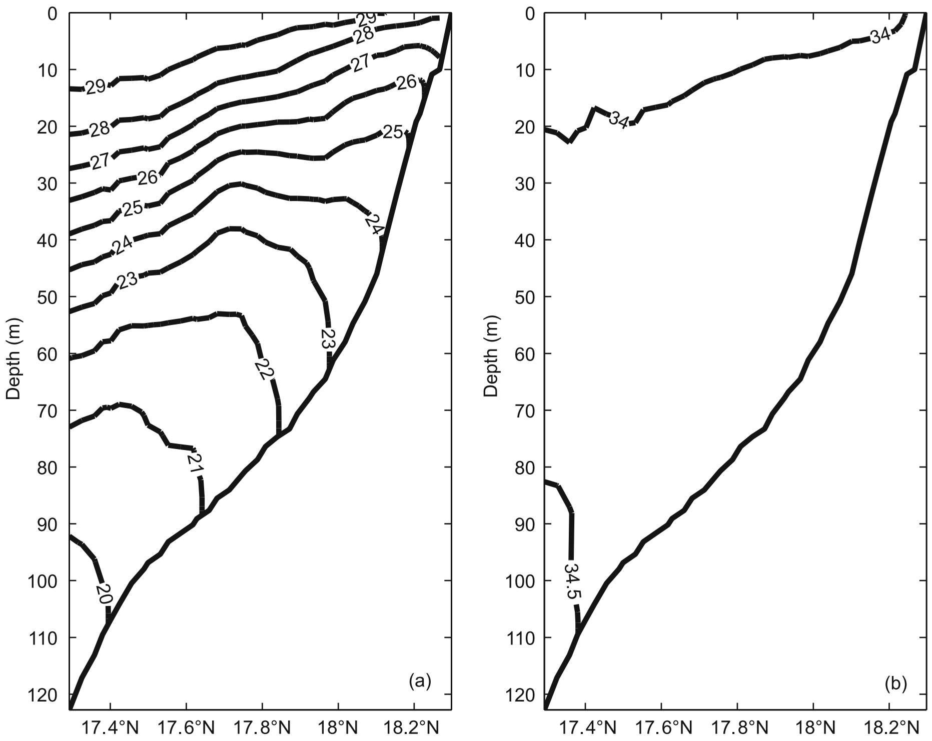


**Figure 7** The modeled temperature (a) and salinity (b) off the southwestern coast of Hainan from July 15 to August 7, 2006.

6(a)). In general, the model results were in good coincidence with the observation, and there was also difference between the model and observation. When the local processes, such as cold water masses or upwelling, are examined in the future, this gap will be reduced by gathering the higher spatial resolutions of the wind and heat flux or using finer grid in the local regions.

## 3 Circulation structure

The summer circulation was vertically averaged in the Beibu Gulf, shown in Figure 8. It was concluded that the southern Gulf was occupied by an anticyclonic eddy whereas the gyre in the northern Gulf was cyclonic. They were separated by the current between the HSQ of Vietnam and Qiongzhou Strait, with their locations labeled in Figure 1. In June, the cyclonic gyre in the northern Gulf was in development. So there was a northeastward current along the western coast of the Beibu Gulf, which turned eastwards at ~21°N and lastly flew into the QS combined with the northeastward current off the northwestern coast of Hainan. The cyclonic gyre matured in July 2006 when the northeastward current along the western Gulf coast contracted southwards to 20.5°N (Figure 8(d)). In July 2007, the whole northern Beibu Gulf was occupied by a cyclonic eddy (Figure 8(b)), and the northeastward current along the western Gulf coast contracted southwards to 19°N. In short, the northern Beibu Gulf was dominated by a cyclonic gyre in summer, and the gyre contained three main limbs of the northeastward current off the northwestern coast of Hainan, the westward current off the southern coast of Guangxi Zhuang Autonomous Region (called "Guangxi" hereinafter), and the eastward current in the central Gulf (~18.5°N). This circulation structure was in accordance with the observed results in Xu et al. (1980), Xia et al. (2001), Yang et al. (2003), and Wu et al. (2008). In addition, the northward current along the western Gulf coast in June 2006, June and July 2007 was verified by the observed data in the China-Vietnam joint survey report (State Science and Technology Commission, 1964), Wang (1998), and Sun et al. (2001). Therefore, the model results were in coincidence not only with the observation data from the project 908 but also with the historical observed results.

The above analysis revealed that the circulation major structure was stable in the northern Gulf whereas it also had annually and monthly oscillation. This characteristic was also reproduced in the southern Gulf. For example, the southern Gulf was occupied by an unclosed anticyclonic gyre in June 2006 and July 2007, but it was occupied by an anticyclonic eddy in July 2006 and June 2007. Besides, the anticyclonic gyre in July 2007 penetrated into the northern Gulf more northward than others, but the strength and area of the anticyclonic eddy was the largest in July 2006. And there was a good correlation between the low-passed currents and winds in the southern Gulf, with the vector correlation coefficient ( $\rho_v^2$ : 0–2, Crosby, 1993) of 1.1 and 0.8 in the eastern and western regions, respectively (Gao et al., 2013). In the northern Gulf, the vector correlation coefficient

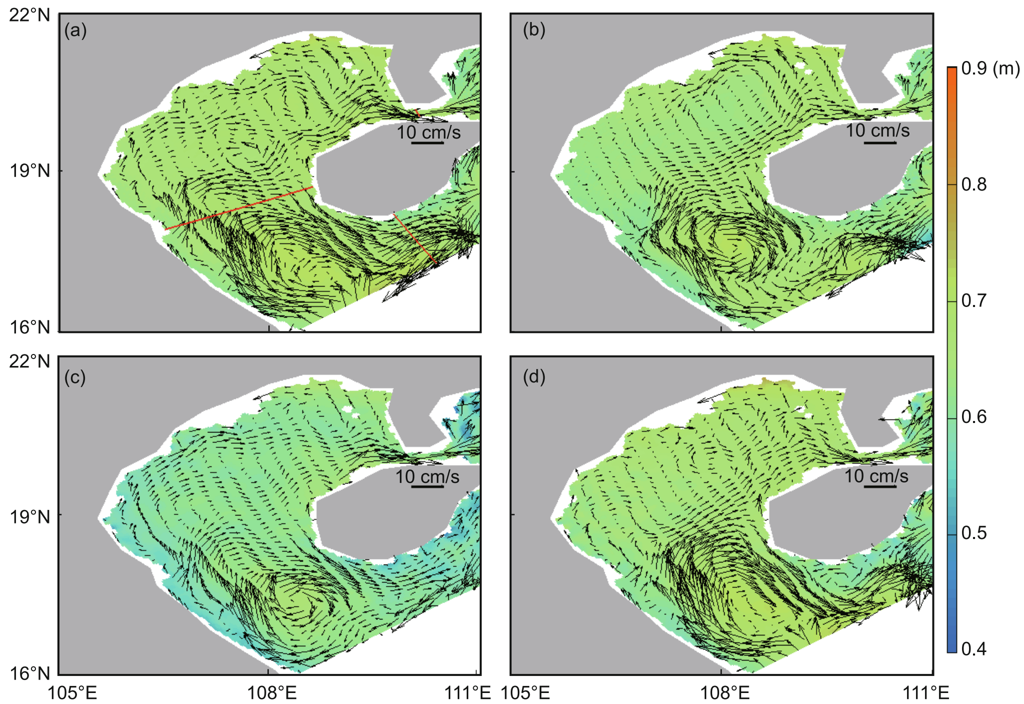


**Figure 8** The vertically averaged circulation in June 2006 (a), July 2006 (b), June 2007 (c), and July 2007 (d), with the color representing elevation (m). The three red lines, located in the QS, off the western coast of Hainan, and in the southern Gulf, respectively, would be utilized as the boundaries to examine the potential vorticity budget.

was of 1.1 in the northeastern Gulf, and the northward current along the western Gulf coast was also highly correlated to the wind (Gao et al., 2013). With the gulf-scale averaged wind and heat flux, it was revealed that the daily averaged meridional wind ($v$) was in good correlation with the daily averaged heat flux, with the Pearson coefficient of 0.77. Generally, the circulation major structure was stable in the Gulf, but its strength and range had annually and monthly oscillation under the force of the wind and heat flux. The vector correlation coefficient utilized above describes the correlation of direction and amplitude changes between two vectors, with the value between 0 and 2. However, the Pearson coefficient describes the correlation of amplitude changes between two components, with the value between 0 and 1.

Due to the stable circulation major structure, the circulation in July 2006 was selected to analyze the currents variability in vertical profile, shown in Figure 9. The anticyclonic gyre in the southern Gulf was unclosed at surface whereas it was totally closed but weaker at 10 and 20 m (Figure 9(b) and (c)). And the current weakened much at 40 m depth (Figure 9(d)). In the northern Gulf, the current was essentially northeastward at surface, nested a small cyclonic eddy in the northwestern Gulf (Figure 9(a)). However, the whole northern Gulf was occupied by a large cyclonic eddy at 10 and 20 m depth (Figure 9(b) and (c)). At 40 m, the weakened northeastward current was dominant in the northern Gulf (Figure 9(d)). In a word, the circulation structure below the thermocline layer (~10 m) differed from that at surface, with stronger current at surface.

For the Qiongzhou Strait (QS), one month observation data in the western end of the QS (Zhang et al., 2009) showed that the current was eastward in late July of 2006 and had strong daily oscillation in August with several strong westward current events induced by the tropical cyclones. The mechanism analysis indicated the elevation difference between the two ends of the QS was dominant in the current in the QS (Gao et al., 2013). Driven by the southwesterly wind, sea water in the eastern end of the QS was transported seawards, while the elevation in the western end of the QS was piled up due to the northeastward current off the northwestern coast of Hainan. Therefore, the pressure gradient between the two ends of the QS drove the eastward current in the QS. When the centers of the tropical cyclones were located in the Beibu Gulf or off the eastern coast of Hainan Island, the elevation in the eastern end of the QS would be sharply increased to result in the strong westward current events in the QS (Gao et al., 2013). However, Shi et al. (2002) concluded the flow was always westward in the QS in summer by the analysis of the short-term (25 h) current observation data over years. In fact, there were two reasons explaining this difference. Firstly, the short-term observation was usually operated under weak or no wind when the westward tide-induced residual current was dominant in the QS. Secondly, the observed daily averaged current was more likely westward contributed from the strong daily oscillation of the current in the QS.

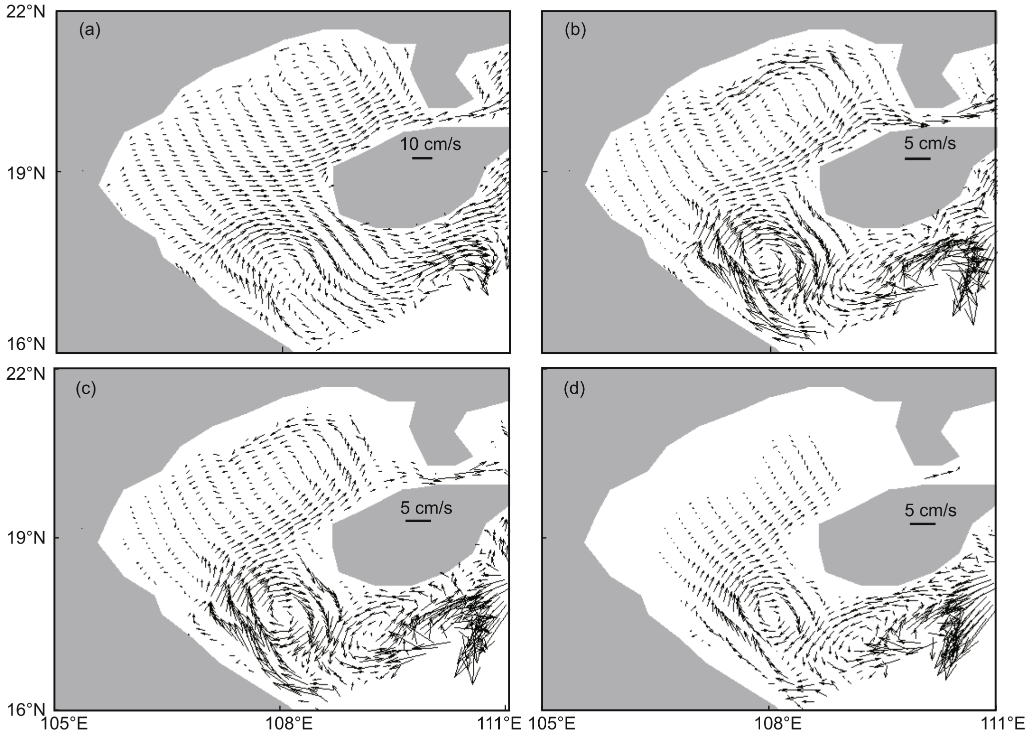


**Figure 9** The vertically averaged circulation in July 2006. (a), (b), (c), and (d) representing the circulation at surface, 10 m, 20 m, and 40 m, respectively.

# 4 Formation mechanism

## 4.1 Sensitive experiments

In this study, three sensitive experiments, including no tide, no heat flux and no wind, were carried out to analyze the formation mechanism of the summer circulation in the Gulf, shown in Figure 10(b)–(d). Without the force of tide (Figure 10(b)), the circulation major structure was similar to the control run (Figure 10(a)) except the stronger current in the southern Gulf because the tide-induced gyre was cyclonic. Without heat flux, the currents in the southern and northern Gulf were strengthened and weakened, respectively (Figure 10(c)). Without wind, the southern Gulf was still occupied by an anticyclonic eddy whereas the circulation in the northern Gulf changed from a cyclonic gyre to an anticyclonic gyre. It could be inferred that the circulation in the southern and northern Gulf was dominated by the SCS circulation and local wind, respectively. Comparison of wind stress and wind stress curl fields in summer of 2006 and 2007 revealed that the positive wind stress curl drove the cylonic gyre in the northern Gulf while the northward current along the western Gulf coast was driven by the wind stress. To quantitatively analyze the formation mechanism, the potential vorticity budget in the Beibu Gulf would be further examined.

## 4.2 Potential vorticity budget

The vorticity equation can be derived from the sum of the partial difference zonal and meridional momentum equations, shown in eq. (1). Because the vertical advection term is small (or hypothesis of incompressible fluid), it is not written in the equation:

$$\frac{\partial \xi}{\partial t} = -\left(u\frac{\partial \xi}{\partial x} + v\frac{\partial \xi}{\partial y}\right) - \left(\xi + f\right)\nabla\cdot\vec{u} - v\frac{\partial f}{\partial y} + \frac{g}{\rho^2}\left(\frac{\partial \rho}{\partial x}\frac{\partial}{\partial y}\int_z^0 \rho dz - \frac{\partial \rho}{\partial y}\frac{\partial}{\partial x}\int_z^0 \rho dz\right) + \mu\frac{\partial^2 \xi}{\partial z^2}. \quad (1)$$

The term on the left side of the equation represents local changes. And the right terms represent the advection of relative vorticity, stretch of absolute vorticity (convergence and divergence), advection of planetary vorticity, baroclinic change, and input of vorticity (called vorticity dissipation term in this study), respectively. $\mu$ is kinematic viscosity coefficient, of $10^{-4}$ m$^2$ s$^{-1}$.

Referring to the analysis method for Beibu Gulf circulation utilized by Wu et al. (2008), the same potential vorticity equation (Yang, 2005) will be adopted to examine the formation mechanism of the summer circulation in the Beibu Gulf. Different from Wu et al. (2008), the current is baroclinic in this study. And the potential vorticity equation is available in an isopycnal layer or a barotropic water column. Therefore, the potential vorticity integral constraint can be applied for the vertically averaged circulation after being vertically integrated. In addition, Yang (2005) revealed that the movements crossing isopycnal layers (upwelling or downwelling) could drive the recirculation

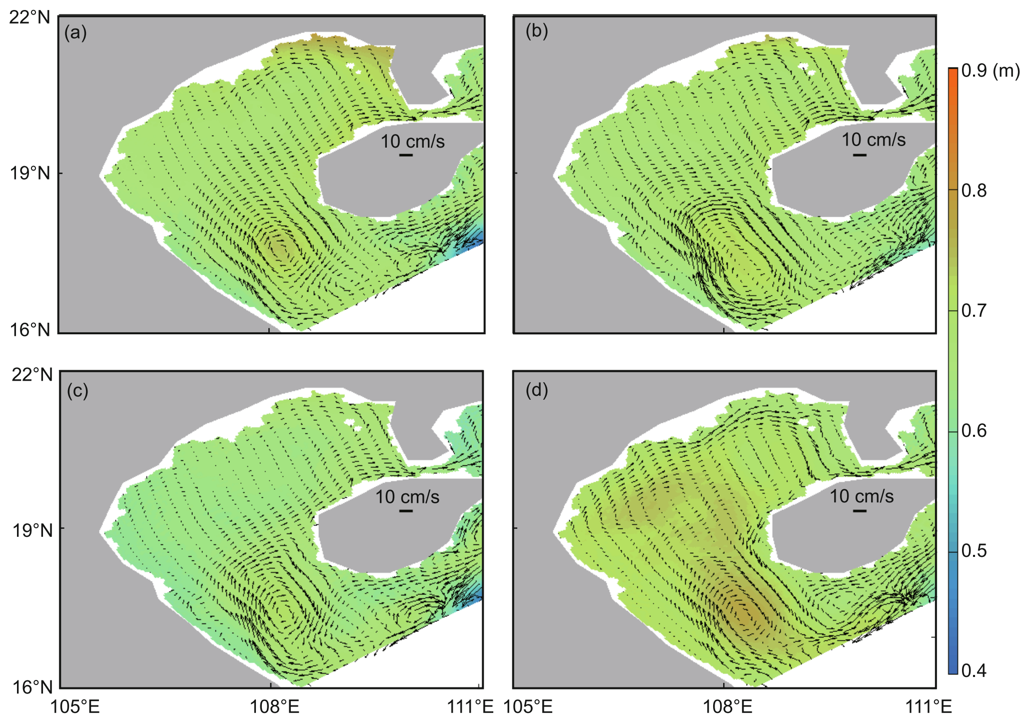


**Figure 10** The vertically averaged circulation in July 2006 derived from the four experiments, namely, the control run (a), without the force of tide (b), without the force of heat flux (c), and without the force of monsoon (d), respectively. The color represents the distribution of elevation (m).

but had no contribution to the vertically integral potential vorticity. Thus, eq. (1) can be transferred as follows:

$$\int_{-h}^{0}\frac{\partial\xi}{\partial t}\mathrm{d}z+\int_{-h}^{0}\nabla\cdot\left[\vec{U}\left(f+\xi\right)\right]\mathrm{d}z=\int_{-h}^{0}F\mathrm{d}z. \tag{2}$$

The variable "$F$" in eq. (2) is corresponding to the last term on the right side of eq. (1), which represents the input of outside vorticity. And the second term on the left side of eq. (2) was the sum of the first three terms on the right side of eq. (1). In eq. (2), $\xi$ is relative vorticity, $f$ is planetary vorticity, $\vec{U}$ is horizontal velocity vector, and $h$ represents the thickness of an isopycnal layer. Owing to the short response time of Beibu Gulf circulation to outside forces (Wu et al., 2008), the first term (time-independent term) on the left side of eq. (2) can be neglected. After vertical integration, new equation (3) can be obtained as

$$\iint_{\mathrm{c}}(h\vec{U}\cdot\vec{n})\left(\frac{f+\xi}{h}\right)\mathrm{d}s\mathrm{d}z=\iiint_{\mathrm{A}}F\mathrm{d}x\mathrm{d}y\mathrm{d}z. \tag{3}$$

Equation (3) in this study differs from those in Yang (2005) and Wu et al. (2008), because it is vertically integrated. $\vec{n}$ is unit vector perpendicular to the lateral boundary, with positive and negative associated with inflow and outflow, respectively. The integration subscript "c" on the left side represents the integration over the lateral boundary. However, another subscript "A" on the right side represents the whole domain integration. According to the dimensional analysis, the planetary vorticity $f$ is far larger than relative vorticiy $\varepsilon$, same as the conclusion in Wu et al. (2008). So eq. (3) can be transferred as follows:

$$\iint_{\mathrm{c}}(h\vec{U}\cdot\vec{n})\left(\frac{f}{h}\right)\mathrm{d}s\mathrm{d}z=\iiint_{\mathrm{A}}F\mathrm{d}x\mathrm{d}y\mathrm{d}z. \tag{4}$$

With the deduced results in Yang (2005), the right term of eq. (4) can be divided as follows:

$$\iint_{\mathrm{A}}F\mathrm{d}x\mathrm{d}y=\iint_{\mathrm{A}}D_p\mathrm{d}x\mathrm{d}y+\oint_{\mathrm{C}}(F\cdot L)\mathrm{d}s, \tag{5}$$

where $D_p$ is the dissipation term of the potential vorticity,

$$D_p\left(x,y\right)=\frac{\partial}{\partial x}\left[\frac{A_H}{H}\nabla\cdot\left(H\nabla v\right)\right]-\frac{\partial}{\partial y}\left[\frac{A_H}{H}\nabla\cdot(H\nabla u)\right],$$

balanced with the input of outside vorticity. In addition, the second term on the right side of eq. (5) represents the vorticity input of the wind stress, with positive wind stress curl corresponding to positive vorticity input of wind in the Beibu Gulf. Because the vorticity input of wind can be described as $1/\rho\ \mathrm{curl}\ \tau_w/H$, , eq. (6) can be derived combined with eqs. (4) and (5):

$$\frac{\iint_{\mathrm{c}}(h\vec{U}\cdot\vec{n})\left(\frac{f}{h}\right)\mathrm{d}s\mathrm{d}z}{H}+\iint_{\mathrm{A}}\frac{1}{\rho}\mathrm{curl}\frac{\tau_w}{H}\mathrm{d}x\mathrm{d}y=\frac{\iiint_{\mathrm{A}}D_p\mathrm{d}x\mathrm{d}y\mathrm{d}z}{H}, \tag{6}$$

where H is the thickness of the whole water column, and $\tau_w$ represents wind stress. If current velocities are the same in a vertical profile and the thickness of every isopycnal layer ($h$) is equal, there will be

$$\frac{\int \vec{U}\cdot\vec{n}\mathrm{d}z}{H}=\vec{U}\cdot\vec{n}\quad\text{and}\quad\frac{\int D_p\mathrm{d}z}{H}=D_p\,.$$

As a result, the first term on the left side will be

$$\sum_{i=1}^{n} Q_i\frac{f_i}{H_i}\,,$$

where $Q_i$ represents the water column flux. And the first terms on the two sides of eq. (6) will be transferred as ones in the barotropic water column equation in Yang (2005) and Wu et al. (2008).

In this study, the east boundary of the model was located around 117°E, so the potential vorticity budget in the Beibu Gulf could not be examined by the integration over the lateral boundary as in Wu et al. (2008). For the northern Beibu Gulf, two boundary lines, labeled in Figure 8(a), were picked out. Because the input of the potential vorticity has a strong response to the water depth, these two lines were set up around the edges of the northern Gulf circulation. In addition, the potential vorticiy integral constraint required that the inflow and outflow water column fluxes must be in balance (Yang, 2005). The calculation revealed that the inflow water column flux from the southern Gulf circulation was balanced with the outflow water column flux in the QS. And the circulation chart (Figure 8) also showed that the current from the southern Gulf circulation flew northeastward off the northwestern coast of Hainan and most of the water column flew out of the Gulf via the QS. At the same time, the inflow and outflow potential vorticities were canceled each other due to the similar depths over the two boundaries, presented in Table 2. According to the conclusion of Yang (2005), cyclonic gyre was driven by the input of positive potential vorticity. In the northern Gulf, the input of the potential vorticity induced by the wind was the largest among the input of outside positive potential vorticities. Therefore, the input of positive potential vorticity induced by the monsoon wind drove the cyclonic gyre in the northern Gulf. Table 2 shows that the input of the positive potential vorticity to the northern Gulf was larger in July 2006 than in the rest of the year. This characteristic was corresponding to that the cyclonic gyre was more mature in July 2006 than in other months. In addition, the chart (Figure 11) showed the northern Beibu Gulf was totally occupied by the positive wind stress curl in July 2006, and the wind stress curl was larger as getting closer to the northern Gulf coast. As a result, the strongly positive wind stress curl drove the cyclonic eddy in the northern Gulf in July 2006 (Figure 8(b)). In general, qualitative and quantitative analysis results revealed the cyclonic gyre in the northern Gulf was dominated by the positive wind stress curl. This conclusion differed from that of Wu et al. (2008) who suggested the cyclonic gyre in the northern Gulf was driven by the input of the westward potential vorticity from the QS to the Gulf. In fact, the analysis of the potential vorticity budget showed that it would be favorable to strengthen the cyclonic gyre if the current in the QS was westward in the summer.

For the southern Gulf, it was found the input of the wind potential vorticity was one order of magnitude smaller than the input of boundaries inflow and outflow potential vorticities. Thus, the monsoon wind did not play a control role on the southern Gulf circulation. However, the drift current directly driven by the southwesterly monsoon wind was favorable to the formation of the southern Gulf anticyclonic gyre. Generally, the total input of negative potential vorticity in the southern Gulf was needed to be balanced with an anticyclonic gyre. On the other hand, although the vertical integration of the baroclinic term was zero, it still had a significant effect on the circulation (Yang, 2005). As the intrusion of the hot and saline SCS circulation into the southern Gulf, the strong baroclinic current would drive the anticyclonic gyre, and the anticyclonic gyre in the southern Gulf would still exist even without the force of monsoon wind (Figure 10(d)).

### 4.3 River effect

As the river discharged into the sea, the elevation in the river plume raised and the density structure changed in vertical profile. Thus, the river barotropic and baroclinic effect was significant to the circulation. However, the effect of the rivers along the western coast of the Beibu Gulf on the circulation had attracted less attention. Among the rivers around the Beibu Gulf, the Red River discharge was far larger than the rivers around Guangxi (Figure 1). Thus, the summer vertical circulation would be examined off the mouth of the Red River, shown in Figure 12. In the upper few meters, the fresh water was transported seawards, and the isohaline contour of 31% extended to ~107.15°E. However, the saline sea water crossed this isohaline contour, and

**Table 2** The input of the potential vorticity to the northern Beibu Gulf contributed from outside forcing ($\mathrm{m^2\ s^{-2}}$)

| | June 2006 | July 2006 | June 2006 | July 2007 |
|---|---|---|---|---|
| Inflow from the southern Gulf | 0.106 | 0.0817 | 0.1704 | 0.1648 |
| Outflow in the QS | −0.1678 | −0.1057 | −0.1765 | −0.1361 |
| Monsoon in the northern Gulf | 0.1846 | 0.8465 | 0.13 | 0.1337 |

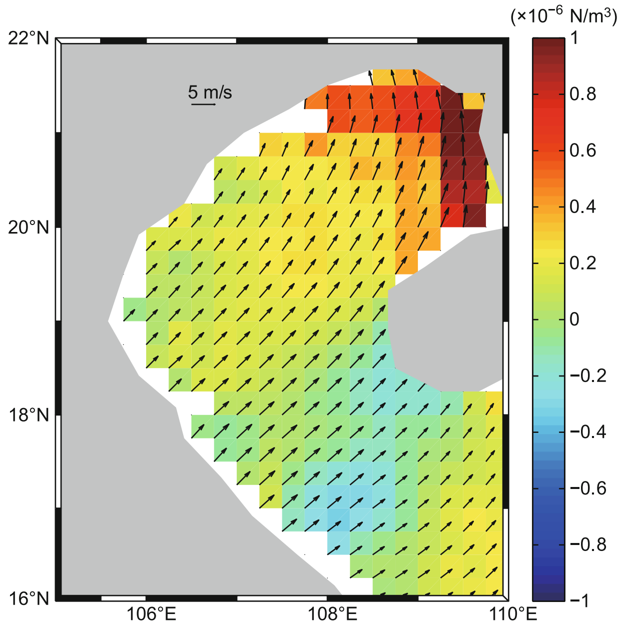


**Figure 11** The wind vector and wind stress curl in July 2006. The arrows and background color represent the wind vector and the wind stress curl, respectively.

flew shoreward to ~106.95°E where it was mixed with the seaward fresh water and sank together to the bottom boundary layer. As a result, a closed vertical (*u* and *w*) circulation with two layer structures was formed off the mouth of the river. In the upper layer, one branch of the seaward fresh water sank at ~106.85°E, which flew shoreward in the middle layer to result in the strong compensation current near the shore with the largest upward current speed of $5\times10^{-5}$ m s$^{-1}$.

## 5 Conclusions

There have been mainly three times of field observation since 1964, including the China-Vietnam Joint Survey during 1964 and 1965 (Su and Yuan, 2005), and the project 908 carried out in the eastern Gulf between 2006 and 2007. Therefore, the observation data are limited in the Beibu Gulf. Besides, the numerical models developed in the Beibu Gulf were mostly diagnostic, and they were in the absence of complete forces. The temporal and spatial resolutions of the forces were not fine enough, and the observed data for the validation were not quite enough in the previous models. As a result, there were great controversies about the circulation structure and formation mechanism in the Gulf. In this study, a three-dimensional baroclinic hindcast numerical model was developed in the northwestern SCS, in which the results were in a good agreement not only with the synchronously observed data from the project 908 but also with the historical observation data.

As a result, the Beibu Gulf circulation in summer was revealed: the southern Gulf was occupied by an anticyclonic eddy, and the northern Gulf was dominated by a cyclonic gyre containing three main limbs of the northeastward current separated from the southern Gulf circulation, the northeastward current off the northwestern coast of Hainan, and the westward current along the northern Gulf coast. The

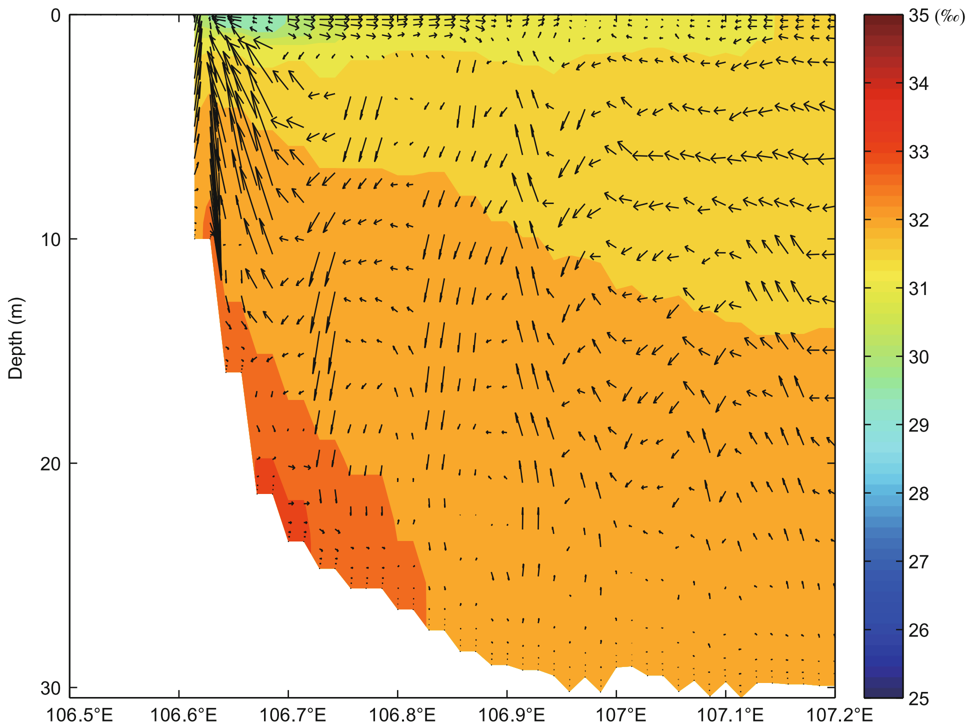


**Figure 12** The vertical distribution of circulation and salinity in the cross section (Figure 2) in the Red River plume, averaged in July 2006.

cyclonic gyre in the northern Gulf formed in June and matured in July when the northward current along the western Gulf coast contracted southwards to ~20.5°N.

Besides, although the major structure of the cyclonic gyre was stable during 2006 and 2007, the strength and range had some changes, especially the northward current along the western Gulf coast. Likewise, the strength and range of the anticyclonic eddy dominant in the southern Gulf had annually and monthly oscillation. In general, the circulation major structure in the Beibu Gulf was stable, but it still had some yearly and monthly oscillation adjusted by the monsoon wind and heat flux. The vertical distribution of circulation showed that the circulations structures were similar in the lower layers below 10 m but the current speeds became weaker with depth. However, the circulations at depth differed from the circulation at surface, especially in the northern Gulf.

Based on the control run and other three sensitive experiments, it was indicated the southern Gulf was controlled by the SCS circulation whereas the local wind was dominant in the northern Gulf. The density current induced by the heat flux and the tide-induced current changed the circulation strength, but they did not affect the circulation major structure. The analysis of the potential vorticity budget revealed that the potential vorticity from the QS to the Gulf was negative in this study. However, the wind and southern Gulf circulation potential vorticities were both positive, but the former was far larger than the latter. Therefore, it was concluded the cyclonic gyre in the northern Gulf was driven by the wind stress curl. In addition, the potential vorticities between the inflow from the southern Gulf circulation and outflow in the QS were essentially canceled each other. Nevertheless, they were dominant in the northeastward current off the northwestern coast of Hainan. In the southern Gulf, although the potential vorticiy from wind was one order less than that from the boundaries inflow and outflow, the drift current directly induced by the southwesterly wind stress was favorable to the formation of the anticyclonic circulation. In general, the input of negative potential vorticity was required to be balanced with the anticyclonic circulation. On the other hand, the baroclinic term induced by the intrusion of the hot and saline SCS circulation was significant to the circulation in the southern Beibu Gulf.

Besides the wind, heat flux, and tidal harmonic effect, the barotropic and baroclinic contribution from the fresh water along the western Gulf coast was also important to the circulation. The vertical circulation had two layer structures, with the clockwise circulation in the upper layer. Specifically, the fresh water near surface flew seaward and sank ~3 km outside the river mouth. Then it flew shoreward in the middle layer to result in the compensation upwelling near the shore.

The general circulation in the Gulf has an important role on the nutrient transport and sedimentary dynamic environment (Tong et al., 2012). Thus, the settlement of the controversies about the circulation structure and formation mechanism was favorable to the further research of other subjects in the Gulf. According to the hindcast model in this study, the forecast circulation and ecological models will be further developed, which can provide scientific reference data for the marine development and environment protection in the Beibu Gulf.

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Blumberg A F, Mellor G L. 1987. A description of a three-dimensional coastal ocean circulation model, in Three-Dimensional Coastal Ocean Models. Coastal Estuarine Stud, 4: 1–16

Chen Z Z, Hu J Y, Sun Z Y, et al. 2009. Distributions of temperature, salinity characteristics in the eastern Beibu Gulf in July and August of 2006 (in Chinese). The Essay Collection of the Researches on the Ocean Science in the Gulf of Tonkin- PT I. Beijing: China Ocean Press. 79–87

Crosby D S, Breaker L C, Gemmill W H. 1993. A proposed definition for vector correlation in geophysics: Theory and applications. J Atmos Oceanic Technol, 10: 355–367

Durski, S M, Glenn S M, Haidvogel D B. 2004. Vertical mixing scheme in the coastal ocean: Comparison of the level 2.5 Mellor-Yamada scheme with an enhanced version of the K-Profile parameterization. J Geophys Res, 109: C01015

Flather R A. 1976. A tidal model of the northwest European continental shelf. Mem Soc Roy Sci Liege, 6: 141–164

Gan J P, Li L, Wang D, et al. 2009. Interaction of a river plume with coastal upwelling in the northeastern South China Sea. Cont Shelf Res, 29: 728–740

Gao J S, Xue H J, Chai F, et al. 2013. Modeling the circulation in the Gulf of Tonkin, South China Sea. Ocean Dynam, 63: 979–993

Guo Z X, Wang W Z. 1983. Numerical simulation of wind-induced current in Beibu Gulf (in Chinese). Tropical Oceanol, 2: 207–215

Hu J Y, Kawamura H, Tang D L. 2003. Tidal front around the Hainan Island, northwest of the South China Sea. J Geophys Res, 108: C113342

Huang Z D, Hu J Y, Sun Z Y. 2009. Distributions of temperature, salinity and density in the eastern Beibu Gulf in spring 2007 (in Chinese). The Essay Collection of the Researches on the Ocean Science in the Gulf of Tonkin-PT II. Beijing: China Ocean Press. 92–99

Liu F S, Yu T C. 1980. Preliminary study on the oceanic circulation in Beibu Bay (in Chinese). Trans Oceanol Limnol, 1: 9–15

Lu X G, Qiao F L, Wang G S, et al. 2008. Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. Geophys Res Lett, 35: L02604

Manh D V, Yanagi T. 2000. A study on the residual flow in the Gulf of Tonkin. J Oceanogr, 56: 59–68

Mellor G L, Yamada T. 1982. Development of a turbulence closure model for geophysical fluid problems. Rev Geophys Space Phys, 20: 851–875

Shi M C, Chen C S, Xu Q, et al. 2002. The role of Qiongzhou Strait in the seasonal variation of the South China Sea circulation. J Phys Oceanogr, 32: 103–121

State Science and Technology Commission. 1964. China-Vietnam Joint Beibu Gulf Comprehensive Survey Report

Su J L, Yuan Y L. 2005. Hydrography of China Seas (in Chinese). Beijing: China Ocean Press. 367

Sun H L, Huang W M, Zhao J S. 2001. Three-dimensional numerical simulation of tide-induced,wind-driven and thermohaline residual currents in the Beibu Bay. Oceanol Limnol, 32: 561–568

Tong G B, Chen L, Long J P, et al. 2012. Surface pollen distribution patterns in Beibu Gulf and corresponding sediment dynamics environment. Chin Sci Bull, 57: 902–911

Van Maren D S, Hoekstra P. 2004. Seasonal variation of hydrodynamics and sediment dynamics in a shallow subtropical estuary: The Ba Lat River, Vietnam. Estuar Coast Shelf S, 60: 529–540

Wang D R. 1998. Study of the dynamic-thermodynamic mechanic of Beibu Bay cool water masses. Doctoral Dissertation. Qingdao: Ocean University of China

Wang J F, Wang Y, Sun S W. 2009. Tidal currents and residual currents in the southeastern Beibu Gulf in spring (in Chinese). The Essay Collection of the Researches on the Ocean Science in the Gulf of Tonkin-PT II. Beijing: China Ocean Press. 47–55

Wong, L A, Chen J C, Xue H J, et al. 2003. A model study of the circulation in the Pearl River Estuary (PRE) and its adjacent coastal waters: 1. Simulations and comparison with observations. J Geophys Res, 108: C53156

Wu D X, Wang Y, Lin X P, et al. 2008. On the mechanism of the cyclonic circulation in Gulf of Tonkin in the summer. J Geophys Res, 113: C09029

Xia H Y, Li S H, Shi M C. 2001. Three-D numerical simulation of wind-driven current and density current in the Beibu Gulf. Acta Oceanol Sin, 20: 455–472

Xu X Z, Qiu Z, Chen H C. 1980. The general descriptions of the horizontal circulation in the South China Sea (in Chinese). In: Proceedings of the 1980 Symposium on Hydrometeorology, Chinese Society of Oceanology and Limnology. Beijing: Science Press

Xue H J, Chai F. 2002. Coupled physical-biological model for the Pearl River estuary: A phosphate limited subtropical ecosystem. In: Spaulding M L, ed. Proceedings of the 7th International Conference on Estuarine and Coastal Modeling, ASCE. 913–928

Xue H J, Chai F, Pettigrew N R, et al. 2004. Kuroshio intrusion and the circulation in the South China Sea. J Geophys Res, 109: C02017

Yang J Y. 2005. The Arctic and subarctic ocean flux of potential vorticity and the Arctic Ocean Circulation. J Phys Oceanogr, 35: 2387–2407

Yang SY, Bao X W, Chen C S, et al. 2003. Analysis on characteristics and mechanism of current system in west coast of Guangdong Province in the summer (in Chinese). Acta Oceanol Sin, 25: 1–8

Yang S Y, Chen B, Li P L. 2006. A study of the characteristics of water transport from the South China Sea into Beibu Bay via the Qiongzhou Strait in summer in terms of temperature and salinity data (in Chinese). Trans Oceanol Limnol, 1: 1–7

Yu M G, Liu J F. 1993. South China Sea circulation system and situation (in Chinese). Mar Forecast, 10: 13–17

Yu L, Jin X, Weller R A. 2008. Multidecade global flux datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, OAFlux Project Technical Report. OA-2008-01, 64pp Woods Hole Massachusetts

Yuan S Y, Deng J Z. 1999. Numerical research on the circulation in the Beibu Gulf (in Chinese). Nanhai Yanjiu Yu Kaifa, 2: 41–16

Zhang G R, Ma T, Pan W R, et al. 2009. The characteristics of low-frequency flow in the west mouth of Qiongzhou Strait and its response to the seasonal wind field (in Chinese). The Essay Collection of the Researches on the Ocean Science in the Gulf of Tonkin- PT II. Beijing: China Ocean Press. 64–76

Zhang H M, Bates J J, Reynolds R W. 2006. Assessment of composite global sampling: Sea surface wind speed. Geophys Res Lett, 33: L17714

Zu T T. 2005. Analysis of the current and its mechanism in the Gulf of Beibu. Master Dissertation. Qingdao: Ocean University of China

Zu T T, Gan J P, Erofeeva S Y. 2008. Numerical study of the tide and tidal dynamics in the South China Sea. Deep-Sea Res I, 55: 137–154