

Simulating summer circulation and water exchange in the Beibu Gulf

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A cyclonic gyre and a semi-closed anti-cyclonic gyre exist respectively in the north and south of Beibu Gulf. Water exchange is calculated using tracer-tracking model in FVCOM via adding an imaginary conservative material as the tracer material. After circularly using the wind condition of August 2012 for 800days, we get spatial and temporal distribution of the tracer concentration of Beibu Gulf of summer in 2012. Forced by circulation, Qiongzhou Strait, Da Nang sea area and Sanya sea area are main mass transport galleries of Beibu Gulf. The half exchange period of the Beibu Gulf in summer is 518 days while the value of average residence time is 588 days. Considering that summer lasts for 3 months, water exchange rate of the whole gulf is 13.73%.

[Key words: Beibu Gulf; FVCOM; Tracer-tracking model; half exchange period; average residence time]

Introduction

It is widely accepted that a gulf-wide cyclonic circulation dominate Beibu Gulf in winter, however, the summer circulation structure are still under disputed. In the past decades, several views has been presented. Earlier researchers believed that the gulf was controlled by an anti-cyclonic circulation in summer^{1,2,3}. Another mainstream view manifested that summer circulation was cyclonic^{4,5,6}, which is mainly forced by East Asian Monsoon^{7,8,9}. The third mainstream view pointed out that two circulations existed in the gulf that a cyclonic circulation in the northern gulf and an anti-cyclonic one in the south^{10,11}. For the territorial issues between china and Vietnam in the Beibu gulf with directly measured data have been quite scarce, especially in large-scale and international cooperation oceanographic survey⁴. Existing measured data demonstrate that current is apparent westward in the northern area and southwestward at the northwest of Hainan Island, which means that the northern of the Beibu Gulf are more like to be under the control of cyclonic

gyre. Besides, currents flows northward along the coast of Vietnam in summer, which signifies that it would probably be an anti-cyclonic gyre in the southern gulf. Which means that a cyclonic gyre and an anti-cyclonic gyre respectively take control of north and south of the gulf. In this study, we hope that the circulation of the Beibu gulf was simulated to calculate the water exchange of the gulf.

Literatures touching upon water exchange of Beibu Gulf were scarce. For being teem with oil, gas and marine living resources and being a hub of economic communications with Southeast Asia nations, the environmental status of the Beibu Gulf receives much concern¹². Capacity of water exchange is an important hydrodynamic and environmental characteristics of gulf and coastal areas, which plays a vital role in assessing and evaluating marine environmental capacity and environmental quality. Up to now, common numerical model in water exchange studies are measuring indicator concentration, box type model, advection-diffusion water exchange model, tracer-tracking model, 3-D Lagrange particle

tracking model¹³. In this study, we choose the tracer-tracking model in FVCOM^{14,15} based on advection-diffusion model to simulate the water exchange in the Beibu Gulf. The objective of this study is to calculate the water exchange in the Beibu Gulf with an applicable circulation. To carry out this objective, this paper is organized as follows: circulation simulation will be stated first, and after that water exchange of the Beibu Gulf will be proceeded.

Materials and Methods

The Beibu Gulf (Gulf of Tonkin), located at 17°~22°N and 105°~110°E, is a semi-closed gulf in the northwest of the South China Sea (SCS, Fig.1). Bounded by Hainan, Luichow Peninsula, Guangxi and Vietnam in Indo-China Peninsula, it connects to the SCS through the Qiongzhou Strait (QS) and the expanses of waters to the south of Hainan. Being a shallow shelf sea area, the gulf deepens gradually from north to south and from the edge to center, which has an average depth of 45 m and a maximum depth of 100 m^{17,18}.

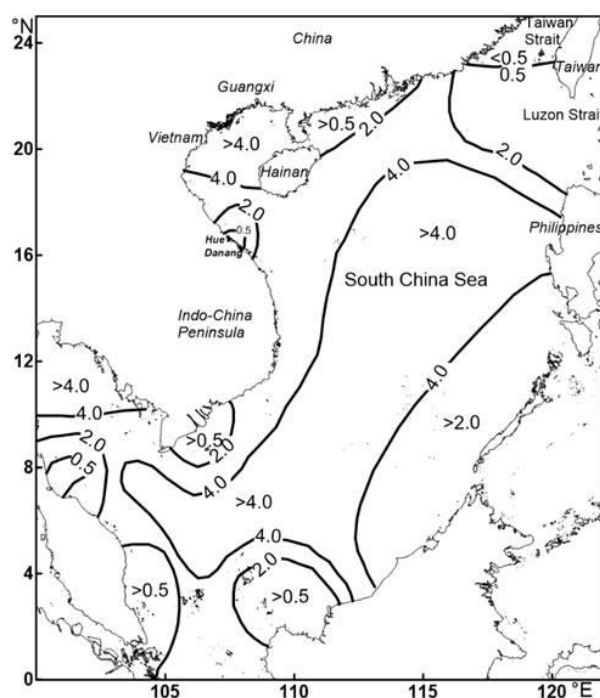


Fig. 1 Index of Tide Type in the SCS¹⁶

In this paper, the tracer-tracker model in FVCOM based on advection-diffusion water exchange model is applied under the hypothesis that climates in summer control the Beibu Gulf all the time. The tracer-tracking equation has the form

$$\frac{\partial DC}{\partial t} + \frac{\partial D\mu C}{\partial x} + \frac{\partial D\nu C}{\partial y} + \frac{\partial \omega C}{\partial \sigma} - \frac{1}{D} \frac{\partial}{\partial \sigma} \left(K_h \frac{\partial C}{\partial \sigma} \right) - DF_c = DC_0(x, y, \sigma, t)$$

Where C is the concentration of the tracer, D is the total water depth, μ , ν , and ω are the x , y , and σ components of the water velocity, K_h is the vertical thermal diffusion coefficient, F_c is the horizontal diffusion term, and C_0 is the concentration injected from a source point given as

$$C_0(x, y, \sigma, t) = \begin{cases} 1 & t_s \leq t \leq t_e; \sigma_k \leq \sigma \leq \sigma_{k+n}; x = \{x_i\}; y = \{y_i\}; i = 1, N \\ 0 & \text{otherwise} \end{cases}$$

Where t_s and t_e are the start and end time of the tracer injection, σ_k and σ_{k+n} refer to the upper and lower-bound σ -levels in which the tracer is injected; n can be an integral from 0 to K_B-1 (K_B is the total number of the σ -levels specified in the model), i is the node ID, and N is the total node numbers where the tracer is injected. K_h is vertical diffusion coefficient that is calculated using the selected turbulent closure scheme in FVCOM and the horizontal diffusivity in F_c is calculated using the Smagorinsky eddy parameterization method¹⁷ in FVCOM.

A kind of imaginary conservative material was put into the study area as the tracer in this study. At the very beginning, concentration of the tracer was spatial uniform with a value of 1, while outside it was 0. In order to know the evolution of the tracer concentration well, two water exchange boundaries were set in this region. One is the line of Xindi Village, located in southwest of the Luichow Peninsula, and Port of Macun in Hainan, the other connects Sanya of Hainan and Hue of Vietnam. Land boundaries were set as solid wall boundaries. Dye model was turned on only until the hydrodynamic model of FVCOM had operated for 3days. After simulating another 800days, we got spatial-temporal concentration distribution of the tracer.

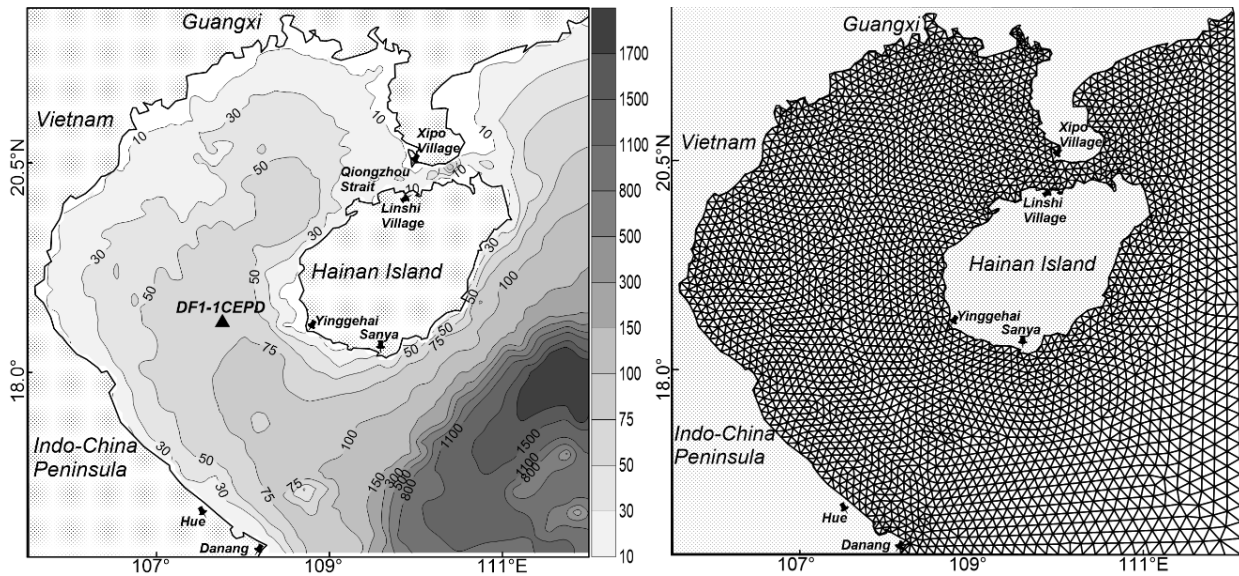


Fig.2 Computational domain (left: topography, right: grid)

Results and Discussion

Numerical scheme and computational grid

Finite Volume Coastal Ocean Model (FVCOM) was applied in this study. FVCOM have been successfully applied to bays, estuaries and coastal waters with complex terrain¹⁹. The simulation domain is situated in the northwest part of SCS, including the whole Beibu Gulf and waters to the east and south of Hainan Island (16°~22°N, 106°~112°E). Data of coastline and water depth (Fig.2 left) were featured on chart issued in 1998 and modified by Google Earth. With the resolution of 5 km in coastal areas and 10 km on the open boundary, the computational domain was subdivided into unstructured meshes with 27282 cells and 14054 nodes (Fig.2 right). Nine Sigma layers were set uniformly in the vertical direction. With time splitting techniques in this model, the internal mode time step is 60s and external mode time step is 6s. The prescribed bottom friction coefficients in this model was 0.0025^{19,20}. Due to the key elements determining circulation structure were SCS circulation and local wind, while the density current and the tide-induced current had little influence on the circulation structure²⁰, the impacts of the variation of the temperature and salinity were not considered, deposition and runoff were ignored, either. At the very beginning, the state of the harmonic field was regarded as resting ($\xi = u = v = 0$).

Boundary conditions and wind field data

This model is driven by water surface elevations along the open boundaries, which are

calculated by the following equations.

$$\xi = \sum_{i=1}^n f_i H_i \cos[\omega_i t + (V_0 + u)_i - g_i]$$

Where H and g are harmonic constants which stand for the amplitude and phase-lag respectively, the subscript i stands for either one of the constituents: M2, S2, K1 or O1, which are obtained from the global ocean tide model TPXO 7.2^{21,22} (www.esr.org/~padman/tpxo7.2_load/).

The character ω is the angular speed of the tidal constituents, f is the nodal factor, μ is the nodal angle and V_0 is the initial phase angle of the equilibrium tide.

Monthly averaged wind data of August 2012, procured from the NCEP Climate Forecast System (CFS)²³, are interpolated into the numerical grid as the surface forcing of the model. Fig.3 shows the original wind field in Beibu Gulf in summer, whose prevailing wind direction is southwest. Influenced by shoreline and Hainan Island, the summer leading southwesterly winds turn into southward and eastward after approaching Town of Yinggehai in Hainan Island.

Model verification

Due to the Territorial issues between China and Vietnam, direct measurements of the flow field have been few and far between⁴. We choose observed data of a monitoring stations called DF1-1CEPD which contains current and tidal level for nine representative days (from June 28th to August 5th of 2012), during when a spring tide and a neap tide are included.

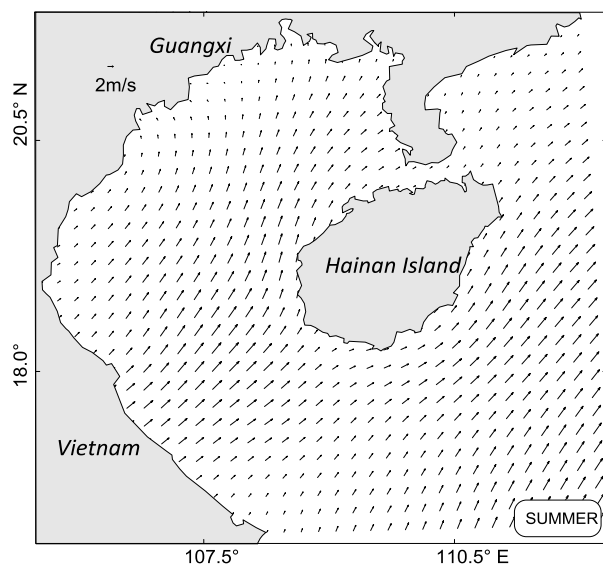


Fig.3 The upper-layer wind field of Beibu Gulf in summer

The accuracy of the model results are verified by comparing observed data with the simulated data (see Fig.4 & Fig.5). The tidal patterns of Beibu Gulf is reversing current, whose direction is consistent with the shoreline trend.

In terms of current speed, the maximum flow velocities in the surface, middle and bottom layer are 1.45m/s, 1.29m/s, 1.03m/s respectively at high spring tide and 1.26m/s, 0.80m/s, 0.66m/s at low spring tide, which all appear at the southwest of Luichow Peninsula. The mean velocity of the whole gulf is 0.24m/s at high tide and 0.16m/s at low tide.

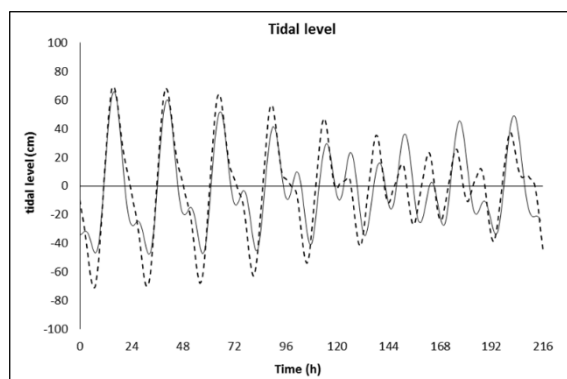


Fig.4 Observed and computed tidal curves of DF1-1cepd (Jun 28th~Aug 5th, 2012)(Solid line: computed, dashed line: observed)

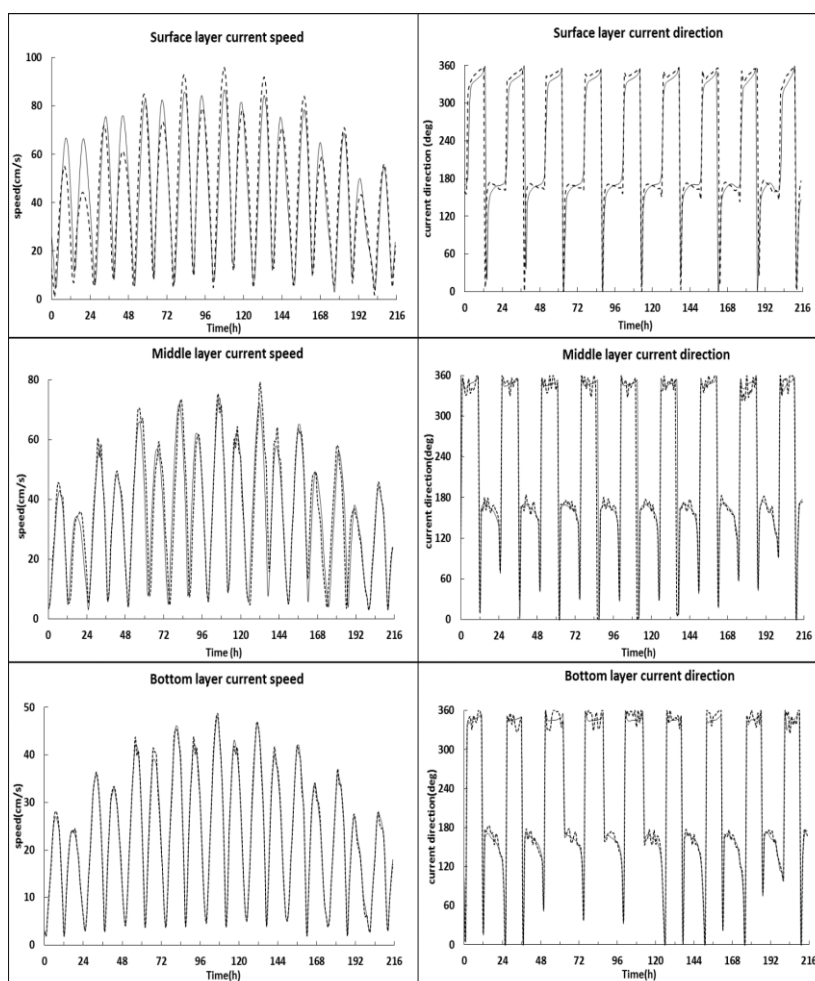


Fig.5 Observed and computed tidal current of DF1-1cepd (Jun28th~Aug5th, 2012)(Solid line: computed, dashed line: observed)

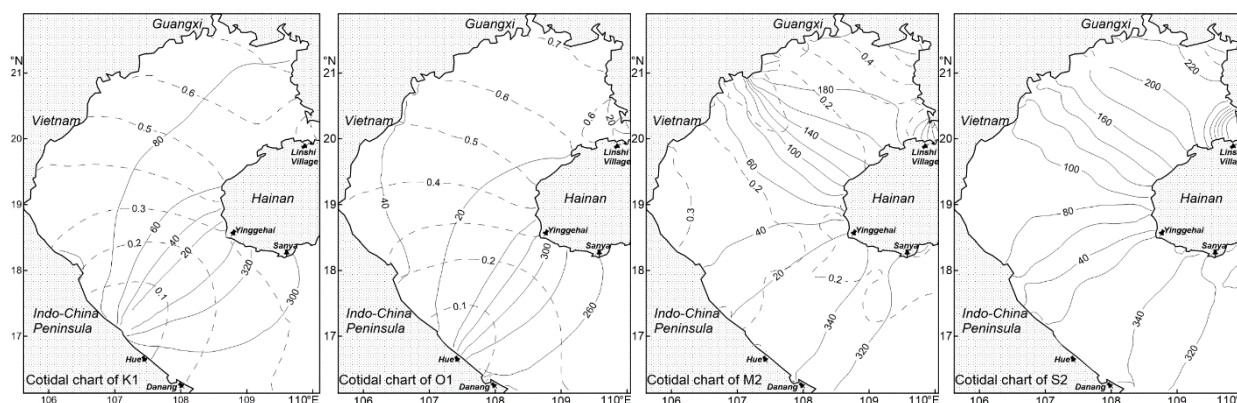


Fig. 6 Cotidal chart of K1, O1, M2 and S2

As a marginal sea of SCS, tidal system in the Beibu Gulf mainly comes from SCS. Tides in SCS spread from Taiwan Strait and Luzon Strait²⁴, then spread to other waters along southwest direction (Fig. 1). After reaching Hainan Island and Vietnam, tides access to the Beibu Gulf through southern bay mouth, where the diurnal constituents of K1 and O1 develop amphidromic points apiece and the amphidromic point of K1 is northwest of O1. Due to the shallow water friction, reflex wave is weakened and amphidromic points shift left, which degenerated the two amphidromic points, and tidal range around the left bank is larger than that of the right bank. Semidiurnal constituents of M2 and S2 have not formed typical tidal amphidromic systems. Inside the gulf, the amplitudes of K1 and O1 increase from south to north and maximizing at the bay head, and the maximum amplitude of K1, O1 and M2 are 90cm, 100cm and 40cm²⁵ (shown in Fig. 6). According to the Index of Tide Type calculated in this study (Fig. 7), waters to the north of the 19N are all diurnal tide, while semidiurnal tide sea area only exist around the amphidromic point of K1.

Circulation structure

For the circulation structure of the whole gulf in August of 2012, a cyclonic circulation controls the northern gulf, while an anti-cyclonic one exists in the south (Fig. 8), which is correspond with the consequences of former researchers. In north, current flows through the QS from east to west, which is identical to the theory that the averaged residual current in the QS is westward all the year round²⁶. Along the coast of Luichow Peninsula and Guangxi Province, current direction is westward in the north, which can be confirmed by observation data and simulating results^{4,5,6}. Besides, current direction of Weizhou Island in the surface layer, middle layer and bottom layer respectively are 255°, 305°

and 301°.

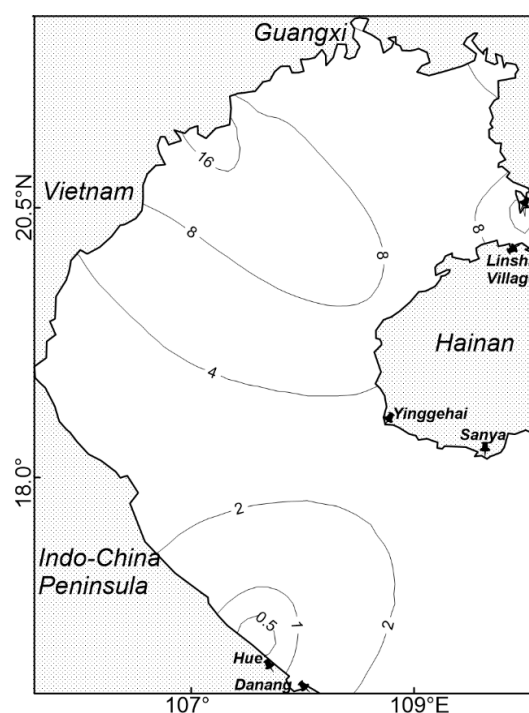


Fig. 7 Index of Tide Type in the Beibu Gulf

In this respect, the tidal current data at 10m, 20m, and 30m layer observed near the Weizhou Island from October 1988 to August 1989, were analyzed using the spectrum method, and the averaged residual current direction was 246°, 298°, 292°²⁷. To the north of 18°N, southward current dominates the coast of Vietnam while northward current take control to the west of Hainan. At this point, there forms a cyclonic gyre circulation in the northern part of the Beibu Gulf, with a cyclone center at 107.5°E, 19°N. In south, current direction along the coast of Vietnam is northward^{1,3,9,20}, then turns into a strong eastward flow until leaving the gulf to the south of Hainan Island around Sanya sea area. Till now, a semi-closed anti-cyclonic gyre circulation develop in the south of the Beibu Gulf, which has

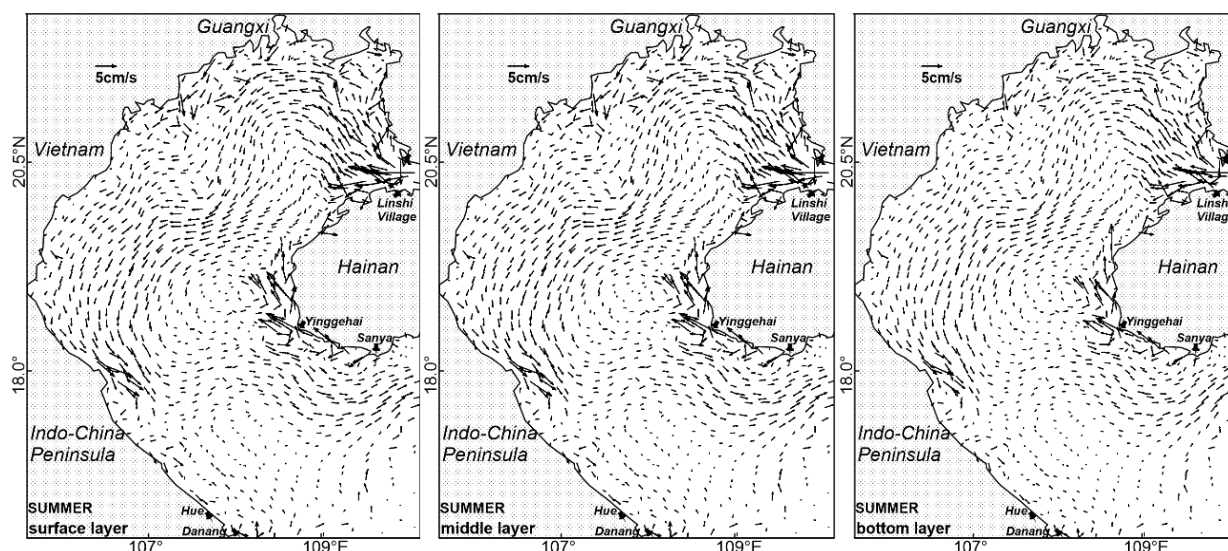


Fig.8 The tide-wind coupled circulation of the Beibu Gulf in summer

a center around 108.5°E, 17.5°N. The circulation structure in this paper is that a cyclonic gyre and an semi-closed anti-cyclonic gyre come into being respectively in north and south.

Residual current direction is westward all the year round and after entering the Gulf, part of the residual current develop into a closed anti-clockwise circulation, and rest flows southward until leaving the southern border. Residual current structures in surface, middle and bottom layer are similar except flow rate decreasing with the increase of depth. The maximum Euler residual current in the surface, middle and bottom layer are 25.3cm/s, 21.6cm/s and 13.0cm/s, while the average ones are 1.82cm/s, 1.60cm/s and 1.06cm/s, which is in accordance with the result of quantitative research of Chen Bo²⁸.

In order to tell how contribution tidal residual current makes, we take the surface layer as an example and define θ as:

$$\theta = \frac{V_{\text{residual current}}}{V_{\text{circulation}}}$$

Which reflects the contribution the residual current makes in qualitative research to some extent (shown in Fig. 9). For circulation is forced by wind field and tide, we can infer that the cyclonic circulation in north is mainly forced by residual current and the semi-closed anti-cyclonic gyre is mainly forced by wind field.

Water exchange

The tracer concentration envelope curves on the 50d, 200d, 400d and 800d in summer are shown in Fig. 10.

We can figure that the tracer concentration adjacent to the north water exchange boundary sharply reduces and none of the tracer is found out of the northern boundary. Meanwhile, the attenuating intensity of the tracer is weakened from boundary to interior, from littoral to the deep sea and from north to south. In the south, tracer is constantly transformed out from west to east through south of Hainan around 18°N. Driven by the circulation, the concentration distribution are consistent with circulation structure. Fresh waters from the QS and south boundary along the coast of Vietnam flow into the gulf and mix with the internal water, which dilutes the tracer concentration. Meanwhile, waters near the inner south boundary with high tracer concentration severely flow out mainly though the south boundary.

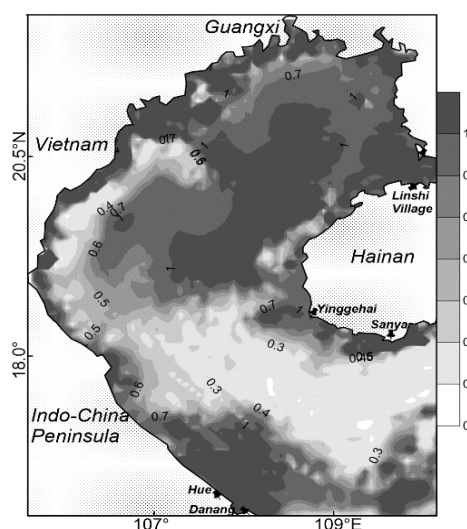


Fig. 9 Residual current contribution

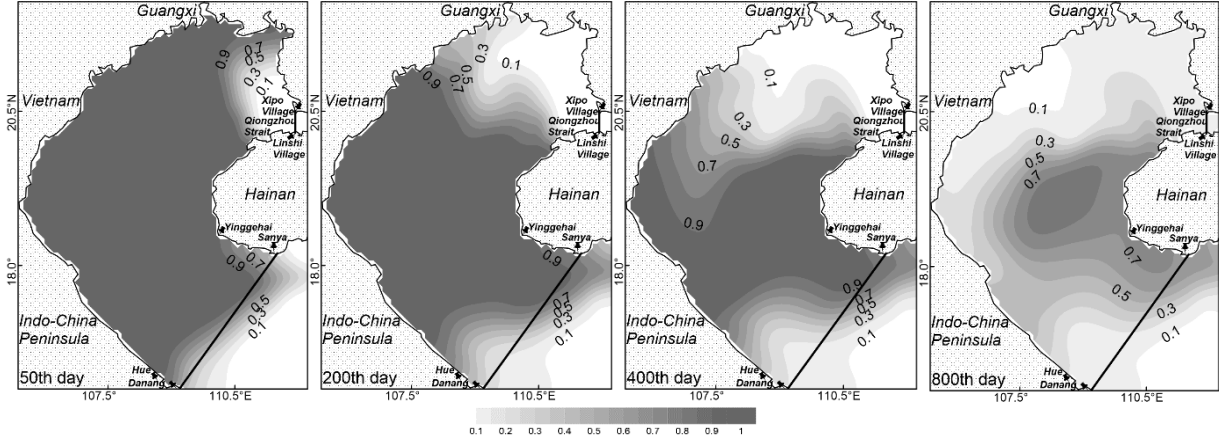


Fig.10 surface average concentration distributions of the passive tracer in summer

Forced by circulation, gallery of mass transport in Beibu Gulf is mainly through QS, Da Nang sea area and Sanya sea area.

Half exchange time and average residence time

In order to manifest intuitively the capacity of water exchange in summer, the concept of the half exchange period was introduced in this paper, which is defined as the time the concentration in a region needed to reduce to 50% of its initial value²⁸. In this model, the average concentration can be calculated by the following equation.

$$C_n = \frac{\sum_{i=1}^{14054} S_i \cdot d_i \cdot C_{i,n}}{\sum_{i=1}^{14054} S_i \cdot d_i}$$

Where i is the node number, n is the day number, C_n is the average concentration of the n day, $C_{i,n}$ is the concentration of the node of number i in the n day, S_i is the area of grid cell, d_i is the depth of grid cell.

With the curve of the average tracer concentration, half exchange time is easy to get. It can be read in Fig.11 that the average half exchange period of the whole Beibu Gulf in summer is 519 days. Considering that summer lasts for 3 months, we can figure that 13.73% of the tracer has been transformed out of the Beibu Gulf. Three typical location are chosen to contrast the ability of water exchange in different region, which are Weizhou Island, DF1-1CEPD, Da Nang of Vietnam. From Fig.11, concentrations near Da Nang and Weizhou Island decrease faster than the average of the whole domain, however, the CEPD attenuates much slower than that. Which means that water mainly exchange through the QS and southern boundary while the middle of the gulf exchange little. Besides, circulation structure also plays a decisive role. CEPD situates at the center of the northern circulation, which impedes the transport of substances.

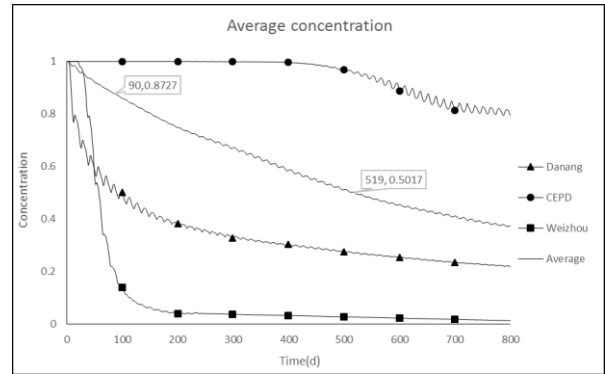


Fig.11 Average concentration curve

To further illustrate the capacity of the water exchange in different region of the Beibu Gulf, we introduce the concept of average residence time (ART), which is defined as the average time that water parcels need to leave the domain of interest³⁰, and it has the equation of the following form:

$$\theta = \int_0^{\infty} \frac{C(t)}{C(t_0)} dt$$

Where $C(t_0)$ is the initial concentration, $C(t)$ is the concentration at time of t , θ is ART. For convenient calculation, we consider 800 as the infinity in this paper.

In Fig.12, the deeper the color is, the larger the ART is and the longer the tracer will take to leave the gulf. The distribution of the ART is controlled by the circulation structure. Due to the cyclonic gyre in north, the contour lines there bend towards south along the coast of Guangxi Province and Vietnam, while bending towards north to the west coast of Hainan Island. Influenced by the semi-closed anti-cyclonic gyre in the south, contour lines bend towards north along the coast of Vietnam and east to the south of Hainan Island.

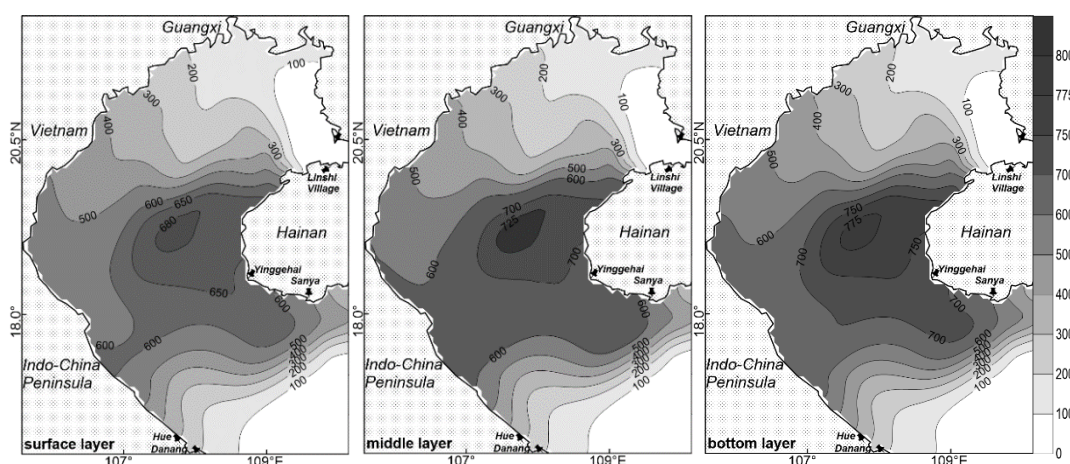


Fig.12 ART in summer

These phenomenon declare that the process of mass transport is controlled by circulation and channels of mass transport are mainly through QS, Da Nang sea area and Sanya sea area. The direction of the maximum gradient of the contour lines correspond with the direction of the circulation. The center of the contour lines lie in around 107.8°E and 19.2°N, which means that the center of the northern cyclonic gyre is the weakest water exchange place. And the maximum ART in the surface, middle, bottom layer respectively are 686d, 729d, 778d, while the value of ART in the whole Beibu Gulf is 588 days.

Conclusion

On the basis of a reasonable tide field simulated with FVCOM, we get wind-tide coupled circulation by adding the wind data from NCEP as the driving force. Then we calculated the water exchange in Beibu Gulf under the ideal summer circumstances using tracer-tracking model of FVCOM. Conclusions are obtained as follows.

A cyclonic circulation and a semi-closed anti-cyclonic circulation exist respectively in north and south of the Beibu Gulf, whose center are around 108°E, 19°N and 108.5°E, 17.5°N.

Forced by circulation, gallery of mass transport in Beibu Gulf is mainly through QS, Da Nang sea area and Sanya sea area. Receding from boundary to inner, the capacity of water exchange varies in different region. It waken from northeast to southwest along the coast of Guangxi and Vietnam in the north, while on the contrary along the southern coast. The direction of the maximum gradient of the ART contour lines correspond with the direction of the circulation. The center of the northern cyclonic circulation is the weakest place in the whole gulf.

The half exchange period of the Beibu Gulf in summer is 518 days, however, considering that summer lasts for 3 months, water exchange rate of the whole gulf is 13.73%. The maximum ART in the surface, middle, bottom layer are 686d, 729d, 778d respectively, while ART of the whole gulf is 588 days.

We simplified some facts at the beginning of building models, such as ignoring the thermohaline variation and without considering rainfall and runoff. Maybe density current would play an important role in water exchange of Beibu Gulf. These may would be discussed in subsequent studies.

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