Numerical study of the circulation and water transport in Beibu Gulf: A short communication

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Abstract. The Beibu Gulf, located in the northwestern South China Sea, is rich in oceanic energy and biological resources. Based on the FVCOM model, a three-dimensional numerical model was adopted in the study, which was validated with the observation data. The results show that Beibu Gulf is a typical diurnal tidal area. The $K_1$ and $O_1$ tide have an amphidromic point near Hue, Vietnam, forming a rotary tidal system. From the amphidromic point, the amplitudes increase gradually, eventually reaching more than 80 cm and 100 cm, respectively. The maximum amplitudes of $M_2$ and $S_2$ tide are about 70 cm and 10 cm, respectively. Meanwhile the tidal current presents a typical rectilinear flow in Beibu Gulf, with strong the diurnal tidal currents. Seasonal changes in the circulation structure of Beibu Gulf are obvious. The Beibu Gulf is generally controlled by a non-closed anticlockwise circulation in winter. In summer, there are two counterclockwise eddies. The tidal residual current flowing through Qiongzhou Strait goes west all year round, with the largest average flow flux of 0.07 Sv in winter. Based on DYE module from FVCOM, pollutants from the Pearl River Estuary pass through Qiongzhou Strait, and reach Weizhou Island after 109 days. This is of great significance to the monitoring and control of red tide, and the protection of marine ecological environment in Beibu Gulf.

1. Introduction

The Beibu Gulf is a semi-closed shallow gulf on the continental shelf, with an average depth of 46 m and a maximum depth of less than 100 m, which is located in the northwestern of the South China Sea ($17^\circ 00^\prime-21^\circ 30^\prime$N, $105^\circ 40^\prime-110^\circ 00^\prime$E) (Fig.1). It plays an important role in national security and material export for Southeast Asian, and it is an important economic base for cross-border, cross sea and cross regional development [1, 2]. The investigation and study of Beibu Gulf began with two comprehensive investigations between China and Vietnam in the 1960s [3]. Since the 1980s, some scholars have begun to use numerical models to simulate the overall circulation structure of Beibu Gulf. However, compared with the eastern seas of China, the investigation of Beibu Gulf is relatively less, and the circulation structure and its mechanism still need to be further understood and discussed. The research of hydrodynamic environment in Beibu Gulf is urgent, and it has an important impact on marine ecological environment, marine fishery economy and national border security [4, 5]. Therefore, Therefore, it is of great significance to establish a complete high-resolution coupling model for the study of hydrodynamic and ecological environment in Beibu Gulf.
Figure 1. (a) The bathymetry and model grid of Beibu Gulf. (b) The tidal elevation indicated by red points and current station indicated by yellow triangle.

2. Materials and Methods

This paper used the unstructured Finite Volume Community Ocean Model (FVCOM) [6] to establish a three-dimension numerical model of Beibu Gulf. Compared with other models, FVCOM has more advantages. First, it can simulate complex shoreline more accurately by using triangular mesh. Instead, due to wet and dry grid technology adopted, the variations can be better reproduced at intertidal zone. Third, it is diversified and Interdisciplinary, including the water quality models and ecological models, and it can reproduce the oceanic ecological environment. Here the coastline and water depth in model with respect to theoretical lowest low tide were obtained from the official marine charts published by the Maritime Safety Administration of P.R. China. Considering that the maximum depth exceeds 3000 m, 21 sigma layers are set vertically. It is driven by four diurnal tides ($K_1$, $O_1$, $P_1$ and $Q_1$) and four semi-diurnal tides ($M_2$, $S_2$, $N_2$ and $K_2$) at the open boundary (Table 1). The selected harmonic constants are...
from the Oregon State University tidal model. The river discharges are based on the annual average climate data in previous academic papers [7]. Hence we can establish a three-dimension tidal dynamic model of Beibu Gulf. The model is cold started and run from 1 Jan, 2019 to 31 May, 2020. Then the robust T_TIDE harmonic analysis program [8, 9] is adopted to analyze the model results. To validate the model, we adopt the measured tidal elevation and currents as well as harmonic constants of four principal tidal components ($K_1$, $O_1$, $M_2$ and $S_2$) from 13 observation stations (Fig. 1b). Here, the tidal elevations were recorded at Beihai station from 1 to 30 April 2020. The currents were collected by 25-hour ship-board ADCPs at eight stations near the Bailongwei from 1 to 2 April 2020 (Fig. 1b).

| Model setup          | Variations               | Source                          | Properties                                      |
|----------------------|--------------------------|---------------------------------|-------------------------------------------------|
| Open Boundary        | Tides                    | the Oregon State University     | 1, Jan, 2019 to 31, Dec, 2020                   |
|                      | Temperature & Salinity   | HYCOM                           | 1, Jan, 2019 to 31, Dec, 2020 ; 0.04°×0.04°    |
| Coasts & Depth       | The official marine charts|                                 |                                                  |
| River discharges     | Previous academic papers |                                 | the annual average climate data                  |
| Surface forcing      | Wind                     | ECMWF                           | 1, Jan, 2019 to 31, Dec, 2020, 0.125° × 0.125° |
|                      | Heat flux                | HYCOM                           | 1, Jan, 2019 to 31, Dec, 2020, 0.08°×0.08°     |
| Validation           | Tidal elevation          | Tidal table                     | 1 to 30 April 2020                              |
|                      | Current                  | ADCPs                           | 1 to 2 April 2020                               |
|                      | Harmonic constants       | Previous academic papers[10]    |                                                  |

After the tidal dynamic model verifications are completed, we will add external forcing to analyze the mechanism of circulation in Beibu Gulf, including wind, temperature, salinity and heat flux. The wind data was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), with the resolution of 0.125° × 0.125°. The temperature and salinity was derived from HYCOM, as well as heat flux (Table 1).

Eventually we used the DYE module provided by FVCOM to discuss the impact of pollutants from the Pearl River Estuary on the Beibu Gulf. In the Pearl River Estuary, we set the initial concentration to 10 and continuously release for 1 year. Then the distributions of pollutants along the Coast of Guangxi and in Beibu Gulf are analyzed.

3. Results and Discussion

3.1. Model validation

The tidal system of Beibu Gulf is mainly composed of $K_1$, $O_1$ and $M_2$. In order to validate the model results, four principal tidal components ($K_1$, $O_1$, $M_2$ and $S_2$) are used for analysis from 13 observation stations (Fig. 1b). Table 2 shows the calculated and observed harmonic constants at each station. The results show that the mean absolute difference of the amplitudes of $K_1$, $O_1$, $M_2$ and $S_2$ are 6.3 cm, 8.9 cm, 8 cm and 1.4 cm respectively, and that of their phase are 8.5°, 8.3°, 15° and 15° respectively. Fig 2 shows the comparison between observed and modelled results. This indicates that the model reproduces the variations in the tidal current but not exactly the same as observed. This is likely because the observed current includes the wind-driven current, the baroclinic current and the coastal current. Hence, we believe the model is applicable and valuable for tidal dynamic system in Beibu Gulf.
Table 2. Simulated (s in table) and observed (o in table) harmonic constants for four principal constituents.

| Station        | K1   | O1   | M2   | S2   |
|----------------|------|------|------|------|
|                | H    | g    | H    | g    | H    | g    | H    | g    |
|                | o    | s    | o    | s    | o    | s    | o    | s    |
| Beihai         | 88   | 84   | 96   | 99   | 96   | 103  | 34   | 33   | 44   | 49   | 177  | 186  | 11   | 8    | 237  | 238  |
| Sanniang Bay  | 82   | 83   | 96   | 99   | 91   | 102  | 28   | 32   | 43   | 47   | 179  | 183  | 7    | 8    | 222  | 235  |
| Shitoupu       | 93   | 90   | 100  | 112  | 100  | 108  | 39   | 45   | 59   | 59   | 194  | 223  | 8    | 9    | 299  | 281  |
| Bailongwei     | 83   | 79   | 99   | 100  | 91   | 99   | 38   | 33   | 31   | 39   | 181  | 179  | 5    | 7    | 227  | 228  |
| Weizhou island | 84   | 79   | 93   | 93   | 93   | 98   | 31   | 27   | 38   | 42   | 171  | 176  | 10   | 7    | 232  | 230  |
| Haian          | 36   | 31   | 86   | 63   | 46   | 44   | 25   | 4    | 22   | 55   | 267  | 296  | 13   | 14   | 328  | 359  |
| Wushi          | 72   | 68   | 91   | 86   | 74   | 86   | 28   | 21   | 24   | 27   | 160  | 189  | 6    | 4    | 294  | 261  |
| Quang Khe      | 21   | 13   | 110  | 88   | 27   | 26   | 53   | 27   | 18   | 28   | 41   | 19   | 5    | 5    | 91   | 69   |
| Oc chur sa     | 80   | 76   | 85   | 101  | 80   | 95   | 33   | 34   | 20   | 32   | 179  | 176  | 10   | 6    | 220  | 224  |
| Tsieng mum     | 73   | 75   | 96   | 104  | 82   | 94   | 30   | 37   | 18   | 26   | 179  | 178  | 6    | 5    | 230  | 223  |
| Hon Ne         | 69   | 44   | 107  | 104  | 69   | 61   | 31   | 36   | 18   | 39   | 20   | 48   | 7    | 7    | 142  | 112  |
| Yangpu         | 73   | 71   | 85   | 87   | 81   | 90   | 18   | 21   | 24   | 32   | 150  | 166  | 9    | 5    | 204  | 226  |
| Sanya          | 29   | 44   | 333  | 320  | 28   | 46   | 283  | 264  | 22   | 37   | 320  | 301  | 8    | 8    | 365  | 352  |

Figure 2. Comparison between the observed (in red) and modelled (in blue) (a) the tidal elevation, (b) eastward current and (c) northward current.
3.2. Tide
The model results can be validated from the cotidal charts. Fig. 3 shows the cotidal charts of K\textsubscript{1}, O\textsubscript{1}, M\textsubscript{2} and S\textsubscript{2} in Beibu Gulf. Beibu Gulf is a typical diurnal tidal area [10]. There is an amphidromic point of the K\textsubscript{1} tide on the shore near Hue, Vietnam, forming a rotary tidal system. From amphidromic point to the coast of Guangxi province, the amplitude gradually increased, eventually reaching more than 80 cm at the top of the Gulf. The distribution of O\textsubscript{1} tide in Beibu Gulf is similar to K\textsubscript{1} tide, except that the position of amphidromic point tends to the southeast of Hue, with a larger amplitude, exceeding 100 cm. The distributions are consistent with the results of sun and Huang [11]. There is a nodal band observed of M\textsubscript{2} tide in the northwest region of the Hainan Island, which ultimately degenerates amphidromic point at the north of Haiphong, Vietnam. From the amphidromic point to Beihai, Guangxi, the amplitude of M\textsubscript{2} tide gradually increases, and reaching more than 70 cm near Beihai. This is slightly different from the previous paper, but more consistent with the result of Chen et al. [12]. The amplitude of S\textsubscript{2} tide is relatively weak, and the maximum amplitude in Beibu Gulf is less than 10 cm. Most of the tidal currents are typical rectilinear currents [13].

![Figure 3](image-url)

*Figure 3.* Model-produced cotidal charts for constituent of (a) K\textsubscript{1}, (b) O\textsubscript{1}, (c) M\textsubscript{2} and (d) S\textsubscript{2}. ——— phase-lag in degree; ······amplitude in cm
3.3. Circulation
There is a non-closed anticlockwise circulation in the winter. The surface circulations are mainly induced by wind. However, the velocity decreases rapidly in the middle-level, which reduce a clockwise circulation in the southern of Bailongwei and an anticlockwise circulation in the southern of Beibu Gulf. There is a strong current along the Hainan Island from the South China Sea, and the current reaches 19°N. There are two anticlockwise eddies in summer. With the increase of river discharges, there is an obvious impact on circulation along the coast, especially in the estuary. In spring and autumn seasons, the wind turns into a transition period, so the circulation appears a non-closed anticlockwise. The mechanism of circulation in each season is different. Tidal residual current plays the most important cause, followed by wind and density [14, 3].

Figure 4. surface (a, b), middle-level (c, d), bottom (e, f) and average (g, h) circulation in winter and summer.
3.4. Current and flux in the Qiongzhou Strait

There is a westward residual current through the Qiongzhou Strait all the year round (Fig 4). The average residual current exceeds 0.1 m/s in the channel, and the maximum residual current exceeds 0.35 m/s. The velocity is biggest at the surface, while the velocity will decrease with the depth.

![Figure 5. The residual current in the Qiongzhou Strait](image)

The water transport from the Qiongzhou Strait to Beibu Gulf is very critical for the circulation structure. In this paper, we select a cross section along 110°9′E. In winter, average flow flux is the largest, with westward flux of 0.07 SV, as well as southward flux of 0.0134SV. Compared with the observed data from Chen et al. [15], the southward flux is almost consistent, only the westward flux is slightly larger. When the model is induced by tide, the flux is 0.0534Sv, which is almost consistent with the observed flux (0.055Sv) from Chen et al. From fig 6, it can be found that there is a good positive linear correlation between the flow flux and wind. The tidal residual current is the fundamental reason for the current existence in Qiongzhou Strait, but the wind plays a key role in the magnitude and convert of the residual current [16].

![Figure 6. The flow flux and wind in winter (a) and summer (b)](image)
3.5. The transport of pollutions

Many researchers believe that the South China Sea water brings the rich nutrients and organic matter through the Qiongzhou strait into the Beibu Gulf [17, 18]. To evaluate the impact, we adopt the DYE module provided by FVCOM. In the Pearl River Estuary, we set the initial concentration to 10 and continuously release for one year. Ultimately we set 1% of the initial concentration as the threshold to judge the influence range. The model results reveal that the pollutions from Pearl River estuary pass through the Qiongzhou Strait to Weizhou Island after 109 days. About five months later, the impact of the pollutants expanded to the entire territory of Guangxi.

Figure 7. the distribution of pollutions transport

4. Conclusion

This study established a high-resolution three-dimensional circulation model based on FVCOM model, to reproduce the tidal wave system of Beibu Gulf. The results show that Beibu Gulf is a typical diurnal tide Bay. The K\textsubscript{1} tide is a rotary tidal system with an amphidromic point near Hue, Vietnam. The maximum amplitude exceeds 80 cm at the top of the Gulf. The amphidromic point of O\textsubscript{1} tide is in the southeast of that of K\textsubscript{1} tide, with a maximum amplitude of 100 cm. There is a degenerated amphidromic point of M\textsubscript{2} tide in the north of Haiphong, Vietnam. And the maximum amplitude exceeds 70 cm near Beihai. The S\textsubscript{2} tide is relatively weak. Overall, there is a cyclonic circulation structure in Beibu Gulf. The circulation structure of Beibu Gulf has obvious seasonal variation. The Beibu Gulf is generally controlled by a non-closed anticlockwise circulation in winter. In summer, there are two anticlockwise eddies. The residual current through Qiongzhou Strait is westward all year round. In winter, average westward flux reaches 0.07 SV. Pollutants from the Pearl River Estuary will reach Weizhou Island after 109 days, then affect the whole coastal waters of Guangxi after five months. So far, there have been few investigations and studies on the Beibu Gulf, and there is still a lack of sufficient understanding of the mechanism of the hydrodynamic and ecosystem environment. More attention is needed for the marine scientific research in Beibu Gulf.

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