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Impact of the water input from the eastern Qiongzhou Strait to the Beibu Gulf on Guangxi coastal circulation

Bo Chen[1]*, Zhixin Xu[1], Hanzheng Ya[1], Xianyun Chen[1], Mingben Xu[1]

[1] Guangxi Key Laboratory of Marine Environmental Science, Beibu Gulf Marine Research Center, Guangxi Academy of Sciences, Nanning 530007, China

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Abstract

Based on a comparison of synchronized temperature and salinity data collected in the eastern Qiongzhou Strait and at coastal marine stations, this study finds that, in summer, the variation in salinity near the Weizhou Island in Guangxi is similar to that in the eastern and central portions of the Qiongzhou Strait. Additionally, the Beihai Station in Guangxi exhibits a small salinity variation, whereas the Longmen and Bailongwei Stations, both of which are located far from the Qiongzhou Strait, mainly exhibit continental hydrological characteristics in summer. Moreover, a comparison of the multi-year ocean current data from the Qiongzhou Strait and ocean current observations from the Weizhou Island Station and recently installed current-measuring stations shows that the residual current in the Qiongzhou Strait flows westward in winter and summer. The numerical simulation results also indicate that water from the eastern Qiongzhou Strait enters the Beibu Gulf. The characteristics of the temperature and salinity distributions and analyses of the residual currents further confirm that the western Guangdong coastal current is the main source of the westward transport of water in the Qiongzhou Strait. The primary driver of the formation of the western Guangdong coastal current is the westward flow of freshwater from the Zhujiang (Pearl) River. This water enters the Beibu Gulf via the Qiongzhou Strait and enhances the formation of the cyclonic circulation in the northern Beibu Gulf. In summer, the strong influence of the southwesterly wind leads to the formation of a strong northward coastal current along the western coast of the Beibu Gulf. This process promotes the transport of low-salinity diluted water toward the open ocean and the formation of larger-scale cyclonic circulation around Weizhou Island in the eastern Beibu Gulf. The results of this study regarding the effects of the water inflow from the eastern Qiongzhou Strait to the Beibu Gulf on the Guangxi coastal circulation directly challenge conventional conclusions concerning the transport direction of water through the Qiongzhou Strait in winter and summer.

Key words: temperature and salinity characteristics, circulation mechanism, Qiongzhou Strait, Guangxi coast

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1 Introduction

The Beibu Gulf is located in the northwestern portion of the South China Sea, between 16°–22°N and 105°30′ –110°E. The gulf is characterized by the Hainan Island, the Qiongzhou Strait and the Leizhou Peninsula to the east; the Guangxi Zhuang Autonomous Region to the north; the coast of Vietnam to the west; and the South China Sea to the south. The eastern part of the Beibu Gulf connects with Guangzhou Bay via the Qiongzhou Strait. The seafloor topography is relatively flat, with an average water depth of 46 m and a maximum water depth of no more than 100 m. The gulf is a semi-closed, shallow continental sea regionand covers an area of 13×10^4 km^2. The circulation system in the northern Beibu Gulf is affected by wind, the seawater input from the eastern South China Sea and the freshwater inputs from rivers, resulting in a complex situation with variable characteristics. The Qiongzhou Strait is situated between the Leizhou Peninsula in Guangdong Province and the Hainan Island in Hainan Province. The eastern entrance of the Qiongzhou Strait is adjacent to the South China Sea, and the western entrance joins the Beibu Gulf. The strait extends from 19°58′N to 20°19′N and from 109°40′E to 110°30′E. The length of the strait is approximately 80.3 km. The minimum and maximum widths of the strait are 19.4 km (at 110°10′E) and 39.6 km (at 110°E), respectively, and the average width is 29.5 km. The Qiongzhou Strait is an important transportation route between Hainan Province and the mainland and is also the main channel for seawater exchange between the South China Sea and the Beibu Gulf. The input of seawater from the South China Sea to the eastern Qiongzhou Strait and the Beibu Gulf has an important effect on the coastal water bodies of Guangxi.

Most articles on the water exchange in the Qiongzhou Strait have suggested that due to the impact of the northeastern monsoon in winter, water transported through the Qiongzhou Strait flows from the northern South China Sea to the Beibu Gulf, i.e., from east to west. The transport direction is the opposite in summer due to the impact of the southwestern monsoon. Over the

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*Corresponding author, E-mail: cbgxkxy@163.com

past 20 years, research on water exchange in the Qiongzhou Strait region has yielded new discoveries. Shi et al. (1998, 2002), Yang et al. (2003), and Chen et al. (2006) found that the water transport direction in the Qiongzhou Strait was westward all year. Moreover, the volume of the westward water transport was between 0.1×10^6 m^3/s and 0.2×10^6 m^3/s based on numerical calculations. The existence of a year-round westward current in the Qiongzhou Strait suggests that wind stress could not be the main factor controlling the current in the Qiongzhou Strait and that the physical mechanism of water exchange through the Qiongzhou Strait should be more complex. These research conclusions provide new evidence for the formation mechanism of the circulation patterns in the northern Beibu Gulf. However, open questions remain. Since water exchange in the Qiongzhou Strait is westward all year, what is the intrinsic relationship between the direction of exchange and the western Guangdong coastal current? Additionally, what effect does the inflow of eastern water have on the circulation after it enters the Beibu Gulf, and what is its particular effect on the Guangxi coastal current? What is the associated formation mechanism? These issues require further investigation. Therefore, this study uses synchronized temperature and salinity observations collected in 1961 at three observation stations in western Guangdong and two coastal observation stations in Guangxi; a 20-year statistical data set from the Weizhou Island, Longmen and Bailongwei Stations in Guangxi; seven years (1964, 1965, 1966, 1969, 1971, 1972 and 1997) of ocean current field measurements in the Qiongzhou Strait; ocean current data from the fixed-point station at Weizhou Island from October 1988 to August 1989; and four synchronized daily continuous ocean current measurements collected in November 2017 to investigate the effect of the input of water from the eastern Qiongzhou Strait into the Beibu Gulf. The results show that the water inflow from the eastern Qiongzhou Strait plays an important role in the formation of cyclonic circulation in the Guangxi coastal area.

2 Formation of the circulation in the northern Beibu Gulf described in the 1960s

At the beginning of the 1960s, the understanding of the Beibu Gulf circulation pattern was largely based on the map of the South China Sea ocean circulation. In winter, there is a cyclonic circulation pattern in the main basin of the South China Sea. The current along the northern coast is southwestward; most of this current turns southward at the eastern entrance of the Qiongzhou Strait and flows south along the eastern coast of Hainan Island, while a small portion enters the Beibu Gulf through the Qiongzhou Strait and intensifies the cyclonic circulation in the Beibu Gulf. In summer, all these circulation patterns are reversed. Anti-cyclonic circulation patterns form in both the South China Sea and the Beibu Gulf, which lead to an eastward current flowing into western Guangdong via the Qiongzhou Strait. These descriptions are consistent with the results of a joint survey by China and Vietnam. Comprehensive Investigation Office of Ocean Group of the Scientific and Technological Commission of the People's Republic of China (1964) stated that counterclockwise cyclonic circulation is present in the gulf in winter and spring, counterclockwise circulation with clockwise circulation in the northeast is generally present in fall, and clockwise anti-cyclonic circulation is present in summer. In winter, under the influence of the northeastern wind, water in the South China Sea enters the Beibu Gulf via the Qiongzhou Strait. In summer, the southwestern wind drives the water from the Beibu Gulf toward the South China Sea via the Qiongzhou Strait. Therefore, with respect to the Beibu Gulf, the water exchange with the Qiongzhou Strait is in the form of input flows in winter and output flows in summer. Most relevant literature is based on wind-driven circulation and considers wind to be the main driver of these flows. However, over the past 20 years, this conventional view has been constantly challenged.

3 Main characteristics of the water input from the eastern Qiongzhou Strait to the northern Beibu Gulf

3.1 *Changes in salinity anomalies are identical*

To investigate the temperature and salinity characteristics of the Qiongzhou Strait and the northern Beibu Gulf, this study compares the synchronized temperature and salinity data collected at the Naozhou, Haian, Haikou, Weizhou Island and Beihai Stations in 1961. The locations of these marine observation stations are shown in Fig. 1.

In areas not impacted by upwelling, the seawater has high temperature and low salinity due to strong solar radiation and high levels of precipitation in summer. However, the opposite trends are observed in upwelling areas. Because of the upwelling of low-temperature and high-salinity water from the bottom, the seawater in these areas has low temperature and high salinity in summer. The eastern Qiongzhou Strait is controlled by upwelling in summer and exhibits high salinity from June to August. Table 1 shows the monthly vertical distributions of temperature and salinity based on ocean survey data from the eastern Qiongzhou Strait collected in 1997. Table 1 reveals the following characteristics:

(1) The upwelling in the eastern Qiongzhou Strait begins to occur in May. Although the temperature characteristics are not significant, the salinities in the 10 m and 20 m layers in summer are significantly higher than those in winter and spring. From April to May, the salinity increases by 3.45 in the 10 m layer and by 2.97 in the 20 m layer. Due to the effect of precipitation, the surface layer salinity in May is the lowest throughout the year.

(2) The upwelling is the strongest in June and July. The temperature is significantly lower in these months than in May from the surface to the bottom, while the salinity increases continuously from May to July. The temperature of the 20 m layer in July is only 20.87°C, which is lower than the temperatures in June and August. Additionally, the salinity of the 20 m layer reaches a maximum in summer.

(3) In August, the upwelling begins to weaken, the temperature in the bottom layer significantly increases, and the salinity decreases.

If the water in the Beibu Gulf flows eastward into the South China Sea via the Qiongzhou Strait in summer, the salinity of the eastern Qiongzhou Strait should reflect the characteristics of the Beibu Gulf. Conversely, if the water exchange in the Qiongzhou Strait in summer retains the characteristics it exhibits in winter, i.e., westward flow, then the Beibu Gulf should retain the temperature and salinity characteristics of the eastern Qiongzhou Strait. Because the conservation of salinity is more reliable than that of temperature, a comparison of the salinities measured at the coastal hydrological stations in western Guangdong and the northern Beibu Gulf could verify whether the water enters the Beibu Gulf from the Qiongzhou Strait (Table 2).

Table 2 lists the monthly salinity anomalies observed from March to November at the three coastal hydrological stations in western Guangdong and at two coastal hydrological stations in the northern Beibu Gulf. The following trends can be found in Table 2:

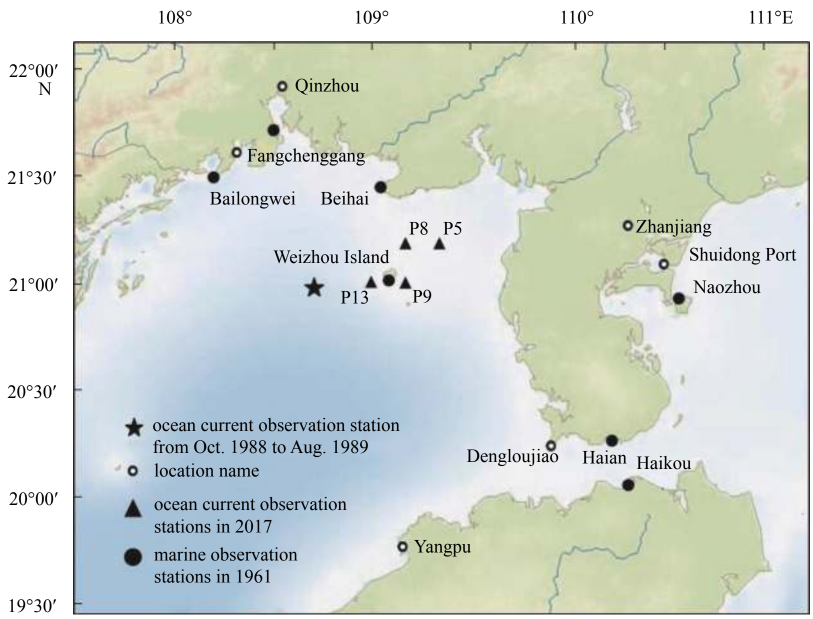

Fig. 1. Locations of the ocean current observation stations and the marine observation stations used for comparative analysis.

Table 1. The temperature (T) and salinity (S) distributions in the eastern Qiongzhou Strait

Factor	Depth/m	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Temperature/°C	0	17.88	24.73	27.16	26.89	27.60	28.43	28.80	27.36	23.69
	10	17.82	24.01	26.48	23.85	27.26	27.10	28.80	27.17	23.68
	20	18.50	23.00	26.12	22.01	20.87	26.36	28.81	26.88	23.69
Salinity	0	32.64	30.35	29.88	33.78	33.29	32.89	31.33	33.07	33.73
	10	32.69	30.72	34.17	34.29	33.49	33.86	31.48	33.17	33.69
	20	33.03	31.37	34.34	34.49	34.60	33.97	32.20	33.47	33.76

Note: The data in Table 1 are from the Marine Survey Dataset (1997) compiled by the Institute of Marine Scientific and Technological Information, State Oceanic Administration, China.

Table 2. Monthly salinity anomalies in western Guangdong and the northern Beibu Gulf in 1961

	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
Naozhou	1.02	1.5	–2.89	–0.11	2.60	2.62	–2.22	–3.58	–1.49
Haikou	1.34	0.43	–2.86	0.45	2.88	2.72	–1.78	–1.7	–2.52
Haian	–2.52	–1.54	–1.07	4.53	4.31	4.34	1.47	–0.24	0.25
Weizhou Island			0.16	0.66	0.74	0.67	0.07	0.06	0.06
Beihai	0.65	0.82	1.78	2.34	1.19	–2.53	–1.70	–2.09	–3.97

Note: The data are from Yang et al. (2006).

(1) Naozhou Island in the eastern Qiongzhou Strait and Haian and Haikou in the central Qiongzhou Strait all exhibit increases in salinity from June through August. However, Weizhou Island, which is located in the western Qiongzhou Strait in the Beibu Gulf and close to the Guangxi coast, also displays a salinity increase in summer. Notably, this increase is first observed in the spring. Even Beihai Station, which is far from the eastern Qiongzhou Strait and located on the Guangxi coast, also presents an anomalous salinity trend in summer.

(2) Most of the precipitation in this area occurs in June, July and August. Specifically, 50% of the annual total precipitation falls in these months. Thus, the salinity should be the lowest during this period. However, the salinities at the five coastal hydrological stations remain high in July and August. This phenomenon is inconsistent with the precipitation pattern and can only be explained by the movement of the water. Thus, these anomalies are likely the result of the westward flow of high-salinity, low-temperature upwelling mixed water from the eastern Qiongzhou Strait.

Therefore, the changes in the salinity anomalies at the two Guangxi coastal observational stations in the Beibu Gulf and the three coastal observation stations in western Guangdong are generally similar. The salinity anomalies are high from June through August and low in September, and these hydrological characteristics reflect the impact of the westward inflow of water from the Qiongzhou Strait into the Beibu Gulf.

3.2 *Monthly changes in salinity are uniform*

Using the 20-year monthly average salinity data from the Weizhou Island, Bailongwei and Longmen Stations published in the Guangxi Marine Development and Protection Management Committee (1996), this study further analyzes the hydrological characteristics of the Guangxi coastal area (Table 3). Bailongwei is located to the west of Fangchenggang and far from the influence of the mixed water associated with upwelling from the Qiongzhou Strait. The Longmen Station is in Qinzhou Bay and is

Table 3. Twenty-year monthly average salinity data from the Weizhou Island, Bailongwei and Longmen Stations

Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Weizhou Island	32.39	32.42	32.11	32.49	32.66	32.45	32.04	31.26	31.17	31.80	31.60	31.80
Bailongwei	30.92	31.03	31.36	29.68	28.12	27.42	26.71	23.86	26.40	28.13	29.54	30.14
Longmen	25.11	25.12	24.85	20.14	16.15	13.41	11.62	12.08	15.13	19.84	21.69	24.09

significantly affected by coastal precipitation and runoff. Weizhou Island is located along the central coast of Guangxi and is close to the Qiongzhou Strait. Table 3 displays the following findings:

(1) Representing a station far from the effects of the mixed water from the Qiongzhou Strait, Bailongwei Station exhibits the highest salinity values in February and March. The salinity then starts to decrease in April and reaches a minimum in August. After September, the salinity gradually increases.

(2) The salinity of the Longmen Station, located in Qinzhou Bay, is highest in January and February before significantly decreasing after April. The salinity reaches a minimum in July and August and then increases after September. This trend is generally similar to that at the Bailongwei Station, although the highest and lowest salinity values occur one month earlier.

(3) The salinity changes at the Longmen and Bailongwei Stations suggest that precipitation is the main factor.

(4) The pattern of salinity changes at the Weizhou Island Station is different from those at the above two stations: the salinity remains high from January to July and decreases to a minimum in August.

(5) At the Weizhou Island Station, precipitation is a secondary factor in the salinity changes.

Figures 2 and 3 show the monthly changes in salinity and precipitation at the Weizhou Island and Bailongwei Stations, respectively. These figures clearly present the impact of precipitation on salinity at the Bailongwei Station. Precipitation starts to increase in March at both the Bailongwei and Weizhou Island Stations. With the increase in precipitation, the salinity starts to decrease at the Bailongwei Station. The salinity at the Bailongwei Station reaches a minimum value in August when precipitation is the highest, demonstrating that salinity and precipitation are significantly negatively correlated.

Unlike the trends at the Bailongwei Station, the salinity at the Weizhou Island Station varies slightly from March to June and even increases slightly in July. The salinity remains high in July and is only 0.07 lower than that in March. Even in August, when the amount of precipitation is highest, the salinity is only 0.85 lower than that in March. The salinity during March and April does not decrease because water from the South China Sea is continuously transported to the Beibu Gulf via the Qiongzhou Strait by the winter monsoon (northeasterly wind) and the salinity of the water in the South China Sea is higher than that in the Beibu Gulf. After May, although the southwestern monsoon becomes dominant, the water continues to be transported westward through the Qiongzhou Strait; therefore, the salinity at the

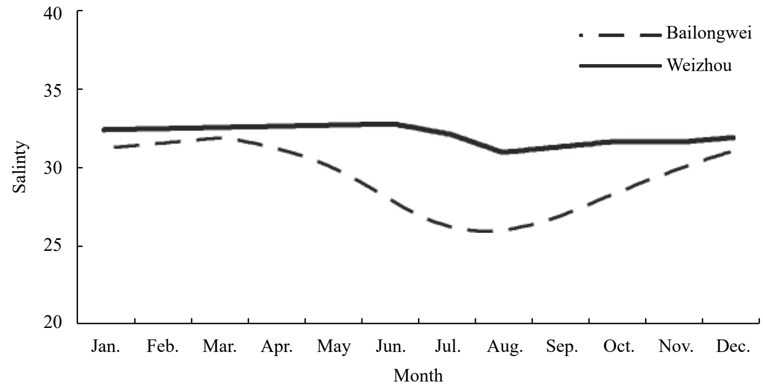

Fig. 2. Twenty-year monthly average salinity at the Weizhou Island and Bailongwei Stations in Guangxi.

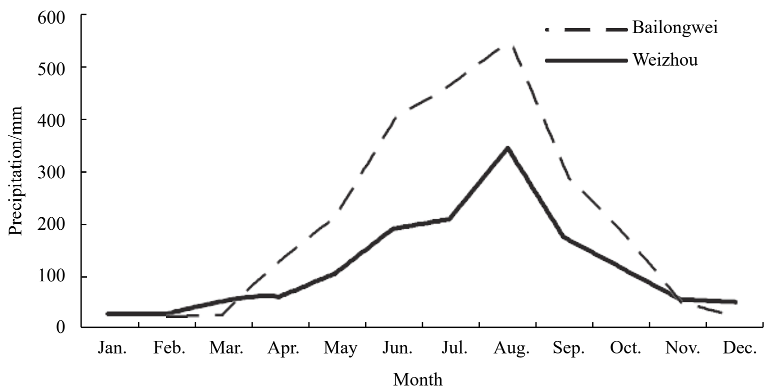

Fig. 3. Twenty-year monthly average precipitation at the Weizhou Island and Bailongwei Stations in Guangxi.

Weizhou Island Station remains high. The effect of precipitation does not become evident until the upwelling starts to weaken, which results in the lowest salinity in August and September.

The results indicate that the salinity changes at Weizhou Island in the Guangxi coastal area are consistent with those in the eastern Qiongzhou Strait in summer. Beihai Station, which is close to Weizhou Island, is slightly affected, whereas the Longmen and Bailongwei Stations, which are far from the Qiongzhou Strait, mainly reflect continental hydrological changes in summer. These findings reveal that water from the South China Sea enters the Beibu Gulf via the Qiongzhou Strait in summer.

3.3 *Direction of the residual current in both winter and summer is westward*

This study uses the measured ocean current data for seven years (1964, 1965, 1966, 1969, 1971, 1972 and 1997) and data from a fixed point near the Weizhou Island and analysis results of the direction of the Guangdong coastal current (Shi et al., 1998) to verify that the water transport direction in the Qiongzhou Strait is southwestward in summer. This finding provides a significant reference for research on the water exchange between the Beibu Gulf and the South China Sea, the circulation in the northern Beibu Gulf and the upwelling in the eastern Qiongzhou Strait.

Each station has a continuous 25-h record of ocean current data, including velocity and direction information. The residual current is calculated based on these data. The residual current is the typical ocean current after periodic flows (e.g., astronomical tides) are removed. It includes non-periodic flows, such as tidal residual currents, wind currents and density currents. The depth of each station varies. If H is used to denote the depth of a station, the surface, middle and bottom ocean current depths are usually given as 0 m, 0.6 H and bottom in the data analysis. The surface layer is from 0–0.5 m and is where ocean-atmosphere interactions occur. The bottom layer is associated with the friction effect of the seafloor, and the middle layer represents the transition zone between the surface and bottom layers.

3.3.1 *Characteristics of the residual current in winter*

The overall direction of the residual current in winter (December to February) is southwestward; that is, water transport occurs from the South China Sea to the Beibu Gulf because the Qiongzhou Strait is affected by the strong and stable northeasterly wind in winter and the wind-driven current flows from east to west. The high-salinity, low-temperature seawater from the western Guangdong coast enters the Beibu Gulf and remains in the bottom layer of the northern and central Beibu Gulf until the end of summer. The distribution of the residual current in winter (Fig. 4) exhibit the following characteristics.

(1) The strongest currents are generally located in the western Qiongzhou Strait, especially in the middle and bottom layers.

(2) Due to topographic effects, the residual current at Jianjiao–Dengloujiao on the western Leizhou Peninsula flows southwestward.

(3) The current velocity increases in the south-central Qiongzhou Strait at approximately 20.108°N, 110.16°E, and this increase is related to topography.

3.3.2 *Characteristics of the residual current in summer*

The distributions of the residual current in summer (Fig. 5) display the following characteristics.

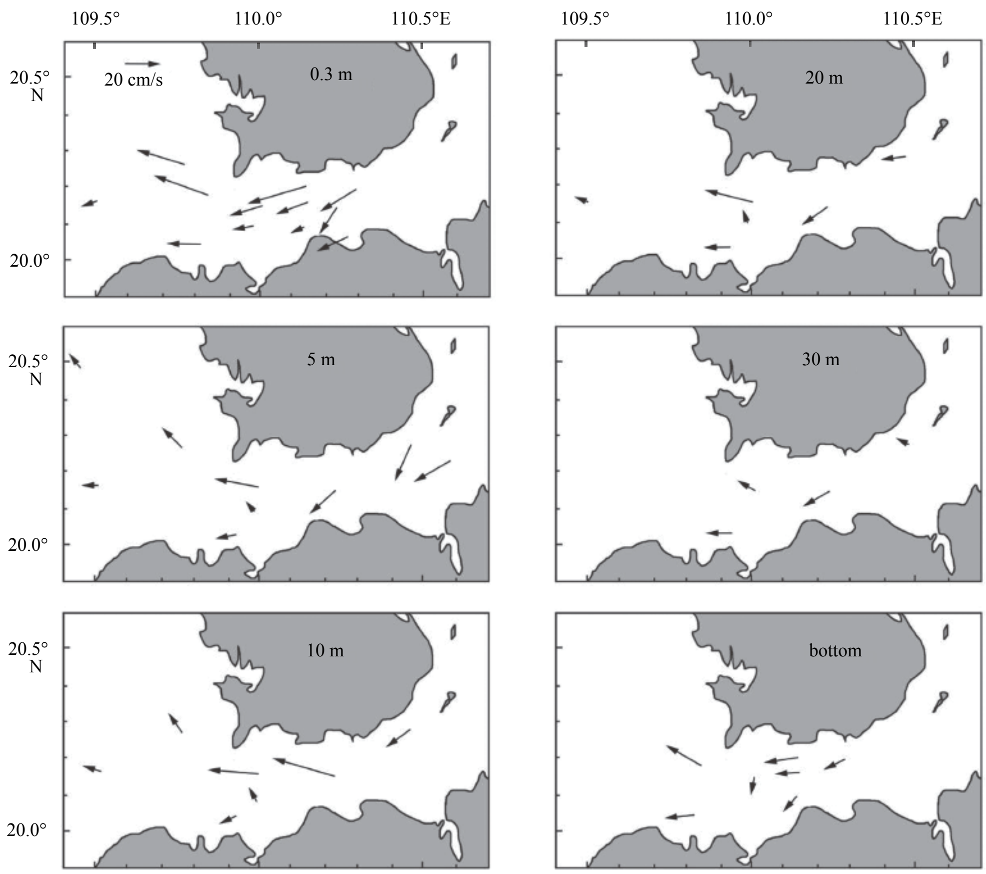

Fig. 4. Distribution of the residual current in winter (December to February).

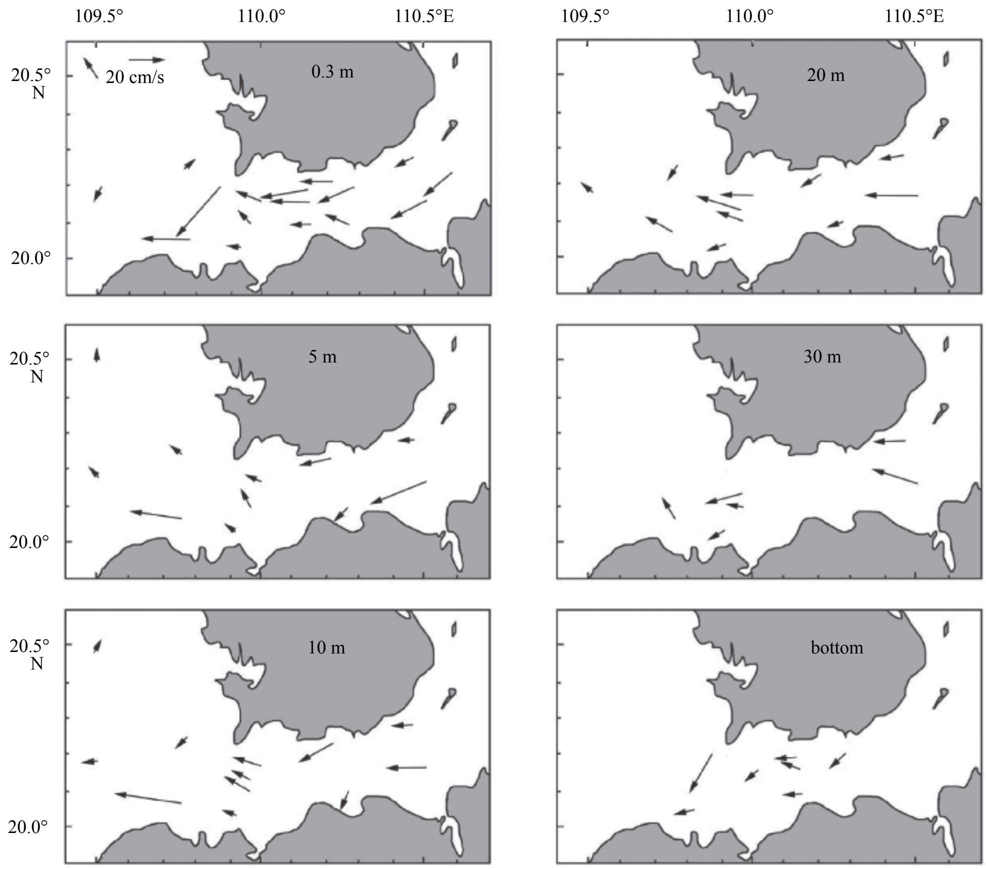

Fig. 5. Distribution of the residual current in summer (June to August).

(1) In summer (June to August), the residual current in the Qiongzhou Strait still flows westward, especially in the middle and bottom layers.

(2) In summer, the strongest current is located in the northern region of the Qiongzhou Strait and is stronger in the middle and bottom layers than in the surface layer. This distribution pattern is different from that of the strong residual currents in winter and spring.

(3) Due to topographic effects, the residual current near Dengloujiao in the western Qiongzhou Strait is strongest in all layers (the surface, middle and bottom layers).

(4) The formation mechanism of the residual current in the Qiongzhou Strait is clearly not wind.

The residual current results for summer clearly indicate that the current direction is generally greater than 180° and varies around 270°, demonstrating that the residual currents flow westward.

3.3.3 *Observational data from Weizhou Island support the view of westward residual currents*

The data used in this section are fixed-point observational ocean current measurements from the southwest of Weizhou Island in an area with a water depth of approximately 40 m (the location is shown in Fig. 1). The coordinates of the observation station are 21°00′N and 108°45′E. The currents were measured in three layers: 10 m, 20 m and 30 m. The sampling interval was 1 h. The duration of the measurement period is eleven months, from October 1, 1988 to August 6, 1989.

Figure 6 shows the wind vector (the topmost plot) and the residual current vectors of different layers (10 m, 20 m and 30 m). Figure 6 demonstrates that the wind direction is generally NNE–NE from October to the following May and that it changes to SW and SE in June and July. The residual current in the 10 m layer generally flows NW from October to the following May and changes to NW–SW after June.

Wind is a significant factor influencing the residual current but is not the only factor. For example, in March, the wind direction varies and the wind velocity decreases. The residual current remains in the winter pattern and is generally similar to the residual current direction from October to February. In addition, the current velocity does not significantly decrease. The difference between the observations and the calculated Ekman wind drift results is quite large. This phenomenon is caused by the circulation in the northern Beibu Gulf.

The above observational results generally agree with the calculations reported by Xia et al. (2001). Regardless of the season, the residual currents around Weizhou Island all flow from SE to NW.

To further analyze the movement of the ocean current around the Weizhou Island, we established four ocean current observation stations to the northeast and southwest of Weizhou Island from November 2–3, 2017, to collect synchronized continuous observations for 24 h (station locations are given in Fig. 1; the results are given in Fig. 7). The sea surface wind during this period was a 6–7-grade northerly wind.

The field observations of the ocean currents show that the flow directions of surface seawater to the northeast and southwest of Weizhou Island are generally similar. The surface current flows southwestward for the majority of each 24-h period and northeastward for only a few hours. The speed of the southwest-

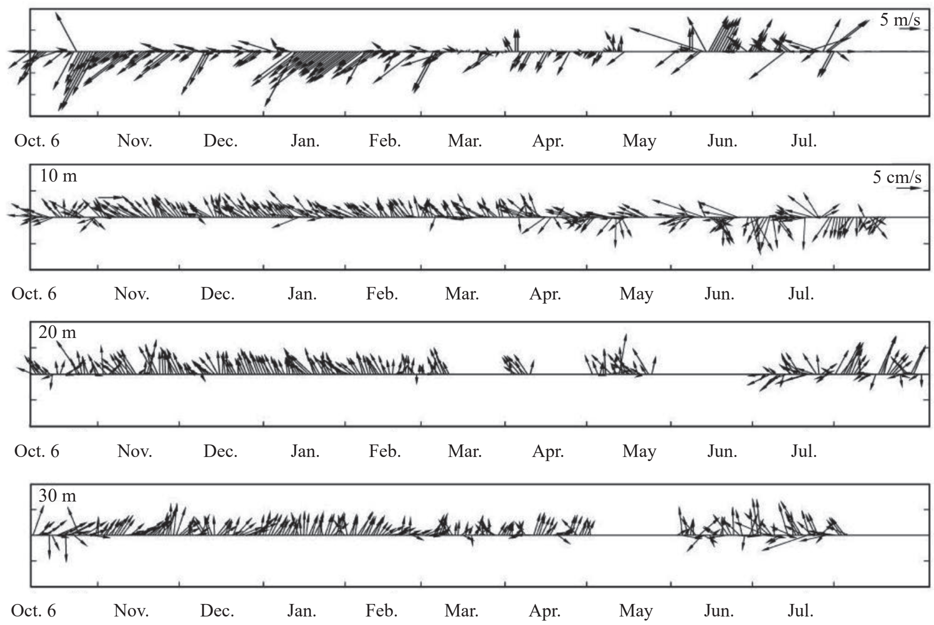

Fig. 6. Distributions of the wind (topmost) and residual current vectors in the 10–30 m layers at the observation points.

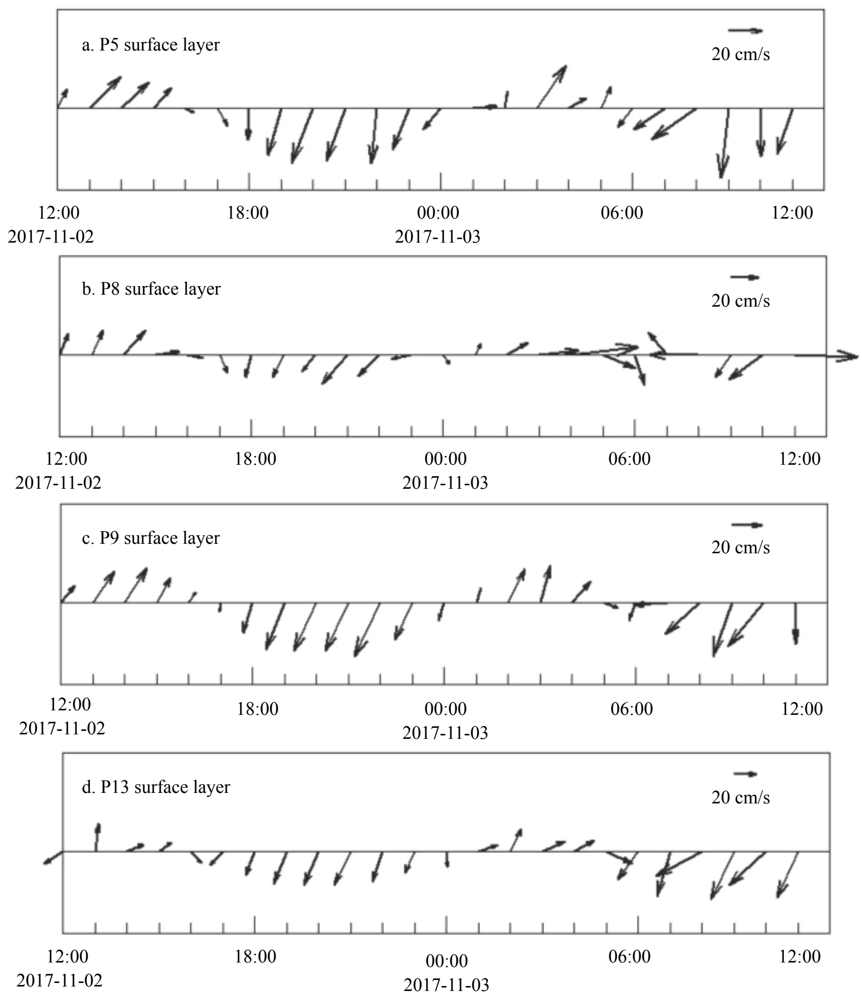

Fig. 7. Continuous observations of the ocean current around the Weizhou Island (November 2017).

ward current is high and stable, and that of the northeastward current is low and unstable. The northeastward current is clearly affected by the wind. A comparison with the surface current observations in Fig. 6 demonstrates that the direction of the field-measured surface current around Weizhou Island is consistent with the historical results and is southwestward.

3.3.4 *Main impact mechanism of the westward flow in winter and summer in the Qiongzhou Strait*

In winter, the main factor is the northeastern monsoon, which is prevalent in the wintertime. The wind period is long and stable and presents an average wind speed of 5–6 grade. The wind current data analysis shows that the maximum velocity of the surface residual current in the Qiongzhou Strait is 20–40 cm/s in winter but 10–30 cm/s in summer. The surface residual current in winter is obviously larger than that in summer, indicating that the northeast monsoon has a much greater effect on the surface current than the southwest monsoon. In winter, although runoff decreases and the flow amplitude narrows, the westward-flowing tendency of the runoff from the eight mouths of the Zhujiang River system is still very strong due to the effects of the northeastern monsoon and the coastal current along the continental shelf of China. A statistical analysis of the recycling results of the 3 400 drifting bottles launched by the South China Sea Research Institute of the Chinese Academy of Sciences on the western coast of the Qiongzhou Strait from 1964 to 1972 shows that 78% of the drifting bottles are in the direction of W, SW and NW (Shi, 2014). The results confirm the fact that the water in the Qiongzhou Strait is transported westward in winter.

In summer, the primary factors are the accumulation of considerable amounts of diluted water at estuaries and the upwelling at the northern continental shelf. An extremely large quantity of precipitation falls in the area around the South China Sea, with the total annual precipitation reaching more than 2 000 mm. During May to August, more than 50% of the annual freshwater runoff flows into the ocean. A large amount of diluted water has accumulated in the estuary area due to the increased runoff into the sea. At the same time, the northern continental shelf of the South China Sea is dominated by upwelling, the continental shelf water is characterized by low temperature and high salinity values, while the nearshore water features high temperature and low salinity values. The baroclinic effect created by mixing waters drives the diluted water to flow southwestward along the western Guangdong coast and enter the Beibu Gulf via the Qiongzhou Strait, which plays an important role in the formation of cyclonic circulation. For example, in June 1981, the nearshore sea level was more than 113 mm higher than the multi-year average. Under the effect of the pressure gradient from the coast toward the open sea, the diluted Zhujiang River water was transported westward. In August 1984, the wind was markedly weak. Although the nearshore average sea level was 77 mm higher than the multi-year average (but lower than that in June 1981), the pressure gradient still forced runoff to flow westward. Therefore, a large amount of runoff water flows westward along the western Guangdong coast due to the pressure gradient in summer and enters the Beibu Gulf via the Qiongzhou Strait. The westward current from the western Guangdong coast is the main reason for the westward transport of water in the Qiongzhou Strait. This result is also confirmed by our analysis of the directions of the residual currents in the Qiongzhou Strait in winter and summer.

4 Impact of the water inflow from the eastern Qiongzhou Strait into the Beibu Gulf on the Guangxi coastal circulation

To investigate the impact of the water inflow from the eastern Qiongzhou Strait to the Beibu Gulf on the circulation, the inner link between the westward transport of water in the Qiongzhou Strait and the westward current along the western Guangxi must be first identified. Then, the impacts of the westward inflow of water into the Beibu Gulf on the circulation can be analyzed. According to a large quantity of observational results from the western Guangdong coast (Yang et al., 2003; Yan and Chen, 2005), the western Guangdong coast experiences a southwestward flow of seawater with relatively low temperature and high salinity values in summer. The western Guangdong coastal current mainly consists of a large volume of diluted Zhujiang River water. In summer, the western Guangdong coast receives significantly more precipitation than other parts of the region. This precipitation enhances the inflow of river runoff into the sea and leads to a significant increase in the sea level. Under the effect of the pressure gradient from the coast toward the open sea, the westward flow of the diluted Zhujiang River water is very strong, and then it enters the Beibu Gulf through the Qiongzhou Strait, which has an important impact on the coastal circulation in Guangxi.

4.1 *Continuous westward flow of water in Qiongzhou Strait in winter and summer is an important factor for the formation of the coastal circulation in Guangxi*

Because of its unique location, the Qiongzhou Strait is an important waterway for the water exchange between the Beibu Gulf and the open ocean. Shi et al. (2002) suggested that westward currents exist year round in the Qiongzhou Strait and that the volume of water transported into the Beibu Gulf is 0.2×10^6–0.4×10^6 m^3/s in winter and 0.1×10^6–0.2×10^6 m^3/s in summer. Chen et al. (2007) and Yan et al. (2008) calculated the volume of water transport through the Qiongzhou Strait in winter. They found that the average value in winter was 0.055×10^6 m^3/s and that the flow direction was westward. Zu (2005) used a flow volume of 0.1×10^6 m^3/s in simulations and concluded that when the westward flow volume from the Qiongzhou Strait was set to 0.1×10^6 m^3/s, the circulation at the top of the bay was counterclockwise with an intensified current along the coast of Vietnam. Except for the currents in the northern bay and along the Hainan Island coast, the inner bay currents flowed out of the southern bay mouth along the central axis of the bay. When the eastward flow volume of the Qiongzhou Strait was set to 0.1×10^6 m^3/s, only the current along the southwestern coast of Hainan Island retained a northward direction, and the circulation in the central bay area near the Weizhou Island was clockwise. These results suggest that a stable westward current in the Qiongzhou Strait favors the formation of cyclonic circulation in the northern Beibu Gulf, whereas an eastward current favors the formation of anti-cyclonic circulation. The waters of the eastern Qiongzhou Strait play an important role in the formation of this cyclonic circulation.

We also use the FVCOM numerical model for calculations. FVCOM is an unstructured grid finite volume ocean circulation model. The finite volume method is adopted in the numerical method of the model, which combines the best functions of the finite element method and the finite difference method. The model uses unstructured triangular meshes in the horizontal direction, which is suitable for the study of complex coastline and island problems. In order to fit complex seabed topography, such as estuaries and shelf slopes, theσcoordinate system is adopted in the vertical direction. The vertical mixing computations are based on the Mellor-Yamada 2.5 order turbulence closure model. The distribution of monthly mean 0–10 layer circulation in the northwest of the South China Sea is calculated based on actual runoff and wind field data from August 1988 and August 1989.

The calculated area covers the Beibu Gulf and its adjacent waters and ranges from 15°30′–21°53′N, 105°37′–112°44′E. The grid resolution in the Beibu Gulf is 15 km. The vertical grid uses hybrid coordinates that are suitable for the topography. The vertical resolution is approximately 2.2 m and is higher in areas with depths of less than 100 m. The global-FVCOM integrates a semi-implicit format with a time step of 300 s (Shi et al., 2016). The model considers the dry-wet grid judgment and sets the minimum water depth to 0.05 m, without considering the effects of temperature and salinity flux, wind field and other physical fields. The results also show the influence of water input from the eastern Qiongzhou Strait on the circulation in the northern part of the Beibu Gulf, as shown in Fig. 8.

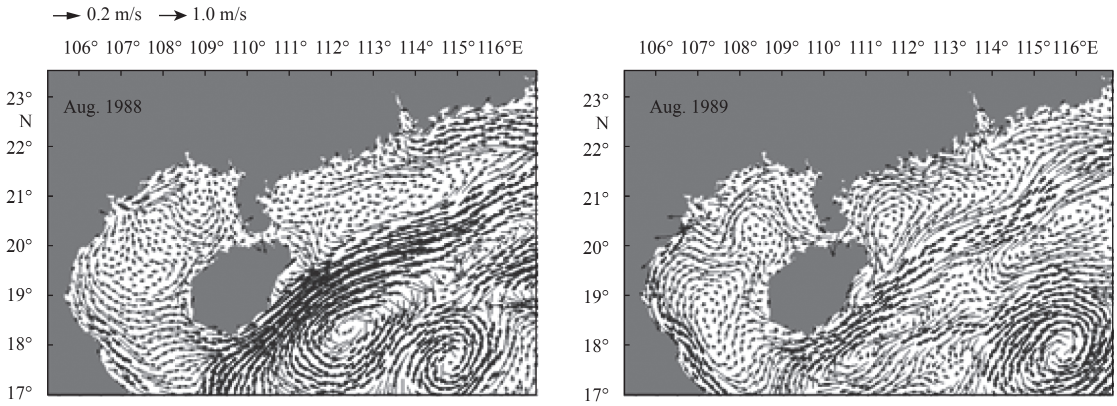

Fig. 8. Model simulated results of monthly mean current distribution at the surface layer in August 1988 and August 1989 (Shi et al., 2016).

Figure 8 shows that: (1) In August 1988, the southwest wind produces a strong northward coastal current on the west coast of the Beibu Gulf, it reaches the west of Qinzhou Bay. The low-salinity diluted water is transported from the coast to the open sea, and then forms a cyclonic circulation near the Weizhou Island. The cyclonic circulation driven by wind and buoyancy mainly appears in the thinner water layer near the surface. After the vertical average of the current, the cyclonic circulation is not obvious. Correspondingly, there is a weak anti-cyclonic eddy in the north-central part of the Beibu Gulf, and a large cyclonic circulation appears in the middle part. (2) The southwest wind is very weak in August 1989, the surface low-salt diluted water mainly flows southward along the west coast of the Beibu Gulf. The residual current from the Qiongzhou Strait forms a larger cyclonic circulation in the northern part of the Beibu Gulf.

We also calculated the circulation of the Beibu Gulf in winter by using FVCOM (Fig. 9). Figure 9 shows that in winter, although the runoff weakens, the water along the western Guangdong coast flows westward through the Qiongzhou Strait into the Beibu Gulf driven by the northeast monsoon. The velocity of westward transport is about 20 cm/s, presenting a strong flow. The Beibu Gulf is generally dominated by the cyclonic circulation, while an anti-cyclonic circulation occurs in the northwestern sea area due to topographic effects.

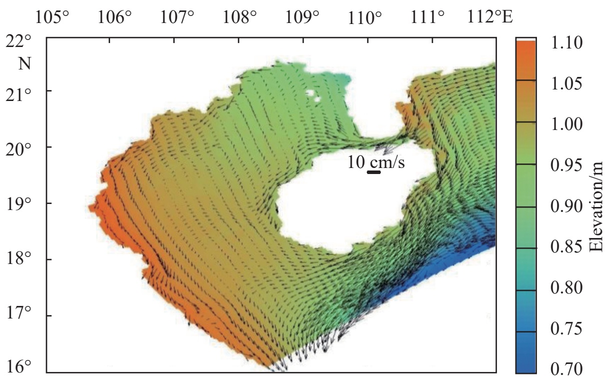

Fig. 9. The surface circulation in the Beibu Gulf in winter (December).

The above numerical simulation results show that the continuous westward flow of water in the Qiongzhou Strait in winter and summer is an important reason for the formation of the coastal circulation in Guangxi. The westward current from the Qiongzhou Strait forms a large-scale cyclonic circulation in the northern Beibu Gulf. Concurrently, a strong cyclonic circulation also occurs in the southern bay. In summer, under the effect of the strong southwestern wind, a strong northward coastal current forms along the western coast of the Beibu Gulf. This current promotes the transport of low-salinity diluted water into the open ocean, which then forms a cyclonic circulation around eastern Weizhou Island. Correspondingly, a weak anti-cyclonic gyre forms in the central northern Beibu Gulf, a large-scale cyclonic circulation occurs in the central part of the gulf, and an anti-cyclonic circulation occurs in the northwestern sea area due to topographic effects. In winter, the northern Beibu Gulf is generally dominated by the cyclonic circulation, while there is an anti-cyclonic circulation in the northwestern sea area. The westward current from the Qiongzhou Strait in winter and summer has an important influence on the formation of cyclonic circulation in the northern part of the Beibu Gulf. These findings suggest that the formation mechanisms of the circulation in the northern Beibu Gulf are completely different from those described in previous studies.

4.2 *Wind plays a role in the formation of the Guangxi coastal circulation but is not the main driver*

The existence of a cyclonic circulation in the northern Beibu Gulf in winter is not controversial; only the cyclonic circulation in summer is controversial. However, a weak cyclonic circulation does exist in the northern Beibu Gulf in summer (Shi, 2014). The reasons for the formation of this circulation are as follows.

(1) Due to the large increase in runoff into the ocean in sum-

mer, a large amount of freshwater accumulates in the estuary and causes the sea level to gradually decrease from the coast to the open ocean. The baroclinic effect created by mixing waters drives the southward flow of diluted water along the Vietnam coast and promotes the formation of cyclonic circulation.

(2) The wind blows from the southwest toward the northern coast in summer, leading to the accumulation of open sea water near the Guangxi shore. Thus, the nearshore sea level becomes higher than that of the open ocean. According to the geostrophic current calculations, the positive pressure from the nearshore to the open sea could drive the westward movement of the coastal water and intensify the formation of cyclonic circulation.

(3) Wind affects the formation of the circulation in the northern Beibu Gulf. In summer, a low salinity area along the coast of Vietnam is formed due to a large amount of fresh water injection. The density gradient distribution caused by temperature and salinity produces an anti-clockwise density current. In the shallow waters of the 15 m contour line in the eastern part of the Beibu Gulf, there is a narrow southwestward current in summer, which is the result of diluted water into the sea driven by the wind stress.

However, wind is not the main driver. First, the southwestern monsoon is unstable and inconsistent, and the average wind speed of the southwestern monsoon is lower than that of the northeastern monsoon in the northern bay. It has limited impact on the formation of the cyclonic circulation. From October 1, 1988 to August 6, 1989, fixed-point observations of the ocean currents were conducted at a depth of 40 m south of Weizhou Island. The currents were measured in three layers: 10 m, 20 m and 30 m. The sampling interval was 1 h. The locations of the observation stations are denoted with "★" symbols in Fig. 1. According to a statistical analysis of the observational data, the average wind velocity and wind direction in July were 5.0 m/s and 155°, respectively. Based on the calculation method for wind-driven Ekman currents, the velocities and directions of the residual currents in the 10 m, 20 m and 30 m layers at the observation point (an oil rig) near the Weizhou Island were 3.1 cm/s and 49°, 1.8 cm/s and 78°, and 1.1 cm/s and 107°, respectively. In contrast, the measured average residual current velocities and directions were 7 cm/s and 246°, 8.4 cm/s and 298°, and 6.1 cm/s and 292° in the 10 m, 20 m and 30 m layers, respectively. The calculated velocities and directions of the currents both differ significantly from the measured results (Table 4). Moreover, the Ekman spiral phenomenon was not present: the flow directions in the 20 m and 30 m layers were generally similar.

Table 4. Comparison between the measurements of the residual current and the Ekman drift calculations in July

	10 m		20 m		30 m		Sea surface wind	
	Velocity/cm·s^{-1}	Direction/(°)	Velocity/cm·s^{-1}	Direction/(°)	Velocity/cm·s^{-1}	Direction/(°)	Velocity/m·s^{-1}	Direction/(°)
Measurement	7.0	246	8.4	298	6.1	292	5.0	155
Calculation	3.1	49	1.8	78	1.1	107		
Difference	3.9	149	6.6	220	7.0	185		

Most previous articles were based on wind-driven circulation patterns and considered wind to be the main driver of the circulation in the northern Beibu Gulf. However, these results do not accurately represent the actual situation. The current measurements in November 2017 also confirm that wind influences the surface current but is not the main driver.

5 Conclusions

(1) In this study, a large quantity of historical hydrological survey data is analyzed, and a long time series of observational data from coastal observation stations is assessed. The results suggest that the changes in salinity anomalies along the Guangxi coast of the Beibu Gulf and the western Guangdong coast are consistent. The salinity anomaly is high in June, July and August and low in September. The variations of salinity reflect the characteristics of the westward flow of water from the Qiongzhou Strait into the Beibu Gulf.

(2) A comparison of the monthly salinity changes between Weizhou Island and the eastern waters of the Qiongzhou Strait indicates that the two areas exhibit similar salinity changes and that the Beihai Station, which is close to Weizhou Island, is slightly affected, whereas the Longmen and Bailongwei Stations, which are far from the Qiongzhou Strait, mostly reflect continental hydrological changes in summer. These results confirm the fact that water from the South China Sea enters the Beibu Gulf via the Qiongzhou Strait in summer.

(3) The analysis of the multi-year ocean current data collected in the Qiongzhou Strait and ocean current data from the Weizhou Island Station and recently established observation stations shows that the residual current in the Qiongzhou Strait flows in a westward direction in both winter and summer. The numerical simulation results also indicate that water from the eastern Qiongzhou Strait enters the Beibu Gulf. This finding provides important support for research on the water exchange between the Beibu Gulf and the South China Sea, the inner circulation in the Beibu Gulf and the upwelling in the eastern Qiongzhou Strait.

(4) The western Guangdong coastal current is the main source of westward water transport in the Qiongzhou Strait. The formation of this western Guangdong coastal current is ultimately due to the westward movement of the diluted Zhujiang River water, which enters the Beibu Gulf via the Qiongzhou Strait and intensifies the formation of the cyclonic circulation in the northern Beibu Gulf. In summer, under the influence of the strong southwesterly wind, a strong northward coastal current forms along the western coast of the Beibu Gulf. This current promotes the transport of low-salinity diluted water toward the open ocean and contributes to the formation of a larger cyclonic circulation near the eastern portion of Weizhou Island.

(5) The formation of the cyclonic circulation in the northern Beibu Gulf is most affected by the westward water current from the Qiongzhou Strait, while the effect of wind is secondary.

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