Regional Studies in Marine Science 18 (2018) 35–43

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Analysis of seasonal characteristics of water exchange in Beibu Gulf based on a particle tracking model

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HIGHLIGHTS

- The residence time in the whole gulf does not vary much between summer and winter.
- The residence times in six sub-regions exhibit a large seasonal difference.
- Water movement in the gulf follows the circulation patterns.
- Currents from Qiongzhou Strait and the south opening help in refreshing the gulf.

ARTICLE INFO

Article history:
Received 19 May 2017
Received in revised form 29 December 2017
Accepted 29 December 2017
Available online 12 January 2018

Keywords:
Water exchange
Beibu Gulf
Residence time
Particle tracking model
Numerical simulation
Qiongzhou Strait

ABSTRACT

The seasonal characteristics of water exchange in Beibu Gulf are investigated based on a particle tracking model. The gulf is divided into six sub-regions in order to better understand the exchange processes and water movement in the gulf. The residence time is computed for each sub-region, and the results show that the whole gulf has a small seasonal variation, with 66 days in winter and 71 days in summer, while the sub-regions exhibit a large seasonal difference with short residence times in summer. Water exchange curves indicate water movement in the gulf follows the circulation patterns. In winter, the water particles move cyclonically and accumulate near the western coast of the gulf. The current flows entering the gulf are dominated by the westward flow from the Qiongzhou Strait. The influence area of this flow can extend to the Vietnam coast. In summer, water particles from the coastal area tend to move offshore and undergo strong mixing in the center of the gulf. The northward current flow from the south opening becomes the dominant flow, with a large influence area in the eastern part of the gulf.

1. Introduction

Beibu Gulf is a semi-enclosed gulf located in the northwestern South China Sea (SCS), with an average depth of about 40 m and a maximum depth less than 100 m. The total area of the gulf is approximately 128 000 km^2. Beibu Gulf is recognized as one of the four largest fishing grounds in China, because of abundant marine life and year-round warm water temperatures. The gulf water is characterized by three major water masses (Chen, 1986), the coastal water supplied by nutrient-rich discharges from numerous rivers along the northern and western coast, the mixed water formed by the current flow from the Qiongzhou Strait (QS), and the sea water coming from the south wide opening between Hainan Island and Vietnam. Water exchange among these water masses has a significant impact on the species composition and distribution in the gulf, providing a greatly diverse marine life. For example, the intrusion of high-salinity and high-temperature water from the SCS contributes to different migration pathways of Paragyrops edita in Beibu Gulf (Chen and Qiu, 2005). Consequently, the study of water renewal and related exchange processes can help us better understand the distribution of biological resources and the formation of fishing grounds, and help provide scientific support for proper management of the ecosystem.

Lagrangian particle tracking methods are very useful tools to investigate and model the transport pathways and mixing processes (Dias et al., 2001; Perianez and Elliott, 2002; Perianez, 2004, 2005; Ninto and Garcia, 1996; Wroblicky et al., 1998; Saxton and Jacobson, 1997). In particular, Random-Walk Particle Tracking (RWPT) models that calculate particle pathways with advection and random displacement are well suited for water exchange studies (Suh, 2006; Zheng et al., 2003; Bilgili et al., 2005; Dimou and Adams, 1993; Signell and Butman, 1992; Liu et al., 2011; Oliveira and Baptista, 1997). When studying large areas, the basic idea is to divide the study area into several zones, and estimate water

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https://doi.org/10.1016/j.rsma.2017.12.009

exchange within and between these zones (Thompson et al., 2002). Here, we adopted this idea to split Beibu Gulf into six sub-regions using the fuzzy C-means clustering technique (Bezdek, 2013). They are coastal areas including Guangxi, Vietnam and Hainan Island, and the interior gulf areas containing the northern, central, southern gulf. The Random-Walk Particle Tracking (RWPT) model was developed to simulate the exchange processes between the sub-regions. The circulation patterns likely to affect water movement (Gao et al., 2014) were calculated using a 3D hydrodynamic model for particle tracking simulation. The circulation patterns in Beibu Gulf have strong seasonality, driven by prevailing wind forcing, and are affected by the exterior circulation from the SCS in the south as well as outflow from the QS in the northeast (Wu et al., 2008; Gao et al., 2013; Shi et al., 2002). The cyclonic circulation in winter has been demonstrated in most observations (Xu et al., 1980; Yu and Liu, 1993; Yuan and Deng, 1999). However, the circulation pattern in summer remains controversial. Recent studies pointed out that the circulation structure remains cyclonic in the summer despite the monsoonal forcing that tends to drive it anti-cyclonically (Wu et al., 2008; Gao et al., 2013; Chen et al., 2015; Bao et al., 2005). Our model result of circulation patterns is consistent with recent studies, and is discussed in Section 3.

The aim of this study is to analyze the seasonal characteristics of water exchange between six sub-regions and water movement pathways in Beibu Gulf. Since the climate around the gulf is subtropical and monsoonal, the southwest (SW) and northeast (NE) monsoons are the two dominant regimes, with transition periods in April and October (Zeng et al., 1989). We chose summer (June, July, and August) and winter (December 2014, January and February 2015) as two representative seasons for seasonal characteristics analysis. The water renewal abilities of the sub-regions were quantified based on the average residence time approach (Takeoka, 1984). Water exchange processes between sub-regions were described using water exchange curves. Moreover, the influence areas of current flows from the QS and the south opening were examined via continuous particle release during winter and summer.

The rest of this paper is organized as follows: Section 2 describes the 3D hydrodynamic model, Random-Walk Particle Tracking model, and definition of residence time used in this paper. Results of circulation patterns, water exchange, and water transport through QS and the south opening during winter and summer are examined in Section 3. Section 4 presents a discussion and a set of conclusions.

2. Model, data, and method

2.1. The 3D hydrodynamic model

The MEC (Marine Environmental Committee) ocean model was developed by the Japanese Society of Naval Architects and Ocean Engineers (Marine Environment Committee, 2003). It has been applied to solve problems involving the physical environment and ecosystem in coastal seas and bays (Sato et al., 2006; Mizumukai et al., 2008; Kano et al., 2010). In this research, the MEC ocean model was used to simulate the velocity fields to drive the RWPT model, as described below.

The model solves the hydrodynamic primitive equations using the hydrostatic assumption in the vertical direction with the Boussinesq simplification for convective flows. Using Cartesian coordinates, the model domain (Fig. 1) is divided into grids of 330 by 315, with a horizontal resolution of 2 km by 2 km, and 10 levels in the vertical. The depth field in the domain is extracted from ETOPO1 with a resolution of 1° by 1°.

In this study, eight tidal harmonics (K_1, O_1, P_1, Q_1, M_1, S_2, N_2, K_2), extracted from the Oregon State University tidal model, are

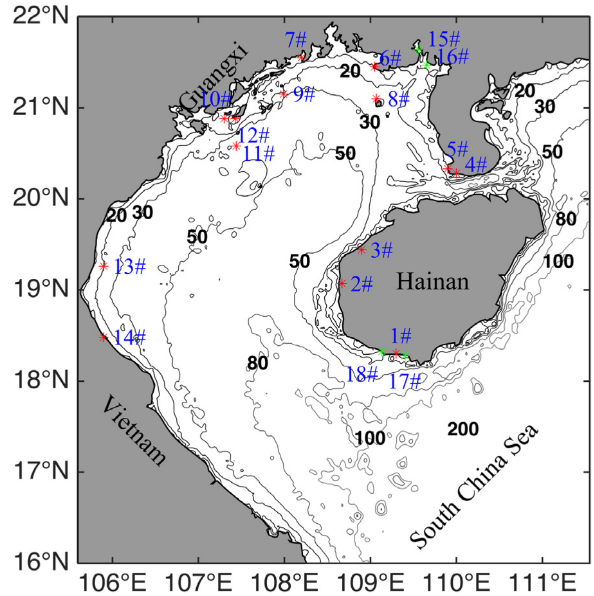

Fig. 1. Topography of Beibu Gulf, with sampling stations for field observations (units: m).

forced at the open boundaries. The daily averaged elevation, temperature, and salinity are obtained from the global 1/12° Hybrid Coordinate Ocean Model + Navy Coupled Ocean Data Assimilation (HYCOM + NCODA) analysis. Daily averaged wind data is derived from the National Climatic Data Center, which is a product merged from multiple satellite scatterometers and model analysis on a global 0.25° grid. The daily averaged heat flux is obtained from NCEP products with 1° resolution. The SST data set uses the Remote Sensing Systems (REMSS) SST product with 9 km and 1 day resolution. The climatological monthly averaged freshwater discharges of eighteen rivers in Guangdong, Hainan, and Vietnam are collected from observations and published papers (Van Maren and Hoekstra, 2004; Pruszak et al., 2005; Gao et al., 2013). The initial temperature and salinity on December 1, 2013 are also derived from the 1/ 12° HYCOM+NCODA analysis. The model is spun up with zero elevation and velocity, and the time step is set to 12 s. The model simulation period lasts through January 1, 2014 to December 31, 2015.

The hydrodynamic model is validated against existing observations. Comparison of computed and measured tide amplitudes and phases at 14 locations is presented in Table 1. For the tidal constituents M_2, K_1, O_1, the mean absolute errors in amplitude are 1.81, 2.9, and 3.4 cm, respectively, and the mean relative errors are 7.1%, 4.9%, and 4.8%, respectively, and the phase mean absolute errors are 4.6°, 5.3°, and 7.2°, respectively. If the mean relative errors in amplitude are lower than 10% and the mean absolute errors are lower than 10°, the agreement between the model results and observations are considered very good. The observed tidal elevation and currents measured at Tieshan Bay tide stations (15# and 16# in Fig. 1) and Sanya Bay station (17# and 18# in Fig. 1) are used for model calibration (Fig. 3). The root mean squared errors (RMSE) for current velocity, current direction and water level in Tieshan Bay station are 13.58 cm/s, 13.93° and 0.0871 m. The root mean squared errors (RMSE) for current velocity, current direction and water level in Sanya Bay station are 8.56 cm/s, 16.06° and 0.0616 m. In general, the simulated and observed values are in a good agreement. Although the errors are not negligible for current velocity and current direction at these two observational stations, they are still acceptable. On one hand, the Tieshan Bay and Sanya Bay are semi enclosed bays with complicated terrain; the input terrain used for model simulation may cause some errors that may influence the model results. On the other hand, the current observed

Table 1
Comparison between observation and simulation of harmonic constants.

No	M_2		K_1		O_1	
	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)
1#	22.1 (22.3)	319.9 (319.9)	33.0 (28.7)	332.8 (333.3)	30.6 (27.7)	285.2 (283.2)
2#	17.2 (18.3)	58.2 (59.7)	52.5 (54.0)	66.4 (71.2)	59.7 (63.3)	2.2 (10.3)
3#	19.4 (18.8)	133.9 (130.2)	71.0 (69.7)	83.1 (85.7)	77.8 (81.4)	16.2 (19.4)
4#	23.6 (25.5)	165.1 (174.7)	66.9 (66.1)	81.0 (88.2)	74.3 (78.5)	14.0 (29.4)
5#	22.9 (23.6)	162.59 (159.8)	69.6 (72.3)	81.6 (90.7)	76.8 (73.5)	14.6 (28)
6#	41.0 (46.2)	173.7 (180.3)	86.4 (89.3)	92.0 (97.3)	92.2 (96.9)	24.2 (34.7)
7#	32.1 (31.4)	177.2 (180.8)	83.4 (83.2)	95.0 (98.9)	89.4 (90.5)	27.2 (37.6)
8#	36.1 (37.9)	168.3 (171.3)	81.9 (84.3)	89.7 (92.9)	87.9 (93.1)	22.1 (30.7)
9#	21.2 (20.0)	176.9 (179.0)	80.7 (80.0)	95.9 (85.0)	86.8 (80.0)	28.1 (33.0)
10#	20.7 (19)	180.7 (179)	79.2 (72)	98.1 (96.0)	85.4 (81.0)	30.2 (30.0)
11#	22.4 (25.0)	171.9 (174)	75.5 (80.0)	96.3 (83.0)	81.9 (79.0)	28.5 (32.0)
12#	9.3 (10.0)	115.1 (129.0)	63.4 (65.0)	92.2 (95.0)	70.3 (71.0)	25.0 (26.0)
13#	23.0 (20.0)	20.5 (26.0)	52.3 (60.0)	105.8 (107.0)	60.1 (60.0.0)	37.6 (52.0)
14#	25.9 (30.0)	22.1 (31.0)	47.3 (50.0)	108.6 (102.0)	55.2 (59.0)	40.1 (45.0)

in these stations is influenced by many factors such as small river inputs that the model simulation did not take into consideration. The maps of monthly mean MODIS SST observations are selected to assess the model performance in simulating the temperature. As Fig. 4 shows, the averaged model surface temperature in June 2014 and January 2015 over Beibu Gulf is similar to the satellite SST patterns. The modeled SST pattern in the coastal area in June is a little different from the observations because the low resolution of the satellite data may cause low-accuracy observations in coastal areas. The elevation, current, and temperature results show that the model is able to provide a hydrodynamic field for further study of water exchange processes.

2.2. Particle tracking model

The Random Walk Particle Tracking (RWPT) model is used for the water exchange simulation. The RWPT model runs offline with hydrodynamic model outputs of velocity to calculate particle paths. The equation for particle locations is integrated using a fourth-order accurate Runge–Kutta method, and can be described as advection because of the currents and random walk associated with the sub-grid-scale diffusion (Tompson, 1993; Dimou and Adams, 1993; Salamon et al., 2006).

$$\boldsymbol{X}^{t+\Delta t} = \boldsymbol{X}^{t} + \boldsymbol{U}\Delta t + \boldsymbol{R}(t)\sqrt{2\boldsymbol{K}_{\mathbf{h}}\Delta t}. \tag{1}$$

where $\boldsymbol{X}^t$ and $\boldsymbol{X}^{t+\Delta t}$ are, respectively, the position vectors of a passive particle at time t and $t+\Delta t$, $\boldsymbol{U}$ is the velocity vector of the model flow field, Δt is the random walk time step, $\boldsymbol{R}(t)$ is the uniform distribution random number in the interval −1 to 1, here a uniform deviate given by the Fortran 90 random number generator. $\boldsymbol{K}_{\mathbf{h}}$ is the eddy diffusivity coefficient for the random walk in the horizontal directions, derived from the hydrodynamic model.

2.3. Residence time calculation

Many concepts of time scales such as age, residence time, transit time and flushing time (Monsen et al., 2002; Prandle, 1984) have been introduced to quantify the exchange and transport processes and to assess the self-purification and assimilative capacity of a water body. Bolin and Rodhe (1973) summarize the concepts on the basis of "age", which is defined as the time that has elapsed since the material element entered the reservoir. Zimmerman (1976) introduced the residence time as a complement to the age. The residence time for each material element is defined as the time taken for the element to reach the outlet.

Here we adopt the average residence time defined by Takeoka (1984) as the renewal time for a given water parcel in this study. Consider a parcel of material in a reservoir. Let the initial time be t_0, the amount of the material at t_0 be R_0, and the amount of the material which still remains in the reservoir at time t be R_t. R_t is the amount of the material whose residence time is larger than t. The function of the distribution of residence time can be defined as:

$$\tau_r' = -\frac{1}{R_0}\frac{dR_t}{dt}. \tag{2}$$

After an integration by parts, the average residence time τ_r is defined as:

$$\tau_r = \int_0^{\infty} \frac{R_t}{R_0} dt = \int_0^{\infty} r(t)\, dt. \tag{3}$$

Here, $r(t) = R_t/R_0$ is called the remnant function. The function $r(t)$ denotes the decrease in the material considered and the exchange or transport of the material that is directly described by this function.

3. Circulation patterns

The mean circulation pattern in the gulf is one of the significant factors responsible for water exchange and water movement in the gulf. We obtained the mean current fields in July and December, representing the summer and winter circulation patterns in 2014 (Fig. 5).

The result shows that the cyclonic circulation patterns appeared both in summer and winter, consistent with recent studies (Gao et al., 2013; Chen et al., 2015). The cyclonic circulation forms two main flow systems. One flows into the northern part of the gulf from the QS and feeds the cyclonic circulation (Wu et al., 2008). The other flows northward from the southern and western coasts of Hainan Island. This northward current originates from one portion of the SCS southwestward shelf current, most of which turns southward and bypasses the gulf (Gao et al., 2013).

In the summer, the northward flow moves to the north of the gulf and joins the westward flow coming from the QS. The joint flow is northwestward, forming the western limb of the cyclonic circulation. An anti-cyclonic flow appears in the northwestern gulf, and an enclosed cyclonic circulation exits south of the gulf. Driven by the summer monsoon, flows in the summer are mostly eastward and northeastward. The maximum velocity occurs along the Vietnam coast. The current velocity in coastal areas is larger than in the outer sea.

In the winter, the westward flow from the QS is separated into two branches. One branch flows northwestward along the Guangxi coast and joins the gulf-wide cyclonic circulation. The other branch flows along the northwestern Hainan Island coast and joins the aforementioned northward current. The joint northward current moves westward across the gulf at ~19.5°N. The enclosed circulation in the south of the gulf is anti-cyclonic in winter. Flows are mostly westward and southwestward under the northeasterly monsoon forcing. The current velocity in the north of the gulf is larger than in the south of the gulf. The maximum velocity appears in the QS.

4. Water exchange

The Beibu Gulf water is divided into nine groups (Fig. 2) using the fuzzy C-means clustering technique (Bezdek, 2013), based on the yearly averaged sea surface temperature (SST) and Chlorophyll-a (Chl-a) concentration data which is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS Aqua) with 4 km spatial resolution. The groups (G7, G8 and G9 in Fig. 2) are characterized by high Chl-a contents. The Group 6 (G6 in Fig. 2) has low SST with the mean value of 24.8°. Group 5 has high SST with the mean value of 27°. According to the topography, and physical parameters (SST and Chl-a contents) in each group, we combine some groups and divide the gulf into six sub-regions (Fig. 2). The water in these sub-regions can be characterized with coastal waters and mixed waters. The coastal waters in Guangxi and Vietnamese coasts has high Chl-a contents may be contributed by nutrients from the river discharges into the gulf (Deetae and Wisespongpand, 2001). The coastal water in the west coast of Hainan Island has low surface temperature and High Chl-a content. This may be because of the local upwelling and tidal mixing (Lü et al., 2008). The gulf mixed waters in the Northern, Central and Southern sub-regions are influenced by the water intrusion through Qiongzhou Strait and the south opening. Contrary to the Central and the Southern Gulf sub-regions, the Northern Gulf exhibits low surface temperature characterization.

In order to study the water exchange between these sub-regions, particles are released near the surface in each sub-region with a uniform distribution, and tracked with a 60-minute time step for 90 days in each season or until they cross the boundaries. In addition to analyzing the water exchange in the interior gulf, the influence areas of current flows from the Qiongzhou Strait (QS) and south opening are quantified. Particles are released across transects of the QS and south opening during the winter and summer seasons (Fig. 8, red lines).

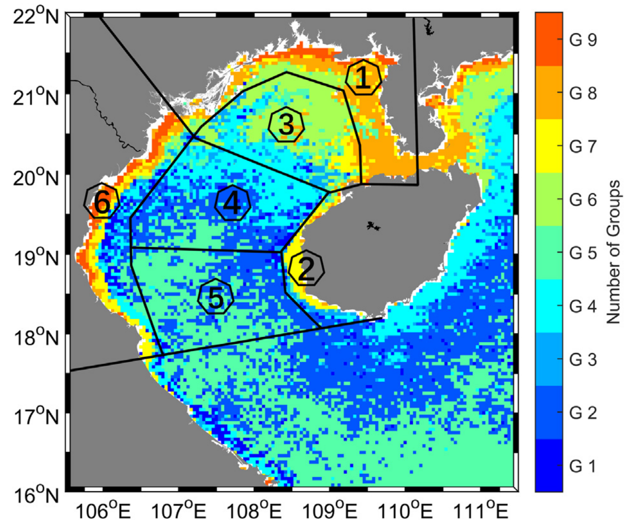

Fig. 2. Sub-regions defined by fuzzy C-means clustering method. They are 1. The Guangxi Coast. 2. The West Coast of Hainan Island. 3. The Northern Gulf. 4. The Central Gulf. 5. The Southern Gulf. 6. The Vietnamese Coast. (The rest is the outer sea.) The color bar represents original nine groups divided by fuzzy C-means clustering method.

Table 2
Average residence times in sub-regions (days).

Sub-regions	Winter	Summer
Guangxi coast	33	49
Hainan Island coast	5	22
Northern gulf	9	39
Central gulf	17	40
Southern gulf	24	32
Vietnamese coast	71	49
Whole gulf	66	71

4.1. Residence times

The residence times are computed for the whole gulf and each sub-region. Table 2 shows that the residence time for the whole gulf has a small seasonal variation, 66 days in winter and 71 days in summer, while the residence times for the sub-regions have larger seasonal variations. Generally, the sub-regions exhibit short residence times in winter, except for the Vietnamese coast. This might be caused by the fact that movement of particles near the Vietnamese coast is limited by the topography and coastal current, leading to a long residence time in winter. The regional residence times show a spatial difference. Among the six sub-regions, particles off the west coast of Hainan Island have the shortest residence times, and the Vietnamese coast has comparative long residence times, reaching 71 days in winter.

4.2. Water exchange in summer

The water exchange curves show that about 40% of Guangxi coast particles are exported to the central gulf (Fig. 6a, green line), while only 19% remains along the Guangxi coast by the end of the simulation for the summer season (Fig. 6a, red line). The exported Guangxi coast particles work their way through the northern gulf (Fig. 6a, blue line) and central gulf (Fig. 6a, green line), eventually reaching the southern gulf (Fig. 6a, pink line) as incrementally increasing fractions in the southern gulf.

About 60% of the Hainan Island west coast particles are rapidly flushed out within the first 15 days of simulation (Fig. 6b, orange line). Most of the flushed particles move into the northern gulf (Fig. 6b, blue line) and remain there for a considerable amount of

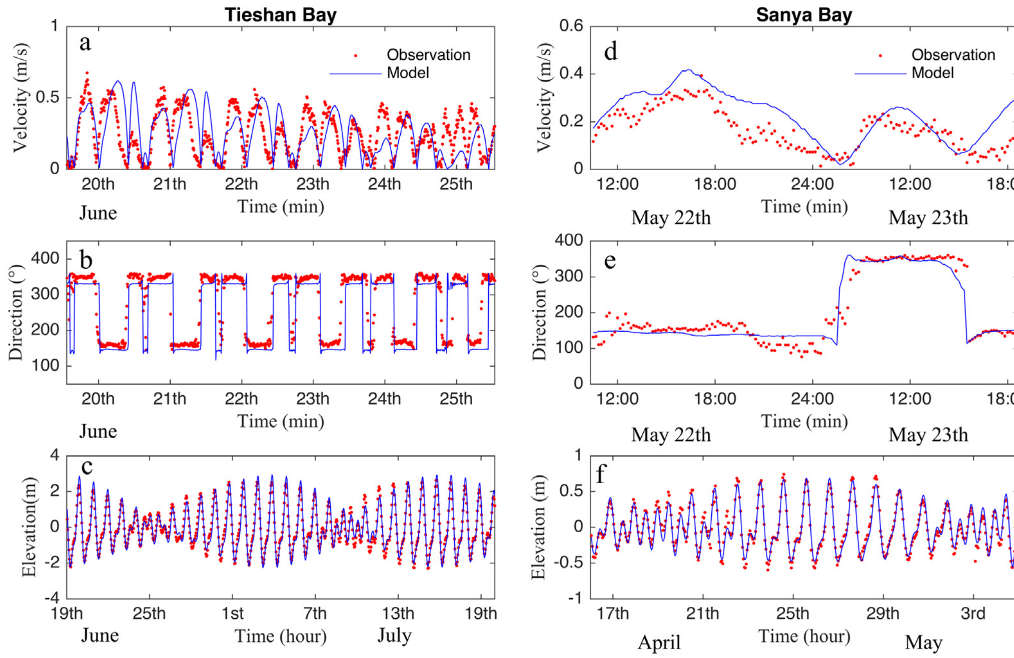

Fig. 3. Comparison of observed and modeled water levels, current velocity, and current direction at Tieshan Bay station (a, b, c) and Sanya Bay station (d, e, f).

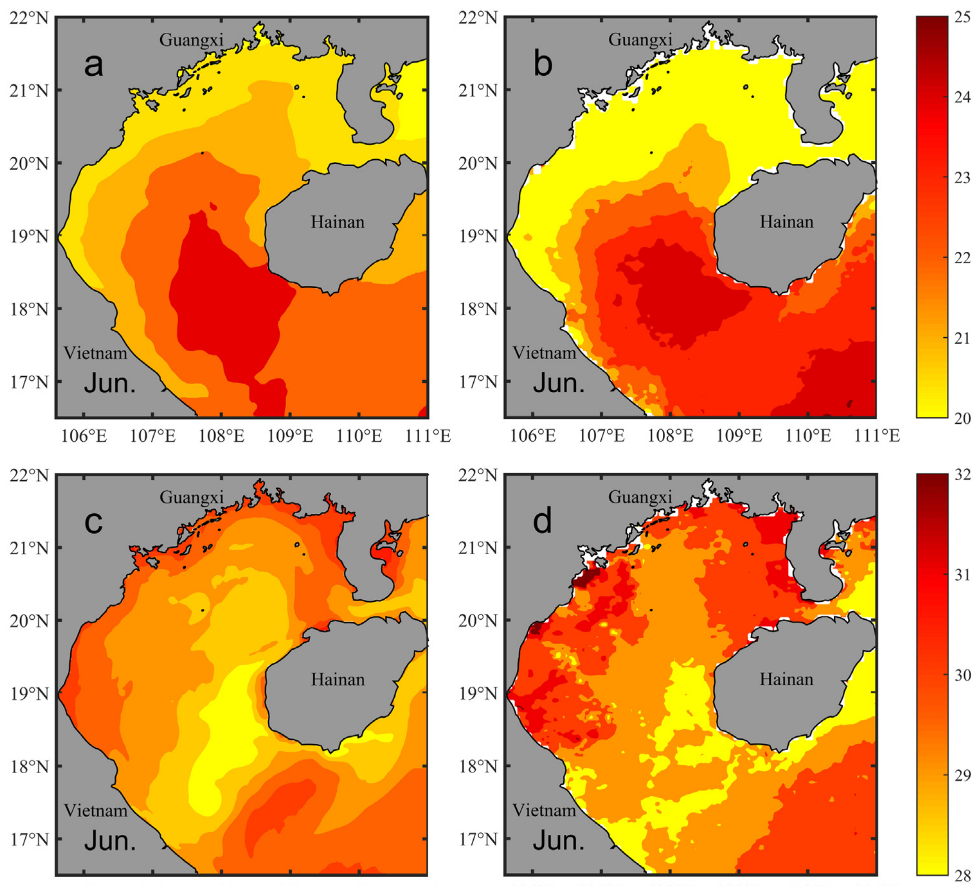

Fig. 4. Monthly mean SST (°C) calculated by model for (a) January 2015 and (c) June 2014; monthly mean satellite SST (°C) maps for (b) January 2015 and (d) June 2014.

time before being slowly flushed out to the central gulf in the final 20 days (Fig. 6b, green line). Although few Guangxi coast particles are found along the west coast of Hainan Island, they do communicate with each other, as evidenced by a fraction of the Hainan

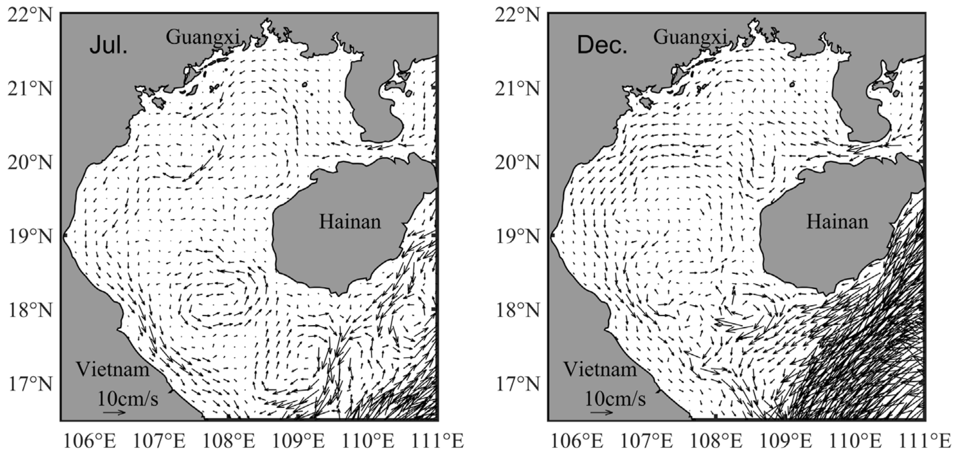

Fig. 5. Vertically averaged circulation in July and December 2014.

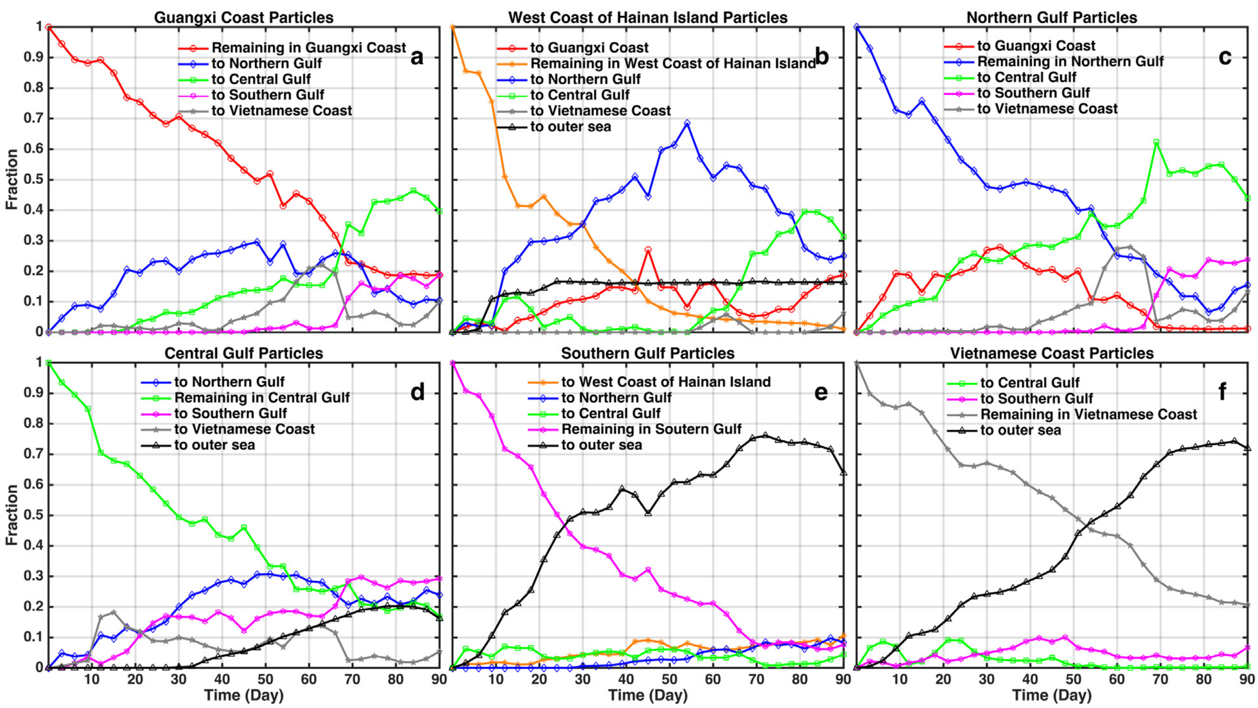

Fig. 6. Graphs showing fraction of particles remaining in starting area or traveling to other areas during summer. Sub-regions are colored red, orange, light blue, green, pink, gray, and black, representing Guangxi coast, west coast of Hainan Island, northern gulf, central gulf, southern gulf, Vietnamese coast, and outer sea, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Island west coast particles reached the Guangxi coast (Fig. 6b, red line). Another small fraction (about 20%) moves southward along Hainan Island to the outer sea (Fig. 6b, black line).

The northern gulf exports about 44% of its particles to the central gulf (Fig. 6c, blue line) by the end of the simulation. Meanwhile, it has received 24% of the central gulf particles (Fig. 6d, blue line). The central gulf particles show a trend similar to the northern gulf particles. Roughly 30% of the particles are transported into the southern gulf, with only 17% retained (Fig. 6d, green line) by the end of the simulation. In addition, a small portion of the central gulf particles is found in the outer sea (Fig. 6d, gray line). As the gate to the South China Sea, the southern gulf and Vietnamese coast mainly export their particles to the outer sea (Fig. 6e and f).

As Fig. 8a indicates, the current flow coming from the south opening is dominant, and influences most of the eastern part of the gulf in summer. In contrast, the current flow from the QS moves cyclonically along the Leizhou Peninsula and Guangxi coast region. Its influence area shrinks to a narrow band along Guangxi and the Leizhou Peninsula near the shore.

4.3. Water exchange in winter

During winter, a large percentage of the Guangxi coast and northern gulf particles reach the Vietnamese coast by the end of the simulation (Fig. 7a and c, gray lines). The Guangxi coast particles travel through the northern and central gulfs into the region off the Vietnamese coast. (Fig. 7a, blue line and green line), and the northern gulf particles move through the Guangxi coast and central gulfs (Fig. 7c, red line and green line) to the Vietnamese coast (Fig. 7c, gray line). The pathways suggest that the Guangxi coast and northern gulf particles have a tendency to follow the western limb of the cyclonic circulation.

The west coast of Hainan Island still has a high rate of water exchange, similar to summer (Fig. 7b, orange line). These flushed

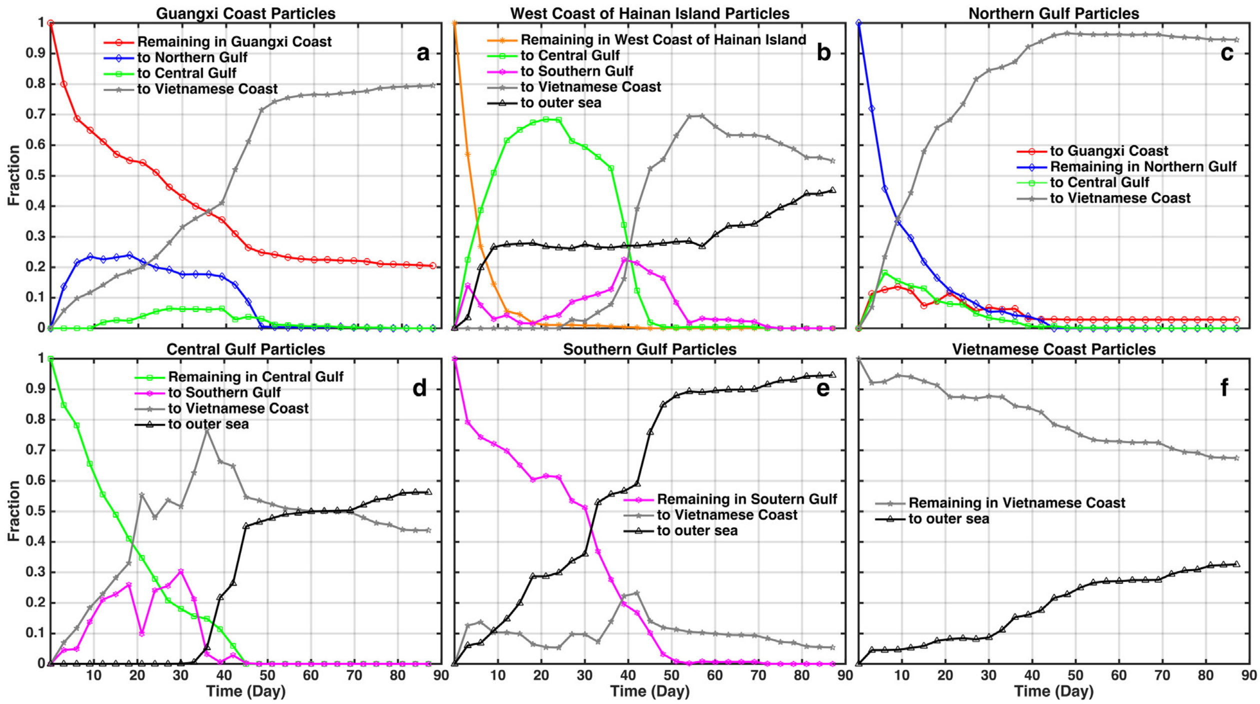

Fig. 7. Graphs showing fraction of particles remaining in starting area or traveling to other areas during winter. Sub-regions are colored red, orange, light blue, green, pink, gray, and black, representing Guangxi coast, west coast of Hainan Island, northern gulf, central gulf, southern gulf, Vietnamese coast, and the outer sea, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

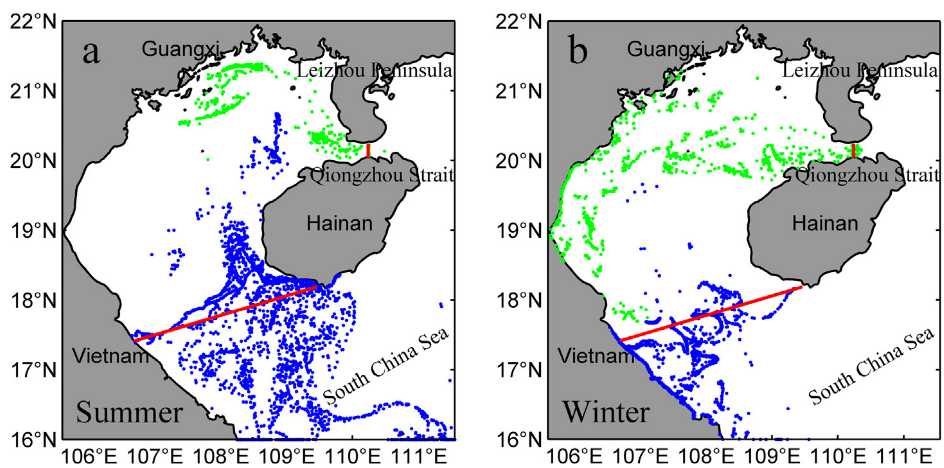

Fig. 8. Position of particles released to QS (green) and south opening (blue) in summer (a) and winter (b); red lines are original release transects. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

particles move westward across the gulf, reaching the Vietnamese coast (Fig. 7b, gray line). The other exported particles move along the near-shore region of Hainan Island to the sea, which can be seen from the increased fraction in the outer sea (Fig. 7b, black line).

Almost 80% of the central gulf particles are drained out within the first 30 days of the simulation (Fig. 7d, green line), moving toward the Vietnamese coast (Fig. 7d, gray line). The drained particles eventually end up along the Vietnamese coast or are transported to the outer sea (Fig. 7d, gray line and black line). On the other hand, the central gulf shows the characteristics of a transitional region, where particles originating from adjacent sub-regions do not reside for long, but move through to other regions (Fig. 7d). This is obvious from the large number of Hainan Island west coast particles exported into this region (Fig. 7b, green line), but which are slowly flushed during the final 20 days to the Vietnamese coast (Fig. 7b, gray line).

The southern gulf exports almost 90% of its particles to the outer sea, and a small portion to the Vietnamese coast (Fig. 7e, black line and gray line). A small fraction of its particles that exist in the central gulf during the early simulation period indicates that the southern gulf particles move northward as well (Fig. 7e, green line). The majority of Vietnamese coast particles remain in the original region, while a small fraction (about 32%) are transported to the South China Sea (Fig. 7f, black line).

The distribution of current flow through the QS shows a tendency to move cyclonically, following the winter current pattern. The QS current flow has a great influence on gulf water

Table 3
Monthly averaged water transport in QS in 2014 (Sv: $10^6\ m^3s^{-1}$).

	1	2	3	4	5	6	7	8	9	10	11	12
Q (u)	0.12	0.11	0.06	0.05	0.03	0.03	0.08	0.03	0.07	0.13	0.14	0.16
Q (v)	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.03	0.03	0.03

refreshment. However, the current flow from the south opening is blocked at the mouth of the gulf (Fig. 7b).

5. Discussion

The residence times identify the time taken by water particles to leave the release areas. The residence time for the whole gulf varies little between winter and summer. The comparatively longer residence time in summer may be caused by weak currents in the gulf and the strong northeast SCS current in the mouth of the gulf limiting the particles' transportation to the outer sea. The residence time for each sub-region reveals strong seasonal variation. The sub-regions exhibit shorter residence times in winter. This might be related to the circulation patterns in Beibu Gulf. Currents in the gulf are stronger in winter than in summer, forcing water parcels to move out faster from the original sub-regions, resulting in shorter residence times. The Vietnamese coast, however, is an exception, with an extremely long residence time in winter. This can be seen in Fig. 7f (gray line), where most of the Vietnamese coast particles are retained in this region. This retention may coincide with the location of water pile-up, which is caused by the force of the northeasterly monsoon (Gao et al., 2013). Since the prevailing northeasterly wind is favorable to downwelling, the coastal waters are pushed close to shore, resulting in a water pile-up along the western shore. In contrast, the upwelling-favorable southwesterly monsoon wind causes the coastal water to spread further offshore (Lü et al., 2008; Gao et al., 2014), leading to a short residence time.

The spatial difference of the sub-regions may also be related to local currents. For example, the shortest residence time (Table 2) in both seasons, and the variable transported destinations (Figs. 6b and 7b), indicate the region off the west coast of Hainan Island has an active water exchange ability. This coincides with the strong current and upwelling along the west coast of Hainan Island (Hu et al., 2003; Lü et al., 2008; Kuo et al., 2000).

The water exchange curves provide us clear insights into the water exchange processes and water movement pathways in the sub-regions. The journey of particles originating from the sub-regions suggests water movement in the gulf tend to follow the circulation patterns. In winter, the cyclonically alongshore movement is consistent with the gulf-wide cyclonic circulation pattern. In summer, it is observed that water particles released from coastal sub-regions tend to move offshore and mix strongly with particles released in the center of the gulf. The offshore particles' movement is consistent with the southwesterly wind-induced offshore currents. Knowledge of how water interact between these critical areas is very important for understanding the distribution of biological resources in the gulf. The freshwater river discharge in coastal areas, in some cases, carries abundant nutrient salts into the gulf (Lai et al., 2014), which is necessary for fish, shrimp, and shellfish growth (Chen et al., 2009). In other cases, these discharges may upset nutrient balances and bring toxic materials (Zheng et al., 2012; Kaiser et al., 2015). The offshore water movement in summer is favorable for spreading nutrients. The cyclonical alongshore water movement in winter is beneficial for water refreshing by the outer sea.

In addition, the Qiongzhou Strait and the south opening play a significant role in gulf water refreshment. According to Shi et al.'s (2002) study, the QS may cause up to 44% of gulf water to be refreshed each season through the year-round westward flow. Additionally, discharge from the Pearl River is reported to reach the gulf through the QS (Tang et al., 2003). Our result also shows a strong westward current through the QS and a northward current along the west coast of Hainan Island that exceeds 1 m/s of velocity, implying the current flow from these two openings have a significant impact on gulf water refreshment. The water transport through the QS transect is estimated as 0.18 Sv (Sv $\equiv 10^6\ m^3s^{-1}$) in summer and 0.52 Sv in winter based on the hydrodynamic model, consistent with previous studies (Shi et al., 2002; Chen et al., 2007). The mean westward water transport was 0.08 Sv in 2014, four times larger than the mean southward water transport (Table 3), indicating cold and less saline water is transported into the gulf (Bao et al., 2005). Also, the strong current flow from the south opening, with its high temperature and high salinity, can provide nutrients and a warm water environment for marine life in the gulf.

6. Conclusion

The seasonal characteristics of water exchange and water movement in Beibu Gulf were investigated using the particle tracking method. Specifically, we paid attention to the water exchange processes and water movement pathways of six sub-regions in the gulf. We also quantified the influence areas of the current flows from the QS and the south opening.

The residence time in the whole gulf was 66 days in winter and 71 days in summer. The regional residence times exhibit seasonal and spatial differences. Except for the Vietnamese coast, other sub-regions have shorter residence times in winter. The west coast of Hainan Island had the shortest residence time, while the Vietnamese coast had the longest residence time, which is associated with the topography and complex local currents.

Water exchange analysis provides a description of how water parcels from different sub-regions interact with one another. The water particle movement pathways suggest that the gulf water moves cyclonically in winter. The water particles from coastal areas have offshore movement and mix strongly in the gulf during summer. The current flows from the QS and the south opening were observed by continuously releasing particles across the two transects. The westward water transport from the QS influences the most northern part of the gulf in winter. The current flow from the south opening moves along the west coast of Hainan Island and influences the most eastern part of the gulf.

The Random Walk Particle Tracking model is useful for examining the regional water exchange in Beibu Gulf. Moreover, it provides a more intuitive viewpoint of how current flow influences gulf water by releasing particles along the QS and south opening transacts. In future research, it would be worthwhile to include the spring and fall seasons in the simulations, to provide more details on seasonal variation. Also, the distribution of pollutants and nutrients in the gulf requires further investigations, as we only studied the potential pathways of pollutants and nutrients carried by water from different sources.

Acknowledgments

This study is supported by the National Key Research and Development Program of China [No. 2016YFA0601201], by the program of Xiamen Southern Oceanographic Center [No. 15PZB009NF05], by a joint effort of the University of Delaware and Xiamen University's Joint Institute for Coastal Research and Management (Joint Institute of CRM), by the Natural Science Foundation of China

[41476007 and 41630963], and by the State Oceanic Administration of China Global Change and Air–Sea Interaction Project [GASI-IPOVAI-01-04 and GASI-02-PAC-YGST2-02]. The authors would like to thank Young-Heon Jo and Jinku Park for providing technique support and useful comments.

References

Bao, X., Hou, Y., Chen, C., Chen, F., Shi, M., 2005. Analysis of characteristics and mechanism of current system on the west coast of Guangdong of China in summer. Acta Oceanol. Sin. 24, 1–9.

Bezdek, J.C., 2013. Pattern Recognition with Fuzzy Objective Function Algorithms. Springer Science & Business Media.

Bilgili, A., Proehl, J.A., Lynch, D.R., Smith, K.W., Swift, M.R., 2005. Estuary/ocean exchange and tidal mixing in a Gulf of Maine Estuary: A Lagrangian modeling study. Estuar. Coast. Shelf Sci. 65, 607–624.

Bolin, B., Rodhe, H., 1973. A note on the concepts of age distribution and transit time in natural reservoirs. Tellus 25, 58–62.

Chen, B., 1986. Preliminary discussion on the formation and characteristic of the water system in the Beibu Gulf. J. Guangxi Acad. Sci. 2, 92–95 (in Chinese).

Chen, B., Yan, J.H., Wang, D.R., Shi, M.C., 2007. The transport volume of water through the Qiongzhou Strait in the winter season. Period. Ocean Univ. China 37, 357–364.

Chen, Z., Qiao, F., Xia, C., Wang, G., 2015. The numerical investigation of seasonal variation of the cold water mass in the Beibu Gulf and its mechanisms. Acta Oceanol. Sin. 34, 44–54.

Chen, Z.Z., Qiu, Y.S., 2005. Ecological distribution of Parargyrops edita Tanaka in the Beibu Gulf. Mar. Fish. Res. 26, 16–21.

Chen, Z., Xu, S., Qiu, Y., Lin, Z., Jia, X., 2009. Modeling the effects of fishery management and marine protected areas on the Beibu Gulf using spatial ecosystem simulation. Fisheries Res. 100, 222–229.

Deetae, S., Wisespongpand, P., 2001. Sub-thermocline Chlorophyll maximum in the South China Sea, area IV: Vietnamese waters. In: Proceedings of the SEAFDEC Seminar on Fisheries Resources in the South China Sea 4, pp. 251–264.

Dias, J.M., Lopes, J.F., Dekeyser, I., 2001. Lagrangian transport of particles in Ria de Aveiro lagoon, Portugal. Phys. Chem. Earth Part B: Hydrol. Oceans Atmosphere 26, 721–727.

Dimou, K.N., Adams, E.E., 1993. A random-walk, particle tracking model for well-mixed estuaries and coastal waters. Estuar. Coast. Shelf Sci. 37, 99–110.

Gao, J., Shi, M., Chen, B., Guo, P., Zhao, D., 2014. Responses of the circulation and water mass in the Beibu Gulf to the seasonal forcing regimes. Acta Oceanol. Sin. 33, 1–11.

Gao, J., Xue, H., Chai, F., Shi, M., 2013. Modeling the circulation in the gulf of Tonkin, South China Sea. Ocean Dyn. 63, 979–993.

Hu, J.Y., Kawamura, H., Tang, D.L., 2003. Tidal front around the Hainan Island, northwest of the South China Sea. J. Geophys. Res.: Oceans 108, 3342.

Kaiser, D., Hand, I., Schulz-Bull, D.E., Waniek, J.J., 2015. Organic pollutants in the central and coastal Beibu Gulf, South China Sea. Marine Pollut. Bull. 101, 972–985.

Kano, Y., Sato, T., Kita, J., Hirabayashi, S., Tabeta, S., 2010. Multi-scale modeling of CO 2 dispersion leaked from seafloor off the Japanese coast. Marine Pollut. Bull. 60, 215–224.

Kuo, N.J., Zheng, Q., Ho, C.R., 2000. Satellite observation of upwelling along the western coast of the South China Sea. Remote Sens. Environ. 74, 463–470.

Lai, J., Jiang, F., Ke, K., Xu, M., Lei, F., Chen, B., 2014. Nutrients distribution and trophic status assessment in the northern Beibu Gulf, China. Chin. J. Oceanol. Limnol. 32, 1128–1144.

Liu, W.C., Chen, W.B., Hsu, M.H., 2011. Using a three-dimensional particle-tracking model to estimate the residence time and age of water in a tidal estuary. Comput. Geosci. 37, 1148–1161.

Lü, X., Qiao, F., Wang, G., Xia, C., Yuan, Y., 2008. Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. Geophys. Res. Lett. 35, L02604.

Marine Environment Committee, 2003. MEC Ocean Model Operation Manual Ver. 1.1. Soc. Naval. Archit., Japan (in Japanese).

Mizumukai, K., Sato, T., Tabeta, S., Kitazawa, D., 2008. Numerical studies on ecological effects of artificial mixing of surface and bottom waters in density stratification in semi-enclosed bay and open sea. Ecol. Modell. 214, 251–270.

Monsen, N.E., Cloern, J.E., Lucas, L.V., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnol. Oceanog. 47, 1545–1553.

Ninto, Y., Garcia, M.H., 1996. Experiments on particle—turbulence interactions in the near–wall region of an open channel flow: Implications for sediment transport. J. Fluid Mech. 326, 285–319.

Oliveira, A., Baptista, A.M., 1997. Diagnostic modeling of residence times in estuaries. Water Resour. Res. 33, 1935–1946.

Perianez, R., 2004. A particle-tracking model for simulating pollution dispersion in the Strait of Gibraltar. Mar. Pollut. Bull. 49, 613–623.

Perianez, R., 2005. An operative Lagrangian model for simulating radioactivity dispersion in the Strait of Gibraltar. J. Environ. Radioact. 84, 95–101.

Perianez, R., Elliott, A.J., 2002. A particle-tracking method for simulating the dispersion of non-conservative radionuclides in coastal waters. J. Environ. Radioact. 58, 13–33.

Prandle, D., 1984. A modelling study of the mixing of 137Cs in the seas of the European continental shelf. Philos. Trans. R. Soc. Lond. Ser. A 310, 407–436.

Pruszak, Z., Van Ninh, P., Szmytkiewicz, M., Hung, N.M., Ostrowski, R., 2005. Hydrology and morphology of two river mouth regions (temperate vistula delta and subtropical red river delta). Oceanologia 47, 365–385.

Salamon, P., Fernàndez-Garcia, D., Gómez-Hernández, J.J., 2006. A review and numerical assessment of the random walk particle tracking method. J. Contam. Hydrol. 87, 277–305.

Sato, T., Tonoki, K., Yoshikawa, T., Tsuchiya, Y., 2006. Numerical and hydraulic simulations of the effect of density current generator in a semi-enclosed tidal bay. Coastal Eng. 53, 49–64.

Saxton, M.J., Jacobson, K., 1997. Single-particle tracking: Applications to membrane dynamics. Annu. Rev. Biophys. Biomol. Struct. 26, 373–399.

Shi, M., Chen, C., Xu, Q., Lin, H., Liu, G., Wang, H., Wang, F., Yan, J., 2002. The role of Qiongzhou Strait in the seasonal variation of the South China Sea circulation. J. Phys. Oceanogr. 32, 103–121.

Signell, R., Butman, B., 1992. Modeling tidal exchange and dispersion in Boston Harbor. J. Geophys. Res. 97, 591–615.

Suh, S.W., 2006. A hybrid approach to particle tracking and Eulerian–Lagrangian models in the simulation of coastal dispersion. Environ. Model. Softw. 21, 234–242.

Takeoka, H., 1984. Fundamental concepts of exchange and transport time scales in a coastal sea. Cont. Shelf Res. 3, 311–326.

Tang, D., Kawamura, H., Lee, M.A., Van Dien, T., 2003. Seasonal and spatial distribution of chlorophyll-a concentrations and water conditions in the Gulf of Tonkin, South China Sea. Remote Sens. Environ. 85, 475–483.

Thompson, K.R., Dowd, M., Shen, Y., Greenberg, D.A., 2002. Probabilistic characterization of tidal mixing in a coastal embayment: A Markov Chain approach. Cont. Shelf Res. 22, 1603–1614.

Tompson, A.F.B., 1993. Numerical simulation of chemical migration in physically and chemically heterogeneous porous media. Water Resour. Res. 29, 3709–3726.

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 Sci. 60, 529–540.

Wroblicky, G.J., Campana, M.E., Valett, H.M., Dahm, C.N., 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. Water Resou Res. 34, 317–328.

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

Xu, X., Qui, Z., Chen, H., 1980. Summary of the horizontal circumcurrent in south china sea(in chinese with english abstract). In: Chinese Society of Oceanology and Limnology. Proceedings of the Hydrology and Meteorology. Science Press, Beijing, pp. 137–145.

Yu, M.G., Liu, J.F., 1993. The system and pattern of the South China Sea circulation (in Chinese with English abstract). Ocean Predict. 10, 13–17.

Yuan, S., Deng, J., 1999. A numerical study on circulation in the Beibu Gulf (in Chinese with English abstract). Nanhai Yanjiu Yu Fazhan 12, 41–46.

Zeng, B., Zhang, J., Chen, G., 1989. Survey of Fishery Resources and Regional Fisheries Planning in South China Sea. Guangdong Scientific & Technological Press, Guangzhou (in Chinese).

Zheng, L., Chen, C., Liu, H., 2003. A modeling study of the Satilla River Estuary, Georgia. I: Flooding-drying process and water exchange over the salt marsh-estuary-shelf complex. Estuaries 26, 651–669.

Zheng, Q., Zhang, R., Wang, Y., Pan, X., Tang, J., Zhang, G., 2012. Occurrence and distribution of antibiotics in the Beibu Gulf, China: Impacts of river discharge and aquaculture activities. Mar. Environ. Res. 78, 26–33.

Zimmerman, J.T.F., 1976. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea part I: Distribution of salinity and calculation of mixing time scales. Neth. J. Sea Res. 10, 149–191.