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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.

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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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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

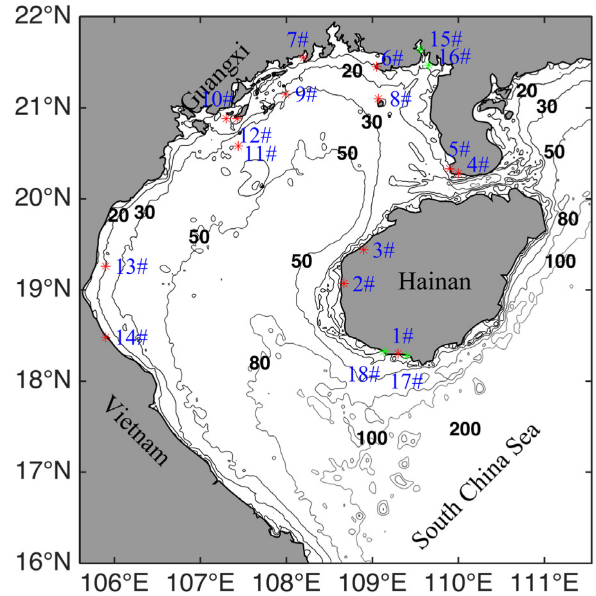

Fig. 1. Topography of Beibu Gulf, with sampling stations for field observations (units: m).

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