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RESEARCH ARTICLE

Surface currents measured by GPS drifters in Daya Bay and along the eastern Guangdong coast

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Abstract GPS-based surface drifters were used to investigate the surface currents in Daya Bay and along the eastern Guangdong coast in China. Surface current vectors were measured based on the GPS location and corresponding time information sent by drifters through the mobile phone network. The analysis of data from 120 drifters, deployed in late spring 2018 in the case-study region, shows that the drifters are generally capable of capturing the surface (tidal and residual) currents. The drifter trajectories suggest an anticlockwise surface current inside Daya Bay and a north-eastward current along the eastern Guangdong coast, where the coastal current along the eastern Guangdong coast is faster than that inside Daya Bay. The surface currents in the investigated region follow an irregular semidiurnal cycle due to the influence of the tidal current, while the currents inside Daya Bay are strongly affected by the topography. According to the harmonic analysis, an irregular semidiurnal type of tidal current is evident at a study grid inside Daya Bay, with an Eulerian residual current speed of 9.0 cm/s and a direction of 276°. The Lagrangian residual current outside Daya Bay moves north-eastward with a mean speed of 22 cm/s along the eastern Guangdong coast, while the current inside Daya Bay moves northward to the bay head with a mean speed of about 8.0 cm/s, which agrees well with the one reported in other literatures.

Keywords drifter, surface current, residual current, Daya Bay, eastern Guangdong coast

1 Introduction

Daya Bay is located in the Guangdong Province and opens to the South China Sea. However, a nuclear power plant is located on its western coast, thus ocean currents can easily carry away the pollutants, such as the residual chlorine discharge of the cooling seawater from the nuclear power station, sediments, etc. Note that the surface currents are also influenced by wind, the Coriolis effect, topography, and tidal current. Therefore, it is of great importance to assess the characteristics of the ocean currents and its influence inside Daya Bay and along the adjacent coastal areas.

Xu and Zeng (1991) used the RCM4S ocean current meter (Aanderaa Data Instruments) to measure ocean currents in Daya Bay in winter and discovered that the current is composed of a diurnal current, semidiurnal current, and shallow water constituents. Yang (2001) studied the tidal movement in Daya Bay based on three hydrological investigations conducted from 1996 to 1999. Results showed that the tidal current inside Daya Bay belongs to the categories of irregular semidiurnal tidal current and reversing tidal current. In addition to the time- and labor-consuming ship-based surveys, numerical models have also been used to simulate the currents in Daya Bay. For instance, Wu et al. (2007) employed a three-dimensional shelf sea model (HAMSOM) to simulate the tide, tidal current, and residual current in Daya Bay, which agree well with the observed currents. Based on tidal equations, Chen et al. (2009) reproduced the tidal current field via a pseudo-spectral method. It is pertinent to note that in model simulations, the model parameters are determined by the observational data.

The use of drifters to study currents has been proposed to overcome the drawbacks of both field surveys and model simulations. After the TIROS-N satellite was launched in late 1978, scientists could map the position of the drifters through the Argo system, which served many programs, such as the Tropical Ocean and Global Atmosphere (TOGA) program. Special buoys were designed for TOGA and deployed throughout the tropical

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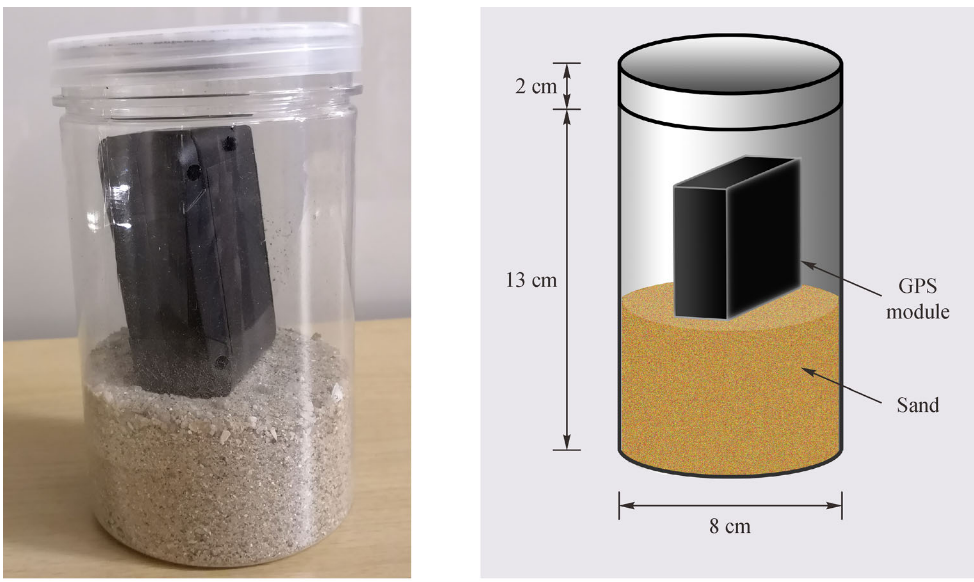
Pacific to measure surface currents by exploiting the capacity of these drifters to follow the water (David, 1995). Apart from the TOGA drifters, the Surface Velocity Program (SVP) drifters have been deployed in the oceans since the early 1980s to measure the ocean currents at a depth of 15 m (Qiu et al., 2011; Prasad et al., 2017; Tseng et al., 2017). Researchers can also use GPS-based drifters to improve the accuracy of geolocation (2–50 m) and sampling frequency (Centurioni, 2018). The operators can receive in situ data through the satellite in a very short time, e.g., 1 min. For instance, Schmidt et al. (2003) designed a GPS-tracked drifter to measure surf zone circulation, and Perez et al. (2003) developed a GPS-based surface drifter for closed shallow water bays. Major drawbacks of the above-mentioned drifters are a relatively high cost (e.g., about $500 each) and a limited radio communication range (about 900 m). As a solution, Nasello and Armenio (2016) designed a GSM phone network-based drifter that can remotely map every 2 min through the GPS system, subsequently transmitting such information back using a cellphone network. This drifter was tested by measuring the surface currents in Muggia Bay (Italy), providing accuracy results. With the development of the Internet and communication and positioning technologies, surface drifters have become cheaper and smaller; hence, numerous drifters can be widely used in nearshore areas to observe the surface currents in a more efficient way.

In this work, we designed several small and inexpensive (about $30) Surface Current Experiment (SUCE V1.0) drifters to measure surface current in Daya Bay. Before this observation, Lin et al. (2019) tested the SUCE drifters inside the Daya Bay in January 2018. They compared the drifter-derived velocities with available coastal current reanalysis data along the Guangdong coast. The results suggest that such drifters are generally capable of capturing the characteristics of surface coastal currents. Figure 1 displays the cylindrical structure of each SUCE drifter, which has a diameter of 8 cm and height of 15 cm. Drifters were ballasted with sand and tested in a bucket of sea water to ensure that they can float with a small portion, e.g., 2 cm, above the sea surface. The GPS module with a geolocation accuracy around 10 m was located above the sand. SUCE drifters were then covered with waterproof transparent adhesive and expected to work continuously around 20 days with a signal transmission frequency of about 0.1 Hz, corresponding to a temporal resolution of 10 s. However, the signal was sometimes irregularly transmitted due to several problems. A field experiment was performed in Daya Bay and along the adjacent coastal area with 120 SUCE drifters, where the Eulerian residual current was obtained within a defined grid inside Daya Bay. Moreover, based on the trajectories of the drifters, the Lagrangian residual current was also calculated to study the characteristics of the surface water movement in Daya Bay and along the eastern Guangdong coast.

2 Data and methods

From May 16 to June 14, 2018, the SUCE drifter experiment was performed to assess the trajectories of the surface currents in Daya Bay and along its adjacent coastal area (see square area in Fig. 2(a)). As aforementioned, the GPS module powered by a built-in battery was installed in the SUCE drifter to send its location through the mobile phone network. The direct effect of the wind on the SUCE drifter can be ignored since a very small portion of the float, e.g., around 2 cm, is above the sea level (see



(a) (b)

Fig. 1 (a) The appearance of the SUCE drifter; (b) the design structure of the SUCE drifter.

Fig. 2(b)), and has also been proved by Lin et al. (2019). Figure 3 shows the initial locations of SUCE drifters depicted as red triangles, in which 120 were deployed along two sections across in Daya Bay and at one station in the Huidong coastal area. The northern section (Section 1) is completely inside Daya Bay and is aimed to catch the surface current features inside the bay; while the southern section (Section 2) is designed to analyze the surface current along the eastern Guangdong coast. The mean lifespan of these SUCE drifters is about 6 days with a standard deviation of also about 6 days. The highest probability lifespan was found to be around 2 days due to the inward mean flow direction in the bay, and SUCE drifters were probably trapped on account of the existence of nearshore marine constructions.

Based on the geolocation of each drifter, the distance between them was calculated using the great-circle distance equation (Kells et al., 1940), as follows:

$$d = r \cdot \arccos(\sin\phi_1 \cdot \sin\phi_2 + \cos\phi_1 \cdot \cos\phi_2 \cdot \cos(\Delta\lambda)), \tag{1}$$

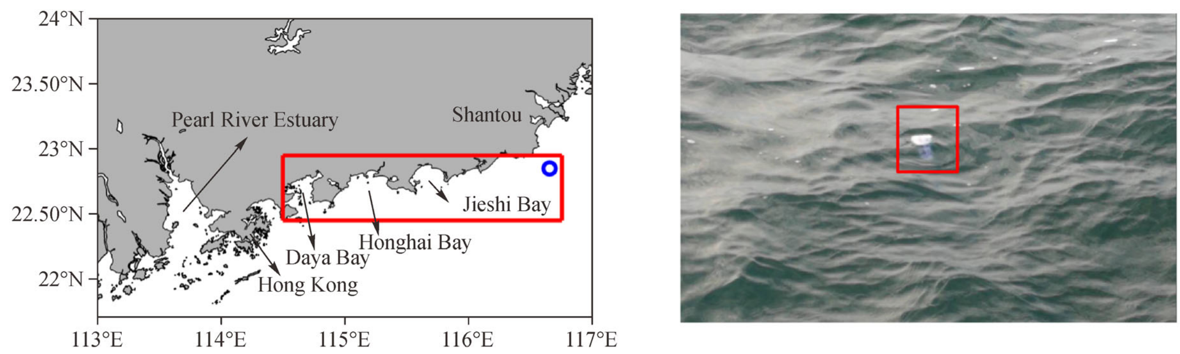
where $\Delta\lambda = \lambda_1 - \lambda_2$; ϕ_i, $\lambda_i (i = 1,2)$ are the geographical latitudes and longitudes; and r is the mean Earth radius, which is estimated as 6371 km. To retrieve a better signal-to-noise ratio, the current velocity is then determined by first calculating the great circle distance d between the 10 data points before and after the given geolocation. The surface current velocity is estimated by dividing d by the corresponding time span, since the wind effect could be ignored. Moreover, the flow direction is determined by the velocity vector. Using the time, geolocation information, and measured velocity vector of all drifters, the Eulerian residual current and surface Lagrangian residual current, which represents the surface mass transport, can be studied.

To assess the tidal current and Eulerian residual current, we first divided the research area into small grids of about 0.02° × 0.02° in longitude and latitude, in which only the area with 25 h of continuous observation was considered. A quasi-harmonic analysis was performed with inference parameters extracted from a water level gauge data near the considered grid.

3 Results

3.1 Surface trajectory

Considering quality control, the data from 72 drifters are



(a) (b)

Fig. 2 (a) The research area of Daya Bay and its adjacent coastal area illustrated as a red box. The blue circle indicates the farthest place the drifters reached; (b) a drifter float in the sea.

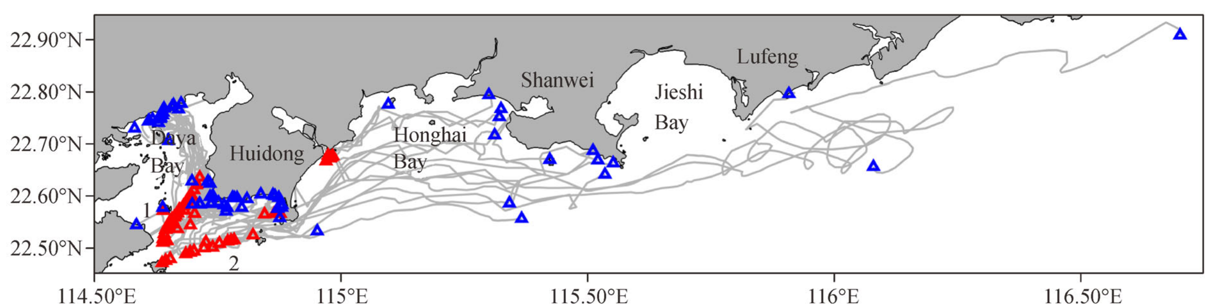


Fig. 3 The releasing locations (red triangles) and end locations (blue triangles) of drifters in the study region. The gray lines represent the trajectories of all the drifters.

considered in the following analysis. The corresponding trajectories of these SUCE drifters are illustrated as gray lines in Fig. 3, where the blue triangles represent the end points. About two thirds of the drifters deployed along Section 1 moved northward toward the Daya Bay head, while the rest moved north-eastward. In Section 2, one drifter reached the Shantou coastal area, i.e., about 190 km far from its deployment point, after 12 days (see the blue circle in Fig. 2(a)). For display clarity, Figure 4 shows the velocity vectors along the trajectories of 5 typical SUCE drifters, which visually captures both the flow pattern and velocity amplitude.

Three typical flow patterns were recognized in Daya Bay. 1) The drifters inside the eastern area of Daya Bay moved north-westward toward the bay head; see Traj1 in Fig. 4 as an example. The maximum current speed was found to be 41 cm/s with a mean speed of 13 cm/s. 2) The drifters inside the western part of Daya Bay moved north-eastward, bypassing a small island in the south-east region of Huidong. Most drifters then moved eastward until reaching the coastal cape, while a few bypassed the cape and traveled to the eastern Guangdong coast, see the Traj2 in Fig. 4. The maximum speed for these drifters was found to be 43 cm/s with a mean speed of 22 cm/s. 3) To investigate the surface currents near the tip of the southern Huidong coastal cape, the SUCE drifters were also deployed at this location. These drifters bypassed the cape and headed north-eastward along the coast, see Traj3 in Fig. 4, with a maximum speed of 61 cm/s and a mean speed of 29 cm/s. Note that such flow patterns are due to the fact that both the summer monsoon, which usually begins in late spring, and the coastal topography affect the surface currents along the eastern Guangdong coast.

For comparison, 20 SUCE drifters were released in Honghai Bay, an open bay in the eastern Huidong coastal area. Two additional flow patterns were recognized. 1) The first type of trajectory, see Traj4 in Fig. 4, followed the longshore current and flowed along the coastline. The maximum speed in this case was found to be 68 cm/s with a mean speed of 29 cm/s. The drifters exhibited the same type of pattern as Traj3 since both belong to the Guangdong coast current. Within 6 days, the drifters reached the offshore area of Lufeng, i.e., about 120 km away from its deployment point. 2) The second type of trajectory showed the movement inside the Honghai Bay and then landed on the beach (see Traj5 in Fig. 4) with a maximum speed of 36 cm/s and mean speed of 19 cm/s. Detailed information of these five typical patterns are summarized in Table 1.

To compare the flow patterns inside and outside Daya Bay, the trajectories of Traj1 and Traj3 were reproduced in Fig. 5, where the current speeds are color coded. Visually, the surface current along the eastern Guangdong coast is much faster than that inside Daya Bay (see also Table 1). The peak speed of the Traj1, e.g., 41 cm/s, was observed from the dusk of May 17 to the evening of May 18 close to the Daya Bay mouth, which agrees well with the findings of Yang (2001) and Wu et al. (2017). The mean speed was around 20 cm/s in this region, which is nearly twice as large as the speed inside Daya Bay. Traj3 indicates that the surface current moves north-eastward along the eastern Guangdong coast in late spring, which corresponds to the seasonal monsoon direction. Relatively large speeds occurred from the afternoon of May 19 to the dusk of

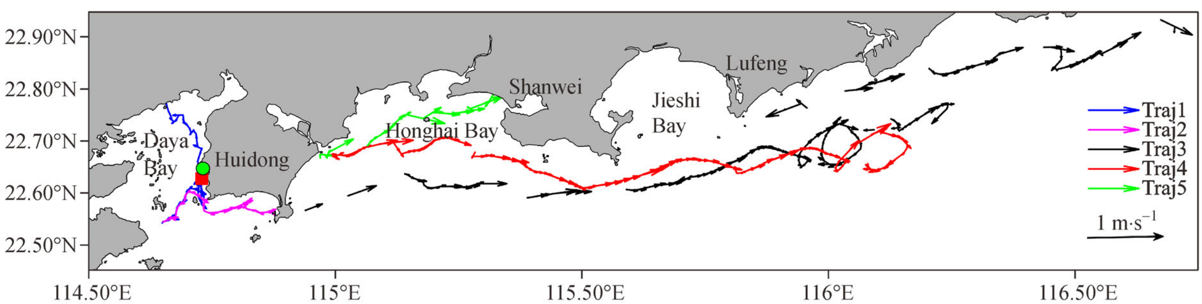


Fig. 4 Velocity vectors measured by 5 typical drifters in Daya Bay and along the eastern Guangdong coast. The red square is the grid for harmonic analysis, and the green dot symbol is the location where the water level gauge is mounted.

Table 1 Surface currents observed by 5 typical drifters

	Traj1	Traj2	Traj3	Traj4	Traj5
Position	Inside the eastern Daya Bay	Inside the western Daya Bay	In southern Huidong coastal cape	In eastern Huidong coastal area	In eastern Huidong coastal area
Max speed/$(cm \cdot s^{-1})$	41	43	61	68	36
Mean speed/$(cm \cdot s^{-1})$	13	22	29	29	19
Direction	North-westward	Eastward	Eastward	Eastward	North-eastward

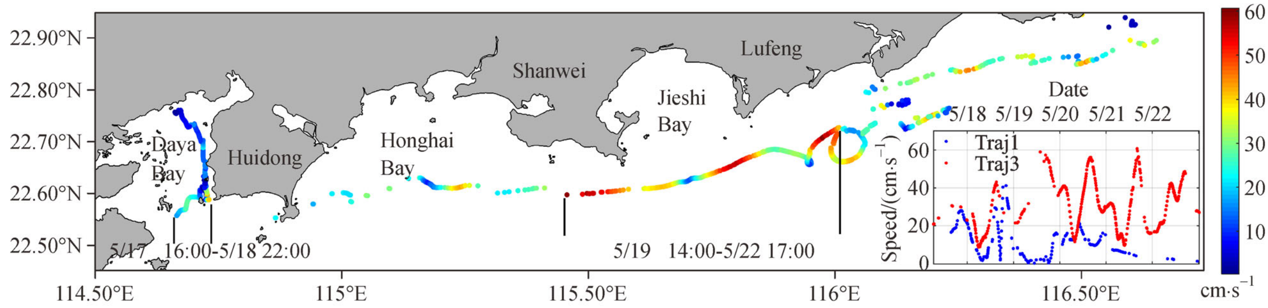


Fig. 5 Surface current speed of Traj1 and Traj3, where the current speed is encoded in color. Inset shows the surface current speed evolutions of Traj1 (blue dots) and Traj3 (red dots).

May 22 in the south area of Jieshi Bay. When the drifters that moved along the eastern Guangdong coast arrived south of the Lufeng coast, some clockwise drifting trajectories can be clearly observed. These cycles had a time span of approximately 25 h, corresponding to a tidal cycle. This means that the surface flow along the eastern Guangdong coast is controlled by the seasonal winds, coastal topography, and also the strong tidal current. The speed evolutions of Traj1 and Traj3 from May 17 to May 23 are shown in the inset of Fig. 5. Notwithstanding several data gaps, it was possible to detect a strong irregular semidiurnal periodic pattern of the surface current along the eastern Guangdong coast, as well as a relatively weak periodic pattern of the surface flow inside Daya Bay.

3.2 Tidal and residual currents

Because of the limited number of drifters, only one grid at 114.73°E, 22.64°N is identified (see the red square in Fig. 4), which contains continuous effective current velocity data for more than one tidal period. Both the tidal current and Eulerian residual current were calculated for this location using the velocity of 31-h surface currents, which were resampled as hourly data. Because the harmonic analysis cannot be directly applied due to limited data, a quasi-harmonic analysis using inference parameters via the MATLAB package T_TIDE (Pawlowicz et al., 2002) was performed, as subsequently described.

The inference parameters were calculated via the T_TIDE package using a water level gauge data collected with a time interval of 1 min from May 17 to July 16, 2018. Note that this water level gauge is very close to the research grid, as indicated by the green dot symbol in Fig. 4. Based on the calculated harmonic constants of the water level, the inference parameters for the 3 pairs of tidal constituents, O_1, K_1; M_2, S_2 and M_4, MS_4, were obtained as follows:

$$\frac{H_{k_1}}{H_{O_1}} = 1.2,$$

$$g_{k_1} - g_{O_1} = 0,$$

$$\frac{H_{S_2}}{H_{M_2}} = 0.4,$$

$$g_{S_2} - g_{M_2} = 18,$$

$$\frac{H_{MS_4}}{H_{M_4}} = 0.6,$$

$$g_{MS_4} - g_{M_4} = 52,$$

where H_{O_1}, H_{K_1}, H_{S_2}, H_{M_2}, H_{MS_4}, and H_{M_4} and g_{O_1}, g_{K_1}, g_{S_2}, g_{MS_2}, g_{MS_4}, and g_{M_4} represent the amplitudes and phases of the O_1, K_1, S_2, M_2, MS_4, and M_4 tidal constituents, respectively. Based on these parameters, the quasi-harmonic analysis was applied to the hourly velocity data. Six major tidal current constituents (i.e., O_1, K_1, M_2, S_2, M_4, and MS_4) of the research grid were successfully retrieved. Figure 6 shows the observed current components and the reconstructed tidal components based on these constituents.

The tidal ellipses of the six tidal constituents are illustrated in Fig. 7. The M_2 tidal current constituent is clearly dominant over the others for the tidal current in this grid. The amplitude of the M_2 tidal current is about 25 cm/s, which is slightly lower than the value of 34 cm/s measured by Wu et al. (2007) and Wu et al. (2017). All tidal ellipses revealed ellipticity smaller than 0.25, implying that the tidal current in the research grid belongs to the reversing tidal current. Furthermore, the direction of the tidal movement is mainly toward north-south for the S_2 and M_2 tidal current constituents and north-east-south-west for the others. These results agree well with those of Yang (2001) and Wu et al. (2017).

We introduce the following formula to determine the type of tidal current (Chen, 1980):

$$k = \frac{H_{O_1} + H_{K_1}}{H_{M_2}}, \tag{2}$$

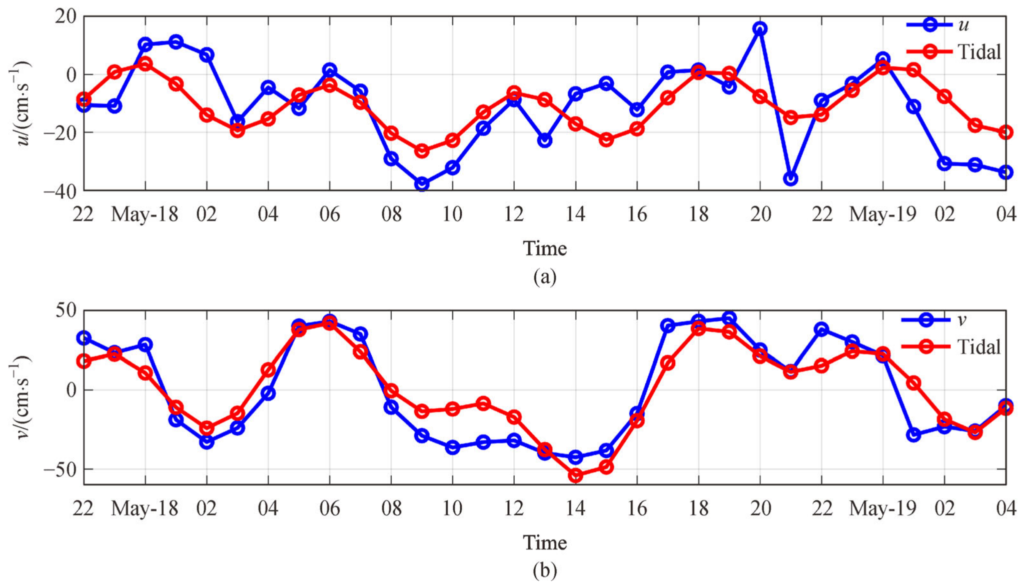


Fig. 6 Observed velocity data (blue lines) and composition of 6 major tidal constituents (red lines).

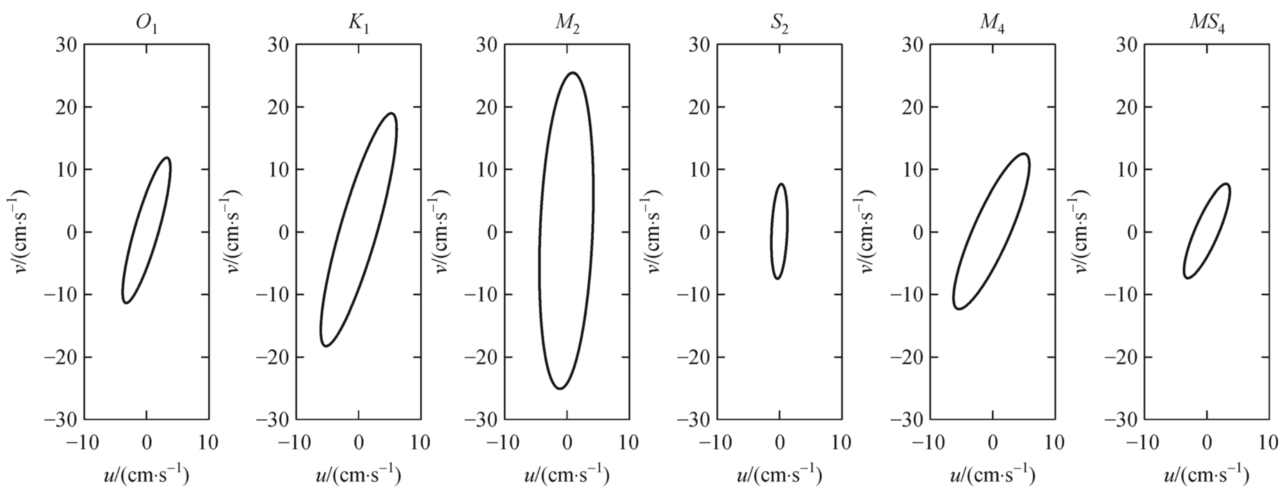


Fig. 7 Experimental tidal current ellipses of 6 tidal constituents.

where $k < 0.5$ indicates regular semidiurnal tidal current, $0.5 \leqslant k < 2$ means irregular semidiurnal tidal current, $2 \leqslant k < 4$ represents irregular diurnal tidal current, and $k > 4$ refers to regular diurnal tidal current. For the current case, k was determined to be 1.24, indicating an irregular semidiurnal tidal current, which is consistent with the values reported in other literatures (Xu, 1989; Yang, 2001; Wu et al., 2017). For example, Yang (2001) discovered values of 1.08 and 1.56 with research areas close to the current position, and Wu et al. (2017) calculated $k = 1.27$ in a station near our grid. Xu (1989) concluded that the tidal current in the majority of Daya Bay is mostly of the irregular semidiurnal tidal type. To our best knowledge, our results for the first time derive this tidal type by using a Lagrangian drifter in this area.

Since the timespan of the velocity data at the grid exceeded one single tidal period, the Eulerian residual current can be separated from the original current signal through harmonic analysis. The Eulerian residual current is defined as the observed current signal minus the composition of the tidal constituents. Previous studies found that the Eulerian residual speed is on the order of several cm/s for most areas in Daya Bay (Yang, 2001; Wu et al., 2017) with speed values reaching 10 cm/s in locations near the islands or along the coast. The mean speed of the Eulerian residual current of this study was determined to be about 9.0 cm/s with a direction of 276°.

Since the residual current is often affected by tides, atmospheric forcing, and density-driven currents (Muller et al., 2009), 10-m wind field data were collected from 17 to 19 May, 2018 (Fig. 8) from the European Centre for Medium-Range Weather Forecasts (ECMWF). Wind blew north-eastward in the research area during the investigated period with a mean wind speed of 3 m/s. According to the Ekman theory, if the current is only driven by the wind, it should deflect to the right following the wind direction in the northern hemisphere. For this grid point, however, the Eulerian residual current deflects 130° to the left in the sense of wind direction. Considering that there is no river nearby and that this grid point is very close to the Huidong coast, we suspect that the Eulerian residual current in this position is not driven by the wind or by a density gradient, but may be influenced by the topography.

In addition to the Eulerian residual current, the Lagrangian residual current could be approached using an approximation algorithm introduced by Awaji et al. (1980). Suppose that X_t is the position of one drifter at time t and X_{t+T} is the position of that drifter after one tidal period T, then the speed of the Lagrangian residual current can be estimated as follows:

$$U_L = \frac{X_{t+T} - X_t}{T}. \tag{3}$$

Figure 9 shows the estimated Lagrangian residual current in Daya Bay and along the eastern Guangdong coast. Graphically, the research area can be divided into two regions, which is indicated by a dashed red line in Fig. 9. The first region is completely located inside Daya Bay, while the second region is located outside Daya Bay and along the eastern Guangdong coast. It also indicates the presence of an anticlockwise surface current inside Daya Bay. The mean speed of the Lagrangian residual current for the first region was equal to 8.0 cm/s with a mean direction of 353° and was equal to 22 cm/s with a direction of 78° in the second region, thus deflecting 32° to the right compared to the 10 m wind direction. It can be concluded that the Lagrangian residual current in the second region is driven by the wind and influenced by the coastal topography.

4 Conclusions

In this work, GPS-based SUCE drifters were designed to measure the surface currents in coastal areas. A SUCE drifter experiment was performed in Daya Bay and its adjacent coastal area to obtain the surface currents. Results indicate that there is an anticlockwise current inside Daya Bay in late spring. The surface currents outside Daya Bay and along the eastern Guangdong coast move north-eastward along the coastline with a strongly irregular semidiurnal periodic speed pattern, which is controlled by the wind and influenced by the coastal topography and tidal current. The speed of these currents is higher than that inside Daya Bay with the highest speed detected in the south region of Jieshi Bay. The surface currents inside the eastern part of Daya Bay move northward toward the bay head with a relatively weak periodic pattern, which seems

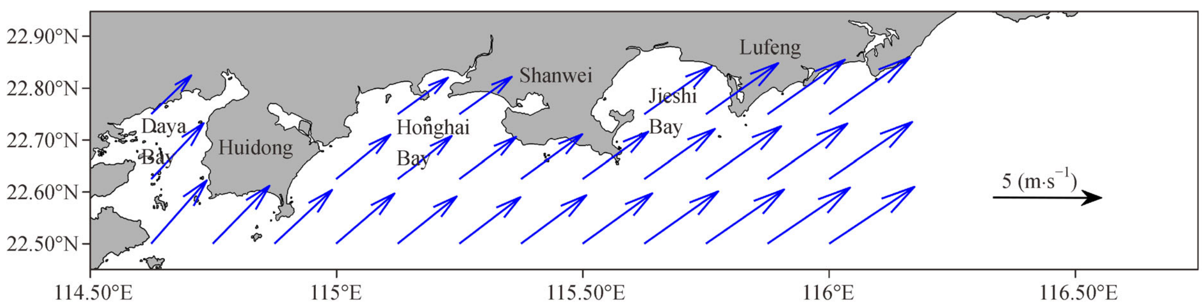


Fig. 8 The mean 10 m wind velocity vectors during May 17 to May 19, 2018.

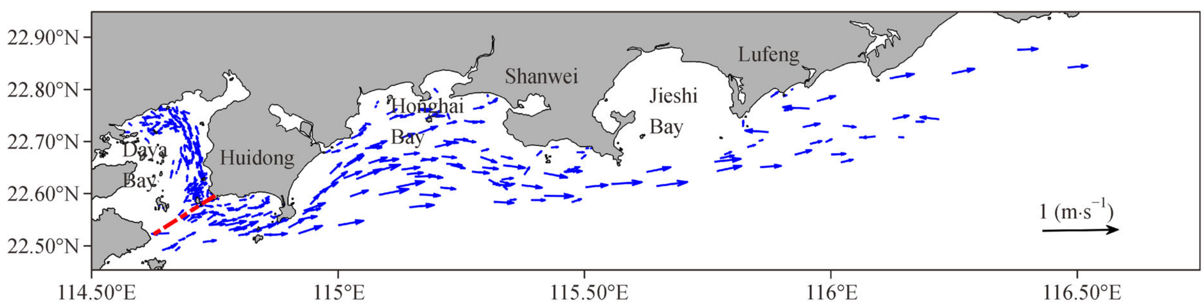


Fig. 9 The Lagrangian residual current in the Daya Bay and its adjacent area.

to be strongly impacted by topography. The tidal current at 114.73°E, 22.64°N displays characteristics of both irregular semidiurnal tidal and reversing tidal currents. The Eulerian residual current in the analyzed grid position exhibited a speed of 9.0 cm/s with a direction of 276°. Due to the influence of topography, the speed of the Lagrangian residual current inside eastern Daya Bay was about 14 cm/s smaller than that outside the bay and along the eastern Guangdong coast. In addition, the Lagrangian residual current inside eastern Daya Bay first flows northward toward the bay head then westward, while the current outside the Daya Bay moves eastward along the eastern coastline of Guangdong.

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