Study on characteristics of tidal dynamics and vortex in Zhoushan Archipelago sea area

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Abstract. Numerical modelling is used to study the characteristics and mechanisms of tidal dynamics and vortex in Zhoushan Archipelago sea area. Results show that amplitudes and current speeds of the semidiurnal tides decrease significantly when passing through the islands. Conversion of tidal energy, archipelago topography and formation of shallow-water tides are important reasons for the evolution of tidal waves. The ebb tide has a longer duration in the archipelago sea area, particularly in narrow channels. The $M_2-M_4$ constituents play a major role in tidal asymmetry. The flow paths of tidal currents change much, causing the high speed flooding/ebbing near the north/south bank. The tidal vortex is mainly distributed on both sides of and behind the islands, which is related to the shape of islands and the flow velocity. Referring to the current directions, positive/negative vorticity generally appears on the right/left side of the islands.

1. Introduction

Zhoushan Archipelago is the largest archipelago in China, with about 1390 islands. It connects the Hangzhou Bay and the East China Sea, and was impacted by the runoff from the Yangtze River [1]. Zhoushan Archipelago attracts lots of attentions due to its important location and strong tidal conditions. Generally, the sea area is dominated by ebb tides, the flow paths of flooding and ebbing tides are different because of Coriolis force [2-3]. The lateral variation of hydrodynamics is caused by water depth between the channels [4]. Estuary topographic conditions lead to the tidal energy conversion among constituents, and thus affect tidal asymmetry [5].

Obvious reciprocating flows can be formed from Ningbo. Due to constraints of topography, vortices appear when currents rising and falling near the islands [6]. The multiple narrow channels in Zhoushan islands separate the flow and form tide-induced vortices [7]. Many vortices was generated by the large number of islands, and the tidal asymmetry was increased consequently [8], and the tidal energy was partly dissipated [9].

In Zhoushan Archipelago sea area, due to the strong tides and archipelago topography, the distribution and mechanism of vortices are complex and need further investigation. In this study, we consider the influence of runoff and wind, establish a hydrodynamic numerical model based on FVCOM (Finite-Volume Coastal Ocean Model). We study the characteristics of tidal dynamics and vortices in Zhoushan Archipelago sea area, so as to help coastal management.

2. Model setup and validation

2.1. Governing equation
FVCOM uses 3-D unstructured-grids and the finite volume method to discretize the integral form of the governing equations, and adopt σ coordinate transformation vertically. The governing equations consist of the following momentum, continuity:

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - f v = - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \left( K_m \frac{\partial u}{\partial z} \right) + F_u \]  

(1)

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + f u = - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \left( K_m \frac{\partial v}{\partial z} \right) + F_v \]  

(2)

\[ \frac{\partial p}{\partial z} = -\rho g \]  

(3)

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

(4)

where \( x, y, \) and \( z \) are the east, north, and vertical axes in the Cartesian coordinate system; \( u, v, \) and \( w \) are the \( x, y, \) and \( z \) velocity components; \( \rho \) is the density; \( P \) is the pressure; \( f \) is the Coriolis parameter; \( g \) is the gravitational acceleration; \( K_m \) is the vertical eddy viscosity coefficient; \( F_u, F_v \) represent the horizontal momentum diffusion terms. For detailed control equations, see FVCOM user manual [10].

2.2. Model set up

Considering the impact of the Yangtze River, the model domain covered the Yangtze Estuary, of the Xiangshan Port, Hangzhou Bay and Zhoushan Islands. The calculation range is 29.2–32.5°N, 120–123°E, number of grid elements is 132,577, number of grid nodes is 69,064, and the minimum resolution is 70 m. Water depth distribution and grid quality of the model are shown in Figure 1 (a, b, c). There are 11 sigma layers in the vertical direction, with high resolution near the bottom and surface levels and uniform thickness in the middle.

The model time is for November to December in 2014. The global ocean tide model TPXO 7.2 is used to determine the open boundary conditions. Temperature and salinity are set as constants, which are 18 °C and 35 PSU respectively. Surface wind field data are from ECMWF (European Centre for Medium-Range Weather Forecasts, https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc). The Yangtze River and the Qiantang River data are from the China River Sediment Bulletin (http://www.mwr.gov.cn/sj/#tjgb).

2.3. Model validation

We collected observation data of tidal levels and tidal currents. Station distribution is shown in Figure 1(d). The comparison between hourly simulated data and measured data is shown in Figure 2. The performance of numerical model is evaluated by comparing the difference between simulation results and measured data. The accuracy of model prediction is evaluated by statistical error Skill value, which is defined as follows:

\[ \text{Skill} = 1 - \frac{\sum_{i=1}^{N} | X_{\text{mod}} - X_{\text{obs}} |^2}{\sum_{i=1}^{N} (| X_{\text{mod}} - X_{\text{obs}} | + | X_{\text{obs}} - X_{\text{obs}} |)^2} \]  

(5)

where \( X_{\text{mod}} \) and \( X_{\text{obs}} \) are simulated values and measured values, respectively. The value of Skill is between 0 and 1. The closer to 1, the simulated value is more consistent with measured value. The statistical error values of tidal level at each station are 0.97, 0.98, 0.98, 0.98, 0.97, statistical error values of current velocity are 0.93, 0.95, 0.98, and statistical error values of current direction are 0.82, 0.81, and 0.94. It can be seen that the accuracy of model is high, and the model can better reflect the three-dimensional hydrodynamics in Zhoushan Archipelago sea area.
Figure 1. (a) Model grids; (b) Zhoushan islands grids; (c) bathymetry; (d) gauge stations

Figure 2. Verification of (a) tidal elevation and (b) flow velocity and flow direction
3. Tide characteristics

3.1. Main constituents

The amplitude of constituents is obtained by harmonic analysis. The average amplitude of $M_2$ tidal component is about 1.34 m, accounting for about 42.2% of the total elevation. The amplitude of $S_2$ is about 0.39 m, accounting for about 12.4%. The amplitudes of $K_1$, $N_2$, $O_1$ and $M_4$ constituents are smaller, accounting for about 9.9%, 6.6%, 5.1% and 4.0%. Amplitudes of other constituents are all below 0.1 m.

Cortical chart of representative tidal components is shown in figure 3(a, b, c). The semidiurnal constituents mainly deflect through islands in northwest direction, and enter Hangzhou Bay in west direction. Tidal amplitudes increase from east to west. Due to geometric convergence effect [11], amplitudes increase when tidal wave reaches coast.

In the narrow channel, the amplitude of semidiurnal constituents decreases significantly (19.2–21.4%), and increases gradually (18.2–33.3%) after crossing the channel. The amplitude of $M_2$ constituent near east of Zhujiajian island is 1.2 m, which decreases to 1.15 m near Zhoushan island. It is reduced to less than 1.1 m and even less than 0.7 m when passing through Luotou channel and Guanmen channel. Amplitude increases gradually after crossing the islands, and reach more than 1.5 m after entering the Hangzhou Bay. The amplitude of the diurnal tide does not change much, so amplitude of tidal wave is mainly affected by semidiurnal tide. Due to the complex topography of islands, the generation of shallow water constituents is also important.

Conversion of tidal energy can affect the change of amplitude [12]. We use ratio of kinetic energy and potential energy ($E_k/E_p$) [13] to represent the proportion of tidal energy distribution (Figure 3d). The ratio increases to 10 times or more when semidiurnal tides passing through the narrow channel from the East China Sea, where potential energy is converted to kinetic energy. The generation of various compound tides and shallow water tides dissipate part of the tidal energy and reduce tidal amplitudes. Rapidly increasing water depth in the channel scatter the tidal energy transmitted here. Due to complex topography, dissipation of tidal energy may also lead to the decrease of amplitudes.

3.2. Tidal asymmetry

The interaction between constituents will lead to tidal asymmetry. We use skewness value to analyse characteristics of asymmetric tidal distribution. Skewness is obtained by introducing each harmonic function of tidal division as follows [14]:

$$ \gamma = \frac{\sum_{a_i + a_j = a_k} 3}{\left[ \frac{1}{2} \sum_{i,j} (a_i^2 a_j^2) \right]^{3/2}} \left( \omega_i + \omega_j - \omega_k \right) + \sum_{2(a_i = a_j)} \frac{3}{4} a_i^2 \omega_i^2 a_j \omega_j \sin(2\theta_j - \theta_i) $$

where $a$ is partial tide amplitude; $\omega$ is tide frequency; $\theta$ is phase lag. Negative value of $\gamma$ indicate that the duration of flood tide is longer than that of ebb tide, otherwise, the duration of ebb tide is longer than that of flood tide. Larger the absolute value of $\gamma$, the greater the tidal asymmetry.

The total skewness value in Zhoushan archipelago ranges from -0.93 to 0.90, calculated using constituents with amplitudes greater than 0.1 m (accounting for 85% of total amplitudes). The ebb tide has a longer duration throughout the entire area. In particular, the skewness values of Foshan channel, Luotou channel and Cezi channel are greater than 0.6. Tide asymmetry is strong and the duration of ebb tide is longer. A few channels have longer duration of flood tide, and there is a small area of obvious flood tide lasts longer in Guishan Hangmen channel, with skewness value of -0.93.

The skewness distribution of $M_2$-$M_4$ constituents is close to total skewness (Figure 4), and skewness value ranges from -0.38 to 0.44, accounting for 54% of total. This combination plays a major role in controlling the degree of tidal asymmetry.
Figure 3. Cortical chart of (a)M$_2$, (b)K$_1$, (c)M$_4$ tidal components (Colour represents amplitude; line represents phase lag) and (d) Ratio of kinetic energy and potential energy

Figure 4. Skewness (a. total skewness; b. skewness of M$_2$-M$_4$ constituents)

4. Characteristics of tidal current and vortex

4.1. Characteristics of tidal current
The tidal current type is reciprocating flow (Figure 5). Flood currents flow from east side of archipelago area. After blocked by islands, currents flow into Hangzhou Bay in different directions. Ebb currents point to southeast through Zhoushan archipelago, then flow to the sea. Due to the shape of inlet and outlet of the channels and the Coriolis force, high speed flood currents are incline to north bank while high speed ebbing currents are incline to south bank. On both sides of archipelago, due to the narrow channel of tidal inlet and diffusion effect at tidal exits [4], velocity of flood currents is higher than that of ebb currents in west side of archipelago area, and vice versa in east side. In the archipelago, currents change more complicated due to topography. Due to complicate coastlines and water depth, velocity increases significantly in the channels after currents entering archipelago. There are obvious jet streams in the tidal channels. The maximum velocity can reach more than 2.5 m/s. Near the coasts of channels, velocity is relatively small, about 1.5 m/s. After passing through the channels, high speed water disperse, and its velocity gradually decreases, slightly larger than that in the open sea.

4.2. Characteristics of tidal vortex
We use W method (Okubo-Weiss function method) to identify vortex [15, 16], and to quantified the relative importance of deformation and rotation. The function is defined as:

\[ W = S_n^2 + S_s^2 - \omega^2 \]

where \( \omega \) is vorticity pseudo energy, represents rotation of fluid; \( S_n^2 + S_s^2 \) is square deformation rate, represents deformation of the fluid. The parameter \( w_0 \) (set as -0.2\( \sigma_w \), \( \sigma_w \) is standard deviation of \( W \)) is taken as criterion. The flow field where \( W \geq -w_0 \) (red) is dominated by deformation. The flow field where \( W \leq -w_0 \) (blue) is dominated by rotation; it exists in the form of vortex. A large number of small-scale vortices are distributed in the archipelago sea area (Figure 6). At the time of flood tides and ebb tides, relative to the direction of tidal current, vortices mainly exist on both sides of and at the back of islands. This is consistent with the findings of Geyer and Signell (1990) [17]. The vorticity distribution is calculated according to formula (7), as shown in Figure 7. During period of flood tides, vorticity ranges from -923.5 to 1 401.4; during period of ebb tides, vorticity ranges from -1812.4 to 1943.5. The intensity of vorticity is related to flood tides and ebb tides. Influenced by longer duration of ebb tide, vorticity is stronger at ebb tides than at flood tides. We select Xiushan island and Daxie island with obvious vortices to analyse vortex characteristics. In coastal region, relative to direction of current, positive vorticity (counter clockwise) generally appears
on the right side of the island and negative vorticity (clockwise) generally appears on the left side of the island.

Near Daxie island, at flood tides, there is a significant counter clockwise single vortex (vorticity value is 400) on the northwest part of Daxie island. Here, shoreline is almost perpendicular to the main flow. A strong negative vorticity (vorticity value is 500) appears on the west side of Damao island. Part of currents form after flood from east coast, then meet high speed currents on west side. At this time, velocity in the channel from south of Damao island to north of Daxie island is large, which is about 2.0-2.5 m/s. At ebb tides, there is a strong positive vorticity (500~1000) on the west side of Damao island, and here is a slightly weaker negative vorticity (vorticity value is 500) in the northeast of Daxie Island. At this time, velocity of main flow in north of Daxie island is about 1.1~2.0 m/s. The velocity on the west side of Damao island is about 2.3~3.6 m/s. Velocity on the west side of Damao island is about 2.3~3.6 m/s. In summary, generation and intensity of vortices are related to the current velocity and shape of islands, namely the angle between shoreline and main flow here.

![Flow field partitioning based with W method](image)

**Figure 6.** Flow field partitioning based with W method (a. flood tide; b. ebb tide)

5. Conclusions

This paper studied the tidal dynamics and small-scale vortex around Zhoushan islands. The main conclusions are as follows:

1. \( M_2 \) constituent is the main tidal component in Zhoushan islands. The amplitude of semidiurnal constituent decreases significantly and tidal wave propagates slower. The conversion of tidal potential energy to kinetic energy affects the amplitudes. The rapid increase of water depth and formation of shallow water tide dissipate the tidal energy, which are important for the evolution of tidal wave.

2. Ebb tide generally lasts longer in the archipelago sea area and more pronounced in the narrow channel in south. The \( M_2-M_4 \) constituents plays a major role in controlling tidal asymmetry. Tidal currents are dominated by reciprocating flow. Due to the shape of inlet and outlet of channel and Coriolis force, high speed flood currents tend to north bank, and high speed ebb currents tend to south bank.

3. Along tidal current direction, vortices are mainly distributed on both sides of and at the back of island. In coastal region, referring to direction of tidal current, positive vorticity generally occurs on right side of the islands, while negative vorticity occurs on left side. The vorticity at ebb tides is stronger than that at flood tides. The generation and intensity of vortex are related to tidal asymmetry, island shape and tidal current velocity.
Figure 7. Distribution of vorticity (Color represents vorticity, arrow represents tidal current; a.c.e. flood tide, b.d.f. ebb tide)

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