A NUMERICAL STUDY ON THE EFFECT OF TYPHOON ON THE HYDRODYNAMIC AND MASS TRANSPORT IN COASTAL AREAS

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Abstract: A three-dimensional storm surge model was developed in Xiangshan Bay (XSB) and adjacent areas in Zhejiang Province in China, based on the finite-volume coastal ocean model FVCOM. Based on the windfields calculated from the typhoon model, the storm surge was simulated during the typhoon “Haikui” landing. Three Lagrangian methods, named Lagrangian particle tracking (LPT), Lagrangian residual current (LRC) and Lagrangian Coherent Structures (LCS) were applied to analyze the effect of typhoon on the hydrodynamic and mass transport. The results reveal that the transport distance of the water parcel in the mouth of XSG increased obviously during the typhoon, which results in the LRC is not suitable for the description of the mass transport. The daily-average Eulerian residual current is then applied and it is mainly affected by the wind. The distribution of LCS shows that the water region division with different transport characteristics are significantly changed and the horizontal surface water mixing increased due to the typhoon. LCSs is a useful tool to understand the water transport and mixing processes. The Combination of Lagrangian particle tracking and LCSs could better uncover the mass transport in the abnormal climate.

Key words: Xiangshan Bay; Storm surge; Residual current; Particle tracking; Lagrangian methos; FVCOM

1 INTRODUCTION

The location of China belongs to the typhoon-prone areas in the northwest of Pacific and the storm surge caused by typhoon is one of the most serious marine disasters. Many researchers have conducted a great deal of work on the storm surge. Skinner et al (2015) applied a 2D model to simulate the tidal and storm surge hydraulics in the Humber Estuary, UK and the results show that the model could reproduce the storm surge. The storm surge induced by “Fanbiya” in Taiwan Strait was simulated by Xu et.al (2015). Qi et.al (2015) simulated the typhoon waves in Lianyunn Harbor during “Dawei”. Based on the ground-based observations data, the intensity variation of Haikui before and after its landing was analyzed (Qian, 2013). The above researches are mainly focus on the simulation and prediction of the typhoon. Besides, Zhao et.al (2015) simulated the spatial distribution patterns of tidal flat accretion/erosion under both usual weather and storm surge conditions. Based on the two field investigations on the sandy beach, erosion/accumulation change on beach profiles is analyzed and the response feature on the beach is discussed before and after No. 1211 typhoon “HaiKui” (Tong, et.al, 2014). The research of the effect of typhoon mainly focus on the hydrodynamic characteristic (Wang, et.al 2011), the erosion-deposition in the beach and water ways (Tong, et.al, 2014) by now. Due to the strong dynamic process during the storm surge happening in a short period, it can have great influence on the circulation, sediment transport and pollutant transport, etc.
Studies of mass transport could be conducted from the circulation, particle tracking perspective et al. The long-period mass transport and distribution in the coastal area are decided by the residual current but not the periodic tidal current. Averaging the velocity at a fixed position for one or several cycles or by using other filtering methods could obtain the Euler residual current (Dong, et.al, 2000). However, Longuet–Higgins[7] pointed out that the mass transport velocity is not solely controlled by the mean velocity, but also determined by the Stokes drift velocity. The mass transport velocity could be successfully applied in weakly nonlinear systems (Muller, et.al, 2009). In a nonlinear coastal system, the Lagrangian residual current has been studied by Feng (2008). The mass transport pathways could be clearly described by Lagrangian particle tracking. However, it’s difficult to obtain the completed circulation in the region (Lipphardt, 2006). In recent years, as the extent of the Lagrangian method, Lagrangian Coherent Structure (LCS) has been introduced in oceanography to analyze the circulation (Shadden et.al, 2005), which not only could be applied to study the mass transport based on the velocity, but also to uncover the transport barriers in the ocean.

XSB locates in the north coast of Zhejiang Province, where is affected by typhoon frequently. In the study, taking XSB and adjacent areas as the study area, the influence of storm surge on the mass transport was studied based on a storm surge model by LPT, LRC and LCS methods.

2 THE SIMULATION OF STORM SURGE

2.1 Model Introduction

XSB is a semi-closed narrow-shaped bay with complex topography and there are numerous islands in the bay (as shown in Fig. 1). Therefore, the finite-volume coastal ocean model (FVCOM) is employed to simulate the hydrodynamic process, which was developed by UMASSD-WHOI based on 3D primitive equations ocean model (Cheng, 2003). A non-overlapping unstructured triangular grid is used in the horizontal direction and σ coordinate is used in the vertical direction, which can describe the complex topography well. Besides, the wet/dry treatment technology is introduced to provide an accurate simulation in the inter-tidal zone. The detail governing equations and the finite volume discrete method could be found in Chen et al(2013).

Based on the above hydrodynamic model, the pressure and wind-stress forcing were added to simulate the storm surge. Therefore, the accuracy of the fields of typhoon wind and pressure is the key for the storm surge simulation. There are several wind filed simulation model, such as theoretical pressure model, empirical model and semi-theoretical model. In the study, the nesting of Fujita-Takahashi pressure field model was applied to compute the typhoon wind fields.

2.2 The Simulation of Tide and Storm Surge

Fig. 1 shows the water depth of study area of XSB and adjacent areas. The area is from the section of Zhenhai-Daishan (P1-P2) at its north, Zhushanjian island and P2 at its east and end to Sanmen Bay in the south. There are 76990 triangle meshes and 40722 nodes in the computation area. Eleven σ layers are adopted vertically which results in a vertical resolution of between 0.1 m to 10m in most areas. The external and internal time step are 1s and 10s, respectively. The bottom roughness in the study area varies from 0.6×10⁻³ to 1.4×10⁻³ m in different areas.
The verification of the tide model
The validity and accuracy of the hydrodynamic model are verified by comparing the simulated results with the field data. The results show that the model can simulate the tidal level and tidal current well, and could be applied to study the tidal surge. The development, verification and application of the hydrodynamic could refer to (Han, 2014; Han, 2014; Liang, 2015; Liang, 2014).

Calculation of the typical typhoon wind field
By statistical analysis of the typhoon movement trajectory in XSB in the last 5 years, “Haikui” was selected as the typical typhoon, whose landing point is very near the study area. “Haikui” generated in the northwest Pacific at 8am on August 3, 2012, and entered in East China Sea at 5pm on August 5. Then it landed in Hepu town Xiangshan county Ningbo city of Zhejiang province at 3:20am on August 8. The center pressure was 965hPa and the wind speed level was 14 (42m/s). The typhoon data was obtained from the CMA tropical cyclones data in Chinese typhoon net (http://www.typhoon.gov.cn/), including the center position of typhoon, center pressure and maximum wind velocity every 6 hours. Applying the above typhoon parameters, the typhoon wind fields are computed by the typhoon model.

Fig. 2 shows the wind field in the study area when the typhoon landed at 1am Aug. 8 in 2012. Fig. 3 shows the comparison of the calculation wind speed with the observed data at Shipu station. It shows that the wind direction is North at the beginning of the typhoon landing and the maximum wind speed reached 30 m/s. Then the wind direction changed to southeast and it was South at last. Due to the typhoon landed near the Shipu station, its maximum wind speed reached 38 m/s before it’s landing, and decreased to 5 m/s after its landing. Although the simulated wind speed decreased as the observed data after 48 choosing hours, it still larger than the observed data. The reason lies in the calculation inaccuracy of the radius of maximum typhoon wind speed. However, the time series of wind speed could reflect the main characteristic of the typhoon wind filed.
Figure 2-The field of typhoon wind at 1:00 on Aug.8 in 2012

Figure 3- Comparison of the wind speed between the model and observations at ShiPu station. The observed data cited from the reference Qian et.al (2013).

(3) The simulation of storm surge
The storm surge of typhoon “Haikui” was simulated using the calculated wind field data based on FVCOM model during August 8 to August 31, 2012. The storm surge variation was calculated by the total water level minus the astronomical tide level. Fig. 4 shows the Distribution of maximum storm surge in XSB and the comparison of the simulated storm surge with the observed data is shown in Fig. 5.

The figure shows that the variation tendency of storm surge agrees well with the observed data at Hutoudu station. The maximum of observed storm surge was 2.19m and the absolute error of simulated result is 10 cm. The maximum of storm surge in the study area is about 1.0-2.4m as shown in Fig. 4. The storm surge increased from the mouth to the head of bay. Due to the limited observed water level data, the verification of storm surge model in the study is less sufficient. In view of the results have reflected the variation of storm surge driven by the typhoon, and the model can be applied to study the mass transport in the bay.
3 STUDY METHODS

Several Lagrangian methods, named Lagrangian particle tracking (LPT), Lagrangian residual current (LRC) and Lagranigan Coherent Structures (LCS) are adopted to study the characteristics of mass transport. The details are as followed.

3.1 Lagrangian Particle Tracking

The particles in the water are tracked by solving the equation,

\[ \frac{dx}{dt} = v[x(t), t] \]  

(1)

where \( x \) is the position of water parcel at the time \( t \). \( v \) is the flow velocity, which was calculated by the hydrodynamic model. The trajectory of water parcel is given by

\[ x(t) = x(t_0) + \int_{t_0}^{t} [v[x(t), \tau]] d\tau \]  

(2)
and which can be solved by using the fourth order Runge-Kutta scheme. The flow velocity at
the water parcel position is interpolated by the adjacent elements and then the trajectory of
the water parcel is obtained.

3.2 Lagrangian Residual Current

Residual current is aperiodic current after removing periodic astronomic tide in ocean current,
which is induced by tide residual current, wind current, density current and runoff etc. (Shi,
2005). Residual current can be studied from the view of Lagrange and Euler. Euler residual
current can be obtained simply by time-averaging velocity vector from the hydrodynamic
model. The Lagrangian residual current $U_L$ is defined as the net displacement vector of the
water parcel over a period $T$ and is calculated by the Lagrangian particle tracking method. It is
expressed as

$$U_L = \frac{x_f - x_i}{T}$$

(3)

Where $x_f$ and $x_i$ are the end and start position of the water parcel over the period $T$.

3.3 Lagrangian Coherent Structures

LCSs are defined as the material lines in the FTLE filed. The FTLE values are calculated by
Lagrangian particle tracking. For two particles of fluid in the study area, one of them located
at $x$, the FTLE value at time $t_0$ and at the spatial position $x$ is given by the formula

$$\sigma_0^+ (x) = \frac{1}{\tau} \ln \sqrt{\lambda_{\text{max}} \left( \Delta(x, t, \tau) \right)}$$

(4)

Where $\tau$ is the advection time and $\lambda_{\text{max}}$ the largest eigenvalue of the Cauchy-Green
deformation tensor $\Delta(x, t, \tau)$, computed from the flow map of the artificial particles [5]. The
particles are tracked using Eq.(2) to compute the positions in time and space. Eq.(5) represents
the FTLE at the point $x$ at time $t_0$ with a finite integration time $\tau$. When the FTLE fields
are computed forward in time $\tau > 0$, the material lines in the FTLE fields represent the repelling
LCSs, and when $\tau < 0$, they represent the attracting LCSs. In this study, the attracting LCSs are
not considered. If $\sigma_0^+ > 0$, the system is unstable, which means that the neighboring points will
separate from each other no matter how close they are initially.

4 RESULTS AND DISCUSSION

4.1 The Influence of Typhoon on Lagrangian Particles’ Trajectories

The characteristic of mass transport in water can be described by Lagrangian particle tracking
method. It gives the pollutant movement trajectories, resident time and the fate by the particles
released in water. Fig. 6 shows the particles’ trajectories in XSB for only tidal current and with
both tidal current and storm surge. The particles were released at 14:00 Aug. 7 before the
typhoon landing at the surface layer of water and were tracked for 48h.
For the tidal current condition, the particles in the bay are reciprocating motion and the moving trajectories are in ellipse shape in the mouth of the bay. Due to the island and the two channels, the water transport is complex in the mouth of bay. With both the tidal current and storm surge, the particles’ trajectories changes greatly. The particle in the mouth of bay could move to Sanmen bay and the distance reach 50km. It shows that the short-time strong wind could change the characteristic of mass transport and distribution greatly.

(a) only tidal current  
(b) both tidal current and storm surge

Figure 6- The trajectory of particles in Xiangshan Bay during the typhoon of Haikui under different cases.

4.2 The Influence of Typhoon on Residual Current

The simulation results of particle’s trajectories show that the maximum movement distance could reach 50km in a tidal period. Based on the Lagrangian method, the LRC direction will flow to the land, which become meaningless for the circulation. Therefore, it could not analyze the LRC from the Lagrangian view. The following the field of ERC are given and discussed. Fig. 7 and 8 show the distribution of ERC at the surface layer on Aug. 7 and 8 during the typhoon landing for the two conditions.

The average speed of ERC for the tidal current was 0.05 m/s for the tidal current and it’s similar on Aug. 7 and 8. This indicates that the ERC has small changes for the different days. With the tidal current and storm surge, the speed of ERC reaches 1 m/s and the direction was agree well with the wind direction. The distribution of ERC are totally different for the two days, which shows that it was dominated by typhoon wind. After the typhoon passed, the influence of typhoon on the ERC field disappeared quickly.

(a)  
(b) 

Figure 7- Distribution of Eulerian residual current field at surface layer in Xiangshan Bay on Aug. 7, computed by tidal current (a) and with tidal current and storm surge (b).
4.3 The Influence of Typhoon on LCS

Fig. 9 shows the distribution of Lagrangian coherent structures in XSB during the typhoon landing. The color contours in the figures represent the FTLE values. The higher value means higher separation rate between two neighboring particles. The LCSs are the ridges of the FTLE fields, which are moving separatrixes along with the tidal current. As can be seen from the figure, remarkable LCS are mainly appeared in the mouth of XSB. The neighboring particles being separated mainly induced by one of them transport to the island or coastline, therefore one side of the LCS generally connects with the island or coastline. In the Fig. 9 (a)-(c), the main feature is a LCS (L1) in the Fodu channel and several LCSs (L2-L4) divide the Niubishan channel to several parts. Overall, the LCSs are developed along with the tidal current movement and they evolve periodically in time as the tidal current oscillates.

With the tidal current and storm surge, the distribution of LCSs (as shown in Fig. 9 (d)-(f)) are different. More LCSs are evolved by the driven of strong wind and the LCSs are more complex. The spatially averaged value of FTLE are 0.257 h\(^{-1}\), 0.231 h\(^{-1}\) and 0.25 h\(^{-1}\) for the tidal currents at different time. For the same time the spatially averaged value of FTLE for the tidal current and storm surge case are respectively 0.365 h\(^{-1}\), 0.340 h\(^{-1}\) and 0.352 h\(^{-1}\), which increased 43%. The time series of the averaged FTLE values are for the two condition are shown in Fig. 10. It can be seen that the effects of the storm surge is to increase water mixing.

In order to better understand the effect of LCSs on the mass transport, four sets of particles are assigned in both sides of the remarkable LCSs. The location of the particles are given in the Fig. 9. It shows that the particles at the south of L6 (the green and pink color in Fig. 9 (d)) moves to Damuyang at 20:00, Aug, 7 and reach to Sanmen bay at 2:30, Aug, 8. The particles at the north of L6 (the black color) are prevented by L6 and stay between the L8 and coastline area. The blue color particles always stay in the areas between L6 and coastline due to the effect of L6.

![Figure 8](image1.png)

**Figure 8- Distribution of Eulerian residual current field at surface layer in Xiangshan Bay on Aug, 8, computed by tidal current (a) and with tidal current and storm surge (b).**
Figure 9-Distribution of Lagrangian Coherent Structures in Xiangshan Bay during the typhoon of Haikui, computed by tidal current (a)-(c) and with tidal current and storm surge (d)-(f).

Figure 10-The time series of the mean FTLE during the typhoon.

4 CONCLUSIONS

The storm surge model in XSB was established based on FVCOM model, and the hydrodynamics by typhoon in this area was simulated. Further, the influence of typhoon on mass transport was analyzed by Lagrangian particles tracking, residual current and Lagrangian coherent structures respectively. The conclusions are as follows:

(1) The pollutant trajectory in the study area changed obviously under the influence of typhoon. The particles at the mouth of bay move to Sanmen bay and the maximum movement distance reaches 50km. It indicated that the strong wind during the typhoon significantly changes the transport and distribution characteristics of pollutant.

(2) The transport distance of water particles during the typhoon landing is rather large in a tidal period, which induced that the Lagrangian residual current is not suited to study the features of circulation. The daily-averaged Eulerian residual current shows that the wind fields during the typhoon are the main driving factors for mass transport.

(3) The distribution of LCSs shows that the characteristics of the water region dividing changed with the effect of typhoon, and it also could increase the water mixing. It demonstrates that the LCSs is a useful tool to understand the water transport and mixing processes by comparing the results of different methods. The Combination of Lagrangian particle tracking and LCSs could better uncover the mass transport in the abnormal climate.
REFERENCES