THE COASTAL MACRO-VORTICES DYNAMICS: A CASE STUDY IN HONG KONG WATERS

Chang HE, The Hong Kong Polytechnic University, daisy.he@connect.polyu.hk
Alessandro STOCCHINO, The Hong Kong Polytechnic University, alessandro.stocchino@polyu.edu.hk
Zhen-Yu YIN, The Hong Kong Polytechnic University, zhenyu.yin@polyu.edu.hk

INTRODUCTION

Coastal circulations are basic information when considering sediment transport and water quality in the oceanic environment, particularly the macro-vortices dynamics which greatly affected the mass transfer and extended the residence time (Hasegawa et al., 2009). Large-scale macro-vortices could be formed in the lee or around natural obstacles such as islands and headlands during the interaction between geographical features and coastal circulations induced by tides and winds.

Pearl River is the second largest river in China considering discharge, delivering 3.26×10^{11} m^3 freshwater every year into the South China Sea (SCS) through eight outlets (Wu et al., 2016). Hong Kong (HK) is located downstream of the Pearl River Estuary (PRE), acting as a bridge between the PRE and the SCS, as shown in Figure 1. HK possesses more than 200 islands as well as narrow channels and complex coastlines, which have a great impact on shaping local flow structures. In addition, prevailing southwest winds blow during the summer, while stronger northeast winds gust during the winter. Embracing tides from the SCS and river discharge from the PRE, HK waters is an energetic and interesting area and worth a detailed investigation.

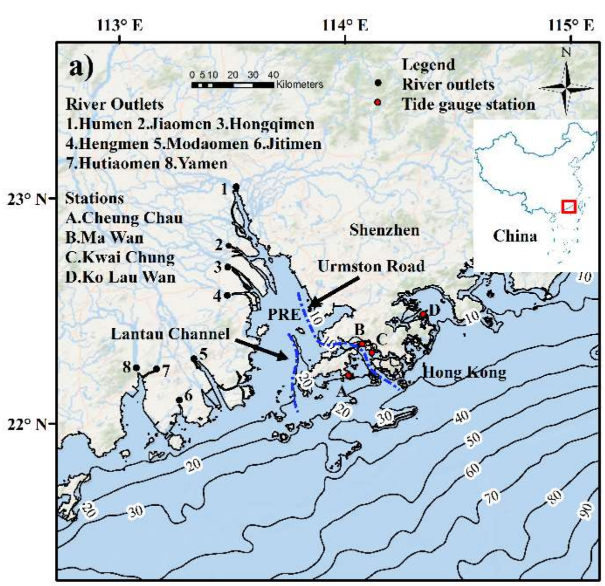

Figure 1 - Map of the HK waters showing topographic features and isobaths (in meters), blue lines represent two channels around the PRE, black points represent the eight outlets of the Pearl River, and red points represent the tide gauge stations.

MODEL CONFIGURATION

The Finite Volume Coastal Ocean Model (FVCOM) was implemented with an unstructured grid and three-dimensional (3D) primitive equations (Chen et al., 2003). Our study domain covered the entire PRE-HK area with an open boundary in the SCS. The model resolution varied from 70 m around HK waters to 10 km on the open boundary. Ten uniform sigma layers were used in the vertical direction. A whole-year simulation was conducted based on the monsoon wind, periodical tides, and river discharge of 2017. Simulations without winds or tidal forcing were also conducted as comparisons to further analyze the role of wind or tides in coastal circulations. The model was validated against the free surface elevation of four tide gauge stations A, B, C, and D, presented in Figure 1. The correlation coefficient between model results and observation data reached 96%.

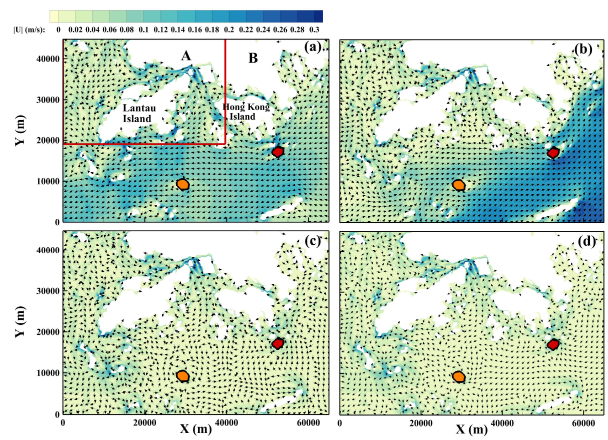

Figure 2 - Monthly-averaged velocity maps of HK waters: in December (a) and July (b) under both wind and tidal forcing; in December (c) and July (d) under tidal forcing only. Area A in the red rectangle in (a) represents the waters blocked by islands, while Area B is closer to the SCS with less blockade. Those highlighted two islands are taken as examples when discussing island wakes.

RESULTS

Monthly-averaged velocities as well as normalized velocity vectors were shown in Figure 2. Panel (a) and (b) present the monthly-averaged velocities in December and July 2017, respectively. Velocities in Area A showed similar patterns and comparable magnitudes, especially inside the channel, lying to the north of Lantau Island. Intenser velocities were observed in Area B during both July and December but aligned with the direction of the monsoon winds. Low-velocity zones were observed in the lee of islands concerning the direction of the monsoon. To further clarify the role of tides and winds in coastal circulations, panel (c) and (d) present the monthly-averaged velocities of simulations without wind during December and July, respectively. Comparable velocities were observed inside Area A in all four panels, indicating that tide was the dominant forcing. However, in Area B, the intensity of velocity was greatly decreased in absence of the monsoon. This implied that the prevailing wind played a more significant role in the outside HK waters. The roles of wind and tide were strongly correlated with the coastlines and distribution of islands. Area A was shielded by complex coastlines and currents were shaped according to geometry. Under this condition, the prevailing wind was unable to generate constant wind current, while tidal current could pass through and dominate this area. On the contrary, Area B showed great potential in the generation of the persistent wind current.

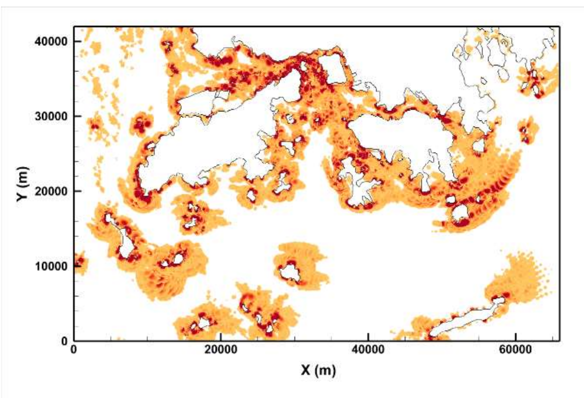

Figure 3 – The density map of the coastal macro-vortices in HK waters in July 2017. The darker the area was, the more frequent vortices appeared.

The vortical structures were identified using vorticity and the Okubo-Weiss parameter λ_0 (Günther and Theisel, 2018). Figure 3 displayed the monthly maps superimposing the trace of the vortices identified using λ_0 on an hourly basis in July 2017. The densest concentration of vortices appeared around the north Lantau Island and around Hong Kong Island, where tidal currents were the intensest. Those vortices around islands and headlands in Aera A were classified as tidal vortices. It is worth noting that the behavior shown was typical for the entire year, suggesting that macro-vortices were persistent flow structures with no seasonality. In addition, vortex streets were shown in the lee of islands, especially for the two islands specified corresponding to Figure 2. Wind acted as a promoting role which helped transport the vortices and enlarge the area affected by vortices, especially in the wind-dominated Area B. Correspondingly, those vortex streets in the wind directions were classified as wind wake vortices.

Geometric features of vortices were evaluated by identifying the position of the core of the vortex, the radius of the area-equivalent circle R_{eq}, and the eccentricity ϵ of the vortices, defined as the ratio between the minor and major axes of the vortex (ϵ = 1 represents a perfectly circular vortex), etc. It has been found that vortices with R_{eq} of 500 – 600 m and ϵ of 0.6 - 0.7 had the largest probability density. It should be noticed that this analysis was based on a number of identified macro-vortices of the order of 10^6 during the entire year.

CONCLUSION

To sum up, one-year simulations of 2017 were conducted using FVCOM to understand the role of tide and monsoon wind in coastal circulations around HK waters. The plenty of islands with different sizes and complex coastlines were responsible for the generation of hundreds of coherent macro-vortices that dominated the coastal hydrodynamics. Tide and wind had different dominant areas and generated two patterns of distribution of vortices with similar geometric features. Further research could be focused on the relationship between vortices distribution and water quality and sediment transport.

ACKNOWLEDGMENT

This work is supported by the Research Impact Fund of the Research Grants Council of Hong Kong (RGC R5037-18).

REFERENCES

Chen, C., Liu, H., Beardsley, R.C. (2003): An Unstructured Grid, Finite-Volume, Three-Dimensional, Primitive Equations Ocean Model: Application to Coastal Ocean and Estuaries, Journal of Atmospheric and Oceanic Technology, AMS PUBLICATIONS, vol. 20, pp. 159-186.

Hasegawa, D., Lewis, M.R., Gangopadhyay, A. (2009): How islands cause phytoplankton to bloom in their wakes, Geophysical Research Letters, AGU PUBLICATIONS, vol. 36, L20605, doi:10.1029/2009GL039743.

Wu, C.S., Yang, S., Huang, S., Mu, J. (2016): Delta changes in the Pearl River estuary and its response to human activities (1954-2008), Quaternary International, vol. 392, pp. 147-154.

Günther, T., Theisel, H. (2018): The State of the Art in Vortex Extraction: The State of the Art in Vortex Extraction, Computer Graphics Forum, vol. 37, pp. 149-173.