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# SOME FEATURES OF CURRENT FIELDS CALCULATED IN THE GULF OF TONKIN

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**ABSTRACT**: There have been many investigations, studies and calculations of the dynamic fields (including the sea current fields) in the Gulf of Tonkin (Vietnam), which are affected not only by the fresh water from Red river but also by the western boundary current system in the East Sea through the gulf mouth and Qiongzhou Strait (between Leizhou peninsula and Hainan island (China). At present, economic activities are very active in both east coast and west coast, waters and islands of the Gulf of Tonkin. Up to now, research results, calculations and simulations of the flow system in the Gulf of Tonkin under the influence of the water exchange through straits, bay mouth, river input and climate change are still very few and sparse. In this paper we tried to solve the three-dimensional (3D) nonlinear model of currents during northeast and southwest monsoons in this region using finite element method (FEM) with complementary conditions as described above. The calculation results showed the main characteristics, the spatial and vertical variations of intensity and direction of the current fields during typical monsoons in the Gulf of Tonkin. Our research results show that: Inlet and outlet flows from the Gulf of Tonkin through the Qiongzhou Strait have the potential to form an anti-counterclockwise flow region (cyclone gyre) at the top of the bay, transporting material and affecting the quality of the sea water in this area; The flow into the bay from the main south-east mouth of the bay is not only responsible for the formation of a strong current on the eastern shore of the bay (west coast of Hainan Island) but also has an effect on the whole system flows in the gulf and creates a regular southward nearshore flow to the west coast of the gulf; The wind driven currents play an important role inside the Gulf of Tonkin and the density currents (thermo-haline, regular currents) play an important role in and outside of the main mouth of the gulf; Cyclone gyres have been formed in northeast monsoon and anticyclones have been formed in southwest monsoon in the gulf.

**Keywords**: Tide, current, three-dimensional (3D) nonlinear model, cyclone gyre, anti-cyclone gyre, Gulf of Tonkin.

## INTRODUCTION

Gulf of Tonkin is a large bay in the East Sea, approximately 123,700 $km^2$ in area, where the widest width is about 320 km and its narrowest is about 220 km, in which the Vietnamese coast of the gulf is about 763 km long and the Chinese side is about 695 km.

The gulf has one main door (approximately 270.4 km in width, from Con Co island, Vietnam to Hainan island, China) and one strait (Qiongzhou Strait, approximately 35.2 km in width lying between Leizhou peninsula and northeast Hainan island). The part of the gulf in Vietnam (Ha Long and Bai Tu Long bays) has around 2,300 islands. The largest island in the gulf is Bach Long Vi island, lying about 110 km from the mainland of Vietnam and 130 km from Hainan island. Gulf of Tonkin has important strategic location for both Vietnam and China in economics and defense security. Northern part of the bay is one of the fisheries and seafood supplying areas, important for both Vietnam and China.

The Red river (Vietnam) provides the major riverine discharge of about 130 Mt/year total terrestrial materials into the gulf, and the Pearl river (China) provides the discharge with total materials of about 90 Mt/year through Qiongzhou Strait. The seasonal reversing monsoon wind plays an important role in hydrological features and the general circulation pattern in the study region. In the East Sea, the northeast monsoon (winter season) is from October to next March and the southwest monsoon is from May to August.

The main expeditions concerning the study issues:

The Vietnam - China integrated surveys which were carried out during 1959 - 1961.

The Vietnam - Soviet fishery surveys which were carried out during 1961 - 1964. Unfortunately, these surveys were limited to western coastal waters, without covering the entire gulf. During the period of 1964 - 1975 because of the war situation and up to now because of managing authority division of the waters in the gulf, surveys were only carried out in the waters managed by Vietnam or China.

Some related research publications:

3D nonlinear model for the calculations of tide and tidal current in the Gulf of Tonkin. Manh, D. V., and Yanagi, T., (1997) [1].

Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. Xingang Lu et al., (2008) [2].

Modeling the circulation in the Gulf of Tonkin, South China Sea. Jingsong Gao et al., (2013) [3].

Tidal dynamics in the Gulf of Tonkin. P. Marchesiello, Minh Nguyen et al., (2014) [4].

## MATERIALS AND METHODS

### Input data

The daily-averaged wind data was derived from website ftp://ftp.ssmi.com/qscat/bmaps_v03/ (from 1996 to 2003) and http://www.remss.com/windsat/windsat_browse.html (from 2003 to 2013). Wind vectors were reconstructed with the accuracy of 1 m/s in speed and $15^o$ in direction. With comprehensive wind data source, seasonal and monthly average wind speeds and directions calculated from the statistical analysis of wind field, the interpolation of wind data in mesh distribution (finite element) was easily carried out using Matlab R2013b. The wind data from 1987 to 2007 at the areas of Tuy Hoa, Nha Trang, Phu Quy and Vung Tau checked with a measuring frequency of 6 hours per day were used to validate the procedure.

The used atmospheric parameters were derived from NCEP (National Centers for Environmental Prediction), including wind speed (m/s) at 10 m above the sea level, atmospheric pressure, air temperature and specific moisture/humidity at 2 m above the sea level, total cloud cover (%), rainfall ($kg/m^2/s$), short wave and long wave radiation fluxes ($W/m^2$).

Thermo-haline data was derived from 4 sources: 1) the VODC database of the Institute of Oceanography; 2) the Russian website http://pacificinfo.ru/; 3) the PHC 3.0 downloaded freely from: http://psc.apl.washington.edu/POLES/PHC2/Climatology.html; 4) the data collected from the investigations of the Vietnam - German Upwelling Project (2003 - 2006).

From the above-mentioned data sources, we choose that from Russia as the basis and updated it by adding data from other sources.

The harmonic constants used for the calculations of tidal effects in the Gulf of Tonkin were 9 main tidal constituents as: $M_2$, $S_2$, $N_2$, $K_2$, $M_4$, $K_1$, $O_1$, $Q_1$ and $P_1$. The harmonic constants were calculated by the same method but with a large scale of the whole East Sea (carried out under the framework of the international Vietnam - German Cooperation Project), then they were interpolated to match with the open boundaries of the study area using the interpolation program *Griddata* in Matlab.

**Methodology of nonlinear 3D model**

The model is performed based on the three-dimensional hydrodynamic equations with the conventional Boussinesq and hydrostatic assumptions. Temperature and salinity transport and sea water density are defined from the equation of state. The subgrid-scale dissipation is represented in eddy viscosity (diffusivity) form, parameterized in terms of stratification plus turbulent kinetic energy and mixing length, both of which evolve at the macro-scale.

***Governing equations***

There are six state variables in the 3D model, which are represented in the following equations. The two horizontal components ($x$, $y$) of the momentum equation are:

$$\frac{d\vec{v}}{dt} + \vec{f} \times \vec{v} = g\nabla_{xy}\zeta - \frac{\partial}{\partial z}\left(N_m \frac{\partial \vec{v}}{\partial z}\right) = -\frac{g}{\rho_0}\int_z^{\zeta} \nabla_{xy}\rho dz + \vec{F}_m + \frac{\sigma}{\rho}\left(\vec{v}_\sigma - \vec{v}\right) \quad (1)$$

Equations for heat and salt conservation:

$$\frac{dT}{dt} - \frac{\partial}{\partial z}\left(N_h \frac{\partial T}{\partial z}\right) = F_T + \frac{\sigma}{\rho}\left(T_\sigma - T\right) \quad (2)$$

$$\frac{dS}{dt} - \frac{\partial}{\partial z}\left(N_h \frac{\partial S}{\partial z}\right) = F_S + \frac{\sigma}{\rho}\left(S_\sigma - S\right) \quad (3)$$

Equations of the turbulent kinetic energy and mixing length:

$$\frac{dq^2}{dt} - \frac{\partial}{\partial z}\left(N_q \frac{\partial q^2}{\partial z}\right) = 2\left[N_m\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right) + \frac{g}{\rho_0} N_h \frac{\partial \rho}{\partial z}\right] - 2\left[\frac{q^3}{B_1 l}\right] + \frac{\sigma}{\rho}\left(q_\sigma^2 - q^2\right) \quad (4)$$

$$\frac{dq^2 l}{dt} - \frac{\partial}{\partial z}\left(N_q \frac{\partial q^2 l}{\partial z}\right) = lE_1\left[N_m\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right) + \frac{g}{\rho_0} N_h \frac{\partial \rho}{\partial z}\right] - lW\left[\frac{q^3}{B_1 l}\right] + \frac{\sigma}{\rho}\left(q_\sigma^2 l_\sigma - q^2 l\right) \quad (5)$$

***Boundary conditions***

Tidal oscillation was introduced into nodes at open boundary to create appropriate general tidal force and impose accurately Dirichlet boundary conditions. Following equation has to be summated from all tidal components:

$$\zeta(t) = Z_0 + \sum_k f_k(t) \cdot A_k \cdot \cos\left(\omega_k\left[t - t_0\right] + \left(V(t_0) + U(t)\right)_k - \frac{\pi}{180} g_k\right) \quad (6)$$

We solved these equations under the conventional horizontal boundary conditions.

Vertical boundary conditions are posed as follows. For the horizontal velocity, the atmospheric shear stress is specified at the surface:

$$N_m \frac{\partial \vec{v}}{\partial z}\bigg|_{z=\zeta} = H\vec{\Psi} = \vec{\tau}_w \quad (7)$$

With: $$\vec{\tau}_w = C_{ds}\rho_a \vec{W}\left|\vec{W}\right| \quad (8)$$

Where: $\vec{W}$ : Wind velocity vector at the sea surface; $\rho_a$ : Air density ($\rho_a$ = 1.25 kg.m$^{-3}$).

For the calculations on this page, a non-linear drag coefficient was used (based on Large and Pond (1981) [5] modified for low wind speeds as in Trenberth et al., (1990) [6]:

$$C_{ds} = \begin{cases} 0.00218 \ \text{ cho: } |\vec{v}| \le 1(\text{m/s}) \\ (0.62 + \dfrac{1.56}{|\vec{v}|}) \times 10^{-3} \ \text{ cho: } 1(\text{m/s}) < |\vec{v}| < 3(\text{m/s}) \\ 0.00114 \ \text{ cho: } 3(\text{m/s}) \le |\vec{v}| < 10(\text{m/s}) \\ (0.49 + 0.065|\vec{v}|) \times 10^{-3} \ \text{ cho: } |\vec{v}| \ge 10(\text{m/s}) \end{cases} \quad (9)$$

At the bottom, we used conventional quadratic slip conditions relating shear stress to bottom velocity $\vec{v}_b$ via dimensionless quadratic bottom stress drag coefficient, $C_d$.

$$N_m \frac{\partial \vec{v}}{\partial z}\bigg|_{z=-h} = C_d |\vec{v}_b| \vec{v}_b = k\vec{v}_b \quad (10)$$

Where $k$ is the linear bottom stress coefficient.

Atmospheric heat input is determined at surface as a “type III” or radiation condition with heating rate α and equilibrium temperature $T_o$:

$$N_h \frac{\partial \vec{v}}{\partial z}\bigg|_{z=-h} = -\alpha \left(T - T_o\right) \quad (11)$$

At the bottom, heat flux is assumed negligible:

$$N_h \frac{\partial T}{\partial z}\bigg|_{z=-h} = 0 \quad (12)$$

**Computational grid**

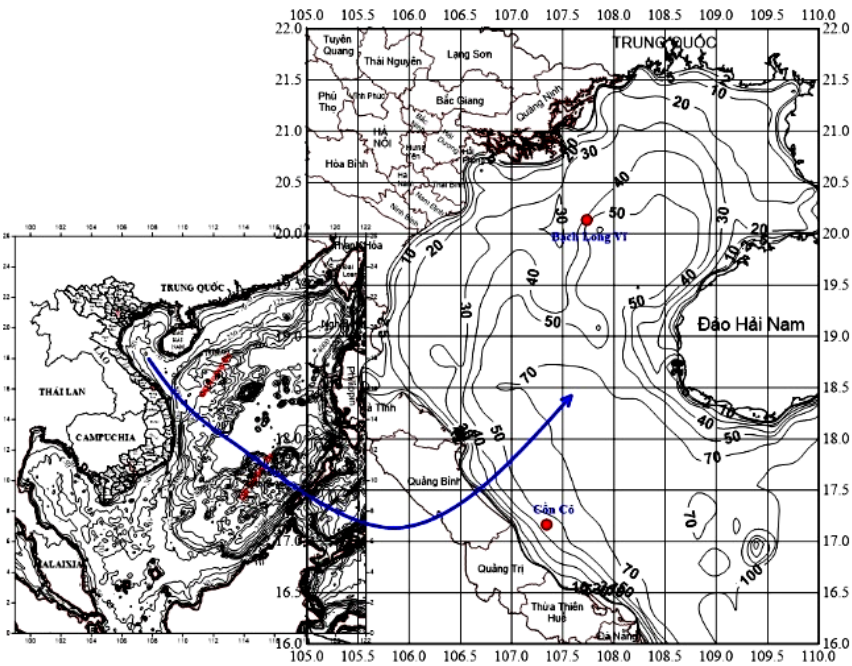


*Fig. 1.* Bathymetric map (m) in the Gulf of Tonkin

With finite element grid (simulation of large areas): The computational domain was from 100.0883°E to 117.9899°E longitude and from 4.4546°N to 23.6867°N latitude (fig. 1). For computation, finite element method with triangular computational grid was used (fig. 2). The minimum grid angle was 25°; total computation area was 2,646,196.4505 km$^2$. Computational points were 5,366 with 10,204 triangles. Triangular area was 81.9732 km$^2$ at the minimum, 259.3293 $km^2$ on average, 774.2812 $km^2$ at the maximum. The boundaries of the nonlinear 3D model cut by finite element method were relatively flexible in open boundary setting. In the vertical, we divided calculated horizons into 20 layers (0 m layer - the surface, the 10 m, 20 m, 30 m, 50 m, 75 m, 100 m, 125 m, 150 m, 200 m, 250 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, 1000 m, 1,200 m, 1,500 m layers). The bathymetry map and triangular grids for the whole East Sea and the Gulf of Tonkin are depicted in the fig. 1, 2.

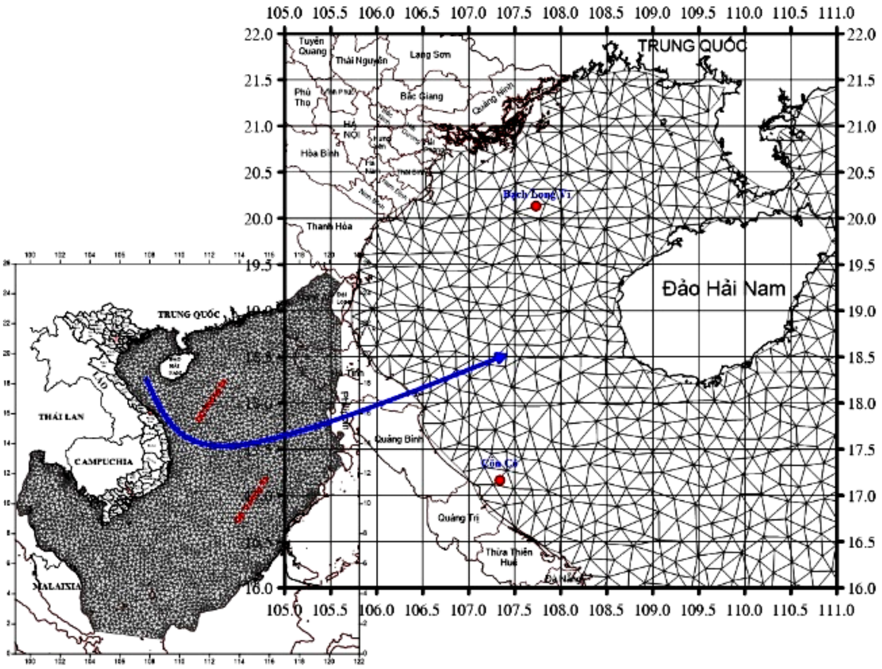


*Fig. 2.* Triangular grids for current computation

The run includes a tidal forcing along the open-water boundary featuring the $M_2$, $S_2$, $N_2$, $K_2$, $M_4$, $K_1$, $O_1$, $Q_1$ and $P_1$ tidal constituents and the resultant currents under the influence of the two main monsoon regimes (interpolated from the wind database in the whole East Sea): The strong northeast monsoon, typically from last December to next February; and the strong southwest monsoon, typically from June to August.

The 3D nonlinear FEM model used in this study was developed by authors of this paper [7, 8]...

## RESULTS

### The current profiles in the two typical monsoon fields

***In the northeast monsoon***

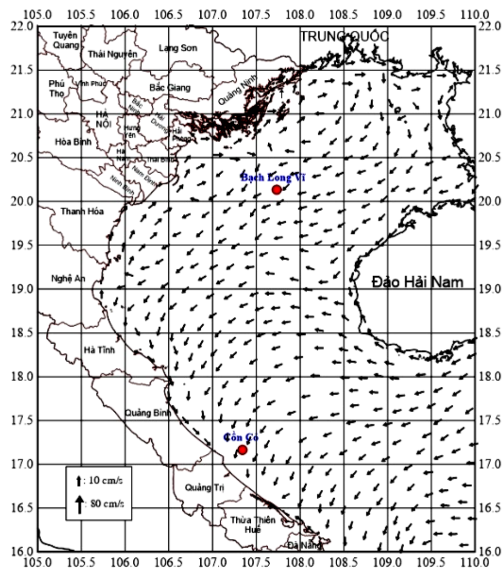


*Fig. 3a.* Distribution of wind currents at the surface layer in NE monsoon

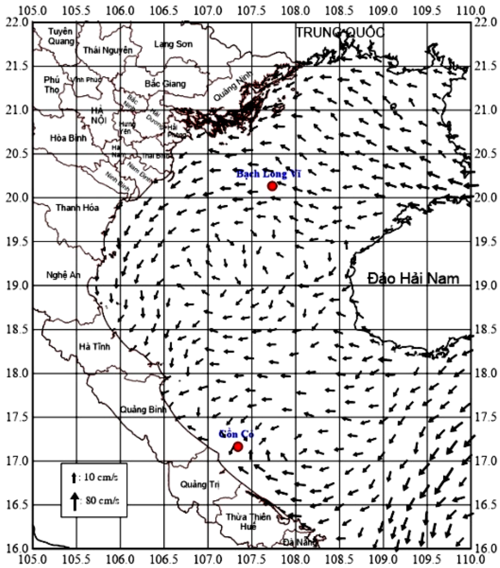


*Fig. 3b.* Distribution of general currents at the surface layer in NE monsoon

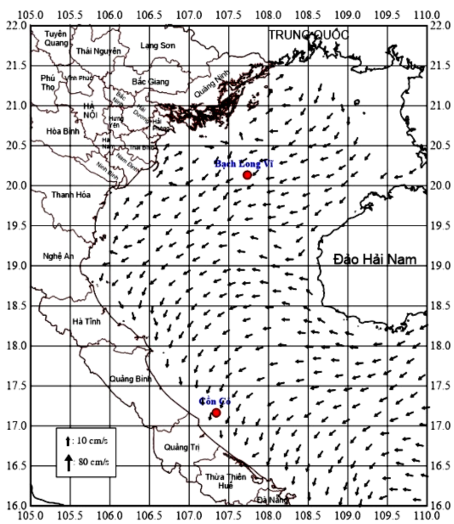


*Fig. 4a.* Distribution of wind currents at the 20 m layer in NE monsoon

During the northeast monsoon, a strong regular current appears through Qiongzhou Strait (from China), calculated current velocities can achieve speed of 52 cm/s and generate a strong current region located in the northwest of Gulf of Tonkin. In the center of Gulf of Tonkin, an area with relatively weak flow rate of less than 10 cm/s is formed, in addition there also appear several small vortices located in the center of the gulf. Meanwhile, outside the main entrance from Con Co (Vietnam) to Hainan island (China) due to the influence of the northeast monsoon, the strong flow rate affected by the density current (probably greater than 60 cm/s) is formed: A small flow goes into the gulf and the main flow goes to southwest coast outside the gulf. This has contributed to a decline in influence of tidal flow entering the main entrance of the gulf. If considered separately, only just wind current (fig. 3, 4, 5), the above picture will not be reflected.

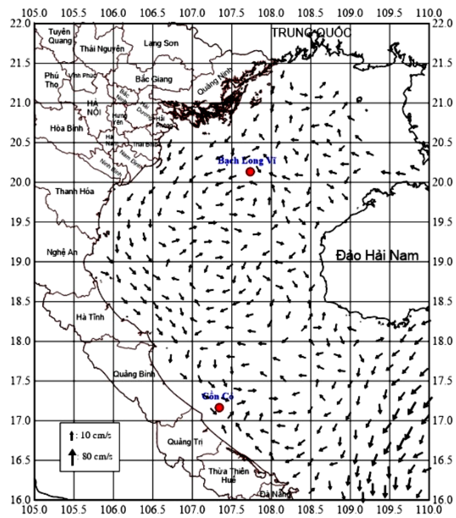


*Fig. 4b.* Distribution of general currents at the 20 m layer in NE monsoon

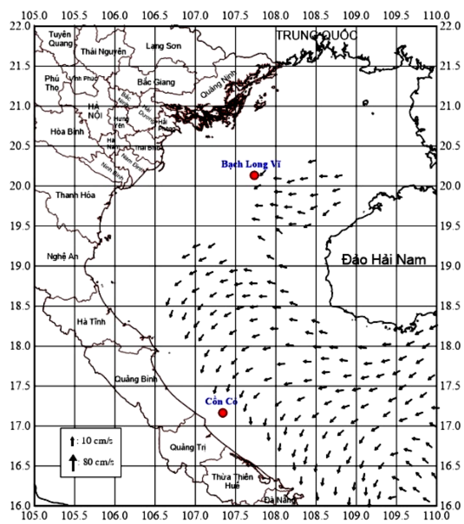


*Fig. 5a.* Distribution of wind currents at the 50 m layer in NE monsoon

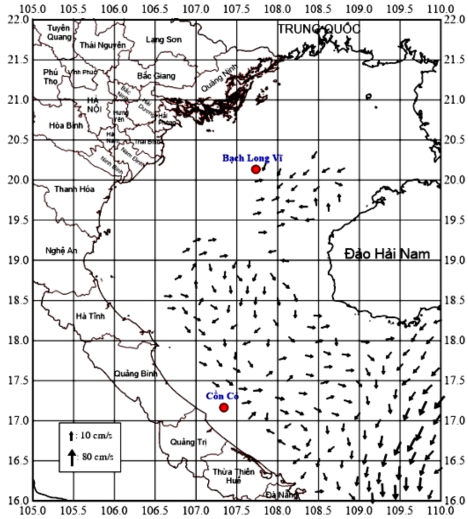


*Fig. 5b.* Distribution of general currents at the 50 m layer in NE monsoon

***In the southwest monsoon***

During this period the flow out of the gulf is dominant (at ebb tide), the outflow reaches over 80 cm/s at Qiongzhou Strait. In the middle of the gulf, there usually appears on the surface a flow of greater than 20 cm/s going to the west towards Hainan island. Outside the main entrance of Gulf of Tonkin, effects of density flow are showed quite clearly, especially when the wind and tide current are not clear (strong enough) (fig. 6, 7, 8).

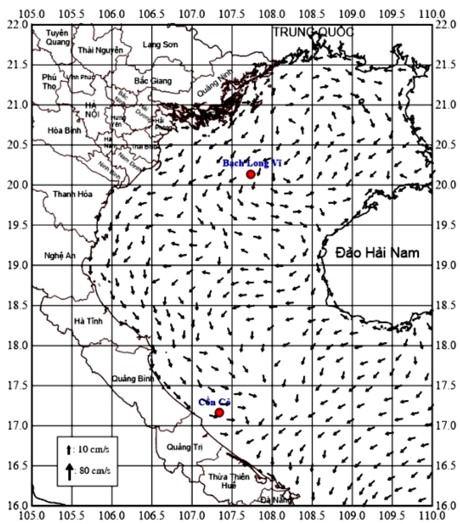


*Fig. 6a.* Distribution of wind currents at the surface layer in SW monsoon

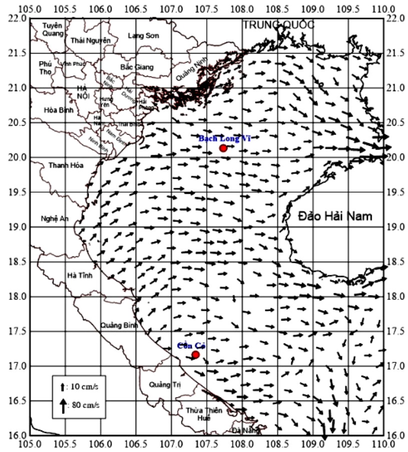


*Fig. 6b.* Distribution of general currents at the surface layer SW monsoon

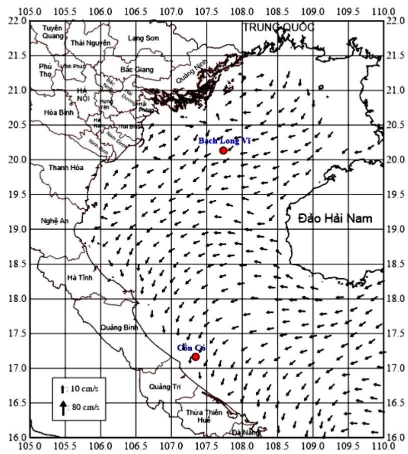


*Fig. 7a.* Distribution of wind currents at the 20 m layer in SW monsoon

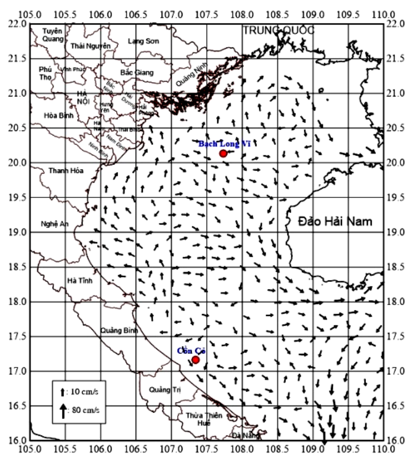


*Fig. 7b.* Distribution of general currents at the 20 m layer SW monsoon

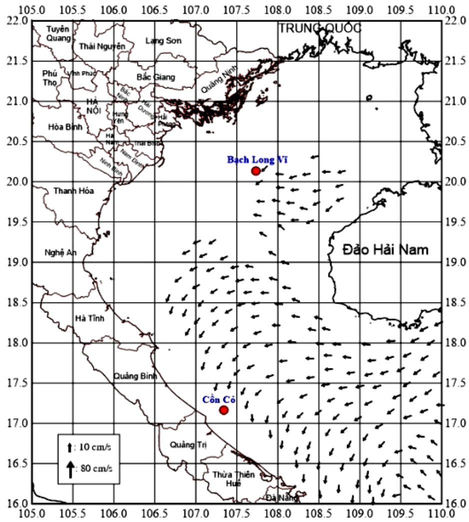


*Fig. 8a.* Distribution of wind currents at the 50 m layer in SW monsoon

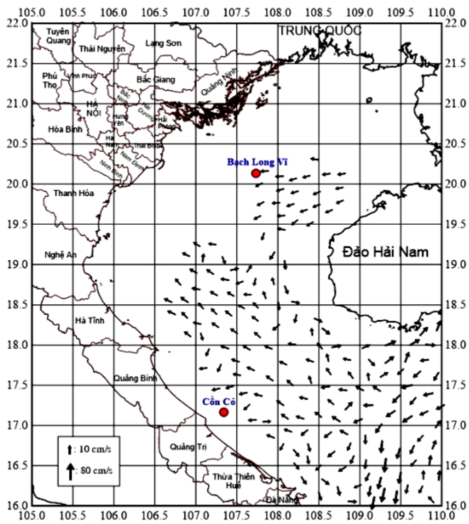


*Fig. 8b.* Distribution of general currents at the 50 m layer SW monsoon

**DISCUSSION**

The calculation results showed that Qiongzhou Strait plays an important role in water exchange between the Gulf of Tonkin and the East Sea.

The wind currents play an important role inside the Gulf of Tonkin and the density currents (thermo-haline, regular currents) play an important role in and outside the main mouth of the gulf.

Strong regular currents are existing (in the whole year with two wind seasons) from north to south through the gulf mouth (this has been approved by some previous study results), the density currents play the main role.

Cyclone circulation has been formed in northeast monsoon and anticyclone circulation has been formed in southwest monsoon in the gulf.

The current direction and intensity change very little with depths.

The initial findings of the flow rule under the influence of monsoon have not been clearly expressed in the article. Unfortunately, we still lack a series of measured data to test and calibrate the model. However, by the model results we can realize the potential, future prospect and development direction of FEM. The results obtained by full 3D nonlinear finite element model show that FEM is better for simulating the current system in coastal waters with complex bottom topography and expanded boundary. Currents flowing along the shore and island boundaries are represented more accurately by this method. Testing the accuracy of FEM using the field data will help us calibrate the required computational parameters for a better simulation of specific features of marine currents. Accurate, reliable and comprehensive field data will provide good input data, so the FEM model will give us high quantitative and more reliable results.

A number of issues for both scientific and practical needs that we will continue to study in more detail:

Clarification of the role of Qiongzhou Strait through the exchange of water for hydrology (terrestrial water volume), dynamics, material transport, environmental quality and biodiversity in the north area and peak of the Gulf of Tonkin.

Ability of transportation, dispersion (longshore and cross-shore sediment transportation) and deposition of materials from the gate area of the Red river system in the Gulf of Tonkin under the impacts of climate change and human activities.

Study on the process of transportation and distribution of resources as sea creatures in the bay area to contribute to the conservation and sustainable development of marine economy.

The viability of local upwelling (time and scope) at the mouth of the Gulf of Tonkin in transition monsoon seasons (NE - SW) and SW and its impacts on resources and biodiversity in the waters adjacent to the mouth of the bay.

Accurate determination and clarification of the position of the amphidromic point at the coastal region in the gulf mouth.

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# MỘT SỐ ĐẶC TRƯNG DÒNG CHẢY TÍNH TOÁN TRONG VỊNH BẮC BỘ

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**TÓM TẮT:** Đã có nhiều chuyến khảo sát, nghiên cứu, tính toán các trường động lực (bao gồm trường dòng chảy biển) trong vịnh Bắc Bộ, là nơi chịu ảnh hưởng không chỉ dòng nước ngọt từ hệ thống sông Hồng mà còn chịu tác động của hệ thống dòng chảy ven bờ tây Biển Đông thông qua các eo Quỳnh Châu (nối giữa bán đảo Lôi Châu và đảo Hải Nam, Trung Quốc) và cửa vịnh Bắc Bộ. Hiện nay các hoạt động kinh tế đang trở nên hết sức sôi động ở cả hai bờ, trong vùng nước và trên các đảo trong khu vực vịnh. Cho đến nay các kết quả nghiên cứu, tính toán, mô phỏng hệ dòng chảy trong khu vực vịnh dưới sự tác động của các quá trình trao đổi nước qua các eo, cửa, dòng đi từ sông ra và ảnh hưởng của biến đổi khí hậu còn rất ít và chưa có tính hệ thống. Trong bài báo này chúng tôi đã sử dụng mô hình ba chiều (3D) phi tuyến được giải bằng phương pháp phần tử hữu hạn để tính toán trường dòng chảy trong vịnh Bắc Bộ cho các mùa gió Đông Bắc, Tây Nam với các điều kiện bổ sung như đã trình bày ở trên. Các kết quả tính toán đã cho các đặc trưng của hệ thống dòng chảy: Phân bố không gian, phân bố thẳng đứng, cường độ, hướng dòng chảy trong các mùa gió mùa chính trong vịnh Bắc Bộ. Các kết quả nghiên cứu cho thấy: Dòng đi vào và đi ra từ vịnh Bắc Bô qua eo Quỳnh Châu có khả năng hình thành nên vùng dòng chảy ngược chiều kim đồng hồ (xoáy thuận), vận chuyển vật chất và ảnh hưởng đến chất lượng nước ở khu vực đỉnh vịnh; Dòng đi vào và đi ra khu vực cửa vịnh chính ở phía đông nam không những làm hình thành một vùng dòng chảy mạnh ở phía bờ đông vịnh (bờ phía tây đảo Hải Nam) mà còn ảnh hưởng lên hoàn lưu chung toàn vịnh và tạo ra một hệ thống dòng thường kỳ đi về phía nam ở vùng ven bờ phía tây nam cửa vịnh; Dòng chảy gió đóng vai trò quan trọng bên trong vịnh còn dòng mật độ (dòng nhiệt-muối ổn định) ưu thế ở cửa và bên ngoài cửa vịnh; Các xoáy thuận hình thành trong mùa gió Đông Bắc và các xoáy nghịch hình thành trong mùa gió Tây Nam.

**Từ khóa:** Thủy triều, dòng chảy, mô hình phi tuyến ba chiều (3D), xoáy thuận, xoáy nghịch, vịnh Bắc Bộ.