CHARACTERIZING THE SEA-SURFACE CIRCULATION IN THE GULF OF TONKIN BY USING NUMERICAL MODEL AND HF RADAR DATA

Kim-Cuong Nguyen[1], Manh-Cuong Tran[2], Akihiko Morimoto[3]

[1]Department of Marine Science and Technology, VNU University of Science, Vietnam
[2]Centre for Oceanography, Vietnam Administration of Sea and Islands.
[3]Center for Marine Environmental Studies (CMES), Ehime University, Japan.

I. INTRODUCTION

The Gulf of Tonkin, which locates in the north-west of South China Sea, is enclosed by North Vietnamese coast in the west, the Chinese coast to the north and Leizhou peninsula and Hainan island in the east. The gulf extends from 105°36'E to 109°55'E and from 17°N to 21°52'N. Tonkin gulf is quite shallow, the water depth ranges mostly from 40 – 70m and the deep water locates in the south of the gulf, which also is the main entry for water interactions between Tonkin gulf and the South China Sea.

Although having numerous studies conducted by numerical model, the circulation in Tonkin gulf remains controversial due to the lack of observational data over the entire domain. In the previous LaMer collaboration project "Sea-surface current features in the Gulf of Tonkin observed from altimetry satellite and High-Frequency Radars" (June 2017), we have successfully applied the methods and technique of combining HF Radar data and satellite altimetry data in analyzing the surface circulation in Tonkin Gulf. The positive outcomes of the mini-project have revealed the inter-annual and seasonal variations of the surface current in this region (Figure 1). Although data collected from High-Frequency Radars and satellites are reliable with high resolution of both spatial and temporal, the characteristics of sea-surface current in the Tonkin Gulf are investigated and described for a relatively limited area. The reason for the limitation of the results is the lack of drifter buoys data and the spatial coverage of HF Radar in Tonkin Gulf (Figure 2). The study of the sea-surface current in the entire Gulf of Tonkin is necessary to not only characterize the sea-surface circulation but also serve other environmental research. The purpose of this study is that we continue to investigate the ocean hydrodynamics of the Tonkin Gulf by taking advantage of the state-of-the-art numerical model by ROMS and the continuous monitoring of High Frequency radar system in Vietnam.

Surface current in Summer | Surface current in Winter

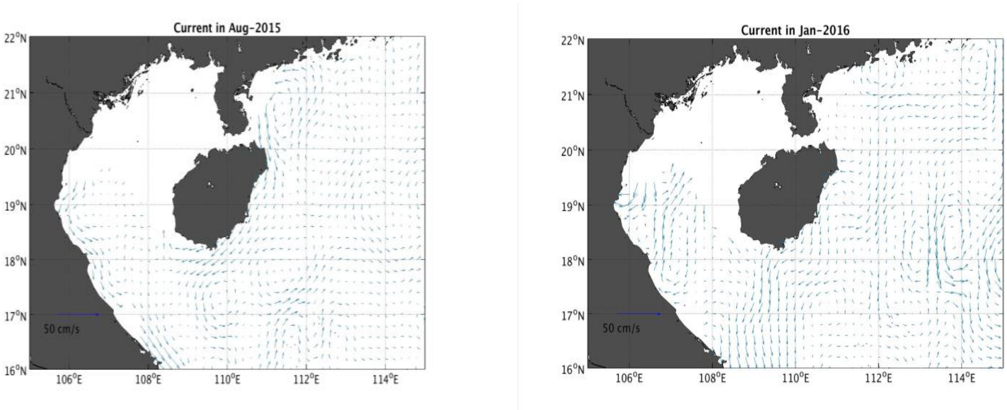
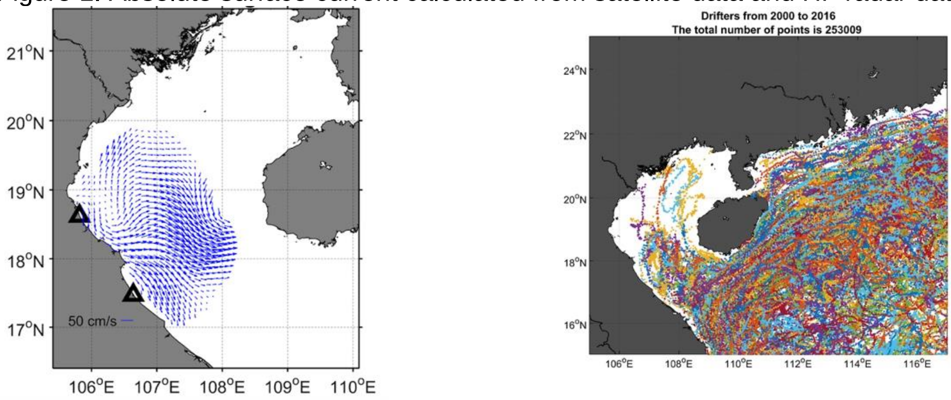


Figure 1. Absolute surface current calculated from satellite data and HF radar data



(a) (b)

Figure 2. The HF Radar coverage (a) and the Drifter Buoys (b)

II. METHODS

2.1. *Regional Ocean Modeling System*

The ROMS (Regional Ocean Modeling System) model (Rutgers version) is a new generation ocean circulation calculation model built to simulate regional dynamic processes. The ROMS model was built based on SPEM and SCRUMS hydraulic models, but was completely rewritten by Sasha Shchepetkin, Hernan Arango and John Warner, and is a ROMS platform community model built with contributions of many other scientists in the world. The model was developed based on a finite and numerical mesh-based finite element method of the Reynolds average Navier-Stokes equations for 2 or 3-dimensional uncompressed fluids combined with the Boussinesq hypothesis and assumption of hydrostatic pressure. Therefore, the model includes equations: continuous equations, momentum conservation equations, propagation equations, material diffusion, material conservation equations, state equations and they are closed by the tangled diagrams. For a three-dimensional case, the transient surface is also calculated using the approximation to convert the sigma coordinate system. The model is written in Fortran code and runs on UNIX operating systems, so the model is capable of parallel computing with MPI or OpenMP libraries. Input files use standard NetCDF format (Hedström, 2009).

2.2. *Verification Method*

In order to verify the quality of the model results, we used statistical indicators as below:

a. Mean errors

$$ME(Bias) = \frac{\sum_{i=1}^{n} F_i - O_i}{n} \qquad (1)$$

b. Mean absolute errors:

$$MAE = \frac{\sum_{i=1}^{n} |F_i - O_i|}{n} \qquad (2)$$

c. Root mean square errors:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (F_i - O_i)^2}{n}} \qquad (3)$$

In which, F_i is the model results, O_i is the observed data and n is the length of records.

d. Nash – Sutcliffe indicators (1970) for assessment of model accuracy compare to observation data:

$$F^2 = \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2 - \sum_{i=1}^{n}\left(X_i^{'} - X_i\right)^2}{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2} \qquad (4)$$

In which:

F^2 : Nash – Sutcliffe indicator

n : length of the record

X_i : Observation data

$X_i^{'}$: Model results

$\bar{X}$: Average of Observed data

Table 1: The quality of simulation results based on Nash – Sutcliffe indicator

F^2	0.9-1	0.7 - 0.9	0.5 – 0.7	0.3 - 0.5
Simulation Quality	Very Good	Good	Average	Below Average

III. DATA FOR MODEL VERIFICATION

3.1. *Tide Gauges*

In this study, we collected the water level data from 17 stations along the coast of Vietnam and compare this data with the model results. The data are collected during the survey in Vietnam in 2011 and 2012. The position of tidal stations is indicated as green pins in Figure 3.

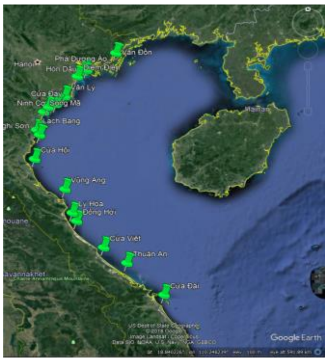


Figure 3. The position of tidal stations for mode validation

3.2. Altimetry data

The tidal gauge measurement, although provided continuous data record with sufficient accuracy, has some limitations. The first is due to its position which is limited to the coastal location. The data collected was strongly influent by local and shallow water dynamics (Minh et al., 2014). The second limit is the difficulty to collect the data in the open sea, which is also important to verify the model. Therefore, in the open ocean we used the altimetry data to compare with the model results. The satellite provides a global coverage of tidal elevation and the four main tidal harmonic constants (M2, S2, K1, O1) can also be estimated from this data with an accuracy few centimeters (Minh et al., 2014). The altimetry data we in this study is collected from the Centre for Topographic studies of Ocean and Hydrosphere (CTOH/LEGOS, France) server. The tidal harmonic constants were extracted and analyzed by X-TRACK toolbox which is developed by CTOH.

3.3. High Frequency Radar surface current data

Three long-range HF radar observation systems have been established along the coast of Vietnam in western of Tonkin gulf since 2011. All three stations operate at 4.65 MHz with horizontal resolution of 5.825 km and azimuthal resolution of and 5^{o}.

The High Frequency radar measures the sea surface velocity component in the direction toward the radar, using the Doppler frequency shift of the radio wave backscattered by ocean surface wind waves, so that at least two radars are normally used to construct a total vector from each site's radial components. At the central data combining station, the radial vector maps from multiple radar stations are merged to create a total velocity vector current map.

IV. RESULTS

4.1. *Model Setup*

4.1.1. Grid Generation

The domain of Tonkin gulf is defined from 105ºE to 116ºE and from 14ºN to 22ºN. We used SEAGRID toolbox for creating the grids. SEAGRID is an old toolbox written in MATLAB for generating grids in oceanography numerical model. It is able to generate the rectangular or the curved orthogonal grid and also calculate the land masking of the grid.

For the grid of Tonkin Gulf, we set up the grid as follows:

- Grid Resolution: 2.3 km
- Vertical layers: 40 Sigma layers
- Maximum depth is 5,000m, minimum depth is 10m.
- Bathymetry data:
  - o For the deep water: SRTM30+ with the resolution of 1km retrieved from http://topex.ucsd.edu/WWW_html/srtm30_plus.html.
  - o For the coastal zone: Vietnam Navy nautical charts from various sources: minimum resolution of 50m.

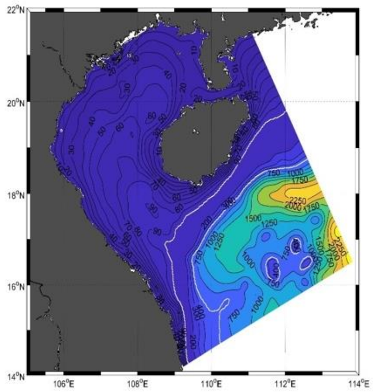


Figure 4. Interpolated bathymetry of Grid of Tonkin

4.1.2. Initial and Boundary Conditions

- For the surface boundary forcing: Meteorological data is collected from European center for Medium-range Weather Forecasts (ECMWF) with a timestep of 3-hours: 10 m wind speed, temperature, humidity, heat flux, solar radiation. Horizontal resolution is 0.125 degrees.

- For the fresh input: Monthly average river discharge data was collected from various sources from 2006 to 2012, data up to the present time are repeated on the existing data series.

- For the lateral boundary forcing:

  - o Tidal conditions are collected from the global tidal harmonic constants TPXO;
  - o Daily Temperature and Salinity are collected from the global HYCOM model.

4.2. Model Validation

4.2.1. Tidal Gauges comparisons

In this part we compare the water level collected from the tidal station and the results from the model. The results are shown in Table 2 and Figures 5-6. In most case, the model results are well agreed with the observation data. In the northern part of Vietnam, most of the Nash-Sutcliffe indicator shows good value (> 0.96). It is decreases in the middle of the gulf (about 0.79 to 0.85). The absolute difference between model and observation are about 4 - 5 cm in the north and increases to 8 – 11 cm in the middle of the gulf.

Table 2: Comparison of tidal gauges and model results

Stations	ME (cm)	MAE (cm)	RMSE (cm)	Nash – Sutcliffe	Stations	ME (cm)	MAE (cm)	RMSE (cm)	Nash – Sutcliffe

Vân Đồn	-0.07	6.30	8.50	0.95	Lạch Bạng	-0.23	8.94	11.34	0.85
Hòn Dấu	-0.05	4.45	6.52	0.96	Nghi Sơn	-0.31	11.26	13.46	0.80
Phà Dương Áo	-0.07	4.96	6.48	0.91	Cửa Hội	-0.27	10.26	13.35	0.80
Diêm Điền	-0.08	5.01	6.68	0.92	Vũng Áng	-0.27	11.79	14.37	0.83
Văn Lý	-0.07	4.54	7.12	0.91	Lý Hòa	0.04	10.62	14.33	0.79
Ninh Cơ	-0.10	5.85	7.78	0.93	Đồng Hới	0.04	8.45	11.24	0.76
Cửa Đáy	-0.05	6.75	8.13	0.96	Cửa Việt	0.05	5.94	7.53	0.84
Sông Mã	-0.09	6.78	8.76	0.96	Thuận An	0.00	4.11	5.18	0.96
					Cửa Đại	-0.08	5.29	6.50	0.90

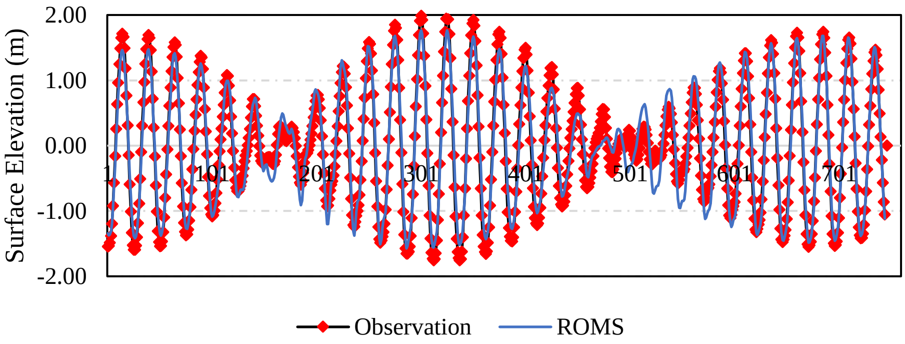


Figure 5. Comparison of tidal gauges and Model results at Vân Đồn station from Oct 18, 2011 to Nov 18, 2011

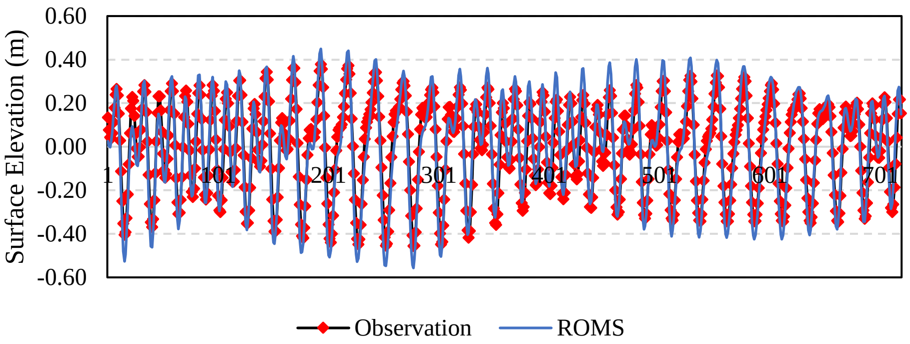


Figure 6. *Comparison of tidal gauges and Model results at Cửa Đại station from Sep 14, 2012 to Oct 13, 2012*

4.2.2. Altimetry Satellite Harmonic Constants comparisons

To compare mode to results with observation, we applied a harmonic analysis by MATLAB toolbox which is called T_tide software. The T_tide toolbox is written by Rich Palowiz and utilizes the least square fit method for decomposing tidal signal from a record of water level time series. The model results of 1-year are used for harmonic analysis in order to well distinguish between K_2 and S_2 frequency.

The difference between the model and altimetry data are represented in Figure 7 and Figure 8 along the satellite track for 4 main constituents K1, O1, M2, S2. The comparison shows that in the deep water the model agrees well with altimeter data. The errors for the depth > 80m are less than [2cm, 4^o] for K1 and O1; less than [4cm, 6^o] for M2 and S2. This means the tidal open-boundary are properly set in the model. The errors increase when getting into the shallower water. In the offshore region of Tonkin Gulf, the errors are about [3-4 cm, 4^o] for K1 and O1; [6 - 8cm, 8 – 10^o] for M2 and S2. There are higher error values exists at the eastern Hainan Strait and to the north of the gulf. The increase of the error in the model is could be either the erroneous in altimeter data in the coastal zone or the model coastal bathymetry which is not completely accurate. There are higher errors along the coastal of China than in Vietnam which we don't have any better bathymetric data. Also note that insufficient model resolution could be another cause of the error (Minh et al., 2014).

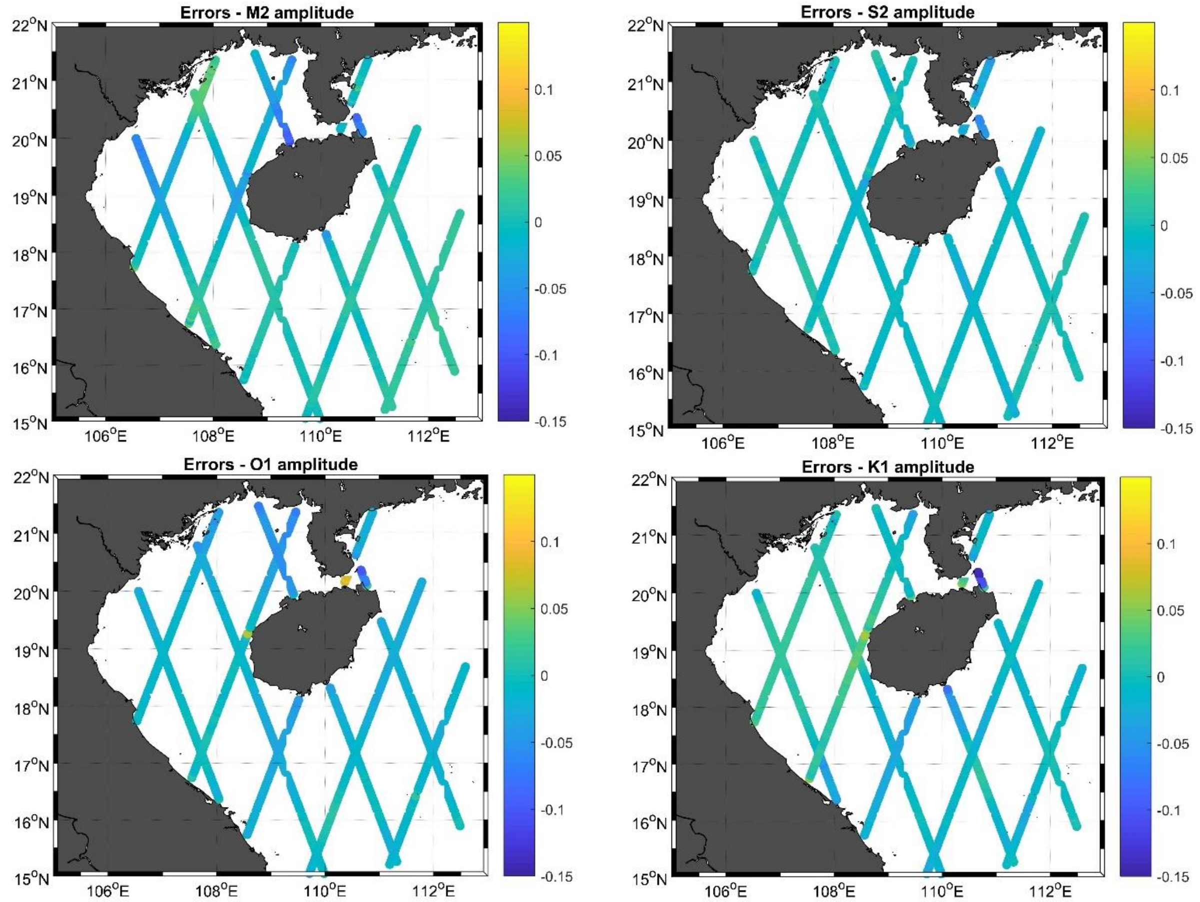


Figure 7. Tidal amplitude errors in meters

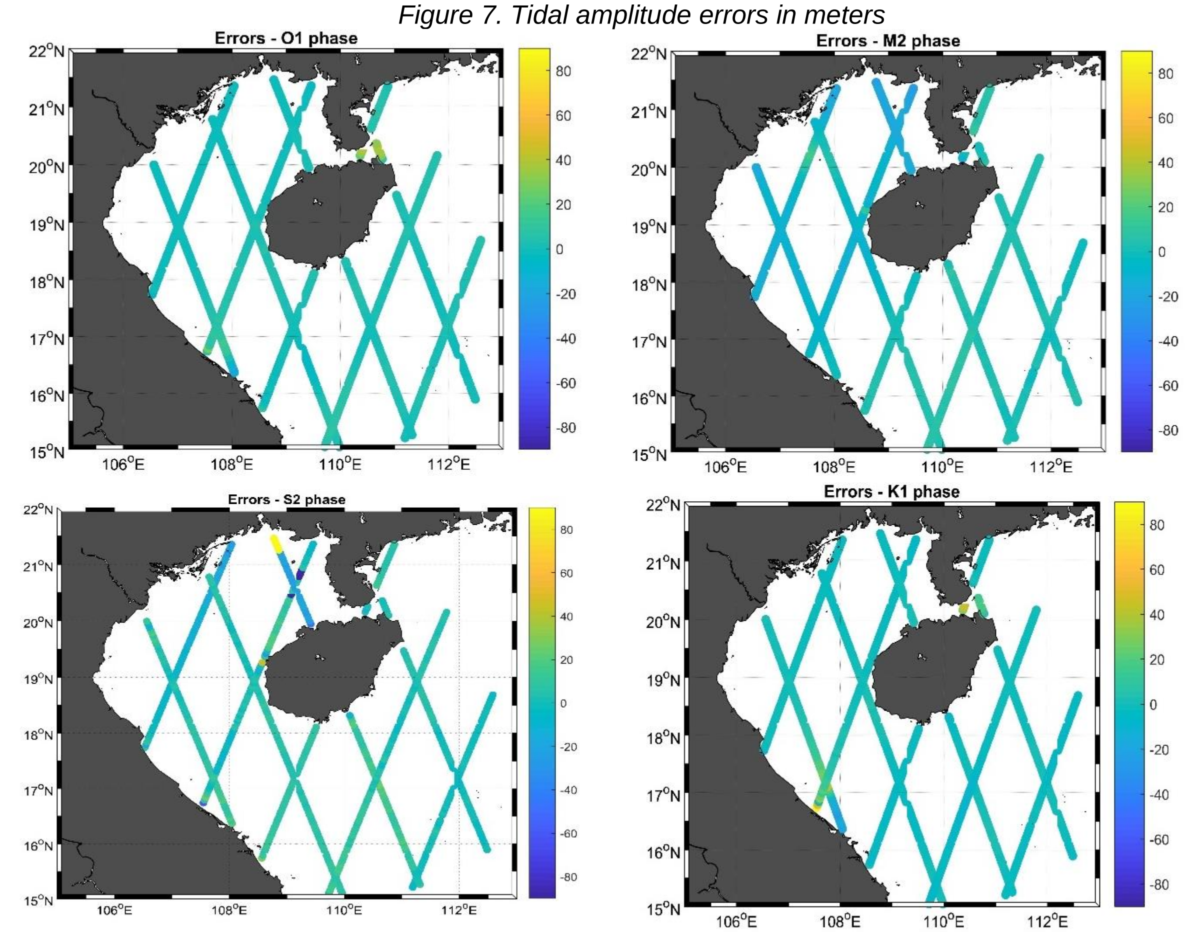


Figure 8. Tidal phase errors in degrees

4.2.3. Ocean current comparisons

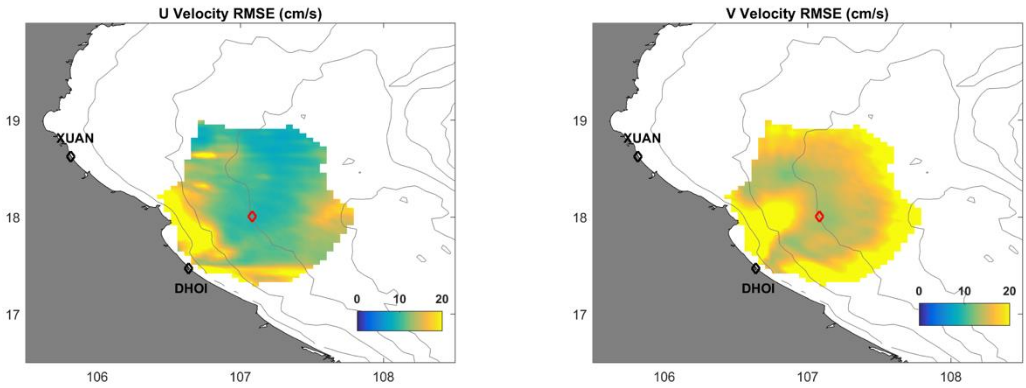


Figure 9. Comparison of sea surface current between model and HF radar from Dec 01, 2014 to Dec 31, 2014

In this part, we collected the surface current data from HF radar systems and compare with the results of the model (Figure 9). We extracted the region of HR radar data which covers more than 90 percent of data return for this comparison. The results show that the model and the current data are well agreed in the offshore region (Figure 10). The mean differences between model and HF radar data are 9.1 cm/s for u component and 12.4 cm/s for v component. Also note that there is higher error in the coastal region near DHOI site. The erroneous of the HF current data in this region caused by the baseline of DHOI-XUAN sites, in which the angle between radial beams are nearly parallel to each other (Kim et al., 2014).

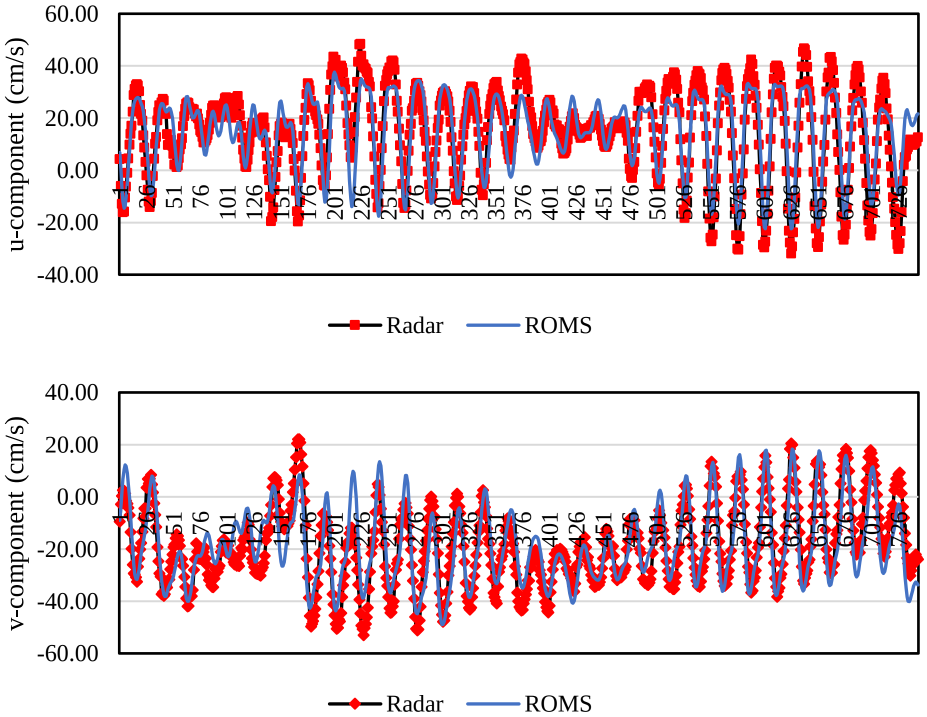


Figure 10. Comparison of sea surface current between Model and HF radar at position (107ºE, 18ºN) from Dec 01, 2014 to Dec 31, 2014

4.3. Surface circulation of Gulf of Tonkin

We ran the model from June 5, 2012 to November 15, 2014, then calculated and analyzed the average monthly flow in the Gulf of Tonkin.

In the winter months: December, January and February, the monthly mean surface of the Gulf of Tonkin has the following points: the southern flow of Hainan Island along the shore. The water in the western part of the island goes into the gulf then goes up to the north in combination with a small amount going from the Quynh Chau Strait to the east of the Vietnamese coast, this circulation follows the topography of the North Gulf coastline then goes to the south. During these months, the central area of the bay has a vortex with an average speed of about 10-15 cm/s. The sea area south of Thanh Hoa and northern Quang Binh has a higher speed of 25-30 cm/s. Northern part of the gulf exists a small scale with diameter of about 50 - 70 km with an average speed of about 5-8 cm/s.

In the spring months (March, April and May), the average circulation structure of the surface of the Tonkin Gulf has a small change compared to the winter time. At the centre of the gulf, a cyclonic eddy exists with the amount of water flowing through the mouth of the bay from the west side of Hainan Island with an average speed of about 8 - 12 cm, the flow of the sea area south of Thanh Hoa and northern Quang Binh still maintain a high speed, reaching 18-25 cm/s. The northern eddy of the gulf tends to widen and shift southward but in May the eddy is broken.

The summer months of the circulation of the Gulf of Tonkin have a big change. In June, the area between the Gulf of Tonkin formed a reverse circulation. The velocity of this circulation is not large, averaging about 8-12 cm/s. The north part of the gulf has a small-scale eddy. This circulation exists until the end of August. In overall, the current pattern in summer seems to be more stable than other seasons

For the autumn months (September, October and November), the cyclonic circulation in the area between the Gulf of Tonkin is reset. The average velocity of this circulation is quite large, about 15-20 cm, in which the southern waters of Thanh Hoa and northern Quang Binh have average surface velocities of 30-40 cm/s with points up to 45 cm/s. The north of the gulf always has two small-sized eddies, swirling at the top of the bay and swirling underneath it. The scale of these two vortices is about 70-90 km with an average speed of about 8-10 cm/s (Figure 11).

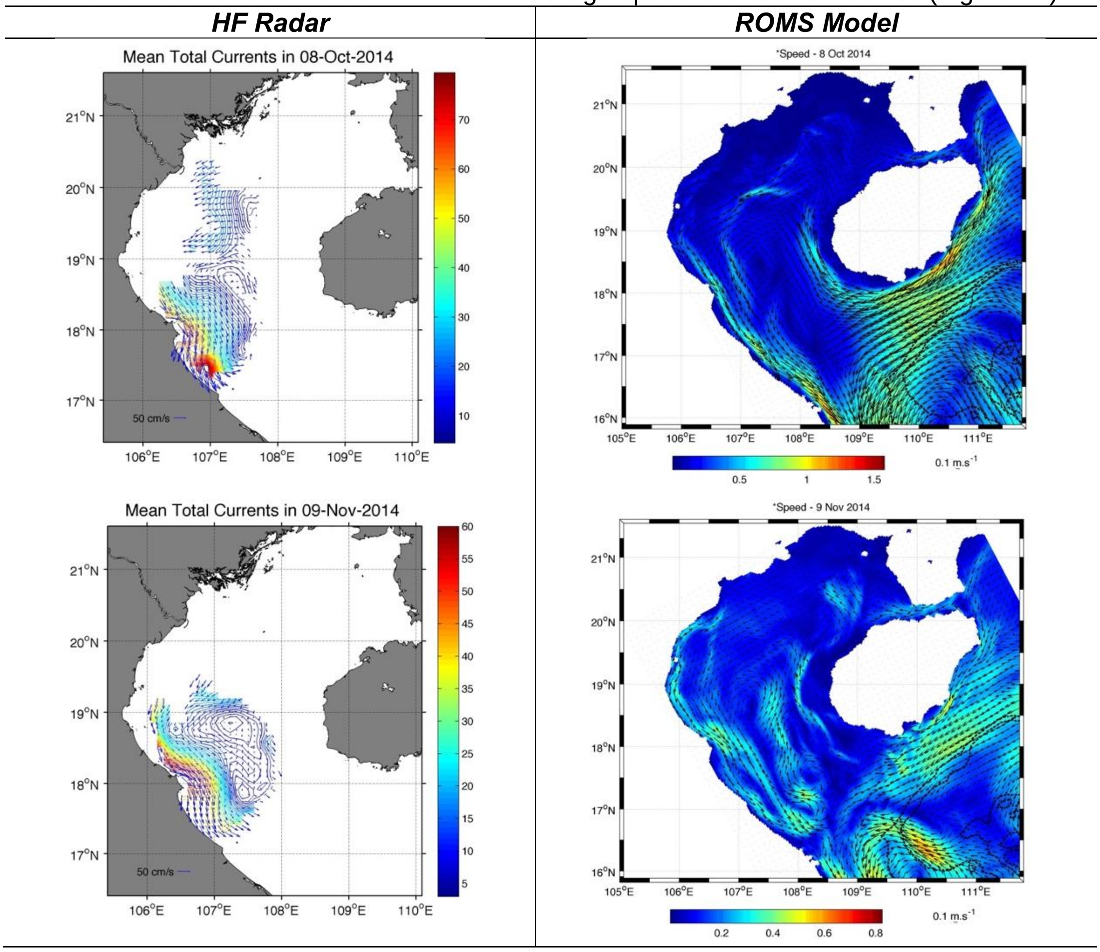


Figure 11. HF Radar current and Model results

V. SUMMARY AND DISCUSSIONS

The surface seasonal circulation is shown to have similarities with previous research results. However, according to the results of this analysis, some small circulation above the Gulf of Tonkin operates in a seasonal cycle, which is shown quite clearly. In summary, ROMS model performed very well to simulate the Tonkin gulf dynamic. The differences between the model and observation are quite acceptable and the model is able to simulate the Tonkin gulf hydrodynamic features. However, the works we did above is just limited to the hydrodynamic comparison, the temperature and salinity comparison are not considered. In the next step, we keep continue the works to compare both features with observation data.

REFERENCES

1. Y. Ding, C. Chen, R. C. Beardsley, X. Bao, M. Shi, Y. Zhang, Z. Lai, R. Li, H. Lin và N. T. Viet (2013). Observational and model studies of the circulation in the Gulf of Tonkin, South China Sea, Journal of Geophysical Research - Ocean, VOL. 118, pp. 1–16.

2. B. M. Emery, L. Washburn và J. A. Harlan (2004). Evaluating Radial Current Measurements from CODAR High-Frequency Radars with Moored Current Meters, Vol. 21, pp. 1259-1271.

3. K. S. Hedström, Technical Manual for a Coupled Sea-Ice/Ocean Circulation Model (Version 3) (2009). Anchorage, Alaska: U.S. Department of the Interior Minerals Management Service Anchorage.
4. K. C. Kim (2014). Calibration and Validation of high frequency radar for ocean surface current mapping, Master thesis, Naval Graduate School, Monterey, California, 2014.
5. N. N. Minh (2013). Tidal characteristics of the Gulf of Tonkin, PhD thesis, Toulouse University.
6. Skarke, B. L. Lipphardt Jr., P. Muscarella, K. C. Wong, A. Trembanis, M. Badiey (2008). Comparison of HF Radar and ADCP Surface Currents at the Delaware Bay Mouth, Proceedings of the IEE/EOES/ CMTC Ninth Working Conference on Current Measurement Technofogy, pp.189-193.