MINISTRY OF NATURAL RESOURCES AND ENVIRONMENT

VIET NAM INSTITUTE OF METEOROLOGY, HYDROLOGY AND CLIMATE CHANGE

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RESEARCH ON CURRENTS IN TONKIN GULF BY USING DATA ASSIMILATED FROM HF RADAR AND NUMERICAL MODEL

Majors: OCEANOGRAPHY
Code: 9440228

SUMMARY OF OCEANOGRAPHY DOCTOR THESIS

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Thesis was completed at:

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Thesis will be defended in front of Institutional Thesis Judging Committee at: Viet Nam Institute of Meteorology, Hydrology and Climate Change

At on ……. …, 2022

Thesis can be found at:

- Library of Institute of Meteorology, Hydrology and Climate Change

PREFACE

1. Urgency of the topic

To study the flow in Gulf of Tonkin, there have been many scientific studies conducted since the 60s such as the cooperated programs between Viet Nam and China or programs between Viet Nam and Soviet Union in the 90s or Viet Nam's programs then. To achieve assessment on characteristics of currents in Tonkin gulf, many previous studies usually based on two main approaches. Firstly, using observed data from surveys to evaluate the characteristics of the flow, however, there requires a large amount of money, the data is fragmentary, inconsistent temporally and limited in addition. Secondly, applying numerical models to calculate and simulate 2-dimensional and 3-dimensional flow-fields to examine current circulation and structures of temperature and salinity structures for the domain. For latter method, there will illustrate overall features of currents 2-D or 3-D fields for higher resolution and long-term. However, there is a limitation that this method comprise some certain errors depending on the inputs as well as the parameterization in model.

In the calculation processes, especially the simulation and analysis of dynamics in the world by using data assimilation method which has yielded positive results. Besides that Viet Nam currently is operating the marine radar system including of 03 HF marine radar monitoring stations along the Gulf of Tonkin since 2011. The marine radar system is collecting the data with frequency of 1 hour per observation. The largest monitoring range is up to 300 km with a spatial grid of 5.825 km and transmission frequency of 4.65 Mhz. The monitoring data from this marine Radar system are displayed for 2-dimension current and waves within the radar's operating range and is automatically and continuously updated to the central station via internet connection. On the other hand, there has not been any research on the flow field by using data assimilation and numerical modeling in Bien Dong sea and in Tonkin. Stemming from the above reasons, thesis **“Research on currents in tonkin gulf by using data assimilated from hf radar and numerical model”** would contribute its scientific and practical necessary to academy as well as reality. The objectives of this study are:

- Applying the technique of assimilating the observed flow from marine radar to ROMS model;
- Analyze the flow regimes in the Gulf of Tonkin on the basis of monitoring data from marine radar and assimilate into ROMS model.

3. Research contents

- Overview on current studies in the Tonkin gulf, studies related to data assimilation methods;
- Collect, analyze and evaluate relevant documents: current monitoring data by marine HF radar system; monitoring data of surface sea temperature, sea surface level analyzed from satellite images; topographic data, shoreline; meteorology, oceanographic data and documents related to the topic of this study;
- Research and apply assimilation techniques to assimilate current monitoring data from the `Marine HF Radar' system, monitoring data of surface seawater temperature, analyzed sea surface level from satellite images to insert into ROMS model;
- Simulate 3D flow field by ROMS model using assimilation of flow monitoring data from marine HF radar system, monitoring data of surface sea temperature, sea surface level analyzed from satellite images.
- Evaluate the current field in the Gulf of Tonkin based on analysis and simulation results from re-analyzed data of ROMS model and remote sensing data.

4. Object and scope of research

*- **Spatial scope:*** domain in Tonkin gulf.

*- **Research object:*** current field in Tonkin gulf based on marine HF radar data assimilated in ROMS model

5. Research Methods

To achieve the research objectives and content, the thesis has used a combination of modern research methods, including:

- Numerical modeling method;
- Data assimilation method;
- Statistical analysis methods.

6. Scientific and practical conribution

- Scientific contribution: Application of current data assimilation technique for Vietnam marine HF radar system.

- Practical significance: Improve efficiency in exploiting and using monitoring current data from marine HR radar. The re-analysis data of currents is of significant contribution to study of hydrodynamic characteristics in Tonkin gulf for socio-economic development, national defense and security and natural disaster prevention and control marine environment protection.

7. Thesis defense

- *Thesis 1:* The reanalytical data of current in Tonkin gulf with more reliable when applying the 4D-Var assimilation technique and the ROMS model for Vietnam marine HF radar data.

- *Thesis 2*: The re-analyzed data of the flow field from the numerical model after assimilation of current monitoring data by marine HF radar which will give a more detailed and objective assessment on characteristics of 3D-current field in Tonkin gulf

8. The state of the art of thesis

- Using 4D-Var assimilation technique and ROMS model to improve the efficiency of using Vietnam HF marine radar data and enhance the reliability of the results of re-analyzed current data in the Gulf of Tonkin.

- Evaluated detailedly the spatial characteristics of monthly mean 3D reanalyzed flow field in Tonkin gulf.

9. Dissertation layout

In addition to the prologue; Conclusions and recommendations; References, the thesis includes 3 chapters:

Chapter 1. Overview of research related to currents and data assimilation.

Chapter 2. Methods, implementation procedures and data

Chapter 3. Study on current in Tonkin gulf by using marine HF radar data assimilated in ROMS model.

Chapter 1. Overview of research on data current and assimilation

1.1. Overview of studies on data assimilation

1.1.1.Studies all over the world

There are many studies on data assimilation all over the world, including the use of current monitoring data from marine radar systems that are of interest to many scientists when applying 3D-Var, 4D-Var assimilation schemes and Kalman filters in combination with POM and ROMS modelings to re-analyze oceanographic factors for marine areas. Some works have been applied in practice in forecasting and monitoring the sea current field.

1.1.2.Local studies

Domestic data assimilation is still limited, the main reason is that the monitoring system has not been properly invested. There are several studies focusing on the application of 3D-Var assimilation scheme or optimum filtration method in meteorological problems and using Kalman's data assimilation scheme in combination with SWAN modeling in wave forecasting.

1.2.Overview of current studies on the Gulf of Tonkin

1.2.1. On the world

Some authors have deeply studied the current field of the Gulf of Tonkin, mainly using mathematical modeling methods to simulate and evaluate the seasonal current field characteristics of the year.

1.2.2. In Vietnam

Since the 1960s, there have been many research projects on the circulation of the Gulf of Tonkin through general surveying trips. In recent years, there have been many studies on the current field of the Gulf of Tonkin using 2-D and 3-D mathematical modelings. However, there have been no studies that combine numerical modeling and use data assimilation method to evaluate the current field in the Gulf of Tonkin.

1.2. Introduction of marine radar system in Vietnam

The Marine Radar System consists of 4 stations, including: 2 coastal stations, 1 station in island, and 1 central operating station. Currently, the operating range of this Radar system allows the collection of surface current field data from Thanh Hoa to Quang Tri, the largest range of about 250 to 300 km. With the data of the current field observed every 1 hour, even in adverse weather conditions, it will be an extremely precious valuable source of data for many related fields.

Summary of Chapter 1

In Chapter 1, the thesis has reviewed domestic and international studies on the application of data assimilation techniques in flow simulation using numerical models and studies of flows in the Gulf of Tonkin region with the following main conclusions:

The study of using data assimilation techniques into numerical models to simulate the current has attracted the attention of the scientific community and has been studied for a long time in the world.

The main research directions include: 1) Develop techniques to assimilate data (3D-Var, 4D-Var,...) in numerical models; 2) Apply data assimilation techniques with different types of data (measurement data, remote sensing data,...) in simulation and forecasting problems of the current field. The researchers of scientists in the world all share the opinion on the effectiveness of synchronizing data combined with the numerical modeling with results that are more suitable and observable than the reality than the data only simulated by the numerical value model.

In Vietnam in general and in the Gulf of Tonkin in particular, there have also been many simulation and forecasting studies on current that have scientific and practical significance in analyzing and evaluating the surface current field according to the characteristic seasons as well as current structure in deep layers. In addition, there have been a number of studies using assimilation techniques in simulation and meteorological forecasting problems and some oceanographic factors such as waves, sea water temperature.

In addition, with the sea radar system in this area, there has been a large dataset with quite a thick frequency (1 hour/time from 2011 to now), but has not been exploited and applied effectively. On the other hand, there has not been any research on the current field using data assimilation and numerical modeling in the East Sea area in general and the Gulf of Tonkin in particular. Therefore, the study of the Gulf of Tonkin current field using observational data from the marine radar system and assimilation in numerical model is of scientific and practical importance.

Chapter 2. Methods, implementation process and usage data

2.1. Methods of use

2.1.1 Data assimilation method

In this study, the thesis applies a 4-dimensional variable assimilation scheme combined with ROMS model to perform re-analysis of the Gulf of Tonkin current field. In the 4D var diagram, use the R-4DVAR method to process the calculation.

2.1.2 Mathematical modeling methods

ROMS is a regional ocean circulation model built on the Boussinesq hydrostatic approximation system. The model is built with orthogonal curvilinear coordinates and the vertical sigma grid allows to increase the horizontal and vertical resolution in shallow water areas, areas with coastlines and complex topography. Due to the special features in solving momentum and diffusion equations as well as the choice of parameterization for solving horizontal and vertical perturbation problems, although the ROMS model is built for hydrodynamic simulation problems in coastal areas, it is also well applied in deep waters, basin and global scale.

2.1.3. Statistical analysis method

The statistical analysis method is used to calculate the average monthly current. The average monthly current is calculated as follows:

Split the current into its meridian and latitudinal components at each grid point and each time step. Calculate the average of each velocity component in the longitude and latitude directions for each month. Take the average of the sum of the latitude and longitude components of the velocity. Aggregate the velocity of the two velocity components in the meridian and latitude directions to obtain the current velocity and current direction values for each grid point.

2.2. The current field calculation procedure using marine radar data assimilated in the numerical model

The research process of the thesis consists of 4 main steps as follows:

1) Collect data for research work

2) Application of 4D-Var data assimilation diagram combined with

ROMS model to re-analyze the current field in the Gulf of Tonkin

3) Re-analysis of the 3-D current field in the Gulf of Tonkin:

4) Analyze the current field characteristics of the Gulf of Tonkin.

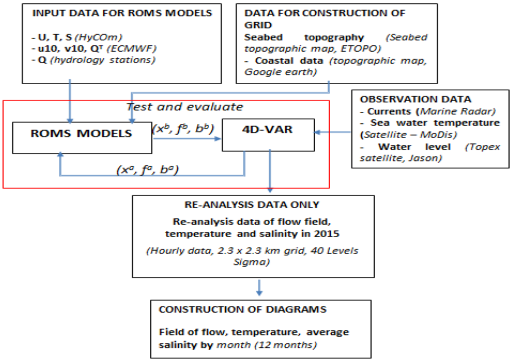


Figure 2. 2. The current field calculation procedure using marine radar data assimilated in the numerical model

2.3. Usage data

2.3.1. Terrain data

Data for the entire East Sea and its vicinity are collected from NOAA's ETOPO data source with a resolution of 1 x 1 minute. The Gulf of Tonkin and coastal areas of Vietnam are compiled from topographic maps of the seabed, including: 117 pieces of maps scale 1:50,000, 143 pieces of maps scale 1:5,000 published by the Department of Survey, Mapping and Geographic Information of Vietnam. The area off the East Sea and its vicinity was collected from the ETOPO1 model with a resolution of 1 minutes x 1 minutes, equivalent to 1.8 km x 1.8 km.

2.3.2. Meteorological, hydrological, oceanography data

a. Meteorological data: 10 meter floor wind speed; surface heat flux; solar radiation.

b. Hydrological data: average monthly river water discharge is collected at hydrological stations of 4 main rivers including: Da Bach and Cam River; Van Uc River; Thai Binh River; Hong river.

c. Oceanography data: Surface current monitoring data from marine radar system; Current, heat-salt data from the HyCom model; Current measurement data by ADCP, temperature and salinity by CTD equipment; Surface seawater temperature data are analyzed from Modis images; Sea level data is the product of the Jason satellite, Envisat.

2.4.1. Building the domain, the grid

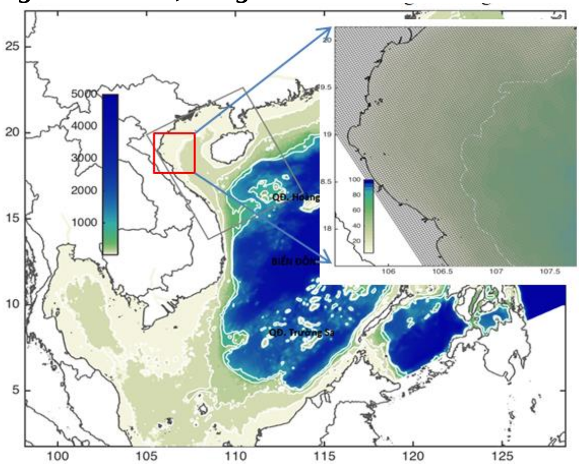


Figure 2.14. Calculation domain for the whole East Sea and details for the Gulf of Tonkin waters

The calculated grid is built as a horizontal square grid consisting of 2 grids, the grid for the entire East Sea has a horizontal resolution of 7 km x 7 km. The detailed nested grid for the Gulf of Tonkin region has a horizontal resolution of 2.3 km x 2.3 km. The grid is divided into 40 layers according to sigma.

2.4.2. Building the input data

a. Boundary condition data: including surface boundary, flexible boundary by the sea and flexible boundary in the river built from the collection source in section 2.3.2

b. Data for data assimilation software includes: Hourly surface current velocity data from marine Radar system; Surface sea water temperature data analyzed from satellite images; Jason-2 satellite sea level elevation data.

c. Data used for evaluation and comparison: Surface sea water temperature data are obtained from NODC/UKMO database; Water level data at coastal tidal stations; Current monitoring data by ADCP equipment in Nghi Xuan sea area.

Summary of Chapter 2

In chapter 2, the thesis has proposed research diagram and process, proposed methods and data with the following main conclusions:

There are many hydrodynamic simulation models that have been using. However, the open source ROMS modeling has advantages in small and medium scale marine hydrodynamic simulations, suitable for the problem of applying data assimilation techniques and has been widely applied in selected recent studies.

There are different techniques and methods in data assimilation. The 4D-Var assimilation technique with the R4D-Var method with its advantages have been analyzed and evaluated from previous studies selected in the assimilation of current data from marine Radar into the ROMS model.

The data used in the thesis include: 1) Data on topography, meteorological and hydrographic conditions serving the problem of setting up and testing numerical models; 2) Current monitoring data from marine radar, sea surface temperature data and water level from satellites for data assimilation. The data used in the thesis has clear origin and high reliability.

Chapter 3. Studying the Gulf of Tonkin current field using marine radar data assimilated in the ROMS model

3.1. Evaluation of the ROMS Modeling

3.1.1. Comparison between simulation by ROMS modeling and monitoring data by sea radar

From the visual comparison of the simulation results by the model with the monitoring data by the marine Radar system, it is shown that the matching of the phase and the value of the component velocity as well as the current rate value of the calculation and monitoring data is quite good. The average error between calculated data and radar data ranges from -0.1 to 0.25 m/s. In which, the coastal area from Nghi Xuan to Dong Hoi has the largest average error from - 0.1 to 0.1 m/s.

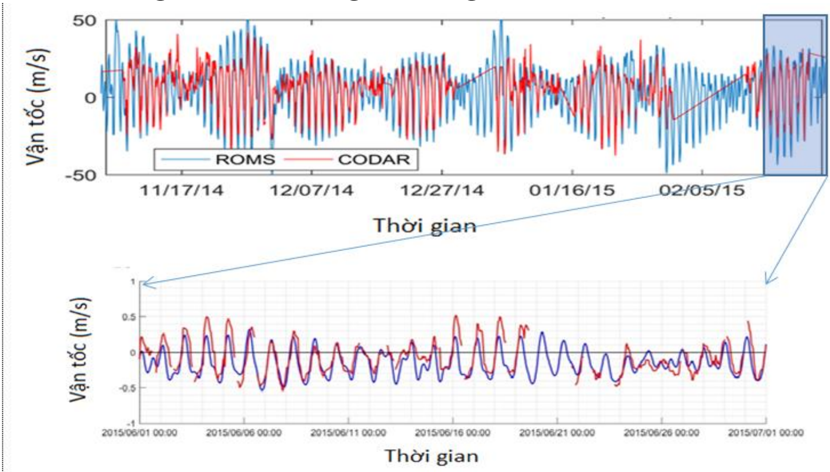


Figure 3. 4. Comparison of current velocity between simulation by model and observed data from marine radar at a point of Nghi Xuan 1 station in December 2014

3.1.2. Comparison with water level monitoring data

The calculation results show that the ROMS model simulates the water level very well in both phase and magnitude. The model captured all tidal phases even during the birth water period. In terms of tidal magnitude, the computational model gives very good accuracy during springs tides and more limited accuracy during neaps tides.

3.1.3. Comparison with ADCP measurement data

The comparison results show the matching of the direction and magnitude of the current calculated by the model and the results of direct monitoring by ADCP equipment on April 13, 2016. Regarding direction, both data sources describe the direction of surface current from north to north-northeast. However, sometimes, the data measured by ADCP equipment has a smaller current value than the simulated current value by the model at ebb tide periods.

3.1.4. Model evaluation when taking into account the effect of density current

When the river boundary conditions are included in the model, the value of the magnitude of the current in the coastal area has been improved and is close to the real data measured by ADCP equipment and marine radar system during springs tide periods. However, during the neaps tide periods, the calculated coastal current velocity tend to be larger than the measured data (Figure 3.17).

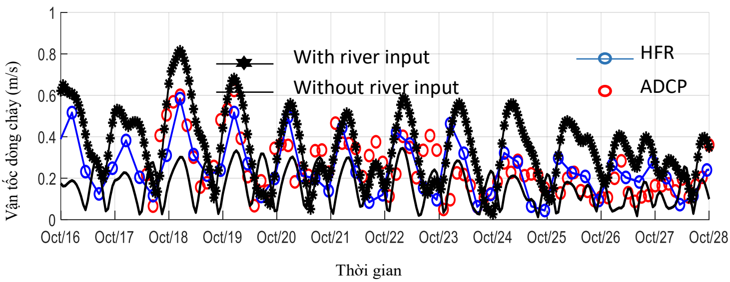


Figure 3. 17. Comparison of current velocities in the cases with and without river boundary conditions in Nghi Xuan 1 sea area

3.2. Setting up the ROMS Modeling – 4D VAR

3.2.1. The data for the data assimilation problem

Monitoring data for the assimilation problem includes hourly surface current data from the marine Radar system; data of sea temperature and sea level elevation observed from satellites. These data are described in detail in section 2.3. Chapter 2.

3.2.2. Set up the data assimilation problem

To evaluate the effect of 4D-Var assimilation on the model's calculation results, the study set up 2 tests: 1) Test 1: The ROMS modeling runs independently for 1 month with the set of surface boundary and liquid sea conditions as of October 2015; 2) Test 2: The ROMS model uses data assimilation with SST and SSH from satellite data and sea surface currents from Marine Radar data.

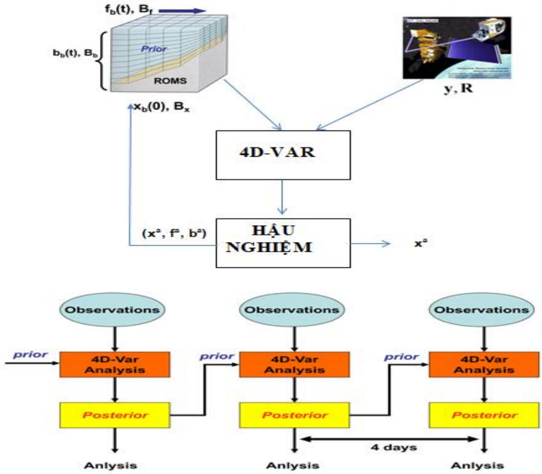


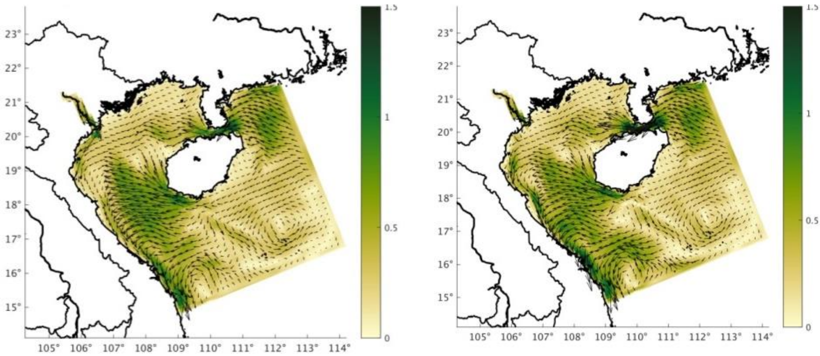
Figure 3. 21. Diagram of data assimilation process combined with numerical model

The study uses 4D-Var assimilation parameters of Moore et al (2011b) in the East Pacific Ocean to select the calculation parameters, the parameter of annual standard deviation of the variables (ξ, U, V, T, S) based on the calculation results from the model over a period of 10 years (2008 – 2018). The assimilation window selected in this study was 4 days.

3.3. Results of analysis and evaluation of the effectiveness of data assimilation

3.3.1. Evaluate the effectiveness of data assimilation

For the SST field in Test 2, after data assimilation, there is a rather strong invasion of cold water from the mouth of the Gulf of Tonkin inward with increasing temperature distribution from the mouth of the bay, areas with high temperature distinct from surrounding areas such as in the middle of the bay and to the east of Quynh Chau strait show a continuum, which is no longer as localized as in the unassociated case in Test 1.



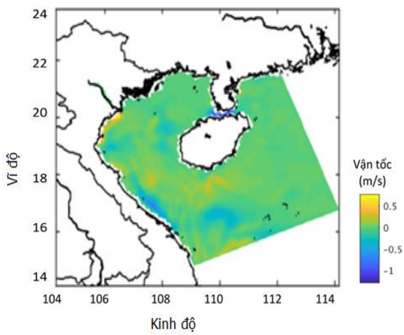
a) Not assimilated yet b) After assimilation

Figure 3. 23. Surface current field at 00 o'clock on October 11, 2015

For the surface laminar current field, the coastal area from Nghe An to Quang Binh has a large difference in current velocity. In Test 1, surface current velocities in this area ranged from 0.4 – 0.5 m/s but in Test 2, after assimilating data, current velocities in this area ranged from 0.7 – 0.9 m/s, even in coastal areas of Ky Anh and Ha Tinh, the current velocity can reach over 1 m/s. This result is consistent with the observed current field from the marine radar system shown in Figure 3.23.

3.3.2. The impact of data assimilation

After assimilating the surface velocity, there is a difference of -0.2 to +0.2 m/s, the area has a big difference in the coastal strip, especially the coastal strip from Thanh Hoa to Thua Thien Hue and the sea area in Quynh Chau Strait from -0.5 to +0.5 m/s.



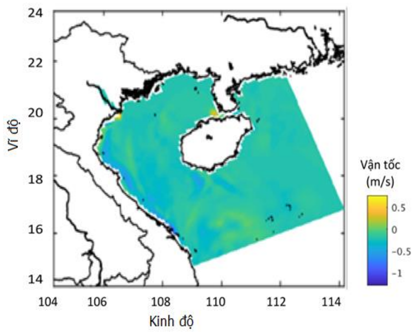
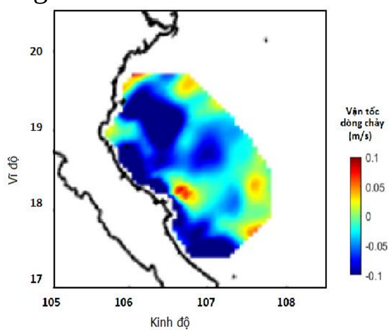


Figure 3.28. Difference of velocity component u before and after data assimilation at 00 o'clock on October 11, 2015

Figure 3.29. Difference of velocity component u before and after data assimilation at 00 o'clock on October 11, 2015

3.3.3. Error assessment after data assimilation

When not assimilated, the area with BIAS error above 0.1 m/s and below -0.1 m/s accounts for a large proportion. Areas with BIAS error above 0.1 m/s are concentrated in the coastal area from Nghe An to Quang Binh and the offshore Ha Tinh area. The area with the error below -0.1 m/s is concentrated in the offshore area from Thanh Hoa to Quang Binh. After assimilation, the areas with BIAS error above 0.1 m/s and below -0.1 m/s narrowed significantly, the average BIAS error ranged from -0.05 to +0.05 m/s.



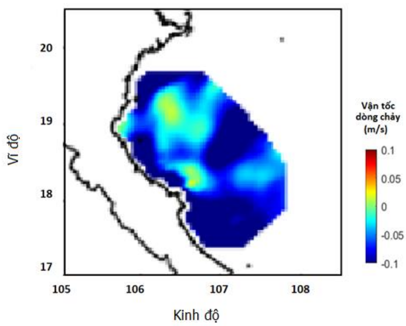


Figure 3.44. BIAS error between observed data from marine radar

Figure 3.45. BIAS error between observed data from marine radar

system and calculated data of velocity component u (m/s)Not assimilated data yet	system and calculated data of velocity component u (m/s)Not assimilated data yet

In the absence of assimilation, the area with RMSE error of over 0.2 m/s accounts for a large proportion, over 50%. After assimilation, the areas with RMSE error of 0.2 m/s were greatly reduced, especially the sea area from Nghe An to Ha Tinh, this error only fluctuates between 0.1 and 0.15 m/s (Figure 3.44, 3.45).

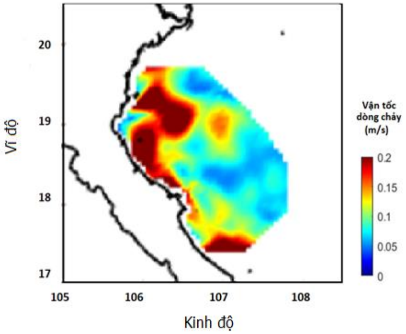


Figure 3.48. RMSE error between observed data from marine radar system and calculated data of velocity component u (m/s) not assimilated data yet

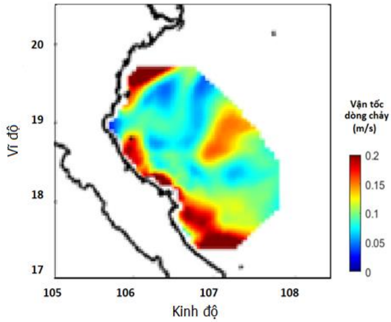


Figure 3.49. RMSE error between observed data from marine radar system and calculated data of velocity component u (m/s) not assimilated data yet

3.4. Studying the current field in the Gulf of Tonkin

3.4.1. Characteristics of the current field in the Gulf of Tonkin in the northeast monsoon months

During the prevailing northeast monsoon, in the surface layer, the Gulf of Tonkin area always exists a current system with a relatively high velocity, approximately 0.6 m/s along the west coast of the Gulf of Tonkin and out of the mouth of the bay, joining the cold western circulation of the East Sea. At the mouth of the Gulf of Tonkin, there exists an anticyclonic with a spatial scale of about 150 km with a velocity of about 0.3 m/s. In addition, in the middle of the Gulf of Tonkin, there exists a cyclonic vortex with a spatial scale of about 200 - 250 km with a speed of about 0.3 m/s (Figure 3.60).

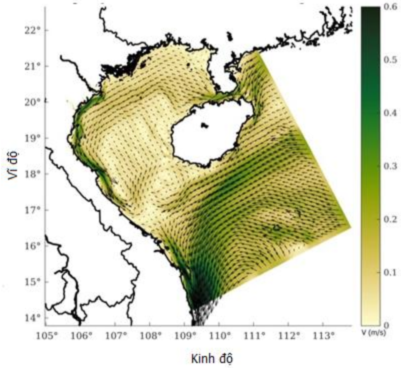


Figure 3.60. January at Surface layer average current on field in the Gulf of Tonkin

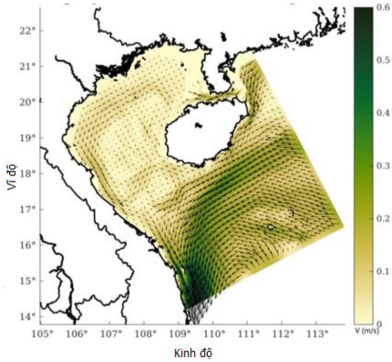


Figure 3.62. January layer at a depth of 20 meters average current on field in the Gulf of Tonkin

In the middle layer (20m depth), the inshore current system still exists but with a much smaller scale and the current velocity in the coastal area is quite small (less than 0.2 m/s). At the mouth of the Gulf of Tonkin, there exists a counter-vortex with the same spatial scale as for the surface layer but with a lower velocity, about 0.1 - 0.15 m/s. In the southern Gulf of Tonkin, there is still a cyclone, but the scale is smaller than the surface layer, about 200 km in diameter and about 0.1 - 0.15 m/s speed (Figure 3.62).

3.4.2. Characteristics of the current field in the Gulf of Tonkin in the months changing from the northeast monsoon to the southwest monsoon

During the summer months (March to May) the circulation is not stable during this time. In these months, due to the change of prevailing wind direction from Northeast to Southwest, the current picture of the Gulf of Tonkin has changed greatly. Cyclone in the southern part of the bay has been broken and there is no longer any anticyclone in the western part of the bay mouth. Instead of the trend of the current field in the Gulf of Tonkin, the main direction is northeast. In late April and early May, the eastern half of the Gulf of Tonkin appeared a small-scale cyclone (Fig. 3.74, 3.76).

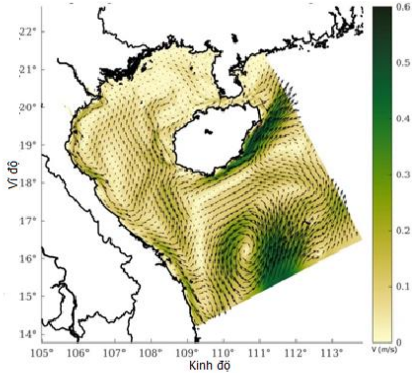


Figure 3.74. April at surface layer average current field in the Gulf of Tonkin.

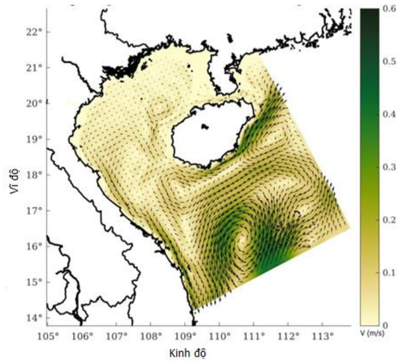


Figure 3.76. April at a depth of 20 meters average current field in the Gulf of Tonkin.

3.4.3. Characteristics of the current field in the Gulf of Tonkin in the southwest monsoon months

At the surface layer, like the northeast monsoon, there is always a system of coastal currents in the direction from north to south but with a smaller velocity (about 0.3 m/s) and the range of occurrence only from the coastal area from Ha Tinh to Da Nang. In the west of the mouth of the Gulf of Tonkin, a strong current system is formed with a speed of about 0.6 m/s moving to the south of Hainan island and following the island to the north of the East Sea. Also due to this current system, at the mouth of the Gulf of Tonkin, there exists a spatial counter-vortex of about 250 km with a velocity of about 0.3 - 0.35 m/s (Figure 3.87).

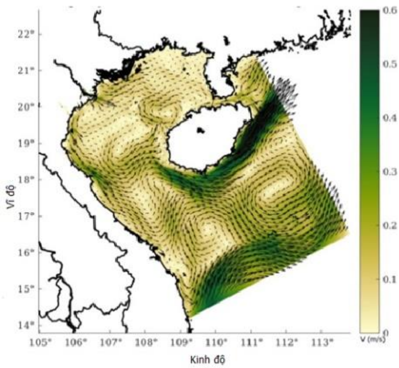


Figure 3.87. July at surface layer average current field in the Gulf of Tonkin.

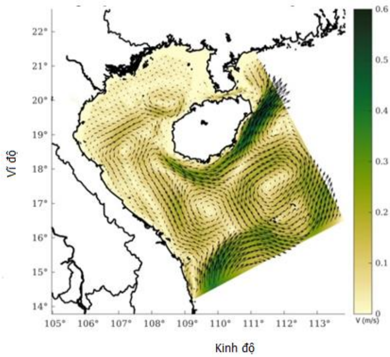


Figure 3.91. April layer at a depth of 20 meters average current field in the Gulf of Tonkin.

Figure 3.87. Javerage current field in the Gulf of Tonkin.

In the middle layer (20 m depth), unlike the surface layer, the coastal current system is not clear and the current velocity in the coastal area is quite small (less than 0.1 m/s). At the western estuary of the Gulf of Tonkin, there is still a current system, but with a smaller scale than the surface layer, the maximum current velocity is about 0.3 m/s. The counter-vortex of the Gulf of Tonkin in this layer is also smaller than the surface layer with a spatial scale of about 200 km with a speed of about 0.2 - 0.25 m/s (Figure 3.91).

3.5.4. Characteristics of the current field in the Gulf of Tonkin in the months changing from the southwest monsoon to the northeast monsoon

During the transition period from summer to winter (September to November), a cyclone in the southern Gulf of Tonkin is gradually formed and by November the size of this cyclone is comparable to that in the winter months. The area outside the mouth of the gulf during the summer months has been replaced by a large-scale cyclone in the months of September and October, by November, this retrograde vortex ceased to exist and instead a cold circulation from the north of the East Sea entered the central coastal area. During this period, there was always a current from north to south along the west coast of the Gulf of Tonkin (Figure 3.103).

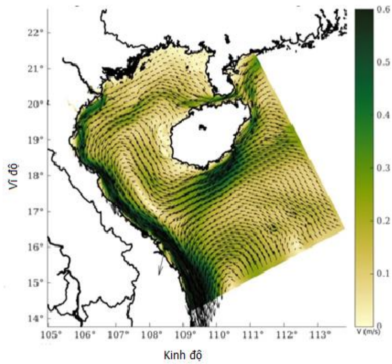


Figure 3.103. October at surface layer average current field in the Gulf of Tonkin.

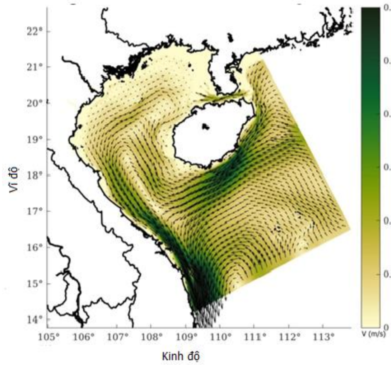


Figure 3.105. April layer at a depth of 20 meters at surface layer average current field in the Gulf of Tonkin.

Conclusion of chapter 3.

In Chapter 1, with the application of the four- direction variable assimilation scheme to the ROMS model, which gave positive results, the errors of BIAS and RMSE are all significantly reduced compared to the unassimilated solution. Along with the assessment based on the above two errors, the correlation coefficient between the data after assimilation with the observation data from the marine Radar system gives positive results. With the above assessments, it is shown that, after assimilation of data, the results of the current field calculation are closer to the actual data when compared with the observed current data from the marine Radar system.

The thesis has given the characteristics of the Gulf of Tonkin current through calculation results, re-analysis of dynamic factors based on surface current data observed by marine radar system, data of surface sea temperature and water level observed from satellites are assimilated into ROMS model. The results of research and evaluation of current field characteristics for specific seasons on the basis of monthly average data are objective and consistent with the main characteristics in previous studies. In addition, the research results of the thesis have shown that the coastal area from Thanh Hoa to Da Nang always has inshore currents, however, the intensity and scale of the current depends on the season. During the winter months and changing from summer to winter, this current reaches the highest speed, averaging up to 0.6 m/s and extending northward to the coastal area of Hai Phong.

CONCLUSIONS AND RECOMMENDATIONS

I. Conclusions

The thesis has applied data assimilation technique to assimilate marine radar data into ROMS model to simulate and analyze the flow field in the Gulf of Tonkin with the following main conclusions:

Established and applied R4D-Var method in assimilation of marine Radar current data into ROMS model. ROMS model, after using data assimilation technique, has increased the accuracy in simulating sea surface currents in the Gulf of Tonkin, BIAS indexes (commonly less than 0.05 m/s) and RMSE (common from 0.1 to 0.15 m/s) between calculated and measured results decreased significantly while the correlation coefficient between them increased significantly (common > 0.7), there is a high similarity between the simulated current velocity and the observed current from the marine Radar.

The results of re-analysis of the 3-D current field with horizontal resolution (2.3 x 2.3 km) with 40 vertical layers after applying data assimilation techniques show that:

At the surface layer, the coastal area from Thanh Hoa to Da Nang always has a coastal current system. In the winter months, the scale of this system can be extended to the coastal area of Hai Phong, the current velocity in this area can reach about 0.6 m/s. In the remaining months, the scale of this system was narrowed and only evident from the coastal area from Ha Tinh to Da Nang, the current rate also decreased significantly and the smallest in the summer months was only about 0.3 m/s. In the mouth of the Gulf of Tonkin, there is always an anti-cyclone, the center of this anti-cyclone during the northeast monsoon months is pushed back into the southern half of the bay and has a small scale (about 150 km) with a speed of about 0.3 m/s. During the southwest monsoon months, the center of this anticyclone is pushed outside the mouth of the bay and has a larger scale (about 250 km) and a greater speed (about 0.35 m/s). There is a cyclone in the middle of the Gulf of Tonkin, the activity of this cyclone also changes according to the wind seasons of the year. In the Northeast monsoon, this cyclone has a large scale, about 200-250 km in diameter, with a current velocity of about 0.3 m/s. During the southwest monsoon, the scale of this cyclone is sharply reduced, about 150 km in diameter and the center of the cyclone may move to the north of the Gulf of Tonkin.

In the deeper layers, the coastal current system persists during the winter at most of the depths with a velocity decreasing with depth. However, in the remaining months, according to the depth, this system weakens and disappears from a depth of more than 30 meters. Anticyclonic systems at the mouth of the bay and in the middle of the Gulf of Tonkin still exist, but their scale is narrowed and the current velocity decreases with depth.

For a depth of 50 meters or more in the Gulf of Tonkin, the current characteristics are faint, but the estuary area is quite clear, especially the area with great depth, which is a continental slope adjacent to the bed area of the East Sea. The characteristics of the upper strata are still maintained in character, but the current intensity has been greatly reduced

II. Recommendations

1. On the obtained results, it can be seen that the assimilation of data in general and the assimilation of marine Radar current data in particular into the ROMS model has created a detailed re-analytical current field, close to reality. Therefore, in order to create the initial field for marine forecasting models, it is necessary to continue researching and applying this assimilation technique to improve the accuracy of future marine environmental forecasting models.

2. Continue to exploit and apply oceanography observations data to build a multi-year re-analytical data set on the Gulf of Tonkin current field on the basis of assimilation of current monitoring data from the

marine Radar system, observational data of hydrographic factors from many different sources combined with ROMS model to serve for research and application in fields related to the marine environment of the Gulf of Tonkin.

LIST OF SCIENTIFIC WORKS OF THE AUTHOR RELATED TO THE THESIS

1. **Nguyen Thanh Trang,** Pham Van Huan, Tran Manh Cuong, Vu Tien Thanh, Luu Quang Hai (2021), "Research on assimilation of monitoring data from marine radar and remote sensing images in a marine hydrodynamic model of the ROMS area", *Journal of Climate Change Science*, 2021, No. 18 June 2021, pp. 35-44.

2. **Nguyen Thanh Trang**, Tran Hong Lam, Tran Manh Cuong, Nguyen Anh Ngoc, Vu Tien Thanh, Luu Quang Hai (2021), "Application of ROMS model to simulate the current field in the Gulf of Tonkin", *Journal of Hydrological Meteorology*, Vol. 12, No. 732, pp. 28-37.