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NGUYEN AN BINH

RESEARCH ON WATER QUALITY MONITORING OVER THE VIETNAMESE SOUTHERN COASTAL USING REMOTE SENSING TECHNOLOGY

Major: Geospatial Science and Technology
Code : 9440214

SUMMARY OF EARTH SCIENCE DOCTORAL THESIS

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Science instructor 1: Assoc Prof. Dr. Pham Viet Hoa
Science instructor 2: Dr. Ho Dinh Duan

Reviewer 1: Assoc Prof. Dr Doan Minh Chung
Reviewer 2: Prof. Dr. Vo Chi Minh
Reviewer 3: Assoc.Prof. Nguyen Van Trung

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INTRODUCTION

1. The necessity of the project

Coastal regions play a vital role and strategic position in economic and social development. The areas would be the hotspots for future growth over the next 50 years. This will lead to a significant increase in conflicts between environmental and social issues, demanding comprehensive planning. Decision No. 36-NQ/TW for the strategy of sustainable development of marine economy in Vietnam to 2030, a vision to 2045, which identified coastal environmental protection as a cross-cutting mission.

Water quality monitoring over the coastal environment by remote sensing technologies takes advantage of optical instruments for identifying the ocean color in the visible spectrum. The spatiotemporal solution is considered as a unique tool for understanding marine ecosystems in the context of climate change as well as anthropogenic threats.

Even though Vietnam is a coastal country with more than 3000km of coastline, research on ocean color remote sensing has recently started with few studies published in the past decade. The current status is due to numerical issues related to field data collection, new technologies, weather conditions, and the quality of satellite images.

Based on the aforementioned obstacle, it is clear that the selection of the thesis "Research on water quality monitoring over the Vietnamese southern coastal environment by remote sensing technology" is essential.

2. Research objectives

General objective

Determining scientific principles and estimated model for coastal water quality variables retrieval using remote sensing technology.

Specific objectives

- Establishing a procedure for quantifying chlorophyll-a concentration in coastal areas using remote sensing with reliable scientific principles, demonstration based on case study experiments, and statistical analysis.

- Evaluation of the capacity of ocean satellites in monitoring Vietnam's coastal waters under tropical monsoon climate, as well as implementing solutions to improve spatiotemporal monitoring capabilities.

3. Research scope

- Subjects: chlorophyll-a (chl-a) estimation using Sentinel 3

- Study area: Coastal waters from Khanh Hoa to Ninh Thuan

4. Research contents

- Scientific principles in remote sensing of ocean color.

- Atmospheric correction method for ocean satellites data.

- Bio-optical algorithms for biogeochemical retrieval in coastal water based on remote sensing data.

- Post-processing methods, the synergy of different ocean satellite generations to improve spatiotemporal monitoring.

CHAPTER 1. LITERATURE REVIEW, SCIENTIFIC PRINCIPLES IN REMOTE SENSING OF OCEAN COLOR

1.1. The importance of the coastal regions

Anthropogenic pressures will exacerbate the deterioration of the coastal environment. A variety of explanations for this have been mentioned since 1995, including (1) densely populated areas, (2) high population growth rates, (3) tourism, (4) 90 % of pollution sources from the mainland discharged to coastal areas, (5) drastic changes in land use, (6) the proportion of waste sources increased rapidly beyond the permissible level, (7) the rate of sedimentation decreased due to the construction of dams and irrigation works, and (8) the proportion of dissolved nutrients, the main cause of eutrophication, has exceeded permissible levels.

Vietnam's coastal area plays a vital role in social-economic development. Therefore, the coastal water environment is significantly affected by economic activities as well as natural drivers. National water quality monitoring programs with a network of stations are insufficient to meet the needs of scalable and continuous monitoring. The observed results cannot meet the need for marine environment warning, which has been proven for environmental incidents that have taken place recently in Van Phong Bay or Formosa in 2016.

1.2. Optical properties of ocean water

From the preliminary observation of ocean color based on earth observation satellite images, it is clear that while ocean waters have consistent colors, coastal waters have different colors. Case-1 waters are those in which the contribution of phytoplankton to total absorption and scattering of light is higher than other substances. Meanwhile, case-2 water significantly contains suspended matter and dissolved organic matter.

Case-1 waters tend to be distributed over offshore oceans, while case-2 waters belong to the rest of the ocean or the coastal waters. However, it should be noted that not all coastal waters belong to case-2. About 98% of the world's oceans and coastal waters are considered case-1, while the rest belong to case-2. Notwithstanding, ocean color remote sensing focuses on case-2 waters due to these being areas of coastal waters and estuaries related to anthropogenic activities.

For distinguishing case-1 and case-2 waters, studies focused on determining different optical properties. The optical properties of ocean waters are divided into two main characteristics: (1) internal optical properties (IOP) and (2) external optical properties (AOP). IOPs are independent of the ambient light. Whereas AOPs are those that vary based on IOPs as well as the change of the light transmission, becoming unique properties to describe specific waters. The value of the water-leaving reflectance is the most critical AOP in the field of ocean color remote sensing

1.3. Atmospheric correction

The goal of the atmospheric corrections is to remove the contribution of different components to the total signal reflectance, including aerosol, Rayleigh scattering, and whitecaps, in order to obtain water-leaving reflectance p_w.

To date, different atmospheric corrections have been developed as the topic continues to be discussed. The most atmospheric processors include SeaDAS, C2RCC, Acolite with EXP and DSF algorithms, iCOR and Polymer. Other problems related to the performance of the atmospheric correction model are adjacency effects, clouds and cloud shadow pixels in remote sensing images, sunglint, whitecaps, as well as match-up protocols for accuracy assessment.

1.4. Ocean varaibles retrieval from remote sensing data.

Particularly in ocean color remote sensing, the most studied ocean variables include chlorophyll-a, turbidity, suspended matter, sea surface temperature, particulate organic carbon POC, colored dissolved organic matter CDOM, and sea surface salinity.

Chlorophyll-a remains one of the most crucial biogeochemical variables due to its relevance to eutrophication monitoring and primary production models. Bio-optical algorithms have been proposed for quantifying individual ocean variables water taking advantage of the spectral wavelengths on the ocean color satellite sensor.

1.5. Literature review

1.5.1. Foreign studies

Remote sensing technology offers a wide range of advantages including (1) unique data source allowing large-scale monitoring or hard-to-reach areas (2) long time series allowing monitoring of dynamic processes and trend analysis (3) consistent global geodatabase (4) valid for different studies (5) comparison and complementation with in situ data (6) Most data sources are free and open access

Research related to the field of ocean color remote sensing involves four functional elements: (1) the capacity of satellite missions to collect spectral information and spatial and temporal resolution, (2) an algorithm that connects information obtained from satellites with ocean water quality variables including optical properties and biogeochemical indicators, (3) field data collection method including sampling, storage, and analysis, match-up protocol with satellite data for calibration and validation, and (4) operational capacity for specific purposes such as availability of products, processing software, training.

1.5.2. Vietnamese studies

Research on ocean color remote sensing has recently started, with few studies published in the past decade, partly because of the availability of satellite datasets. Initially, numerical projects have approached novel technology solutions, including geospatial and remote sensing-based technologies, aiming to create a geodatabase of ocean color variables in different space and time resolutions. Most published studies were affected by the cloud cover issue, leading to the failure of estimated model evaluation and complete spatial information mapping. However, it would be confirmed that these are essential studies in Vietnam, which provided the scientific and practical basis for developing new computational models for accurate coastal water quality quantifying, cause and effect assessment, and improve the quality and quantity of geospatial datasets in the field of the marine environment.

CHAPTER 2. RESEARCH SCOPE, METHODOLOGY FOR RETRIEVING OCEAN WATER QUALITY VARIABLES BASED ON REMOTE SENSING DATA.

2.1. Research scope

As the main phytoplankton pigment, chl-a is considered a proxy for biomass in water, which is directly related to eutrophication and primary ocean productivity. Chl-a is the most important variable in the field of marine environment, as well as the most significant ocean biogeochemical variable in remote sensing of ocean color.

2.2. Study area and data

The study area is located in southern coastal Vietnam, spanning from 11°20’ to 12°53’ north latitude, covering an approximately 5848.7 km^2. Along the coastal line of nearly 600km, there are five bays with different optical properties: Van Phong, Nha Phu, Nha Trang, Cam Ranh Bays located in Khanh Hoa province, and Phan Rang belongs to Ninh Thuan province.

Field data were collected in five different periods and locations includes: four campaigns organized in Van Phong and Nha Trang in 2018 and 2019, and an additional field survey occurred in PR in 2018 with total 49 field samples

Satellite images Sentinel 3 with spatial resolution 300m were downloaded includes 46 scenes from 1/10 to 30/11/2018 (S-3A: 21, S-3B: 24) and 56 images from 1/7/ to 31/8/2019 (S-3A: 26, S-3B: 30)

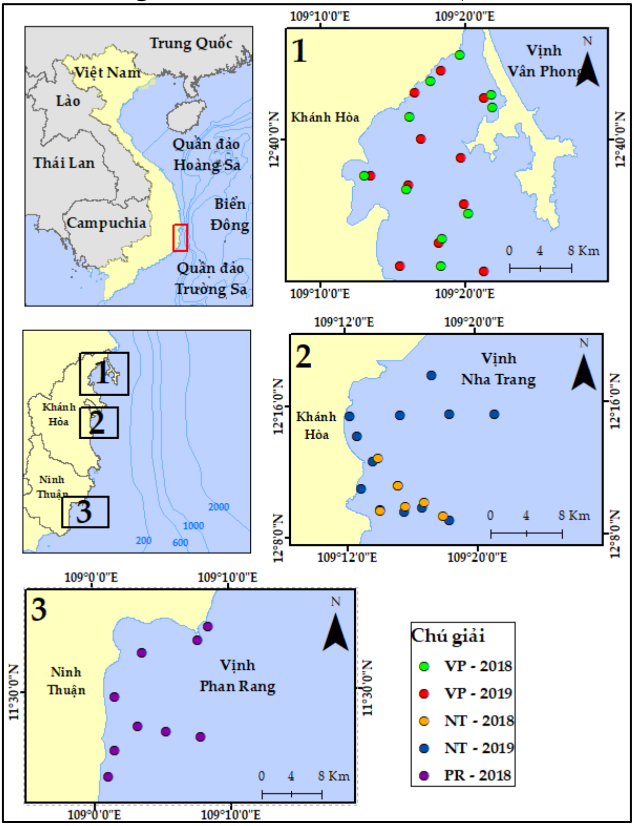

Figure 2.1. Location of the study area and field sampling

2.3. Methodology

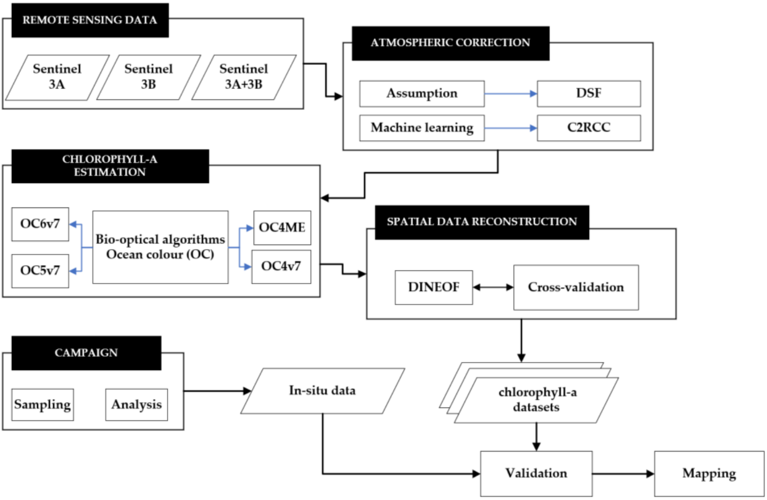

Figure 2.2. Workflow diagram

2.4. Accuracy assessment

Cross-validation of DINEOF

Validation the DINEOF reconstruction using cross-validation, with 3% (automatic random selection) of original pixels were compared to the reconstructed pixels. Missing data (or percentage of cloud cover) were calculated by the percentage of missing water pixels against all water pixels over the research area. Root mean square error (RMSE) for each process was determined following the equation:

$$\mathrm{RMSE}_{DINEOF} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i^{ref} - x_i^{org}\right)^2}{n}} \tag{2.3}$$

where n is the number of cross-validation pixels, x_i^{ref} and x_i^{org} represent the chl-a values from reconstructed datasets and original datasets, respectively.

Model performance with in-situ measurement data

Statistical errors were calculated following the equations:

$$R_{Pearson} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (2.4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \quad (2.5)$$

$$MAPE = 100 \times median\left(\frac{|y_i - x_i|}{x_i}\right) \quad (2.6)$$

$$MAE = 10\hat{}\left(\frac{\sum_{i=1}^{n} |\log_{10} y_i - \log_{10} x_i|}{n}\right) \quad (2.7)$$

$$bias = 10\hat{}\left(\frac{\sum_{i=1}^{n}(\log_{10} y_i - \log_{10} x_i)}{n}\right) \quad (2.8)$$

where, n is the number of samples (49), y_i is the chl-a values estimated from satellite data and, x_i is the chl-a values measured in-situ. In order to show the comparison between different procedures, the study also applied Taylor diagram.

CHAPTER 3. RESULTS AND DISSCUSION

3.1. Results

3.1.1. Atmospheric correction

With the C2RCC corrector, water-leaving reflectance based on C2RCC processors reaches the highest value of 0.082 at 560 nm

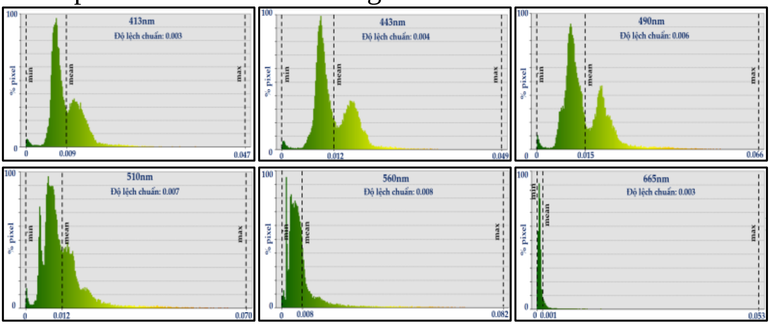

Figure 3.2. Histogram of water-leaving reflectance distribution in the wavelengths of 413nm, 443nm, 490nm, 510nm, 560nm, and 665nm over the research area. The atmospheric correction C2RCC (satellite S-3A, date of 16/10/2018)

The variation of water-leaving reflectance retrieving from DSF atmospheric correction at 560 nm (standard deviation 0.011), while the band with the lowest deviation is 413 nm (standard deviation 0.004).

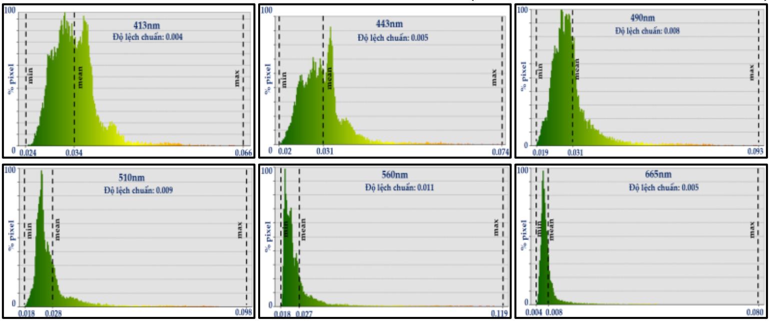

Figure 3.4. Histogram of water-leaving reflectance distribution in the wavelengths of 413nm, 443nm, 490nm, 510nm, 560nm, and 665nm over the research area. The atmospheric correction DSF (satellite S-3B, date of 05/07/2019)

3.1.2. Full spatial data reconstruction of chl-a datasets

Table 3.1. Description of datasets, dimensions, missing data, and $RMSE_{DINEOF}$ (optimized) for DINEOF reconstruction from different chl-a algorithms. The atmospheric correction C2RCC

Periods	Satellites	Dimensions	Missing data (%)	$RMSE_{DINEOF}$ ($mg\ m^{-3}$)			
				OC4ME	OC4	OC5	OC6
2018	S-3A	179 × 537 × 21	61.17	0.815	0.786	0.785	0.864
	S-3B	179 × 537 × 24	66.25	0.795	0.805	0.769	0.797
	Total	179 × 537 × 28	60.58	0.715	0.708	0.714	0.755
2019	S-3A	179 × 537 × 26	50.87	0.522	0.540	0.498	0.550
	S-3B	179 × 537 × 30	49.17	0.667	0.669	0.686	0.644
	Total	179 × 537 × 49	46.80	0.507	0.550	0.501	0.639

The OC5 algorithm gives the lowest statistical errors compared to each satellite S-3A, S-3B, and synergy S-3A+S-3B or based on C2RCC and DSF atmospheric corrections. OC6 is only the model which yielded the significantly highest errors in almost cases.

Table 3.2. Description of datasets, dimensions, missing data, and $RMSE_{DINEOF}$ (optimized) for DINEOF reconstruction from different chl-a algorithms. The atmospheric correction DSF

Periods	Satellites	Dimensions	Missing data (%)	$RMSE_{DINEOF}$ (mg m^{-3})			
				OC4ME	OC4	OC5	OC6
2018	S-3A	178 × 37 × 22	66.95	0.634	0.556	0.619	0.699
	S-3B	177 × 37 × 24	67.34	0.669	0.650	0.775	0.832
	Total	178 × 37 × 31	65.70	0.535	0.552	0.546	0.662
2019	S-3A	177 × 37 × 20	57.31	0.507	0.547	0.508	0.646
	S-3B	178 × 34 × 24	53.94	0.462	0.452	0.476	0.565
	Total	178 × 37 × 42	53.38	0.423	0.408	0.387	0.552

Another point is the temporal dimension of combination datasets. Due to the concurrent overlapping of acquisition dates in S-3A and S-3B, total number of scenes in 2018 and 2019 datasets is different

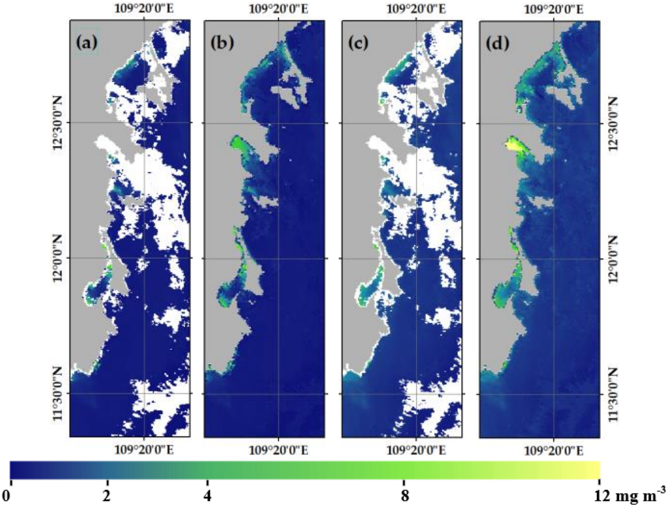

Figure 3.6. Illustration of DINEOF performance for the merged datasets in 2019: (a) original C2RCC, (b) filled C2RCC, (c) original DSF, (d) filled DSF

3.1.3. Model performance with in-situ measurement data

Evaluation of the overall accuracy for C2RCC-based products is presented in table 3.3, with the estimation from S-3B outperforming S-3A, and the OC6 algorithm reaching the highest error.

Table 3.3. Statistical metrics for the four chl-a algorithms retrieved from each satellite S-3A and S-3B. The atmospheric correction C2RCC (p-value < 0.00001)

	R^2	slope	intercept	RMSE	MAPE	MAE	bias
S-3A							
OC4ME	0.58	0.552	0.494	1.021	41.2	1.693	0.916
OC4	0.57	0.618	0.401	1.037	48.6	1.871	0.807
OC5	0.58	0.586	0.421	1.018	49.4	1.762	0.848
OC6	0.56	0.508	0.503	1.056	35.9	1.657	0.921
S-3B							
OC4ME	0.74	0.728	0.401	0.785	40.5	1.634	1.027
OC4	0.74	0.809	0.377	0.803	38.1	1.650	1.069
OC5	0.75	0.730	0.419	0.776	37.3	1.618	1.060
OC6	0.46	0.496	0.687	1.139	44.0	1.690	1.009

The performance of the chl-a estimation procedure based on the DSF processors is provided in table 3.4. It is clear that C2RCC performed better while applied in both satellites 3A and 3B.

Table 3.4. Statistical metrics for the four chl-a algorithms retrieved from each satellite S-3A and S-3B. The atmospheric correction DSF (p-value < 0.00001)

	R^2	slope	intercept	RMSE	MAPE	MAE	bias
S-3A							
OC4ME	0.49	0.713	1.692	1.755	110.5	2.324	2.246
OC4	0.48	0.624	1.674	1.608	99.1	2.287	2.177
OC5	0.51	0.697	1.531	1.586	98.9	2.156	2.060
OC6	0.58	0.464	1.817	1.451	112.8	2.337	2.223
S-3B							
OC4ME	0.56	0.670	1.825	1.706	130.5	2.422	2.357
OC4	0.56	0.610	1.696	1.526	118.8	2.257	2.185
OC5	0.54	0.601	1.714	1.541	108.5	2.269	2.194
OC6	0.53	0.519	1.997	1.666	145.8	2.528	2.433

Taylor diagram shows a comparison of predicted Chl-a by the different model. The diagrams also confirmed the best performance of C2RRC processor. Furthermore, water models OC4ME and OC5 based on C2RCC achieved the best assessment in all cases.

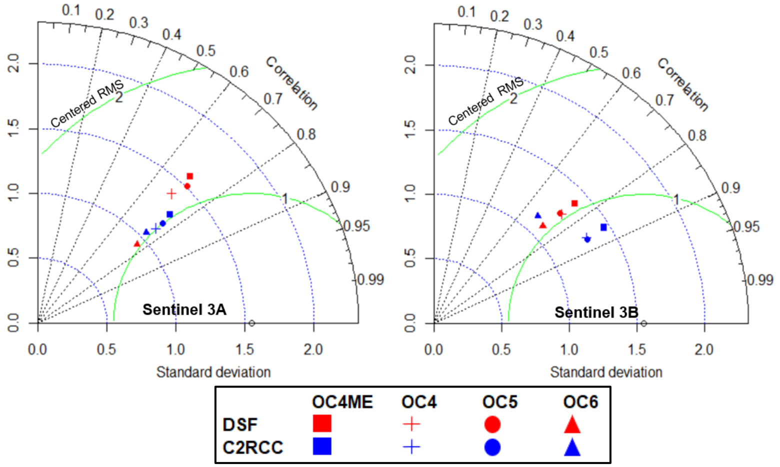

Figure 3.15. Taylor diagram represent the performance of different chl-a algorithms based on C2RCC and DSF, S-3A (left) and S-3B (right)

3.2. Discussion

3.2.1. Atmospheric correction

The results showed that C2RCC outperformed DSF in both case of S-3A and S-3B as all listed error metrics. C2RCC is an atmospheric correction algorithm based on a machine learning approach, applying Neural Network algorithm. The processors can customize parameters for each specific study area. Meanwhile, DSF uses a band of 1020 nm on Sentinel 3 images, assuming that the water reflectance is negligible.

3.2.2. Performance of bio-optical algorithms

Statistics showed the best performance of OC4ME and OC5 compared to others in all cases. OC4ME was first designed for MERIS, then switching to apply appropriately in Sentinel 3 due to the similar orbit characteristics of the instruments. The following algorithm, OC5, also confirmed worked well. Particularly in the study area, OC5 was demonstrated for the best performance in coastal Vietnam through MERIS.

3.2.3. Overcoming the disadvantages of optical satellite image data when observing tropical monsoon climate areas for monitoring the Vietnamese coastal environment

DINEOF provides a reliable method for full spatial reconstruction in spatiotemporal patterns, as demonstrated in this study, with two outstanding advantages enhancing spatial information and temporal resolution when combining different sources

3.2.4. Capacity of Sentinel 3 for Vietnamese coastal environment observations

This thesis aims to evaluate the performance of the Sentinel 3 data, which is the first study to analyze OLCI sensor on both 3A and 3B satellites over coastal Vietnam. With the demonstration and statistical metrics provided in the thesis, the high-resolution data will definitely contribute to the time-series ocean datasets, as well as the efficient sources for in-depth research

3.2.5. Synergy of different ocean remote sensing data to enhance the space and time resolution

In this study, S-3A and S-3B images taken with different dates provide the possibility to increase the temporal resolution of the dataset. Scenes acquired on the same day can be combined for cloudy pixel gap-filling. For the synergy chl-a datasets on two satellites S-3A and S-3B based on C2RCC, the statistical results show that OC4ME, OC4 and OC5 obtain the best performance compared to OC6

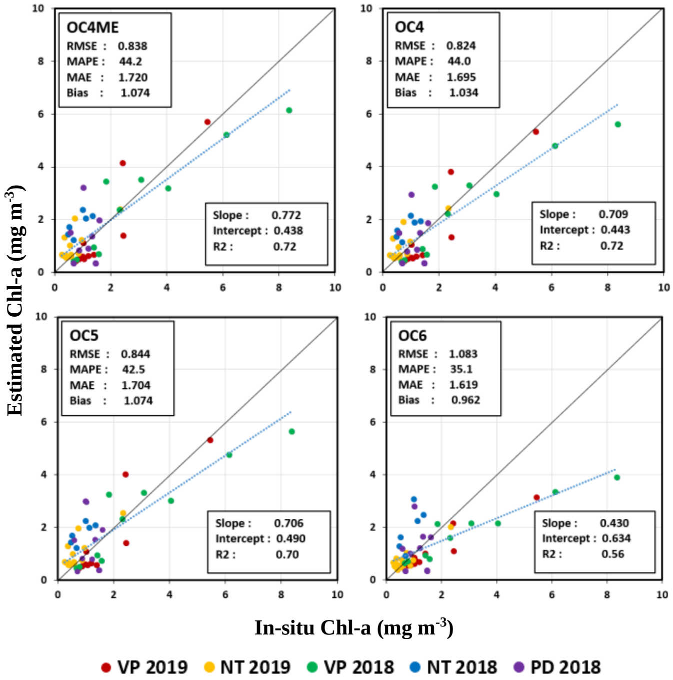

Figure 3.23. Performance of C2RCC-based chl-a products derived from different algorithms when combining S-3A and S-3B. (p-value < 0.00001)

Compared between two atmospheric corrections, C2RCC outperforms DSF in all four chl-a algorithms. C2RCC-based OC4ME and OC5 algorithms achieve the highest accuracy for combining data from two satellites S-3A and S-3B. In addition, the OC5 also gives consistent products while considering the spatial relationship.

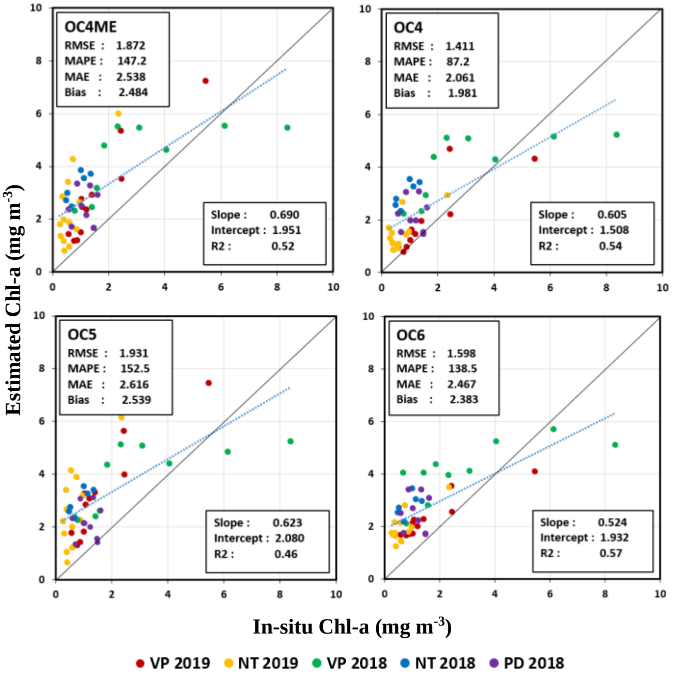

Figure 3.24 Performance of DSF-based chl-a products derived from different algorithms when combining S-3A and S-3B. (p-value < 0.00001)

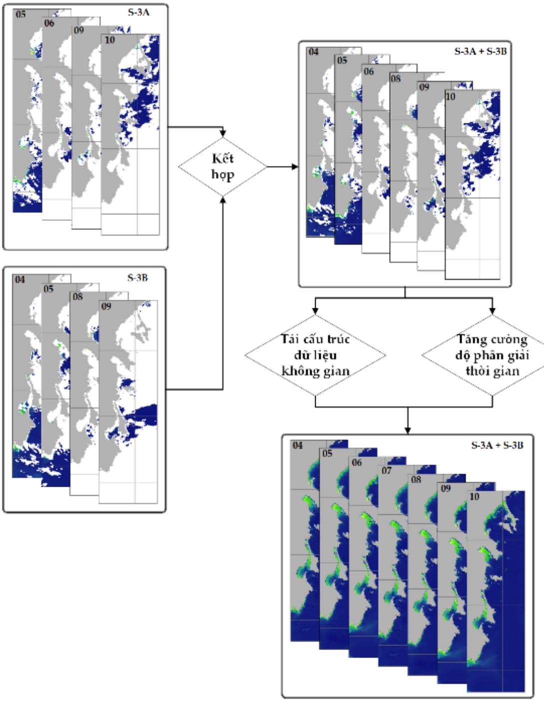

Figure 3.25. The solution handles spatial data affected by cloud cover and enhances temporal resolution when combining two satellites S-3A and S-3B, and the spatial data reconstruction model DINEOF. Illustration of datasets acquired from 04/08 to 10/08/2019

3.2.6. Future implementation

With validation results through statistical errors and regression models, the use of these algorithms in building daily time-series will help to understand the dynamic of ocean processes, trends, seasonal conditions, as well as the influence of tropical monsoon regimes on Vietnam's waters. Therefore, the spatiotemporal solution will be applied successfully and effectively.

The research opens a new application in the future in estimating different ocean biogeochemical variables such as chl-a, turbidity, suspended matter for coastal waters, improve our knowledge and understanding in the field of ocean color remote sensing in the waters of Vietnam.

The pre-processing and post-processing steps in the procedure lead to the accumulation of errors. All mentioned processing steps are necessary when applied to Vietnamese waters due to the influence of weather factors on the quality of remote sensing. Therefore, each step in the process needs to be evaluated separately in order to mitigate the accumulated errors as well as confirm the reliability of each processing step. Particularly in Vietnam, while more research needs to focus on new methods, field data sources is also one of the necessary tasks.

Our study covered short periods used only to evaluate the performance of water models. Therefore, we conducted datasets in 2018 (October-November) and 2019 (July-August). Statistical errors indicate that the procedure can be applied for different ocean variables mapping in order to monitor continuously through time-series datasets. Consequently, this can help improve the knowledge of seasonal characteristics, trends, and the impact of human activities.

Cloud cover is a major issue affecting the quality of satellite images in coastal areas of Vietnam. The solution of spatial data reconstruction in satellite-based biogeochemical products will undoubtedly be used for future research. When the satellite image becomes a big geospatial data, spatial data reconstruction based on machine learning and deep learning algorithms can be applied with high accuracy. Therefore, in the future, combining remote sensing image data sources not only increases the quantity and quality of remote sensing images for marine environment monitoring but also opens up the possibility of applying high-performance algorithms by interacting with artificial intelligence and big data.

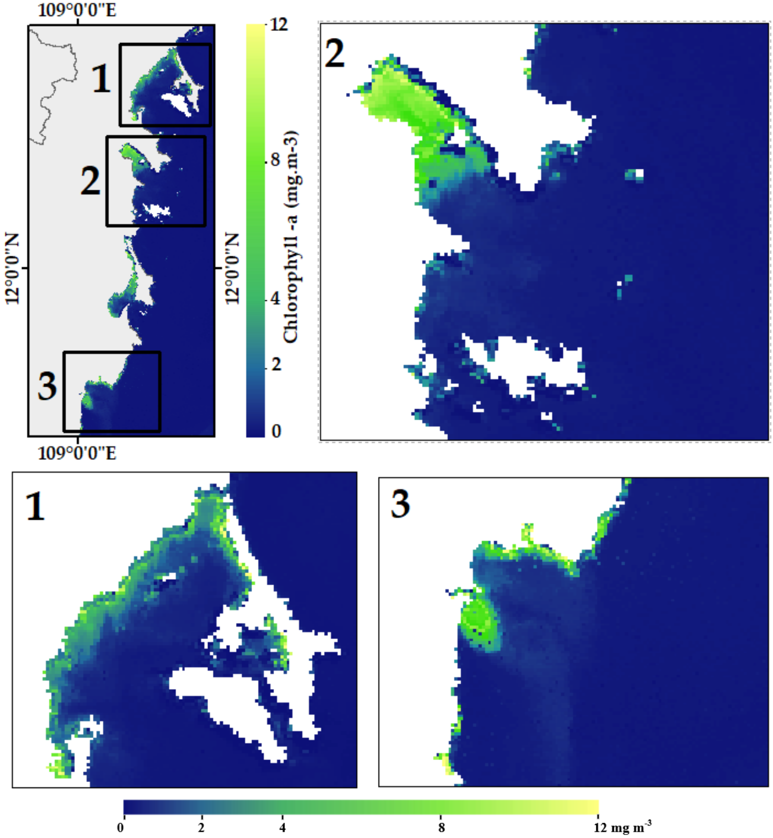

Figure 3.26. Synergy of both satellite S-3A and S-3B for Chl-a derived from OC5, July 31st, 2019, Atmospheric correction C2RCC

3.2.7. Towards coastal eutrophication monitoring by geospatial solutions

Chl-a datasets in July and August, 2019 were used for classifying eutrophic level following the threshold in table 3.5.

Table 3.5. Eutrophic classification over coastal waters

Index	Oligotrophic	Mesotrophic	Eutrophic
Chl-a	Chl-a ≤ 0.1	0,1 < Chla < 1.67	Chla ≥ 1.67

Based on the given thresholds, weekly composite of chl-a maps were classified according to the oligotrophic, mesotrophic, and eutrophic levels. Figure 3.28 shows maps of different eutrophic levels in the study area. While water in Van Phong is eutrophic almost in the regions with a distance of around 5km from the coast, Nha Phu, Cam Ranh in Khanh Hoa, and Phan Rang in Ninh Thuan are considered eutrophic water. Nha Trang is the only bay with mesotrophic levels. Over weeks, a significant change occurred in the waters near Phan Rang with increased eutrophication levels. Results showed that the dynamic of marine environmental factors is very complex and constantly, leading to the necessity for continuous tracking (i.e., daily, weekly)

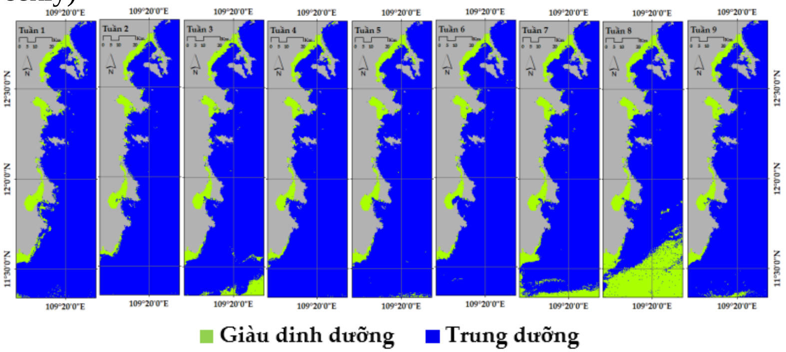

Figure 3.28. Weekly maps of eutrophic level from 01/07 to 31/08/2019

Figure 3.29 shows the area affected by different eutrophic levels, indicating that the status also fluctuated even in the small observation area (5000 km^2). Note that the oligotrophic pixels were grouped into the mesotrophic pixels due to the small percentage area (less than 0.2% for all time steps).

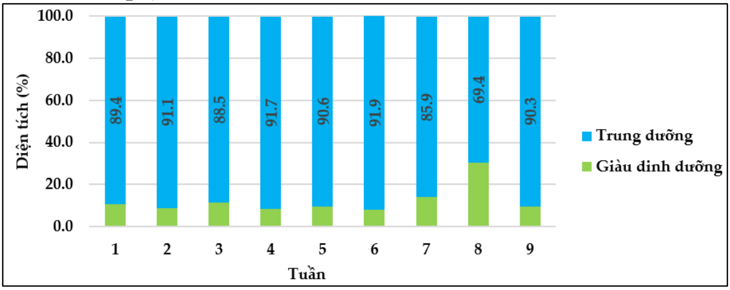

Figure 3.19. Statistics of eutrophic levels by percentage (%) over the study area. Pixels in oligotrophic were grouped to mesotrophic due to the negligible (< 0,2%)

CONCLUSIONS AND RECOMMENDATION

Conclusion

Through a comprehensive literature review in remote sensing of ocean water quality, the thesis has addressed issues corresponding to the scientific basis, methods and models for biogeochemical variables estimation over coastal waters by remote sensing technology. From these insights, the research aims of the thesis were entirely determined

The thesis has established a complete procedure with essential multi-processing steps, including atmospheric correction, ocean variables bio-optical algorithms, and full spatial data reconstruction while overcoming cloud cover in Vietnamese coastal waters. Results and statistical metrics have proven the accuracy of the proposed approach.

The thesis has demonstrated the new ocean color satellites' capacity to monitor water quality over the Vietnamese coast based on Sentinel 3 images (300m) and a spatial data reconstruction model overcoming the cloud cover frequency under the tropical monsoon climate. Additionally, monitoring tasks have been revealed to increase the spatial information and temporal resolution of product datasets when combining Sentinel 3A and 3B satellites.

Remote sensing of ocean color is considered to be more challenging than land-based studies. The research improves our understanding of ocean color remote sensing in Vietnam in the context of limited studies while overcoming different challenges. Future implementations need to be done in order to promote marine environmental sciences in general as well as particular remote sensing, towards potential scientific articles and international information publishing, contributing to the protection of sovereignty in Vietnam's maritime.

Recommendation

It is clear to emphasize that the proposed process would be retrieved accurately for other ocean variables such as turbidity, suspended matter, temperature, and carbon-based indicators, as also look insight into environmental phenomena like algal blooms, and eutrophication.

Future studies need to keep effort for validation of separate processing steps, evaluating the entire estimated solutions, and approaching novel model, as a consequence of complementing the high performance of automatic methodologies.

Scaling up allows for increasing the product datasets of ocean variables over time and space dimensions, resulting in a big geospatial database with diverse marine environmental factors. Therefore, it provides the tracking history and current situation as well forecasts the future, enabling the capacity for the global ocean processes explanation to further improve our knowledge of the spatio-temporal dynamics of coastal ecosystems.

NOVEL CONTRIBUTION OF THE THESIS

- Successful identification of atmospheric correction model, chlorophyll-a algorithm representing coastal waters quality, and remote sensing data reconstruction model for the marine environment to overcome the disadvantages of cloud cover over the coastal waters in the South of Vietnam.

- Implementation of procedure to monitor coastal water quality with the first application of Sentinel 3 satellite data over the southern coastal waters of Vietnam. Moreover, the synergy of Sentinel 3A and 3B satellite data has been successfully demonstrated to increase the monitoring frequency for the research area with challenges in the quantity and quality of ocean remote sensing satellites.

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