Detecting Chlorophyll *a* Concentration and Bloom Patterns at Upwelling Area in South Central Vietnam by High Resolution Multi-satellite Data

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Abstract: Study on Chlorophyll *a* (Chl. *a*) distribution and bloom patterns is essential in the upwelling areas that constitute the main fishery grounds of Vietnam. Based on high resolution satellite imagery and monthly in-situ data in period from 2007 to 2008, the spatial and temporal variations of Chl. *a* in the upwelling region including algal blooms have been detected. Anomalies of higher Chl. *a* concentration and bloom patterns occurred at different periods, locations, and bloom shapes in coastal waters of Southern Center of Vietnam. The appearances of these bloom are related to four difference reasons, such as: (i) Their locations coincided to main center of upwelling phenomena that usually occur during southwest monsoon (SWM); (ii) Effect of northeast monsoon (NEM) that brings and attaches the nutrient into the coast and created “floating” algae bloom patches in coastal zones; (iii) The algae blooms can be potentially associated with Harmful Algae Bloom (HAB) during the SWM or local eddies during NEM and (iv) Their appearances are also as a result of distinctive nutrient inflow from Mekong delta and pumping of nutrients by internal waves in coastal shallow waters.

Key words: Chlorophyll *a*, bloom pattern, fisheries resources, coastal waters, remote sensing, upwelling.

1. Introduction

Eastern Sea (synonym for South China Sea) is the largest marginal sea in Southeast Asia region of Pacific Ocean. The East Sea is located in a region strong of East Asia monsoon activity [1]. Moreover, the variability of East Sea’s atmosphere is typically controlled by the East Asia monsoon and makes upwelling off the Vietnam coast that bringing high nutrient concentrations favorable for phytoplankton photosynthesis [2]. The East Sea also has a large continental shelf from the northwest to the south, with abundantly sediment and runoff from several large rivers such as Mekong River as well as a deep basin (4,700 m depth) in the central region [2]. The south of central Vietnam where upwelling occurs during southwest monsoon (SWM) is a major fishery ground.

Therefore, this upwelling is essential for marine fisheries industry as well as for marine science in Vietnam.

In 1959-1961, the research cruise NAGA recognized the south of central Vietnam as coastal upwelling area [3]. To date, several research programs associated with this area have been carried out [4-6]. In period of 1992-1995, Nha Trang Institute of Oceanography conducted research on meteorology, hydrological dynamics, ecology and other important marine resources in this area [7]. The cooperation project between Vietnam and Germany (2002) was implemented to investigate the upwelling phenomenon in detail [8]. In particular, satellite imagery was applied to study the hydrodynamic conditions such as sea surface temperature (SST), sea surface height (SSH) and surface winds [9, 10]. Among these, Chl. *a* is one of the good indicators for recognizing the upwelling phenomena and HABs as well as forecasting the fishery grounds. So far, the

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application of satellite oceanography to the study of relationships among hydrodynamic properties, the distribution of phytoplankton biomass in terms of Chl. *a* in relation to algal bloom, and fisheries resources have been limited in Vietnam waters.

The present paper aims to present the distribution of algal blooms through Chl. *a* concentrations derived from satellite imagery high resolution for central Vietnam waters in 2007-2008.

2. Materials and Methods

2.1 Materials

Satellite imagery and geographical information system (GIS) techniques were used as primary tools to determine the distribution of Chl. *a* in upwelling region in the coastal of South Central Vietnam. Upwelling occurs in coastal waters of the Vietnam Sea especially in waters adjacent to the coastal of Ninh Thuan, Binh Thuan and Ba Ria-Vung Tau provinces.

Software: ENVI v4.4, SeaDAS v5.4 were used for processing and analyzing satellite imagery; MapInfo 7.5, Ocean Data View 4.2 were used to procedure the maps. Software R 2.10.0 Patched and Microsoft Office Excel were integrated with remote sensing and GIS software to analyzing data and algorithms for computation phases.

Types of satellite images: The time-series remote sensing imagery (including the original image Level 1, 2B and Level 3 imageries were processed with different ground resolution as follows:

The Moderate Resolution Imaging Spectroradiometer (MODIS) 1.1 km imagery downloaded from on NASA's Aqua were used to distinguish concentration and distribution of Chl. *a* (Table 1) [11]. Color composite images were constructed to calculate monthly-averaged Chl. *a* concentration;

Landsat ETM⁺ imagery (30 m) consist of 14 scenes and 6 scenes the Advanced Land Observing Satellite (ALOS)-Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) (10 m) imagery which coverage for the period 2007-2008 were used to detect

the distribution of surface Chl. *a* concentration and the occurrence of HAB in the study area;

In addition, time-series averaged data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) imageries were also used in the analysis of seasonal variation of Chl. *a* concentration in the study area [12];

In-situ observation data: Monthly surface Chl. *a* concentration in-situ data collected at 21 stations from May to September in 2007 and from April to September in 2008 (Fig. 1). They were used to build standard algorithms for the assessment of the distribution of Chl. *a* concentration from high resolution satellite imagery.

2.2 Methods

Algorithms: OC3 algorithm was used to determine the distribution of surface Chl. *a* concentration from MODIS images [13].

$$\text{Chl. } a \text{ (mg} \cdot \text{m}^{-3}) = 10 \times (0.283 - (2.753 \times R) + (1.457 \times R^2) + (0.659 \times R^3) - (1.403 \times R^4)) \quad (1)$$

Where,

$$R = \log_{10}[\max(\frac{Rrs(443)}{Rrs(551)}, Rrs(488)/Rrs(551))]$$

The detailed distribution of surface Chl. *a* concentration for each specific time and location where algal blooms occurred was determined using Landsat ETM⁺ (30 m) and AVNIR-2 (10 m) imageries. Surface Chl. *a* concentration was calculated based on surface reflectance spectrum of blue band and red band of the Landsat ETM⁺ and AVNIR-2 imagery [14]. The results of in-situ surface Chl. *a* concentration in Binh Thuan waters were used to build standard algorithms for assessing the distribution of Chl. *a* concentration in both ALOS-AVNIR-2 and Landsat ETM⁺ as in Eq. (2):

For Landsat ETM⁺ (30 m):

$$\text{Chl. } a =$$

$$\begin{cases} 3.3987 \times R^2 - 10.368 \times R + 8.2128 & \text{if Chl } a \leq 1 \\ 1287.7 \times R^2 - 3431.7 \times R + 2289.2 & \text{if Chl } a > 1 \end{cases} \quad (2)$$

Fig. 1 The study area (107°00'-112°00' E and 09°00'-13°00' N) and field stations for detection of Chl. *a* distribution at upwelling area in the South Central Vietnam.

Table 1 86 scenes of MODIS imagery coverage of the study area were taken daily for two years 2007-2008.

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
2007	5	3	4	5	6	3	6	4	4	3	4	5	48
2008	4	3	5	6	2	4	4	3	2	2	1	2	38

Where, $R = \log(B_3) / \log(B_1)$; B_3 is surface reflectance spectrum of red band; B_1 is surface reflectance spectrum of blue band. B_1 and B_3 were computed by the method of reflection correlation based on original Landsat ETM⁺ imagery information parameters on date, time of image capture, sun-synchronous orbit, reflection indices and reflectance correction at the Top of Atmospheric (TOA) for each band (Figs. 2a and 2b).

For AVNIR-2 (10 m) imagerys:

The algorithm to detect the distribution of Chl. *a* based on the ratio B_3/B_1 .

$$\text{Chl. } a \text{ (mg} \cdot \text{m}^{-3}\text{)} =$$

$$(48.812 \times R^2) + (2.0294 \times R) - 6.9266 \quad (3)$$

Where, $R = B_3/B_1$; B_3 is surface water reflectance spectrum of red band; B_1 is surface water reflectance spectrum of blue band. B_1 and B_3 were calculated through the reflection correlation method and atmosphere correlation based on original AVNIR-2 images including information on date, time of image

Fig. 2 The algorithm to detect the distribution of Chl. *a* from Landsat ETM⁺ imageries: (a) with Chl. *a* concentration ≤ 1 ; (b) with Chl. *a* concentration > 1 .

capture, sun-synchronous orbit, reflection indices and reflectance correction at TOA for each band (Fig. 3).

3. Results and Discussion

3.1. Temporal and Spatial Variability in Chl. *a* Concentration in the Upwelling Area

Chl. *a* concentration is strongly variable temporally and spatially in the study area. Higher Chl. *a* concentration was observed along the coastline and lower Chl. *a* concentration in the offshore area. On the other hand, this Chl. *a* concentration pattern was observed throughout the 5 years.

Based on the time-series variation of Chl. *a* concentration from SeaWiFS imagery from 2004 to 2008, Chl. *a* concentration varied from $0.1 \text{ mg}\cdot\text{m}^{-3}$ to $1.513 \text{ mg}\cdot\text{m}^{-3}$. Maximum Chl. *a* concentration $1.917 \text{ mg}\cdot\text{m}^{-3}$ in the area was observed on December 2006, value $1.513 \text{ mg}\cdot\text{m}^{-3}$ on January 2007. In 5 years-averaged, the maximum Chl. *a* concentration ranged from $0.5\text{-}0.8 \text{ mg}\cdot\text{m}^{-3}$ was observed from August to October (Fig. 4).

Based on MODIS imagery, the Chl. *a* concentration is always higher in the NEM season (December to February) with the monthly-average value about $0.88 \text{ mg}\cdot\text{m}^{-3}$. The spatial distribution also showed the high

Fig. 3 The algorithm to detect the distribution of Chl. *a* from AVNIR-2 images based on field data during two years 2007-2008.

concentration of Chl. *a* in coastal area during the NEM tending to decrease gradually from inshore to offshore by spreading in the northeast-southwest direction.

In the inter-monsoon season (March to May), due to the disturbance of currents by wind, high Chl. *a* concentration is confined to a narrow coastal area, and the monthly average value is about $0.19\text{-}0.25 \text{ mg}\cdot\text{m}^{-3}$. With the onset of inter-monsoon, the NEM starts to decline the wind direction changes; the cold water currents spread to the northern area. Therefore, the concentration of Chl. *a* is low during early two month of the season. In May, due to higher SST and SWM

Fig. 4 Annual temporal variation of Chl. *a* concentration during 2004-2008 from SeaWiFS time-series images in the study area.

winds, Chl. *a* concentration has an average value slightly higher compared with the previous period.

During transition period from the end of May to early June, Chl. *a* concentration increases significantly, with occurrence of the second higher peak of Chl. *a* average value about $0.72 \text{ mg}\cdot\text{m}^{-3}$ in July. The concentration of Chl. *a* also tends to decrease gradually from inshore towards offshore due to the SWM winds. During July, algal bloom is concentrated and gradually spread towards northwest-southeast on Binh Thuan coastal region (Fig. 5). With stronger SWM winds, this bloom is dispersed more quickly.

In inter-monsoon season (September to October), the SWM wind is weakened and the Chl. *a* peak has narrow distribution, spreading in coastal water of Khanh Hoa region. Chl. *a* concentration is slightly lower in this period, with the average value of $0.36 \text{ mg}\cdot\text{m}^{-3}$. However, this is the period that shows the widest ranges of Chl. *a* concentration distribution offshore, which could be due to changes in wind directions from the SWM to NEM.

During SWM, higher Chl. *a* concentration was found in areas such as along the coastal of Ninh Thuan-Binh Thuan, associated with upwelling (Fig. 5c); during the NEM and inter-monsoon season, the highest Chl. *a* concentration is observed offshore region of Ninh Thuan (Figs. 5a and 5d) and Phan Thiet, near the northwest shallow banks of Phu Quy island. In the Ninh Thuan region, the interaction of

internal waves and also offshore cyclonic eddies could be the principal reasons for these high biomass areas, which can be considered as an indicator of upwelling in offshore during NEM. This anomaly is also associated with sudden topography change of shallow waters including the system of subsurface island at the northwest of Phu Quy Island. The shallow waters along the coast where high nutrient concentration are found, and high average light intensity, create optimal environment conditions for phytoplankton growth, resulting in high Chl. *a* concentration [15].

3.2 Distribution of Chl. *a* Concentration and Algal Blooms in the Upwelling Region

Based on the high resolution satellite images Landsat ETM⁺ (30 m) and AVNIR-2 (10 m), together with monthly in-situ data, the spatial and temporal variations of Chl. *a* and algal blooms can be characterized.

During SWM, Chl. *a* concentration is lowest in early spring (March) in coastal water of Ninh Thuan province with average value of $0.1\text{-}0.2 \text{ mg}\cdot\text{m}^{-3}$, and increases continuously in the following months, from $0.2\text{-}0.4 \text{ mg}\cdot\text{m}^{-3}$ in April, from $0.8\text{-}1.0 \text{ mg}\cdot\text{m}^{-3}$ in May-June; and highest during July-August with value about $1.0\text{-}2.5 \text{ mg}\cdot\text{m}^{-3}$. High anomaly of Chl. *a* concentration is observed in offshore of Phan Ri with maximum value of $2.5 \text{ mg}\cdot\text{m}^{-3}$ during July and August. Although a similar anomaly is also observed in March it is

weaker and confined to a smaller area (Figs. 6a and 6d). The above-mentioned high anomaly and algal bloom are located within the center of upwelling region during SWM (from March to August annually) as has also been highlighted by previous studies [8, 15, 16].

In coastal water of Binh Thuan province, Chl. *a* concentration is relatively low with average value of $0.2\text{--}0.3\text{ mg}\cdot\text{m}^{-3}$. A strong bloom of Chl. *a* exists at Ne Cape reaching $1.5\text{ mg}\cdot\text{m}^{-3}$ occurs during June 2007; another lies at Ke Ga cape during July 2007 with maximum value of $10\text{ mg}\cdot\text{m}^{-3}$ (Figs. 6 e-f).

During NEM, Chl. *a* concentration is relatively high

with average value of $0.6\text{--}0.7\text{ mg}\cdot\text{m}^{-3}$. A one kilometer wide strip of high Chl. *a* exists along coastal region of Ninh Thuan province. This strip lies much closer to the coast but is not attached to it. The distinct feature of this area is the numbers of small rivers and short river cascade system. That fresh water runoff is not sufficient for creating algal blooms. Thus, “floating” material from the offshore is believed to be reach to the coast with NEM currents (Figs. 7a and 7b).

In coastal waters of Binh Thuan province, there exist patches of high Chl. *a* including a patch in southern-Ke Ga cape and another lying near Mui Ne

Fig. 5 The distribution of Chl. *a* concentration in (a) January, (b) April, (c) July and (d) October in 2008 from MODIS monthly composite images.

Fig. 6 Chl. *a* distribution of coastal waters in different regions during SWM: (a-d): An anomaly of high Chl. *a* center of upwelling usually exists in Phan Ri Bay, Ninh Thuan province; (e, f): Chl. *a* distribution in Binh Thuan waters during SWM with anomaly close to coast and on southern side of headlands such as in Ne cape and Ke Ga cape.

Fig. 7 Chl. *a* distribution in coastal waters of Binh Thuan region during NEM (a-b); Chl. *a* distribution in coastal and offshore of Binh Thuan region during NEM (c-d) showed high biomass patches in both coastal and offshore waters near Phu Quy Island.

cape. Another broad patch of high biomass bloom also occurred offshore of Phu Quy Island during November 2008.

The formation of coastal lanes and patches of high biomass offshore is related strongly to the abundant biological resources in this region. They include important grounds of bivalve *Chamis nobilis*, *Anadara antiquata*, *Modiolus philippinus* near the coast and also pelagic fishery schools (e.g. *Decaterus kuroides*, *Decaterus maruadsi*, *Taius tumifront* and *Saurida* sp.) on a series of shallow banks in offshore waters of

Binh Thuan province near Phu Quy Island [5]. The study of upwelling in this area also showed that the position of coastal mollusk grounds and pelagic fishery schools in related with the high volume of phytoplankton, zooplankton and benthos [16].

From high resolution imagery, anomalies of higher Chl. *a* offshore of Phu Quy Island were found, associate with the position of shallow banks (8-10 m deep compare with 40-50 m deep water in the vicinity). AVNIR-2 scene, taken on 21 December 2008, shows clearly the algal blooms of difference

Fig. 8 Distribution of high biomass patches offshore of Phu Quy Island during (a) winter (21 December, 2008) and (b) summer (19 June, 1989).

shapes as “patch”, “lane” and “half moon”. Landsat TM scene taken 19 June 1988, also recorded such phenomena (Figs. 8a and 8b). The effect of sediment plume from Mekong Delta, together with bathymetry “break” of shallow bank as well as local eddies (anticyclonic) creating upwelling currents are main causes of these high biomass patches. During 4th December 2008, there appearances a “silk lane” curl shape in coastal water of Vung Tau, only 200 m wide but with Chl. *a* concentration $> 20 \text{ mg}\cdot\text{m}^{-3}$. However, it existed for only a short time, disappearing on 16th December 2008. Similar features were seen elsewhere but not clearly. The mechanism creating this lane and its relationship with HAB or non HAB is question that needs further study.

4. Conclusions

Based on various of optical satellite images (include 84 scenes of MODIS image, 14 scenes Landsat ETM⁺, 6 scenes of AVNIR-2) together with monthly in-situ data obtained from 21 stations during 2007-2008 in the upwelling region, the spatial and temporal variations of Chl. *a* and algal blooms have been elucidated.

The detailer distribution of phytoplankton high

biomass-algal bloom areas in both SWM and NEM has been determined. The close relationship between algae bloom area and existence ability of fisheries resource grounds is apparent as a result of this study.

Detailed study on relationship between in-situ and remote sensing derived data is essential for studying ecological changes in the upwelling area important as a fishery ground in Vietnamese waters.

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