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Assessment and analysis of the chlorophyll-*a* concentration variability over the Vietnamese coastal waters from the MERIS ocean color sensor (2002–2012)

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ABSTRACT

Spatio-temporal patterns of the chlorophyll-*a* concentration, *Chla*, have been assessed from the MEdium Resolution Imaging Spectrometer (MERIS) over the whole Vietnamese coastal waters from 2002 to 2012. For that purpose, six bio-optical algorithms already documented and based on different approaches have been tested over a large in situ data set collected at different seasons and locations along the Vietnamese coast. The OC5 algorithm (Gohin, Druon, and Lampert, 2002) presents the best performances and has been selected to assess *Chla* in the studied region. The notion of optimal bio-optical environment associated with the best performance of OC5 has been introduced. For suspended particulate matter concentration, *SPM*, lower than 100 $g \cdot m^{-3}$, and colored dissolved organic matter, $a_{cdom}(443)$, lower than 0.5 m^{-1}, *Chla* is estimated with an uncertainty of 36% and a bias of 5%. A *Chla* climatology has been generated and the temporal patterns (seasonal variability, long term trend, and irregular component) have been described using the Census-X-11 time series decomposition method. Three-dimensional hydrodynamical numerical simulations have been used to analyze the spatio-temporal patterns of *Chla*. The seasonal contribution dominates the variance of the signal, in good relationship with the dynamic of the mixed layer depth as well as with the occurrence of a seasonal upwelling induced by the summer monsoon. The irregular variability of *Chla* which may reach up to 35% of the total variance in the central part of the Vietnamese coast, can be explained through the surface kinetic energy and its standard deviation which is associated with small scales processes. A long term monotonic trend from about 2 to >5%$\cdot yr^{-1}$ (that is 20 to >50% from 2002 to 2012) have been noticed in different coastal areas where aquaculture activities exhibit a concurrence increase, ranging from 31% to 113% (in production weight) over the same time period. In situ measurements, and especially of nutrients, are however necessary to confirm the link between aquaculture activities and phytoplankton biomass long term evolutions.

1. Introduction

The Eastern Sea of Vietnam (ESA, 99–122 E, 0–25 N), along the edge of the Eurasian plate, consists of a deep basin (>5000 m) surrounded by Borneo, Palawan, Luzon and Taiwan, and bordered by two continental shelves (~55% in surface, <200 m in depth) to the west: the Gulf of Tonkin in its northwestern part and the Sunda shelf (including the Gulf of Thailand) in its southwestern part, from each side of the Indo-China peninsula (Fig. 1). The ESV is the largest marginal sea in the northwestern Pacific and one of the largest in the world. Along Vietnam, the continental shelf is very wide (>500 km) to the North, very narrow in its South-Central part (~30–40 km width from Qui Nhon to Nha Trang), then wider along the southern coastal areas which open to the Sunda shelf (>300 km off the Mekong River delta).

Along the Vietnamese coasts (3250 km long), the physical and biogeochemical features of estuaries and continental shelves are mainly

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controlled by the Red River to the North and by the Mekong River to the South. Phytoplankton diversity, abundance and distribution are driven by solar energy and by salinity, turbidity and nutrients distributions which depend on riverine inputs and on the prevailing processes of tides, waves, and wind induced currents. Changes in land use (and thus in nutrient ratios and concentrations) combined with the increases in rainfall and temperature over the last two decades were likely responsible of the observed change in phytoplankton diversity and abundance in the Red River distributaries, with the appearance of some potentially toxic species (Chu et al., 2014). The impact of eco-toxic heavy metals released by human activities was also shown to influence the phytoplankton diversity and activity in these estuarine environments (Rochelle-Newall et al., 2011). In this context, remote sensing represents a very powerful tool to assess the spatiotemporal variability of water quality of surface coastal waters of Vietnam.

Seasonality of the phytoplankton distribution in the ESV was shown to be closely related to the coupled processes driven by the East Asian Monsoon in the ESV, from in situ measurements and from coupled physical-biogeochemical model (Ning et al., 2004). Few studies were published on *Chla* distribution from remote sensing data in this coastal area: its seasonality over the Gulf of Tonkin was assessed from SeaWiFS data by Tang, Kawamura, Lee, and Dien (2003), while Ha, Koike, and Nhuan (2014) studied eutrophication in a Bay in North Vietnam from MODIS/Terra data.

The aim of this study is to describe the spatio-temporal patterns of the chlorophyll-*a* concentration in the Vietnamese coastal waters over the last decade (2002–2012) using ocean color remote sensing data collected by the MEdium Resolution Imaging Spectrometer (MERIS). For that purpose, an extensive in situ data set of chlorophyll-*a*, *Chla,* remote sensing reflectance, R_{rs}, and inherent optical properties, IOPs, gathered within different areas of the Vietnamese coastal waters is presented. Various published *Chla* inversion algorithms are then evaluated using this in situ data set. The performances of the most suitable bio-optical algorithm are discussed with regards to geographical location and bio-optical environment. This algorithm is then applied to the MERIS monthly remote sensing reflectance archive. Finally, the temporal variability patterns (seasonal, inter-annual, and long-term trend) of *Chla* over coastal waters of Vietnam are described and discussed. To rely the observed patterns of chlorophyll concentration to ocean dynamics, we use the results of a three-dimensional hydrodynamical numerical simulation performed with the SYMPHONIE primitive equation model (Marsaleix et al., 2008) developed by the SIROCCO group (http://sirocco.omp.obs-mip.fr).

2. Data and method

2.1. The sampling area

The Eastern Sea of Vietnam receives high amounts of freshwater and suspended sediment from the Red River and the Mekong River. The discharge of the Red River was in average 3350 $m^3\ s^{-1}$ and its sediment discharge was 46 × 10^6 t yr^{-1} for the period 1989–2010 (Vinh, Ouillon, Tanh, and Chu, 2014). 71–79% of the water discharge flows during the rainy season (June to October), while 9–18% flows during the dry season (December–April). Since the Hoa Binh impoundment in 1989, the water regulation has changed, and the sediment input to the ESV decreased by 61%, with consequences on harbor silting and coastal erosion (Vinh et al., 2014). The Mekong River discharge is estimated to be 15,000 $m^3\ s^{-1}$ on average and its suspended sediment discharge 144 × 10^6 t yr^{-1} in the upper delta (Vinh, Ouillon, Thao, and Tien, 2016 and ref. therein). Almost 90% of the sediments brought by the Mekong River are trapped in the estuaries and nearshore area. The across-shelf transport is very limited, even close to the river mouth, but a remote depocenter is developing around the tip of Ca Mau peninsula, around 300 km from the river mouths (Liu et al., 2009).

The coastal distribution of phytoplankton is driven by the riverine inputs and strongly constrained by the prevailing processes of tides, waves, and wind induced currents. Tides in the ESV are essentially maintained by the energy flux through the Luzon Strait (Fang, Kwok, Yu, and Zhu, 1999). Diurnal tides are generally larger than semi-diurnal tides in the ESV because of Helmholtz resonance (Zu, Gan, and Erofeeva, 2008; Nguyen et al., 2014). The tidal energy is dissipated in the ESV by the bottom friction in shallow areas and by the scattering of surface tide into internal tides (Zu et al., 2008). The ESV is strongly influenced by the periodic semi-annual reversing circulation of the atmosphere associated to the monsoon regime (Pohlmann, 1987). In winter northeasterly wind dominate with an average velocity of 9 m s^{-1} over Vietnam (October–April). In summer, weaker southwesterly winds (~6 m s^{-1}) prevail over most parts of the ESV, and turn to more southerly winds in its northern parts (June–September). The circulation in the ESV is driven by the monsoon winds and by the water exchanges through the Luzon Strait and Taiwan Strait, and constrained by the bottom topography along the continental margins. The monsoon-dominated wind field over the ESV generates a general anticyclonic circulation in summer and a cyclonic circulation in winter (Wyrtki, 1961; Shaw and Chao, 1994; Cai, Huang, and Long, 2003). Wave seasonality follows the regional monsoon wind fields (Vinh et al., 2016).

2.2. In situ measurements

Data from seven field surveys performed between 2011 and 2015 were used in this study (Fig. 1). Four campaigns were organized in the Halong Bay – Haiphong estuary in the frame of the project VITEL (7–18 Nov. 2011, 48 stations; 28 June–5 July 2013, 41 stations; 5–12 July 2014, 36 stations) and of the Black Carbon project (15–17 Oct. 2012, 16 stations). Two campaigns occurred in the Mekong delta coastal zone on 3–4 March 2012 (12 stations) and 19–27 June 2014 (44 stations within the VITEL project, including in the Saigon River estuary). One additional campaign was performed off Nha Trang in April 2014 (16 stations).

Among the 229 sampling stations visited from 2011 to 2015, 160 have been kept for the present study based on the availability of reliable pairs of ($R_{rs}(\lambda)$, *Chla*) data points. Hyperspectral (every 3 nm) radiometric measurements were performed in the 350–950 nm spectral range from TriOS radiometers. Over the 160 $R_{rs}(\lambda)$ spectra, 26 have been obtained from vertical profiles of in-water radiance measurements following the standard protocols of Mueller (2003). The majority of the $R_{rs}(\lambda)$ spectra (134 over 160) were obtained from an upwelling Trios sensor pointed downward and fixed on a floating structure allowing to measure the upwelling radiance, $L_u(\lambda, 0^-)$, at few centimeters (1 to 3 cm) below the sea surface. Based on radiative transfer numerical simulations performed with the Hydrolight, 5.0 code for the conditions encountered during the measurements, the maximum uncertainty related to the impact of the variability of sensor immersion depth on the $L_u(\lambda, 0^-)$ values is assumed to be of about 5%. A down-welling irradiance sensor was fixed on the boat to measure the above water down-welling irradiance, $E_d(\lambda, 0^+)$. Inclination of the different sensors with respect to the vertical was permanently recorded during the measurements. Each $L_u(\lambda, 0^-)$ and $E_d(\lambda, 0^+)$ spectrum represents the average value of individual spectra acquired during few minutes, depending on the sea and sky state, for which an iterative procedure was applied to remove the inappropriate spectra (i. e. with regards to the standard deviation). The remote sensing reflectance was then obtained, after instrument self-shading effect correction (Leathers and Downes, 2004), using the following formulation:

$$R_{rs}(\lambda) = \frac{1-\rho}{n^2}\ \frac{L_u(0^-,\lambda)}{E_d(0^+,\lambda)} \tag{1}$$

where $(1-\rho)$ / n^2 (*n* being the refractive index of water, and ρ the Fresnel reflectance of the air sea interface) is the upward radiance transmittance of the sea surface for normal incidence from below and has a