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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\textsuperscript{A B S T R A C T}

Spatio-temporal patterns of the chlorophyll-a concentration, \(\text{Chla}\), 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 \(\text{Chla}\) 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·m\(^{-3}\), and colored dissolved organic matter, \(\text{CDOM}(443)\), lower than 0.5 m\(^{-1}\), \(\text{Chla}\) is estimated with an uncertainty of 36% and a bias of 5%. A \(\text{Chla}\) 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 \(\text{Chla}\). 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 \(\text{Chla}\) 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 \(\text{Chla}\) of \(\text{Chla}\) has 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.

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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 northeastern 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...
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 Nhu (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 MERIS Resolution Imaging Spectrometer (MERIS). For that purpose, an extensive in situ data set of chlorophyll-a, Chla, remote sensing reflectance, Rrs, 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 m³ s⁻¹ and its sediment discharge was 46 × 10⁶ 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 m³ s⁻¹ on average and its suspended sediment discharge 144 × 10⁶ 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 north-easterly 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 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 \( R_{\text{rs}}(\lambda), \text{Chla} \) data points. Hyperspectral (every 3 nm) radiometric measurements were performed in the 350–950 nm spectral range from TriOS radiometers. Over the 160 \( R_{\text{rs}}(\lambda) \) spectra, 26 have been obtained from vertical profiles of in-water radiance measurements following the standard protocols of Mueller (2003). The majority of the \( R_{\text{rs}}(\lambda) \) 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:

\[
R_d(\lambda) = \frac{1 - \rho}{n^2} \frac{L_u(0−, \lambda)}{E_d(0+, \lambda)}
\]

where \((1 - \rho) / n^2\) being the refractive index of water, and \(\rho\) 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
Fig. 1. Location of sampling stations. Each color corresponds to a specific location and sampling time period: yellow for Mekong Delta in March 2012 (MD-03/2012), blue for Mekong Delta in June 2014 (MD-06/2014), and pink for Nha Trang in April 2015 (NT-04/2015). Halong Bay and Haiphong Estuary have been sampled in November 2011 (HB/HE-11/2011) (red), October 2012 (HB/HE-10/2012) (black), from May to July 2013 (HB/HE-05-07/2013) (green), and July 2014 (HB/HE-07/2014) (grey). Isobaths are indicated on each map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
nearly constant value ($\approx 0.543$) regardless of the sea state (Austin, 1974). Quality controls based on the application of several criteria such as unusual $R_{rs}(\lambda)$ spectral shapes, noisy spectra in the red part of the spectrum, and deviation within the mean $R_{rs}(670)$ vs. suspended particulate matter, SPM, (in g·m$^{-3}$), relationship, were systematically applied.

Water samples were collected just below the sea surface and at 1.5 m deep using a 5-L Niskin bottle. The chlorophyll-a concentration ($Chla$) values reported in the present study represent the average value calculated from the values obtained at these two different depths, from which only slight differences in $Chla$ have been observed. $Chla$ was measured fluorometrically on methanol-extracted samples collected on GF/F filters using the method of Holm-Hansen, Lorenzen, Holmes, and Strickland (1965). Besides $Chla$, the bio-optical environment of each station is simply characterized by the suspended particulate matter concentration, SPM, (in g·m$^{-3}$), the absorption coefficient of colored dissolved organic matter at 443 nm, $a_{cdom}(443)$, (in m$^{-1}$), the $a_{cdom}(443)/a_{nw}(443)$ ratio, where $a_{nw}(443)$ represents the non-water absorption coefficient, and the $b_{bp}(650)/Chla$ ratio, (in mg·m$^{-2}$), where $b_{bp}(650)$ is the particulate backscattering coefficient at 650 nm. The $b_{bp}(650)/Chla$ and $a_{cdom}(443)/a_{nw}(443)$ ratios provide general information on the scattering and absorbing environment, respectively. The $b_{bp}(650)/Chla$ ratio, used to identified turbid waters (Loisel, Lubac, and Dessailly, 2010), depends on the bulk particulate matter assemblage (mineral vs. organic; size, etc.) and the $a_{cdom}(443)/a_{nw}(443)$ ratio gives the relative proportion between absorption by dissolved and particulate matter.

$b_{bp}(650)$ is estimated from WET Labs ECO BB-9 measurements processed according to Neukermans, Loisel, Mériaux, Astoreca, and McKee (2012). Note that, due to missing $b_{bp}(650)$ data at some stations (25%), this parameter was alternatively estimated from SPM using the model of Neukermans et al. (2012) which has been successfully tested over the existing 120 $b_{bp}(650)$ data. SPM and $a_{cdom}(443)$ were measured following the same protocols than the ones presented in Lefebvre et al. (2012) based on GF/F filters, and Vantrepotte et al. (2015) based on 0.22-μm Millipore membrane, respectively. Despite the deployment of a WET Labs ac-s, $a_{nw}(443)$ was estimated from the present study as the sum of the measured $a_{cdom}(443)$, and calculated $a_{bpw}(443)$ and $a_{bpg}(443)$ obtained by the models of Briand, Claustre, Ras, and Oubelkheir (2004) and Babin et al. (2003), respectively. The use of these two models, which provide relatively good estimates of these two absorption coefficients (at least for the purpose of this study for which only rough estimate of $a_{nw}(443)$ is needed), is motivated by the fact that measurements were not always available for the selected 160 stations used in the present study, and is further supported by the good results obtained from the comparison of the measured (when available) and modeled $a_{nw}(443)$ values.

### 2.3. Satellite data

Reduced spatial resolution (1 × 1 km$^2$ at nadir) of daily $R_{rs}(\lambda)$ data collected over the Vietnamese coastal waters by the Medium Resolution Imaging Spectrometer (MERIS) [Rast and Bézy, 1995] from the 28/04/2002 to the 08/04/2012 were downloaded from the NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Only pixels presenting the shortest distance to the coast lower than 200 km and with a bottom depth not deeper than 4000 m were kept. Monthly products have been processed from arithmetic mean, after application of the different recommended masks.

### 2.4. Tested algorithms

Different bio-optical algorithms already documented and based on different approaches have been tested in the frame of this study. First, three different standard algorithms developed for open ocean waters were examined. The OC4v6 and OC4E empirical algorithms developed for the SeaWiFS and MERIS sensors, respectively, are based on blue-to-green (BG) reflectance ratios. OC4v6 is an updated (2009) version of OC4v4 (O’Reilly et al., 1998). They both follow a fourth-order polynomial switching relationship between the maximum BG reflectance ratios and $Chla$:

$$Chla = 1g(a + b\times BG + c\times BG^2 + d\times BG^3 + e\times BG^4)$$

(2)

where

$$BG = \log_{10}\left[\max\left(\frac{R_{rs}(\lambda_{\text{blue}})}{R_{rs}(\lambda_{\text{green}})}\right)\right]$$

(3)

with $\lambda_{\text{blue}}$ equal to 443, 490, 510 nm for SeaWiFS and MERIS; and $\lambda_{\text{green}}$ is 555 nm and 560 nm for SeaWiFS and MERIS, respectively. For OC4v6, the values of the $a$, $b$, $c$, $d$, and $e$ coefficients are 0.3272, −2.9940, 2.7218, −1.2259, and −0.5683, respectively. For OC4E, the values of the $a$, $b$, $c$, $d$, and $e$ are 0.3255, −2.7677, 2.4409, −1.1288, and −0.4990 (O’Reilly et al., 2000), respectively.

The third algorithm is the GSM semi-analytical algorithm (Maritorena, Siegel, and Peterson, 2002) which is based on the standard quadratic relationship between $R_{rs}(\lambda)$ and the $b_{bp}(\lambda) / (b_{bp}(\lambda) + a(\lambda))$ ratio, where $b_{bp}(\lambda)$ and $a(\lambda)$ are the backscattering and absorption coefficients, respectively. GSM involves a set of three parameters (spectral slopes of $b_{bp}(\lambda)$ and $a_{dom}(\lambda)$, and specific phytoplankton absorption, $a_{phy}(\lambda)$) allowing the chlorophyll concentration, the particulate backscattering coefficient, $b_{bp}(\lambda)$, and the colored detrital matter absorption coefficient, $a_{det}(\lambda)$, to be assessed. For the present study, the standard GSM parameterization documented in IOCCG (2008) was considered. The latter settings have been optimized over an open ocean data set, and are therefore not representative of coastal oceans.

In contrast with the three previous algorithms, used to assess the performance of open ocean waters algorithm over the present data set, three additional algorithms developed for coastal waters were also considered. The first one is based on the Tassan (1994) formulation for which the parameters have been optimized over a large data set collected in the Yellow and East China Sea (Siswanto et al., 2011):

$$Chla = 1g(0.342 - 2.511\times\log(R) - 0.277\times\log^2(R))$$

(4)

with

$$R = \left(\frac{R_{rs}(443)}{R_{rs}(555)}\right) \left(\frac{R_{rs}(412)}{R_{rs}(490)}\right)^{-1.012}$$

(5)

The second algorithm (MERIS2B), developed by Curlin, Gitelson, and Moses (2011), is based on the use of NIR-red bands to assess the chlorophyll concentration from MERIS over turbid productive waters:

$$Chla = 25.28 \times \left(\frac{p(665)}{p(705)}\right)^2 + 14.85 \times \left(\frac{p(665)}{p(705)}\right)^{-15.18}$$

(6)

with $p(\lambda) = \pi R_{rs}(\lambda)$. The last algorithm is the OC5 Look-Up Table (LUT) based approach developed by Gohin et al. (2002). This algorithm was designed to give similar $Chla$ values than OC4 (or similar algorithms) over open ocean waters, but lower $Chla$ values in turbid waters. The OC5 LUT has been built based on a validation data set gathering measurements performed all along the year over three contrasted coastal sites (Bay of Biscay, English Channel, and North-Western Mediterranean waters), ensuring the lowest possible bias throughout the seasons for these three regions (Gohin, 2011). Many other bio-optical algorithms exist to assess $Chla$ in coastal waters. However, the objective of this paper is not to perform an extensive review of all algorithms, but whether to find the suitable ones for Vietnamese coastal waters, and also to select an algorithm which has been already tested in other areas to evaluate its “universality”. 


2.5. Statistical indicators

The accuracy of Chla estimates has been evaluated using the root mean squared difference, RMSD, the mean absolute relative difference (i.e. uncertainty), MARD, and the mean relative difference (i.e. bias), MRD, expressed respectively as:

\[
\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{N}(\text{Chla}_{\text{meas}} - \text{Chla}_{\text{inv}})^2}{N}}
\]

(7)

\[
\text{MARD} = 100 \frac{1}{N} \sum_{i=1}^{N} \frac{|\text{Chla}_{\text{meas}} - \text{Chla}_{\text{inv}}|}{\text{Chla}_{\text{meas}}}
\]

(8)

\[
\text{MRD} = 100 \frac{1}{N} \sum_{i=1}^{N} \frac{\text{Chla}_{\text{meas}} - \text{Chla}_{\text{inv}}}{\text{Chla}_{\text{meas}}}
\]

(9)

where \(N\) is the number of samples in the data set, \(\text{Chla}_{\text{meas}}\), the measured Chla value and \(\text{Chla}_{\text{inv}}\) the inversed Chla value. Linear regression on Log transformed data is also used for evaluation purpose.

2.6. Temporal pattern analysis

Monthly Chla time series were decomposed using the Census X-11 method (Pezzulli, Stephenson, and Hannachi, 2005), whose application to time-series analysis of satellite ocean color data has been extensively documented (Vantrepotte and Mélin, 2011) in order to take into account the potential presence of missing data. Briefly, if a defined month presents >50% of

\[
X(t) = S(t) + T(t) + I(t)
\]

(10)

where \(S\) is the seasonal signal, \(T\) the trend cycle signal and \(I\) the irregular or residual signal. The Census X-11 method is based on an iterative bandpass filtering procedure that describes the seasonal signal as non-periodical thus explicitly allowing the consideration of inter-annual variations in the seasonal cycle shape (Pezzulli et al., 2005; Vantrepotte and Mélin, 2011). In order to identify the main spatial patterns of temporal variability, maps of the relative part of variance of the initial series associated with the component \(S(t), I(t)\) and \(T(t)\) can be then computed. The trend-cycle term derived from the X-11 decomposition procedure has been shown to be particularly adapted for describing non-linear patterns from various applications performed on a variety of ocean color products (Vantrepotte and Mélin, 2011; Vantrepotte et al., 2011). In addition to the latter statistical method, the presence of significant monotonic change in the data over the MERIS time period has been assessed using the seasonal Kendall test applied while the amplitude of the observed trends (in %·yr\(^{-1}\)) has been quantified using the Sen’s slope estimator (Gilbert, 1987).

A pre-processing of the Chla monthly series was performed on each time series prior further temporal analysis (see the detailed method in Vantrepotte and Mélin, 2011) in order to take into account the potential presence of missing data. This statistical analysis is conducted at the level of each grid point and aims at decomposing a time series \(X(t)\) (here monthly OCS Chla products) into three additive components such as:

![Fig. 2. Bathymetry and grid (1 over 10 points are represented) of the modeled domain (left) and detailed bathymetry of the study area (right).](image)

### Table 1

Median, minimum, and maximum values for different parameters as indicated over the three sampled regions at different time period (see Fig. 1). MD, NT, and HB/HE stand for Mekong Delta, Nha Trang, and Halong Bay and Haiphong Estuary, respectively. \(N\) represents the number of data points.

<table>
<thead>
<tr>
<th>Location and time period</th>
<th>Chla mg·m(^{-3})</th>
<th>SPM g·m(^{-3})</th>
<th>(\alpha_{443}(443)) m(^{-1})</th>
<th>(b_{650}/(\text{Chla m}(^{2})·mg(^{-1}))</th>
<th>(\alpha_{443}/\alpha_{443})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD-06/2014</td>
<td>1.94 [0.3; 7.1] N = 37</td>
<td>5.61 [1.0; 240] N = 37</td>
<td>0.08 [0.014; 0.75] N = 38</td>
<td>0.032 [0.0045; 1.23] N = 36</td>
<td>0.30 [0.073; 0.53] N = 36</td>
</tr>
<tr>
<td>MD-03/2012</td>
<td>5.52 [0.68; 10.4] N = 4</td>
<td>12.3 [4.6; 33.7] N = 4</td>
<td>0.033 [0.0095; 0.061] N = 4</td>
<td>0.013 [0.0044; 0.123] N = 16</td>
<td>0.69 [0.135; 0.832] N = 14</td>
</tr>
<tr>
<td>NT-04/2015</td>
<td>0.57 [0.13; 0.74] N = 16</td>
<td>1.12 [0.47; 7.5] N = 16</td>
<td>0.102 [0.03; 0.21] N = 14</td>
<td>0.013 [0.0044; 0.123] N = 16</td>
<td>0.69 [0.135; 0.832] N = 14</td>
</tr>
<tr>
<td>HB/HE-07/2014</td>
<td>2.81 [0.37; 33.4] N = 23</td>
<td>3.13 [1.05; 28.3] N = 23</td>
<td>0.13 [0.06; 0.42] N = 23</td>
<td>0.0068 [0.0008; 0.030] N = 23</td>
<td>0.47 [0.28; 0.70] N = 23</td>
</tr>
<tr>
<td>HB/HE-05-07/2013</td>
<td>4.04 [1.0; 21.0] N = 39</td>
<td>32.7 [5.23; 147.7] N = 39</td>
<td>0.39 [0.13; 1.16] N = 33</td>
<td>0.081 [0.013; 0.31] N = 39</td>
<td>0.34 [0.087; 0.66] N = 33</td>
</tr>
<tr>
<td>HB/HE-11/2011</td>
<td>2.64 [1.46; 10.2] N = 27</td>
<td>5.13 [2.05; 13.4] N = 27</td>
<td>0.129 [0.049; 0.16] N = 22</td>
<td>0.012 [0.0028; 0.046] N = 27</td>
<td>0.34 [0.15; 0.57] N = 22</td>
</tr>
<tr>
<td>HB/HE-10/2012</td>
<td>2.16 [1.44; 4.51] N = 14</td>
<td>7.76 [4.2; 27.2] N = 14</td>
<td>0.079 [0.042; 0.11] N = 14</td>
<td>0.021 [0.0085; 0.052] N = 14</td>
<td>0.25 [0.11; 0.32] N = 14</td>
</tr>
</tbody>
</table>
missing data over the whole number of available years, then all values for that month were discarded, leading then in practice to the creation of shortened time series (periodicity for a defined pixel ≤ 12 months).

If \( N > 25\% \) of the remaining data were missing for the obtained time series, then no further analysis was performed for the corresponding pixel, otherwise gaps in the series, when existing, were filled using the eigenvectors filtering method proposed by Ibanez and Conversi (2002).

2.7. The three-dimensional hydrodynamical numerical simulation

The SYMPHONIE primitive equation model (Marsaleix et al., 2008) was used for oceanographic studies covering a wide range of regions and processes: dense water shelf and open ocean formation (Herrmann, Somot, Sevault, Estournel, and Deque, 2008a; Herrmann et al., 2008b, Estournel et al., 2016), internal waves (Auclair et al., 2011), wave-current interactions (Michaud et al., 2011), radioactive elements propagation (Estournel et al., 2012). The curvilinear orthogonal grid covers most of the South China Sea, with a varying mesh size decreasing linearly from ~6.5 km offshore to ~1.5 km along the Vietnamese coast, and 30 vertical generalized sigma-coordinates models (Fig. 2). The surface forcing is prescribed using the 3-hourly output of the ECMWF 1/8° atmospheric analysis (ECMWF, 2011). The initial and lateral ocean boundary conditions are prescribed using the daily outputs of the global ocean 1/12° analysis distributed by the COPERNICUS European service on http://marine.copernicus.eu. Tidal forcing is based on FES2012 (Carrère, Lyard, Cancet, Guillot, and Roblou, 2012). Too few river runoff data are available to prescribe interannual daily or even monthly water runoff to the model, we therefore build a monthly climatology of freshwater river runoff for the 30 main rivers of the modeled domain by compiling different sources of information available (e.g. from the Mekong River Commission). The simulation covers the period January 2013–April 2016.

3. Results

3.1. Description of the in situ data set

The chlorophyll and suspended particulate matter concentrations span over more than two orders of magnitude; from 0.13 mg·m\(^{-3}\) (in Ninh Thuan – Binh Thuan coastal areas) to 33.4 mg·m\(^{-3}\) (in Halong Bay) for Chla, and from 0.47 g·m\(^{-3}\) (in Ninh Thuan – Binh Thuan coastal areas) to 240 g·m\(^{-3}\) (in the Saigon River) for SPM (Table 1). According to the criteria proposed in Loisel et al. (2010), and based on the \( b_{650}/\text{Chla} \) value, most of the sampling stations (126; 78%) can be classified as turbid waters (Fig. 3). The remaining stations were sampled in coastal waters of Ninh Thuan – Binh Thuan (NT-04/2014), in mesotrophic offshore waters of the Mekong delta (part of the MD-06/2014 data set), and in eutrophic waters of Halong bay-Haiphong Estuary (part of the HB/HE-07/2014 and HB/HE-11/2011 data sets). The \( b_{650}/\text{Chla} \) values range between 0.00084 m\(^2\)·mg\(^{-1}\) (NT-04/2014) and 1.24 m\(^2\)·mg\(^{-1}\) (Saigon River). Removing the four stations sampled in the river, the maximum value is 0.12 m\(^2\)·mg\(^{-1}\). This high range of variability in \( b_{650}/\text{Chla} \) stresses the great variability of the particulate pool.

![Fig. 3.](image3) \( b_{650}(650) \) as a function of Chla for the 161 stations considered in this study. The dashed line corresponds to the turbid water criteria provided in Loisel et al. (2010). Each color data point corresponds to a specific region and time period as indicated. MD, NT, and HB/HE stand for Mekong Delta, Nha Trang, and Halong Bay and Haiphong Estuary, respectively.

![Fig. 4.](image4) \( R_s(\lambda) \) spectra collected over the three selected regions at different time periods. (a) Halong Bay and Haiphong estuary in November 2010 and October 2011 (b) Halong Bay and Haiphong estuary between May and July 2013 and 2014 (c) Nha Trang in April 2015 and (d) Mekong delta area in March 2012 and June 2014.
assemblage in terms of chemical composition and size. For a given Chla concentration, bulk particulate matter composed of individual particles with different size and refractive index, or aggregates will scatter light differently in the backward direction, providing very different \(b_{bp}(650)/\text{Chla}\) values. For instance, high \(b_{bp}(650)/\text{Chla}\) are observed in mineral dominated waters, while phytoplankton dominated waters provide the lowest \(b_{bp}(650)/\text{Chla}\) values. The absorption by colored dissolved organic matter ranges between 0.014 m\(^{-1}\) in offshore waters of the Mekong delta (in MD-06/2014) and 1.16 m\(^{-1}\) in Haiphong estuary (HB/HE-11/2011). The highest contribution of colored dissolved organic matter to the non-water absorption process \(a_{cdom}(443)/a_{nw}(443) = 83\%\) is observed in the Ninh Thuan - Binh Thuan coastal areas (NT-04/2015) which are characterized by the lowest Chla and SPM concentrations. The lowest \(a_{cdom}(443)/a_{nw}(443)\) ratio values are observed in the Saigon river in July 2014 (even if they present very high \(a_{cdom}(443)\) values) and in the Haiphong estuary in July 2013 (HB/HE-05-07/2013).

The wide biogeochemical and optical variability of the sampled stations directly impact the shape and intensity of the remote sensing spectra (Fig. 4). Over most of the stations considered here (except for Ninh Thuan - Binh Thuan and some off shore stations), \(R_{rs}(\lambda)\) starts increasing from 350 nm to about 580 nm, from which \(R_{rs}(\lambda)\) starts decreasing toward the red part of the spectrum for some data (Fig. 4a), but remains relatively constant up to 700 nm for others (Fig. 4b). This plateau is explained by high scattering level mainly due to mineral particles. The highest level of reflectance is observed within the Mekong delta area (Fig. 4d) and in the Halong bay and Haiphong estuary during the summer period (Fig. 4b). Stations sampled in Nha Trang (Fig. 4c) are characterized by typical mesotrophic/eutrophic \(R_{rs}(\lambda)\) spectral shape with a maximum around 490 nm (except for the three more coastal

![Graphs and diagrams showing comparisons of measured and inverted Chla values](image-url)
stations). The impact of the chlorophyll absorptions maxima may also slightly be noticed on the $R_\text{c}(\lambda)$ spectra around both 440 (Fig. 4c) and 660 nm (for almost all spectra). For turbid waters, the peak observed around 800 nm is due to the pure water absorption depression.

3.2. Performance of Chla algorithms

The performance of the six selected algorithms, used in their original form, has been evaluated from the in situ data set to select the most appropriate ones for the assessment of Chla content from ocean color remote sensing over Vietnamese coastal waters (Fig. 5). The performance of these 6 different algorithms does not seem to be regionally dependent, at least from the present data set. As expected, the three algorithms (OC4v6, OC4E, and GSM) developed and optimized for open ocean waters, present poor Chla retrieval. Chla is over-estimated with bias values of 82% and 72% using the OC4v6 (Fig. 5a) and OC4E (Fig. 5b), respectively. The RMSE value is around 4 $\text{mg} \cdot \text{m}^{-3}$ for these two models. The uncertainty values for OC4v6 and OC4E are 88% and 80%, respectively. The GSM model, based on the version optimized for open ocean waters, overestimates Chla with a bias of 188% and an uncertainty of 196% (Fig. 5c). The slope value of the linear regression is however better than the two previous models. Note that GSM provides unrealistic (very high) Chla values for about 19% of the data points, certainly due to the spectral slopes values of $a_{\text{cdom}}(443)$ and $b_{\text{bp}}(\lambda)$ that may differ significantly from the ones fixed in the model. These results strongly emphasize that standard bio-optical algorithms dedicated to open ocean waters cannot be applied over Vietnamese coastal waters.

The MERIS two bands algorithm (Gurlin et al., 2011), dedicated to the assessment of Chla in coastal waters, provides negative Chla values for about 20% of the data points (not shown). Although the slope of the linear regression between the estimated and measured Log(Chla) calculated over the 131 remaining data points is very close to unit, this algorithm tends to over-estimates Chla (Fig. 5d). The uncertainty and bias values are 149% and 132%, respectively. In comparison, the model of Siswanto et al. (2011) (Fig. 5e) is characterized by lower RMSE (3.95 $\text{mg} \cdot \text{m}^{-3}$), bias ($-9\%$), and uncertainties ($44\%$). However, this model drastically underestimates Chla over 1 $\text{mg} \cdot \text{m}^{-3}$, as shown by the linear regression slope value of 0.53 calculated between the estimated and measured Log(Chla) value. In contrast to the latter two algorithms, OC5 is able to assess Chla with a relatively good accuracy over the whole tested Chla range (Fig. 5f). The RMSE, bias, and uncertainty values are 3.7 $\text{mg} \cdot \text{m}^{-3}$, 27%, and 54% respectively. Also, the slope of the relationship between the modeled and the measured Chla values is close to 1. The relatively good performance of OC5 is consistent with previous studies performed in other contrasted coastal areas such as the highly turbid coastal waters of the Ganges Delta in the Bay of Bengal (Tilstone et al., 2011) or in the Bay of Biscay (Novoa et al., 2012). OC5 also provides relatively good retrieval over moderately turbid areas of the Mediterranean waters: the Rhone river plume (Fontana, Christian, Pinazo, Marsaleix, and Diaz, 2009), the Ligurian and Tyrrhenian seas (Lapucci et al., 2012) and the Alboran Sea (Gomez-Jakobsen et al., 2016). A recent study performed over the Baltic sea, where different Chla algorithms were compared in the frame of an extensive match-up data set (N = 4492), shows that OC5 presents slightly better Chla retrieval in this relatively high absorbing environment (Pitarch, Volpe, Colella, Krasemann, and Santoleri, 2016).

Based on this comparison exercise, the OC5 algorithm is selected to assess the spatio-temporal variability of Chla in Vietnamese coastal waters. While the OC5 performance does not depend on the sampled region (Fig. 5f), the impact of the bio-optical environment is now examined more precisely. Regression analysis between the Chla relative error ($\text{Chla}_{\text{inv}} - \text{Chla}_{\text{meas}}$) / $\text{Chla}_{\text{meas}}$, and SPM, $a_{\text{cdom}}(443)$, $b_{\text{bp}}(650)$ / Chla and $a_{\text{cdom}}(443)$ / Chla are performed to assess the limit of applicability of OC5 (Fig. 6). While no significant trend is found with $a_{\text{cdom}}(443)$ / $\text{Chla}_{\text{meas}}$, the relative error depends on the SPM, $a_{\text{cdom}}(443)$, $b_{\text{bp}}(650)$ / Chla values (Fig. 6). The mean relative error is around 800 nm is due to the pure water absorption depression.

Fig. 6. Evolution of the OC5-Chla relative error, ($\text{Chla}_{\text{inv}} - \text{Chla}_{\text{meas}}$) / $\text{Chla}_{\text{meas}}$, as a function of SPM, $a_{\text{cdom}}(443)$, and $b_{\text{bp}}(650)$ / Chla. The solid curve represents the best exponential fit to the data set.

Fig. 7. Comparison of the measured and OC5-inversed Chla excluding the 29 data points with SPM values > 100 $\text{g} \cdot \text{m}^{-3}$, $b_{\text{bp}}(650)$ / Chla values > 0.1 $\text{m}^{-2} \cdot \text{mg}^{-1}$, and $a_{\text{cdom}}(443)$ value > 0.5 $\text{m}^{-1}$.
around 0 over a large range of values, and then starts increasing sharply from the higher range values for each of the latter parameter. Based on this result, the optimal bio-optical environment of OC5 corresponds to situations when $SPM$, $a_{cdom}(443)$, and $b_{bp}(650)/Chla$ values are lower than about $100 \, g \cdot m^{-3}$, $0.5 \, m^{-1}$, and $0.1 \, m^2 \cdot mg^{-1}$, respectively. This result emphasizes that OC5 fails in very turbid waters ($SPM > 100 \, g \cdot m^{-3}$) dominated by mineral particles (very high $b_{bp}/Chla$ value), and in very absorbing waters ($a_{cdom}(443) > 0.5 \, m^{-1}$). Note that such conditions are rarely observed in coastal waters. For instance, $SPM$ values higher than $100 \, g \cdot m^{-3}$ are likely to be observed mainly over very turbid river plums, or strong resuspension areas in shallow waters, where $Chla$ concentration is generally very low due to a limited light level. In the same way, over the whole CoastalCo data base gathering measurements performed around European coastal areas, only 4 stations over 345 presented $a_{cdom}(443)$ values higher than $0.5 \, m^{-1}$ (Babin et al., 2003), these 3 stations belonging to the data set of 57 stations sampled in the Baltic sea.

The performance of the OC5 algorithm is now evaluated by keeping only the data points following the criteria previously defined ($SPM < 100 \, g \cdot m^{-3}$, $a_{cdom}(443) < 0.5 \, m^{-1}$, and $b_{bp}(650)/Chla < 0.1 \, m^2 \cdot mg^{-1}$). By removing these 29 data points, the performance of OC5 significantly increases (Fig. 7). The RMSE, uncertainties, and bias values are $2.93 \, mg \cdot m^{-3}$ (instead of $3.7 \, mg \cdot m^{-3}$), $36\%$ (instead of $54\%$), and $5\%$ (instead of $27\%$), respectively. The slope of the linear regression between the inversed and measured Log($Chla$) values however slightly decreases from 0.858 to 0.79.

3.3. Application to satellite images

$Chla$ variation coefficient, RSD, (i.e. $100 \times$ standard deviation / mean) computed over the entire MERIS archive on a pixel basis using the OC5 algorithm exhibits a very specific spatial pattern (Fig. 8). The main temporal variability, with a variation coefficient varying from 50 to 70%, is generally observed along the coast and decreases offshore. The center of the Tonkin gulf in the north, and off-shore of the Ca Mau peninsula in the South, also shows a marked temporal variability. The lowest $Chla$ temporal variability is observed in some specific areas: in front of the Mekong and Red River deltas, the Rach Gia bay, and at the Camau peninsula. These $Chla$ temporal patterns should however be interpreted with caution taking into account the limitation of the OC5 algorithm.

![Fig. 8. Variation coefficient of Chla calculated over the entire study period.](image1)

![Fig. 9. Relative contribution (in %) of the (a) seasonal, (b) trend, and (c) irregular components to the total variance of Chla (OC5 algorithm) as calculated with the Census X-11 method over the MERIS time period.](image2)
previously emphasized, and considering that these coastal areas can present SPM concentration higher than 100 g·m$^{-3}$ for some specific months especially at the Mekong and Red River deltas (Loisel et al., 2014a).

To better characterize the temporal variability patterns stressed by the variation coefficient, the Census X-11 method is used to assess the relative contribution of the seasonal, trend, and irregular components to Chla temporal variability patterns over the whole studied area (Fig. 9). Between 50% and 90% of the total variance is dominated by the seasonal component (Fig. 9a). Lower seasonal contributions (40% to 50%) are found off-shore, between 12° to 14° north, and all along the Northern coast of the gulf of Tonkin. These two specifics areas present

Fig. 10. Chla (OC5 algorithm) monthly climatology over the study area and calculated from the monthly Chla products over the MERIS time period.
conversely higher contribution of the trend (20%) and irregular (30–40%) components when compared to other coastal areas where these two components represent about 5–10% of the total variance (Fig. 9a–b). The relatively high contribution of the irregular component observed between 12° to 14° north, could partly be explained by the occurrence of the non-permanent central upwelling system (between about 10° and 15° N) induced by the summer monsoon, which influence on nutrients distribution and therefore on the Chla spatio-temporal patterns in this region has been already documented (Xie, Xie, Wang, and Liu, 2003; Liu et al., 2002). This latter feature is clearly supported by the monthly Chla climatology showing that Chla starts increasing along the coast in June, while a pattern of higher Chla value is later observed offshore until October when the wind direction reverses (Fig. 10).

These Chla spatio-temporal patterns are analyzed with regards with the modeled summer (July–August) and winter (December–June) mixed layer depth (MLD), sea surface temperature (SST) and salinity (SSS) (Fig. 11), as well as with surface kinetic energy (KE) (Fig. 12). MLD is computed using a 0.01 kg·m$^{-3}$ sigma threshold. This threshold was selected by examining the density profiles in the area of study and testing several threshold values, both in the open sea and on the shallow shelf submitted to river influence. Comparison with previous studies suggest that our model represents correctly this variability in the South China Sea and the associated ranges (from 40 m in summer to 100 m in winter, Wyrtki, 1961), though more extensive comparisons with hydrological profiles obtained from in-situ observations will be necessary to evaluate more quantitatively the realism of the MLD representation in our model. (Sub)mesoscale ocean dynamics can influence significantly primary production, in particular through their impact on nutrient vertical and horizontal distribution (Oschlies and Garçon, 1998, Lévy et al., 2012). This influence is complex and involved mechanisms that depend on the area and period considered are the scope of a large number of studies (e.g. coastal vs. open sea regions, anticyclonic vs. cyclonic eddies... Hu et al., 2014, José et al., 2014). Here we use the small scale KE as an indicator of (sub)mesoscale ocean activity in order to identify the areas of periods of strong turbulent activity and thus partly explain the observed Chla variability. We computed the...
Fig. 12. Average surface kinetic energy (left) and standard deviation of the small scale kinetic energy (right) over the December-January (top) and July-August (bottom) periods between July 2013 and January 2016 as derived from the hydrodynamical simulation.
standard deviation over the summer and winter periods of small scale KE, which corresponds to the KE associated with processes of a scale smaller than 100 km (Fig. 12). For each years of our simulation, the summer and winter averages of SSS, SST, MLD, KE, standard deviation of small scale KE physical are comparable over the years at the first order, and show interannual variations at the second order (figures not shown). This simulation can therefore be used for our objectives in this paper, which is to use the model to qualitatively explore how chlorophyll concentration spatial and temporal variations can be explained by ocean dynamics.

Over the shelf of the gulf of Tonkin, ocean dynamics show a strong seasonal variability. In winter, northeasterly cold winds blowing along the coast induce the cooling and hence a densification of the surface water resulting in strong vertical mixing (Fig. 11): the mixed layer depth reaches the bottom in most of the region, therefore contributing to the nutrient enrichment of the surface layer, therefore favoring the photosynthetic activity. Phytoplankton blooms offshore-ward from the northeast coast to the central part of the gulf during the northeast monsoon, with the highest Chla values observed in December or January (Fig. 10), as shown by Tang et al. (2003) from SeaWiFS and field data over the 1999–2000 time period. While the photosynthetic available radiation, PAR, values are relatively low during this period, the subtropical location of the gulf of Tonkin provides all along the year favorable light conditions for photosynthesis processes. This high Chla signal, which is induced by the northeast monsoon and the strong currents in the Qionzhou Strait responsible for the nutrients upwelled, is typically seasonal. Conversely, the water column is strongly stratified in summer, because of relatively weak winds and sea surface heating (Fig. 11). High Chla values may also be observed in a narrow band along the northern coast in summer, but the nutrient supply associated to the floods likely showed a high interannual variation, as did the river and sediment discharge (Vinh et al., 2014; their Fig. 4). April is the transitional month between winter and summer conditions. Such a seasonal contrast for the vertical mixing is also observed over the south Vietnam shelf, west of 108°E. The strong contribution of the seasonal component for the Chla temporal variability previously reported in those regions (Fig. 9), associated with winter maximum and summer minimum concentrations (Fig. 10), can thus be mostly explained by the seasonal variability of the vertical mixing processes, with however a higher contribution of irregular component in the Red River region of freshwater influence, due to its inter-annual variability.

The upwelling already observed in summer off the central Vietnam in previous studies (see for example Xie et al., 2003; Liu et al., 2002; Dipper, Nguyen, Hein, Ohde, and Loick, 2007) is clearly observed between 10° N and 13° N on the SST and SSS fields derived from our simulation (Fig. 11). It is responsible for the strong photosynthetic activity observed in this area in summer (Fig. 10). A seasonal upwelling also occurs in summer at ~109° E between 14° N and 17° N, as can be seen on modeled SST and SSS fields (Fig. 11). It is associated with strong turbulent dynamics, as shown by the variability of the small scale KE in July–August (Fig. 12). Moreover, this area, departing from the coast and following the break of the continental shelf (Fig. 2), is also characterized in winter by the presence of the northern boundary current (Fig. 12) that follows the shelf edge and belongs to the large scale South China Sea winter oceanic cyclonic circulation (Wu, Shaw, and Chao, 1998).

The vertical mixing that occurs on the Gulf of Tonkin in winter is particularly strong on the edge of the continental shelf, following the west side of this northern current, where it reaches 100 m (Fig. 11). The seasonal and high frequency variability of the hydrodynamical circulation can thus explain the small local maximum observed for the Chla summer concentration (Fig. 10) and as well as for the contribution of irregular variability (Fig. 9) at ~109° E between 14° N and 17° N.

The turbulent KE in winter is maximum along the coast between 11° N and 15° N. In summer, the upwelling region around 12° N also shows a strong turbulent activity. Moreover, the water upwelled along the coast in this area is advected offshore under the influence of the large scale circulation. This could explain the maximum of irregular variability contribution observed between 10° N and 15° N (Fig. 9).

Hydrodynamical simulations provide indications about the potential contribution of physical processes like MLD and (sub)mesoscale activity on primary production. However, the understanding of detailed mechanisms involved in the co-variations of the physical and biological variables requires the implementation of coupled a hydrodynamical – biogeochemical high resolution model over the area of study, that will allow examining in the four dimensions the relationships between the ocean dynamics and the chlorophyll spatio-temporal variability. We are currently developing such simulations with the coupled model SYMPHONIE - Eco3M-S (Herrmann, Diaz, Estournel, Marsaleix, and Ulses, 2013). Results of this work will be presented in future papers.

No significant long-term Chla evolution has been noticed over coastal waters of Vietnam, except in four specific areas. Indeed, the analysis of MERIS time series reveals the presence of significant trend in Chla in front of Quang Ninh, Khanh Hoa, and Binh Thuan provinces (Fig. 13). Over these different coastal areas (Fig. 1), Chla increases by about 4–5% per year, which represents an increase of about 40 to 50% over the whole time period considered. The maximum and mean values of SPM and a\textsubscript{dom}(412) for these pixels, as estimated using the models of Han et al. (2016) and Loisel et al. (2014b), respectively, fall within the range previously defined for an optimal Chla inversion from OCS. Note that based on a mean spectral slope value of 0.0176 nm\textsuperscript{-1} for a\textsubscript{dom}(λ)
in coastal waters (Babin et al., 2003), the maximal a_{cdom}(λ) value of 0.5 m^{-1} found at 443 nm becomes 0.86 m^{-1} at 412 nm. The mean (maximum) SPM values over the four areas (from the South to the North) are 2.17 ± 1.64 g·m^{-3} (9.7 g·m^{-3}), 1.85 ± 2.3 g·m^{-3}(14.8 g·m^{-3}), 1.64 ± 0.7 g·m^{-3}(4.5 g·m^{-3}), and 2.5 ± 1.2 g·m^{-3}(6.8 g·m^{-3}), respectively. In the same way, the mean (maximum) values of a_{cdom}(412) are 0.12 ± 0.07 m^{-1} (0.44 m^{-1}), 0.11 ± 0.10 m^{-1} (0.68 m^{-1}), 0.09 ± 0.02 m^{-1} (0.18 m^{-1}), and 0.16 ± 0.06 m^{-1} (0.37 m^{-1}).

The origin of these temporal trends can be diverse, and should be examined more deeply in future studies, especially from in situ monitoring of nutrients long term evolution. However, these areas are characterized by intense commercial aquaculture activities (fish and shrimp farms) which undeniably increase the pressure on the natural resources. For instance, a recent study has shown that aquaculture activities play the most important role in nutrient cycling in Sanggou Bay in China (Li, Liu, Zhang, Jiang, and Fang, 2016). Indeed, among the different disturbances that aquacultures may cause to the environment, the release of uneaten food and fecal material from the farms supplies the surrounding coastal waters into organic matter and nutrients, favoring the development of the phytoplankton biomass. In this context, we examined the evolution of the aquaculture production for the Quang Ninh, Khanh Hoa, and Binh Thua provinces, based on data gathered in General Statistics Office of Vietnam (https://www.gso.gov.vn). A sharp increase in aquaculture production has been observed over the latter different regions (Fig. 14). Over the MERIS time period, the aquaculture productivity over the Quang Ninh, Khanh Hoa, and Binh Thua provinces has indeed increased by 38%, 31%, and 113%, respectively. Chla shows parallel evolution over the same time period, with the highest increase (about 50%) for the Binh Thuan province, and the lowest in coastal waters of Khanh Hoa (about 20%). In situ measurements of nutrients should be conducted to confirm the link between aquaculture production and Chla evolution.

4. Concluding remarks

This paper presented the validation of different Chla algorithms over the Vietnamese coastal waters, based on in situ measurements. The OC5 algorithm showed the best and most stable retrievals. This results is coherent with previous studies (Fontana et al., 2009; Tilstone et al., 2011; Novoa et al., 2012; Lapucci et al., 2012; Gomez-Jakobsen et al., 2016; Pitarch et al., 2016; Tilstone et al., 2017), stressing the potential of OC5 for a satisfactory assessment of Chla over a large range of coastal waters. Unfortunately, no match-up data points are available over the MERIS period due to cloud coverage. However, the OC5 algorithm has already been validated, through match-up exercises, over many different regions, as already described in the paper. Through collaboration between France and Vietnam, an AERONET-Ocean Color station will be installed in Vietnam in the future for such exercise. This paper introduced the notion of bio-optical environment to be associated with the performance of a given bio-optical environment, which enhance our confidence in the exploitation of the observed Chla spatio-temporal patterns. Note that similar results can be obtained using classification approaches (Lahet, Ouillon, and Forget, 2001; Lubac and Loisel, 2007; Vantrepotte, Loisel, Dessailly, and Mériaux, 2012). The spatio-temporal Chla patterns reported here over the MERIS time period have been explained using...
three-dimensional hydrodynamical numerical simulations. The satellite data set used in this study, with the associated Chla climatology is available through the website of the HILO laboratory (http://hilo.usth.edu.vn).

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