Int J Appl Earth Obs Geoinformation 66 (2018) 184–195

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Seasonal variability in bio-optical properties along the coastal waters off Cochin

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ARTICLE INFO

Keywords:
Southwest monsoon
Bio-optical properties
Pigment packaging
Phytoplankton
Coastal waters off Cochin

ABSTRACT

Strong seasonal upwelling, downwelling, changes in current patterns and the volume of freshwater discharge from Cochin Estuary defines the coastal waters off Cochin. These coastal waters were investigated through monthly sampling efforts during March 2015 to February 2016 to study the seasonal and spatial variability in bio-optical properties for the four different seasons mainly Spring Inter Monsoon (SIM), South West Monsoon (SWM), Fall Inter Monsoon (FIM) and Winter Monsoon (WM). The Barmouth region is the meeting place where freshwater from Cochin Estuary directly enters to the sea through a single narrow outlet, was dominated by highly turbid waters during the entire period of study. Among the four seasons, chlorophyll *a* (Chl_*a*) concentration showed a high value during SWM, ranged from 2.90 to 11.66 mg m^{-3} with an average value of 6.56 ± 3.51 mg m^{-3}. During SIM the distribution of coloured dissolved organic matter (CDOM) is controlled by decomposition of phytoplankton biomass and the river discharge, whereas during SWM the temporal distribution of CDOM is controlled only by river discharge. The highest value for CDOM spectral slope (S_{CDOM}) was observed during SWM, ranged from 0.013 to 0.020 nm^{-1} with an average value of 0.015 ± 0.002 nm^{-1}. During WM, the high S_{CDOM} with lower a_{CDOM} (443) indicates the photo-degradation affects the absorption characteristics of CDOM. The observed nonlinearity between Chl_*a* and the ratio of phytoplankton absorption a_{ph} (443)/a_{ph} (670) indicating the packaging effect and changes in the intercellular composition of pigments. During the study period, a_{ph} (670) was strongly correlated with Chl_*a* than a_{ph} (443), which explains the accessory pigment absorption dominating more than Chl_*a* in the blue part of the spectrum. Similarly, the results obtained from seasonal bio-optical data indicating that Chl_*a* significantly contributes light attenuation of the water column during SIM, whereas detritus (a_d) significantly contributes light attenuation during SIM and WM. During the study period, the relative absorption of detritus materials dominates the relative absorption of phytoplankton and CDOM at 443, 555 and 670 nm wavelengths.

1. Introduction

The coastal oceans are among the most dynamic environments, covering around 8% of the surface area of the globe, 15% of the global biological production, 80% of the global organic burial and around 75–90% of the global sink of suspended river load (Tilstone et al., 2012; Bauer et al., 2013; Loisel et al., 2013). However, these dynamic systems are now affected by harmful algal blooms, eutrophication and climate change (Shanmugam 2011; Davidson et al., 2014; Blondeau-patissier et al., 2014). Therefore, it is necessary to monitor the coastal oceans on a synoptic scale to observe the changes caused by the environment as well as human interventions (Mélin and Vantrepotte, 2015), which is possible through the remote estimation of ocean colour components. The retrieval of Inherent Optical Properties (IOPs − absorption and

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https://doi.org/10.1016/j.jag.2017.12.002
Received 7 July 2017; Received in revised form 7 December 2017; Accepted 10 December 2017

scattering) from remote sensing reflectance are well documented for the clear oceanic waters and a few for the coastal waters (Brewin et al., 2012; Bélanger et al., 2013; Zheng et al., 2014; Siegel et al., 2013; Knaeps et al., 2015; Dogliotti et al., 2015). Therefore, to improve the ocean colour estimates, it is essential to develop the robust regional algorithms for the coastal waters. An accurate estimation of ocean colour of bio-optical variables in the complex coastal waters is still a challenging task (Gokul et al., 2014). The bio-optical properties of the coastal water bodies are understudied (Tilstone et al., 2013; Ferreira et al., 2014) due to the optical complexity of the waters. Understanding the spatiotemporal variability of bio-optical properties in the coastal water bodies is essential to studies concerned with the upper ocean biogeochemical processes as well as the condition of the ecological environment. However, it required more efforts to characterize the bio-optical properties of coastal waters (Devred et al., 2013; Garaba et al., 2014; Mouw et al., 2015; Han et al., 2016). The coastal waters are influenced not only by phytoplankton and its byproducts, but also by other optically active substances (Moore et al., 2014; Barnes et al., 2014; Zhang et al., 2014a, 2014b; Sun et al., 2014) that vary independently of phytoplankton, like particles in suspension and CDOM (Blondeau-patissier et al., 2017; Menon et al., 2011; Tilstone et al., 2012; Brezonik et al., 2015; Pérez et al., 2016). CDOM is a part of the dissolved organic carbon (DOC) pool composed essentially fulvic and humic acid (Tiwari and Shanmugam, 2011; Organelli et al., 2014; Xing et al., 2014). It plays a significant role in underwater light attenuation and photochemically mediated biogeochemical processes in the clear and coastal waters (Nelson et al., 2010; Campanelli et al., 2017). The critical sources of CDOM in coastal waters are river discharge, upwelled bottom water and biological origins such as decomposition of phytoplankton, bacterial degradation, and photodegradation of other organic matter (Mannino et al., 2014). The spectral signature of detritus or non-algal particles can significantly alter the colour of coastal ocean (Zhang et al., 2014a,b). The retrieval of detritus substances is complicated due to the different types of organic and inorganic particles. (Zhang et al., 2014a,b; Riddick et al., 2015). Knowledge on the phytoplankton absorption (a_{ph}) spectra in seawater are necessary for modeling underwater light availability, primary productivity, and even for studying mixed layer dynamics (Zhai et al., 2011; Varunan and Shanmugam, 2015; Uitz et al., 2015). However, the penetration of light into the water column is necessary for understanding photosynthesis, optical bathymetry and photochemical process involved in the biogeochemical cycling of various elements.

Bio-optical studies reported along the coastal waters of South Eastern Arabian Sea (SEAS) are scarce due to lack of bio-optical measurements. The optically active constituent of SEAS, particularly the coastal waters off Cochin have only recently been studied (Minu et al., 2014; Shaju et al., 2015; Minu et al., 2016) and the *in-situ* bio-optical data available are meager (Menon et al., 2011). Menon et al. (2006) studied the variability of remote sensing reflectance (R_{rs}) along the coastal and northeastern waters of Arabian Sea and reported that CDOM is one of the significant optical constituents making the area optically complex. Tilstone et al. (2013) reported that Chl_*a* was maximum during SWM and evaluated the performance of 3 MODIS-Aqua algorithm along coastal shelf waters of eastern Arabian Sea. Seasonal variability of the bio-optical properties along the coastal waters of Cochin is complex and affected by various physical processes and seasonal monsoon. On the other hand, knowledge of the processes responsible for variation in bio-optical properties is a necessary basis for understanding remote sensing data from this area. Sravanthi et al. (2013) have been found a significant correlation ($R^2 = 0.62$) between the in-situ Surface Sediment Concentration (SSC) and retrieved SSC from Oceansat-2 along the coastal waters off Cochin. This study further found a high concentration of SSC (> 20 mg/l) in the onshore waters and minimum (< 2 mg/l) was observed towards the offshore region. Minu et al. (2014) studied the effects of optically active components at a coastal site off Cochin, reported that Chl_*a* is the major light absorbing component and described the main source of CDOM as terrestrial during SWM. Recently, Minu et al. (2016) evaluated the performance of the six bio-optical algorithms to retrieve Chl_*a* at off Cochin and concluded that the performances of the tested algorithms were found inadequate in the near coastal waters.

To improve the retrieval accuracy of ocean colour components requires a detailed understanding of the mechanisms that regulate the variability of optically active components. Using the in-situ bio-optical data from the coastal waters off Cochin, we examined the seasonal variability of the phytoplankton absorption coefficient, coloured dissolved organic matter absorption coefficient, detritus matter absorption coefficient, chlorophyll *a*, total suspended matter, and diffuse attenuation coefficient. Our bio-optical data representative of the four different seasons namely Spring Inter Monsoon (SIM; March-May), South West Monsoon (SWM; June-September), Fall Inter Monsoon (FIM; October-November) and Winter Monsoon (WM; December-February) were assessed during the present study. Thus, the focus of this study is to characterize the optically active constituents and cause of seasonal and spatial variability of the bio-optical properties along the coastal waters off Cochin.

The specific objectives of this study are (1) to characterize the seasonal and spatial variability in the absorption components and its relationship with physical and biogeochemical variables along the coastal waters off Cochin and explore the source characterization of CDOM. (2) to study the seasonal and spatial variability in phytoplankton absorption coefficient and specific absorption coefficient and its relation with Chlorophyll *a* concentration and (3) to understand the seasonal variability in the relative contribution of bio-optical components.

2. Data and methods

2.1. Study area

Cochin Estuary is one of the largest estuarine systems in the south west coast of India, which Joins to the Arabian Sea at two main regions, (i.e., Cochin and Azhikode). The width of Cochin inlet is about 450 m, and Azhikode has a narrow width of 250 m respectively. Due to anthropogenic activity, Cochin estuary receives $1.04 \times 10^5\,m^3$ of untreated industrial effluents and $260\,m^3$ of domestic or sewage wastes, which alters the biogeochemical properties of coastal water off Cochin (Gupta et al., 2016; Sudheesh et al., 2016). The coastal waters off Cochin in SEAS is typical optically complex Case 2 water (Minu et al., 2014). During WM and SWM, seasonally changing West India Coastal Current, (WICC) flowing northward and southward influence the oceanography of coastal waters of SEAS. During SWM coastal waters off Cochin experience significant upwelling and vertical mixing leading to high primary productivity and high suspended sediment concentration (George et al., 2013; Gupta et al., 2016; Shynu et al., 2017). The SIM and FIM exhibit a transitional condition between two monsoons. During WM, the northerly current brings low saline water originating from the Bay of Bengal, which enhances stratification in the upper water column of SEAS. Fig. 1 shows the surface current vectors for SIM, SWM, FIM and WM averaged for the years 2015–2016 and map of locations of sampling stations along the coastal waters off Cochin. Surface water samples were collected from four stations with bathymetric variations. The station B1 (09° 58.178′ N, 76° 13.328′ E) is located at Barmouth having a depth of 10 m. The Barmouth region is the meeting place where freshwater from Cochin estuary enters into the sea through a single narrow outlet. The Station B2 (09° 58.976 N', 76° 10.117′ E) has a bathymetric depth of 10 m. The station B3 (09° 58.97′ N, 76° 06.149′ E) has a bathymetric depth of 20 m and station B4 (09° 58.523 N', 76° 02.747′ E) has a bathymetric depth of 30 m which is the farthest station located from the coast. These stations cover the waters influenced by a seasonal change in freshwater input, upwelling and other physical properties and the associated change in the biological production (Gupta et al., 2016; George et al., 2013).