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ORIGINAL RESEARCH ARTICLE

Performance of operational satellite bio-optical algorithms in different water types in the southeastern Arabian Sea

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Summary The *in situ* remote sensing reflectance (R_{rs}) and optically active substances (OAS) measured using hyperspectral radiometer, were used for optical classification of coastal waters in the southeastern Arabian Sea. The spectral R_{rs} showed three distinct water types, that were associated with the variability in OAS such as chlorophyll-*a* (chl-*a*), chromophoric dissolved organic matter (CDOM) and volume scattering function at 650 nm (β_{650}). The water types were classified as Type-I, Type-II and Type-III respectively for the three R_{rs} spectra. The Type-I waters showed the peak R_{rs} in the blue band (470 nm), whereas in the case of Type-II and III waters the peak R_{rs} was at 560 and 570 nm respectively. The shifting of the peak R_{rs} at the longer wavelength was due to an increase in concentration of OAS. Further, we evaluated six bio-optical algorithms (OC3C, OC4O, OC4, OC4E, OC3M and OC4O2) used operationally to retrieve chl-*a* from Coastal Zone Colour Scanner (CZCS), Ocean Colour Temperature Scanner (OCTS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), MEdium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectroradiometer (MODIS) and Ocean Colour Monitor (OCM2). For chl-*a* concentration greater than 1.0 mg m^{-3}, algorithms based on the reference band ratios 488/510/520 nm to

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547/550/555/560/565 nm have to be considered. The assessment of algorithms showed better performance of OC3M and OC4. All the algorithms exhibited better performance in Type-I waters. However, the performance was poor in Type-II and Type-III waters which could be attributed to the significant co-variance of chl-*a* with CDOM.

1. Introduction

Ocean colour remote sensing has been widely used as a tool to determine the surface chlorophyll-*a* (chl-*a*) concentration which acts as a proxy for phytoplankton biomass. Several empirical and semi-analytical algorithms have been proposed for the retrieval of chl-*a* from satellite ocean colour data. These algorithms were based on the non-linear relationship between oceanic reflectance and *in situ* measured chl-*a*, more precisely the ratios of reflectance in blue and green bands or their combinations (Lee et al., 2002; O'Reilly et al., 1998, 2000). These algorithms using the spectral ratios of reflectance were mainly attributed to Case 1 waters where the optical properties were determined mainly by phytoplankton and their accessory pigments. For Case 2 waters, apart from phytoplankton, other optically active substances (OAS) such as chromophoric dissolved organic matter (CDOM) and total suspended matter (TSM) contribute significantly to the reflectance (Morel and Prieur, 1977).

The development of ocean chlorophyll 2-band (OC2) and ocean chlorophyll 4-band (OC4) algorithms was done using SeaBAM data set. The OC2 algorithm was revised (OC2 v2) based on an extensive data set of 1174 *in situ* observations and thereafter with the SIMBIOS data set (McClain and Fargion, 1999). O'Reilly et al. (2000) updated OC2 and OC4 with 2853 *in situ* data sets (OC2v2 and OC4v4) and suggested the need to determine accuracy of these revised algorithms in lowest chl-*a* concentrations.

The characteristics of the reflectance spectrum, in terms of shape and magnitude, are largely influenced by the presence of OAS within the water column (Minu et al., 2014; Pierson and Strombeck, 2000). In other words, the apparent optical properties (AOP) of aquatic media, such as remote sensing reflectance (R_{rs}), largely affected by OAS and geometry of ambient light field can be quantified using inherent optical properties (IOPs) of the OAS (Mobley, 1994; Morel, 1991). The fundamental IOPs influencing the R_{rs} are absorption (a), scattering (b) and volume scattering function (β). The phytoplankton pigment, chl-*a*, has a tendency to absorb light in the blue and red bands of the visible electromagnetic spectrum (V-EMS) with the former being the primary peak. The CDOM also exhibits strong absorption in UV and the shorter wavelength band of V-EMS whereas the suspended matter usually scatters in the longer wavelength band. Apart from this, the water molecules themselves absorb strongly in the red part of V-EMS. Further, the volume scattering describes the angular distribution of light scattered from an incident beam. In the absence of inelastic scattering, IOP of a medium is completely determined by the absorption coefficient and β. These when combined with the angular and spectral distribution of the incident radiance field, just below the surface, the full radiative flux balance of the ocean can be simulated (Lee and Lewis, 2003). Studies using hyperspectral radiometers, on the relationship between IOP and concentration of OAS, indicated the presence of identifiable sub-types of coastal water within the conventional Case 2 classification (Mckee and Cunningham, 2006).

The ratio based empirical algorithms for the retrieval of chl-*a* from CZCS, MOS-B, IRS-P4-OCM and SeaWiFS have been already carried out in the southeastern Arabian Sea. Sathe and Jadhav (2001) studied retrieval of chl-*a* using sea-leaving radiance from MOS-B and showed that the single ratio of CZCS algorithm fails in the Arabian Sea. They also reported that the two factor algorithm of SeaWIFS fails in 30% of the cases. Further, Nagamani et al. (2008) reported that OC4v4 algorithm overestimates chl-*a* in the northern Arabian Sea when compared to MBR based OCM-2 algorithm. In addition to these, Chauhan et al. (2002) evaluated the accuracy, precision and suitability of different ocean colour algorithms for the Arabian Sea. According to their study, OC2 and OC4 algorithms performed well in Case 1 waters of the Arabian Sea. But both algorithms failed to estimate chlorophyll in *Trichodesmium* dominated waters. Tilstone et al. (2011) also assessed three algorithms, OC4v6, Carder and OC5, for retrieving chl-*a* in coastal areas of the Bay of Bengal and open ocean areas of the Arabian Sea. Based on the accuracy assessment, they recommended the use of the OC5 algorithm in the area of study. Most of these studies were confined to oligotrophic to mesotrophic waters. Assessment of MODIS-aqua chlorophyll-*a* algorithms in coastal and shelf waters of the southeastern Arabian Sea showed better performance of OC3M than GSM and GIOP (Tilstone et al., 2013). However, our study deals with mesotrophic to eutrophic waters. The problem with estimating chl-*a* from an ocean colour satellite sensor involves two critical steps. The first step is to eliminate the effect of the atmospheric contribution and the second step is to select a suitable bio-optical algorithm. In this study, we have focused on *in situ* bio-optical data, measured using hyperspectral radiometer, in the optically complex waters of the southeastern Arabian Sea, with the following objectives:

1. Analyzing the spectral remote sensing reflectance in the view of distribution of OAS.
2. Evaluation of operational empirical algorithm in different water types.

2. Study area

A part of the southeastern Arabian Sea forms the study area (Fig. 1). The area has a strong monsoonal influence resulting