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# *In situ* spectral response of the Arabian Gulf and Sea of Oman coastal waters to bio-optical properties

Maryam R. Al Shehhi*, Imen Gherboudj, Hosni Ghedira

*Khalifa University of Science and Technology, Masdar Institute, Masdar City, P.O. Box 54224, Abu Dhabi, United Arab Emirates*

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A B S T R A C T

Mapping of Chlorophyll-*a* (Chl-*a*) over the coastal waters of the Arabian Gulf and the Sea of Oman using the satellite-based observations, such as MODIS (Moderate Resolution Imaging Spectro-radiometer), has shown inferior performance (Chl-*a* overestimation) than that of deep waters. Studies in the region have shown that this poor performance is due to three reasons: (i) water turbidity (sediments re-suspension), and the presence of colored dissolved organic matter (CDOM), (ii) bottom reflectance and (iii) incapability of the existing atmospheric correction models to reduce the effect of the aerosols from the water leaving radiance. Therefore, this work focuses on investigating the sensitivity of the *in situ* spectral signatures of these coastal waters to the algal (chlorophyll: Chl-*a*), non-algal (sediments and CDOM) and the bottom reflectance properties, in absence of contributions from the atmosphere. Consequently, the collected *in situ* spectral signatures will improve our understanding of Arabian Gulf and Sea of Oman water properties. For this purpose, comprehensive field measurements were carried out between 2013 and 2016, over Abu-Dhabi (Arabian Gulf) and Fujairah (Sea of Oman) where unique water quality data were collected. Based on the *in situ* water spectral analysis, the bottom reflectance (water depth $< 20$ m) are found to degrade the performance of the conventional ocean color algorithms more than the sediment-laden waters where these waters increase the $R_{rs}$ at the blue and red ranges. The increasing presence of CDOM markedly decreases the $R_{rs}$ in the blue range, which is conflicting with the effect of Chl-*a*. Given the inadequate performance of the widely used ocean-color algorithms (OC3: ocean color 3, OC2: ocean color 2) in retrieving Chl-*a* in these very shallow coastal waters, therefore, a new algorithm is proposed here based on a 3-bands ratio approach using $[R_{rs}(656)^{-1} - R_{rs}(506)^{-1}] \times R_{rs}(661)$. The selected optimum bands (656 nm, 506 nm, and 661 nm) from this approach can be used to retrieve the Chl-*a* more accurately in these coastal *Case II* (turbid) waters which are close to the bands of the current missions such as Sentinel-3 OLCI (Ocean and Land Colour Instrument), MODIS, VIIRS (Visible Infrared Imaging Radiometer Suite) and LandSat 8. However, more uniformly distributed data over the Arabian Gulf is required to have a highly accurate regional model for Chl-*a* retrieval.

## 1. Introduction

The Arabian Gulf is a semi-enclosed region connected to the Sea of Oman through the Strait of Hormuz. These two water bodies are located in the middle of an arid region, which is often hot (water temperature can reach 35 °C in the summer) and dusty (around 20 dust storms per year) [1–3]. The intervention of this harsh climate with the shallow nature of the Gulf has led to the domination of the *Case II* waters. Case *II* waters refer to waters in which the non-algal constituents (sediments and colored dissolved organic matters, generally noted as CDOM) dominate the biological component (chlorophyll *a*: Chl-*a*) and do not co-vary in a similar way in the presence of the algal constituents [4]. However, the sediment loading is commonly associated with the occurrence of algal activities in these waters, known as harmful algal blooms (HABs) [5,6].

The primary application of ocean color remote sensing involves the characterization of the seawater bio-optical properties of the algal and non-algal components. For this purpose, various algorithms have been developed to relate the Chl-*a* to the spectral ocean color bands. The spectral ocean color bands are expressed as reflectance ratios to reduce the uncertainties related to light propagation through water columns (visible: 433/547, 488/547; and Near-Infra-Red (NIR): 748/667, 748/678) [7]. The ocean color algorithms can be categorized into two classes, namely empirical (ocean color 2: OC2, ocean color 3: OC3, and n-bands ratio concept) and semi-analytical (Garver-Siegel-Maritorena model: GSM and Canz) [8–10]. The commonly used algorithms to

* Corresponding author at: P.O. Box 54224, Masdar City, Abu-Dhabi, United Arab Emirates.
*E-mail addresses:* mralshehhi@masdar.ac.ae (M.R. Al Shehhi), igherboudj@masdar.ac.ae (I. Gherboudj), hghedira@masdar.ac.ae (H. Ghedira).

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**Table 1**
Chl *a* MODIS algorithms.

| Algorithm | Category | Bands | Equations | *In-situ* data location | Refs |
|---|---|---|---|---|---|
| OC3 | Empirical | 443 nm<br>488 nm<br>547 nm | $\log_{10}(\text{Chl } a) = 0.283 - 2.753R_{rs} + 0.659{R_{rs}}^2 + 0.649{R_{rs}}^3 - 1.403{R_{rs}}^4$<br>$R_s = \log_{10}(\max[R_{rs}(443/547, 488/547)])$ | US coast, Atlantic, and Pacific ocean | [7,11] |
| Cannizzaro and Carder | Semi-analytical | 412 nm 490 nm<br>555 nm 670 nm | $\log(\text{Chl } a) = a_0 + a_1(\log R) + a_2(\log R)^2 + a_3(\log R)^3$<br>● Shallow designation (curve > *Upper*_limit):<br>$R_{shallow} = R_{rs}412/R_{rs}667$<br>$a_{shallow} = [0.8840, -2.0837, 1.3061, -0.3906]$<br>● Deep designation (curve < *Lower*_limit):<br>$R_{deep} = R_{rs}488/R_{rs}551$<br>$a_{deep} = [0.0597, -2.2291, 2.6691, -3.4144]$<br>● Transitional designation (*Lower*_limit < *curve* < *Upper*_limit):<br>$\text{Chl } a = w \times (\text{Chl } a_{deep}) + (1 - w) \times \text{Chl } a_{shallow}$<br>$w = (\text{curve} - \text{Lower\_limit})/(\text{Upper\_limit} - \text{Lower\_limit})$<br>$\text{With: Curve} = \log_{10}(R_{rs}412/R_{rs}667)/(R_{rs}551)^2$<br>$Upper\_limit = -2.44 + 0.80 \log_{10}(R_{rs}412/R_{rs}667) + 0.080 \log_{10}(R_{rs}412/R_{rs}667)^2$<br>$Lower\_limit = -0.20 + 0.13 \log_{10}(R_{rs}412/R_{rs}667) + 0.130 \log_{10}(R_{rs}412/R_{rs}667)^2$ | West Florida shelf and Bahamian Waters | [8] |
| OC2 | Empirical | 490 nm<br>555 nm<br>547 nm | $\log_{10}(\text{Chl } a) = 0.2974 - 2.2429R_{rs} + 0.8358{R_{rs}}^2 - (0.0077{R_{rs}}^3 - 0.0929)$<br>$R_s = \log_{10}\left[R_{rs}\left(\frac{490}{555}\right)\right] \text{ or } \left[\log_{10}\left(\frac{490}{547}\right)\right]$ | US coast, Atlantic and Pacific ocean | [11] |

estimate the Chl-*a* are based on the bands ratios (visible: 433/547, 488/547; and Near-Infra-Red (NIR): 748/667, 748/678) concept. The most used algorithms considering this concept are OC3 and OC2, which consider the blue/green ratios (433/547, 488/547) (Table 1) [10]. These algorithms perform well for *Case I* (clear) waters, as proved in different studies undertaken over different water bodies including the West Florida [12], southeastern China [13], and Korean coastal waters [14]. However, the performance of these algorithms is generally poor for *Case II* (turbid) waters.

This poor performance is often due to the presence of high concentrations of inorganic particle matters (non-algal components) (*i.e.* 496 nm), CDOM, and bottom reflectance (*i.e.* 530 nm), that cause: (i) overlapping and uncorrelated spectra, and (ii) high absorptions of dissolved organic matters and tripton [15]. To overcome this issue, red/NIR band ratio has been proposed by some researchers as a solution to remove the effect of the other water constituents [16]. The NIR peak near 700 nm is very sensitive to the Chl-*a* concentration, while the red band at 670 nm is sensitive to non-algal suspended matters. The combination of these two bands is also used in few optical algorithms [17]. The details of these algorithms are presented in Table 1. However, these considerations were not validated for Case *II* water under dusty atmosphere, such as the Arabian Gulf [18,19]. Indeed, the few studies undertaken over the region to validate the ocean color algorithms for the retrieval of the Chl-*a* [20–24], fluorescence [19], and water transparency [25] using satellites measurements (MODIS, and MERIS: Medium Resolution Imaging Spectrometer) have suggested that the atmospheric dust is an additional factor that is further limiting the performance of these models [26,27]. This poor performance is partly related to the incapability of the available satellite atmospheric correction algorithms to remove the contribution of the atmospheric aerosols from the remote sensing signals. The most studied atmospheric correction model is based on the black water pixel assumption, which assumes zero water leaving radiance at the near infrared (NIR) range [28,29]. However, this model is only valid for the clear waters (*Case I*) where the sediment loading is low. It is related to the fact that the Chl-*a* is mainly affecting the red and NIR parts of the spectrum, while aerosols, CDOM and sediments affect the blue and red parts of the spectrum, respectively [8]. Thereby, it is important to study the spectral response of the water that contains both algal (noted by Chl-*a*) and non-algal (water turbidity and CDOM) components using the *in situ* data. These data which do not include the atmospheric contribution would be used for better validation and development of the ocean color algorithms over this region.

This study aims to analyze the spectral sensitivity of the coastal waters within the Arabian Gulf and Sea of Oman to the biological and physical properties of their water bodies. To fulfill these objectives, two field campaigns measurements have been conducted over Abu–Dhabi (Arabian Gulf) and Fujairah (Sea of Oman) by MIST (Masdar Institute of Science and Technology, UAE) in 2013–2014 and 2016, respectively. These field campaigns were undertaken to collect the water leaving radiance, water quality parameters (Chl-*a*, water turbidity, and CDOM) and bottom reflectance. These *in situ* measurements are then used to: 1) validate/evaluate the performance of the empirical ocean color algorithms (OC3, OC2, Canz) over the coastal waters within this region in order to understand their limitations, and 2) devise an empirical algorithm for the estimation of the Chl-*a* concentration over coastal waters in this region using the bands ratio technique.

## 2. Material and Methods

### 2.1. Study Sites Location

Two study sites are considered for this research, which are Abu-Dhabi and Fujairah. These sites are located in the Arabian Gulf and the Sea of Oman respectively, as displayed in Fig. 1.

The coastal water of Abu Dhabi extends along 600 km and covers an area of 33,342 $km^2$. It is very shallow (few meters depth) but gets deeper towards the north where it can reach a maximum depth of 40 m. The shallow waters possess very high sediments loading and very high evaporation rate forming distinct morphology mainly called “Sabkha”, which is an extensive area of coastal saline flats [30]. Abu Dhabi's waters are also affected by the flood tide towards Sea of Oman, which pushes the water down towards Abu Dhabi that in turn causes a clockwise water mass. As for Fujairah's coastal water, it covers 3620 $km^2$ area of very deep water (~2000 m). These waters are affected by the frequent water eddies that occur in the Sea of Oman during the summer and winter seasons.

Both sites possess: i) high temperatures that vary from 28 °C to 50 °C in Abu-Dhabi and from 30 °C to 46 °C in Fujairah [30,31], ii) frequent occurrence of intense haze and dust storms where an average of 242 hazy days per year were recorded in Abu Dhabi between 1982 and