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Improved atmospheric correction and chlorophyll-*a* remote sensing models for turbid waters in a dusty environment

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ABSTRACT

This study presents a comprehensive assessment of the performance of the commonly used atmospheric correction models (NIR, SWIR, NIR-SWIR and FM) and ocean color products (OC3 and OC2) derived from MODIS images over the Arabian Gulf, Sea of Oman, and Arabian Sea. The considered atmospheric correction models have been used to derive MODIS normalized water-leaving radiances (nL_w), which are compared to *in situ* water $nL_w(\lambda)$ data collected at different locations by Masdar Institute, United Arab of Emirates, and from AERONET-OC (the ocean color component of the Aerosol Robotic Network) database. From this comparison, the NIR model has been found to be the best performing model among the considered atmospheric correction models, which in turn shows disparity, especially at short wavelengths (400–500 nm) under high aerosol optical depth conditions (AOT (869) > 0.3) and over turbid waters. To reduce the error induced by these factors, a modified model taking into consideration the atmospheric and water turbidity conditions has been proposed. A turbidity index was used to identify the turbid water and a threshold of AOT (869) = 0.3 was used to identify the dusty atmosphere. Despite improved results in the MODIS $nL_w(\lambda)$ using the proposed approach, Chl-*a* models (OC3 and OC2) show low performance when compared to the *in situ* Chl-*a* measurements collected during several field campaigns organized by local, regional and international organizations. This discrepancy might be caused by the improper parametrization of these models or/and the improper selection of bands. Thus, an adaptive power fit algorithm ($R^2 = 0.95$) has been proposed to improve the estimation of Chl-*a* concentration from 0.07 to 10 mg/m^3 by using a new blue/red MODIS band ratio of (443,488)/645 instead of the default band ratio used for OC3(443,488)/547. The selection of this new band ratio (443,488)/645 has been based on using band 645 nm which has been found to represent both water turbidity and algal absorption.

1. Introduction

The Arabian Seas, including the Arabian Gulf, Sea of Oman and Arabian Sea, are considered one of the most productive waters in the world, given the frequent harmful algal blooms (HABs) which have been recorded since 1908 over these seas (Glibert et al., 2002; Padmakumar et al., 2012; Richlen et al., 2010; Zhao et al., 2016a,b). These HAB outbreaks have caused several problems, such as: (1) the death of hundreds of tons of fish (Kuwait 2001, Oman 2005, UAE 2008, and Qatar 1996) (Al-Ansi et al., 2002; Al-Busaidi et al., 2008; Glibert et al., 2002; Richlen et al., 2010), (2) the interruption of desalination plant production (Ghaleelah desalination plant, Ras Al Khaimah, UAE, 2007), (3) the disturbance of the aquatic ecosystem (~95% of coral was killed in Dibba's water), (4) the disturbance of recreational activities (the closing of Jumeirah Beach, near Burj Al Arab in Dubai, UAE, 2009) (Al-Shehhi et al., 2014), and (5) the negative effects on human health (respiratory irritation, abdominal pain, nausea, vomiting, and diarrhea) (Kleindinst and Anderson, 2001; Tomlinson et al., 2009).

Remote sensing combined with bio-optical modeling is increasingly being used to detect the presence of the HABs, and monitor their evolution through the evaluation of chlorophyll-*a* (Chl-*a*), which is the primary photosynthetic pigment in algae. The launch of several ocean color satellite missions (CZCS: Coastal Zone Color Scanner, MERIS: MEdium Resolution Imaging Spectrometer, SeaWiFS: Sea-viewing Wide Field Sensor, MODIS: Moderate Resolution Imaging Spectroradiometer; and VIIRS: Visible Infrared

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Imaging Radiometer Suite; and OLCI: Ocean and Land Colour Instrument SENTINEL-3) has helped to overcome the limitation of *in situ* measurements, which are needed to have an overall assessment of the spatiotemporal variation of Chl-*a* (IOCCG, 2014; Kahru and Mitchell, 1999; Tilstone et al., 2013). Well-established bio-optical models (such as OC3 - Ocean Color 3 and OC2 - Ocean Color 2) (O'Reilly et al., 1998) perform well for *Case I* waters, where other optically active constituents including CDOM (colored dissolved organic matter) and detritus co-vary with Chl-*a*. However, these models show poor performance for *Case II* waters, which refers to turbid and shallow coastal waters with complex optical properties (Ali et al., 2013; Chen, 2014).

Indeed, Arabian seas are found to have diverse water properties combining both *Case I* (open water offshore the Arabian Gulf, Sea of Oman and Arabian Sea) and *Case II* (turbid and shallow inshore the Arabian Gulf) waters. This specific property increases the complexity of estimating the algal productivity in this region where water turbidity and water depth should be taken into consideration to estimate the water productivity by remote sensing (Matthews, 2011). Applying Chl-*a* ocean color algorithms (OC3 and OC2) over these seas has shown an overestimation of Chl-*a* concentration (Alsahli, 2007; Loisel et al., 2017; Tayebi and Saradjian, 2011; Zhao et al., 2015; Zhao and Ghedira, 2014). However, this overestimation was also caused, in addition to the complicated water properties of the Arabian Seas, by the dusty atmosphere produced by the surrounding dust source areas to these seas, such as the *Ad-Dahana desert* in Saudi Arabia, the *Tigris-Euphrates* basin in Iraq/Kuwait, the *Sistan basin* in Iran-Afghanistan, the *Makran desert* in Pakistan, and the *Thar desert* in northwest India (Gherboudj et al., 2016; Goodie and Middleton, 2001). The discrepancy observed between the retrieved and the *in situ* measurements proved that the existing atmospheric correction methods (e.g. NIR: zero near-infrared, reflectance assumption) are inadequate in removing the effect of aerosols from the water remote sensing reflectance (R_{rs}) spectrum (Ali et al., 2013; Alsahli, 2007; Chen, 2014; Goyens et al., 2013; Jamet et al., 2011; Li et al., 2003; Zibordi et al., 2011). These atmospheric correction models, specifically the NIR model, are commonly used for *Case I* waters under clear atmospheric conditions (Shanmugam, 2011; Son and Wang, 2012). Later on this model was combined with those of Stumpf et al. (2003) and Bailey et al. (2010), which became the standard atmospheric correction model used by NASA to better estimate water reflectance. However, these models are known to be less performant for *Case II water* under even the same atmospheric conditions (Ali et al., 2013; Dall'Olmo et al., 2005; Hu et al., 2010).

To reduce the impact of the atmospheric effect and the water turbidity from the ocean color imagery, atmospheric correction models have been developed by considering different approaches based on the artificial neural network (ANN) (Brajard et al., 2012; Schroeder et al., 2007), the spectral matching algorithm (SMA) (Banzon et al., 2009; Brajard et al., 2008; Chomko and Gordon, 1998; Diouf et al., 2013; Jamet et al., 2005; Kuchinke et al., 2009; Moulin et al., 2001) combined with *in situ* dataset, and Rayleigh-corrected radiance with normalized Gaussian distribution function (Singh and Shanmugam's 2014 model).

These models have successfully showed noticeable improvement in retrieval accuracy. For instance, the use of the ANN model under clear atmospheric conditions has showed enhanced performance over the *Case II* water of Chesapeake Bay (Son and Wang, 2012), Adriatic (Brajard et al., 2012), Baltic Seas (Goyens et al., 2013; Schroeder et al., 2007) and Indian coast (Brajard et al., 2008). Similarly, the use of a spectral matching algorithm (SMA) for atmospheric correction under dusty conditions has performed better than the NIR atmospheric correction scheme over the Mediterranean Sea (Banzon et al., 2009) and Chesapeake Bay (Kuchinke et al., 2009). Specifically, the use of the Rayleigh-corrected radiance with normalized Gaussian distribution function and Singh and Shanmugam's (2014) model over the Arabian Sea has also shown improved results compared to the NIR and NIR-SWIR where the mean relative error decreased by 22.59% and 23.06%, respectively (Singh and Shanmugam, 2014). This is a significant improvement since 5% error from the atmospheric correction procedure can cause up to 25% uncertainty of Chl-*a* estimation (Chen, 2014).

This paper aims to improve the satellite-based retrieval of Chl-*a* concentration over the Arabian seas by: (1) proposing an adequately tailored atmospheric correction model for MODIS images adapted to the dusty atmosphere and mixed waters nature (*Case I* and *Case II* waters) in the Arabian Seas, and (2) improving the existing Chl-*a* models for *Case II* waters. To reach these objectives, we have used *in situ* measurements (Chl-*a* and nL_w, i.e. normalized water leaving radiance) collected over the region between 2006 and 2014 by different organizations, including MIST (Masdar Institute of Technology and Science, UAE), MRRC (Marine Environment Research Center, UAE), NIO (National Institute of Oceanography, India), SQU (Sultan Qaboos University, Oman), UN (United Nations, Canada), and MSFC (Marine Science and Fisheries Center, Oman), in addition to AERONET-OC (the ocean color component of the Aerosol Robotic Network), and SEABASS (SeaWiFS Bio-optical Archive and Storage System, USA) databases.

2. Background

2.1. Arabian Seas water bodies

The Arabian Gulf (hereafter refer to as the Gulf) is a semi-enclosed basin interconnected to the sea of Oman through the Strait of Hormuz, which is in turn connected to the Arabian Sea (Fig. 1). The waters of this region are characterized with high residence time, low water inflow, and high evaporation rates especially during the summer where the sea surface temperature reaches 35 °C (Shenn-Yu et al., 1992). The limited source of freshwater comes seasonally from the decreasing Shatt Al-Arab discharge located at the maritime border between Kuwait and Iraq, which results in high salinity in the Gulf that could exceed 40 ppt (Smith et al., 2007; Zhao et al., 2017).

The water depth of the Arabian Gulf is shallower in its southern region where it remains below 20 m near the coastline of the United Arab Emirates (UAE). However, it increases toward the northern part of the Gulf in front of the Iranian offshore where the depth reaches its maximum value of about 80 m (Hamza and Munawar, 2009). In the eastern side, water depth can reach 3000 m in the Sea of Oman, while the depth can reach more than 4600 m in the Arabian Sea (Pous et al., 2004).

The chemical and biological characteristics of these water bodies are mainly affected by human (anthropogenic) activities and natural phenomena. The anthropogenic activities consist of the discharge of nutrient-rich contaminants from: (1) desalination and power plants that produce high-temperature brine, which perturbs the Gulf ecosystem and fosters the growth of HABs (Alsahli, 2007), (2) industrial wastewaters, and (3) dense maritime traffic where ~14 oil tankers pass through the Straits of Hormuz daily and may cause oil and pollutants spill (Alsahli, 2007; Nezlin et al., 2010; Trainer et al., 2000). As for the natural phenomena, they include wind-driven dust, discharge of rivers (Tigris-Euphrates and Shat-Al-Arab), upwelling currents, and convection (Al-Shehhi et al., 2014; Hamza and Munawar, 2009). All these sources bring large amounts of sediments/nutrients (iron, nitrate and phosphate) to the water surface, which can increase the productivity of algae, mainly dinoflagellate and, to a lesser extent, diatom and cyanobacteria (Al-Shehhi et al., 2014).