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Regional ocean-colour chlorophyll algorithms for the Red Sea

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ABSTRACT

The Red Sea is a semi-enclosed tropical marine ecosystem that stretches from the Gulf of Suez and Gulf of Aqaba in the north, to the Gulf of Aden in the south. Despite its ecological and economic importance, its biological environment is relatively unexplored. Satellite ocean-colour estimates of chlorophyll concentration (an index of phytoplankton biomass) offer an observational platform to monitor the health of the Red Sea. However, little is known about the optical properties of the region. In this paper, we investigate the optical properties of the Red Sea in the context of satellite ocean-colour estimates of chlorophyll concentration. Making use of a new merged ocean-colour product, from the European Space Agency (ESA) Climate Change Initiative, and *in situ* data in the region, we test the performance of a series of ocean-colour chlorophyll algorithms. We find that standard algorithms systematically overestimate chlorophyll when compared with the *in situ* data. To investigate this bias we develop an ocean-colour model for the Red Sea, parameterised to data collected during the Tara Oceans expedition, that estimates remote-sensing reflectance as a function of chlorophyll concentration. We used the Red Sea model to tune the standard chlorophyll algorithms and the overestimation in chlorophyll originally observed was corrected. Results suggest that the overestimation was likely due to an excess of CDOM absorption per unit chlorophyll in the Red Sea when compared with average global conditions. However, we recognise that additional information is required to test the influence of other potential sources of the overestimation, such as aeolian dust, and we discuss uncertainties in the datasets used. We present a series of regional chlorophyll algorithms for the Red Sea, designed for a suite of ocean-colour sensors, that may be used for further testing.

1. Introduction

The Red Sea is a narrow, semi-enclosed oceanic basin situated between the continents of Africa and Asia. At its southern end, it is connected to the Gulf of Aden and Arabian Sea, through the strait of Bab-el-Mandeb, and at its northern end to the Mediterranean Sea through the Suez Canal. Situated between 12°N and 28°N, it provides the shortest commercial shipping route between the Atlantic and Indian Ocean and thus is a major economic asset to the region (Johns & Sofianos, 2012). The Red Sea is also the world's northernmost tropical sea and among the warmest and most saline seas on the planet (Belkin, 2009; Longhurst, 2007; Raitsos et al., 2011). These unique environmental conditions (high temperature and salinity) reflect those predicted in other marine regions several decades from now (Christensen et al., 2007).

The Red Sea is categorised as a large marine ecosystem (Belkin, 2009) and sustains coral reefs that provide habitat for a diverse range of marine organisms (Baars, Schalk, & Veldhuis, 1998), including sponges, bi-valves, pelagic larvae, fish, crustaceans, mollusks and echinoderms. At the base of the marine food-web, phytoplankton act as an integral component of these coral reef ecosystems transferring energy to higher levels of the marine food-web, sustaining fisheries and providing sustenance to many inhabitants of the region. Despite the economic and ecological importance of the Red Sea, despite extensive knowledge on its physical characteristics (e.g. Sofianos & Johns, 2003; Yao, Hoteit, Pratt, Bower, Köhl, et al., 2014; Yao, Hoteit, Pratt, Bower, Zhai, et al., 2014) given its strategic position as a commercial shipping route, and despite extensive studies analysing the bio-optical properties of the Gulf of Eilat (Iluz, Yacobi, & Gitelson, 2003; Labiosa, Arrigo, Genin, Monismith, & Van Dijken, 2003; Sokoletsky, Dubinsky, Shoshany, & Stambler, 2003; Sokoletsky, Dubinsky, Shoshany, & Stambler, 2004; Stambler, 2005, 2006) located at the northern tip of the Red Sea, knowledge on large-scale biological dynamics in the region is limited to knowledge on the phytoplankton seasonal cycle, rates of uptake of

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carbon and nitrogen by phytoplankton, and the influence of coral reef ecosystems on Red Sea productivity (Acker, Leptoukh, Shen, Zhu, & Kempler, 2008; Qurban, Balala, Kumar, Bhavya, & Wafar, 2014; Racault et al., 2015; Raitsos, Pradhan, Hoteit, Brewin, & Stenchikov, 2013).

The main source of data used to investigate large-scale biological dynamics in the Red Sea has been synoptic estimates of chlorophyll concentration (denoted here as C and referred to in this paper as the chlorophyll concentration, being the sum of monovinyl chlorophyll-a, divinyl chlorophyll-a, chlorophyllide-a, and chlorophyll-a epimers and allomers (Werdell & Bailey, 2005), a measure of phytoplankton biomass) derived using satellite ocean-colour data (Acker et al., 2008; Brewin, Raitsos, Pradhan, & Hoteit, 2013; Raitsos et al., 2013). The temporal and spatial coverages of ocean-colour data surpass that of any *in situ* biological datasets currently available for the Red Sea. Since the advent of the first ocean-colour sensor, NASA's Coastal Zone Color Scanner, satellite ocean-colour data have been used to understand the optical properties of the Red Sea (e.g. Kirby, Parmeter, Arnone, & Oriol, 1993) and other biogeochemically-relevant variables such as the chlorophyll concentration. More recently, Acker et al. (2008) used ocean-colour data from the SeaWiFS and MODIS-Aqua sensors to investigate variations in chlorophyll concentration in the northern Red Sea, and Raitsos et al. (2013) used data from MODIS-Aqua to describe the seasonal succession of chlorophyll and its relationship to the physical forcing.

A difficulty with biological interpretation of ocean-colour data from the Red Sea has been the lack of *in situ* data required for validation and uncertainty characterisation. There have been some validation efforts: for instance, Barbini et al. (2004) showed reasonable agreement between satellite-derived chlorophyll and *in situ* lidar fluorescence-derived chlorophyll in the Red Sea. Using *in vivo* fluorometric chlorophyll measurements collected over large spatial scales, Brewin et al. (2013) demonstrated that the performance of standard MODIS-Aqua chlorophyll products in the Red Sea was comparable to that in other regions of the global ocean. Nonetheless, conclusions drawn on biological variability using ocean-colour data in the Red Sea still remain uncertain, due primarily to lack of suitable *in situ* datasets and limited understanding of the optical properties. A further complication in using ocean-colour data for the Red Sea is difficulties in atmospheric correction, for instance, due to the presence of high concentrations of atmospheric dust aerosols from the surrounding arid continents which can render many satellite ocean-colour pixels unusable for analysis of chlorophyll concentration (Acker et al., 2008).

Between September 2009 and March 2012, the Tara Oceans expedition conducted an ~91,000 km voyage to capture the global distribution of marine planktonic organisms (Boss et al., 2013; Werdell, Proctor, Boss, Leeuw, & Ouhssain, 2013). A hyperspectral absorption and attenuation meter (WETLabs, Inc. AC-S) together with a flow-through system (Boss et al., 2013; Slade et al., 2010) was used for continuous measurements of absorption and attenuation by marine particles along the entire Tara cruise track (Boss et al., 2013). During January 2010, the Tara cruise conducted a meridional transect of the Red Sea (Fig. 1) providing the first comprehensive dataset of absorption and attenuation by particles at large spatial scales in the Red Sea.

Recently, efforts have also been made to improve coverage of ocean-colour data through the merging of data from different ocean-colour platforms (e.g. the GlobColour project; Maritorena, Fanton d'Andon, Mangin, & Siegel, 2010). In 2010 the European Space Agency launched the Ocean Colour Climate Change Initiative (OC-CCI; Brewin et al., 2015) with the goal of creating a long-term, consistent, error-characterised time series of merged ocean-colour products (MODIS-Aqua, SeaWiFS and MERIS), for use in climate-change studies. One of the advantages of the OC-CCI dataset (version 1, see http://www.oceancolour.org/) is that, by using an atmospheric correction algorithm called POLYMER (Steinmetz, Deschamps, & Ramon, 2011) on MERIS, which performs retrievals in the presence of sun glint, significant increases in ocean-colour coverage were attained (Steinmetz et al., 2011).

In this paper, we make use of *in situ* bio-optical data collected in the Red Sea as part of the Tara Oceans expedition (Boss et al., 2013; Werdell et al., 2013), together with previous *in situ* datasets (Barbini et al., 2004; Brewin et al., 2013), to investigate the optical properties of the Red Sea in the context of satellite ocean-colour estimates of chlorophyll concentration. Using satellite (OC-CCI data) and *in situ* match-ups, we evaluate the performance of a suite of chlorophyll algorithms in the Red Sea. Discrepancies between satellite and *in situ* chlorophyll are investigated by developing an ocean-colour model for the Red Sea, parameterised to data from the Tara Oceans expedition. The model describes relationships between inherent optical properties of water constituents (absorption and backscattering) and chlorophyll concentration. The ocean-colour model is used to: i) improve our understanding of the optical properties of the region and ii) tune empirical satellite chlorophyll algorithms for use in the Red Sea. Uncertainties in our approach are discussed and conclusions are cautiously stated given the under-sampled nature of this region and its unique atmospheric properties.

2. Methodology

2.1. Study site

The Red Sea is an elongated basin with a mean depth of 524 m and a surface area of ~4.5×10^{11} m^2 (Patzert, 1974). A deep trench runs along the centre of the Red Sea from north to south reaching a

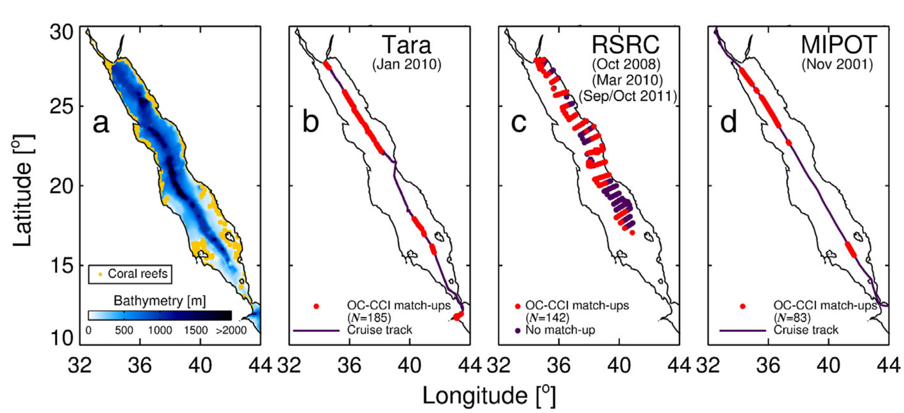

Fig. 1. (a) Bathymetry of the Red Sea (using ETOPO5 sea-floor elevation data obtained from the National Oceanographic and Atmospheric Administration (NOAA) at http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML, regridded to 4 km spatial resolution) with the locations of coral reefs overlain (from the Global Distribution of Coral Reefs dataset (version 2010) compiled by UNEP-WCMC available at http://data.unep-wcmc.org/datasets/13 in ArcGIS vector format, which was then converted to NetCDF and gridded to 4 km spatial resolution). Figures (b) to (d) show the distribution of the *in situ* and satellite match-up data used in the study.