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Ocean color satellite determinations of phytoplankton size class in the Arabian Sea during the winter monsoon

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ABSTRACT

A regionally tuned three component "abundance" model of Brewin et al. (2012) has been used to discriminate satellite ocean color derived fields of phytoplankton biomass observable as Chlorophyll-a (Chl-a), into three size classes, i.e. microplankton (>20 μm), nanoplankton (>2 to <20 μm) and picoplankton (<2 μm). The model has been applied to MODIS-Aqua and Oceansat-2, Ocean Color Monitor (OCM) derived fields of Chl-a data between Nov. and Mar. In the Arabian Sea, during the evolution of blooms of the large (>800 μm sized) green mixotrophic dinoflagellate *Noctiluca scintillans*. A comparison of shipboard measured and model derived values of phytoplankton size classes (PSCs) show the superiority of the regionally tuned model over parameterizations used in the original model of Brewin et al. (2012). A total number of 39 in situ data points have been used for the tuning of the regional model and 5 different in-situ data points have been used for the comparison with in situ data in this remote region of data paucity. The absolute mean and the maximum absolute errors for all size fractions are 4.7% and 17.2% respectively, as compared to the values of 9.6% and 26% respectively obtained using Brewin et al. (2012).When applied to a weekly time series of Chl-a images, the regionally tuned model is able to capture the seasonal cycle of PSC in the Arabian Sea associated with the tail end of the fall inter-monsoon (Nov.), the winter monsoon (Dec. to Feb.) and the transition to the spring inter-monsoon Although ocean color remote sensing is a useful tool for studying phytoplankton processes in regions like the Arabian Sea that suffer from a paucity of in-situ observations, enhancing the validity and confidence in satellite ocean color derived products such as PSC, will require additional shipboard datasets.

1. Introduction and background

Ocean color satellites have revolutionized the way biological oceanographers view and study the oceans (McClain, 2009). Synoptic fields of phytoplankton biomass now available operationally, as chlorophyll-a (Chl-a) maps from earth observing missions have been utilized for a variety of purposes ranging from: i) assessments of ocean primary productivity (Field et al., 1998; Falkowski et al., 2004) and export/new production (Goes et al., 2000; Laws et al., 2000) ii) air-sea CO_2 exchanges and the role of ocean biology in modulating atmospheric CO_2 concentrations (Friedrich and Oschlies, 2009) iii) response of ocean ecosystems to climate change (Goes et al., 2005; Behrenfeld et al., 2006; Martinez et al., 2009), v) fisheries (Solanki et al., 2001; Zainuddin et al., 2004) etc. Although most phytoplankton are intimately linked with all of the aforementioned processes, certain groups of phytoplankton have distinct physiological and biogeochemical attributes that afford them specialized functional roles in the oceans. For example, diatoms are extremely important in the global carbon cycle (Smetacek, 1999); they account for ~20% of the global carbon fixation and are essential to the marine food chain and fisheries (Cushing, 1995; Buesseler et al., 1998; Siegel et al., 2016 and references cited therein). However they are distinct from other phytoplankton because of their ability to assimilate silicic acid. Consequently diatoms play an important role in silicic acid cycling, in particular the export of biogenic silica into the oceans interior. Cyanobacteria also contribute significantly to carbon fixation, in particular in waters that are devoid of nitrogen (Sohm et al., 2011). However, what distinguishes them from the other phytoplankton is their ability to fix nitrogen suggestive of their special role in the oceans nitrogen cycle. Other phytoplankton such as Prymnesiophytes and certain Dinoflagellates which are capable of producing dimethylsulfoniopropionate (DMSp) make them particularly important to the oceans sulfur cycle (Townsend and Keller, 1996).

Because of their importance to ocean ecosystems and biogeochemical processes, ascertaining the distribution of individual phytoplankton functional groups or phytoplankton functional types (PFTs) has led to a surge in efforts to extend the utility of ocean color measurements beyond Chl-a to maps of PFTs (Nair et al., 2008). Several in-situ bio-optical methods have been developed that now make it possible to distinguish PFTs based on their pigment composition and/or the special

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optical signatures they impart to the water column (Sathyendranath et al., 2004 and references cited therein). However, application of these methods to satellite ocean color data has been challenging because of the limited number of spectral bands available in the present generation of ocean color sensors for robust discrimination of PFTs (Werdell et al., 2014a, 2014b).

An alternate approach suggested for distinguishing phytoplankton from space is phytoplankton size classes (PSCs). Many ocean biogeochemical processes are closely linked to PSC (Sieburth et al., 1978; Richardson and Jackson, 2007; Marañón, 2015; Bach et al., 2016; Siegel et al., 2016), and there is growing recognition that satellite maps of PSC (Hirata et al., 2008; Kostadinov et al., 2009; Mouw and Yoder, 2010; Brewin et al., 2011, 2012) could provide a useful measure of ocean ecosystem state and function (Siegel et al., 2016), although not always (Nair et al., 2008).The PSC method involves partitioning of the autotrophic pool into different size groups; typically, i.e. microplankton (>20 μm), nanoplankton (<20 μm and >2 μm) and picoplankton (<2 μm). For example, most diatoms classify as microplankton. These particular groups of organisms are responsible for a sizeable fraction of carbon exported out of the euphotic zone, and are associated with highly productive areas that also support large fisheries (Legendre, 1990; Cushing, 1995). Picoplankton on the other hand are made up largely of Cyanobacteria and Prochlorophytes. These organisms are usually found in nutrient poor waters offshore, because their small cell size confers on them a greater capacity and hence advantage to acquire nutrients for growth over larger phytoplankton. Thus there is general consensus, that picoplankton play a greater role in recycling of carbon in oligotrophic waters (Agawin et al., 2000; Irwin et al., 2006; San Martin et al., 2006).

Because of the strong relationship between phytoplankton cell size and various aspects of phytoplankton physiology (Chisholm, 1992; Raven et al., 2005), the marine food web (Parsons and Lalli, 2002), energy transfer (San Martin et al., 2006) and fish production (Caddy and Griffiths, 1995), PSC measurements from space could greatly enhance the utility of ocean color data beyond what is presently possible by maps of Chl-a alone.

Phytoplankton cell sizes have a direct influence on the water leaving radiance observable by satellites. As a consequence there have been several attempts to partition the biomass of phytoplankton based on changes in the absorption and backscattering of light (Sathyendranath et al., 2004; Ciotti and Bricaud, 2006; Devred et al., 2011, Hirata et al., 2008; Kostadinov et al., 2009; Mouw and Yoder, 2010). Additionally since smaller cells are dominant in oligotrophic, low Chl-a waters, and larger cells dominate at high Chl-a waters, some studies have attempted to partition phytoplankton biomass based on seawater Chl-a concentrations (Hirata et al., 2008; Brewin et al., 2010, 2012). Both the spectral method and the method based on total Chl-a (also known as the abundance method) have been used for mapping PSC from space with varying degrees of success.

Here we present regional maps of PSC for the Arabian Sea that were generated using a regionally tuned version of the three component abundance model of Brewin et al. (2010) utilized previously in the Indian Ocean in Brewin et al. (2012). The Arabian Sea is a tropical ocean ecosystem where seasonal changes in phytoplankton biomass and productivity are largely under the control of the monsoonal winds (Smith, 2005). Our study is focused on a period covering the tail end of the fall inter-monsoon period (November), the northeast monsoon (December to March) and the spring inter-monsoon (April). A synthesis of measurements made during the Arabian Sea JGOFS program of the 1990s (Garrison et al., 2000) revealed that oligotrophic conditions during fall- and spring Inter-monsoon were periods that were dominated by pico-sized cyanobacteria, whereas nutrient enrichment due to convective mixing during winter favored the growth of micro-sized diatoms.

The seasonal shift in PSC was seen to have a huge impact on the vertical flux of carbon out of the euphotic zone (Buesseler et al., 1998; Honjo et al., 1999). Recent studies (Goes et al., 2005; Gomes et al., 2014; Goes and Gomes, 2016) however, indicate that the Arabian Sea ecosystem is undergoing rapid changes due to the warming trend. The study of Gomes et al. (2014) which was focused on the northeast (winter) monsoon showed that the region is experiencing a loss of phytoplankton biodiversity, with traditional diatom blooms being replaced by massive blooms of a large green mixotrophic dinoflagellate *Noctiluca scintillans* (*Noctiluca*) even offshore. Our study is focused on the northeast monsoon and assumes considerable importance in the light of the recent studies by Gomes et al. (2014) and Goes and Gomes (2016), which provide indication that the Arabian Sea is undergoing a radical change in the structure of phytoplankton communities. On account of the limitations of the current generation of ocean color satellites in discriminating phytoplankton functional types, a robust method for monitoring of PSC could offer an alternate satellite-based method for discriminating *Noctiluca* blooms and studying their variability over interannual to decadal time-scales.

2. Methodology

2.1. Shipboard measurements of phytoplankton size classes

Phytoplankton size class data utilized as part of this study were obtained during three cruises to the northern Arabian Sea on board the Indian Fisheries Oceanographic Research Vessel FORV *Sagar Sampada* (Fig. 1(a)) and from the TARA Ocean Expeditions in the Arabian Sea (Fig. 1(b)) available from NASA SeaBASS database. The cruise dates of Indian Expedition onboard FORV *Sagar Sampada* were as follows:12th–21st February 2009, 5th–12th March 2010 and 5th–21st March 2011 and coincided with the presence of large blooms of *Noctiluca*. Because of the piracy problems (which were particularly acute in the northwestern Arabian Sea), all three cruises were confined to the central and eastern parts of the northern Arabian Sea and were of shorter duration, restricting the number of samples that could be collected. The TARA Ocean Expedition in the Arabian Sea was conducted in three phases i.e. 04th to 11th March 2010 between Abu-Dhabi-Muscat, 12th to 22nd March 2010 between Muscat and Mumbai and 23rd March 2010 to 05th April 2010 between Mumbai and Male.

During the FORV *Sagar Sampada* cruises, seawater samples for PSC were collected with 5-l Niskin® samplers mounted on a Sea Bird Electronics® CTD Rosette and then drained very carefully into plastic carboys that were pre-washed using prescribed clean techniques (Knap et al., 1996). For total Chl-a analysis, duplicate sets of whole water samples (250 mL) were filtered onto 25-mm Whatman® GF/F filters (nominal pore size 0.7 μm). The filters were immediately transferred into disposable cuvettes containing 10 mL of cold 90% acetone. Chl-a was extracted under cold (~5 °C) in the dark for 24 h. The extracts were vortex mixed the following day, brought to room temperature in the dark, and quantified in a pre-calibrated Turner Designs® model-10 fluorometer (Knap et al., 1996; Gomes et al., 2014). To estimate Chl-a in the three size fractions (micro-, nano- and picoplankton), duplicate 250 to 500 mL samples from each depth were pre-filtered through a 20-μm pore size Nucleopore® filter. The <20-μm filtrates were collected in a clean flask, and 250-mL samples of each were then filtered through 25-mm Whatman® GF/F filters. Chl-a retained on this filter (<20 μm) was extracted and measured as described above. The rest of the <20 μm filtrate was further pre-filtered through a 2-μm pore size Nucleopore® filter, then collected on a GF/F filter to estimate picoplankton (pico, <2 μm). Chl-a concentrations attributable to the nano phytoplankton (nano, 2–20 μm) fraction were computed as the difference between Chl-a values in the <2-μm and <20-μm fractions. Chl-a attributable to microplankton (micro, >20 μm) was calculated as the difference between total Chl-a and the <20 μm fractions. PSC data used in the present study were measured in surface water samples from a total of 32 stations. The Chl-a content within each fraction has been expressed as mg m^{-3}.