Remote Sensing of Environment 160 (2015) 222–234

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Phytoplankton phenology indices in coral reef ecosystems: Application to ocean-color observations in the Red Sea

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form 5 January 2015
Accepted 21 January 2015
Available online 18 February 2015

Keywords:
Phytoplankton phenology
Ocean-color remote sensing
ESA OC-CCI
Coral reef ecosystems
Monsoon
Ecological indicators
Red Sea

ABSTRACT

Phytoplankton, at the base of the marine food web, represent a fundamental food source in coral reef ecosystems. The timing (phenology) and magnitude of the phytoplankton biomass are major determinants of trophic interactions. The Red Sea is one of the warmest and most saline basins in the world, characterized by an arid tropical climate regulated by the monsoon. These extreme conditions are particularly challenging for marine life. Phytoplankton phenological indices provide objective and quantitative metrics to characterize phytoplankton seasonality. The indices i.e. timings of initiation, peak, termination and duration are estimated here using 15 years (1997–2012) of remote sensing ocean-color data from the European Space Agency (ESA) Climate Change Initiative project (OC-CCI) in the entire Red Sea basin. The OC-CCI product, comprising merged and bias-corrected observations from three independent ocean-color sensors (SeaWiFS, MODIS and MERIS), and processed using the POLYMER algorithm (MERIS period), shows a significant increase in chlorophyll data coverage, especially in the southern Red Sea during the months of summer NW monsoon. In open and reef-bound coastal waters, the performance of OC-CCI chlorophyll data is shown to be comparable with the performance of other standard chlorophyll products for the global oceans. These features have permitted us to investigate phytoplankton phenology in the entire Red Sea basin, and during both winter SE monsoon and summer NW monsoon periods. The phenological indices are estimated in the four open water provinces of the basin, and further examined at six coral reef complexes of particular socio-economic importance in the Red Sea, including Siyal Islands, Sharm El Sheikh, Al Wajh bank, Thuwal reefs, Al Lith reefs and Farasan Islands. Most of the open and deeper waters of the basin show an apparent higher chlorophyll concentration and longer duration of phytoplankton growth during the winter period (relative to the summer phytoplankton growth period). In contrast, most of the reef-bound coastal waters display equal or higher peak chlorophyll concentrations and equal or longer duration of phytoplankton growth during the summer period (relative to the winter phytoplankton growth period). The ecological and biological significance of the phytoplankton seasonal characteristics are discussed in context of ecosystem state assessment, and particularly to support further understanding of the structure and functioning of coral reef ecosystems in the Red Sea.

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1. Introduction

Coral reefs are among the most biologically diverse ecosystems on Earth. They occupy less than 0.1% of the world's oceans, yet they host 25% of all the marine species (Spalding, Ravilious, & Green, 2001). Coral reefs deliver valuable and vital ecosystem services. They offer coastal protection, employment (through fisheries, recreation, and tourism), and are a major source of food for millions of people around the world (Hoegh-Guldberg, 1999). However, coral reefs are fragile ecosystems, facing serious threats from global climate change, marine acidification, destructive and unsustainable fishing practices, and water-polluting land-use activities (Hoegh-Guldberg et al., 2007; Wilkinson, 1999).

The Red Sea hosts thriving coral reef communities that have adapted to one of the most saline and warm basins in the world (Belkin, 2009; Cantin, Cohen, Karnauskas, Tarrant, McCorkle, 2010). The Red Sea is also unique because of its partial isolation from the Indian Ocean, its arid tropical climate, and its prevailing wind system regulated by the monsoon (Halim, 1969). During summer, northwesterly winds predominate in the Southern part of the Red Sea from June to September

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http://dx.doi.org/10.1016/j.rse.2015.01.019
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(i.e. summer NW monsoon period), while during winter, in the southern Red Sea, prevailing winds reverse to southeasterly from October to May (i.e. winter SE monsoon period). Over the northern part of the Red Sea (North of 20°N), wind blow persistently from north-northwest throughout the year (Patzert, 1972). The Red Sea is further characterized by warm water temperature, which has been shown to be rapidly increasing since the mid-90s (from 27.4 °C on average during 1985–2003 to 28.1 °C on average during 1994–2007; Raitsos et al., 2011). These conditions make the Red Sea an excellent laboratory for studying the effects of the environment on marine organisms. In fact, the Red Sea has been shown not to be immune to the effects of global climate change and other disturbances, as evidenced by recent documentation of thermal coral bleaching events (e.g., Furby, Bouwmeester, & Berumen, 2013; Pineda et al., 2013) and historical crown-of-thorns starfish outbreaks (e.g., Riegl, Berumen, & Bruckner, 2013). Furthermore, in some regions, the majority of commercially targeted species have been overfished for decades (Jin, Kite-Powell, Hoagland, & Solow, 2012). High pressure is placed on apex predator populations, which are critical for ecological functioning in coral reefs, and are notably understudied in Red Sea ecosystems (Berumen et al., 2013; Spaet, Thorrold, & Berumen, 2012). For instance, the roving coral-grouper (*Plectropomus pessuliferus*) is highly targeted in the Red Sea, and a marked decline (or even disappearance in certain areas) has been shown, leading to the inclusion of this species into the International Union for Conservation of Nature (IUCN) Red List (Ferreira, Gaspar, Samoilys, Choat, & Myers, 2008).

Located at the base of the marine food web, phytoplankton support the functioning of coral reef ecosystems (Genin, Monismith, Reidenbach, Yahel, & Koseff, 2009; Wild, Jantzen, Struck, Hoegh-Guldberg, & Huettel, 2008; Wyatt, Lowe, Humphries, & Waite, 2010; Yahel, Post, Fabricius, & Genin, 1998), providing a source of food for many coral reef-associated organisms, including zooplankton, benthic grazers such as sponges (e.g., Richter, Wunsch, Rasheed, Kötter, & Badran, 2001; Yahel, Sharp, Marie, Häse, & Genin, 2003), bivalves (e.g., Yahel, Marie, Beninger, Eckstein, & Genin, 2009), and pelagic larvae (e.g., Erez, 1990; Johannes, 1978; Lo-Yat et al., 2011). In fact, the larvae of many marine species (including fish, crustaceans, mollusks and echinoderms) graze on phytoplankton during this vulnerable stage of their lives. Evidence that survival of gadoid fish larvae depends on the timing of the local spring bloom of phytoplankton has been demonstrated by Platt, Fuentes-Yaco, and Frank (2003) using a combination of satellite chlorophyll and in situ observations. Another characteristic example is the tight coupling reported between shrimp hatch time and the timing of remotely-sensed phytoplankton spring bloom peak in high-latitude ecosystems of the North Atlantic basin (Koeller et al., 2009). In a tropical ecosystem, Lo-Yat et al. (2011) have shown a significant positive relationship between remotely-sensed chlorophyll concentrations and the recruitment success of coral reef fish larvae. Assessing the phytoplankton phenology (timing of food availability) is important, as any changes may propagate up the marine food web, which may lead to trophic mismatch and alter the function of marine ecosystems (Edwards & Richardson, 2004).

To investigate trophic interactions in coral reef ecosystems, and to be able to detect anomalous trends or patterns, a comprehensive understanding of the seasonal variability (climatological cycle) of microscopic marine algae, phytoplankton, is required. In the Red Sea, general ecological research (Berumen et al., 2013) and long-term large-scale biological datasets are rare, with the latter mainly limited to satellite-based observations of ocean color (Acker, Leptoukh, Shen, Zhu, & Kempler, 2008; Brewin, Raitsos, Pradhan, & Hoteit, 2013; Labiosa, Arrigo, Genin, Monismith, van Dijken, 2003; Raitsos, Pradhan, Brewin, Stenchikov, & Hoteit, 2013). The color of the ocean is a good indicator of the primary photosynthetic pigment found in phytoplankton, chlorophyll (Sathyendranath & Platt, 1997). Over the past two decades, remote-sensing measurements of chlorophyll have provided unique information on surface marine phytoplankton, allowing us to monitor their distribution at high temporal and spatial resolution in coastal and open oceans (Blondeau-Patissier, Gower, Dekker, Phinn, & Brandoc, 2014). Chlorophyll concentration varies seasonally following the growth and decline of phytoplankton populations, which define the phytoplankton growing period. A suite of indices has been proposed to quantify phytoplankton seasonality (Platt & Sathyendranath, 2008) and to provide support to investigations on the composition, structure and functioning of the marine ecosystem (Racault, Platt, et al., 2014). The study of timing of periodical growth of phytoplankton populations relates to phenology. Phenological indices include timings of initiation, peak, termination, and duration of phytoplankton growing period (e.g., Racault, Le Quéré, Buitenhuis, Sathyendranath, & Platt, 2012). Several methods have been proposed to estimate these indices (see Ji, Edwards, Mackas, Runge, & Thomas, 2010 for a review). Conventionally, the methods involve a threshold criterion, which provides a boundary value to delineate initiation and termination of a phytoplankton growing period. The threshold criterion can be estimated directly from the remotely-sensed chlorophyll time-series (Henson, Robinson, Allen, & Waniek, 2006; Racault et al., 2012; Siegel, Doney, & Yoder, 2002; Thomalla, Fauchereau, Swart, & Monteiro, 2011), or after fitting a density function to the chlorophyll time-series (Platt, White, Zhai, Sathyendranath, & Roy, 2009; Vargas, Brown, & Sapiano, 2009; Zhai, Platt, Tang, Sathyendranath, & Hernández Walls, 2011; Sapiano, Brown, Schollaert Uz, & Vargas, 2012; González Taboada & Anadón, 2014; Ardyna et al., 2014), or performing a cumulative summation of the chlorophyll concentration (Brody, Lozier, & Dunne, 2013). Although different methods and threshold criteria may yield similar results, the choice of method and threshold requires scrutiny of the shape of the phytoplankton seasonal cycle. A further caution is that phenological studies require data well distributed in time (i.e. with few missing data), to enable resolution of timings of seasonal events with sufficient precision (Cole, Henson, Martin, & Yool, 2012; Land, Shutler, Platt, & Racault, 2014; Racault, Sathyendranath, & Platt, 2014).

Using SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) and MODIS (Moderate Resolution Imaging Spectroradiometer) observations of chlorophyll, Acker et al. (2008) described the general seasonal variability of phytoplankton in the northern Red Sea. Using MODIS data, Raitsos et al. (2013) further examined phytoplankton seasonality in relation to environmental conditions in the Red Sea, and based on biological and physical characteristics, the latter authors proposed a partitioning into four provinces: the northern-Red Sea (NRS), the north-central Red Sea (NCRS), the south-central Red Sea (SCRS), and the southern Red Sea (SRS). However, in spite of the remarkable sampling coverage provided by remote-sensing technology, the presence of persistent clouds and atmospheric aerosol, sun-glint, and sensor saturation over sand have significantly limited data acquisition in the Arabian Sea and Red Sea regions. Specifically, during summer NW monsoon period, in addition to relatively frequent sand storms, the southern Red Sea is affected by hazy–cloudy conditions, which had prevented retrieval of useful remotely-sensed chlorophyll data until recently (Steinmetz, Deschamps, & Ramon, 2011). In 2014, the European Space Agency (ESA) Ocean-Colour Climate Change Initiative (OC-CCI) project produced and validated a consistent, stable, and error-characterized time-series of global ocean-color products based on merged SeaWiFS, MODIS and MERIS (MEdium Resolution Imaging Spectrometer) data (Hollmann et al., 2013; http://www.esa-oceancolour-cci.org). The progress made in the OC-CCI project has permitted improved coverage of remotely-sensed chlorophyll measurements in summer months in the Arabian Sea and southern Red Sea regions.

In the present study, we use ESA OC-CCI data to provide the first quantitative investigation of the phenology of phytoplankton in the Red Sea for both the winter and the summer growing periods. The research outcomes unfold as follows: 1) we assess and compare the spatial and temporal coverage of ocean-color observations from OC-CCI products with previously-available single-sensor SeaWiFS, MODIS and MERIS products; 2) we examine the performance of the ESA OC-CCI

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