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Review

A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans

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ABSTRACT

The need for more effective environmental monitoring of the open and coastal ocean has recently led to notable advances in satellite ocean color technology and algorithm research. Satellite ocean color sensors' data are widely used for the detection, mapping and monitoring of phytoplankton blooms because earth observation provides a synoptic view of the ocean, both spatially and temporally. Algal blooms are indicators of marine ecosystem health; thus, their monitoring is a key component of effective management of coastal and oceanic resources. Since the late 1970s, a wide variety of operational ocean color satellite sensors and algorithms have been developed. The comprehensive review presented in this article captures the details of the progress and discusses the advantages and limitations of the algorithms used with the multi-spectral ocean color sensors CZCS, SeaWiFS, MODIS and MERIS. Present challenges include overcoming the severe limitation of these algorithms in coastal waters and refining detection limits in various oceanic and coastal environments. To understand the spatio-temporal patterns of algal blooms and their triggering factors, it is essential to consider the possible effects of environmental parameters, such as water temperature, turbidity, solar radiation and bathymetry. Hence, this review will also discuss the use of statistical techniques and additional datasets derived from ecosystem models or other satellite sensors to characterize further the factors triggering or limiting the development of algal blooms in coastal and open ocean waters.

Contents

Abbreviations: AVHRR, Advanced Very High Resolution Radiometer; Chl-i, Chlorophyll concentration of pigment i; CDOM, Colored Dissolved Organic Matter; CIA, Color Index Algorithm; CZCS, Coastal Zone Color Scanner (NASA); EMD, Empirical Mode Decomposition; EOF, Empirical Orthogonal Function; FAI, Floating Algae Index; FLH, Fluorescence Line Height; GSM, Garver–Siegel–Maritorena model; HAB, Harmful Algal Bloom; HNLC, High Nutrient–Low Chlorophyll; HPLC, High Performance Liquid Chromatography; KBBI, *Karenia brevis* Bloom index; MCI, Maximum Chlorophyll Index; MERIS, Medium Resolution Imaging Spectrometer (ESA); MODIS, Moderate Resolution Imaging Spectroradiometer (NASA); NIR, Near Infrared (>700 nm); PAR, Photosynthetically Active Radiation; PCA, Principal Component Analysis; QAA, Quasi-Analytical Algorithm; RBD, Red Band Difference; RCA, Red tide index Chlorophyll Algorithm; RGB, Red–Green–Blue true color satellite image; RI, Red Tide Index; Rrs, Remote Sensing Reflectance; SeaWiFS, Sea-viewing Wide Field-of-view Sensor (NASA); SSH, Sea Surface Height; SST, Sea Surface Temperature; TSM, Total Suspended Matter.

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1. Introduction

Over 5000 species of marine phytoplankton have been described worldwide (e.g., Sournia et al., 1991). Typically ranging from less than 1 μm to over 100 μm in size, a phytoplankton cell, also known as an 'algal' or 'algae' cell, is a planktonic photosynthesizing organism. Increases in phytoplankton cell numbers can result from favorable environmental conditions, which include water column stratification, increase in light availability (e.g., Gohin et al., 2003; Kogeler and Rey, 1999), water temperature (Thomas et al., 2003) and/or nutrient levels (e.g., Santoleri et al., 2003; Siegel et al., 1999). The global distribution of Chlorophyll-a (Chl-a), the direct proxy for phytoplankton biomass (Cullen, 1982), shows that Chl-a–rich regions are located along the coasts and continental shelves, north of 45° North (Fig. 1a), mostly because of a strong nutrient supply. Moderate Chl-a concentrations are found in the equatorial regions of the Atlantic and Pacific, caused by the upwelling of deep, nutrient-rich, cool waters from the divergence of the ocean water masses along the equator. Moderate Chl-a concentrations are also found in the subtropical convergence zone (south of 45° South), where cool, nutrient-rich sub-Antarctic water masses mix with warm, nutrient-poor subtropical waters. However, most open ocean regions typically appear low in satellite-derived Chl because they are far from land. Ocean color observations are limited to the first optical depth; consequently, deep chlorophyll maxima (DCM) are not always captured by satellites (e.g., Huisman et al., 2006; Cullen, 1982). Many phytoplankton blooms (see Section 2) occurring deep in the water column or with extremely low Chl-a (<0.1 mg m^{-3}) remain unreported because they are not always observed in satellite images but yet are known to occur (e.g., Dore et al., 2008; Villareal et al., 2011). Algal blooms (see Section 2) detected by satellite sensors often cover large areas, but their typically "patchy" distributions make them difficult to model (Martin, 2003) (Fig. 1b–d). The visualization of satellite images (Fig. 1) is the primary technique used to identify their presence, particularly when phytoplankton blooms occur as a regular event in a specific ocean region (e.g., Srokosz and Quartly, 2013) or in regions where they are not usually expected, such as oligotrophic gyres (e.g., Wilson, 2003; Wilson et al., 2008; Wilson and Qiu, 2008). Over the last 13 years, there has been an increase in peer-reviewed publications on the study of algal blooms using ocean color satellite data (Fig. 2). Algal blooms in coastal ocean regions have been the primary focus of those studies, mainly due to the direct connectivity between the land and continental shelf waters (e.g., Gazeau et al., 2004) and the impact of coastal harmful phytoplankton blooms on anthropogenic activities (Frolov et al., 2013). Important technological progress in the design of satellite ocean color sensors from the second and third generations greatly improved coastal water algorithms, resulting in a more accurate retrieval of phytoplankton proxies in coastal waters (see Table 1 of Shen et al. (2012); Fig. 3).

Phytoplankton blooms affect the color of the water by increasing light backscattering with spectrally localized water-leaving radiance minima from generic (Chl-a) and species-specific algal pigment absorption, such as phycobiliproteins for cyanobacteria, fucoxanthin for diatoms and peridinin for dinoflagellates. Ocean color remote sensing, the passive satellite-based measurement of visible light emerging from the ocean surface (Robinson, 2004), has provided more than two decades of near-real-time synoptic and recurrent measurements of global phytoplankton biomass (Figs. 1 and 4), evolving from qualitative (e.g., Gordon et al., 1980) to quantitative estimates (e.g., Kutser, 2009). The accumulation of scientific knowledge on the temporal and spatial dynamics of phytoplankton in the world's oceans from earth observations was largely assisted by rapid advances in marine science technologies (e.g., Babin et al., 2008; Dickey et al., 2006) and has had many global and local applications (Table 1). Recent reviews on satellite ocean color remote sensing have reported on, but are not limited to, scientific advances in this field (e.g., McClain, 2009a, 2009b), its societal benefits (e.g., IOCCG Report 7, 2008) and its valuable applications to coastal ecosystem management (e.g., Kratzer et al., 2013; Klemas, 2011), including that of fisheries (e.g., Wilson, 2011) and in the detection of (harmful) algal blooms (Shen et al., 2012) (Table 2).

The reviews of Matthews (2011) and Odermatt et al. (2012) discussed the various ocean color models used for the retrieval of water quality parameters in open and coastal ocean waters, from empirical to more complex approaches. More recently, Brody et al. (2013) compared different methods to determine phytoplankton bloom initiation. The present article will complement those recent reviews by providing the following: