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A novel ocean color index to detect floating algae in the global oceans

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ABSTRACT

Various types of floating algae have been reported in open oceans and coastal waters, yet accurate and timely detection of these relatively small surface features using traditional satellite data and algorithms has been difficult or even impossible due to lack of spatial resolution, coverage, revisit frequency, or due to inherent algorithm limitations. Here, a simple ocean color index, namely the Floating Algae Index (FAI), is developed and used to detect floating algae in open ocean environments using the medium-resolution (250- and 500-m) data from operational MODIS (Moderate Resolution Imaging Spectroradiometer) instruments. FAI is defined as the difference between reflectance at 859 nm (vegetation "red edge") and a linear baseline between the red band (645 nm) and short-wave infrared band (1240 or 1640 nm). Through data comparison and model simulations, FAI has shown advantages over the traditional NDVI (Normalized Difference Vegetation Index) or EVI (Enhanced Vegetation Index) because FAI is less sensitive to changes in environmental and observing conditions (aerosol type and thickness, solar/viewing geometry, and sun glint) and can "see" through thin clouds. The baseline subtraction method provides a simple yet effective means for atmospheric correction, through which floating algae can be easily recognized and delineated in various ocean waters, including the North Atlantic Ocean, Gulf of Mexico, Yellow Sea, and East China Sea. Because similar spectral bands are available on many existing and planned satellite sensors such as Landsat TM/ETM+ and VIIRS (Visible Infrared Imager/Radiometer Suite), the FAI concept is extendable to establish a long-term record of these ecologically important ocean plants.

1. Introduction

Beginning with the Coastal Zone Color Scanner (1978–1986), all satellite ocean color sensors have been designed to measure the spectral water-leaving radiance or surface reflectance in order to derive concentrations of the various water constituents including chlorophyll-*a*. Indeed, the phrase "ocean color" is often regarded as equivalent to chlorophyll-*a* concentration. Significant progress has been made in the past two decades, through modern sensor development, calibration, validation, and algorithm improvement, to derive a suite of the ocean's bio-optical properties such as chlorophyll-*a* concentration, absorption coefficient of colored dissolved organic matter (CDOM), diffuse attenuation coefficient, and euphotic depth (Yentsch, 1960, 1983; Morel & Prieur, 1977; Austin & Petzold, 1981; Gordon & Morel, 1983; Sathyendranath et al., 1989; Cullen et al., 1997; Gordon, 1997; O'Reilly et al., 2000; Maritorena et al., 2002; Lee et al., 2002, 2005; McClain et al., 2004; IOCCG, 2005; others). Algorithms have also been developed to detect some phytoplankton functional groups due to their unique optical properties, including Coccolithophores (Brown & Yoder, 1994; Gordon et al., 2001), cyanobacteria *Trichodesimum* spp. (Subramaniam et al., 2002), cyanobacteria *Nodularia spumigena* (Kahru et al., 2007), diatoms (Sathyendranath et al., 2004), harmful algae (Cannizzaro et al., 2008), and other groups (Morel et al., 1993; Alvain et al., 2005). Consequently, in addition to the application of the science-quality ocean color data in global and regional biogeochemical studies, ocean color data have also been used to monitor and study harmful algal blooms (HABs), sediment resuspension, coral reef environmental health, coastal and estuary water quality, and to help fisheries management (Kahru & Brown, 1997; Miller et al., 2005; Friedl et al., 2006; IOCCG, 2008; and references therein).

However, all these efforts have been dedicated to derive and study the ocean constituents suspended/dissolved in water. On the other hand, algae floating on the water surface, such as the brown macroalgae *Sargassum* spp., have been reported in the literature (e.g., Parr, 1939; Butler & Stoner, 1984; Chernova & Sergeeva, 2008) as well as in various local news media. These surface plants are known to provide important habitat (food and shade) for fish, shrimp, crab, and other marine organisms, including several threatened species of turtles (South Atlantic Fishery Management Council, 2002; Witherington & Hirama, 2006), yet their potential relationship with fish populations and larvae transport has not been documented, possibly due to lack of concurrent data. They also play a role in defining ocean productivity and carbon flux (Muraoka, 2004). *Sargassum* is now considered critical and protected marine habitat and its harvesting in some ocean regions is regulated to protect the associated marine species (South Atlantic Fishery Management Council, 2002). Some species of floating algae can also be used for human food and phycocolloid production (Zemke-White & Ohno, 1999). Conversely,

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excessive amount of floating algae in coastal oceans can cause significant adverse impact on local environments and economy, such as the extensive and long-lasting bloom of the green macroalgae *Enteromorpha prolifera* in the Yellow Sea (China) between May and August 2008 (Hu & He, 2008). Dead algae washed onto the beaches must be physically removed in a prompt fashion, and represents an economic burden to local management. Timely information on the size and location of the floating algae is important to help understand fish ecology and to help make management plans. Until recently, however, nearly all reports of these surface organisms are from *in situ* observations that are limited in both space and time, and detection of floating algae from space has been rare.

Gower et al. (2006) first used 300-m full-resolution (FR) MERIS (Medium Resolution Imaging Spectroradiometer, 2002–present) data and 1-km resolution MODIS (Moderate Resolution Imaging Spectroradiometer, 1999–present for Terra, 2002–present for Aqua) data to show the extensive surface slicks, thought to be *Sargassum* spp. (brown or dark-green macro algae), in the Gulf of Mexico (GOM). However, MERIS FR data are available for only limited regions in the world (primarily European waters), and the MODIS 1-km data lack spatial resolution to detect small-scale floating algae. Furthermore, the algorithms used to detect these surface features are not specific to floating algae. While the MCI (Maximum Chlorophyll Index, Gower et al., 2005) is useful in detecting the reflectance peak at 709-nm due to the combined effect of chlorophyll-*a* absorption and fluorescence as well as particulate backscattering, high MCI values can be caused by algae floating on the surface or suspended in the water column, or by sediment plumes. Therefore, the MERIS reflectance spectra from the visible to the near-IR as well as the spatial contrast were examined to distinguish the two types of blooms (Gower et al., 2006). Without referencing the nearby water or examining the full spectral shape, the spatial shape of the detected feature was used to confirm the presence of these surface plants, as floating algae often form thin slicks following wind and currents.

Recently, using the MCI algorithm and MERIS data at reduced resolution (RR, ~1.2 km per pixel), Gower and King (2008) provided the first systematic assessment of *Sargassum* distributions in the GOM and North Atlantic Ocean. Global applications of MCI and MERIS RR data to detect other phytoplankton blooms have also been reported (Gower et al., 2008). Due to the relatively coarse resolution and narrow swath width (~1150 km) of MERIS, small algae slicks might have been missed, which could create errors in understanding their origin, initiation, and distribution statistics.

The MODIS instruments are equipped with several "sharpening" bands designed for land and atmospheric applications with 250-m and 500-m resolutions. Specifically, the 645- and 859-nm bands are 250-m resolution, and the 469-, 555-, 1240-, 1640-, and 2130-nm bands are 500-m resolution. Further, the two MODIS instruments onboard Terra (1999–present) and Aqua (2002–present) satellites with swath widths of 2300 km and equatorial crossing times of 10:30 am and 1:30 pm, respectively, provide more frequent and higher-resolution data than MERIS on a global scale. Several pioneering studies have shown that MODIS medium-resolution data (250- and 500-m) provide great potential in monitoring surface oil slicks (Hu et al., 2003, 2009), algal blooms (Kahru et al., 2004), and coastal/estuarine water quality (Hu et al., 2004; Miller & McKee, 2004; Chen et al., 2007). Large-scale applications of MODIS medium-resolution data in the global ocean to study algae blooms, however, could not been found in the literature. Hu and He (2008) first used these data to study floating algae in the Yellow Sea, yet the simple method used in the study suffered from several problems (see below).

Here, a Floating Algae Index (FAI) is introduced for mapping floating algae in various aquatic environments, the concept of which can be applied to several existing and planned satellite instruments. First, traditional methods to map surface vegetation are introduced, followed by model simulations and data comparisons to show the advantages of the FAI concept. Finally, several examples in the Yellow Sea, East China Sea, North Atlantic Ocean, and Gulf of Mexico from MODIS and Landsat-7/ETM+ are presented and discussed. The objective of this work is to demonstrate the FAI concept to help implement targeted mapping and research plans for any region of interest in the global oceans using MODIS and other fine-resolution satellite instruments.

2. Traditional methods for vegetation mapping

In 1973, Rouse et al. introduced the concept of NDVI (Normalized Difference Vegetation Index) using MSS (MultiSpectral Scanner) data from the US NASA's Earth Resources Technology Satellite (ERTS was later renamed as Landsat-1) (Rouse et al., 1973). NDVI is defined as:

$$\mathrm{NDVI} = (R_{\mathrm{NIR}} - R_{\mathrm{RED}}) / (R_{\mathrm{NIR}} + R_{\mathrm{RED}}), \quad (1)$$

where R_{NIR} and R_{RED} are the reflectance in the near-infrared (NIR) and red bands, respectively. The underlying principle is that all forms of vegetation have a sharp increase in the reflectance spectra (the "red edge") near 700 nm. The difference between R_{NIR} and R_{RED} serves as an index of the vegetation density. Normalization against ($R_{\mathrm{NIR}}+R_{\mathrm{RED}}$) can partially remove the atmospheric effects from different measurements. Some published works also reference radiance instead of reflectance, but the principle is the same.

NDVI is related to the photosynthetic capacity and therefore energy absorption of plant canopies (Sellers, 1985; Myneni et al., 1995). Many applications have utilized NDVI for land cover/land use such as mapping global vegetation and land-based primary production. Its application to AVHRR (Advanced Very High Resolution Radiometer) data to study algae blooms in oceanic and inland waters has also been reported (Prangsma & Roozekrans, 1989; Kahru et al., 1993).

The NDVI concept has been applied to MODIS 250-m resolution data to study the origin and evolution of a massive bloom of the floating algae *E. prolifera* in the Yellow Sea that posed severe management problems for the 2008 Olympic sailing games (Hu & He, 2008). The NDVI method was useful in delineating floating algae from nearby waters. However, NDVI values of both the floating algae and nearby waters are sensitive to variable environmental and observing conditions such as aerosols and solar/viewing geometry. These variable conditions create difficulties in visualization and quantitative analysis since they affect not only the visual contrast between floating algae and nearby waters in the NDVI imagery but change their absolute NDVI values as well. Consequently, interactive color stretching and manual delineation of the region of interest are often required (Hu & He, 2008), making it difficult to implement routine applications to large regions such as the Yellow Sea and East China Sea. In the GOM, MODIS 250-m NDVI images have been found to be able to detect floating algae slicks, thought to be *Sargassum*, but the same limitation apply.

Similar problems have also been found for land vegetation mapping, as NDVI suffers from atmospheric effects, thin clouds, and is also sensor dependent (Holben 1986; Trishchenko et al., 2002). Several modified indexes have been proposed to overcome these difficulties. These include the EVI (Enhanced Vegetation Index) that was designed to strengthen the vegetation signal in high biomass regions and to reduce atmosphere influences. EVI is defined as (Huete & Justice, 1999):

$$\mathrm{EVI} = G \times (R_{\mathrm{NIR}} - R_{\mathrm{RED}}) / (R_{\mathrm{NIR}} + C_1 \times R_{\mathrm{RED}} - C_2 \times R_{\mathrm{BLUE}} + C_3), \quad (2)$$

where G is the gain factor, and C_1, C_2, and C_3 are the pixel-independent coefficients to compensate for aerosol effects and vegetation background, respectively. For MODIS data, $G=2.5$, $C_1=6$, $C_2=7.5$, and $C_3=1$ (Huete & Justice, 1999).