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A model for estimating size-fractioned phytoplankton absorption coefficients in coastal and oceanic waters from satellite data

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ABSTRACT

One of the central goals of using satellite ocean color remote sensing is to detect and identify different phytoplankton groups (size classes) and describe their variability continuously and synoptically for various applications including marine ecosystem dynamics, carbon and biogeochemical cycles, and related fields in oceanography. Taking the advantage of phytoplankton communities having distinct optical properties, this study presents a new model to explicitly detect and differentiate between three phytoplankton size-classes namely, picophytoplankton, nanophytoplankton, and microphytoplankton, based on distinct differences in the optical signatures of these phytoplankton groups in a wide variety of coastal and oceanic waters. The model is based on the assumption that there is a significant relationship between chlorophyll-*a* concentration, and total as well as the size-fractioned absorption coefficients of phytoplankton. The new model is validated using three different in-situ datasets collected from a wide variety of locations in the global and regional oceans (including turbid coastal and eutrophic waters) and its results are further compared with those of the existing two- and three-component models. The new model performs better than other models in terms of yielding more accurate estimates of the total and size-dependent phytoplankton absorption coefficients across the entire visible wavelengths. Since satellite observation of 'ocean color' as detected by a remote sensor provides an estimate of the chlorophyll-*a* concentration, commonly used as an index of phytoplankton biomass, the new model is also applied to regional and global images of seasonal climatology over a decade of satellite ocean color observations provided by the MODIS-Aqua sensor. When applied to the MODIS-Aqua images of the Arabian Sea dominated by spatially intense algal blooms, the present model is generally excellent at predicting and describing the spatial distribution of these phytoplankton groups within cyclonic eddies and adjacent regions in the Arabian Sea. Conversely, size-fractioned phytoplankton absorption coefficients derived from global images of seasonal climatology are found to vary depending on the season and ocean basin. These global images imply that when phytoplankton abundance increases, larger size-classes are added incrementally to a background of smaller cells. Further examination of these data showed that picophytoplankton population is generally low, although dominating a major part of the surface ocean during summer and winter. Nanophytoplankton and microphytoplankton populations are high in surface waters of the North and South Atlantic, North and South Pacific Oceans, Arabian Sea, and equatorial region, showing an increasing trend in summer and a decreasing trend in winter in each hemisphere. These results suggest that the new model is an important tool which will inspire further research to investigate different phytoplankton size classes and their variability on regional and global scales.

1. Introduction

Phytoplankton, considered to be the ocean's invisible forest, play a critical role in regulating global climate by means of transferring carbon dioxide from the atmosphere to the ocean and provide half of the world's primary production that sustain the aquatic food web (Falkowski et al., 2004; Field, Behrenfeld, Randerson, & Falkowski, 1998; House, Prentice, & Le Qu'er'e, 2002; Longhurst, Sathyendranath, Platt, & Caverhill, 1995; Parsons & Lalli, 2002; Platt & Sathyendranath, 1988). On the other hand, phytoplankton blooms indicate that high primary productivity could result in severe oxygen depletion locally and such conditions could be conducive to growth of microbes associated with high methane and nitrous oxide (greenhouse gases) with even greater heat-trapping capacity than CO_2 (*e.g.*, the infamous "dead zone" in the northern Gulf of Mexico, Sherman & Capelli, 2012). Thus, description and prediction of changes in phytoplankton species composition are important goals to many fields in oceanography. In the past decades, the near-surface chlorophyll-*a* obtained from in-situ or space-borne observations was often used an index of the phytoplankton biomass. However, it

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becomes increasingly obvious that the use of only chlorophyll-*a* as a proxy for phytoplankton biomass is insufficient, as different communities of phytoplankton explicitly determined in terms of the size class (assigned to small phytoplankton – picophytoplankton and nanophytoplankton and large phytoplankton – microphytoplankton) are responsible for changes in specific biogeochemical processes and carbon cycle. In fact, the structure of these phytoplankton communities is also affected by intervention of the physical processes at different spatial scales ranging from a few meters (*e.g.*, the mixed layer depth) to thousands of kilometers (basin scale). It is recognized that the input of 'new nutrients' in the euphotic layer as a result of vertical mixing caused by water movements such as eddies and jets is the main source for small phytoplankton, whereas the exogenous nutrients are the primary source for large phytoplankton (Vidussi, Claustre, Manca, Luchetta, & Marty, 2001). Thus, both exogenous and new nutrients are expected to modify the composition of the phytoplankton community and the hydrodynamic forcing influences on their distribution at different spatial scales. In recent years, significant effort has been made on the estimation of specific phytoplankton groups (size classes) by explicitly incorporating such information into carbon cycle models, biogeochemical models, multi-phytoplankton coupled ocean-ecosystem models and models for harmful algal blooms and fish production (Baretta-Bekker, Baretta, & Ebenho, 1997; Caddy, Fefk, & Do-Chi, 1995; Gregg, Ginoux, Schopf, & Casey, 2003; Kutser, Metsamaa, Strombeck, & Vahtmae, 2006; Moore, Doney, Kleypas, & Glover, 2002; Platt & Sathyendranath, 2008; Taylor, Harbour, Harris, Burkill, & Edwards, 1993; Uitz et al., 2009; Vanden Berg, Ridderinkhof, Riegman, Ruardij, & Lenhart, 1996).

Since discrete sampling allows different size classes of phytoplankton to be characterized but not simultaneously at very large ranges of spatial scales, given our present day capabilities, several studies have attempted to use satellite ocean color observations to produce global and regional maps of individual phytoplankton size classes (*PSC* – such as picophytoplankton (<2 μm), nanophytoplankton (2–20 μm) and microphytoplankton (>20 μm)) and begun to describe their interannual variability. Ocean color or the sea spectral reflectance, as detected by a remote sensor, varies directly with the backscattering coefficients and inversely with the absorption coefficients (at specific wavelengths) of all optically active components (*i.e.*, water, phytoplankton, suspended sediments and colored dissolved organic matter), and depends on the spectral characteristics and geometrical distribution of the light field (Morel & Prieur, 1977). The backscattering coefficient in the ocean is influenced by different size class of phytoplankton groups (Brewin et al., 2012) and other components such as submicron particles, bacteria and bubbles (Stramski & Kiefer, 1991; Zhang, Lewis, & Johnson, 1998). Though there are methods available to determine size class of phytoplankton groups (Brewin et al., 2012 and references therein), spectral absorption coefficient is the main optical property that can be used to distinguish phytoplankton communities, with the exception of the strong backscattering associated with blooms of coccolithophores, Trichodesmium and other similar species (Balch, Kilpatrick, & Trees, 1996; Ciotti, Lewis, & Cullen, 2002; Sathyendranath, Watts, Devred, et al., 2004; Subramaniam, Brown, Hood, Carpenter, & Capone, 2002). Data from different optical platforms (Morel, 1997; Sathyendranath, Hoge, Platt, & Swift, 1994) and laboratory analyses (Bricaud, Babin, Morel, & Claustre, 1995) suggest that phytoplankton communities are the principal agents responsible for variations in the total absorption coefficient in most oceanic waters. However, the absorption properties of phytoplankton are strongly influenced by pigment packaging (strongly related to cell size, Morel and Bricaud (1981), Stuart et al. (1998), Stuart et al. (2000)) and pigment composition, although differences in the shape of these spectra for different communities of phytoplankton are relatively small to detect, which influence important optical relationships between phytoplankton absorption and chlorophyll concentration (Bricaud et al., 1995), and those between ocean color and the amount of chlorophyll because of differences in packaging (Ciotti, Cullen, & Lewis, 1999; Ciotti et al., 2002; Sathyendranath, Stuart, Cota, Mass, & Platt, 2001).

From the previous studies, it becomes evident that the absorption coefficient of phytoplankton from most oceanic waters is a nonlinear function of the dominant phytoplankton pigment (*i.e.*, chlorophyll-*a* concentration) and this relationship chiefly results from species differing in size, shape, external and internal structures, and pigment composition and packaging (Bricaud et al., 1995; Cleveland, 1995; Hoepffner & Sathyendranath, 1991; Morel, 1991; Prieur & Sathyendranath, 1981). Corroborating the previous findings (*e.g.*, large species dominate in eutrophic environments with high chlorophyll, whereas tiny phytoplankton prevail in oligotrophic zones with low chlorophyll), many of the above studies have shown phytoplankton absorption coefficient as a function of chlorophyll-*a* concentration using a simple power law function. Such a relationship when established using a large dataset from global waters would be effective in representing the observations for a wide variety of typical oceanic waters. However, models which measure the fractional contributions of different size classes have the advantage of providing valuable information than the models considering only about the dominant class (*e.g.*, Brewin, Devred, Sathyendranath, Lavender, & Hardman-Mountford, 2011; Brewin, Sathyendranath, et al., 2010; Brewin et al., 2012; Ciotti et al., 2002; Devred, Sathyendranath, Stuart, & Platt, 2011; Devred et al., 2006; Hirata, Aiken, Hardman-Mountford, Smyth, & Barlow, 2008; Uitz, Claustre, Morel, & Hooker, 2006; Uitz & Huot, 2008).

Recently, a variety of bio-optical models have been developed and applied to satellite ocean color data to differentiate between either specific phytoplankton taxonomic groups (or phytoplankton size class, *PSC*). For instance, spectral response approach utilizes the distinct optical signatures of different phytoplankton communities to discriminate between nanophytoplankton (*Phaeocystis*, coccolithophores), picophytoplankton (*Prochlorococcus*, *Synechococcus*) and microphytoplankton (diatoms) (Alvain, Moulin, Dandonneau, & Breon, 2005, Alvain, Moulin, Dandonneau, & Loisel, 2008). This model exploits the normalized water leaving radiance (nL_w) measured from clear oceanic waters as a main parameter to distinguish between pixels dominated by these phytoplankton communities. It was previously postulated that the shape of the absorption spectra is important when retrieving the cell size over and above the magnitude of the absorption coefficient (Lutz, Sathyendranath, & Head, 1996). Later, Ciotti et al. (2002) utilized the spectral shape of phytoplankton absorption coefficient to estimate the fractions of small and large size classes. However, it is quite complicated to observe small changes in the spectral shape of absorption estimated using satellite data (*e.g.* SeaWiFS, MODIS or MERIS). Abundance-based approach gives the relationship of phytoplankton interaction with its environment where the biogeochemical features of phytoplankton have the direct link to the environment (Sathyendranath, Lazzara, & Prieur, 1987; Sathyendranath et al., 2004). Devred et al. (2006) developed a model to partition the phytoplankton population into two components using the absorption and chlorophyll-*a* data. This model relies on the exponential function that relates the chlorophyll-*a* concentration with fractional contributions of small and large phytoplankton to the total pigment composition and the parameters having biological interpretation (Uitz et al., 2006). Thus, it is applicable only to two size classes as compared to models that extend to three size classes. Uitz et al. (2006) designed a model based on a high performance liquid chromatography (HPLC) pigment dataset to infer the vertical distribution of the three *PSCs*. However, there are unrealistic spatial discontinuities due to its splitting of the global ocean water into small number of trophic classes. Hirata et al. (2008) explored the relationship between $a_{ph}(443)$ and S (slope) (NOMAD in-situ data) to describe the phytoplankton optical properties linkage with *PSCs*. Using diagnostic pigment analysis (Uitz et al., 2006; Vidussi et al., 2001), two models were developed which relate either the phytoplankton absorption at 443 nm or chlorophyll-*a* concentration to the absorption spectral slope in the wavelength range of