Remote sensing of picophytoplankton distribution in the northern South China Sea

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ABSTRACT

By using a global data set (NOMAD), improved algorithms were developed for deducing from ocean color remote sensing data the concentrations of phytoplankton pigments, total chlorophyll a (TChl_a), zeaxanthin (Zea) and fucoxanthin (Fuco), and the associated primary phytoplankton groups, namely, *Prochlorococcus*, *Synechococcus*, haptophytes and diatoms, in the oceans. A modified classification for the waters of the world's ocean based on the dominant phytoplankton group was then devised. By using a local data set from the northern South China Sea (NSCS), algorithms were also developed for assessing the cell abundances of picophytoplankton, *Prochlorococcus*, *Synechococcus* and pico-eukaryotes, in this region. These algorithms were then applied to the remotely sensed data from the MODerate-resolution Imaging Spectrometer at Aqua sensor (MODIS-Aqua) to study the abundances and the distributional patterns of picophytoplankton in the entire NSCS. The results agreed well with field observations, which were available only from selected locations in the study area. On a basin scale, the results were consistent with expected variations in phytoplankton pigments, phytoplankton community composition, and picophytoplankton biomass, in response to the major known environmental phenomena in the NSCS, such as the progressive increase in biological productivity towards the coast, the runoff from the Pearl River, higher biological productivity in the wintertime, upwelling around the Taiwan Bank, winter upwelling northwest of the Luzon Island, and the transformation and dissipation of internal waves off the Dongsha Atoll. This work represents the first effort in estimating the cell abundances of the principal picophytoplankton groups in the oceans from space. The general application of this approach to the global ocean needs to be further validated and calibrated with a more extensive data base from field observations in other parts of the oceans.

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1. Introduction

Picophytoplankton (<2 μm), such as cyanobacteria and prochlorophytes, contribute significantly to phytoplankton biomass, primary production, carbon flux, and nutrient regeneration in the ocean, especially in the oligotrophic waters (Campbell & Vaulot, 1993; Campbell et al., 1994; Li et al., 1983; Liu et al., 2007). Their ability to capture nutrients efficiently and, in selected species such as *Trichococcus*, to fix nitrogen gives them a competitive advantage over other phytoplankton in oligotrophic waters (Campbell & Vaulot, 1993; Campbell et al., 1994; Li et al., 1983). Observations in the oligotrophic subtropical and tropical waters at the Hawaii Ocean Time-series station (ALOHA; 22.77° N, 158.09° W) and the SouthEast Asia Time-series Study station (SEATS; ~18° N, ~116° E) indicate that picophytoplankton can account for up to 80% of the phytoplankton biomass (Campbell & Vaulot, 1993; Liu et al., 2007).

Picophytoplankton are traditionally assessed in discrete water samples by microscopy or flow cytometry (Campbell & Vaulot, 1993;

Campbell et al., 1994; Li et al., 1983; Liu et al., 2007). While this approach may yield detailed information, it requires significant amounts of time and taxonomic expertise. As a result, data on the global spatial and temporal distributions of picophytoplankton are still sparse and the importance of picophytoplankton in marine biogeochemical processes is yet to be fully understood.

Remote sensing of picophytoplankton has been attempted by detecting the distributions of their optically active pigments such as chlorophyll a (Chl_a) and phycocyanin (Kuster et al., 2006; Randolph et al., 2008; Ruiz-Verdú et al., 2008). Chl_a is a common pigment existing in almost all phytoplankton (Jeffrey et al., 1997). Its concentration is roughly associated with the structure of phytoplankton community such that high and low Chl_a concentrations indicate a large proportion of microphytoplankton and picophytoplankton respectively in the phytoplankton community (Chisholm, 1992; Hirata et al., 2011; Pan et al., 2010, 2011; Uitz et al., 2006). However, partitioning and transposing Chl_a into the distribution of picophytoplankton species, as well as other phytoplankton, is still a challenge although chemotaxonomic methods have been recently attempted (Aiken et al., 2008; Alvain et al., 2005; Hirata et al., 2011; Pan et al., 2010, 2011). Phycocyanin is an important accessory

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pigment of a principal species of picophytoplankton, cyanobacteria (Jeffrey et al., 1997). Many studies have shown that its distribution may be related to cyanobacterial blooms, especially in the turbid inland lakes and the coastal waters (Kuster et al., 2006; Randolph et al., 2008; Ruiz-Verdú et al., 2008). There are at least three limitations in inferring the distribution of picophytoplankton using phycocyanin estimated through satellite remote sensing. First, phycocyanin is not a ubiquitous pigment found in all species of picophytoplankton. It is absent in prochlorophytes (Jeffrey et al., 1997) which contribute significantly to picophytoplankton biomass in the oligotrophic waters (Campbell & Vaulot, 1993; Campbell et al., 1994; Li et al., 1983; Liu et al., 2007). Total picophytoplankton biomass, thus, cannot be deduced easily from the concentration of phycocyanin alone. Secondly, phycocyanin is not a pigment that is unique to cyanobacteria. It may also be found in nano- and micro-phytoplankton such as diatoms and cryptophytes (Jeffrey et al., 1997). Therefore, the biomass of cyanobacteria cannot be accurately represented by the concentration of phycocyanin alone. Diatoms and cryptophytes are not expected to contribute significantly to total phytoplankton biomass in the oligotrophic waters, but they can become dominant in mesotrophic waters (Hirata et al., 2011; Pan et al., 2010, 2011). Thirdly, the absorption maximum of phycocyanin is located at around 630 nm (Kuster et al., 2006; Randolph et al., 2008; Ruiz-Verdú et al., 2008). This wavelength is not a nominal band in the widely used satellite sensors such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the MODerate-resolution Imaging Spectrometers at Aqua sensor (MODIS-Aqua) and at Terra sensor (MODIS-Terra). Thus, the concentration of phycocyanin cannot be estimated from the data provided by these sensors with a high degree of sensitivity and accuracy.

Based on direct *in situ* observations, Alvain et al. (2005) reported that water with different phytoplankton community structure may be distinguished from each other by the ratios of the accessory pigments to Chl_*a*. Zeaxanthin (Zea) and fucoxanthin (Fuco) are especially useful as the former is found primarily in cyanobacteria and prochlorophytes, while the latter is a major accessory pigment in diatoms (Jeffrey et al., 1997), and these three phytoplankton, in addition to haptophytes, constitute the principal phytoplankton groups in the oceans (Alvain et al., 2005). Thus, a high ratio of Zea/Chl_*a* suggests that picophytoplankton may be dominant in the water while a high ratio of Fuco/Chl_*a* may indicate that the nano- and micro-phytoplankton, the diatoms, are dominant. Independently, Pan et al. (2010) reported an approach for deducing the concentrations of major phytoplankton pigments, including Chl_*a*, Zea and Fuco, in the coastal waters of the northeastern United States from remotely sensed data obtained from the SeaWiFS and MODIS-Aqua sensors. Therefore, combining these two approaches may provide a tool for evaluating the relative dominance of the picophytoplankton and the nano- and micro-phytoplankton from remotely sensed data. Here, we report the first attempt to estimate simultaneously the phytoplankton composition and the cell abundances of three picophytoplankton categories, *Prochlorococcus*, *Synechococcus*, and pico-eukaryotes, in the oceans from remote sensing data by using this combined approach and applying it to the northern South China Sea (NSCS).

2. Data and methods

2.1. Study area

The South China Sea (SCS) is the largest marginal sea in the tropical and temperate zones. It is a semi-enclosed basin extending from 23° N to 3° S and from 102° E to 121° E in the tropical and subtropical western Pacific Ocean with a maximum depth of over 5000 m. The South China Sea is connected to the East China Sea, the Java Sea, and the Sulu Sea to the north, south, and east respectively, through shallow straits. At its northeast corner, it is connected to the western Philippine Sea through the deep Luzon Strait where exchanges of intermediate and deep waters may occur (Shaw, 1989; Shaw & Chao, 1994). The northern half of the SCS, the northern SCS (NSCS), lies mostly in the subtropics. It is rimmed

by a broad and extensive shelf system, the northern South China Sea Shelf-sea (NSCS Shelf-sea), along its northwestern border at the coasts of southern China and Vietnam. The Luzon Strait and the Luzon Island form its eastern boundary.

The waters in the central basin of the NSCS are warm and oligotrophic. The sea surface temperature typically varies between 20 and 30 °C, and the surface Chl_*a* varies from below 0.1 mg m^3 in the summer to exceeding 0.3 mg m^3 in the winter (Tseng et al., 2005). The dominant phytoplankton species are typically picophytoplankton, such as *Prochlorococcus* and *Synechococcus* (Agawin et al., 2003; Liu et al., 2007; Shiozaki et al., 2010; Wu et al., 2003). Towards the coast, and especially in the river plume area, phytoplankton biomass can be more than an order of magnitude higher (this study). Microphytoplankton and nanophytoplankton become more abundant and even dominant over picophytoplankton (Chen et al., 2007; Qiu et al., 2010).

Distinct monsoonal seasons are found in the NSCS: the stronger northeast monsoon between October and April and the weaker southwest monsoon between June and September. The combination of surface cooling and the stronger wind enhances vertical mixing and elevates biological production in the winter (Chen et al., 2006; Tseng et al., 2005). This results in a distinct seasonal pattern in biological productivity that is unique among tropical and subtropical waters. Because of the seasonally alternating wind direction and the orientations of the coast lines, wind driven coastal upwelling and the associated high biological productivity can be found at multiple locations in the NSCS. Upwelling has been reported along the east coast of Vietnam in the summer and northwest of the Luzon Island in the winter (Shaw et al., 1996; Tang et al., 2006). Topographically induced upwelling has also been found to occur at the Taiwan Bank and along the coasts of southern China in the NSCS Shelf-sea (Hong et al., 2009; Tang et al., 2002). A major river, the Pearl River (Zhujiang), drains into the NSCS from the northwest. Its peak flow occurs in the summer. This input of terrestrial material exerts a significant influence on the physics, biology and biogeochemistry in the inner and even the middle shelf of the NSCS Shelf-sea (Chen & Chen, 2006; Dai et al., 2008; Gan et al., 2010).

The NSCS is also a region that is subject to significant and persistent impacts of internal waves. These waves are generated at the Luzon Strait (Liu et al., 2006; Zhang et al., 2011; Zhao et al., 2004). Some propagate westward into the NSCS and eventually undergo transformation and dissipation in the shallower waters on the continental slope and shelf (Liu et al., 2006; Zhang et al., 2011; Zhao et al., 2004). These internal waves promote vertical exchange and bring nutrients from the subsurface waters to the mixed layer to fuel biological production (Pan et al., 2012; Wang et al., 2007). Other episodic and regional events that can affect biological productivity have also been reported to occur in the NSCS. They include meso-scale eddies (Lin et al., 2010), tropical cyclones (Lin et al., 2003), and atmospheric deposition (Lin et al., 2011). The former two processes can also enhance vertical mixing and elevate biological productivity. Nutrients from atmospheric deposition may stimulate photosynthetic activity directly while atmospherically derived iron may also promote primary production through nitrogen fixation (Lin et al., 2011; Mills et al., 2004). However, the effects of these episodic events last from days to weeks and do not extend beyond a limited geographical area (Lin et al., 2003, 2010, 2011).

2.2. Field experiments

Three cruises, covering the inner shelf to the deep central basin of the NSCS, were conducted between 2008 and 2010 (Fig. 1 and Table 1). In addition to standard hydrographic stations, anchored stations for time-series observations of up to 36 h long were occupied in the inner shelf in the Pearl River plume and at the continental slope over the Dongsha Atoll (Fig. 1). The SouthEast Asian Time-series Study (SEATS) station was occupied 6 times for up to 44 h between September 2002 and July 2005 (Fig. 1 and Table 1).