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Remote quantification of cochlodinium polykrikoides blooms occurring in the East Sea using geostationary ocean color imager (GOCI)

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ABSTRACT

Accurate and timely quantification of widespread harmful algal bloom (HAB) distribution is crucial to respond to the natural disaster, minimize the damage, and assess the environmental impact of the event. Although various remote sensing-based quantification approaches have been proposed for HAB since the advent of the ocean color satellite sensor, there have been no algorithms that were validated with in-situ quantitative measurements for the red tide occurring in the Korean seas. Furthermore, since the geostationary ocean color imager (GOCI) became available in June 2010, an algorithm that exploits its unprecedented observation frequency (every hour during the daytime) has been highly demanded to better track the changes in spatial distribution of red tide. This study developed a novel red tide quantification algorithm for GOCI that can estimate hourly chlorophyll-a (*Chl a)* concentration of *Cochlodinium (Margalefidinium) polykrikoides*, one of the major red tide species around Korean seas. The developed algorithm has been validated using in-situ *Chl a* measurements collected from a cruise campaign conducted in August 2013, when a massive *C. polykrikoides* bloom devastated Korean coasts. The proposed algorithm produced a high correlation ($R^2 = 0.92$) with in-situ *Chl a* measurements with robust performance also for high *Chl a* concentration (300 mg/m^3) in East Sea areas that typically have a relatively low total suspended particle concentration (<0.5 mg/m^3).

1. Introduction

The red tide forming dinoflagellate, *Cochlodinium (Margalefidinium) polykrikoides*, is one of the major species that are responsible for annual massive harmful algal blooms (HABs) in Korean waters, which devastate aquaculture and coastal fisheries. Although *C. polykrikoides* bloom was first identified and recorded in 1982, the area affected by blooms has expanded in geographic distribution across the Korean coastal waters, and the frequency of bloom events has increased since 1993. The largest *C. polykrikoides* bloom, which occurred in 1995, persisted for nearly 8 weeks, covering many coastal areas of the south and east coasts (Lee et al., 2013; Jeong and Kang, 2013). Another massive bloom occurred in 2013, which initiated from the southern coast of Korea and expanded to the middle of the East Sea along the Tsushima warm current (Choi et al., 2014). The economic losses were 95 million and 22 million US dollars, respectively, for 1993 and 2013. These events have drawn considerable attention from scientists, the fishing industry, local governments, and the national government of Korea (Park et al., 2013).

With its capability to quantify pigment amounts in marine organisms, ocean color remote sensing has been an important and powerful tool for characterizing the spatio-temporal distribution of HABs and phytoplankton groups. In the past decades, ocean color sensors, such as the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Medium Resolution Imaging Spectrometer (MERIS), have shown successful detection of various red tide species that occur in coastal areas worldwide (Kahru and Mitchell, 1998; Cannizzaro et al., 2008; Carder and Steward, 1985; Carvalho et al., 2011; He et al., 2008; Huot et al., 2005; Stumpf, 2001; Tomlinson et al., 2004). Remote sensing of *C. polykrikoides* around the Korean coasts using ocean color satellite sensors has been undertaken in several studies, but all have been mainly focused on the detection

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of the bloom and the quantification approaches were not validated with in-situ measurements of red tide intensity such as chlorophyll-a concentration (*Chl a*) or cell counts. For example, the red tide index (RI) developed for SeaWiFS (Ahn and Shanmugam, 2006) provides a qualitative measure of *C. polykrikoides* bloom based on the water-leaving radiance in the blue and green spectral bands (443, 510, 555 nm), but RI was compared only with satellite-driven *Chl a* estimates, which often have significant errors for red tide waters. Another study performed with MODIS data (Son et al., 2011) tested 6 different techniques to detect *C. polykrikoides*, but also did not focus on the estimation of the red tide intensity.

The major limitations in the red tide detection with the polar orbiting satellite sensors (SeaWiFS, MODIS, MERIS, and VIIRS) were low data availability due to the low satellite re-visiting frequency (typically once or twice a day) and high cloud cover during the summer season. GOCI can significantly mitigate these limitations due to its high temporal resolution (every h during day time) with higher spatial resolution (500 m). A previous study (Choi et al., 2014) performed remote detection of *C. polykrikoides* bloom using the field data collected in 2013, in which the two-band ocean color (OC2) *Chl a* algorithm (O'Reilly et al., 1998) was used to quantify the red tide intensity. However, as shown in the later section of this study, *Chl a* estimates from the OC2 algorithm that is based on the blue-green reflectance ratio significantly underestimate *Chl a* over the red tide. To better estimate *Chl a* concentration for red tide, in particular for high concentration bloom, we propose a new algorithm which utilizes both the reflectance of the blue-green spectral range and the near infrared (NIR) reflectance at approximately 700 nm which has a strong signal in high concentration red tide waters (*Chl a* > 100 mg/m^3).

Calibration and validation of the algorithm was performed using in-situ *Chl a* measurements collected from the cruise campaign conducted in the East Sea (Sea of Japan) during the massive *C. polykrikoides* bloom period in 2013. During the cruise, in-situ *Chl a* and remote sensing reflectance were measured simultaneously for the red tide waters, and part of in-situ *Chl a* measurements collected in the cloud-free weather was able to be matched up with GOCI data, allowing satellite validation. It should be noted that this study focuses on quantification of *C. polykrikoides* blooms in the East Sea (Sea of Japan) that have relatively small influence of coastal and riverine water constituents such as suspended sediments and dissolved organic matter. Thus, the proposed algorithm is not intended for the southern coast of Korea where the red tide typically begins.

2. Data and method

2.1. In situ measurements

2.1.1. Chl a and peridinin concentration

The in-situ data used in the study are from the field campaign conducted during 10–13 August, 2013 using R/V Jangmok operated by the Korea Institute of Ocean Science and Technology (KIOST) (Fig. 1). Ten liters of surface water samples were collected from each station and aliquots of waters were subsampled for different analytical purposes. *Chl a* concentration was measured using a Turner 10 AU field fluorometer based on the acidification method after extraction with 90% acetone (Parsons et al., 1984). Among the measurements from the campaign, total 27 pairs of the coincident in-situ remote sensing reflectance (R_{rs}) and in-situ *Chl a* measurements are used for constructing the new quantification algorithm, and 13 match-up pairs between GOCI and in-situ *Chl a* measurements are used for the algorithm validation for GOCI. As an additional method to help determine changes in *C. polykrikoides* biomass, a marker pigment of *C. Polykrikoides*, peridinin was measured using HPLC method (Zapata et al., 2000).

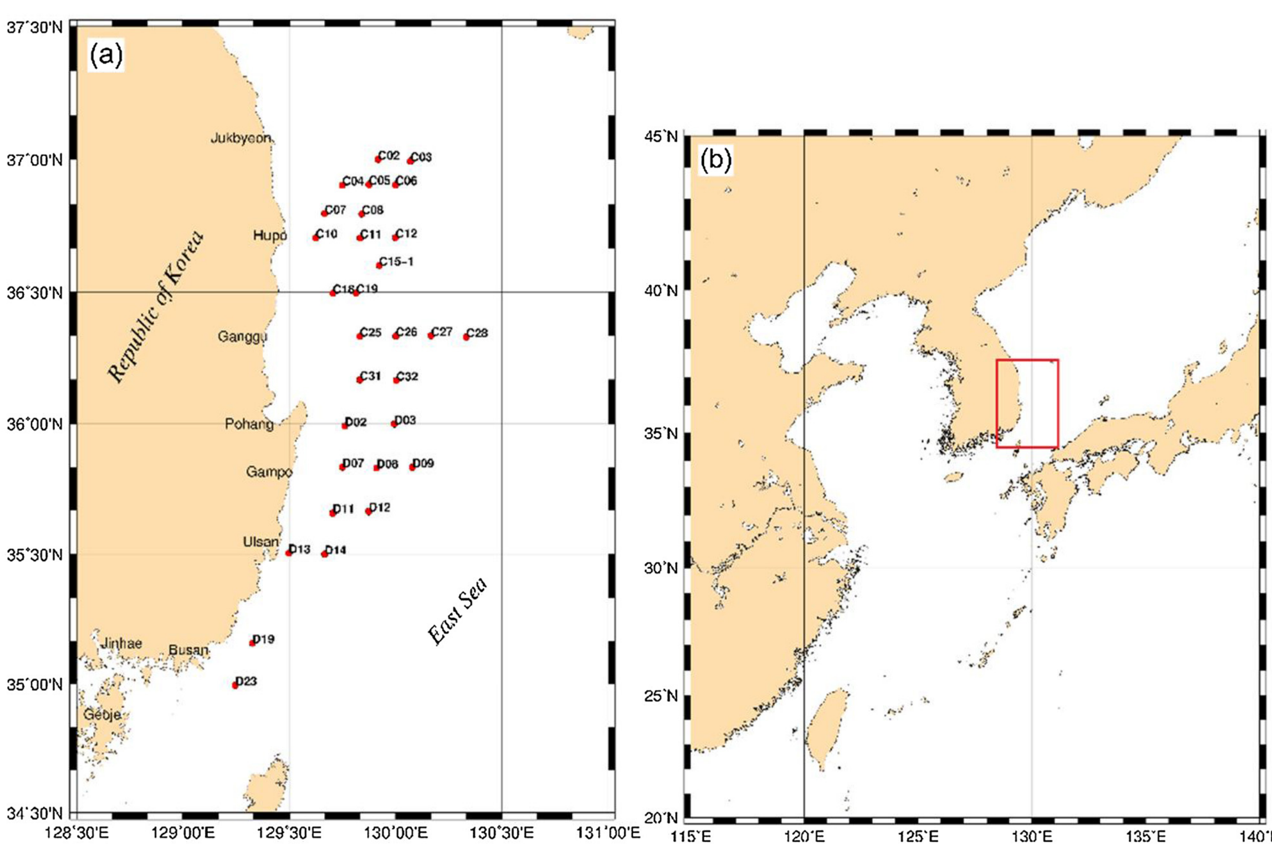

Fig. 1. (a) The study area in the East Sea of Korea, and (b) station locations for in-situ measurements.