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Harmful algal bloom (HAB) in the East Sea identified by the Geostationary Ocean Color Imager (GOCI)

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ABSTRACT

Harmful *Cochlodinium polykrikoides* blooms have frequently appeared and caused fatal harm to aquaculture in Korean coastal waters since 1995. We investigated the applicability of GOCI, the world's first Geostationary Ocean Color Imager, in monitoring the distribution and temporal movement of a harmful algal bloom (HAB) that was discovered in the East Sea near the Korean peninsula in August 2013. We identified the existence of *C. polykrikoides* at a maximum cell abundance of over 6000 cells/mL and a chlorophyll *a* concentration of over 400 mg/m^3. In areas of *C. polykrikoides* blooms, GOCI remote sensing reflectance (R_{rs}) spectra demonstrated the typical radiometric features of a HAB, and from the diurnal variations using GOCI-derived chlorophyll concentration images, we were able to identify the vertical migration of the red tide species. We also found that the formation and propagation of the HAB had relations with cold water mass in the coastal region. GOCI can be effectively applied to the monitoring of short-term and long-term movements of red tides.

1. Introduction

Harmful algal blooms (HABs), also known as red tides due to the reddish discoloration of the water, are known to develop in eutrophic coastal region environments, causing great damage to living sea creatures, including fish kills, shellfish poisoning, and benthic habitat mortality. In particular, HABs in coastal regions may kill organisms grown in aquaculture farms and be detrimental to human health (Carder and Steward, 1985; Hu et al., 2003; Kang et al., 2002; Stumpf et al., 2003; Walsh and Steidinger, 2001). Since 1995, harmful *Cochlodinium polykrikoides* blooms (Kudela and Gobler, 2012) have frequently appeared in semi-enclosed bay environments in the South Sea off Korea and have also occurred throughout the East Sea off the Korean Peninsula (Ahn et al., 2006; Kang et al., 2002; Lee, 2008; Son et al., 2012).

In addition to conventional *in situ* observations, many attempts have been made to identify the development and distribution of HABs and to forecast their spread. In particular, remote sensing techniques, mainly ocean color observation satellite images, have been successfully used to distinguish or look at diurnal variation in HABs in coastal regions ((Hunter et al., 2008; Schofield et al., 1999; Tyler and Stumpf, 1989). The Coastal Zone Color Scanner (CZCS), the first ocean color observation satellite sensor, was used to monitor phytoplankton blooms in the Baltic Sea by comparing the satellite observations to field measurements, employing a modeling technique (Siegel et al., 1999). Stumpf et al. (2003) reported on the use of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in detecting and monitoring HABs in the Gulf of Mexico. Ishizaka et al. (2006) also applied SeaWiFS chlorophyll data to the detection of HABs in Isahaya Bay, Japan, where seaweed cultures had been damaged. Ahn and Shanmugam (2006) developed the red tide index (RI) based on SeaWiFS data to identify potential HABs in the highly turbid waters of Korean and Chinese coastal areas.

The Geostationary Ocean Color Imager (GOCI), a new ocean color satellite imager that has been placed in a geostationary orbit, has an advantage over other ocean color sensors in that it collects hourly images during the daytime, enabling monitoring of temporal variability in the ocean environment. GOCI covers the 2500 km × 2500 km area around the Korean peninsula centered at 36° N, 130° E, and comprises 16 (4 × 4) slot images. GOCI has six

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visible bands centered at 412 nm, 443 nm, 490 nm, 555 nm, 660 nm, and 680 nm, and two near-infrared bands centered at 745 nm and 865 nm (Choi et al., 2012). GOCI has been successfully used to identify short-term variations in coastal water turbidity (Choi et al., 2012, 2014; He et al., 2013; Ruddick et al., 2012), to investigate ocean surface currents (Yang et al., 2014), and to detect eddies (Park et al., 2012a) in Korean coastal waters and the East China Sea at a spatial resolution of 500 m. Thus, GOCI can be effectively applied to monitoring the dynamic movement and spread of red tides. Recently, GOCI was employed to estimate diurnal changes in a HAB of the dinoflagellate *Prorocentrum donghaiense* in May 2011 in the East China Sea (Lou and Hu, 2014). However, the application of GOCI in monitoring the dynamic variability in HAB distributions in combination with *in situ* measurements in the Korean coastal waters has not been attempted.

In this study, the distribution and range of a HAB detected in the East Sea near the Korean peninsula in August 2013 (Fig. 1) was monitored using GOCI. The HAB originally developed in the southeastern coastal area of the Korean peninsula in the middle of July 2013 and spread to the East Sea along the east coast of the peninsula. A 2-day cruise was undertaken to identify the harmful algae species and determine its optical characteristics. Based on the results of the fieldwork, GOCI was employed to detect patches of the HAB and their movement for approximately 1 month.

2. Materials and methods

2.1. *In situ measurements*

In situ observations of the HAB occurrence were taken aboard the R/V Ieordo off of the east coast of the Korean peninsula on 12 and 13 August 2013 (Fig. 1a). During the satellite acquisition time, water samples were collected at 14 sites in the study area to measure chlorophyll *a* concentration (CHL), and the radiometric characteristics of the surface water were recorded in the areas of HAB occurrences (Fig. 1b). Sampling locations were positioned using a differential GPS unit (Trimble Co., Pathfinder Pro XR) with a horizontal accuracy of 1 m. For chlorophyll *a* estimation, fixed volumes of seawater were filtered through 25-mm Whatman GF/F glass fiber filters under low vacuum pressure. The filters were stored frozen in liquid nitrogen until analysis in the laboratory, at which time, pigments were extracted from the filters with 90% acetone and refrigerated at 4 °C for 24 h. Chlorophyll *a* concentrations were estimated with the trichromatic equations reported by Jeffrey and Humphrey (1975) after measuring the pigment absorbance with a Perkin–Elmer Lambda 19 UV/VIS/NIR dual-beam spectrophotometer.

The radiometric characteristics of the surface water were measured at the sampling locations using a spectroradiometer (FieldSpec3, Analytical Spectral Devices; ASD) with a spectral range of 350–1050 nm. Optical properties were measured at an

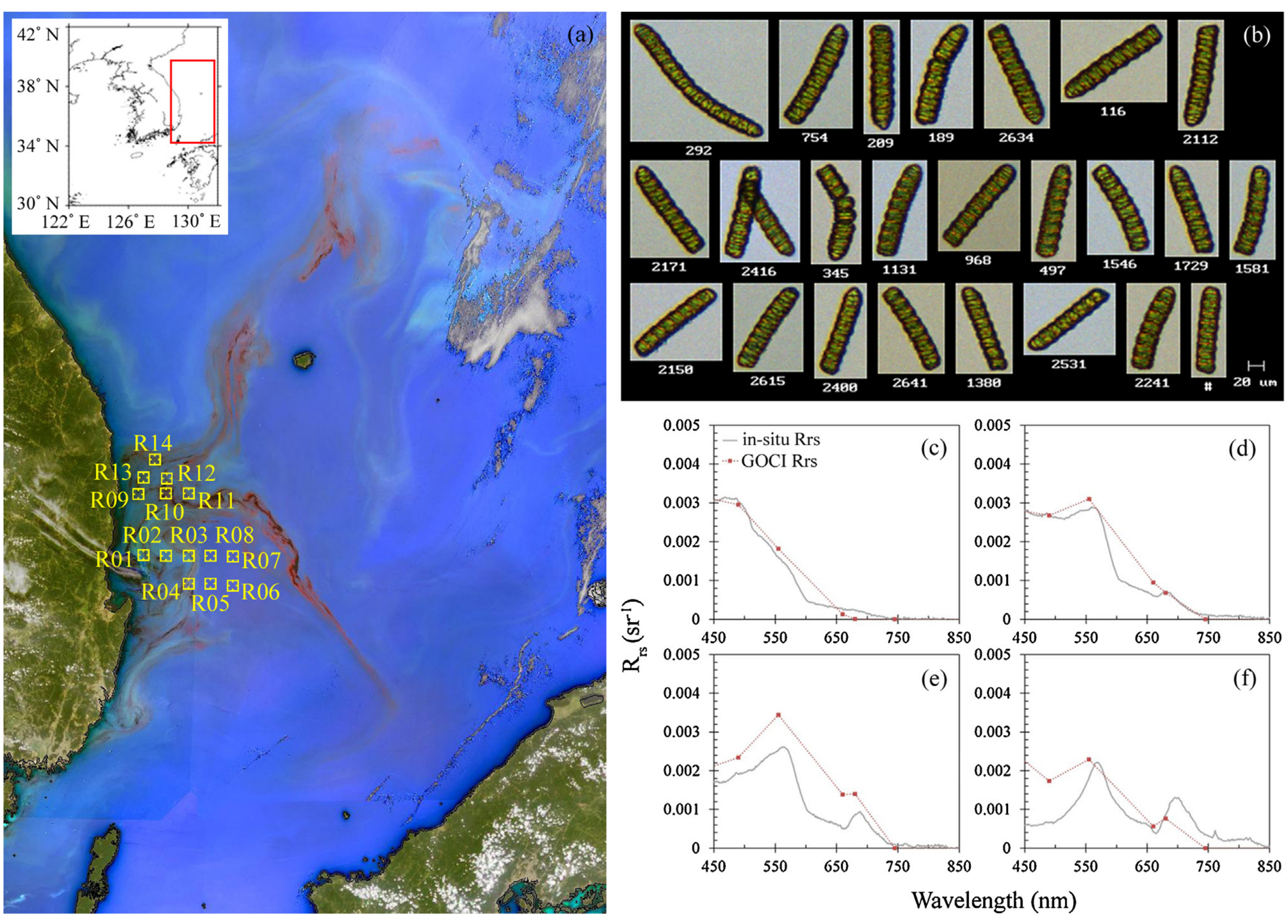

Fig. 1. (a) GOCI L_w RGB (642 bands) composite image acquired at 12:25 local time on 13 August 2013 showing the study area with the *in situ* observation locations on 12 and 13 August 2013. (b) Images of *C. polykrikoides*, collected from the study area, captured by FlowCAM. The R_{rs} spectra measured *in situ* at stations (c) R06: 0.20 mg/m^3 CHL, (d) R12: 10.2 mg/m^3 CHL, (e) R14: 24.06 mg/m^3 CHL, and (f) R04: 250.6 mg/m^3 CHL, along with the concurrently acquired GOCI R_{rs} spectra.