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Physical processes leading to the development of an anomalously large *Cochlodinium polykrikoides* bloom in the East sea/Japan sea

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ABSTRACT

An anomalously large Harmful Algal Bloom (HAB) was observed in the southwest coast of the East/Japan Sea (hereafter the East Sea) during the summer of 2013. During this time period, the presence of *Cochlodinium polykrikoides* (*C. polykrikoides*) was detected by the Geostationary Ocean Color Imager (GOCI) and validated by *in-situ* observations. GOCI observations have been available since 2011, thus allowingto examine various stages of the physical condition of the developing *C. polykrikoides* bloom, thereby other multi-satellite and buoy measurements obtained between 2011 and 2013. Research results indicate that this HAB is related to four processes: the transport of *C. polykrikoides* from the south coast of Korea to the HAB area; a relatively high insolation; continuous coastal upwelling; and a favorable Sea Surface Temperature (SST) for *C.polykrikoide* growth. In examination of the main transport mechanisms, geostrophic current measurements were used to estimate the flow trajectories, showing water from the south coast to the HAB area off the southeast coast of Korea. Result shows that ninety percent of the water from the south coast reached the HAB area in 2013. Furthermore, to examine the insolation mechanism, the Photosynthetically available radiation (PAR) value was derived from the Moderate Resolution Imaging Spectoradiometer (MODIS), showing that PAR values were relatively high in the HAB area during HAB period (47 Ein m^{-1} day^{-1}). Moreover, Upwelling age (UA) was calculated in order to investigate the strength of coastal upwelling events, which were found to support relatively high UA values during the HAB period. The mean UA value during the HAB period was 1.01, higher than those in 2011 and 2012 which were 0.61 and 0.76, respectively. Finally, SST in the HAB area was also analyzed to examine which conditions were most favorable for HAB growth. Therefore, the results of this study suggest that the four mechanisms can explain the relative contributions of the anomalously HAB development observed off the southeast coast of Korea.

1. Introduction

Harmful *Cochlodinium polykrikoides* blooms have been observed globally (Kudela et al., 2008; Kudela and Gobler, 2012) and frequently appeared off the south and east coasts of Korea (Kang et al., 2002; Hu et al., 2003; Ahn et al., 2006; Lee, 2008; Park et al., 2014; Choi et al., 2014). *Cochlodinium* occurs in a wide range of temperature conditions, 11–30 °C, with moderate salinities, 30–34 psu (Kudela et al., 2008). Such harmful algal blooms (HABs) affect fisherman and consumer health (Carder and Steward, 1985; Walsh and Steidinger, 2001; Stumpf et al., 2003; Bauman et al., 2010) and *C. polykrikoides* bloom caused severe fish kills on a global scale in recent decades (Jiang et al., 2009; Tang and Gobler, 2009), making it very important to understand and examine the conditions that contribute to HABs formation around the Korean coastal region. Fig. 1 shows the study area, where the HAB was observed (seen as a brownish color). This HAB first appeared in July 17, 2013 near Yeo-Su bay, and expanded eastward under the influence of ocean currents, reaching as far as the southeast coast of Korea in August and disappeared in September 5 of the same year (NFRDI, 2014). Choi et al. (2014) analyzed the 2013 HAB using Geostationary Ocean Color Imager (GOCI) data and *in-situ* measurements, identifying the particular species of algae within the HAB as *C. polykrikoides*, as well as measuring the HAB's spectral characteristics, and producing a time-series of ocean color variation within the HAB. According to Choi et al. (2014), the maximum *C. polykrikoides* cell abundance was

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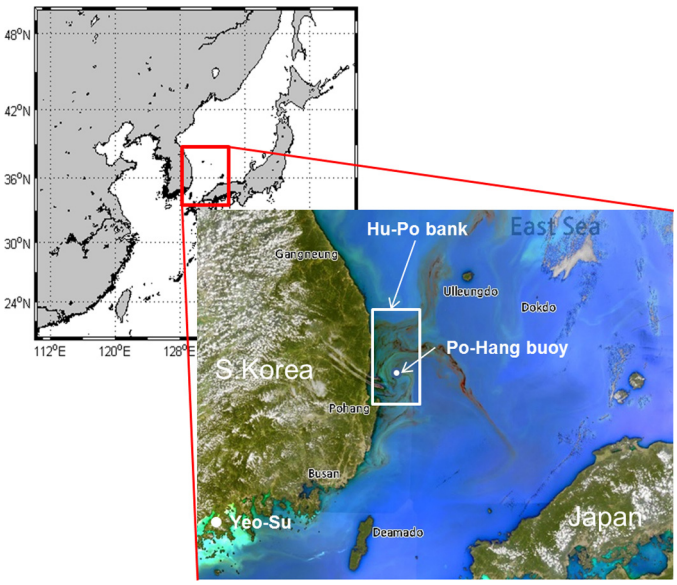

Fig. 1. Image from red tide analyses based on GOCI at 12:16:43 KST on 13 August 2013 (IOCCG, http://www.ioccg.org/news/Nov2013/news.html).

6015 cells/ml^{-1} in the bloom area in August 13, 2013. The study indicates that HAB was flourished due to high *C. polykrikoides* cell abundances (more than 1000 cells/ml^{-1}) .

Many studies have found that water from the south coast of Korea may be transported toward the southeast coast of Korea during the previous HAB events (Kang et al., 2002; Ahn et al., 2006; Lee, 2008; Onitsuka et al., 2010; Son et al., 2012; Lee et al., 2013). In particular, Onitsuka et al. (2010) reproduced the transport *Cochlodinium polykrikoides* using Lagrangian particle-tracking simulations during the time period of 2002–2008. Research suggested that these simulations reflected well movements of *C. polykrikoides*. Following from these results, the pathway of the *C. polykrikoides* was investigated in order to determine their place of origin.

The study area has weak vertical mixing during summer (influenced by high solar energy and weak wind stress), preventing nutrients from subsurface waters to reaching the surface. Hence, coastal upwelling is the dominant process supplying nutrients to the surface and enabling the occurrence of HABs. Several studies have shown that wind-driven upwelling can cause blooms by supplying nutrients to the euphotic zone (Roegner et al., 2002; Ryan et al., 2002; Trainer et al., 2002; Tang et al., 2003). Moreover, Yoo and Park (2009) reported that coastal upwelling is a dominant factor in the subpolar front and in the south-east coast of Korea. In order to understand the conditions of coastal upwelling, non-dimensional numbers were used. One of these is upwelling age (UA), an indicator of the local tendency for coastal upwelling and that can also serve as a parameter for quantifying coastal upwelling conditions (Jiang et al., 2012). The parameter UA was developed through an analytical model based on two time scales: a wind event time scale and an advection time scale, both of which are important elements of coastal upwelling circulation. In this study, UA was used to characterize coastal upwelling events near Hu-Po bank, especially during the HAB period.

Photosynthetically available radiation (PAR) data were used to investigate the condition of insolation at the HAB site. PAR is essentially the major factor controlling the growth of phytoplankton and therefore regulates the composition and evolution of marine ecosystems (Kirk, 1996). Furthermore, White et al. (2007) reported that PAR was a significant stimulator of phytoplankton blooms. Previous research has found no photoinhibition to *Cochlodinium polykrikoides* productivity in similar cases (Lee et al., 2001; Kim et al., 2004; Oh et al., 2006). Their results indicate that high values of PAR boost *C. polykrikoides* blooms. In addition, many researchers have also attempted to explain the relationship between SST and *C. polykrikoides* blooms at the south coast of Korea (Lee and Lee, 2006; Lee, 2008; Lee and Kim, 2008; Lee et al., 2009). Several laboratory studies conducted experiments on the growth rate of *C. polykrikoides*, and their results showed that its maximum specific growth rate occurred at approximately 25 °C (Kim et al., 2004; Oh et al., 2006; Lee and Moon, 2008). Similarly, Lee and Choi (2009) determined, using satellite data, that *C. polykrikoides* blooms occur most easily when sea temperatures are between 25.0 and 26.0 °C. Following these results, SST off the southeast coast of Korea was also investigated during the HAB period.

Although HABs are well understood from a biological perspective, very little is known about the physical mechanisms dominating them, and little is known about their occurrence off the southeast coast of Korea. Choi et al. (2014) also mention SST, coastal upwelling, and ocean currents as possible drivers of the HAB of summer 2013. Nevertheless, their results do not show how *Cochlodinium polykrikoides*, originally from the south coast of Korea, were transported to the southeast coast. Moreover, the occurrence of coastal upwelling was described by Choi et al. (2014) simply as being a result of relatively low SST along with the simultaneous presence of a north-eastward wind, which is a not sufficient criterion for the quantitative detection of a coastal upwelling condition. Accordingly, GOCI, altimetry, MODIS, and buoy data were used to analyze the physical processes leading to HABs off the south-east coast. First, water movement was determined near the south coast of Korea using altimetry data during the HAB period. Then, the relationship between coastal upwelling and *C. polykrikoides* bloom events was investigated using UA. Furthermore, Lagrangian flow using geostrophic current data and the association between geostrophic currents, SST data, and GOCI chlorophyll (Chl) images were examined in August of 2011, 2012, and 2013. Moreover, the potential mechanisms for HAB formation off the southeast coast of Korea, with special emphasis on the characteristics of *C. polykrikoides* and phytoplankton blooms were analyzed. The main aim of this paper is to understand the physical mechanisms of HABs, with special focus on the region off the southeast coast of Korea. Research results describe the physical conditions that allowed *C. polykrikoides* to expand and prosper near Hu-Po bank.

2. Data and methods

GOCI is the first geostationary orbit ocean color satellite imager, which has an advantage over other ocean color sensors by its ability to collect 8 images per day during the daytime, enabling the monitoring of the temporal variability of the ocean environment. The spatial coverage area of the GOCI sensor is 2500 km × 2500 km around the Korean peninsula centered at 36°N, 130°E, and comprises 16(4 × 4) slot images (http://kosc.kiost.ac). In this study, GOCI level 2 Chl data were used with a spatial resolution of 500 m× 500 m. GOCI data are available for dates ranging from April, 2011 to present.

The Group for High Resolution Sea Surface Temperature (GHRSST) level 4 data were used to examine the SST conditions during the HAB period in the south-east coast of Korea. GHRSST data are offered by the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (NASA) (http://podaac.jpl.nasa.gov). This measurement has a 0.011 × 0.011° spatial resolution, and a daily temporal resolution. GHRSST includes Advanced Microwave Scanning Radiometer-EOS (AMSRE) and Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA aqua and terra platforms, the US Navy microwave WindSat radiometer