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Small phytoplankton contribution to the total primary production in the highly productive Ulleung Basin in the East/Japan Sea

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ABSTRACT

The Ulleung Basin in the southwestern East/Japan Sea (hereafter East Sea) is known as a biologically productive "hot spot" but climate-associated changes in the physicochemical oceanographic conditions and some biological changes have been reported. In this study, our main objective was to determine the contribution of small phytoplankton to the total primary production, which is valuable information for detecting marine ecosystem changes in the Ulleung Basin. The small phytoplankton productivity contributions determined by Moderate-Resolution Imaging Spectroradiometer (MODIS)-derived monthly productivities using a phytoplankton community-based productivity algorithm was significantly consistent with the field-measured productivity contributions of small phytoplankton in this study. The daily primary productivity of small phytoplankton ranged from 42.7 to 418.7 mg C m^{-2} d^{-1} with an average of 172.9 mg C m^{-2} d^{-1} (S.D. = ± 61.4 mg C m^{-2} d^{-1}, n = 120), and the annual contribution of small phytoplankton ranged from 19.6% to 28.4% with an average of 23.6% (S.D. = ± 8.1%) in the Ulleung Basin from 2003 to 2012. Overall, large phytoplankton were a major contributor to the total primary production in the Ulleung Basin (76.4 ± 8.2%) from 2003 to 2012, which indicates that the Ulleung Basin is a highly productive region. A significantly negative relationship ($p < 0.05$) was found between the small phytoplankton primary productivity contribution and the annual primary production in this study. This finding revealed that the recent decreasing annual primary production in the Ulleung Basin could be a consequence of the increasing contribution of small phytoplankton. The response of phytoplankton to ongoing climate change depending on different-size phytoplankton compositions should be a subject for further investigation in the Ulleung Basin as a biologically highly productive region in the East Sea.

1. Introduction

The East/Japan Sea (hereafter the East Sea; Fig. 1) has been regarded as a 'miniature ocean' for studying oceanographic processes such as large-scale current systems, mesoscale eddies, subpolar fronts, and deepwater formations (Kim and Kim, 1996; Kim et al., 2001) which makes it highly dynamic in terms of physical phenomena and biological characteristics (Kang et al., 2002; Kim et al., 2012; Lim et al., 2012). Among the different basins in the East Sea, the Ulleung Basin, a deep basin in the southwest region, is known as a biological "hot spot" and is a highly productive region compared with adjacent regions such as the Russian coast and the Japan Basin as well as other offshore waters (Kwak et al., 2013a; Joo et al., 2014). Therefore, Kwak et al. (2013a) proposed that the Ulleung Basin needs careful resource management and conservation efforts. During the past several decades, many dramatic changes in environmental conditions such as physical structure and chemical properties have been reported in the East/Japan Sea (Kim et al., 1999, 2001; Kang et al., 2003; Chiba et al., 2008). The sea surface temperature in the East Sea has increased rapidly over several decades (Kim et al., 2001; Kang et al., 2003; Jo et al., 2014). Recently, Jo et al. (2014) reported that the SST increase rate (0.041 °C y^{-1}) along the east coast of Korea was substantially faster than the global average (0.005 °C y^{-1}). These climate-associated changes in physical oceanographic conditions could cause many alterations in lower trophic levels, such as changes in the seasonal peak abundance of phytoplankton (Chiba et al., 2012) as well as phytoplankton community structure (Chiba and Saino, 2003) and could consequently impact higher trophic levels, such as the recruitment, biomass, and productivity of fishery

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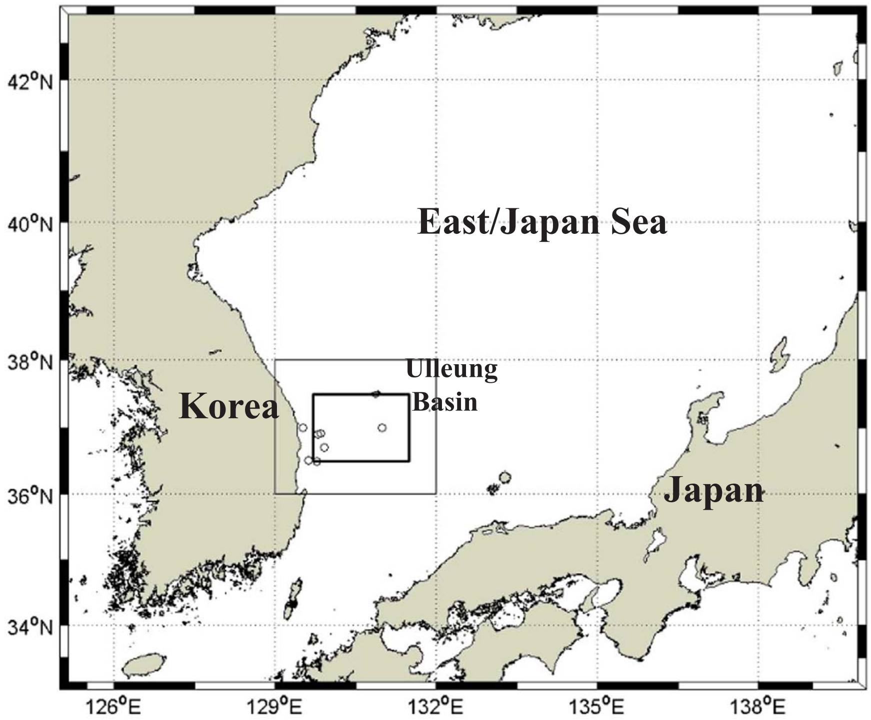

Fig. 1. Study site in the East Sea (Dots are *in situ* measurement stations for small phytoplankton contribution. The Ulleung Basin is marked with a small square box, and the satellite image region in the East Sea is marked with a large square box).

resources (Zhang et al., 2004). Recently, some biological changes in lower trophic levels have also been reported in the East Sea (Lee et al., 2014; Joo et al., 2014). Lee et al. (2014) reported significant changes in the duration and intensity of the phytoplankton spring bloom in the East Sea between the periods 2008–2011 and 1998–2001, although there were no distinct trends in environmental conditions over the study period. Based on the daily primary productivity derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS), Joo et al. (2016) found that the annual primary production in the East Sea had decreased substantially over recent decades.

Since phytoplankton as the base of the oceanic food webs are the principal photosynthetic organisms in the ocean, they can be an indicator in assessing the impacts of climate changes on marine ecosystems (Falkowski and Rave, 1997; Yoder and Kennelly, 2003; Wassmann et al., 2011; Arrigo and Dijken, 2015; Grebmeier et al., 2015). Small phytoplankton (< 2 μm) are ubiquitous and thus contribute significant portions of biomass and production in phytoplankton communities in various marine ecosystems from the Arctic to the Antarctic Ocean (Agawin et al., 2000; Morán et al., 2010; Li et al., 2009; Lee et al., 2012, 2013, 2015). In a warmer ocean, the contribution of small phytoplankton is expected to increase and become more important (Li et al., 2009; Morán et al., 2010; Lee et al., 2013). Thus, small cell contribution to the total biomass and production of the phytoplankton community can be a useful indicator for detecting marine ecosystem changes (Li et al., 2009; Morán et al., 2010). Therefore, it is important to know how much small phytoplankton contribute to overall primary production in marine ecosystems because of their potential impact on primary production under ongoing environmental changes (Lee et al., 2013).

Our main objectives were to characterize the seasonal and interannual variations of small phytoplankton production and to determine the contribution of small phytoplankton to the total primary production in the biologically productive Ulleung Basin in the East Sea.

2. Materials and methods

2.1. Satellite ocean color data

The daily MODIS-Aqua level-2 ocean color data with a spatial resolution of 1×1 km^2 for this study were obtained from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov/). The Level-2 data were remapped to a standard projection at 1-km spatial resolution and then generated for composite images of various products. Mean values of primary production were calculated for seasonal and interannual time series. We used four main satellite products (Chlorophyll-a, $K_d(490)$; diffuse attenuation coefficient at 490 nm; PAR, photosynthetically available radiation; and SST, sea surface temperature) in the East Sea for the decade from January 2003 to December 2012.

2.2. Primary productivity model

In this study, recent decadal primary production patterns of small (< 2 μm) and large (> 2 μm) phytoplankton were analyzed in the Ulleung Basin (36.5–37.5°N, 129.7–131.5°E) in the East Sea. Generally, the primary productions from ocean color data are estimated in various oceans by using the VGPM (Vertical Generalized Production Model) originally developed by Behrenfeld and Falkowski (1997). However, the original VGPM is not suitable for different-size phytoplankton productions. For our purpose, the differently sized primary productions were estimated by the size-fractionated primary productivity algorithm (K & I algorithm) developed by Kameda and Ishizaka (2005). The K & I algorithm is based on the original VGPM, but P^{B}_{opt} (optimal carbon fixation rate) is segmented by two different-size phytoplankton communities, large and small phytoplankton (Kameda and Ishizaka, 2005). More details are as follows:

$$PP_{eu} = 0.66125 \times P^{B}_{opt}\,[E_0/(E_0 + 4.1)] \times Z_{eu} \times Chl - a \times DL \tag{1}$$

where PP_{eu} is daily integrated primary productivity in the euphotic zone (mg C m^{-2} d^{-1}), P^{B}_{opt} is the optimal carbon fixation rate (mg C (mg Chl)$^{-1}$ h^{-1}), E_0 is daily PAR at the sea surface (E m^{-2} d^{-1}), Z_{eu} is the euphotic depth (m), *Chl-a* is chlorophyll-a concentration (mg m^{-3}), and *DL* is day length (photoperiod) in hours. P^{B}_{opt} in the K & I algorithm developed from the original VGPM (Kameda and Ishizaka, 2005) is as follows: