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Influence of the tidal front on the three-dimensional distribution of spring phytoplankton community in the eastern Yellow Sea

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HIGHLIGHTS

- Physical environment, chlorophyll concentration and phytoplankton community were investigated in the eastern Yellow Sea.
- Three-dimensional structure of phytoplankton communities was identified in the tidal front region.
- Phytoplankton abundance and chlorophyll *a* concentration were high in the shore side of the front during the spring tide.
- Subsurface maximum of phytoplankton abundance appeared about 64 km away from the front through the middle layer intrusion.
- Profiles of phytoplankton abundance and chlorophyll *a* concentration were different due to depth-dependent species change.

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ABSTRACT

Hydrographic observation and biological samplings were conducted to assess the distribution of phytoplankton community over the sloping shelf of the eastern Yellow Sea in May 2012. The concentration of chlorophyll *a* was determined and phytoplankton was microscopically examined to conduct quantitative and cluster analyses. A cluster analysis of the phytoplankton species and abundance along four observation lines revealed the three-dimensional structure of the phytoplankton community distribution: the coastal group in the mixed region, the offshore upper layer group preferring stable water column, and the offshore lower layer group. The subsurface maximum of phytoplankton abundance and chlorophyll *a* concentration appeared as far as 64 km away from the tidal front through the middle layer intrusion. The phytoplankton abundance was high in the shore side of tidal front during the spring tide. The phytoplankton abundance was relatively high at 10-m depth in the mixed region while the concentration of chlorophyll *a* was high below the depth. The disparity between the profiles of the phytoplankton abundance and the chlorophyll *a* concentration in the mixed region was related to the depth-dependent species change accompanied by size-fraction of the phytoplankton community.

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1. Introduction

Large spatial gradients of temperature and salinity produces fronts and thermoclines in coastal oceans, and these physical features with the enhanced density gradient works as barriers to partition ecological niches of marine organism (Pingree et al., 1978; Derisio et al., 2014). However, temporal variations in physical forcing such as internal wave propagation, middle layer intrusion, spring-neap cycle of tides, and seasonal changes in solar radiation and wind mixing induce a high biological productivity around the fronts and thermoclines (Pingree et al., 1977; Blauw et al., 2012; Komorita et al., 2016).

The Yellow Sea (YS) has been noted as one of the major coastal oceans with tidal front ecosystems, but its tidal front ecosystems were not extensively studied (Choi, 1991; Liu et al., 2003). As the northwesterly wind weakens and solar radiation increases in spring, the temperature of the upper layer increases and the seasonal thermocline starts to form at 10 to 20 m depths in the deep offshore region. In a stratified ocean, phytoplankton primary production increases and the chlorophyll *a* concentration achieves a maximum at a depth with dim light and rich nutrients when water

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column becomes stable. However, the water column is well mixed in the shallow coastal regions even in spring and summer due to strong tidal stirring, which induces a tidal mixing front between the stratified offshore water and vertically well-mixed coastal water (Simpson and Hunter, 1974; Lie, 1989; Seung et al., 1990).

In May, the water column starts to become stratified and the tidal mixing front intensifies along the 50-m isobath in the eastern Yellow Sea due to vernal warming (Fig. 2). The Korean Coastal Current flows northward along the tidal mixing front in the spring and summer (Seung et al., 1990; Kwon et al., 2011; Lie and Cho, 2016). Secondary circulation across the tidal mixing front generates convergent flow toward the frontal interface and produces chlorophyll patches at the front (Pingree et al., 1974; Franks, 1992). The middle layer intrusion of nutrient-rich water from the mixed region to the stratified region has been suggested to be an important process that induces a subsurface chlorophyll maximum in the stratified region (Yamamoto et al., 2000; Komorita et al., 2016).

Previously, the formation of subsurface chlorophyll maximum (or deep chlorophyll maximum) and influence of the tidal mixing front on the distribution and productivity of phytoplankton had been studied at an offshore site near Gyeonggi Bay in the eastern Yellow Sea (Choi, 1991; Lee et al., 2012). The phytoplankton abundance, chlorophyll concentration and primary productivity of phytoplankton in the frontal region were higher than those in the offshore stratified region and the coastal mixed region (Choi, 1991). The horizontal separation of phytoplankton communities by the tidal mixing front was shown via a two-dimensional cluster analysis (Choi, 1991). A cluster analysis for the three-dimensional distribution of phytoplankton community has not been carried out, which substantially limit studies on the influence of the thermocline, tidal mixing front, river plume on the distribution of phytoplankton community.

The objectives of this study are (1) to investigate the three-dimensional distribution of the phytoplankton community over the sloping shelf of the eastern Yellow Sea (35.8–36.3°N, 125–126.5°E) and (2) to understand the influence of the thermocline, tidal mixing front, and river plume on the distribution of the phytoplankton community. To this end, hydrographic and biological observations were carried out in the offshore and shallow coastal region in May 2012.

Section 2 introduces data sampling and analysis methods. Section 3 compares the cross-shore sections of the physical environment variables and the biological variables. To determine how the physical environment affects the three-dimensional distribution of the phytoplankton community, a cluster analysis is performed based on the phytoplankton species and composition. Section 4 discusses the three-dimensional structure of the phytoplankton community, the formation of subsurface chlorophyll *a* maximum, and a disagreement in the profiles of phytoplankton abundance and chlorophyll *a* concentration. A short summary is given in Section 5.

2. Materials and methods

2.1. Sampling of the water and measurement of the temperature and salinity

R/V Hae Rim II was used for the field survey and the sampling at 42 stations within the field survey region (35.8–36.3°N, 125–126.5°E) (Fig. 1). The depth of the water column is about 20 m in the coastal region. The bottom depth becomes deeper toward the Yellow Sea Trough and reaches about 80 m near 125°E.

The surface water was sampled at the sea surface using a bucket, and the subsurface water was sampled for every 10-m depth using Niskin water samplers. The sampled water was immediately treated according to the chlorophyll measurement protocol and the phytoplankton quantitative analysis method. The temperature and salinity were observed using Conductivity-Temperature-Depth sensor (SBE 19^{+}, Sea-Bird Electronics, Bellevue, Washington, USA). Temperature and salinity data were then subsampled every 0.5 m.

2.2. Measurement of chlorophyll a concentration

A 500 mL water sample was filtered with a 45 mm diameter GF/C filter paper on board, and the filtration pressure was maintained at less than 200 mmHg. After filtering, the filter paper was stored in a 20 mL bottle and the bottles were kept frozen in the dark. The frozen filter paper was melted according to the acetone extraction process. 15 mL of 90% acetone was injected into the melted sample and stirred. Chlorophyll *a* was extracted in a cool and dark room for 24 h. The chlorophyll *a* fluorescence was measured using TU-10 Fluorometer (Turner Designs, Sunnyvale, California, USA) and the fluorescence was converted into the value of chlorophyll *a*:

$$\text{Chlorophyll } a = F_d \frac{r}{r-1} (R_b - R_a) \frac{vol_{ex}}{vol_{fit}}.$$

F_d = door factor from calibration calculations
r = acidification coefficient (R_b/R_a) for pure chlorophyll *a* (usually 2.2)
R_b = reading before acidification
R_a = reading after acidification
vol_{ex} = extraction volume
vol_{fit} = sample volume

2.3. Quantitative analysis of phytoplankton

To quantify the abundance of phytoplankton species, the seawater samples preserved with acidic Lugol's solution (final concentration, 1%) were concentrated to 1/10 using the settling and siphoning method (Welch, 1948). After shaking enough to ensure homogeneity, all or a minimum of 100 cells of phototrophic plankton in 1-ml Sedgwick–Rafter counting chambers were counted under a light microscope (Axioplan, Carl Zeiss, Gottingen, Germany) at a magnification of 200 times. It was then converted into the number of phytoplankton per mL (Throndsen, 1993). Each species of phytoplankton was identified accordingly as described in Shim (1994), Tomas (1997), Chihara and Murano (1997), and Gómez et al. (2008).

2.4. Cluster analysis

To examine the three-dimensional pattern of the phytoplankton distribution, the similarity in species abundance and community composition was calculated for all sampling depths at the stations. The cluster analysis was carried out using a multivariate statistical analysis program (Primer software, Version 6, PRIMER-E, Plymouth, UK).

3. Results

3.1. Temperature, salinity and density

The average temperature was 9.1°C and the temperature ranged from 5.9 to 18.1°C along A, B, C, and D lines in May 2012 (Fig. 2). The depth of the thermocline becomes deeper from the coast to the offshore region, and it was about 10–20 m in the offshore. The

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