Acta Oceanol. Sin., 2013, Vol. 32, No. 9, P. 82-90
DOI: 10.1007/s13131-013-0355-8
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The influence of thermohaline fronts on chlorophyll *a* concentrations during spring and summer in the southeastern Yellow Sea

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Received 19 June 2012; accepted 1 March 2013

Abstract

A spatial and temporal variation in physiochemical parameters in the southeastern Yellow Sea (YS) is investigated in the spring and summer of 2009 to 2011. Nutrient show a strong negative relationship with chlorophyll *a* (Chl *a*) concentration in spring, and the subsurface chlorophyll *a* maxima (SCM) layer was associated with the nitracline in summer. In summer, the SCM was usually found within or above the pycnocline and at the depths of shoals from the open sea to the coastal sea due to tidal and/or topographical fronts in the southernmost study area. High Chl *a* concentrations were found in the central southern YS, where the YS cold water layer expanded under the pycnocline and encountered water masses during spring and summer. After a typhoon in the summer of 2011, Chl *a* concentration increased, especially in the central southern YS, where cold waters occurred below the pycnocline. The results suggest that the development of thermohaline fronts may play an important role in the growth and accumulation of phytoplankton biomass in the upper layer of the southeastern YS during spring and summer.

Key words: Yellow Sea Cold Water, nutrient, chorophyll a, thermohaline front

Citation: Jang Pung-Guk, Lee Tong Sup, Kang Jung-Hoon, Shin Kyoungsoon. 2013. The influence of thermohaline fronts on chlorophyll *a* concentrations during spring and summer in the southeastern Yellow Sea. Acta Oceanologica Sinica, 32(9): 82–90, doi: 10.1007/s13131-013-0355-8

1 Introduction

The Yellow Sea (YS) is a semienclosed shallow water body surrounded by the Korean Peninsula and China's mainland in the northwest Pacific region. The YS is connected to the Bohai Sea in the north and the East China Sea (ECS) in the south. The southern YS has been recognized as one of the most prolific fishing grounds globally. Despite heavy human pressure, such as overfishing and pollutant loading, the YS ecosystem seems to be functioning perfectly well. This seemingly enigmatic situation may be partly due to winter mixing.

In winter, when the water column is vertically homogeneous, water masses in the YS are classified into two types: the low-temperature and low-salinity YS cold water (YSCW), which occurs in the lower layer during summer, and the high-temperature and high-salinity YS warm current, which originates from the Kuroshio-East China Sea (KE, which is split into a surface layer, KES, and a subsurface layer, KEB, in summer) (Hur et al., 1999). The two water masses meet west of Jeju Island and form a strong surface-to-bottom thermohaline front that runs west to east (Lie, 1986). In summer, strong stratification is maintained by warm water masses in the upper layer and cold water masses below the pycnocline. There are four major water masses during summer: the KES, the KEB, YS surface water (YSSW), and the YSCW.

One of the most important physical features of the YS is the existence of the strong cold water mass, the YSCW, throughout the summer season. Two cold water masses occur within the YS during summer: the northern YSCW, which is located in the bottom layer and has a temperature lower than 8°C, and the southern YSCW, which is located in the bottom layer and has a temperature lower than 10°C. Zhang et al. (2008) suggested that there are bottom layer temperature anomalies from February to July in the cold tongue region, and trajectories of the bottom floaters, indicating that the cold water mass in the northeast region experiences displacement from the north into the central area of the YS in summer.

The YSCW has important effects on the hydrographic features and the planktonic ecosystem in the YS (Hur et al., 1999; Chen et al., 2004; Kang and Kim 2008). The influences of physical processes on phytoplankton blooms in coastal areas and on the continental shelf have been widely studied. The primary physical processes that affect the spatial and temporal dynamics of phytoplankton blooms include the stability of the water column, wind speed, water temperature, and water mass movement. Sverdrup (1953) suggested that water column stability enhances spring phytoplankton blooms. Kasai et al. (1997) showed that there is a significant positive relationship between surface chlorophyll *a* (Chl *a*) concentrations and the maximum density gradient within the euphotic layer in April, which demonstrates the importance of vertical stability in the water column for the initiation of spring blooms in the Oyashio and in coastal water masses.

Foundation item: The China-Korea cooperative project on the Yellow Sea Cold Water Mass under contract No. PE99165; the projects under contract No. PM57090, funded by Korea Institude of Ocean Science and Technology.

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We believe that the appearance of cold water masses and other water masses in our study area results in the formation of thermohaline fronts that enhance the stability of water masses. Therefore, we discuss thermohaline fronts through the effects of water masses on Chl *a* concentrations in spring and summer in the southeastern YS.

2 Materials and methods

The study area was the southeastern YS, which spans from 34°30′ to 36°00′N and 124°30′ to 125°40′E (Fig. 1). Here, we discuss only meridional stations in the center of the YS (line CS) and zonal stations in the southern portion of the study area (line E). Water samples were collected during April 15–17, 2010; April 9–13, 2011; August 5–9, 2009; August 17–20, 2010; and August 10–12, 2011. Vertical profiles of temperature and salinity were measured using a SBE911 conductivity-temperature-depth (CTD) instrument. Seawater samples were collected for nutrient and Chl *a* analyses using a rosette with 10-L Niskin bottles at nine water depths (1, 10, 20, 30, 40, 50, 60, 75 and 85 m).

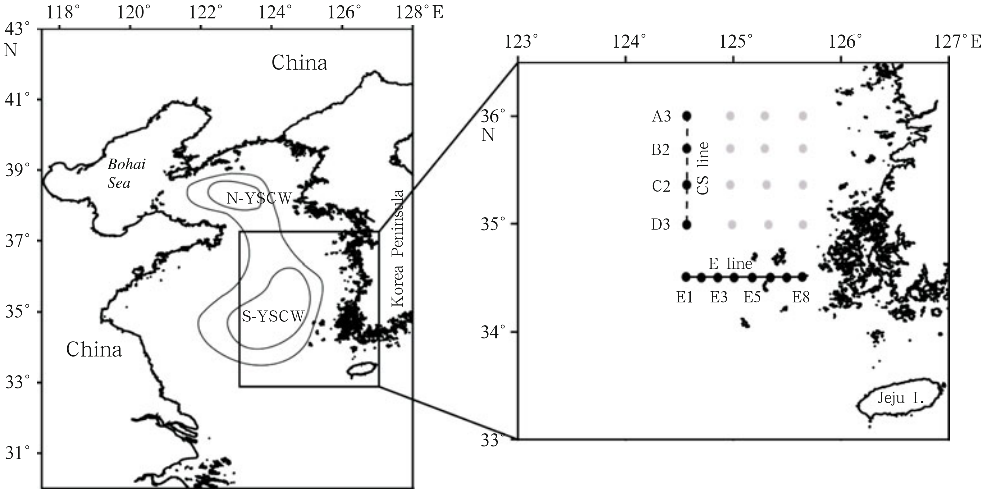

Fig.1. Map showing the study area and sampling stations in the southern Yellow Sea. Stations discussed in detail are marked by filled circles. The CS line is composed of meridional stations in the center of the Yellow Sea and the E line is composed of zonal stations in the southernmost portion of the study area.

Water samples for nutrient and Chl *a* analyses were gently filtered through 47 mm diameter Whatman GF/F filters and then stored at –20°C. Nitrate plus nitrite (hereafter referred to as nitrate), phosphate, and silicate concentrations were measured using a flow injection autoanalyzer (model QuikChem 8000, Lachat, Loveland, CO, USA). Nitrate, phosphate, and silicate were calibrated using brine standard solutions (CSK Standard Solutions, Wako Pure Chemical Industries, Osaka, Japan). Duplicate analyses show the precision of the nitrate, phosphate, and silicate measurements to be 2%, 3%, and 3%, respectively. Chl *a* was extracted in 10 mL of 90% acetone in the dark at 4°C for 14–24 h, and the concentration was then determined using a Turner 10-AU fluorometer (Turner BioSystems, Sunnyvale, CA, USA) (Parsons et al., 1984).

The degree of stratification was calculated using the potential energy anomaly (PEA). The PEA is calculated by integrating the difference between the measured density and an average density over depth (Simpson et al., 1978). The density gradient was calculated according to the distance between stations. To emphasize density changes in the upper layer, for each station we used the average density from 1 to 30 m during spring and from 1 to 40 m in summer. These ranges were related to the subsurface Chl *a* maxima (SCM) layer in the study area.

3 Results

3.1 *Hydrographic, nutrient, and chlorophyll a conditions in spring*

Temperature, salinity, density, nitrate, phosphate, silicate, and Chl *a* profiles recorded in 2010 and 2011 are shown in Fig. 2. Water temperature and salinity varied within narrow ranges of 6.56–8.80°C [avg. (7.50±0.39)°C] and 32.52–33.04 (avg. 32.66±0.10), respectively, in 2010, but had relatively wide ranges of 5.91–10.17°C [avg. (7.98±1.32)°C] and 32.28–34.20 (avg. 33.11±0.60), respectively, in 2011. The variations in water temperature and salinity along the E line were clearly larger in 2011 than in 2010.

Nitrate concentrations showed a similar spatial pattern to silicate concentrations in each period (Figs 2 and 3). Phosphate concentrations also had similar spatial distribution patterns, except for at Stas E7 and E8 in 2010. Nitrate concentrations in the upper layer (1–30 m) of Line CS in 2011 (mean is 3.99 μmol·L^{-1}) were almost two times higher than in 2010 (mean is 2.16 μmol·L^{-1}). However, nitrate concentrations in the upper layer of Line E in 2011 (mean is 4.35 μmol·L^{-1}) were lower than in 2010 (mean is 6.73 μmol·L^{-1}). In 2010, nitrate concentrations in Line E were similar throughout the water column, but in 2011 the concentrations are low in the upper layer and high in the bottom layer.

Chl *a* concentrations were highly variable in the upper layer of Line CS, ranging from 0.71 to 6.03 μg·L^{-1}, with a mean of 2.46 μg·L^{-1} in 2010, and from 0.39 to 6.12 μg·L^{-1}, with a mean of 1.95 μg·L^{-1} in 2011. High Chl *a* concentrations were found in the upper layers Stas A3 and B2 in 2010, and at Stas A3 to C2 in 2011, where the YSCW expanded under the pycnocline (Fig. 2g). Particularly high concentrations of Chl *a*, exceeding 5 μg·L^{-1}, were observed at the depths of 1–20 m at Sta. C2 in 2011. The Chl *a* concentrations in the upper layer in Line E show clear differences between 2010 and 2011, ranging from

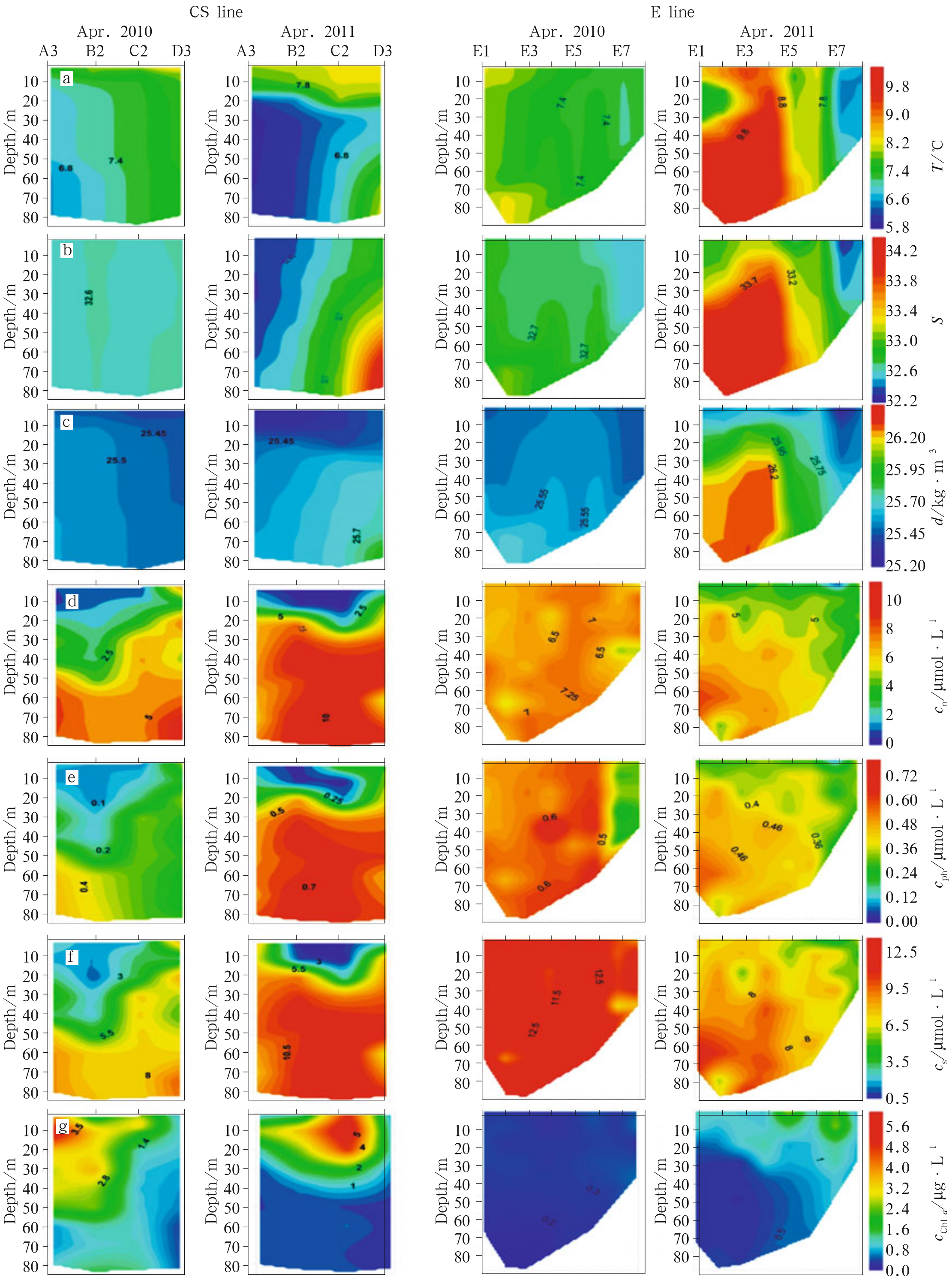

Fig.2. Spring profiles of temperature (T) (a), salinity (S) (b), density (d) (c), nitrate concentration (c_{n}) (d), phosphate concentration (c_{ph}) (e), silicate concentration (c_{s}) (f), and chlorophyll a ($c_{\text{Chl a}}$) (g) in the CS and E lines in April 2010 and 2011.

0.17 to 0.54 μg·L^{-1} (avg. 0.30 μg·L^{-1}) in 2010 and from 0.27 to 2.72 μg·L^{-1} (avg. 1.05 μg·L^{-1}) in 2011.

3.2 *Hydrographic, nutrient, and chlorophyll a conditions in summer*

Figure 3 shows the vertical distributions of temperature, salinity, density, nitrate concentration, phosphate concentration, silicate concentration, and Chl a concentration from the cruises in the summers of 2009, 2010, and 2011. The temperature and salinity ranges in 2009 were similar to those in 2010. However, the ranges of temperature and salinity in 2011 differed, with values of 9.82–20.61°C [avg. (13.65±4.11)°C] and 32.03–33.80 (avg. 33.15±0.57), respectively. This result was probably attributable to a strong typhoon (Typhoon Muifa) that

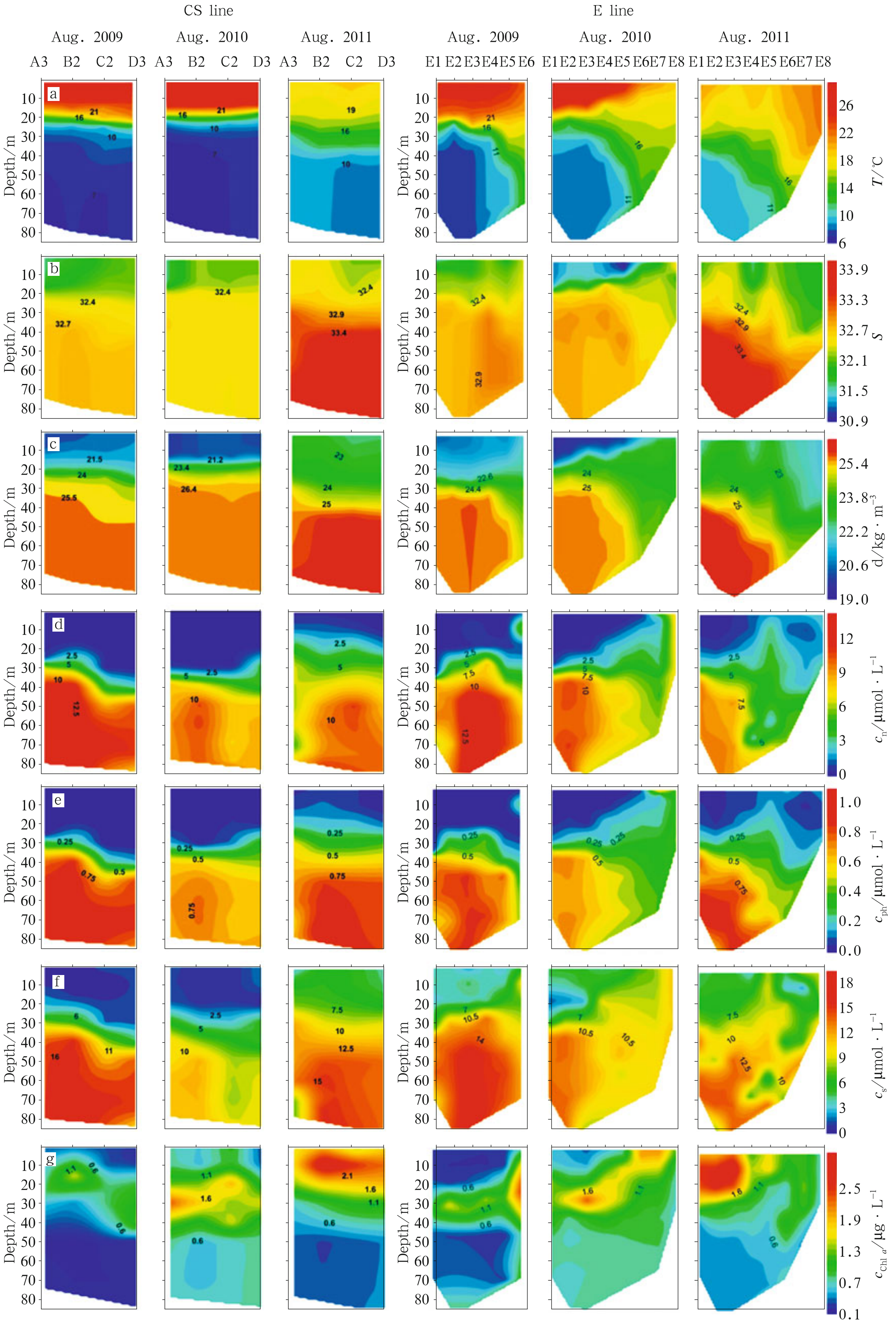

Fig.3. Summer profiles of temperature (a), salinity (b), density (c), nitrate concentration (d), phosphate concentration (e), silicate concentration (f), and chlorophyll *a* concentration (g) in the CS and E lines in 2009, 2010, and 2011.

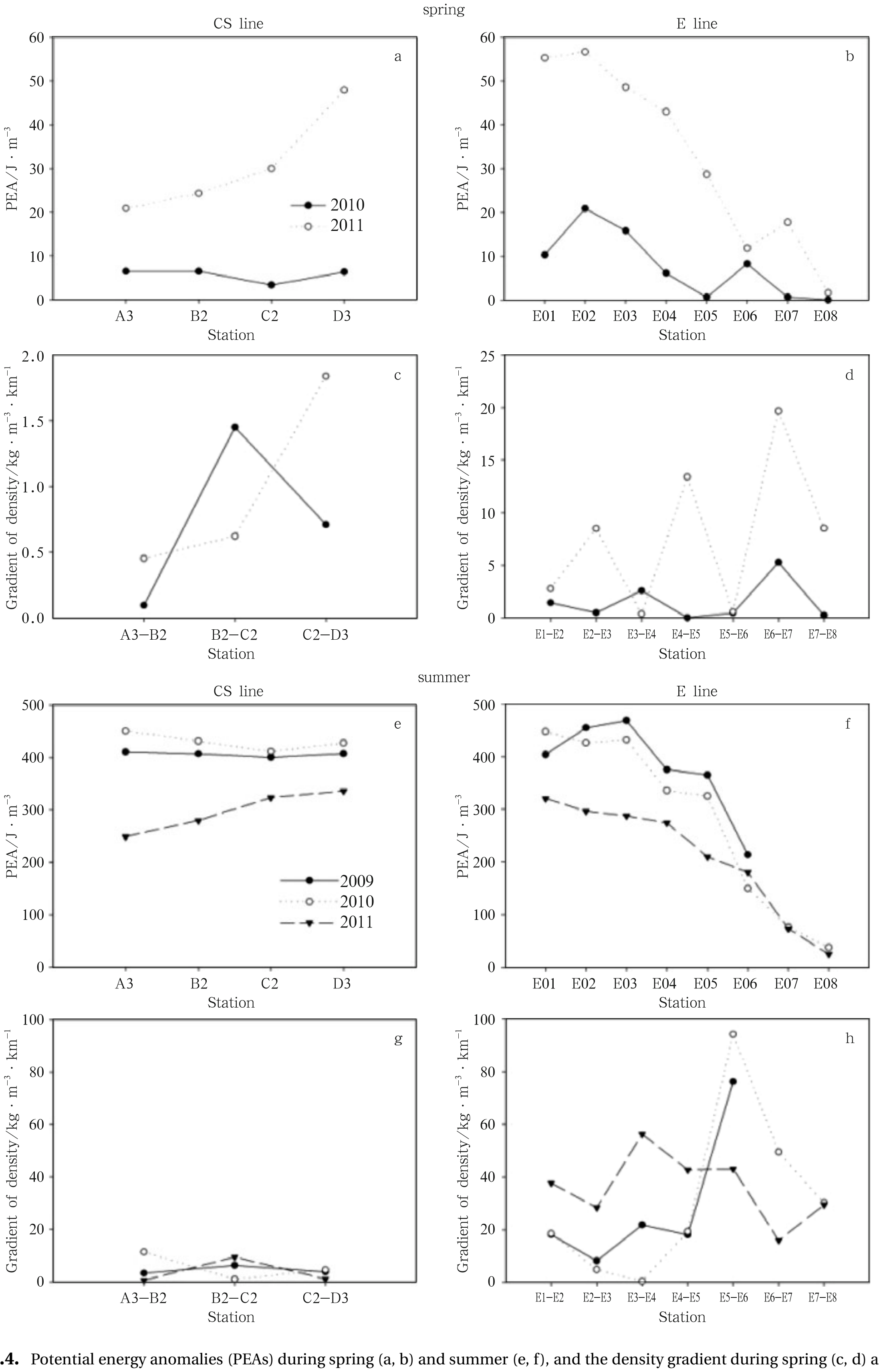

Fig.4. Potential energy anomalies (PEAs) during spring (a, b) and summer (e, f), and the density gradient during spring (c, d) and summer (g, h) in the CS and E lines.

passed over the study area on August 7, 2011. Strong stratification appeared at the depths of 30–40 m in Line CS. In Line E, the cold water mass exited the open sea, which meant that the YSCW extended south of the YS in the summer. The pycnocline became shallower from the open sea to the coastal sea in 2009 and 2010, especially in 2010 when sampling was conducted from Sta. E1 located in the open sea to Sta. E8 located in the coastal sea. The strength of the stratification also decreased from Sta. E1 to Sta. E8 in summer and a slope in the PEA appeared at Line E in summer (Fig. 4).

Nutrients, particularly nitrate and phosphate, were depleted in the upper layer of Line CS in the summers of 2009 and 2010 (Fig. 3), but relatively high concentrations were observed in 2011. Nitrate concentrations in the upper layer of Line E in the summer of 2010 averaged 2.36 μg·L^{-1}, which is higher than the mean of 1.88 μg·L^{-1} in 2011. The concentration of nitrate in the upper layers of Line E increased from E1 to E8 in 2010. Nitrate concentrations in the upper layer were the highest at Sta. E8 and are similar to values in the water column in 2010.

Chl *a* concentrations in the surface water in 2009 and 2010 were low, with mean values of 0.31 and 0.86 μg·L^{-1}, respectively. However, high Chl *a* concentrations, with a mean of 1.50 μg·L^{-1}, were observed in 2011 and attributed to a typhoon (Fig. 3g). At most of the stations in the open sea there were showed high concentrations of Chl *a* (avg. 1.80 μg·L^{-1}) in the upper layers in 2011. The SCM in Line CS was observed at 20–40 m in 2009 and 2010. Chl *a* concentrations in the northern area of Line CS were higher than those in the southern area in 2009 and 2010. The SCM was observed along Line E and its depth became shallower from the open sea to coastal areas in 2009 and 2010, even though high Chl *a* concentrations were observed in surface waters at Stas E6 and E7 in 2010.

4 Discussion

4.1 *The controlling factor of spring phytoplankton blooms*

The physical characteristics of each water type have been described by Hur et al. (1999), who investigated monthly water mass variation in the YS and the ECS using 40 a of historical temperature and salinity observations via a cluster analysis that incorporated geographical distance and depth separation in addition to the temperature and the salinity. They suggested that the major water masses included the KE, the YSSW, the YSCW, the mixed water, and the coastal water. The water masses in the CS line were classified into two types: the YSSW and the YSCW, in 2010 and 2011 (Fig. 5). Waters in Line E generally belonged to one water mass, the YSSW, in 2010, and three water masses: the YSSW, the KE, and the Korea coastal cold water (KCCW), in 2011. Differences in the distributions of physical parameters between 2010 and 2011 may have been caused by the appearance of the KE and changes in the strengths of the YSCW in the CS line and the KCCW in the E line in 2011. Generally, strong mixing in the water column supplies nutrients to the upper layer in winter. However, because of the limitations of low temperature and low light in winter, these nutrients are not consumed by the growth of phytoplankton. Thus, sufficient nutri-

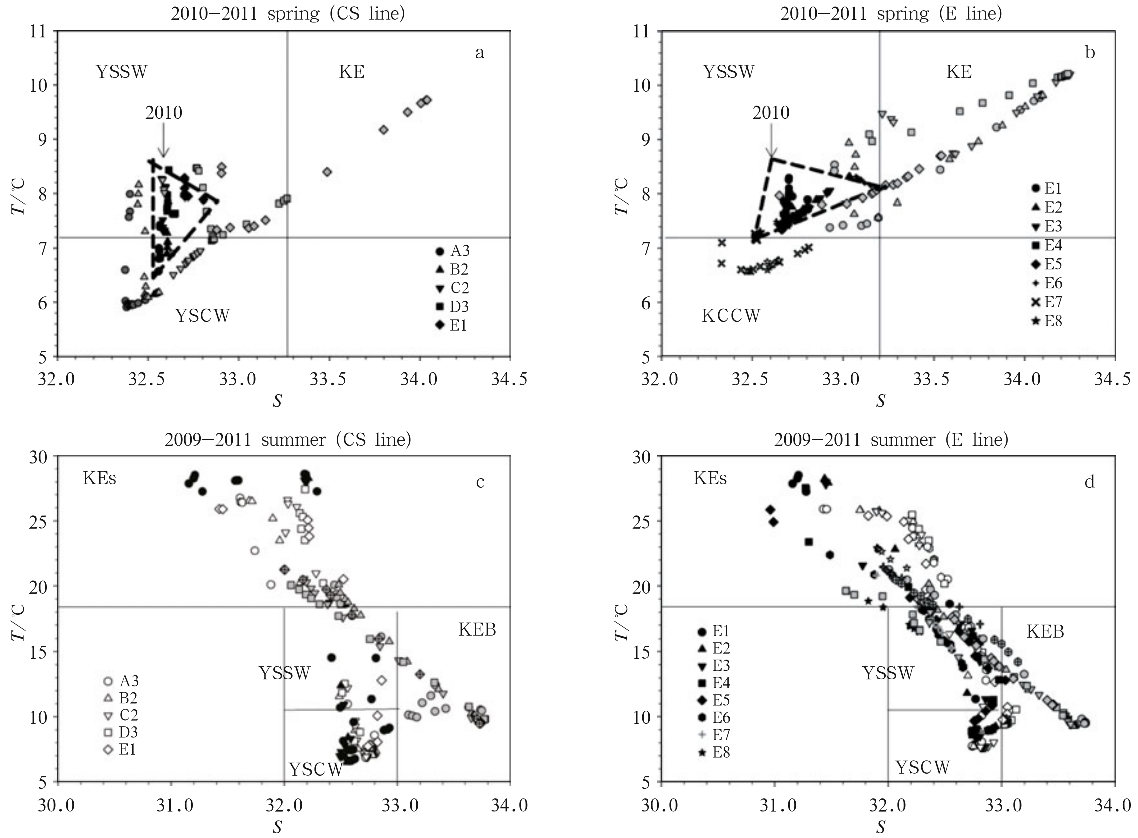

Fig.5. Temperature-salinity diagram of CS line (a) and E line (b) during the spring of 2010 and 2011, and CS line (c) and E line (d) during the summer of 2009, 2010, and 2011 (white: 2009, black: 2010, gray: 2011). Identified water masses are the Yellow Sea surface water (YSSW), the Yellow Sea Cold Water (YSCW), the Kuroshio-East China Sea (KE, which is split into a surface layer, KES, and a subsurface layer, KEB, in the summer), and the Korea coastal cold water (KCCW).

ents could exist in the upper layer in spring, and spring phytoplankton blooms occur in the northwest Pacific. In the present study, nutrient concentrations decreased significantly to the thermocline as a result of algal uptake, as indicated by the Chl *a* concentrations increments. Thus, nutrients concentrations in the upper layers showed strong negative relationships with Chl *a* concentrations in Lines CS and E in spring (Fig. 6). This means that the distribution of nutrients in concentrations spring was controlled by biological activities in Lines CS and E. However, the distribution of phytoplankton biomass in the study area differed between stations in the central YS and in Line E.

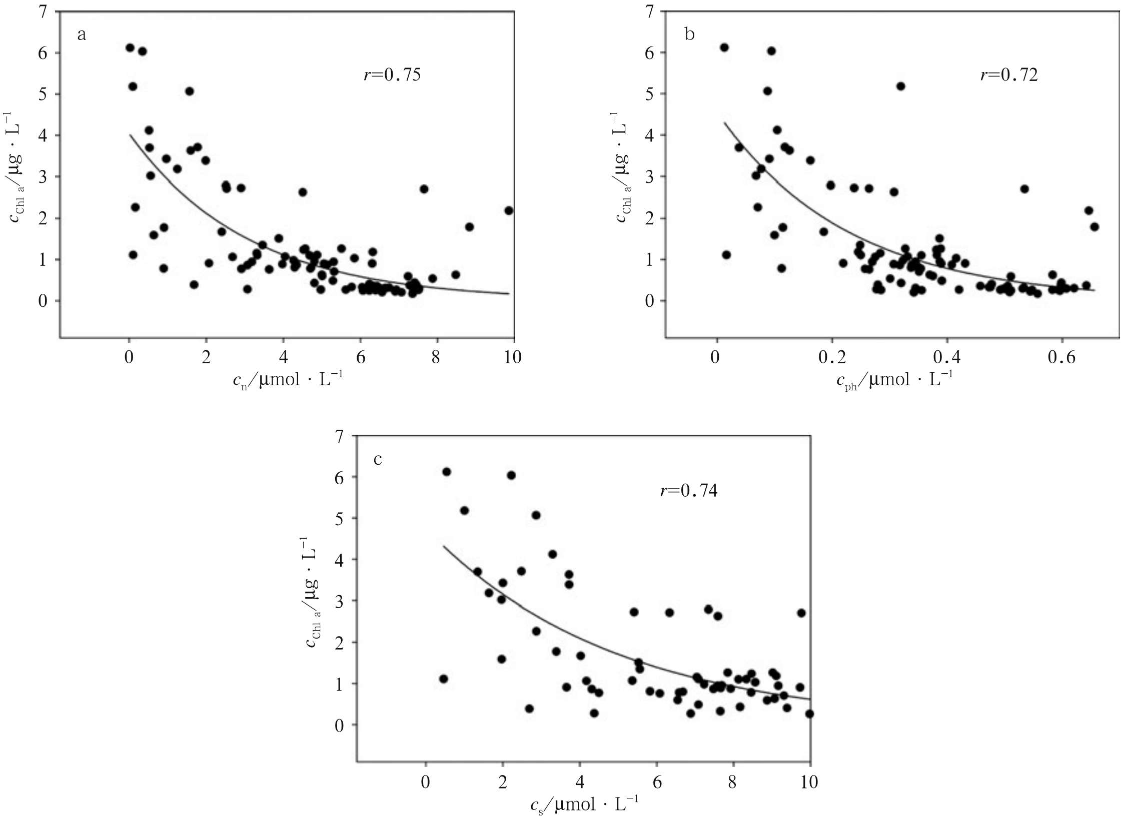

Fig.6. Correlation between chlorophyll *a* concentration and nutrients concentrations in the upper layer (1–30 m) in the spring of 2010 and 2011.

The influence of the YSCW increased substantially in the area north of Line CS, indicating the occurrence of low temperatures below the middle layers in this area. Thus, a weak thermocline developed at around 60 m at Stas A3 and B2 in 2010 and at around 30 m at Stas A3 to C2 in 2011, where it extended the YSCW into the central YS, which may be related to the distribution of Chl *a* concentrations. Chl *a* concentrations in the upper layer of the Line CS increased around Sta. C2, possibly in relation to the density gradient. Relatively high density gradients were found between Stas B2 and C2 in 2010 and between C2 and D3 in 2011, which might indicate that thermohaline fronts existed around Sta. C2 (Fig. 4). Also, the highest Chl *a* concentrations appeared at the upper layers of Sta. C2 in 2011, when the extension of YSCW was wider than in 2010. Thus, thermohaline fronts from the YSSW, the YSCW, and the KE were stronger than those in 2010, which may have caused the compact distribution of density between Stas C2 and D3.

In the E line, the water mass was thoroughly mixed in the spring of 2010, but a pycnocline was observed in the spring of 2011. The PEA in Line E in the spring of 2011 was also higher than that in the spring of 2010 (Fig. 4). This may have been the result of the appearance of the warm saline KE and the cold fresh KCCW in 2011. In addition, the strength of the YSSW decreased from the open sea to the coastal sea; in contrast, the strength of the KCCW decreased from the coastal sea to the open sea in the upper layers in Line E in the spring of 2011. The formation of a pycnocline in the spring of 2011 may have contributed to the higher Chl *a* concentrations in 2011 compared with those of 2010. In the upper layer of Line E, relatively high concentrations of Chl *a* were observed at Stas E5 and E7 in the spring of 2011, where thermohaline fronts among stations may have been stronger than those at other stations. This may have caused the relatively high values in the density gradient, which might have been related to the presence of water masses of the YSWW, the KE, and the KCCW.

Some authors have suggested that the onset of the spring bloom was caused by the interaction between sufficient nutrient accumulation during winter and an increase in water temperature (Huang et al., 2006). However, water temperatures at the stations in Lines CS and E, which had relatively high Chl *a* concentrations, were not significantly higher than around stations in April 2010 and 2011. Even so, at Stas E5 and E7 there are the highest observed Chl *a* concentrations and lower water temperatures compared with the stations in 2011.

This phenomenon seems to have resulted from relatively stable thermohaline fronts rather than the temperature structure in Lines CS and E. Thermohaline fronts can prevent phytoplankton from descending below the euphotic layer and have an important role in the accumulation of phytoplankton biomass along the continental shelf (Kim et al., 2009). Therefore, thermohaline fronts that induce increasing water stability represent all the factors that could influence the distribution of Chl *a* concentrations in the upper layer where the condition of nutrients is suitable for the phytoplankton growth in the southeastern YS in spring. Similar conclusions were reached in studies that examined the controlling effects of spring blooms in the YS (Hu et al., 2004; Fu et al., 2009; Xuan et al., 2011).

4.2 *The controlling factor for phytoplankton biomass in summer season*

The water masses were dominated by the KES and the YSSW in the upper layers and the YSCW below the pycnocline in 2009 and 2010. After nitrate and phosphate depletion during spring phytoplankton blooms, these nutrient deficits prevailed in strongly stratified water in summer that hindered the upward movement of nutrients from nutrient-rich deeper waters. The KES entered the upper layer in the study area in summer and was known to have low nutrient concentrations (Kim et al., 2009). Therefore, Chl *a* concentrations were also low in the upper layer because of nutrient limitations in 2009 and 2010. However, another water mass, the KEB, appeared in Line E in 2011. Nitrate and Chl *a* concentrations in the upper layer were relatively high, with mean values of 2.07 μmol·L^{-1} and 1.47 μg·L^{-1}, respectively. These differences in physiochemical parameters were probably attributable to a strong typhoon. Three days after Typhoon Muifa passed directly by the study area, its effects were investigated. Approaching typhoons can effectively mix stratified layers, which can result in the transfer of nutrients to the euphotic zone and can support phytoplankton blooms during nutrient-poor summers along the continental shelf (Chang et al., 1996; Shiah et al., 2000; Hui et al., 2009; Jang et al., 2013).

Since the oceanic SCM was first described by Yentsch (1965), it has been widely recognized in profiles of stratified water columns. The SCM is usually associated with a density discontinuity, the nutricline, and a surface light intensity range of 0.1%–10% (Longhurst and Harrison, 1989). The distribution pattern of the SCM in Line E in the summer of 2010 may have been caused by tidal and/or topographic fronts in Line E. Fronts occur in shallow seas that experience strong tidal currents and have a sloping bathymetry (Lie, 1986; Odate and Furuya, 1998). A front that is created between the well-mixed inshore waters and the stratified offshore waters is usually seen most clearly in the temperature profile (Franks, 1992), which was the case in our data. The front was remarkable for the complexity of the tidal pattern, with large tidal ranges appearing along the west of Korea, including in the study area.

Internal waves in the pycnocline cause fluctuations in the light environment for photosynthesis, particularly in the SCM, both through vertical displacement of the pycnocline and through mixing processes associated with energy dissipation that influence phytoplankton growth in ocean ecosystems (Holligan et al., 1985). Mixing by the internal waves in the pycnocline of shallow continental shelf waters can lead to pulses of nutrient inputs to nutrient-depleted upper layers (Holligan et al., 1985). Therefore, phytoplankton growth at the stations in Line E appeared to be enhanced by the upward transport of nutrients caused by tidal and/or topographic fronts in the pycnocline, which created large density differences between the KES and the YSCW. Also, the fronts affected the depth of the SCM within the pycnocline in Line E. At Sta. E8, the nearest inshore area, there are low Chl *a* concentrations despite the rich nutrients, perhaps because of light limitation from strong vertical mixing and the presence of suspended solids (data not shown). Therefore, in summer, the vertical distribution of Chl *a* may be controlled by the supply of nutrients to the euphotic zone from tidal and/or topographic fronts in Line E.

After a typhoon, the increased nutrients and a restabilized upper layer can produce favorable conditions for the phytoplankton growth. Therefore, Chl *a* concentrations were higher in summer in 2011 than those in 2009 and 2010, when a strong typhoon affected the study area. High Chl *a* concentrations were observed in the upper layer of the CS line and at Stas E1 to E3 where the cold saline water mass of the KEB (<11°C) may have mixed with water masses in the YSSW, the YSCW, and the TCW during the summer of 2011 because of the effects of Typhoon Muifa. The YSCW was characterized by a more stable water column in the open sea compared with the coastal stations after the passage of the typhoon. The relatively strong water stability that was induced by the YSCW in the central YS may have played an important role in the distribution of Chl *a* concentrations after the summer typhoon, creating conditions that were similar to the beginning of spring blooms.

5 Conclusions

The vertical distributions of nutrient concentrations showed strong negative correlations with Chl *a* concentrations during spring, which confirms that nutrient distributions controlled biological activities in the southeastern YS. High Chl *a* concentrations in spring are often observed at the central stations in the study area where the YSCW occurs. In summer, the vertical distributions of nutrients and Chl *a* concentrations in the upper layer may be primarily affected by tidal and/or topographic fronts and the passage of typhoons. After the passage of a typhoon, high Chl *a* concentrations were observed in the upper layer in the central southern YS where the YSCW occurred below the pycnocline, compared with other stations. These results suggest that thermohaline fronts among the water masses were the primary mechanism controlling phytoplankton growth in the euphotic zone when suitable nutrient supplies were available in the southeastern YS.

Acknowledgements

The authors are indebted to the captain and crew of the R/V Eardo who were most helpful in all our shipboard operations. We also would like to thank Drs. Lee Seok and Oh Kyung hee for advice of a physical process and Mr. Kwon Ohyoun for assistance in the field work.

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