ICES Journal of Marine Science Advance Access published November 17, 2011

ICES Journal of Marine Science; doi:10.1093/icesjms/fsr178

Impact of an anticyclonic eddy on the summer nutrient and chlorophyll *a* distributions in the Ulleung Basin, East Sea (Japan Sea)

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Kim, D., Yang, E. J., Kim, K. H., Shin, C-W., Park, J., Yoo, S., and Hyun, J-H. Impact of an anticyclonic eddy on the summer nutrient and chlorophyll *a* distributions in the Ulleung Basin, East Sea (Japan Sea). – ICES Journal of Marine Science, doi:10.1093/icesjms/fsr178.

Received 25 September 2010; accepted 3 October 2011.

The impact of the anticyclonic Ulleung Warm Eddy (UWE) on the vertical distributions of nutrient and chlorophyll *a* (Chl *a*) concentrations in the Ulleung Basin (UB) was investigated during the contrasting summers of 2005 and 2007. The physical structure of the water column was characterized by an intrathermocline eddy (ITE) in 2005, whereas the UWE remained distant from the sampling transect in 2007. Water column structures appeared to be highly stratified, and nutrients in the surface waters were totally depleted at all stations. In 2005, an exceptionally high concentration of Chl *a* (5.5 mg m^{-3}) was measured below the surface mixed layer in the eddy core (station D3), and values of ~2.5 mg m^{-3} were observed at the eddy edge (stations D2 and D4). Formation of an ITE efficiently mixed surface and deep-ocean waters, the latter supplying sufficient nutrients to generate an extremely high concentration of Chl *a* at the base of the subsurface layer. Overall, the results indicated that the anticyclonic UWE plays a key ecological role in supporting substantial phytoplankton biomass in the nutrient-depleted surface waters in summer and maintaining high benthic mineralization in the deep-sea sediments of the UB.

Keywords: anticyclonic eddy, East Sea (Japan Sea), intrathermocline eddy, nutrients, Ulleung Basin.

Introduction

Mesoscale eddies have significant effects on nutrient distribution, phytoplankton biomass, primary production, and new production. At the centre of cyclonic eddies, upwelling transports nutrient-rich water to the surface, resulting in high phytoplankton biomass and primary production (McGillicuddy and Robinson, 1997; Letelier *et al*., 2000; Garcon *et al*., 2001; Vaillancourt *et al*., 2003). In contrast, anticyclonic eddies have the capacity to reduce primary production by depressing the nutricline, so favouring the development of ecosystems with low biomass and composed of small cells (Franks *et al*., 1986; Burkill *et al*., 1993; Landry *et al*., 1998). Mizobata *et al*. (2002) suggested that nutrient-rich deep water was transported upwards along up-bowed isopycnals at the edges of anticyclonic eddies, stimulating high chlorophyll *a* (Chl *a*) concentrations. In addition, McGillicuddy *et al*. (2007) reported that anticyclonic mode-water eddies could account for the extraordinarily large diatom biomass and high primary production measured in the Sargasso Sea. Recently, Mahadevan *et al*. (2008) proposed that the largest vertical velocities arise at the periphery of the anticyclonic eddy, which may induce the vertical flux of nutrients and stimulate the accumulation of phytoplankton at the centre of the eddy.

An anticyclonic eddy appears once or twice each year within the Ulleung Basin (UB) in the southwestern East Sea/Japan Sea (An *et al*., 1994; Kim, 2000). Known as the Ulleung Warm Eddy (UWE), this anticyclonic eddy is derived from the warm core of its subsurface structure (Kim and Yoon, 1999). The UWE originates from the East Korean Warm Current, a northward branch of the Tsushima Warm Current (Shin *et al*., 2005). The meandering of the East Korean Warm Current, the bottom topography of the basin, and the presence of a Polar Front maintain the UWE (Lie *et al*., 1995; Lim and Kim, 1995), which has a horizontal scale between 50 and 150 km, with the maximum depth of the thermostad being about 150 m at the centre of the eddy. The cycle of rotation is about 13.6 d, and the mean swirl velocity is 24 cm s^{-1} (Lie *et al*., 1995).

Although the physical characteristics of the UWE and its effect on the distribution of planktonic communities in the surface water column have been studied extensively (Chang *et al*., 2004; Kang *et al*., 2004; Ahn *et al*., 2005; Hyun *et al*., 2009), relatively little is known about the effect of the UWE on the vertical distribution of nutrient and Chl *a* concentrations during highly stratified, nutrient-depleted summer conditions in the UB. Here, we report that the occurrence of the UWE enhances the nutrient flux to maintain a high phytoplankton biomass at the centre of the eddy core, supporting high biological productivity under highly stratified, nutrient-depleted summer conditions in the UB.

Methods

Measurements were made during two cruises of the RV "Eardo" during summer (19 July–1 August 2005, and 30 July–11 August 2007) in the UB, located in the southwestern East Sea/Japan Sea (hereafter the East Sea). Water samples were collected every 0.5° of longitude between 130° and 132°E, along latitude 37°N (Figure 1). During the cruises, a shipboard acoustic Doppler current profiler (ADCP) measured the ocean current from 12 m deep to about 284 m. Vertical profiles of temperature and salinity were obtained with a SeaBird conductivity, temperature, and depth sensor (CTD; SBE 9/11 plus; SeaBird, Bellevue, WA, USA). Sea surface height (SSH) data were obtained from the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) centre (http://www.aviso.oceanobs.com). We also used multi-satellite (Topex/Poseidon, Jason-1, ERS, Envisat) weekly delayed-time maps of sea-level anomalies (DT-MSLA) using Mercator 1/3° grid data (CLS, 2008).

Seawater samples were collected for nutrient and Chl *a* analyses using a rosette sampler with 10-l Niskin bottles mounted on the CTD assembly at seven water depths (0, 10, 20, 30, 50, 75, and 100 m) and at the subsurface Chl *a* maximum (SCM) depth. The latter was determined by a submersible fluorometer mounted on the CTD assembly. Water samples for nutrient analysis were filtered through GF/F filter paper (25 mm; Whatman, Brentford, Middlesex, UK), placed in acid-cleaned polyethylene bottles, poisoned with $HgCl_2$ (Kattner, 1999). Nitrate + nitrite (hereafter referred to as nitrate), phosphate, and silicate concentrations were measured using a flow-injection autoanalyser (QuikChem AE, Loveland, CO, USA) and standard colorimetric procedures (Strickland and Parsons, 1972), calibrated using brine standard solutions (CSK Standard Solutions; Wako Pure Chemical Industries, Osaka, Japan). Duplicate analyses showed the precision of the nitrate, phosphate, and silicate measurements to be 3, 3, and 5%, respectively. Water samples for Chl *a* analyses were filtered through GF/F filters (47 mm; Whatman), which were then immediately frozen in liquid nitrogen. The extracted filtrate was mixed with 90% acetone for 24 h, after which the Chl *a* concentration was determined using a fluorometer (TD-700; Turner Designs, Sunnyvale, CA, USA). Water samples for measuring the Chl *a* in organisms $<5\ \mu m$ (the pico-fraction) were filtered through a 5-μm-pore Nucleopore polycarbonate filter, and the Chl *a* in the filtrate was measured with an Aquafluor fluorometer (Turner Designs). To produce vertically continuous distributions of Chl *a*, the *in situ* Chl *a* fluorescence was measured using an underwater fluorometer (SeaTech, Wilmington, NC, USA). Finally, the Chl *a* concentration was calculated from the linear relationship between the *in situ* fluorescence and acetone-extracted Chl *a* concentration.

Results

Physical characteristics of an anticyclonic eddy

Satellite altimetry can be used to identify the location of mesoscale eddies in the ocean. The SSHs of cyclonic eddies are negative, whereas those of anticyclonic eddies are positive. Figure 1 shows the SSH anomaly map for the UB in July 2005 and August 2007. The sampling stations in July 2005 were within the UWE, but outside the UWE in August 2007. In July 2005, the eddy core was located at station D3, with its edge at stations D2 and D4. Shipboard ADCP observations of surface currents showed the influence of the eddy fields on the cruise tracks (Figure 2). Eddy structures were clear in the surface current fields in July 2005, but not in August 2007. In July 2005, the eddy centre was located near station D3, and the vertical current velocities were almost constant in the surface 200 m, showing an increase with distance from the eddy centre, with a maximum velocity of $>50\ cm\ s^{-1}$.

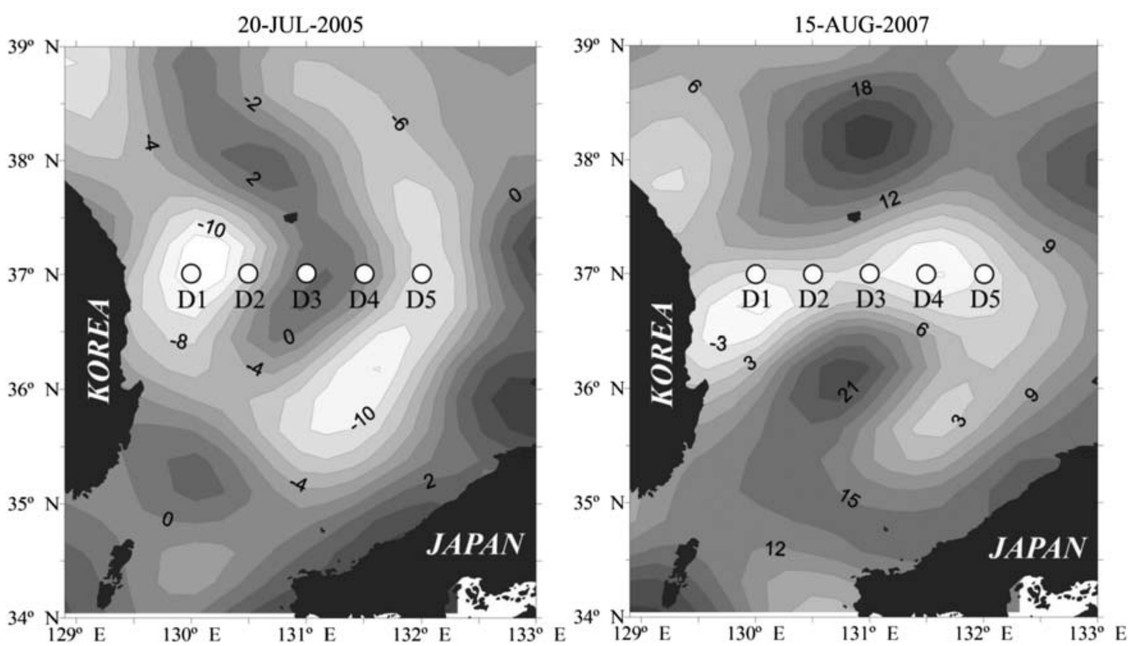

Figure 1. Sea-level anomalies on 20 July 2005 and 15 August 2007. Positive (dark grey) and negative (white) anomalies in SSH (cm) are shown. Open circles indicate the sampling stations. Note that the contours have different intervals.

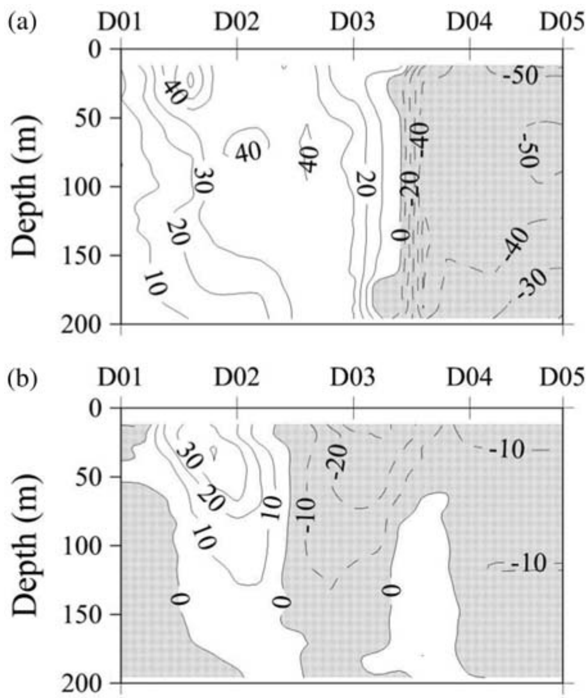

Figure 2. Vertical sections of the meridional current speed measured by a ship-mounted ADCP in (a) July 2005, and (b) August 2007. The area shaded grey indicates southward movement.

The vertical distributions of temperature, salinity, and density in the surface 200 m, as measured during the two summer cruises, are illustrated in Figure 3. Water column structure appeared to be highly stratified. The surface mixed layer depth, defined as the depth at which the temperature change from the surface temperature is 0.5°C (Levitus, 1982), appeared at ~5–20 m (Table 1). A notable feature of the physical properties was that the temperature structure measured in July 2005 showed a thick lens of water with a temperature of 10–11°C located between depths of 70 and 180 m. The salinity structure also displayed a thick lens of 34.3–34.4, located at depths of 70–200 m. These temperature and salinity features indicated that the UWE observed in July 2005 was an intrathermocline eddy (ITE), characterized by a subsurface lens of relatively homogeneous water, with typical spatial scales of 10–100 km horizontally and 100 m vertically (Dugan *et al.*, 1982). Gordon *et al.* (2002) reported the existence of ITEs in the East Sea based on observations from SeaSoar instrumentation, CTD sensors, and airborne expendable bathythermographs. In contrast, the density structure in 2007 did not provide evidence of a thick lens of water in the surface 200 m, indicating that an ITE did not exist along the transect run in 2007.

Vertical distribution of nutrients and Chl *a*

Nitrate and phosphate concentrations were relatively depleted in surface waters, and increased gradually with depth at all stations in both 2005 and 2007 (Figure 4). In contrast, the vertical distribution of silicate was quite different between the summers of 2005 and 2007 (Figure 4). Silicate concentrations were relatively depleted in surface waters, and increased gradually with depth in 2007, but in 2005, high silicate concentrations (about 10 μmol l^{-1}) were found in the surface waters at all stations, except D1. The concentrations of nitrate, phosphate, and silicate in the surface water column were relatively depressed in August 2007 compared with those in July 2005 (Table 1). The vertical distribution of nitrate differed somewhat between the summers of 2005 and 2007 (Figure 4). In 2005, nitrate concentrations clearly increased below a depth of 20 m at stations D2, D3, and D5, whereas the nitrate concentrations in 2007 increased at depths below 30 m.

In 2005, an extremely high concentration of Chl *a* (5.5 mg m^{-3}) was measured at a depth of 41 m at station D3, where the eddy centre was located (Figure 5). An SCM, with a Chl *a* concentration of 2.5 mg m^{-3}, was also observed at the edge of the eddy (stations D2 and D4). The depth-integrated Chl *a* concentration was estimated to be 90.6 mg m^{-2} at the eddy core, much higher than at the eddy edge (Table 1). Moreover, the Chl *a* concentration represented by the pico-fraction (<5 μm) accounted for just 31% of the total Chl *a* concentration (Table 1). In 2007, Chl *a* concentrations were relatively low (<1.5 mg m^{-3}) at all stations, and there was no well-developed SCM at any station (Figure 5). Depth-integrated Chl *a* concentrations were generally lower at all stations in 2007 than in 2005 (Table 1). Overall, the results indicated that the nutrient and Chl *a* distributions differed between 2005 and 2007, according to the location of the UWE, which seems to determine the vertical distribution of nutrients and Chl *a*.

Discussion

Mesoscale eddies play important roles in controlling the biomass and productivity of plankton populations (Landry *et al.*, 1998; Vaillancourt *et al.*, 2003), nutrient flux, and new production (Jenkin, 1988; McGillicuddy and Robinson, 1997; Law *et al.*, 2001; Ledwell *et al.*, 2008) in marine ecosystems. Although the UWE is a well-known oceanographic phenomenon (Chang *et al.*, 2004), little is known about the impact of the UWE in controlling the vertical distributions of nutrients and Chl *a* in the UB. Recently, satellite images of enhanced phytoplankton biomass in surface waters within the eddy ring have been reported in the UB (Ahn *et al.*, 2005; Hyun *et al.*, 2009). Kang *et al.* (2004) also revealed that the UWE-related front and nutrient upwelling strongly influenced the mesoscale latitudinal heterogeneity of plankton through both physical and biological processes in the southwestern East Sea. However, no direct evidence exists of the SCM associated with the upward flux of nutrients at the centre of the UWE. As the surface water column in summer is strongly stratified and nutrient-depleted (Figures 3 and 4), evaluating the impact of the UWE in regulating nutrients and phytoplankton biomass and elucidating the ecological role of the UWE during summer are of particular interest.

Subsurface chlorophyll maximum coupled to the UWE

A striking feature observed in summer 2005 was that an SCM layer with an exceptionally high concentration of Chl *a* appeared at the centre of the UWE (Figure 5). This high Chl *a* concentration may not be supported by ambient nutrient concentrations in the surface mixed layer, so an episodic flux is essential for supporting a high plankton biomass. In summer 2005, the UWE was located within the sampling stations, with its core at station D3 and its edge at stations D2 and D4 (Figure 3). At the eddy core, an extremely high concentration of Chl *a* of 5.5 mg m^{-3} was measured below the surface mixed layer, with values of ~2.5 mg m^{-3} at the eddy edge (Figure 5, Table 1). In summer 2007, however, sampling stations were located outside the UWE

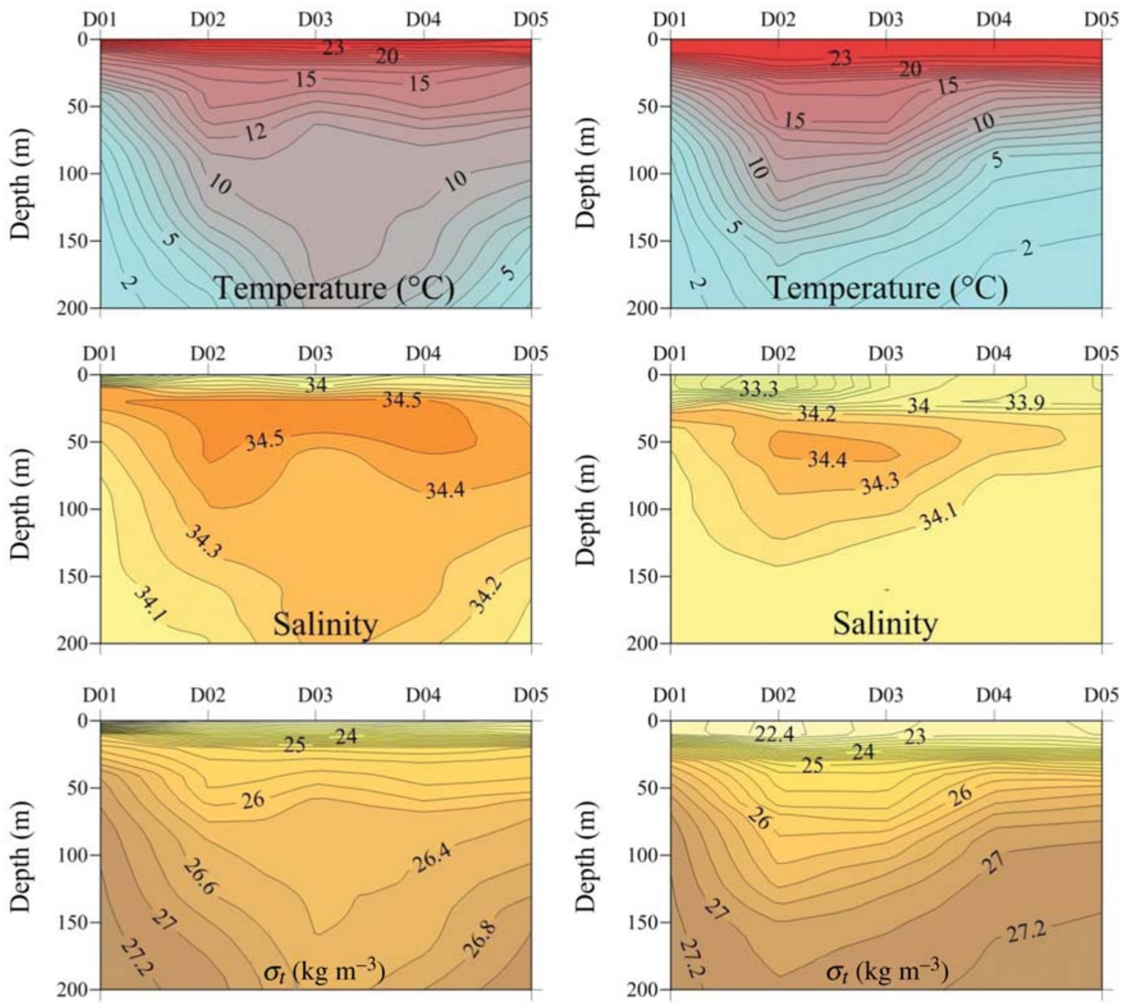

Figure 3. Vertical distributions of temperature, salinity, and density measured in July 2005 (left) and August 2007 (right). Note that the mode-water structure characterized temperature, salinity, and density in 2005.

Table 1. Depth-integrated inventories of inorganic nutrients and Chl *a* down to the euphotic depth (60 m) during the UWE in summer 2005 and without the UWE in summer 2007.

					Nutrients (mmol m^{-2})			Chl *a* (mg m^{-2})	
Year	**Environmental setting**	**Station**	**Mixed layer (m)**	**SCM depth (m)**	**Nitrate**	**Phosphate**	**Silicate**	**Total**	**<5 µm**
2005	With eddy	D1	7	35	172	19.2	579	18.2	13.6
		D2	6	38	168	7.8	665	44.1	33.1
		D3	6	41	114	6.9	590	90.6	28.2
		D4	6	44	150	13.3	524	45.1	37.1
		D5	9	30	123	23.0	1213	38.3	28.7
2007	Without eddy	D1	13	28	158	31.0	524	17.9	14.5
		D2	19	34	51.1	9.5	242	19.4	16.1
		D3	16	33	68.3	13.0	235	28.3	20.4
		D4	15	36	84.7	13.2	189	15.5	12.1
		D5	14	40	43.1	11.9	182	18.8	16.2

and there were no such high concentrations of Chl *a* at any station. Therefore, the UWE may have significantly influenced the distribution of phytoplankton biomass in summer.

An extraordinary phytoplankton biomass in the subsurface layer has been observed frequently at the centre of anticyclonic eddies and might be sustained by the vertical nutrient flux into the SCM layer (Mizobata *et al.*, 2002; Sweeney *et al.*, 2003; Peterson *et al.*, 2005; McGillicuddy *et al.*, 2007; Bibby *et al.*, 2008; Ledwell *et al.*, 2008; Li and Hansell, 2008). Martin and Richards (2001) proposed that the upwelling produced by

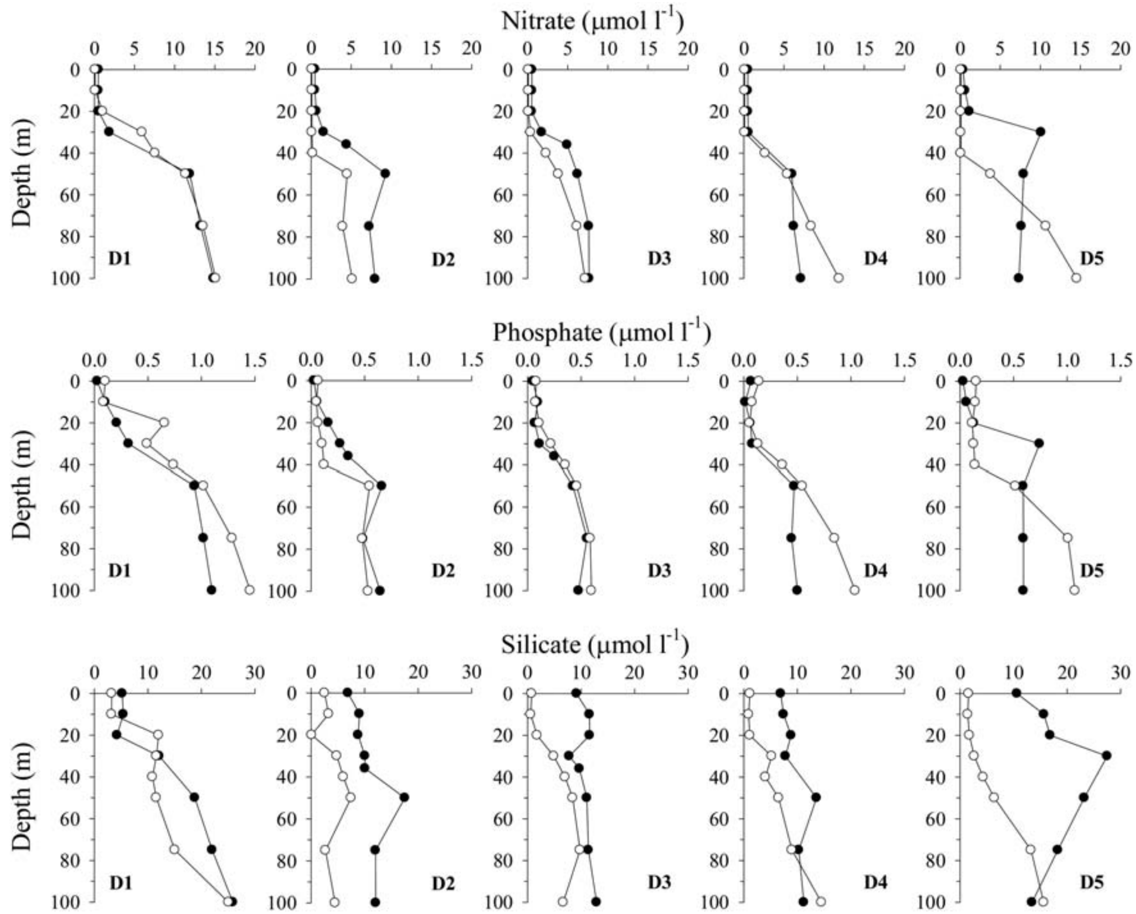

Figure 4. Vertical distributions of nitrate, phosphate, and silicate measured in (filled circles) July 2005 and (open circles) August 2007.

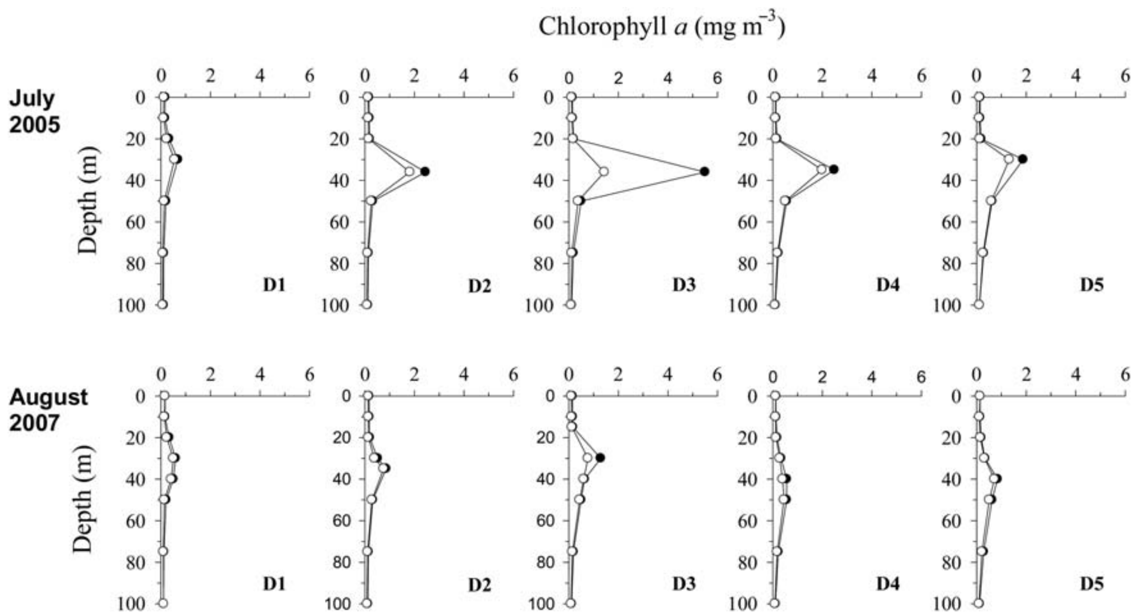

Figure 5. Vertical profiles of Chl *a* concentration (mg m^{-3}) in July 2005 and August 2007. Filled circles represent the total Chl *a* concentration, and open circles the Chl *a* concentration of phytoplankton <5 µm.

geostrophic circulation resulting from perturbation of the circular eddy was a possible mechanism for vertical nutrient transport within an anticyclonic eddy. In addition, McGillicuddy *et al.* (2007) suggested that eddy–wind interactions enhanced the vertical nutrient flux in mode-water eddies. Ledwell *et al.* (2008) reported that tracer released in a mode-water eddy moved upwards at a rate of 0.4 m d^{-1}, and that the upward flux of dissolved inorganic nitrogen supplied about 40% of the nitrogen flux required for new production in the Sargasso Sea.

Based on the vertical structures of temperature and salinity (Figure 3), the UWE observed in summer 2005 was determined to be an ITE, characterized by a subsurface lens of relatively homogeneous water with a temperature of 10°C and salinity of 34.3. The ITE has similar physical characteristics to a mode-water eddy, defined as a thick lens of water that deepens the main pycnocline, and shallowing the seasonal pycnocline (McGillicuddy *et al.*, 1999). Mode-water eddies have been observed sporadically in the North Atlantic (McGillicuddy *et al.*, 1999, 2007; Sweeney *et al.*, 2003; Li and Hansell, 2008). They are characterized by increased nutrient concentration, with enhanced chlorophyll concentration and primary production at the base of the euphotic zone (McGillicuddy *et al.*, 1999; Sweeney *et al.*, 2003; Li and Hansell, 2008). Therefore, the exceptionally enhanced phytoplankton biomass observed at the centre of the UWE (Figure 5) might have been produced by the vertical nutrient flux within a mode-water eddy, as suggested by McGillicuddy *et al.* (2007) and measured by Ledwell *et al.* (2008).

Ecological role of the UWE in summer

One of the prominent ecological properties of the UB is that primary production and the phytoplankton biomass are always higher there than in any other part of the East Sea (Yamada *et al.*, 2005; Yoo and Park, 2009). The higher phytoplankton biomass and primary production in the UB are intriguing because the UB is not influenced by the discharge of any large rivers (Hong *et al.*, 1997), and the Tsushima Warm Current flowing into the UB is characterized as a low-nutrient water mass, with nitrate concentrations <3 μmol l^{-1} year-round (Yoo and Kim, 2004). Recently, Hyun *et al.* (2009) revealed that the combination of enhanced biological production by the southwest wind-driven coastal upwelling and its subsequent entrainment by the UWE delivers highly productive coastal waters into the central UB. In summer 2005, however, coastal upwelling was confined to within ~20–30 km of the coast. Our sampling in summer 2007 was carried out before the upwelled water was transported to the centre of the UB (satellite images not shown), so we assume that nutrient-rich coastal water was not transported to our sampling stations. Without a notable horizontal process (i.e. upwelling) delivering substantial quantities of nutrients to the centre of the basin, the strong stratification in the surface water column in summer further inhibits the supply of nutrients from nutrient-enriched deep water below the pycnocline (Figures 3 and 4), so suppressing primary production. Actually, surface Chl *a* concentrations were always low, <0.3 mg m^{-3} in 2005 and 2007 (Figure 5).

Several lines of evidence have indicated that the occurrence of the UWE plays an important ecological role in supporting enhanced phytoplankton biomass and controlling the composition of phytoplankton in the highly stratified, nutrient-depleted surface water column in summer. First, nutrient concentrations were markedly higher in 2005 than in 2007 (Figure 4, Table 1) as a consequence of the upward flux of inorganic nutrients with ITE formation. Therefore, the phytoplankton biomass in 2005 was much higher than in 2007 (Figure 5, Table 1). Second, phytoplankton organisms larger than 5 μm made up >70% of the total phytoplankton biomass in the SCM layer of the eddy core (Figure 5). Analysis of phytoplankton pigments indicated that fucoxanthin, an indicator pigment of diatoms, was the dominant pigment in the SCM layer of station D3 (KORDI, 2007). Microscopic analysis further revealed that large diatoms (*Chaetoceros* spp.; data not shown) made up most of the phytoplankton in the SCM layer at the eddy core. These results were well explained by the reduced silicate concentration at SCM depth (Figure 4). The community structure of plankton in terms of size and species composition largely determines the downward flux of particulate organic carbon (Karl, 1999; Cotner and Biddanda, 2002). As large diatoms produced in the surface water are the ultimate source of export flux (Boyd and Newton, 1995), the occurrence of larger diatoms at the eddy core of the UB resulting from the existence of the UWE in summer is also important for enhancing carbon mineralization on the deep seabed (>2500 m deep) in the UB.

Acknowledgements

The work was primarily supported by an endowment project of the Korea Ocean Research and Development Institute (KORDI) (PE98564 to DK; PE98561 to SY), and partly by a grant from the EAST-1 programme of the Korean Ministry of Land, Transport, and Maritime Affairs (to J-HH) and the Korea Polar Research Institute, KORDI (PN 10020 to EJY). We thank the captain and crews of the RV "Eardo" for their support during shipboard operations.

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