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Bering Sea cyclonic and anticyclonic eddies observed during summer 2000 and 2001

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Abstract

Using satellite altimeter and ship data, Bering Sea cyclonic and anticyclonic eddies were observed in summer 2000 and 2001 to examine their biological, chemical and physical structures. Results from the ship transect revealed the interactions between the physical and biological conditions of Bering Sea eddies. At the center of a cyclonic (anticlockwise) eddy, upwelling was transporting nutrient ($NO_3 + NO_2$) rich water (>25 μM) to the surface, which resulted in relatively high chlorophyll *a* concentrations (>1.0 mg m^{-3}) developing under the pycnocline. In contrast, in the center of an anticyclonic (clockwise) eddy there was downwelling. This downwelling of surface warm water was destroying a cold layer (at about 150 m depth) caused by winter convection. However, around the periphery of the anticyclonic eddy the isopycnals were tilted up and nutrient-rich water was being transported along with them up into the euphotic zone, so that high chlorophyll *a* concentrations were being developed above the pycnocline inside the anticyclonic eddy. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Bering Sea, well known as a high productivity area, consists of wide, shallow continental shelves (<200 m) and a deep basin (Fig. 1). The continental slope between the shelf and the basin is a part of the highest productivity area, the so-called ‘Green Belt’ (Springer, McRoy, & Flint, 1996). The Bering Slope Current, which generates eddy-like features, flows northwestward along the eastern continental slope (Kinder, Coachman, & Galt, 1975), and complicated currents in this region have been observed by numerous researchers using various methods (Cokelet & Stabeno, 1997; Kinder et al., 1975; Kinder, Schumacher, & Hansen, 1980; Schumacher & Reed, 1992; Stabeno & Reed, 1994). Despite these studies, physical conditions in the Bering Sea are poorly known (Cokelet & Stabeno, 1997).

From 1992 to 1994, Cokelet and Stabeno (1997) observed anticyclonic eddies that propagated westward and remained stationary for several weeks in the southeastern Bering Sea basin. Mooring data revealed characteristics of anticyclonic eddies, which penetrated to depths of at least 500 m. The authors inferred that the eddies preserve pollock eggs from predation. Altimeter data have been used to study Bering Sea eddies (Okkonen, 1993, 2001). Okkonen (2001) showed that mesoscale eddy activity has a seasonal cycle and assumed that eddies in the Bering Sea are contributing to cross-slope exchange of nutrients and biota. According to our analysis using SeaWiFS (Sea-viewing Wide Field-of-view Sensor), chlorophyll *a* concentration images, and TOPEX/POSEIDON sea surface height anomaly images, a ring of high chlorophyll *a*

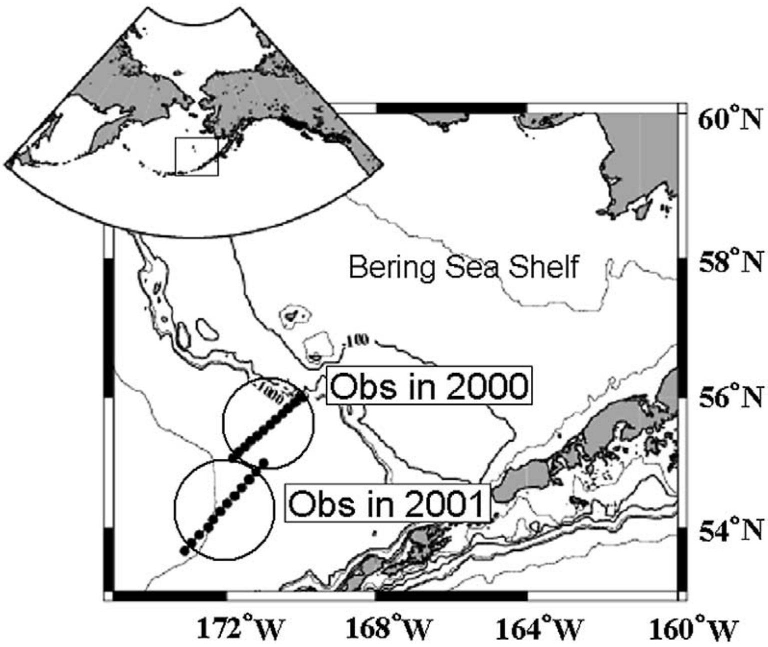

Fig. 1. Study area and observation lines in 2000 and 2001.

concentration existed off the Fox Islands in a region with a 0–8 cm positive sea surface height anomaly (Fig. 2). This indicates that eddies have an influence on primary production in the Bering Sea. Nevertheless only one previous study has described the biological and chemical characteristics of eddies in the western Bering Sea (Sapozhnikov, 1993). Sapozhnikov observed a renewal of waters in the oxygen minimum layer and upwelling of deep waters by strong anticyclonic eddies along the shelf break in adjacent cyclonic circulation. He argued that the intensity of eddy formation determines not only autumnal primary production, but also the quantity of nutrients. Our objectives in this study are to reveal the biological, chemical, and physical structures of Bering Sea eddies, and to understand the eddies' effects on primary productivity in the Bering Sea Green Belt.

2. Data and method

TOPEX/ERS2 data from the CCAR (Colorado Center for Astrodynamics Research) Altimeter Data Sets (http://www-ccar.colorado.edu/research/topex/html/topex.html) were used to detect the daily positions of Bering Sea eddies. After determining the positions of the eddies, conductivity, temperature, and depth (CTD) casts were taken on two cruises (from August 1 to 2, 2000, and from July 26 to 27, 2001) by T/S *Oshoro-Maru*, Faculty of Fisheries, Hokkaido University, and oceanographic stations were occupied in the vicinity of the southeastern Bering Sea slope to observe the cyclonic (anticlockwise) eddy and the anticyclonic (clockwise) eddies in 2000 and 2001, respectively (Fig. 3). The CTD had dual temperature and conductivity sensors, and the data were averaged over 1 m intervals. Conductivity was measured using a salinometer calibrated with standard seawater. Seawater samples were collected in Niskin bottles on the CTD-Rosette system (Neil Brown Mark IIIB) from the surface to a depth of 500 m in 2000 and 1500 m in 2001. Using these seawater samples, concentrations of chlorophyll *a* and nutrients ($NO_3 + NO_2$) were

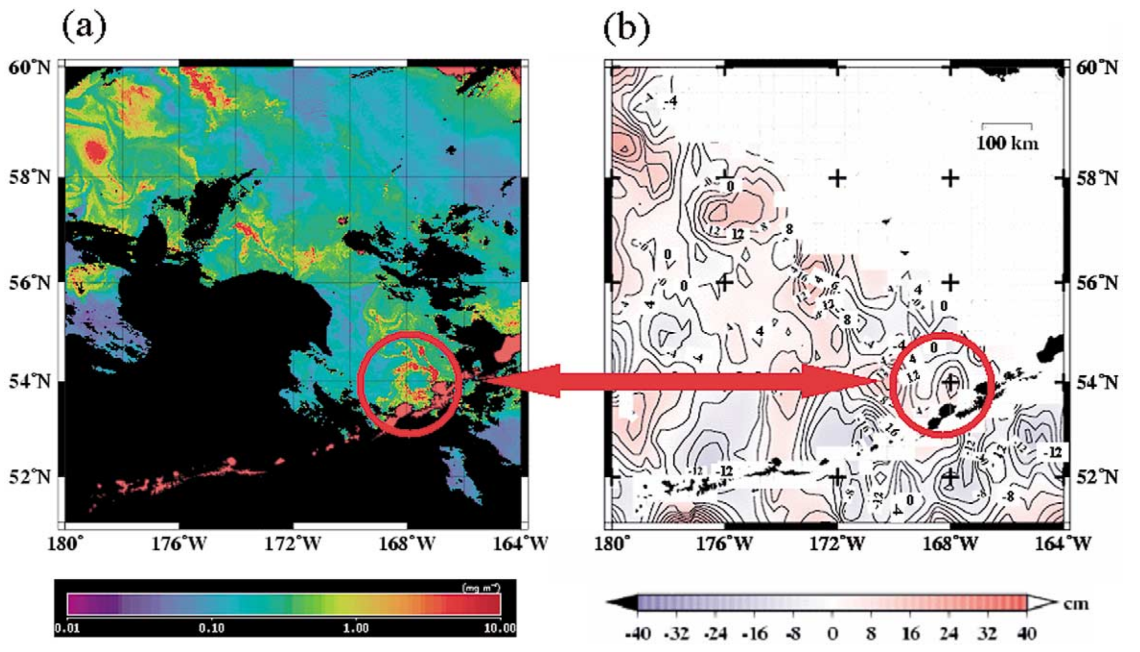

Fig. 2. (a) SeaWiFS Chlorophyll *a* concentration image (June 26, 2000); (b) TOPEX/POSEIDON sea surface anomaly image (Cycle 286, June 21–29, 2000).

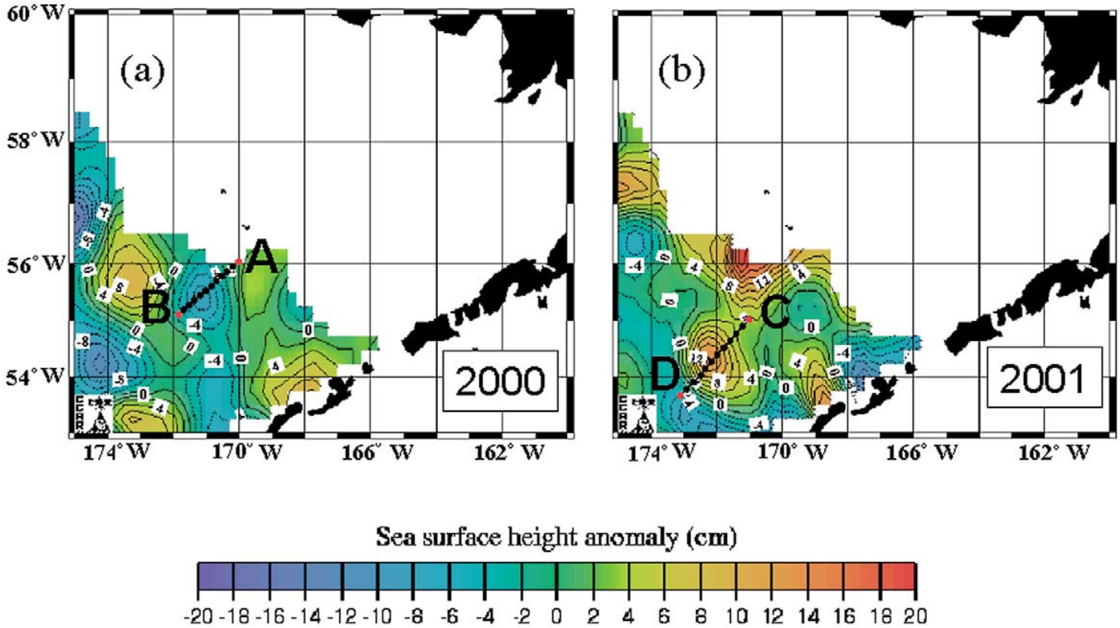

Fig. 3. (a) Sea surface height anomaly map on August 1, 2000 and oceanographic stations in 2000; (b) sea surface height anomaly map on July 26, and oceanographic stations in 2001.

measured. For the geostrophic current calculation, a reference level of 1500 dbar was selected (Kinder et al., 1975). In 2000, however, the weather was too severe (low pressure of 976 hPa located near the observation line) for deep observations and so a reference level of 500 dbar was selected.

3. Results

3.1. Cyclonic (anticlockwise) eddy

Fig. 3(a) shows the sea surface height anomaly map derived from TOPEX/ERS2 altimeter data in the Bering Sea basin on August 1, 2000. Three cyclonic eddies (at 56.8°N, 175°W; 54.5°N, 174.5°W and 55.5°N, 171°W) and two anticyclonic eddies (at 55.5°N, 173°W and 53°N, 173°W) were distributed in the Bering Sea basin. We selected the cyclonic eddy at 55.5°N, 171°W, which was located closest to the Green Belt. This cyclonic eddy, which was determined to be a negative sea surface height anomaly (0 to 4 cm^2), was observed from August 1 to 2 in 2000 (Fig. 3(a), A–B line). While geostrophic velocity at the surface near 55.7°N between this eddy and the shelf edge was about 15 cm s^{-1} northwestwardly, counter flow at the surface near 55.2°N was about 7.5 cm s^{-1} southeastwardly (Fig. 4(c)). Thus, this eddy was cyclonic, about 140 km in diameter and was being influenced by the Bering Slope Current.

The thermal structure showed that there was a cold water layer (<3 °C), correlated with the previous winter's climatic conditions (Odate, Shiga, Saitoh, Miyoi, & Takagi, 1999), at depths of ~100–150 m inside this eddy, but not at its center (Fig. 4(a)). At the center of this eddy, 55.1°N–55.8°N, the distribution of water density σ_θ(kg m^{-3}) shows the isopycnals were uplifted from depths of 100–50 m indicating upwelling was occurring (Fig. 5(c)). As a result of this upwelling, the nutrients (NO_3 + NO_2) were being transported from depths of ~100 m to the surface at about 55.5°N (Fig. 5(a)). Throughout the surface layer, nutrient

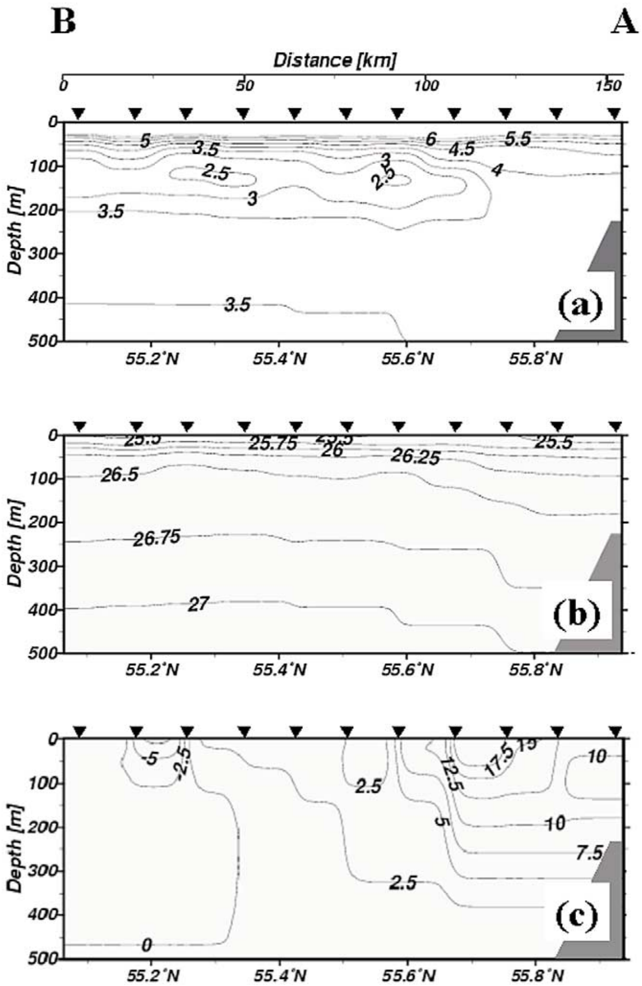

Fig. 4. Cross sections of A–B line (the structure of cyclonic [anticlockwise] eddy) in 2000 (black triangles are the oceanographic stations). (a) Potential temperature (°C) (0–500 m), (b) water density σ_θ (0–500 m), (c) geostrophic velocity (cm s^{-1}) (0–500 m).

concentrations were low. Notably, there was a nutrient minimum (<7 μM) along the shelf edge at 55.8°N (Fig. 5(a)). Inside the eddy, high chlorophyll *a* concentrations were observed beneath the pycnocline at 55.35°N–55.6°N (~1.0 mg m^{-3}) and between the eddy and the shelf edge (~1.2 mg m^{-3}) (Fig. 5(b) and (c)).

3.2. Anticyclonic (clockwise) eddy

Fig. 3(b) shows the sea surface height anomaly map derived from TOPEX/ERS2 altimeter data in the Bering Sea basin on July 26, 2001. Two cyclonic eddies can be seen in the Bering Sea basin (centered at 56.4°N, 174.5°W and at 53.5°N, 173°W) and three clockwise eddies (centered at 57.3°N, 175°W; 54.4°N, 172°W and 56°N, 171°W). We selected the anticyclonic eddy at 54.4°N, 172°W for the study, which was clearly defined as a positive sea surface height anomaly (0–12 cm). This anticyclonic eddy was observed from July 26 to 27 in 2001 (Fig. 3(b), C–D line). According to our geostrophic velocity calculations, its rotational speed was ~15–20 cm s^{-1} at the surface and its diameter was about 150 km. Geostrophic currents

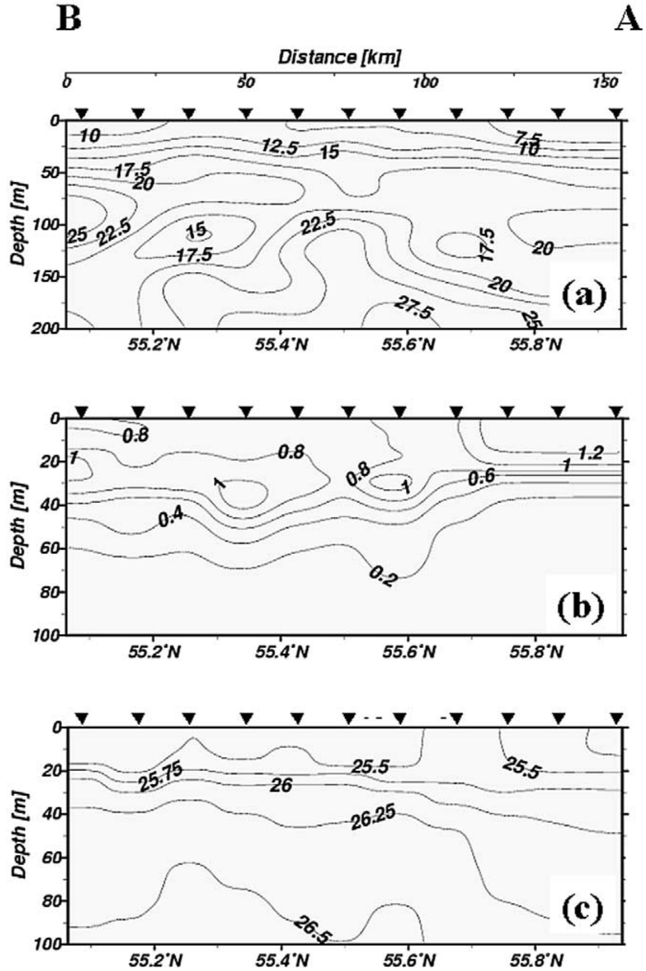

Fig. 5. Cross sections of A–B line (chlorophyll *a* and nutrient distribution) in 2000 (black triangles are the oceanographic stations). (a) (NO_3 + NO_2) concentration of A–B line (μM) (0–200 m), (b) chlorophyll *a* (mg m^{-3}) concentration of A–B line (0–100 m), (c) water density σ_θ (0–100 m).

>10 cm s^{-1} were flowing northwestwards at about 53.95°N and 54.2°N counter to southeastwardly currents of >10 cm s^{-1} at about 54.45°N and 54.8°N (Fig. 6(c)). Hence, this figure shows 'double-core flow' for this eddy. Cold water <3 °C was observed at 150 m depth around this anticyclonic eddy (Fig. 6(a)). Inside this eddy, there was no water colder than 3.2 °C. Isotherms were depressed at depths of 400–500 m, and water warmer than 3.75 °C accumulated at depths from 300 to 500 m. Water density σ_θ (kg m^{-3}) shows that the isopycnals were bowed down inside the eddy indicating downwelling (in contrast to the upwelling seen within the cyclonic eddy) (Fig. 6(b)). This downwelling extended to 500 m depth, and the eddy penetrated to 1000 m (not shown). In the center of this eddy, there were low nutrient and low chlorophyll *a* concentrations (<0.75 mg m^{-3}) (Fig. 7). However, nutrient-rich deep water was present where the isopycnals were tilted upwards along the edge of the anticyclonic eddy (Fig. 7(a) and (c)), and there high chlorophyll *a* concentrations (>2 mg m^{-3}) were observed at 54°N and 54.5°N above the pycnocline inside the eddy (Fig. 7(b)).

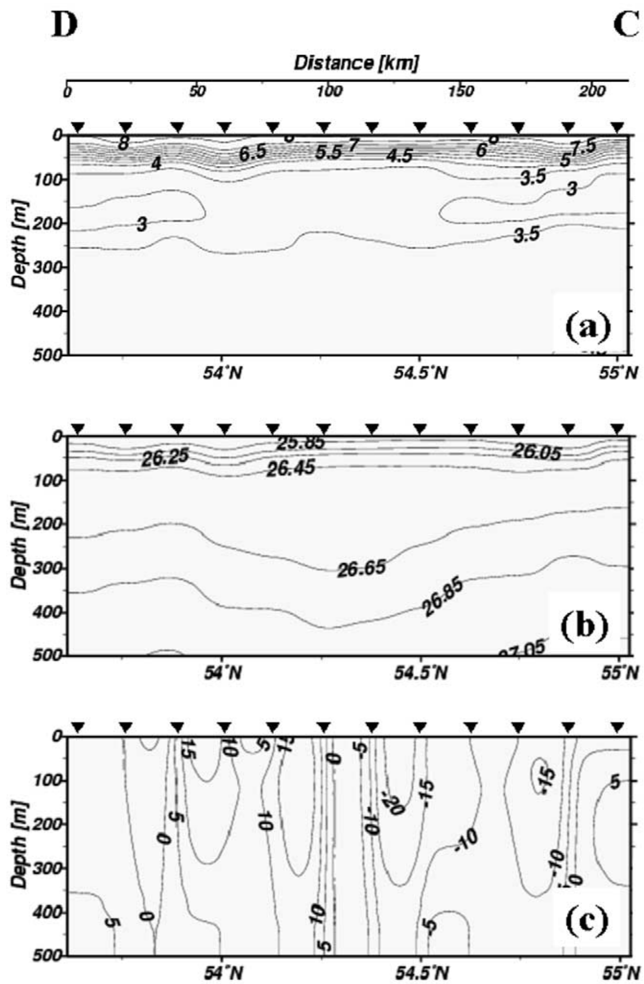

Fig. 6. Cross sections of C–D line (the structure of anticyclonic [clockwise] eddy) in 2001 (black triangles are the oceanographic stations). (a) Potential temperature (°C) (0–500 m), (b) water density σ_θ (0–500 m), (c) geostrophic velocity (cm s^{-1}) (0–500 m).

4. Discussion

4.1. Physical structure and temperature–salinity (T–S) relationship

The data sets of the eddy observations in summer 2000 and 2001 reveal some interesting characteristics. The cool pool of water resulting from the previous winter's convection, which is normally found at ~150 m (Cokelet & Stabeno, 1997; Kinder et al., 1975), is disrupted by eddy circulation. The upwelling at the center of the cyclonic eddy had displaced the water in winter-induced temperature minimum layer toward the fringes of the eddy generating a cold annular core. In contrast, the downwelling at the center of the anticyclonic eddy had carried upper-layer water down, once again displacing the cold layer towards the fringes of the eddy, but this time generating a warm core.

Temperature and salinity diagrams of cyclonic and anticyclonic eddies (Fig. 8(a) and (b)) show similar features. Temperature was affecting water density between the surface and 100 m, whereas salinity was

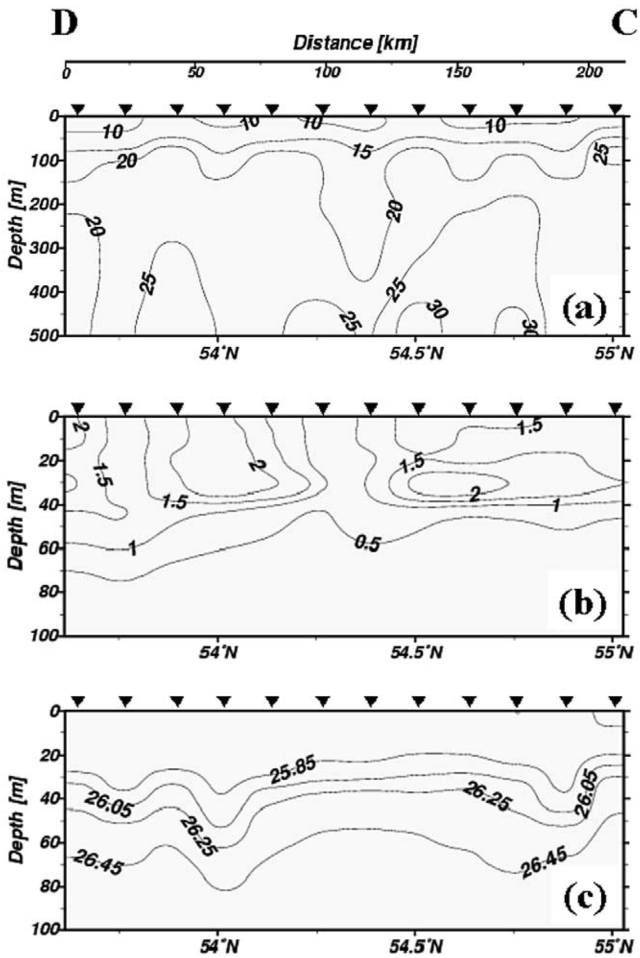

Fig. 7. Cross sections of C–D line (chlorophyll *a* and nutrient distribution) in 2001 (black triangles are the oceanographic stations). (a) (NO_3 + NO_2) concentration of C–D line (μM) (0–200 m), (b) chlorophyll *a* (mg m^{-3}) concentration of C–D line (clockwise[anticyclonic] eddy) in 2000 (0–100 m) (c) water density σ_θ (0–100 m).

affecting the density from 150 to 1000 m. A temperature minimum at 150 m, which corresponds to the deep minimum characteristics of the Bering Sea basin, was at a σ_t of ~26.6 kg m^{-3}. Fig. 8(a) shows that shelf water with relatively low temperatures (3–8 °C) and salinities (32.25–33.25) was distributed in the cyclonic eddy. In Fig. 8(b), the T–S relationship is clustered at 300–1000 m depths and σ_t values are 26.6–27.5 kg m^{-3}. Especially, the temperature at 300 m was near the depth of the deep temperature maximum, which is correlated with the warm Alaskan Stream (Cokelet & Stabeno, 1997).

4.2. Physical forcing to biological and chemical structures

Upwelling at the center of the cyclonic eddy caused not only destruction of the cold water layer, but also enhanced the nutrient supply to the euphotic zone. This enhancement of the nutrient supply stimulated phytoplankton growth and resulted in the production of relatively high chlorophyll *a* concentrations (~1.0 mg m^{-3}) under the pycnocline (McGillicuddy & Robinson, 1997). In addition, convergence results in the

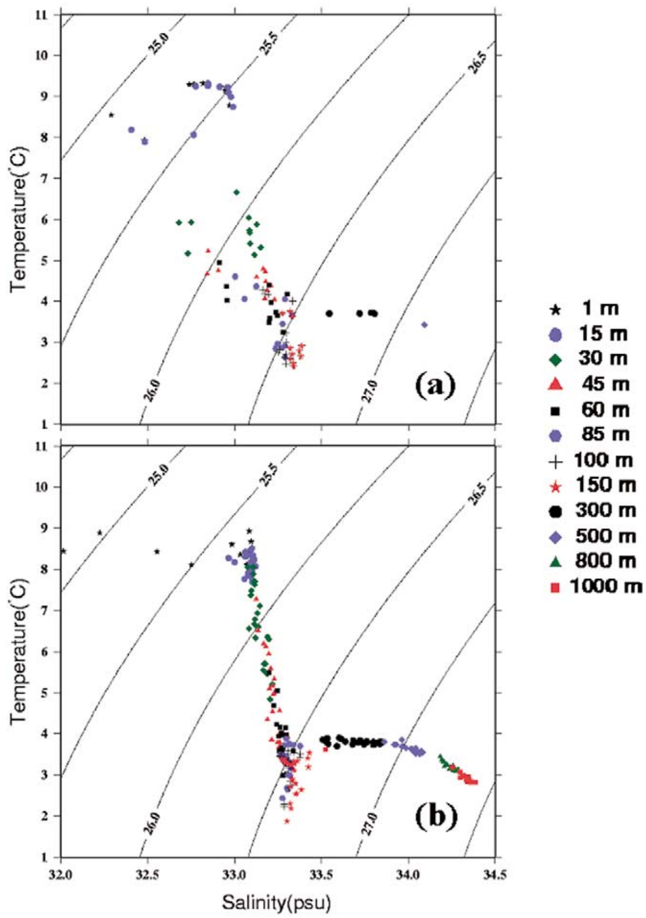

Fig. 8. T–S diagram. (a) Cyclonic eddy in 2000, (b) anticyclonic eddy in 2001.

accumulation of nutrients between the cyclonic eddy and the Bering Slope current (i.e. along the shelf edge). At the shelf edge, the coincidence of a low nutrients concentrations (<7 μM) with high chlorophyll *a* concentrations (>1.2 mg m^{-3}) in 2000 (Fig. 5(a) and (b)) indicates that nutrients were beginning to limit primary production.

McGillicuddy and Robinson (1997) showed no ecosystem response to downwelling in their schematic representation of the eddy mechanism. According to SeaWiFS and TOPEX/POSEIDON images, however, the presence of an anticyclonic eddy, which has a downwelling system at its center, may affect primary production in the Bering Sea Green Belt (see Fig. 2). Some of the results (Fig. 7(a) and (c)) of our study show that nutrient rich water is being transported upwards along the up-bowed isopycnals at the edge of the anticyclonic eddy. In the surface layer of the anticyclonic eddy, convergence associated with the Bering Slope Current will occur, and there the phytoplankton will be utilizing the nutrients imported into the euphotic zone by anticyclonic eddy. As a result of this utilization, we detected a zone of relatively high chlorophyll *a* concentration (~2.0 mg m^{-3}) at 54°N and 54.6°N above the pycnocline inside the anticyclonic eddy (Fig. 7(b) and (c)).

Fig. 9 conceptually illustrated the relationships between Bering Sea cyclonic and anticyclonic eddies, nutrient ($NO_3 + NO_2$) and phytoplankton distributions. Upwelling occurs at the center of a cyclonic eddy

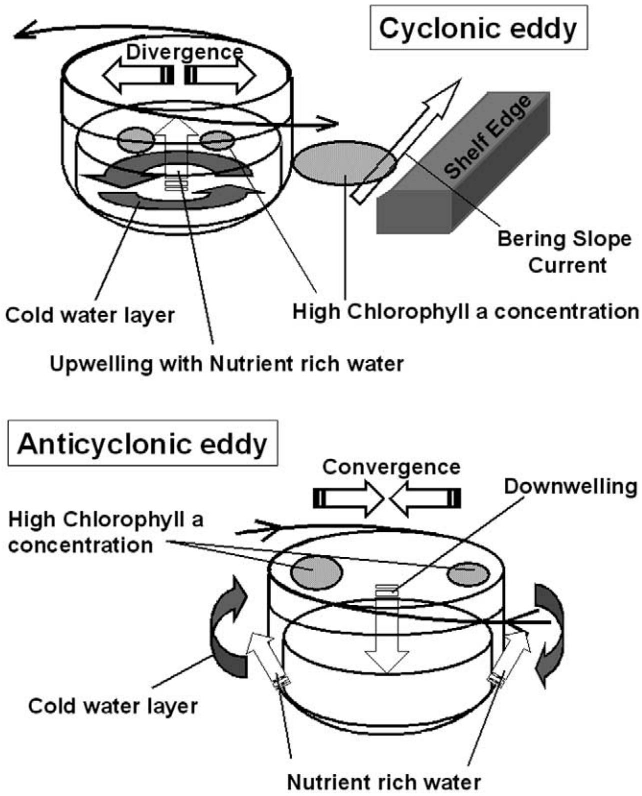

Fig. 9. Schematic representation of the structure of cyclonic and anticyclonic Bering Sea eddies.

and along the edge of an anticyclonic eddy. The difference in the locations of the upwelling affects the distribution of both the cold water layer and the phytoplankton. A cold water layer is maintained within a cyclonic eddy, but is pushed to the periphery of an anticyclonic eddy. High chlorophyll *a* concentrations occur under the pycnocline of a cyclonic eddy, but above the pycnocline of the anticlockwise eddy. The characteristics of the cyclonic and anticyclonic eddies observed in our study are summarized in Table 1. The lifetimes and frequency of occurrence of Bering Sea eddies are still unknown. In future studies, we plan to survey Bering Sea eddies using satellite altimeter data and estimate their contributions to cross-slope exchanges and the Green Belt using an ocean circulation model that can present eddy generation and development processes.

Table 1
Characteristics of Bering Sea cyclonic and anticyclonic eddies

Characteristics	Cyclonic eddy	Anticyclonic eddy
Upwelling	Center	Edge
Cold water layer	Inside	Periphery
High chlorophyll *a* concentrations	Above pycnocline	Beneath pycnocline

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The authors thank the captain and crew of the T/S *Oshoro-maru*, Faculty of Fisheries, Hokkaido University, and all colleagues involved in this cruise, for their efficient help at sea. A part of this study is supported by the National Space Development Agency of Japan (NASDA) through the program of Arctic Research projects using IARC (International Arctic Research Center)-NASDA Information System (INIS) and Satellite Data. Taking this opportunity, I appreciate all the help and support of the concerned research institutes, including UAF and IARC. Cross sections of Bering Sea eddies were drawn using the Ocean Data View and some figures were described using the Generic Mapping Tool (GMT).

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