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The Warm Eddy in the East Korean Bight

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Abstract : Sea surface temperature derived from infrared images of NOAA satellites showed a warm eddy in the East Korean Bight(EKB) or Donghan Man during the winter 1997~2000. To describe the warm eddy in the EKB, hydrographic data collected in 1934 and 1936 were also analyzed. The center of the warm eddy was located at about 39°N and 129°E. The temperature and salinity of the eddy was about 4.0°C and 34.0 psu, respectively, at 100 m depth. The eddy rotated anticyclonically with a geostrophic current speed of about 20 cm/s. The mean state calculated from the data of 1922~1960 showed the existence of a warm eddy over the EKB in winter. The eddy persists until late spring, and disappears from the previous location in summertime, only to be seen again in autumn.

Key words : Warm eddy, East Korean Bight, MCSST, Time variation of water characteristics.

1. Introduction

The bottom topography of the East Sea may be divided approximately into two parts along the 40°N parallel (Fig. 1). The northern half, the Japan Basin, is comparatively flat and deep. The southern part of the East Sea has two smaller basins. One is the Ulleung Basin located in the western side of the East Sea and the other is the Yamato Basin. The East Korean Bight(EKB) or Donghan Man is located off the mid eastern coast of Korea. The EKB has a continental shelf wider than the other regions off the eastern coast of Korea, and the deepest part is connected to the Japan Basin deeper than 3000 m. The southern and eastern part of the EKB called the Korea Plateau is relatively shallow. Therefore, the shape of the bottom topography of the EKB can be described as a bowl-like, with its center around 39°N, 129°E.

The southern part of the East Sea is affected by the Tsushima Warm Current (TWC), which is originated from the Kuroshio and carries warm and saline water into the East Sea. The TWC passes the Korea Strait and branches out in several directions. One of the branching currents is the East Korean Warm Current(EKWC) that steers to the north along eastern coast of Korea. The EKWC is separated from the coastline at around 38~40°N and flows to the northeast. The EKWC meets the North Korean Cold Current(NKCC) at around 40°N and forms a subpolar front.

Infrared images taken from the NOAA satellite show many mesoscale eddies along the subpolar front. By using satellite data, Min *et al.* (1995) analyzed the distribution of eddies off the east coast of Korea from 1987 to 1991. They found a mesoscale eddy of 100~200 km in diameter between Mukho and Wonsan and named it "the Sokcho Eddy". Shin *et al.* (1995) observed the southern part of a warm eddy in the northwest of Ulleung Island in March, May and June 1992. The same eddy was observed by Lee *et al.* (1995) during a different cruise in May 1992. The center of the warm eddy observed in spring of 1992 was located at about 38°N, 130°E. Kim (1995) explained the generation of the Sokcho Eddy using two numerical experiments that considered the effects of the strong offshore winds and the polar front. Suh *et al.* (1999) reported a recurring eddy observed with satellite ocean color and sea surface temperature images in the EKB in spring and autumn.

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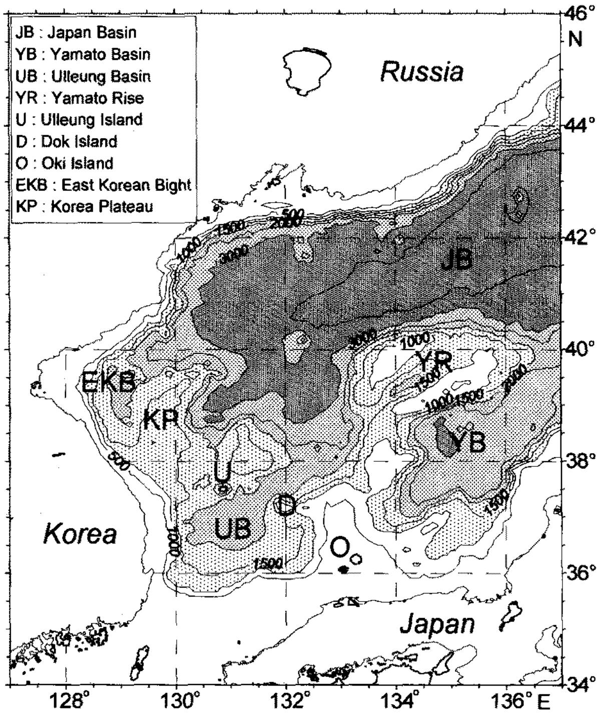

Fig. 1. Bottom topography of the East Sea with depth in meters. The EKB is located in the mid eastern part of Korea.

They called the eddy "the Korea Coastal Cold Eddy" (KCCE), because the sea surface temperature at the center of the eddy was lower than that of the surrounding water.

The existence of the eddy in the EKB is commonly acknowledged. The internal structure and variation of the eddy, however, are not fully understood. Unfortunately, it is impossible to carry out any new field survey on the eddy at the present time, because the region where the eddy appears is the North Korean territory. Only the use of observed historical hydrographic data is the way to study the eddy. In this study, we analyze the characteristics and variations of the eddy using hydrographic data in the EKB.

2. Data

Sea Surface Temperature(SST) estimated from infrared images taken from NOAA satellites by the Korea Ocean Research and Development Institute (KORDI) was analyzed from January 1997 to March 2000.

To investigate characteristics of the warm eddy, historical hydrographic data was searched for survey data around the EKB. The data observed during February ~March 1934 (The Fisheries Experiment Station 1942) contained the necessary information (Fig. 2). Temperature, salinity and nutrients including dissolved oxygen were measured at predetermined depths from the surface to the bottom (0, 10, 25, 50, 100, 150, 200, 300, 400, 600, 1000 m and bottom), and total 63 stations were surveyed in February 1934.

To investigate a seasonal variation in the EKB, the data observed monthly from February to November 1936 were used (The Fisheries Experiment Station 1937). The averaged data for 1922~1960 (Fisheries Research and Development Agency 1964) were also analyzed to describe a mean phenomenon in the EKB. The maximum observation depth of this data was 200 m.

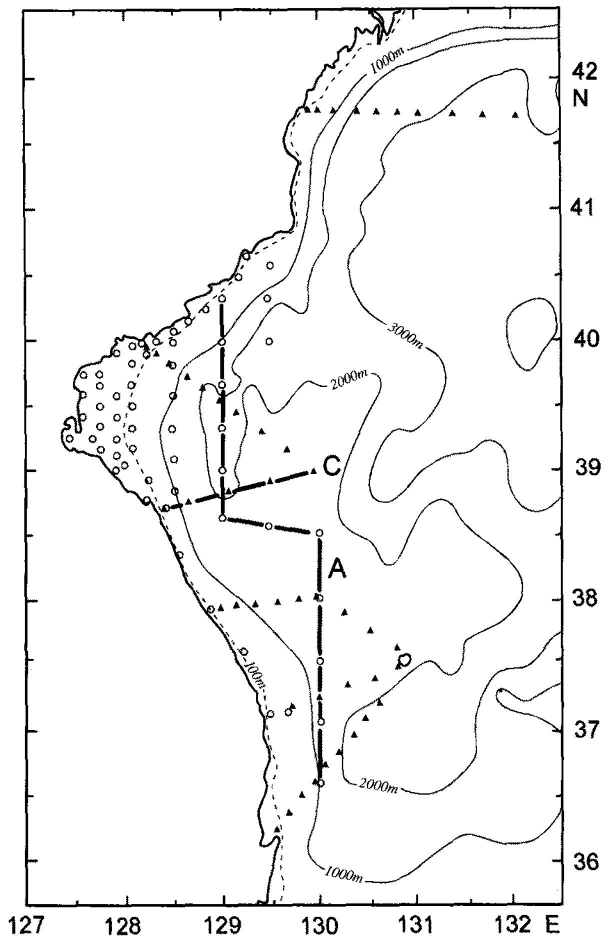

Fig. 2. Map showing hydrographic stations and the bottom topography in meters. The circles and the filled triangles indicate the stations observed in February 1934 and averaged data from February 1922 to 1960.

Although the accuracy of these data was lower than the recent data, they were sufficient for identifying the warm eddy.

3. Infrared images of the EKB in winter

Fig. 3 shows the SST distributions in February from 1997 to 2000. A warm eddy in the EKB was clearly shown in 4 consecutive years indicating the warm eddy is a permanent wintertime phenomenon in the EKB.

In February 1997, the EKWC flowed from the Korean coast at about 37°N and toward the east (Fig. 3 a). The SST of the EKWC was about 10°~12°C The center of the warm eddy in the EKB was located at about 39°00'N and 129°15'E. The eddy's shape was ellipsoid elongated to the zonal direction. Its meridional and zonal diameters were 110 km and 160 km, respectively. The SST of the eddy's interior was 6°C. It was warmer than the surrounding water. The temperature difference between the inner and outer area of the warm eddy was more than 2°C. The only exception was the southwestern part of the eddy where new warm water was being supplied.

The image for February 1998 also showed the warm eddy in the EKB (Fig. 3 b). The warm eddy had a diameter of about 100 km, which was narrower than 1997, and its shape was nearly a circle. The flow pattern of EKWC was different from that in 1997. The EKWC did not flow away from the Korean coast at about 37°N but flowed north along the coastline supplying warm water to the eddy. The SST of the EKWC and the warm eddy were 10~13°C and 6~7°C, respectively. The SST of the northern exterior of the eddy was about 3°C. The location of the warm core was at about 39°00'N and 128°50'E.

In February 1999, the infrared image showed that the warm eddy had elongated on its meridional axis in the EKB (Fig. 3 c). The center of the eddy was located at about 38°50'N, 129°00'E, and its diameter was 160 km on its meridional axis and 100 km on its zonal axis. Most of the EKWC flowed from the coast around 38°N, but a part of it flowed continuously to the northwestward. The SST was 10~11°C in the EKWC and 7~8°C in the center of the eddy.

In February 2000, the location of the warm eddy that was seen in the SST image had departed the coast (Fig. 3 d). The warm streamers originated from the extended EKWC which was separated away from the Korean coast. The shape of the eddy was nearly a circle with a diameter of 110 km and the center was located at about 39°10'N and 129°10'E. The SST was similar to that of 1998, i.e., 10~11°C in the EKWC and 7~8°C in the center of the eddy.

Although the SST, size and shape of the warm eddies were slightly different from each other, all the SST images in February during 1997~2000 consistently showed a warm eddy in the EKB. This strongly suggested that a warm eddy always exist in the EKB during winter seasons.

4. Structure of the warm eddy in winter

To investigate the warm eddy in the EKB, hydrographic data observed in February 1934 was analyzed. The surface temperature decreased with increasing latitude and showed a thermal front around at 38°N (Fig. 4). The EKWC water occupied the southern part of the front. The shape of the warm core was not clear from the surface distributions of temperature and salinity. It was notable that low salinity water appeared in the EKB and the coldest water, less than 1°C, appeared in the westernmost part of the EKB. Fig. 5 shows horizontal distributions of temperature and salinity at 100 m depth. Isolated core water, warmer than the surrounding water, appeared in the EKB. The core was centered at 39°N and 129°E. At the same location, low salinity core water was also evident.

Vertical sections of temperature and salinity along the Line A showed that the warm and saline EKWC water occupied the eddy south of 38°N (Fig. 6). Immediate north of 38.6°N, a bowl-shaped structure was observed. At the center of the bowl structure, the temperature and salinity were homogeneous with 4°C and 34.0 psu, respectively from the surface to the depth of 150 m. The horizontal and vertical distributions of temperature and salinity showed that a warm eddy, with a diameter of about 110 km, existed in the EKB in February 1934. The bowl structure was not clearly definable in the section for dissolved oxygen distribution. The density (σ_t) section showed that the warm eddy affected the vertical structure to more than 1000 m in depth(Fig. 6).

In general, the core water of a warm eddy in the southwestern part of the East sea is warmer (>10°C) and saltier (>34.1 psu) than the surrounding water (An *et al.* 1994; Shin *et al.* 1995). In the EKB, however, the core of the eddy was about 4°C and 34.0 psu for temperature

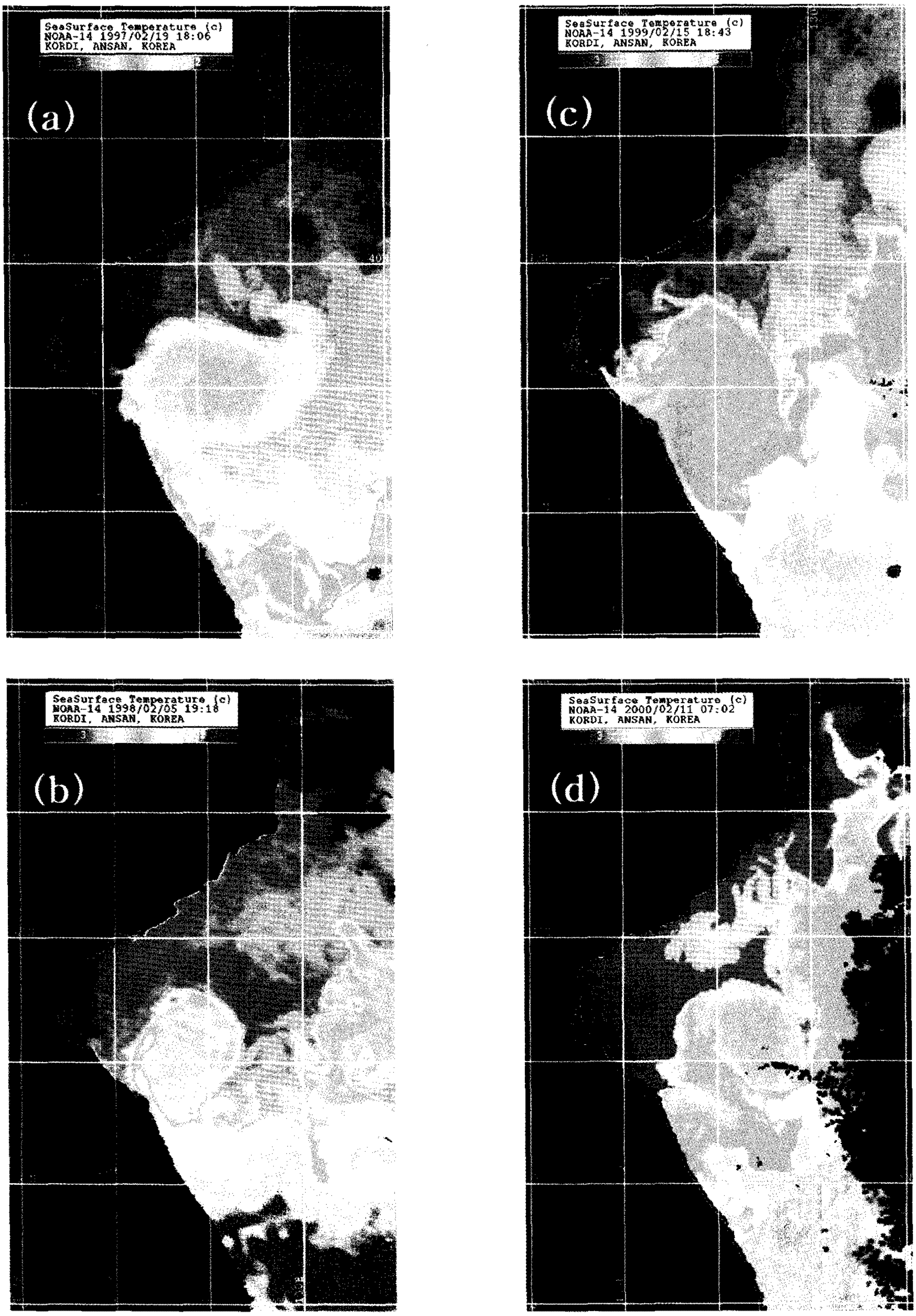

Fig. 3. SST infrared images off east coast of Korea taken from KORDI data system. (a) February 19, 1997, (b) February 5, 1998, (c) February 15, 1999, and (d) February 11, 2000. The range of the temperature scale bar is between 0 and 15°C.

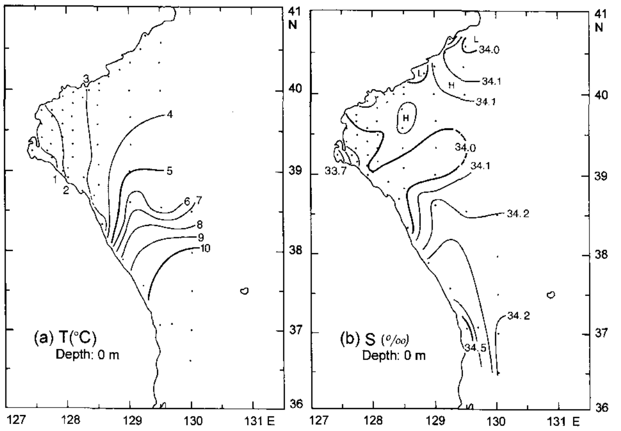

Fig. 4. Horizontal distributions of (a) temperature and (b) salinity at the sea surface in February 1934.

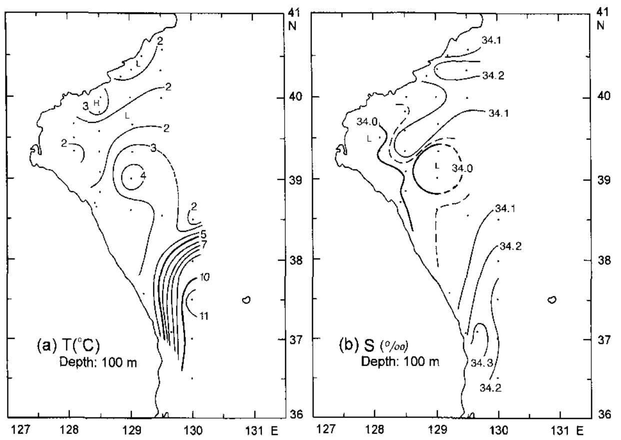

Fig. 5. Horizontal distributions of (a) temperature and (b) salinity at 100 m depth in February 1934.

and salinity, which were colder and fresher than the eddy found around Ulleung Island. This implies that the warm eddy in the EKB was not generated by an instability of the EKWC.

Fig. 7 shows the dynamic topography at the surface, relative to 1000 m depth. The dynamic height was extrapolated in the same manner used by Shin *et al.* (1996) at stations that had shallower bottom depth than the reference layer of 1000 m. The EKWC flowed to the north and then turned to the east at 38°N. The flow in the warm eddy region circulated anticyclonically. The maximum geostrophic current of the warm eddy was about 20 cm/s (Fig. 8). Recently, there was a report that satellite-tracked drifters deployed at 10 m depth entered the warm eddy in the EKB from January to March 1999 and circulated along the fringe of the warm eddy with a

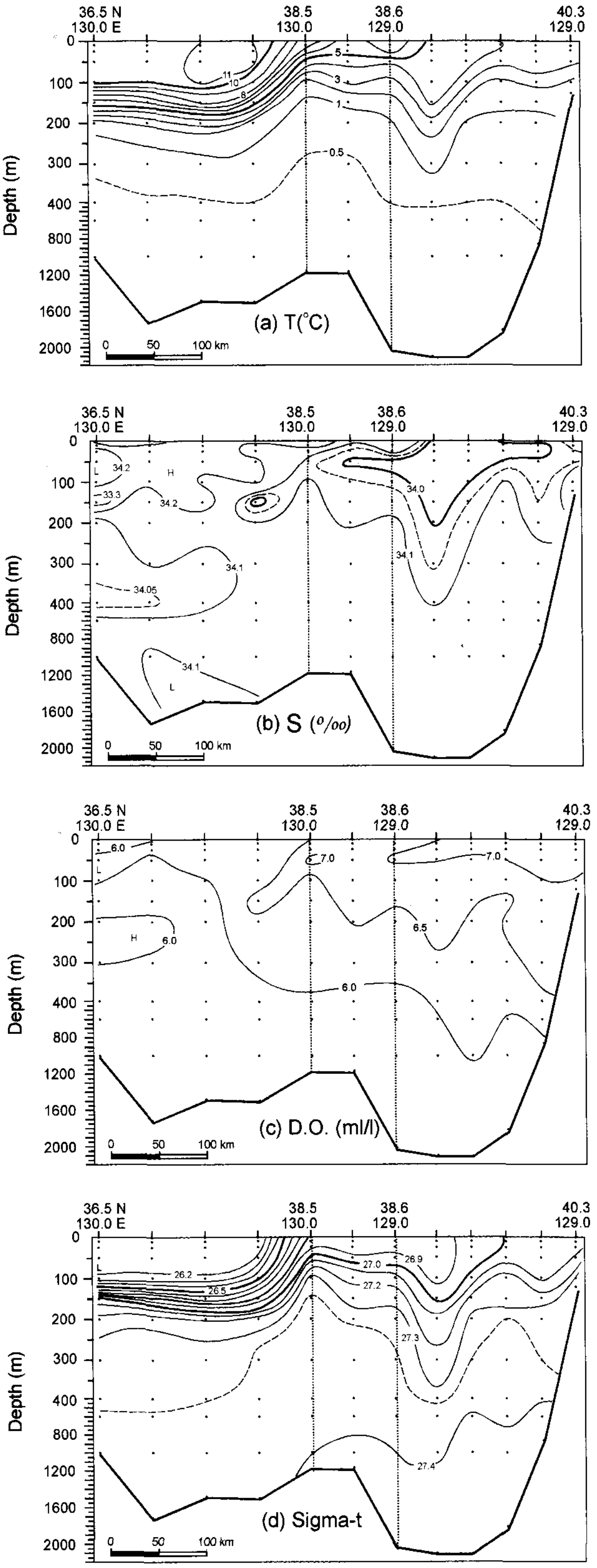

Fig. 6. Vertical sections of (a) temperature, (b) salinity, (c) dissolved oxygen and (d) density (σ-t) along the Line A in February 1934.

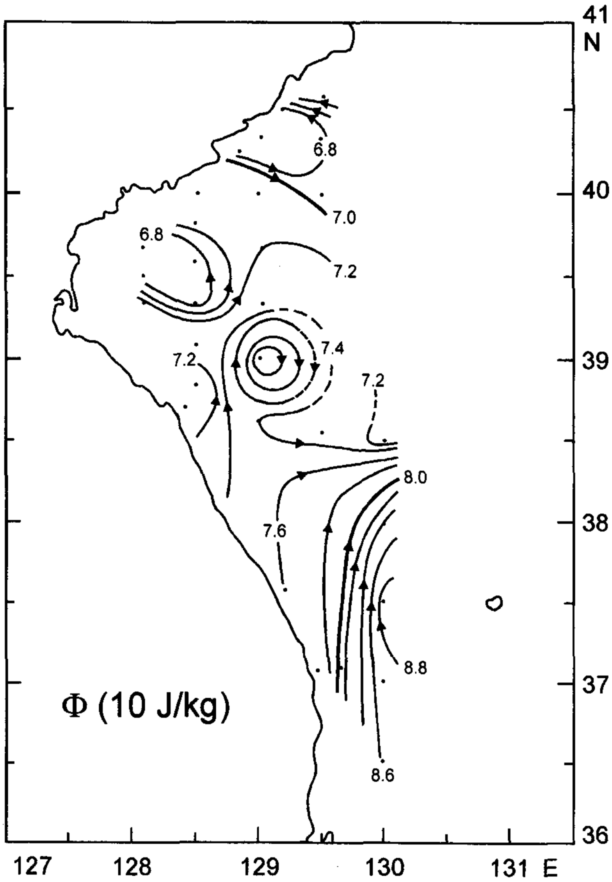

Fig. 7. Dynamic height at the sea surface relative to 1000 m depth in February 1934.

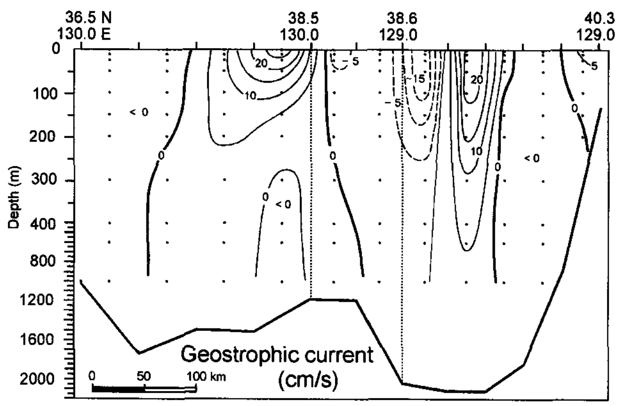

Fig. 8. Geostrophic currents along the Line A relative to 1000 m depth in February 1934.

mean speed of 40 cm/s (Suh *et al.* 2000). The geostrophic current was slower than the speed calculated from the drifters, because the barotrophic component was not included in the geostrophic current.

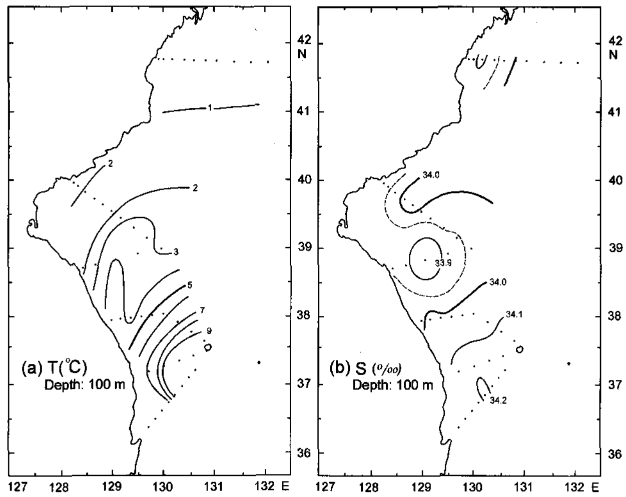

Fig. 9. Horizontal distributions of (a) temperature and (b) salinity at 100 m depth for the averaged data in February during 1922-1960.

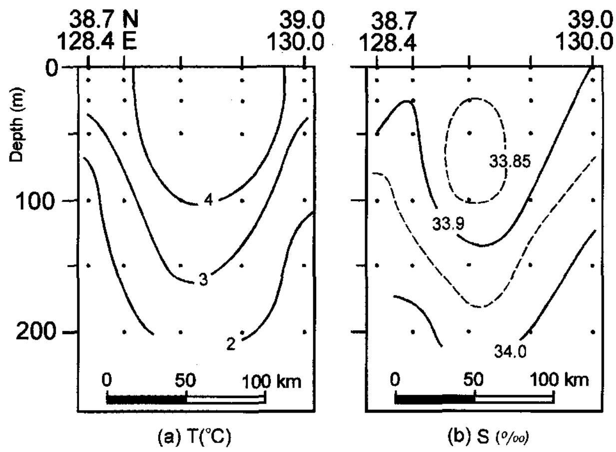

Fig. 10. Vertical sections along the Line C of (a) temperature and (b) salinity for the averaged data in February during 1922-1960.

Fig. 9 shows the horizontal distributions of temperature and salinity at 100 m depth for the averaged data taken during February 1922~1960. The thermal front formed at 38°N and the shape of the warm core were not clear visible in the EKB because of variability in the core position. In the salinity distribution, however, isolated low salinity water was located in the eddy. The bowl-shaped structure was shown in both temperature and salinity vertical profiles along the Line C for the averaged data in February (Fig. 10). This suggested that the warm core frequently occur in the EKB in winter.

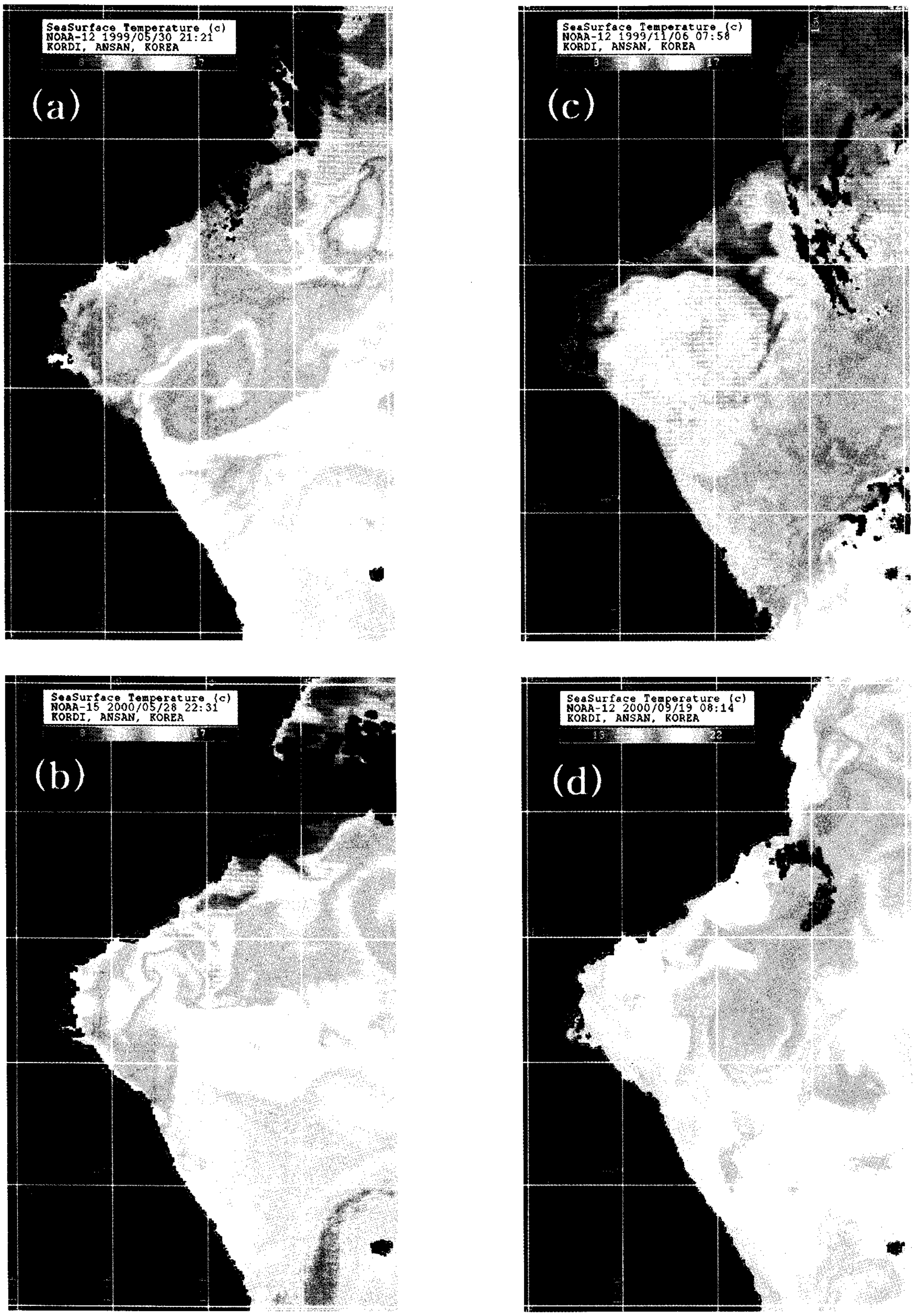

Fig. 11. SST infrared images off east the coast of Korea taken from KORDI data system. (a) May 30, 1999, (b) May 28, 2000, (c) November 6, 1999 and (d) September 9, 2000. The ranges of the temperature scale bar are between 0 and 20°C in spring ((a) and (b)) and between 5 and 25°C in autumn ((c) and (d)).

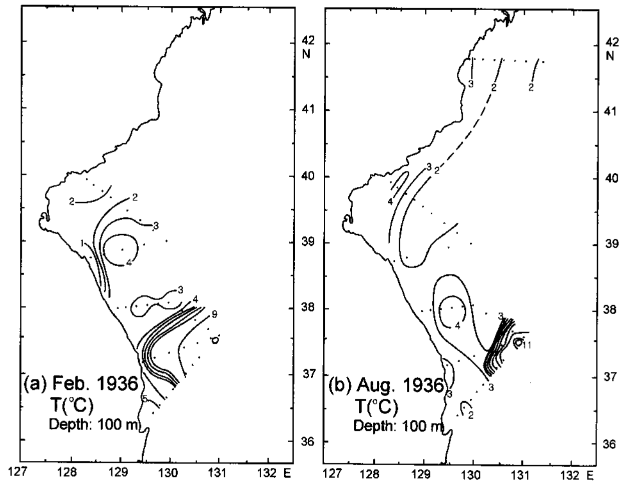

Fig. 12. Horizontal distributions of temperature at 100 m depth observed in (a) February and (b) August 1936.

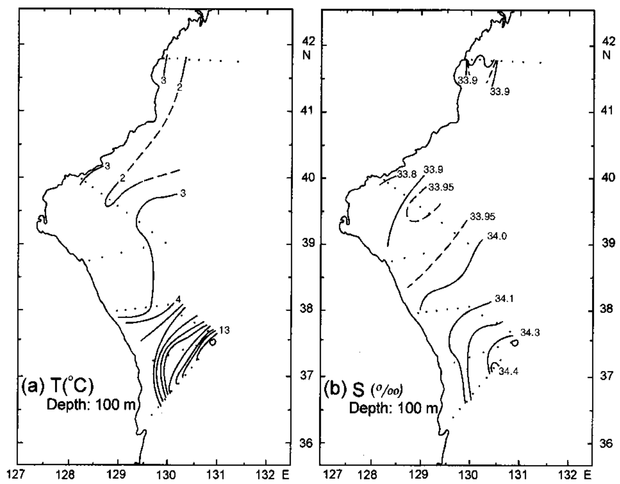

Fig. 14. Horizontal distributions of (a) temperature and (b) salinity at 100 m depth observed in August during 1922-1960.

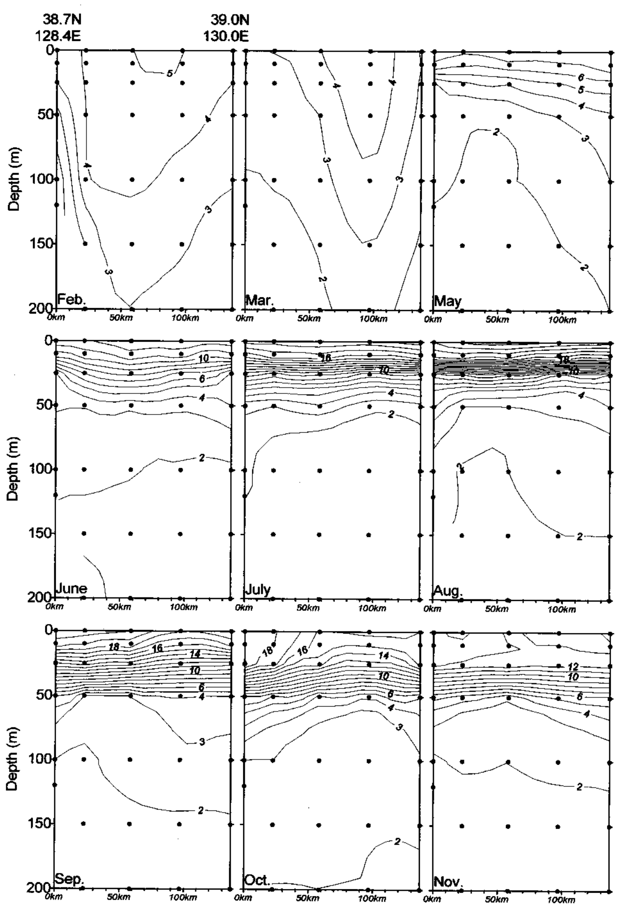

Fig. 13. Vertical sections along the Line C of temperature from February to November 1936.

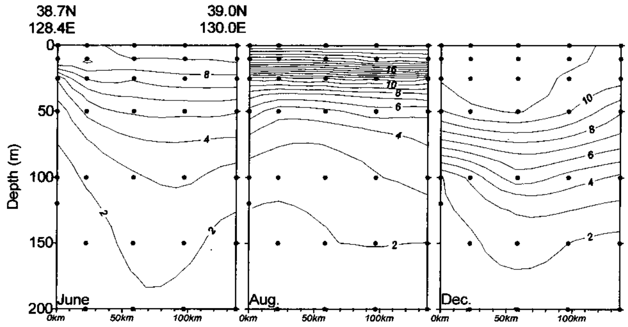

Fig. 15. Vertical sections along the Line C of temperature for the averaged data in June, August and December.

5. Temporal variation of water characteristics in the EKB

During summer, it is difficult to identify the warm eddy from satellite infrared images, because the entire sea surface becomes warmer due to solar heating. Additionally, there are many cloudy days which prevent clear images from being taken. Thus, the warm streamer or core of the eddy was not conspicuous in the EKB during the summer months of the study period.

The warm eddy shown in the EKB every winter, persisted until late May or early June. Fig. 11 a and b are the SST observed on May 30, 1999 and May 28, 2000. The center of the eddy was located at about 39°00'N, 129°00'E in May 1999, and at 39°00'N, 129°25'E in May 2000, respectively. These positions were not much different from those in February. In autumn, the eddy reappeared in the EKB (Fig. 11 c, d) after disappearing from the SST images during summer. The center of the eddy had moved northwestward to about 39°20'N, 128°45'E on November 6, 1999 and to 39°20'N, 129°05'E on September 19, 2000. However it is unclear whether that eddy was the same one that had appeared in winter and spring.

In 1936, there were surveys conducted for the area shown in Fig. 2. Horizontal distributions of temperature at 100 m depth in February and August 1936 are shown in Fig. 12. Isolated core water with temperature warmer than 4°C was located around 39°00'N, 129°00'E as in February 1934. In summer, however, the cold water below 2°C advanced to the place of the isolated warm water. It was not certain whether the eddy warmer than 4°C at the northwest of Ulleung Island was moved from the north. Time sequential vertical sections of the temperature along the Line C from February to November 1936 are shown in Fig. 13. In February, the temperature contours curved downward resembling a bowl shape. The structures of the vertical and horizontal temperature contours indicate the existence of the warm eddy in the EKB. The bowl shaped structure was distanced farther from the coast in March and May. Finally, the bowl structure disappeared sometime after June.

Fig. 14 shows distributions of averaged horizontal temperature and salinity at 100 m depth in August. Compared with the horizontal distribution in February (Fig. 9), the cold water was extended from the northeast to the southwest. The salinity in the EKB was not largely varied except around Ulleung Island. There was no core of warm water or low salinity in the EKB in summer. Vertical sections of the averaged temperature along the Line C in June, August and December are shown in Fig. 15. The bowl-shaped structure appeared in December, was maintained until June, and disappeared in August. If one assumes that the appearance of the bowl structure is a result of a warm eddy, the variation of the temperature structure is consistent with SST images that showed the warm eddy in the EKB, except in summer. However it was uncertain whether the eddy existing in winter moved to another area in summer or just disappeared.

6. Summary

From the analysis of the winter SST derived from infrared images, it was found that a warm eddy appeared in the EKB in February, from 1997 to 2000. The diameter of the eddy was about 100~160 km. Surface temperature of the eddy's center was 6~8°C in February. The temperature and salinity distributions observed in February 1934 showed the warm eddy at the same place as the recent SST images. At the center of the eddy, temperature and salinity at 100 m depth were about 4°C and 34.0 psu, respectively. The averaged data from 1920 to 1960 also revealed a warm eddy structure in February. It is concluded that the warm eddy exists over the EKB in winter as a general phenomenon. In the EKB, the warm eddy persisted until spring but disappeared in summer. In autumn, the eddy appeared again. The SST images also were consistent with hydrographic data. However, it was not clear whether the warm eddy in autumn was the same eddy that had been observed in the previous winter and spring.

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