Structure of a Warm Eddy off Sogcho in May 1992

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Temporal change of a warm eddy off Sogcho was studied using satellite infrared images from January to June 1992 and its structure was investigated by the observations in May. There were two kinds of event for eddy formation. IR images in January indicated that the eddy having a horizontal dimension of about 200km was first formed by an injection of warm water. After some deformation and cooling processes the second restrengthening event took place in late March when a warm filament began to penetrate northward and circumvented the preexisting eddy. This eddy became a complete ring-shape with cooled water arrested inside from April to May. The maximum thickness of the isothermal subsurface layer with temperature of 10.0~10.4℃ was about 170m. Except that the current velocity was about 80cm/sec near the axis of the East Korea Warm Current close to Sogcho, the interior of the eddy had an anticyclonic motion with overall swirl velocity of 30~50cm/sec. Velocity rapidly decreased vertically below the main thermocline.

Key words : eddy, Sogcho, infrared images, East Korea Warm Current, anticyclonic motion

Introduction

Since late 1980's the mesoscale eddies in the East Sea(Japan Sea) have been actively studied by many oceanographers. Ichiye and Takano(1988), who referred the Japan Sea to a miniature ocean, showed that the isolated mesoscale eddies of 30~160km in diameter were found by the isotherms at 100m depth. Isoda (1994) studied movements of warm eddies in the eastern Japan Sea. Off the east coast of Korea, there have been many studies on the warm eddy near Ulleungdo that was called the Ulleung Warm Eddy(Cho et al., 1990; Kang and Kang, 1990; Na and Kim, 1990; Seung et al., 1990; Kim, 1991; An et al., 1994). Tameishi(1987) used the satellite infrared images to describe the process of eddy generation and movements. Isoda and Saitoh(1993) also suggested that the eddies intrude northward along the Korean coast from the analyses of the satellite images. Min et al.(1995), by the statistical analysis of eddy distribution using satellite data, pointed out that a mesoscale eddy off Sogcho was a semi-permanent feature and entitled it the Sogcho Eddy. Therefore, the Ulleung Eddy and the Sogcho Eddy are main features of the mesoscale variability off the east coast of Korea. Because the Sogcho Eddy is mostly found between Mukho and Wonsan Bay, Min et al.(1995) speculated that invariable eddy-generating mechanisms may be responsible for the consistent location of the eddy. This eddy frequently has a ring-shape feature in which the warm streamer circumvents the cold water inside at the stage of the maximum development. Therefore, we have two questions. What are the generating mechanisms? What structure does this eddy have? It seems very difficult to answer the first question. As a part of the efforts to address the second question, we carried out more observations in 1992 and 1993. In this paper the results of the observations in May 1992 are described.

Data and Methods

The satellite infrared images acquired and processed by the Agency for Defense Development were utilized to trace the position and status of the Sogcho Eddy. Before the cruise, the survey tracks for the observations were predetermined based on the infrared images. Considering the limited ship time and safety near the North Korean territory, we chose two cruise tracks. On 21 May, observations began along the Line-A near the southern edge of the eddy and proceeded toward the central region at about 5 miles interval, then along the Line-B toward Sogcho(Fig. 1).

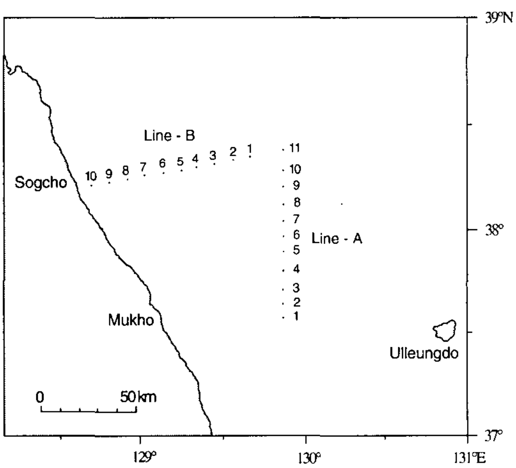

Fig. 1. Stations for observation along the Line-A and B.

At each station the temperature was measured by DBT at 10 m depth interval. Maximum depth of DBT measurement was about 1000 m. Then a current meter(Aanderaa RCM-7) was lowered to measure the current velocity, temperature and salinity. Sampling interval was fixed at 30 seconds and the current meter was stopped at the standard depths for 3~4 minutes to obtain reliable data at the same depth. Velocity data near the surface were not used because of the possible contamination under the lee of the ship. The maximum depth of this measurements was about 300m that was the range of the pressure sensor. During the observation for 30~60 minutes the ship was drifted by the surface current and wind. The mean drift velocity of the ship determined from the GPS records was used for correction of the current meter data to get the actual current velocity. After waiting until the ship stopped completely at each station and the GPS data did not change rapidly the position was recorded. As soon as the observation was finished, the position was also recorded. Several tests of GPS at a fixed location on the ground yielded the maximum error of about 50m when the value of HDOP(horizontal dilution of position) was kept 1.0. Assuming that this maximum error occurred for every reading and was augmented for two positions during the observation for at least 30 minutes, the maximum error affecting the velocity data correction would be about 5cm/sec. Consequently, even the extremely precise measurement of current velocity aboard the vessel cannot avoid the uncertainty of at least 5cm/sec due to the ship drift.

Results and Discussion

1. Satellite AVHRR images

Fig. 2 shows six AVHRR images selected to describe the temporal change of the Sogcho Eddy from January to June 1992. On the image of 27 January (Fig. 2a) a warm eddy about 200km wide was found. The shape of this eddy makes one think that the warm water was injected by the East Korea Warm Current(EKWC) and cut by the intrusion of cold water at the southern edge. This is similar to an 'aneurysm' that the side of the current bulges out and pinches off from the main current as Richardson(1983) described. Strictly speaking, however, the shape of Sogcho Eddy was closer to an injected form rather than an aneurysm of a strong current. Inshore intrusion of the cold water from Ulleungdo appeared to block off the warm water from the south. Although it was not known when this eddy was generated, infrared images in winter of 1991 also proved its prese-

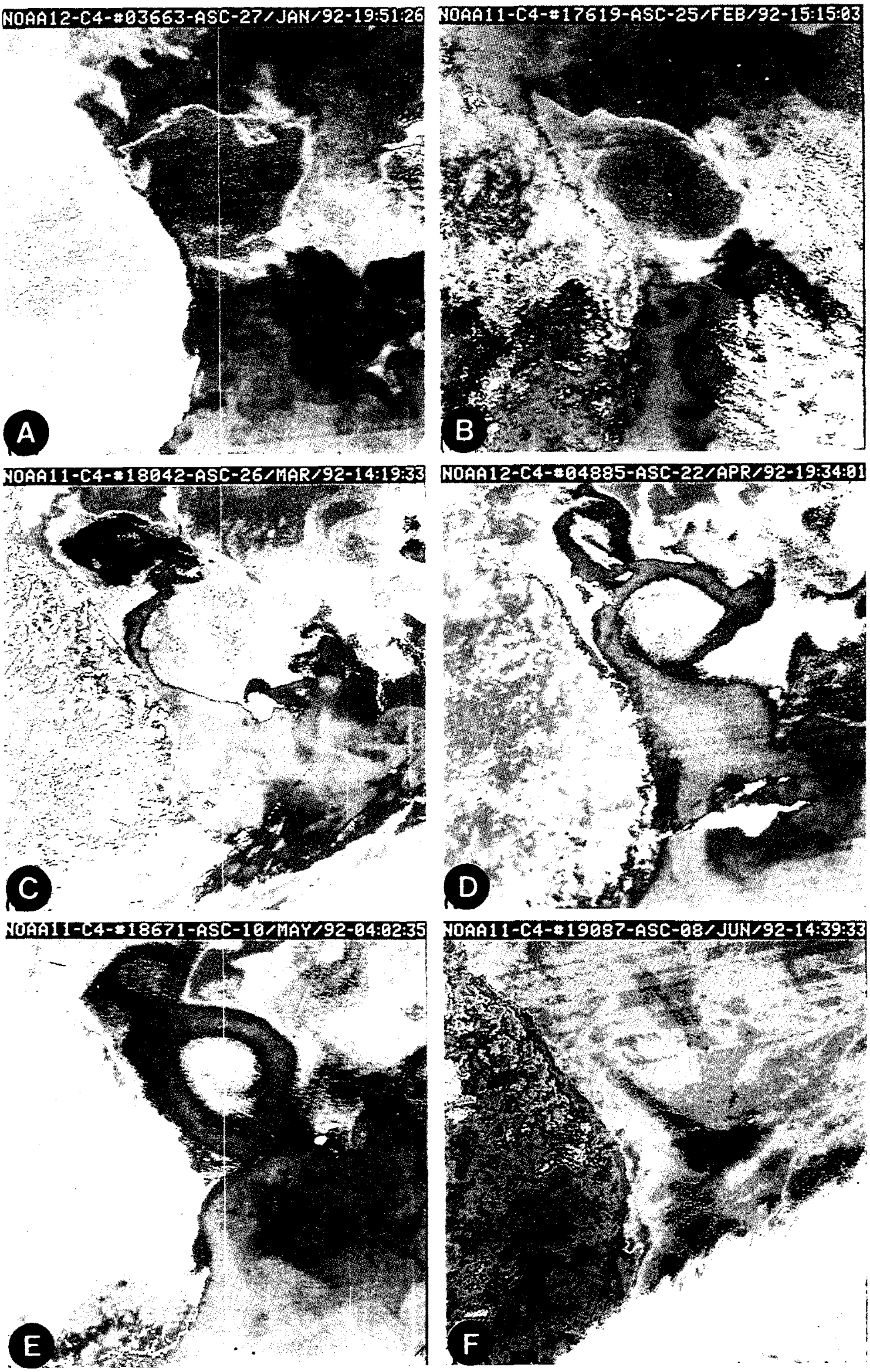

Fig. 2. Satellite AVHRR images off the east coast of Korea from January 27 to June 8, 1992.

nce in the same region. On 25 February(Fig. 2b), the warm water did not penetrate northward and the eddy became weaker. As a result the contrast of the warmer water south and of the eddy had increased compared to the picture in January.

The image of 26 March(Fig. 2c) shows that a warm streamer of the East Korea Warm Current(EKWC) just off Mukho intruded further northward to supply the warm water and make an additional eddy of injected form near Wonsan Bay. This warm streamer surrounded the preexisting Sogcho Eddy on 22 April(Fig. 2d).

On 10 May(Fig. 2e), the warm streamer became wider probably because of the increased supply of warm water and horizontal mixing, and the eddy developed as an isolated ring-shape. Till 20 May when our observations began the shape of eddy was not changed. On 8 June(Fig. 2f) the ring-shape was broken and elongated in NW-SE direction. The eddy appeared somewhat diffused than before. Henceforth this eddy was not traceable by the satellite data due to the overall surface heating and frequent cloud cover.

In summary, the infrared images indicate that there were two kinds of event for eddy formation. One is an injection of warm water similar to the aneurysm

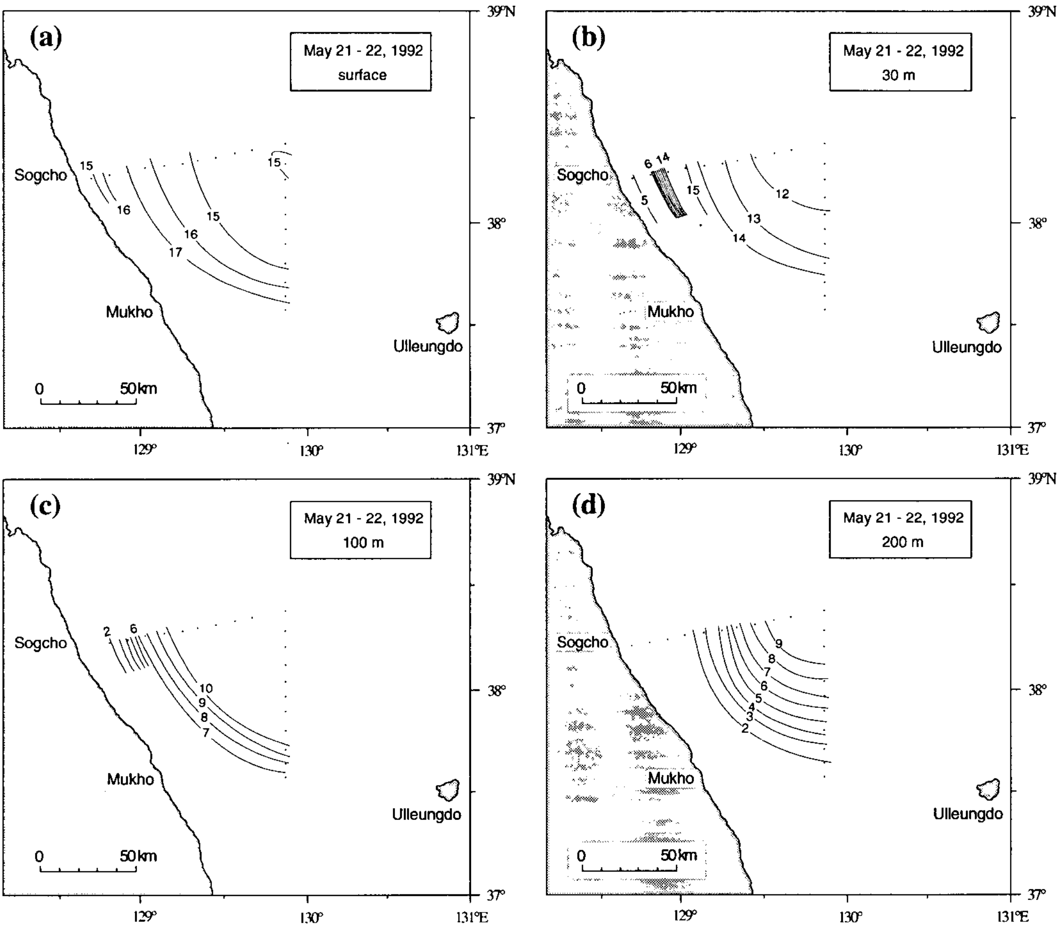

Fig. 3. **Horizontal distributions of temperature at different depths.**

and the other is a warm streamer circumventing the colder water inside to form a ring-shape eddy. When the warm water supply is sufficient or maintained long, the eddy is entirely covered by the injection or aneurysm of warm water as in January, whereas a narrow warm streamer generates a ring-shape eddy enclosing the colder water inside as Tameishi(1987) explained. It is necessary to investigate what conditions enable the two different events to take place in the same region.

2. Temperature distribution

Fig. 3 is the horizontal distribution of temperature constructed from the DBT data and satellite imagery. Although the observations were made for the half of the whole transection of the eddy, it is not difficult to conjecture the structure of the eddy with the help of the satellite imagery. At the surface(Fig. 3a) the isotherm of maximum temperature of 17℃ passing the stations A2 and B8 corresponds to the axis of the warm streamer. Temperature decreases both toward the coast due to the North Korea Cold Current (NKCC) flowing southward and toward the center of the eddy due to the cold water arrested inside the streamer. At 30m depth(Fig. 3b) the basic trend is the same except the strong temperature gradient between B8 and B9 where temperature decreased from 14℃ to 6℃. The temperature drop near the coast amounts to 10℃ for the depth change of 30m. At 100 m depth(Fig. 3c), in contrast to the near-surface layer, temperature keeps increasing from 2℃ near the coast to 10℃ at about A3 and B6. Beyond these stations toward the eddy center the temperature does not change. This result indicates that there is a large homogeneous layer at the mid-depth. If we assume that the eddy is symmetrical at this depth and the center is located between A11 and B1, the diameter of the homogeneous layer would be about 120km. At 200 m depth(Fig. 3d) the temperature increases gradually from 2℃ at the edge to 9℃ near the center.

Vertical temperature profiles at some selected sta-

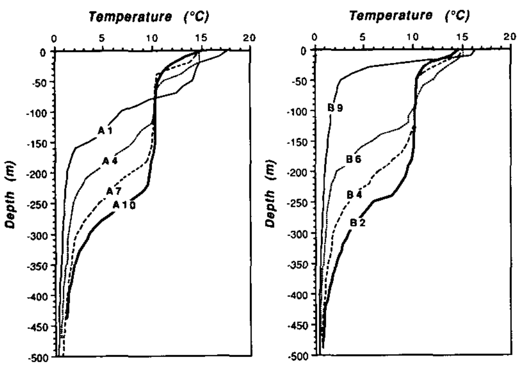

Fig. 4. Temperature profiles at selected stations of Line-A and B.

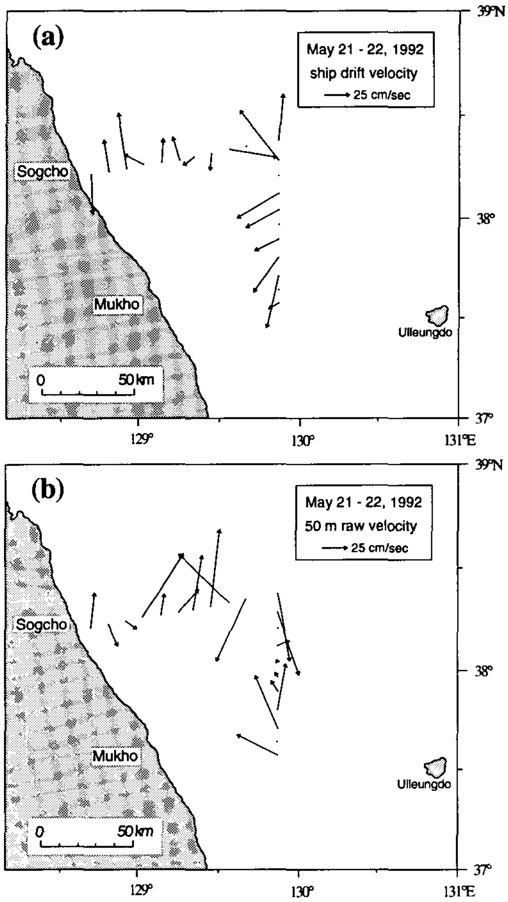

Fig. 5. Mean ship-drift velocity and observed current velocity at 50m depth.

tions(Fig. 4) were presented to compare the thickness of the homogeneous layer with temperature of 10~10.4℃. Near the edge(A1, B6 and B9) the isothermal layer is absent. At other stations the thickness of the homogeneous layer begins with about 50m depth and increases toward the center. The thickness is about 50m at A4, 130m at A7 and 170m at A10. Along the Line-B, it is about 90 m at B4 and 140m at B2. Especially it is notable that the temperature at B9 near the coast drops from 16.3℃ at the surface to about 2℃ at 50m depth because of the NKCC.

3. Velocity distribution

Fig. 5 shows the mean drift velocity of the ship(Fig. 5a) and the horizontal distribution of the observed velocity at 50m depth(Fig. 5b) as an example. It is evident that the raw data is so random that the current field looks very irregular whereas the drift velocity seems to contain more influence of the local current. This result demonstrates that the shipboard current meter data itself does not represent the actual velocity field unless it is corrected by the ship-drift velocity. Therefore the correct measurement of the ship drift is of vital importance for shipboard observation of current velocity.

The current velocity vectors corrected by the ship's mean drift velocity are plotted in Fig. 6. At all the selected depths anticyclonic motion of a warm eddy is

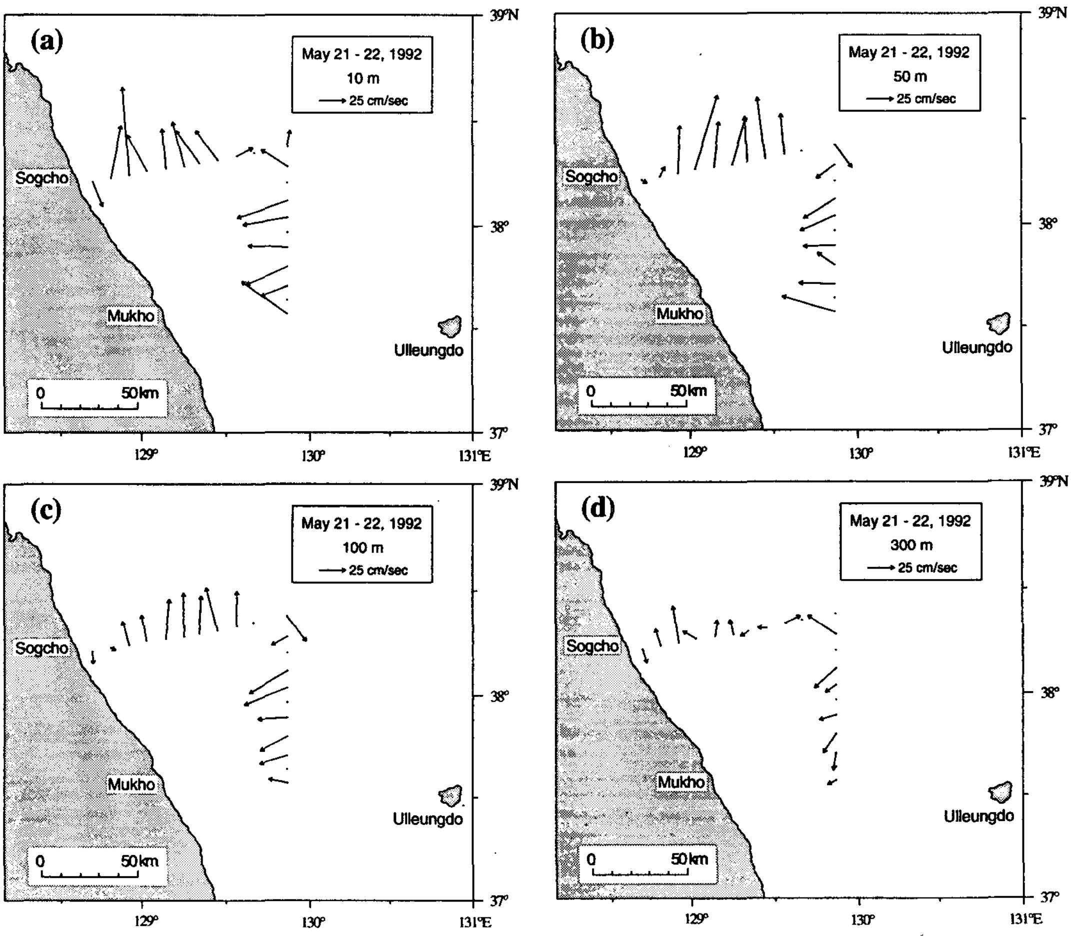

Fig. 6. Horizontal distributions of current velocity at different depths.

evident. Westward and northward components are dominant at the Line-A and the Line-B, respectively. In the central region of the eddy(A10, A11, B1 and B2) the currents are relatively weak and irregular. The strongest current is found in the upper layer of the EKWC off Sogcho, i.e., 83cm/sec at 10m depth at B8 (Fig. 6a) and 73cm/sec at 50m depth at B7(Fig. 6b). At 100m depth(Fig. 6c), currents are relatively strong at the mid-point between the edge and center of the eddy. At 300m depth(Fig. 6d) weak tendency of the anticyclonic motion is still present but the velocity is generally small. Near the coast of Sogcho the southeastward velocity of 25cm/sec at 10m, 12cm/sec at 100m and 14cm/sec at 300 m is due to NKCC.

4. Vertical structure of temperature and velocity

Vertical sections of temperature and current velocity are superposed in Fig. 7 for easier understanding of the eddy structure. Although the eddy is not exactly symmetrical because of the strong EKWC and the presence of the southward NKCC near the coast, the structure of the other side can be obtained crudely from the mirror image extended to the Line-A section. For the velocity vector the upward arrow depicts the northward velocity as indicated by the legend at the upper left of the figure. Westward motion is dominant across the N-S section of Line-A and northward motion across the E-W section of Line-B.

The deepest appearance of the isotherms of 2~8℃ at A10 and B1 implies that the eddy center may be located between two stations. Southeastward current at A11 indicates that the station A11 may be to the northeastern side from the center. The two sections commonly show that there is a homogeneous layer of 10~11℃. Above this isothermal layer the temperature decreases toward the eddy center because of the arrested cold water mass in near-surface layer. This trend might have been absent when the eddy was covered entirely by the injected warm water during January to February before a warm filament of EKWC made a ring-shape eddy. The increasing temperature toward the center in deeper layer is the genuine feature of the anticyclonic eddy. The isothermal mid-layer, observed very frequently in the anticyclonic eddies, is known to be formed in winter by the vertical mixing due to the surface cooling(Nagata at al., 1985; Schmitt and Olson, 1985; Kamenkovich et al., 1986; Kim, 1991; Isoda et al., 1992).

The temperature higher than 15℃ south of A3 and between B4 and B10 is due to EKWC. Near the coast vertical temperature gradient is very large and the slope of the isotherms is steep because of the strong EKWC in the upper layer and NKCC flowing in the opposite direction underneath. Velocity is about 70~83cm/sec in the upper layer at B7~B8 and about 50 cm/sec at A1. Overall velocity in the upper layer above the main thermocline ranges from about 30 to 50cm/sec whereas it is very small in the lower layer.

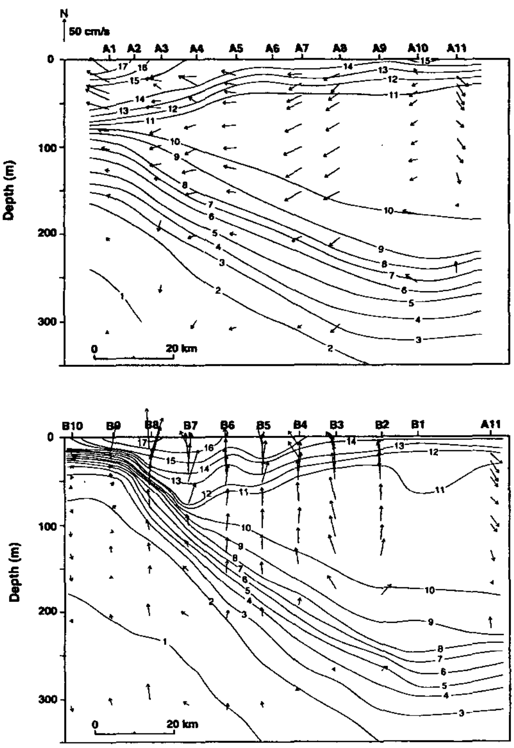

Fig. 7. Vertical sections of temperature and current velocity along the Line-A and B.

Before the beginning of the second event of eddy formation, i.e., warm streamer, structure of the injected warm water would have been simpler without a surrounding band of EKWC and would have had the same overall velocity of 30~50cm/sec. It is not certain if the warm streamer accelerated the rotation of the whole water mass inside the eddy.

A rough estimate of the baroclinic Rossby radius of deformation from the observed temperature and salinity data yields about 15km. Therefore the wavelength of the unstable waves or the horizontal dimension of the eddy generated by the baroclinic instability becomes about 100km as observed in the open ocean and western boundary current regions(Kamenkovich et al., 1986). The dimension of this Sogcho Eddy of about 200km is twice as large as the typical eddies generated by the baroclinic instability. Consequently there should be other mechanisms that account for the formation of large eddy off Sogcho. Because this eddy is known to be generated in winter, strong offshore wind in winter of this region may exert significant influence. In addition to the factors affecting the eddy size, it is an important fact that this eddy always occurs in nearly the same region from Mukho to Wonsan Bay as pointed out by Min et al.(1995).

Summary

Temporal change of the Sogcho Eddy was studied by a series of satellite infrared images from January to June and observations were carried out to investigate the structure of eddy in May 1992. IR images showed that there were two kinds of event for eddy formation. Although it was not certain when the Sogcho Eddy was generated, the IR image in January indicated that it was formed by an injection of warm water having a horizontal dimension of about 200km. In February it became weaker to some extent by cooling processes in winter. In late March the second event took place. A warm streamer of EKWC began to penetrate northward and circumvented the preexisting eddy and completed a ring-shape with an arrested cold water inside from April to May. Observations were conducted on 21~22 May 1992 when the ring-shape eddy was fully developed. The maximum thickness of the isothermal subsurface layer with temperature 10.0~10.4℃ was about 170m. The anticyclonic motion had the overall velocity of 30~50cm/sec but the maximum value was about 80cm/sec near the axis of the EKWC near Sogcho where both the vertical gradient of temperature and the slope of isotherms were also maximum. Velocity in the lower layer below the main thermocline was very weak.

The horizontal dimension of this Sogcho Eddy was too large to be explained solely by the baroclinic instability theory. In addition to the baroclinic instability, other mechanisms that account for the frequent generation of large eddy in the same area should be addressed in near future.

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1994년 12월 31일 접수
1995년 7월 5일 수리

Structure of a Warm Eddy off Sogcho in May 1992

1992년 5월 속초 근해 와동류의 구조

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1992년 1월부터 6월까지의 인공위성 적외선 영상자료를 이용하여 속초 근해에 형성된 와동류의 시간적 변화에 대하여 연구하였고 동년 5월에 그 구조를 관측하였다. 와동류의 형성에는 두가지 종류의 과정이 있는 것으로 나타났는데, 첫번째로 1월의 영상자료에 의하면 난류의 대량 공급으로 인하여 약 200km 크기의 와동류가 형성되었다. 그 이후에 약간의 변형과 냉각과정을 거쳐서 3월에는 난류의 좁은 필라멘트가 북쪽으로 침투하면서 어느정도 냉각된 기존의 와동류를 포위함으로써 4~5월에는 반지모양의 와동류로 발달하는 두번째의 형성과정이었다. 와동류의 내부에는 수온 10.0~10.4℃의 균질 중층수가 최대 170m의 두께로 존재하였다. 속초 근처 동한난류의 축에서의 유속 약 80cm/sec를 제외하면 나머지 부분의 와동류 내부에는 대체로 30~50 cm/sec의 유속분포를 보였고 주수온약층 밑으로는 유속이 급격히 감소하였다.