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On the Warm Eddies in the Southwestern Part of the East Sea (the Japan Sea)

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동해 남서해역에서의 난수성 소용돌이에 대하여

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The characteristics and fluctuations of structures and spatial distributions of warm eddies (anticyclonic eddies)in the southwestern part of the East Sea (the Japan Sea) are discussed based on the data gathered by the Fisheries Research and Development Agency, Korea from 1967 to 1986. The warm eddies existed very often in the southwest of the Ullung Island. The warm eddies are elliptical in shape and the mean size is about 130 km in diameter.

Bimonthly distributions of warm eddies, the largest value of observed frequency and diameter in August and the least in June, indicate that the generation of the warm eddy is related with the development of the East Korean Warm Current. The warm eddies move west-, north- or southward with 0.80~2.50 cm/sec or stay over a few months at the same place southwest of the Ullung Island. Movement of warm eddies may be influenced by the neighboring currents, the Rossby wave and the topography. The relationship between the position of warm eddies and the bottom topography suggests that the development and the movement of warm eddies are controlled by the Ullung Basin.

The warm eddies should be divided into two groups. One group is the shallow warm eddy with strong baroclinic characteristics and the other is the deep one with strong barotropic characteristics. The shallow group seems to be closely related with positive values (in summer) of the sea level difference between Pusan and Mozi (the Tsushima Current), while the deep group has no relation with that.

1967년부터 1986년까지의 국립수산진흥원의 관측자료를 사용하여 동해 남서해역에서 난수성 소용돌이(고기압성 소용돌이)의 구조 및 공간분포의 특성과 변동에 대해 연구하였다. 난수성 소용돌이는 울릉도 남서쪽 부근에서 자주 관측되며, 타원형이 많고, 평균크기는 약 130 km이다.

난수성 소용돌이의 월별분포에 의하면 8월에 관측되는 빈도가 가장 많고, 6월에 가장 적다. 이것은 난수성 소용돌이의 발생이 동한난류 세력의 발달과 관계가 있음을 나타낸다. 난수성 소용돌이는 서쪽이나 북쪽 또는 남쪽으로 0.80~2.50 cm/sec의 속도로 이동하거나 한 장소에서 수개월동안 정체한다. 이러한 움직임은 주변의 해류와 로스비파 및 지형의 영향을 받는다. 또한 난수성 소용돌이의 분포와 해저지형과의 관계는 소용돌이의 이동과 발달이 울릉분지에 의해 영향을 받고 있음을 시사한다.

난수성 소용돌이는 크게 2개의 군으로 나눌 수 있다. 하나는 경압성의 특성이 강한 수심이 얕은 소용돌이 군이고, 다른 하나는 순압성의 특성이 강한 수심이 깊은 소용돌이 군이다. 부산과 일본의 모지와의 해수면 차이로 대마난류의 수송량을 추정할 수 있는데, 수심이 얕은 소용돌이의 분포가 여름철 수송량이 클 때와 일치하였다. 반면에 수심이 깊은 소용돌이 군은 대마난류의 수송량과 아무런 관계도 보이지 않았다.

INTRODUCTION

The East Korean Warm Current flows northward along the eastern coast of Korea and often turns to the east near Jugbyeon and to the south around the Ullung Island. The North Korean Cold Current mixes with the East Korean Warm Current while it flows southward. As the East Korean Warm Current flows back to the south, the anticyclonic eddy which encloses warm water in the center is formed near the Ullung Island (Moriyasu, 1972).

The hydrography of this area has been studied by many oceanographers. Fukuoka (1957), Tanioka (1968) and Moriyasu (1972), who have pointed out that a branch of the Tsushima Current (the East Korean Warm Current) usually flows northward closer to the eastern coast of Korea in the colder season and farther from the coast in the warmer season. An and Chung (1982), and Gong (1985) also investigated the fluctuation and the meandering of the Tsushima Current. They concluded that there are three types of the thermal front off the eastern shore of the Korean Peninsula, and that the existence and the development of the eddy influence shapes of the thermal front. Kang and Kang (1990) studied spatio-temporal characteristics of the warm eddy (they called it Ullung Warm Lens) near Ullung Island using the mean data in the same month during 11 years (1973~1983) and vertically averaged temperature in the subsurface layer of 100~200 m. They presented rough size and observed frequency of it, but detailed characteristics of warm eddy were not presented.

The anticyclonic eddies with warm water mass are sometimes recognized at 100 m depth in the southwest of the Ullung Island (Fig. 1). The existence of the warm eddy in this region is one of the most interesting natural phenomena in relation to the Tsushima Current. Matsuyama (1973) studied the warm water region of the East Sea (the Japan Sea) using the hydrographic data from 1966 to 1969 and concluded that the warm eddies were always found to the east of Korea during the period, and they were almost steady at the fixed locations. However there are many problems still unsolved.

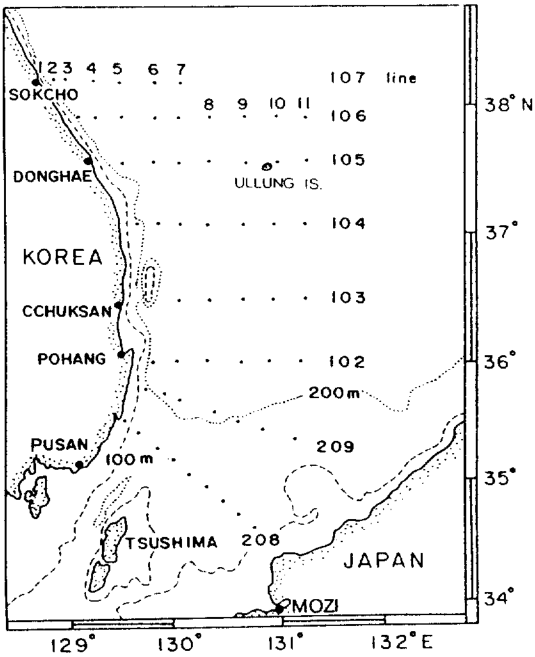

Fig. 1. The map of the area studied and observational stations. The dashed lines indicate the 100 m and 200 m contour lines of bottom topography.

In this study, the following points were investigated. First of all, what is the detailed shape of the warm eddy? Second, is there any range in temporal and spacial distribution of warm eddies? Third, are there any constraints of bottom topography on the warm eddy? Finally, what is the relationship between the fluctuation of warm eddies and the transport of the Tsushima Current?

DATA AND METHOD

Data from 1967 to 1986 gathered by the Fisheries Research and Development Agency of Korea have been used in studying the oceanographical conditions. These observations at stations in the southeastern area off the Korean Peninsula (marked by dots in Fig. 1) have been taken six times each year, in February, April, June, August, October, and December. In spite of small differences

Table 1. Characteristic properties of warm eddies from 1967 to 1986

Year Month	line	Position of center		Diameter		Max. Depth (m)	Max. Temp. (at 200 m) (℃)	Ratio
		Lat. (°N)	Lon. (°E)	E·W	N·S			E·W/N·S
1967 2	104	37.06	130.63	187	161	425	10.03	1.16
10	104	37.06	130.31	>102	201	400	9.98	*
1968 4	104	37.06	130.63	151	155	>500	8.45	0.97
6	104	37.06	130.63	81	161	>500	5.67	0.51
12	104	37.06	130.31	>151	117	400	8.71	*
1969 2	104	37.06	130.63	158	>161	230	4.78	*
4	105	37.55	130.31	89	93	425	6.03	0.96
6	103	36.51	130.31	128	163	480	4.50	0.79
8	106	37.90	130.63	222	*	325	4.36	*
10	104	37.06	130.31	158	*	435	10.29	*
1970 8	104	37.06	130.63	213	202	400	8.61	1.05
1971 6	104	37.06	130.63	130	163	470	7.63	0.80
8	104	37.06	130.63	139	164	>500	9.16	0.85
1973 10	105	37.55	130.31	111	155	175	16.15	1.72
							(at 100 m)	
1974 8	104	37.06	130.63	>135	155	>500	9.20	*
10	104	37.06	130.00	95	155	>500	9.04	0.61
12	104	37.06	130.94	151	*	430	11.57	*
1975 2	105	37.55	130.63	112	128	>500	7.15	0.88
4	103	37.51	130.00	59	109	480	9.91	0.54
1976 12	105	37.55	130.93	83	93	>500	10.31	0.89
1977 4	104	37.06	130.94	151	156	470	8.00	0.97
1978 8	105	37.55	130.93	176	155	>500	12.00	1.14
1979 2	104	37.06	130.31	102	155	>500	12.30	0.66
6	104	36.51	130.63	130	161	450	10.05	0.79
1980 10	103	36.51	130.63	>155	162	190	16.18	*
							(at 100 m)	
1981 2	104	37.06	130.63	>115	156	375	6.58	*
8	104	37.06	130.63	102	117	>500	7.59	0.87
10	104	37.06	130.63	102	117	>500	6.85	0.87
12	105	37.55	130.31	138	93	470	7.84	1.48
1982 4	104	37.06	130.31	151	117	>400	10.31	1.29
8	104	37.06	130.63	138	155	300	8.21	0.89
10	104	37.06	130.31	112	156	380	8.77	0.72
1983 2	105	37.55	130.63	111	93	>400	7.25	1.19
8	104	37.06	130.63	>151	155	375	3.56	*
1984 4	104	37.06	130.94	> 84	155	>400	8.14	*
12	104	37.06	130.94	151	164	390	7.16	0.92
1985 12	105	37.06	130.31	158	156	>400	9.13	*
1986 6	104	37.06	130.31	130	164	340	4.56	0.51
8	104	37.06	130.94	> 84	117	430	7.47	*
10	104	37.06	130.63	112	117	390	6.82	0.87

on the positions of the stations from year to year, they could be considered as the same points in the present analysis. Although these measurements are not sufficient to study the continuous variations of the characteristics of the warm eddy, they are good to define the size, shape, observed frequency and movement of the warm eddy.

In this study horizontal distributions of water

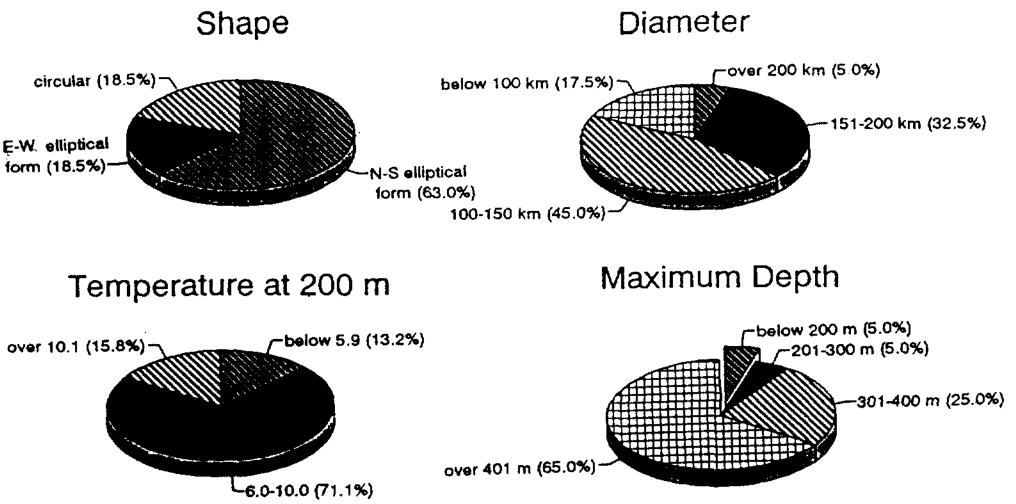

Fig. 2. The statistical data of shape, diameter, temperature at 200 m depth and maximum depth of warm eddies in the southwestern part of the East Sea (the Japan Sea).

temperature at 100, 200 and 300 m depths were made to know the distribution of warm eddies over a 20-year period. The observed times and the locations of warm eddies are investigated by using the horizontal distribution of the temperature mainly at the 200 m depth, because the warm eddy is defined very well at this depth (Moriyasu, 1972).

Next, in order to investigate the vertical structures of warm eddies, the vertical sections of temperature and salinity distribution were also examined along the observation lines at which warm eddies existed. Table 1 shows the characteristic properties of 40 warm eddies found in the area studied. The sea level data at Pusan (Korea) and Mozi (Japan) are also used on behalf of the transport of the Tsushima Current.

RESULTS

The shape of the warm eddy

Fig. 2 shows the statistical data of the shape, diameter, temperature at 200 m depth and maximun depth, which are made based on Table 1. The shape is divided into 3 types of circular, east-west and north-south elliptical forms by ratio (east-west size/north-south size). Circular is defined by the ratio range of 0.9~1.1. The north-south (N-S) elliptical form is defined by the ratio less than 0.9, and the east-west (E-W) elliptical form by the ratio larger than 1.1. Sizes of 27 warm eddies can be distinguished well. N-S elliptical forms occupy about 63%, and are the most frequent.

Diameter is defined by the length of the front from east to west at the surface, because it is observed more precisely than the north-south diameter. Warm eddies with the diameter of 100~150 km are the most frequent (45%). Mean diameter of warm eddies in the East Sea (the Japan Sea) is 132 km and is almost the same size as that of the warm eddies from the Kuroshio to the east of Japan, which is 130 km (Kitano, 1975). There are 27 cases (about 71%) whose core temperature at 200 m depth is 6~10℃ and the mean core temperature at 200 m is 8.1℃. The maximum depth of a warm eddy is defined by the depth of 1℃ isotherm at the center. Warm eddies with depths deeper than 400 m are the most common (65%).

Fig. 3 shows the horizontal temperature distributions of typical warm eddies drawn at selected depths in order to see the position, size, and shape of the warm eddy more clearly. Because the vertical extents of warm eddies are different, depths of the horizontal distributions are not the same

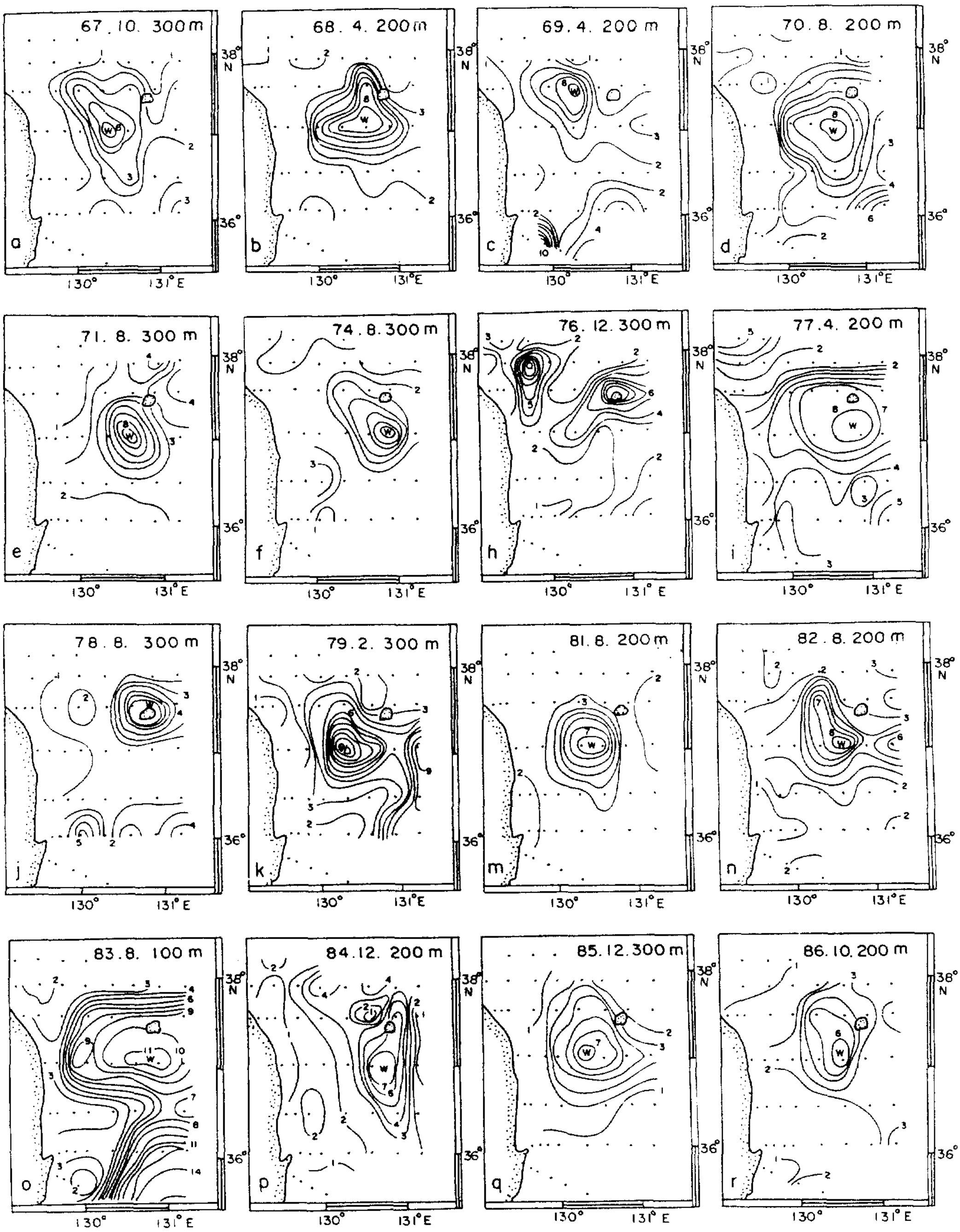

Fig. 3. The horizontal temperature distribution with warm eddies from 1967 to 1986. Depths of the horizontal distributions differ because the existing depths of warm eddies are different.

in Fig. 3. They are usually found as independent warm eddies in the south or southwest of the Ullung Island. In most cases only a single warm eddy was observed in the study area, but in a few cases like 1976, 1978, and 1984, two warm eddies were found simultaneously. The large warm eddies were shown in 1968, 1970, 1974, 1976, and 1981. Though not shown in Fig. 3, warm eddies

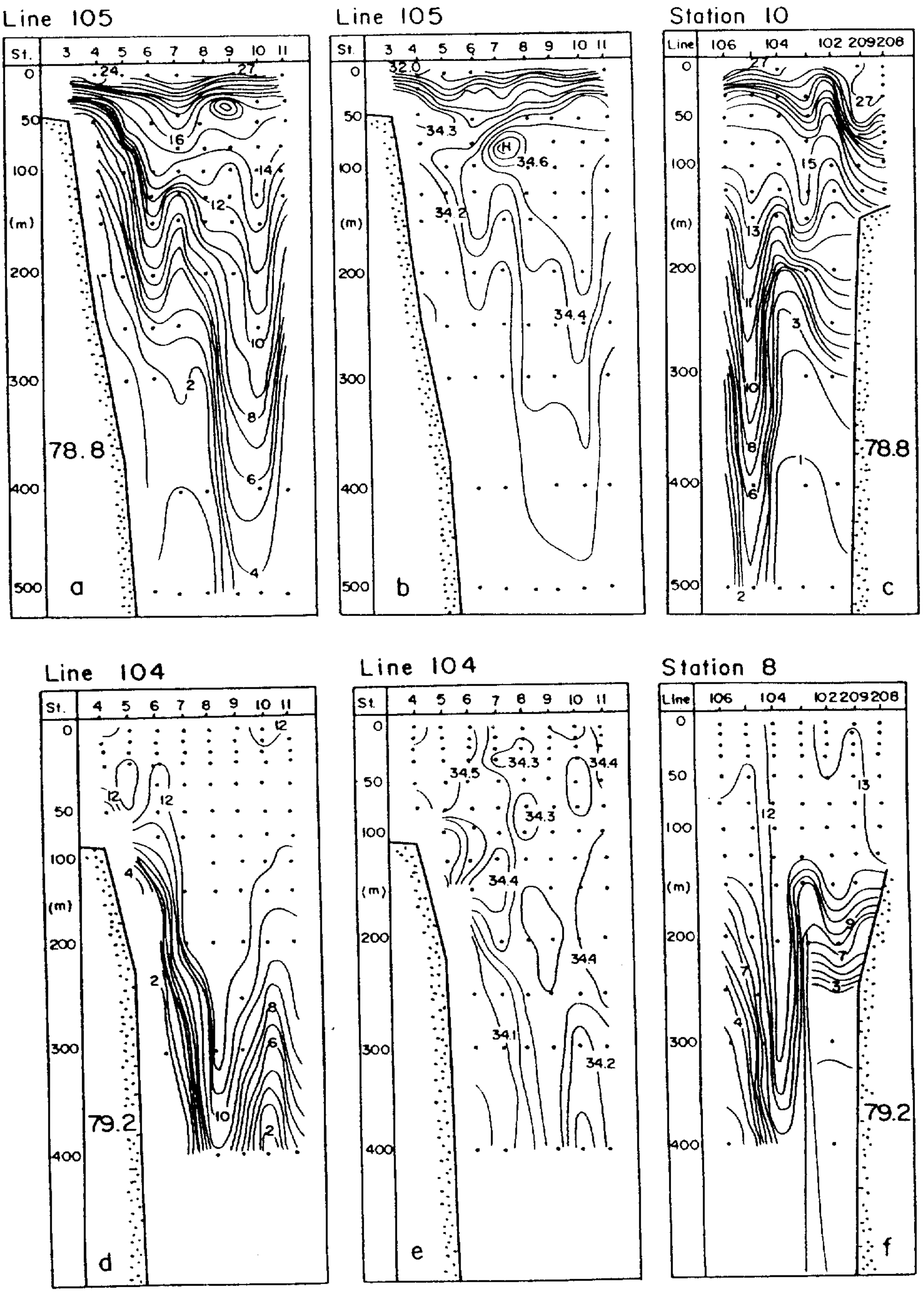

Fig. 4. The vertical structures of the warm eddies in August 1978 and February 1979. The left (a, d) and the middle (b, e) illustrations are the east-west sections of temperature and salinity repectively, and the right (c, f) is the north-south temperature section.

were also observed in 1973, 1975 and 1980. It is interesting to note that a warm eddy was not observed at the study area in 1972.

Vertical structures of the warm eddy

The center of a warm eddy is defined by the

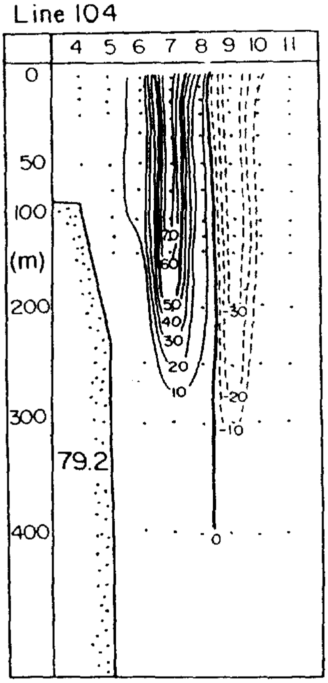

Fig. 5. Vertical distribution of geostrophic current velocity of the warm eddy referenced 400 m depth in February 1979. Solid lines indicate the northward component of velocity and dashed lines the southward component of velocity.

position of the highest temperature on the horizontal temperature distributions at 200 m depth. It is known from the Table 1 and Fig. 3 that warm eddies were often observed in the southwest of the Ullung Island. The most frequently observed position is between 37.00°~37.55°N, 130.00°~131.00°E. This area is the first ridge of the meandering where Tanioka (1968) reported that 80% of the volume transport of the East Korean Warm Current is returned southwards of the Ullung Island and flows eastwards along the polar front. This fact suggests that many warm eddies are formed inside of the first ridge of the meandering main axis.

Fig. 4 shows the typical forms of the vertical structure of the warm eddy along the line 105 in August 1978 and the line 104 in February 1979. The left illustration (Fig. 4a and 4d) in the upper and lower figure is the east-west temperature distribution and the middle illustration (Fig. 4b and 4e) is the salinity distribution and the right illustration (Fig. 4c and 4f) is the north-south temperature distribution. As seen in August 1978, we can find two warm eddies. The shallow one has about 300 m thickness at station 6, while the second warm eddy is quite deep and might have reached the bottom. It is seen in the horizontal temperature distribution that deep warm eddies were separated from the Tsushima Current (Fig. 3j and 3k).

Vertical temperature and salinity structures of warm eddies (Fig. 4a and 4b) show that surface layer above the warm eddy might be covered with another water mass which is made by summer heating or moved from another region. As the surface layer above 100 m is separated from deeper layer by the strong seasonal thermocline, a submerged warm eddy can not be observed through aerial remote sensing. The warm eddy in February 1979 (Fig. 4d~4f) is a typical winter type. Because homogeneous warm water above 12℃ and 34.3‰ occupies the area from the surface to 300 m depth at the center of the eddy, it is thought that the thick homogeneous layer above 12℃ was made by the convection from atmospheric cooling in winter (Tomosada, 1968; Shin et al., 1992). In other words, the warm eddy in February 1979 was generated in 1978 and the occupied depth was deepened in the winter of 1978/1979. While, right after generation, warm eddy has shallow depth less than 300 m (Fig. 4a)

Fig. 5 is the vertical distribution of geostrophic current velocity of the warm eddy referenced to 400 m in February 1979 (Fig. 4d), and indicates that the current of the warm eddy is anticyclonic (clockwise) flow. Maximum northward and southward component of velocity was shown at the western and eastern part of the warm eddy with about 70 and 30 cm/sec, respectively. According to Kim et al. (1993), maximum current velocity of the warm eddy observed in 1992 and 1993 was about 30~70 cm/sec.

The observed frequency of the warm eddy

The bimonthly frequency of observation of the warm eddies is presented in Fig. 6. The frequency decreases from August to the end of June of the

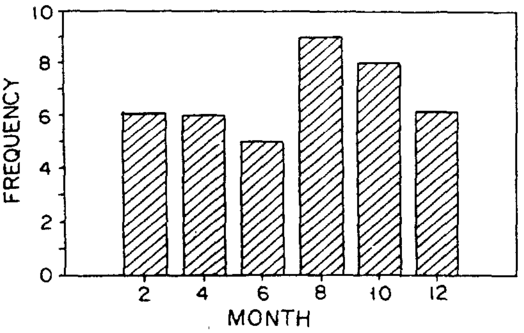

Fig. 6. Bimonthly distribution of the observed frequency of warm eddies in the area studied.

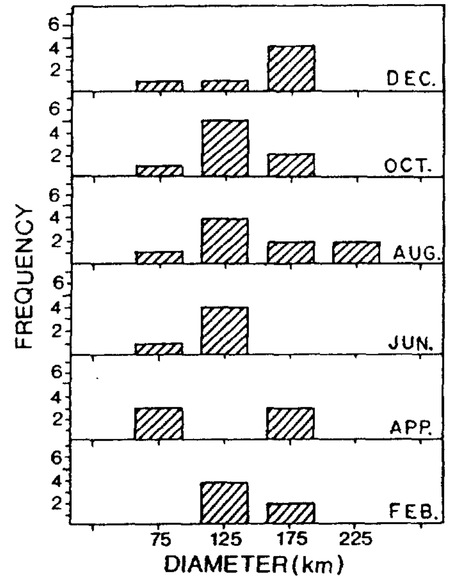

Fig. 7. Bimonthly distribution of the east-west diameter of warm eddies in the area studied.

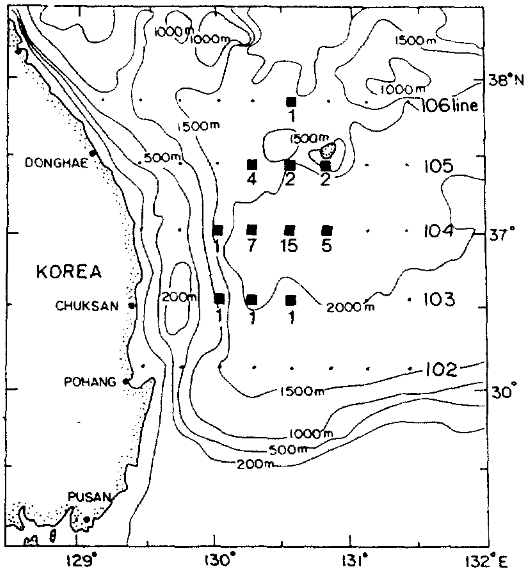

Fig. 8. Spacial distribution of warm eddies at 200 m depth with bottom topography. The number of each station indicates the observed frequency of warm eddies.

next year. Fig. 7 shows the bimonthly distribution of the east-west diameter. The diameter also decreases through the same period. The diameter exceeds 200 km in August and decreases to less than 125 km in June, but the eddies of 100~150 km in diameter are most frequent. In spite of the same summer months, it is interesting that the frequency is maximum and the largest eddy observes in August, and reversed in June as seen in Fig. 6 and Fig. 7. This could be explained as follows: the warm eddies are usually formed or developed in August when the Tsushima Current is strong, and are weakened through the winter up to the next June.

In order to see the place of the most frequent observation of warm eddies, the eddy-centers are plotted on a map with bottom topography (Fig. 8). The number of each station indicates the frequency of observation. Although there were many cases showing eddy-like feature at the edge of the study area, they were excluded in counting the observed frequency because it is unclear whether they are eddies or not.

The most frequently observed position appears at station 8 and 9 of the line 104. Compared with the bottom topography, most of the warm eddies are plotted inside the 1500 m contour line. Na (1988) suggested that the convergence of warm surface water driven by the wind could be referred as the warm core near the Ullung Island. Na and Kim (1990) also suggested cyclonic motion of lower layer in the Ullung Basin may play an important role in the formation of the anticyclonic warm core. Kim et al. (1991) calculated geostrophic westward current with a maximum speed of about 10 cm/sec at the southern part of the Ullung Basin. These mean that the development and the move-

Table 2. Movements of warm eddies

YEAR	DURATION (Month)	direction	VELOCITY (cm/sec)
1967	8~12	NW	1.15
1968	8~12	W	0.80
1970	6~12	N	1.04
1974	6~12	W	1.06
1978	8~10	N	2.56
1981	6~12	N	1.04
1984	10~12	S	1.20
1985	8~12	SW	1.19
1986	6~12	SW	1.86

ment of warm eddies have some relations with the bottom topography and the wind, that is to say, the deep Ullung Basin may control the development and the movement of warm (anticyclonic) eddies. Warm eddy out of topographic constraints of the Ullung Basin may move and dissipate quickly.

Movement of warm eddies

The movement of warm eddies is investigated by a successive picture of the horizontal temperature distribution. The movement of warm eddies is presented in Table 2. The direction of movement does not have any tendency in any one direction, but rather in various directions to the west, south or north. The velocity of their movements ranges from 0.80~2.50 cm/sec.

Movement of a warm eddy may be influenced by the neighboring currents, the Rossby wave and the topography. One example of the warm eddy which moves westward is presented in Fig. 9. From the three successive distributions, they must be the same warm eddy. The warm eddy was discoverd on the eastern edge of the figure for the first time in August and it completely moved into the center of the study area in December. This warm eddy which existed for four months from August to December in 1968, moved from 131.3°E to 130.3°E. The distance it moved for about four months was 84 km, therefore it moved about 0.7 km for one day (about 0.8 cm/sec).

To compare it with the phase velocity of the Rossby wave, the following data are chosen as numerical example:

Boundary depth between upper and lower layer, $h_0 = 200$ m

Upper layer density, $\rho_1 = 1.0255$ gr/cm^3

Lower layer density, $\rho_2 = 1.0274$ gr/cm^3

Acceleration due to residual gravity, $g' = (\rho_2 - \rho_1)g/\rho_1 = 1.82$ cm/sec^2

Beta effect, $\beta = 2 \times 10^{-13}$ cm^{-1} sec^{-1}

Wave length, $\lambda = 200$ km

Wave number, $K = 2\pi/\lambda$

With them, the radius of deformation (Ri) is

$R_i = \sqrt{g'h_0}/f = 19.1$ km,

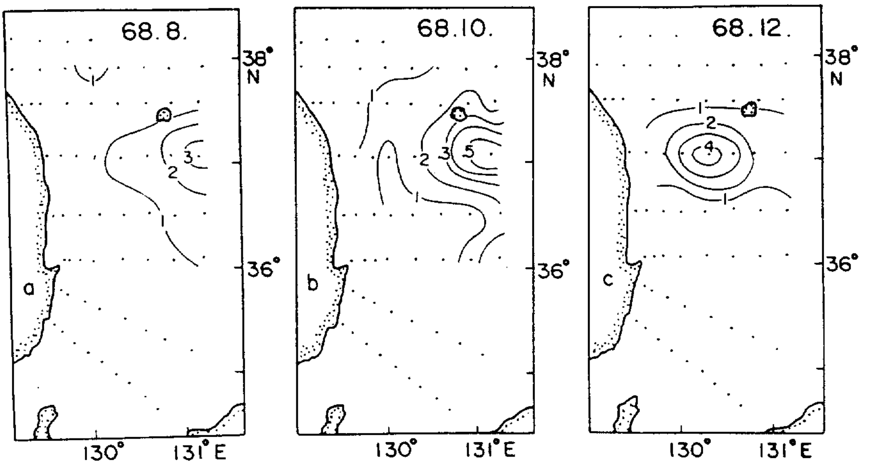

Fig. 9. Horizontal distribution of the warm eddy at 300 m depth during the period from August to December 1968.

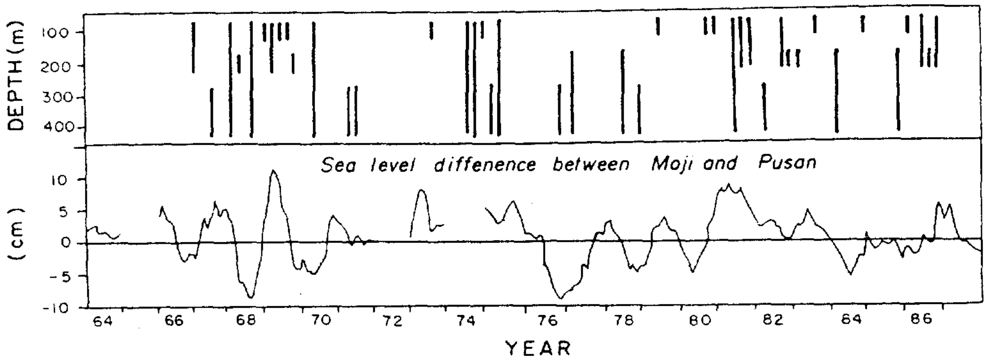

Fig. 10. Time variation of the distribution of warm eddies (above) and the sea level differences between Mozi (Japan) and Pusan (korea) (below). The vertical bars symbolize the depth and the thickness of warm eddies.

and the phase velocity of the internal Rossby wave (C) is

$$C = -\beta/(K_x^2 + K_y^2 + R_i^{-2}) = -0.5 \text{ cm/sec.}$$

0.5 cm/sec is small but in the same order, comparing it with the westward eddy movement speed in 1968, 0.8 cm/sec. It is thought that the movement speeds in Table 2 are the values during active warm eddy movement. According to Kim et al. (1993), average northward movement speed of the warm eddy to the east of Sokcho was 0.5 cm/sec from March 1992 to June 1992. In the Northwest Pacific, the average northward and westward translational speed of warm eddy to the east of Japan were 0.4 and 0.5 cm/sec respectively from December 1986 to March 1987. But, after a warm streamer was supplied from 28 March to 30 April 1987, the average northward speed was 3.2 cm/sec (Yasuda, 1992).

Warm eddies moved during the period from June to December in Table 2. The period is consistent with the time that the East Korean Warm Current moves northward actively. It is thought that the movement of an active warm eddy to the east of Korea is influenced mainly by the neighboring currents, that is to say, the East Korean Warm Current and the North Korean Cold Current.

Relation between warm eddies and the Tsushima current

Fig. 10 shows the thickness of warm eddies and time variation of the sea level difference between Mozi (Japan) and Pusan (Korea). In the figure, the short vertical bars above 200 m display the depth of shallow warm eddy defined by 1℃ isotherm at the center. The indicators appearing at 400 m mean that the depth of warm eddy reach deep layer of more than 400 m. The time variation of the sea level difference between Mozi and Pusan (Mozi-Pusan) was assumed to be the geostrophic transportation of the Tsushima Current.

The shallow warm eddies were observed when the sea level difference was positive in most cases. This indicates that there is a certain relation between the existence of the shallow warm eddies having strong baroclinic component and the sea level difference. The deeper warm eddies having strong barotropic component have no relation with either sea level difference or seasons. As can be seen in Fig. 11, a typical isolated warm eddy was observed in August 1981. Because vertical extent of the warm eddy exceeds 400 m depth (Fig. 10) and it had 7℃ homogeneous layer to about 240 m depth (not presented), it is thought that the warm eddy was generated in 1980.

These facts imply that both of shallow and deep eddies are formed by the water supply of the Tsushima Current in summer, but the wintered deeper eddies have longer life time so that there is no relationship between them.

CONCLUSIONS

It is known that most of warm eddies which

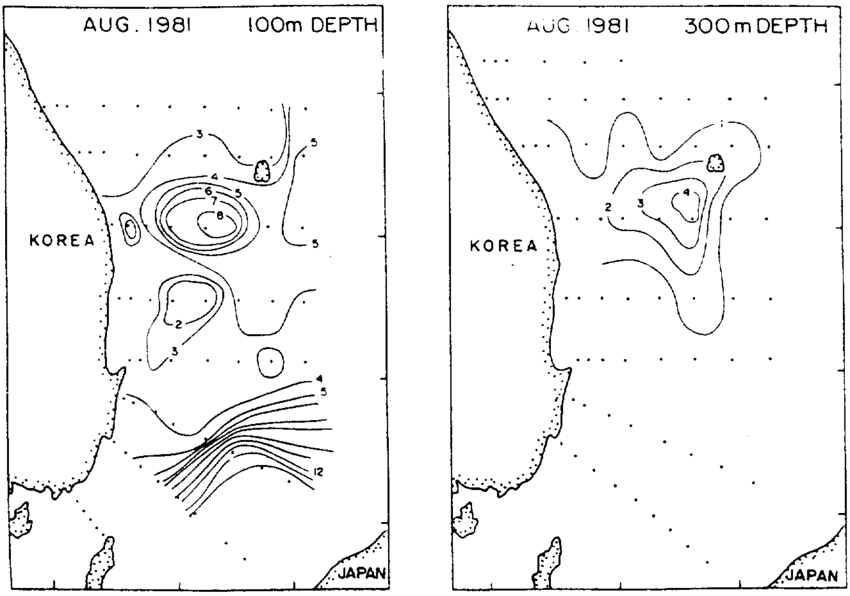

Fig. 11. The example of the warm eddy which is not connected by the Tsushima current.

develop near the Ullung Island have the shape of elliptical form and the sizes ranges from 100 km to 200 km and the core temperature of 6~10℃ at 200 m and the depth deeper than 300 m. The most frequently observed position in the southwestern part of the East Sea (the Japan Sea) is between 37.00°~37.55°N, 130.00°~131.00°E. Bimonthly distributions of warm eddies show the largest value of observed frequency and diameter in August, and the least in June. Therefore it was considered that warm eddies were related with developments of the East Korean Warm Current.

Warm eddies used to move west-, north- or southward in various speeds within a range of 0.80~2.50 cm/sec, or stayed over a few months at the same position in the southwest of the Ullung Island under the influence of the neighboring currents, the Rossby wave and the bottom topography. It is thought that the movement of active warm eddy is influenced mainly by the neighboring currents, that is to say, the East Korean Warm Current and the North Korean Cold Current.

According to the relationship between the position distribution of warm eddies and the bottom topography, the movement and the development of warm eddies seem to be controlled by the Ullung Basin.

The warm eddies should be divided into two groups. One group is composed of the shallow warm eddies with strong baroclinic characteristics, and the other includes the deep eddies with strong barotropic characteristics. The shallow group seems to be closely related with the positive values (in summer) of the sea level differences between Pusan and Mozi (the geostrophic transportation of the Tsushima Current). The deep group has no relation with the Tsushima current and passes a long time from the time of generation.

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