Three Dimensional Structure of the Ullung Warm Lens*

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We studied the existence, form, size, variation and formation of warm lenses in the East Sea(Japan Sea) during 1979~1988 based on annual reports of oceanographic observations published by the National Fisheries Research and Development Agency of Korea and data of the Hydrographic Office of Republic of Korea.

The warm lenses were formed in August, 1981, 1982, 1986 during study periods. The ranges of warm lenses were 50, 60, 90 *km* in the east-west(EW) direction and 100, 150, 120 *km* in the north-south(NS) direction in 1981, 1982, 1986, respectively. Because of the intrusion of cold water near 103 line, they shrink in horizontal scale in 1981. Most warm lenses were found at station 8 of 104 line in the vicinity of Ullung Island but centers of the lenses moved to the north in 1986.

The form and position of warm lenses were related with the intensity of the Tsushima Warm Current and the formation of warm lenses were related with the bottom topography.

Introduction

The Sea of Japan is deeper than any other seas around the Korean peninsular with average depth of 1350 *m* and maximum depth of 3610 *m*. It is semienclosed and surrounded by the Korean peninsula, Eastern Siberia, and Japan. It is connected with the North-West Pacific and the Sea of Okhotsk throug the Korea, the Soya, and the Tsugaru straits whose depth are shallower than 200 *m*.

In the surface layer the sea is mostly influenced by the Tsushima Warm Current entering into the sea through the Korea Strait and by the North Korean Cold Current(NKCC) originating from the Maritime Province-Liman Cold Current. In the middle and bottom layer more than 80% of the volume is "the Proper Water" which is characterized by the homogeniety of 1℃ or below in temperature and 34.00~34.05‰ of salinity. Two layers may be assumed ; the warm water at the top and the cold water(the proper water) beneath it.

Temporal and spatial variation of the temperature can be attributed to the interaction between warm and cold water. Warm water mass appeared near the Ullung Island and cold water. Warm water mass appeared near the Shimane-Ken, Honshu, Japan may be evidences showing interaction between the warm and cold water mass. Another good example of the complex variability in both temporal and spatial scale is appearance of two or three bra-

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nches of the Tsushima Warm Current.

The Ullung warm lens(hence after referred to as the warm water mass) in this study is an eddy defined as the warm water mass in the cold water area near Ullung Island, of which vertical cross section of the temperature shows U or V shape. Warm lenses have either convex or concave shape on the vertical cross section of temperature profiles which are symmetric or antisymmetric.

The horizontal thermal gradient of the warm water mass is larger than 0.03℃/*km* and thickness of the warm water mass is larger than 100 *m*. Shape of the warm water mass is either circular or elliptic on the horizontal distribution of temperature which is higher than the environmental waters.

Studies on eddy, such as warm and cold core ring separation from the Gulf Stream, have been active since 1930's. Williams and Franklin(1793) pointed out for the first time that cold core ring to the south and warm core ring to the north of the Gulf Stream are separated to form eddy due to the meandering of the Gulf Stream using surface thermal structure.

Church(1932, 1937) used thermograph records to study eddy. Iselin(1936) mentioned that warm core ring near the Gulf Stream is characterized by being permanent, whereas cold core ring shows high frequency in appearance because it can be developed by the strong northerly winds.

Rossby(1936) and *Oceanus*(1976) showed that duration of the Gulf Stream ring is 1-2 years with conical structure in the thermal distribution.

In 1960's Fuglister concentrated in origin, growt and decay of the rings. Rhines(1977) and Robinson (1982) showed that mechanism of origin, growht and decay of eddy is strongly related with both topography and strength of the Gulf Stream. Introducing new technology such as XBT, satellite remote sensing, and SIFAR made it possible to understand three dimensional structure of eddy and exact duration of eddies as well as tracking eddies(Richrdson et. al., 1981).

In the Pacific Ocean, Tomosada(1975) found that warm eddies are separated form the Kuroshio twice a year, once in spring and once in summer or fall near eastern sea of Honshu, and mentioned that eddies of 5℃ are mainly originated from depth of 300 *m* with 1-2 years of duration. Hatakeyama et. al.(1985) used satellited images and GEK data to study eddy formation associated with the Soya Warm Current variability near the coast of Japan. Kawabe(1982) studied the secondary Kuroshio front, warm water mass, and warm stream using satellite images and hydrographic data.

However, not much researches on eddy near Korean coast have been done.

Purpose of this study is to understand three dimensional structure of the warm water mass by analyzing not only archived hydrographic data but also all available resources. Endeavor will be focused on relating ocean circulation to the warm water mass near Ullung Island and their interaction.

Data and Method

Temperature data were available from the annual report of oceanographic observations during 1979～1988 published by the Fisheries Research and Development Agency(FRDA) Korea. Fig. 1. shows hydrographic stations of FRDA in research area.

Existences of warm water mass are visually inspected by drawing horizontal temperature distributions at the layers such as 0, 50, 100, 150 and 200 *m* using above mentioned data. The horizontal temperature distribution at 100 *m* depth layer is known to be the best representative of the existence of the warm water mass(Moriyasu, 1972). Therefore, existence of the warm water mass is mainly referred by the horizontal temperature distribution map at 100 *m*. Based upon this distribution map, the structure of the warm water mass such as center, length of the major and minor axis, lenght of north-south(NS) and east-west(EW) axis were analyzed in order to study seasonal and annual variability of the warm water mass and to relate them with warm and cold currents. After careful inspection of the horizontal temperature distribution maps during 1979～1988, it was possible to clearly locate the warm water mass in August, 1981, 1982 and 1986. The rest of this paper is to discuss about the warm water mass appeared during the three years.

Results

1. Structure of the warm water mass

Fig. 3. shows the horizontal temperature distribution at 100 *m* in August, 1981. The warm water mass of 5℃ or higher was found 72 *km* southwest of Ullung Island. It is elliptically centered near the station 8 of the line 104 and its axial lenght is 80 and 100 *km* long in the EW and NS direction, respectively. The most salient feature is the strong termal front slanted to the east. Tempreature of the surrounding water is relatively cold(3~5℃).

The vertical profile of temperature along the line 104 nearly parallel to 37°N of latitude is shown in Fig. 4. The seasonal thermocline, of which temperature is higher than 10℃, can be found in the 10~30 *m* depth layer except 30~50 *m* layer between station 5 and 7. The vertical temperature gradient in the thermocline is larger than 0.2℃/*m*. The vertical temperature gradient in the warm water mass, which is surrounded by the cold water (lower than 2℃), is as small as 0.01℃/*km* due to its isothermal layer of 7~8℃ between 100 *m* and 200 *m* depth.

Overall, the shape of the warm water mass is U-shape with convex cover. Another aspect of the vertical profile of temperature along the 130°20'E longitude passing through the center of the warm water mass is shown in Fig. 5. At station 8 of the line 104 in this figure, the vertical temperature gradient is as big as 0.2℃/*m* in the thermocline layer as before, and is negligibly small in the warm water mass(-270 *m*), which is surrounded by the isothermal waters of 5~6℃. The horizontal temperature gradient of the surrounding water is as large as 0.92℃/*km*. The warm water mass in N-S direction is therfore considered to be V-shape, of which temperature is 4~5℃ higher than that of surrounding cold water.

We repeated the same procedure to analyze the structure of the warm water mass appeared in 1982.

Fig. 6. shows the horizontal temperature distribution at 100 *m* layer during August, 1982. The warm water mass, warmer than 13℃, is half isolated to the east of the strong thermal front which

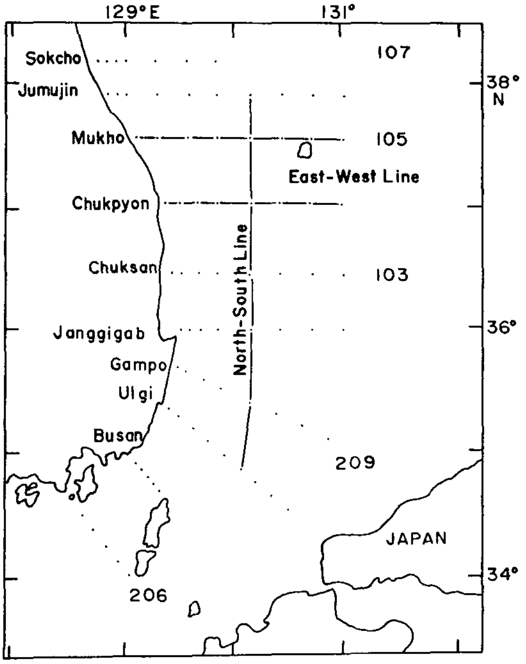

Fig. 1. Hydrographic station of the Fisheries Reseach and Devement Agency.

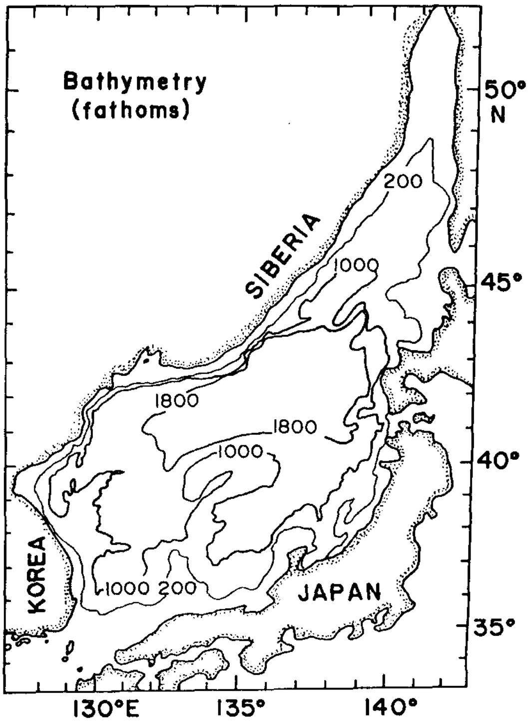

Fig. 2. Bottom topography of the Korea East Sea.

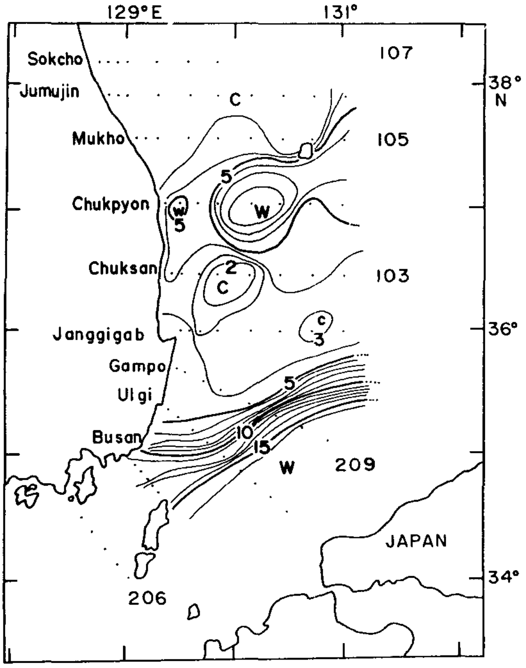

Fig. 3. Horizontal temperature distribution im 100 *m* of water depth in August, 1981.

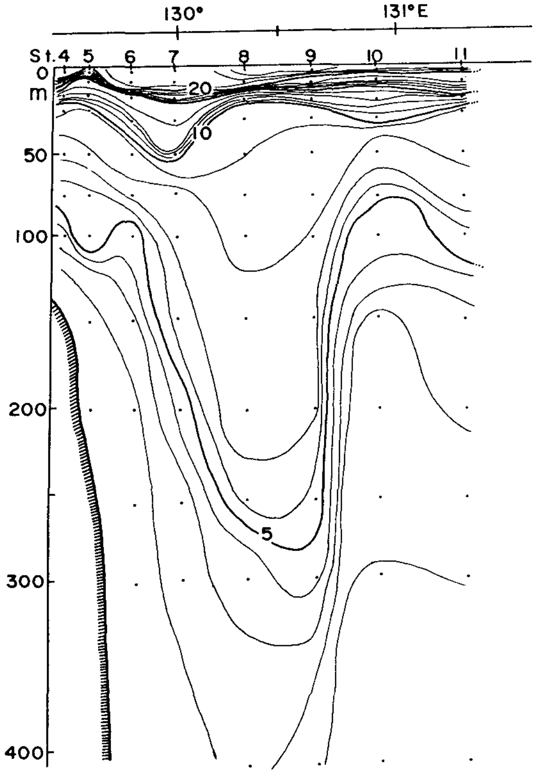

Fig. 4. Vertical profile of temperature along 104 line in August, 1981.

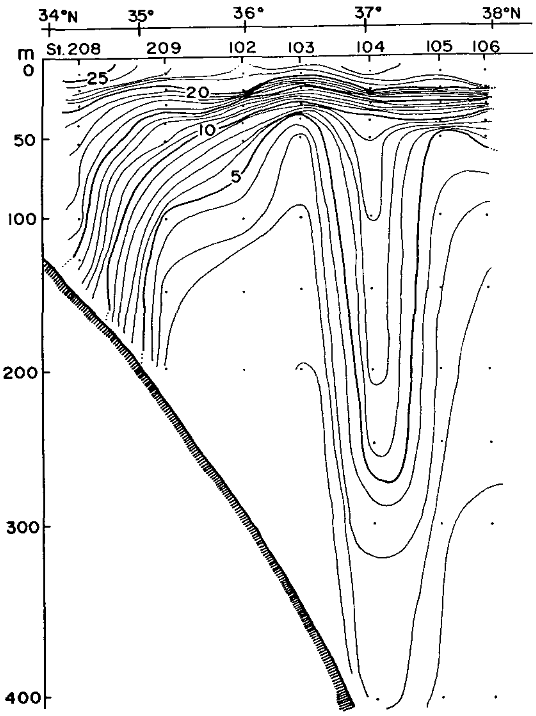

Fig. 5. Vertical profile of temperature along 130.3°E in August, 1981.

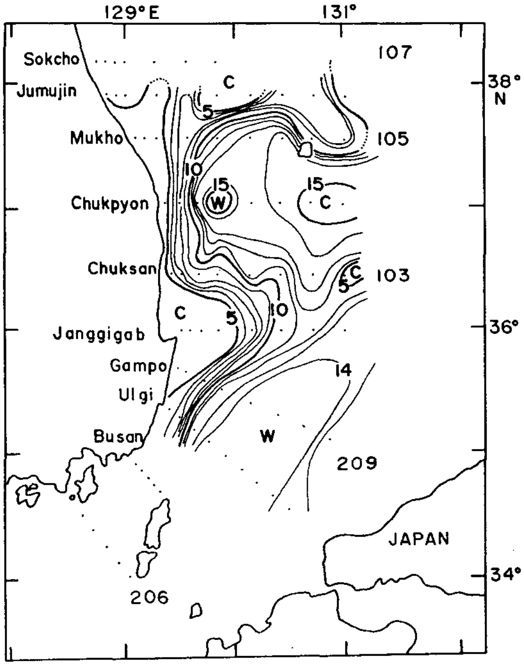

Fig. 6. Horizontal temperature distribution in 100 *m* of water depth in August, 1982.

is development along the eastern coast and started meandering off Mukho toward Ullung Island. Higher than 15℃ is inside the warm water mass in the south of the Ullung Island. The strongest thermal gradient across this thermal front is as large as 0.25℃/*km* near the line 104. The vertical profile of temperature along the 104 line in August, 1982. is shown in Fig. 7. The warm water mass in the figure can be found between seasonal and permanant thermohline. It is warmer than environmental water except between stations 7 and 10 above the 100 *m* depth, which is about 2℃ lower than the rest of the warm water mass.

Fig. 8. is the N-S cross sectional profile of vertical temperautre along the 130°3'E of longitude, which is passing through the center of the warm water mass. The horizontal temperature gradient of the thermocline appears to be 0.73℃/*km* at 120 *m* layer of the line 103 and 0.93℃/*km* at the north near the line 106,respectively. Thickness of this warm water mass can be estimated to be 200 *m*. It shows 2~5℃ differences with the environmental water.

2. Seasonal Variability

Fig. 9. shows the three dimensional distribution of temperature below 100 *m*, in Feburuary, 1986, along 130°E of longitude and 36°N of latitude on the left, and up to 131°20'E of longitude for the same lines on the right. The warm water mass of 7~8℃ can be detected as a double ring shape near Ullung Island, which is surrounded by the cold water of 5℃ or below. Another warm water mass of 8℃ can be found between coast and coastal thermocline near Chuksan. Thickness of the warm water mass is about 150 *m* between 100 and 200 *m* layer, below which temperature is colder than 1℃.

The same for April, 1986 as shown in Fig. 9 is shown in Fig. 10. The warm water mass of 15℃ or higher appears off Chuksan surrounded by the coastal thermal front as in February. Another warm water mass of 10℃ appears west of the Ullung Island. Neither thickness nor vertical structure of the

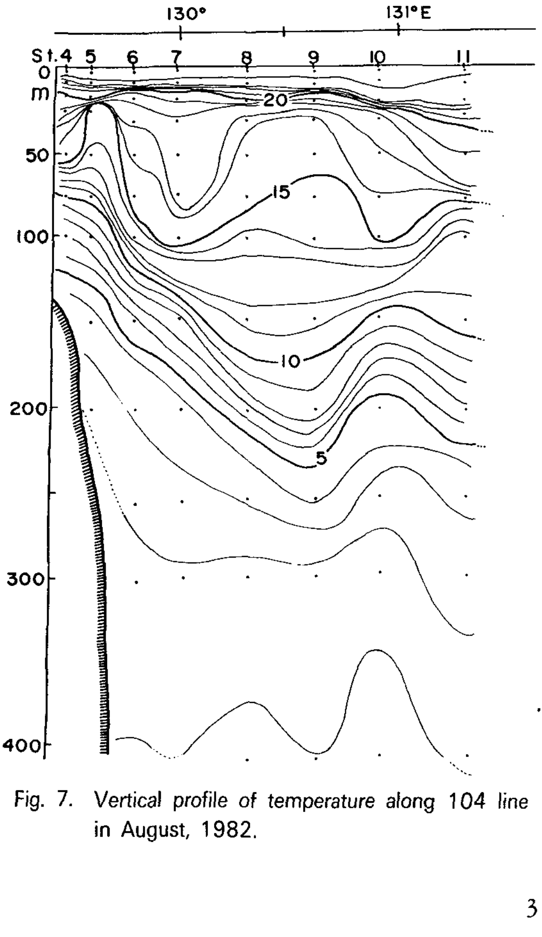

Fig. 7. Vertical profile of temperature along 104 line in August, 1982.

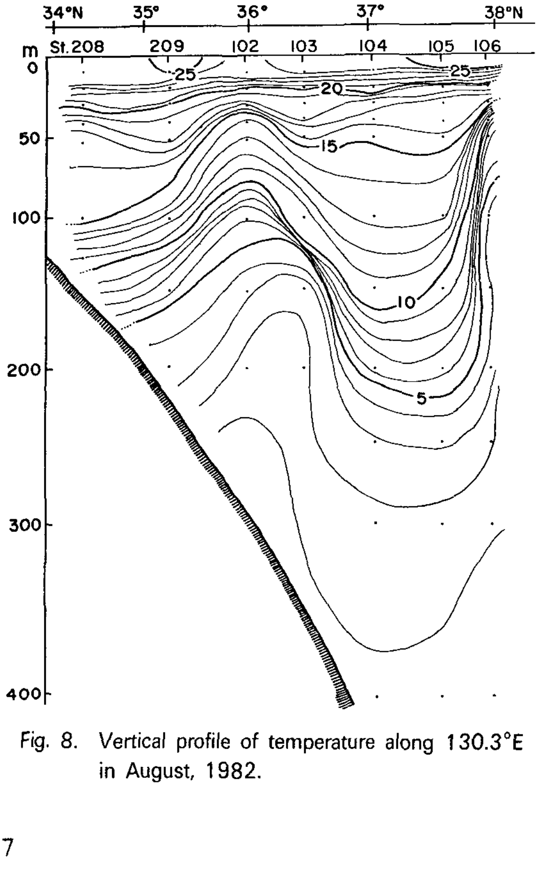

Fig. 8. Vertical profile of temperature along 130.3°E in August, 1982.

warm water mass in April and in February shows much differences.

The same for June as in Fig. 9 is shown in Fig. 11. On the 100*m* layer, the warm water mass was about 200*km* long in N-S direction, which is composed of water 8℃ or warmer. The deepest part of the warm water mass is little bit off toward east from the geometric center and reaches down to the 300*m* depth layer. Thickness of the warm water mass becomes thinner so that its shape is conical. In August, as shown in Fig. 12, the warm water mass of 10℃ appeared west of the Ullung Island.

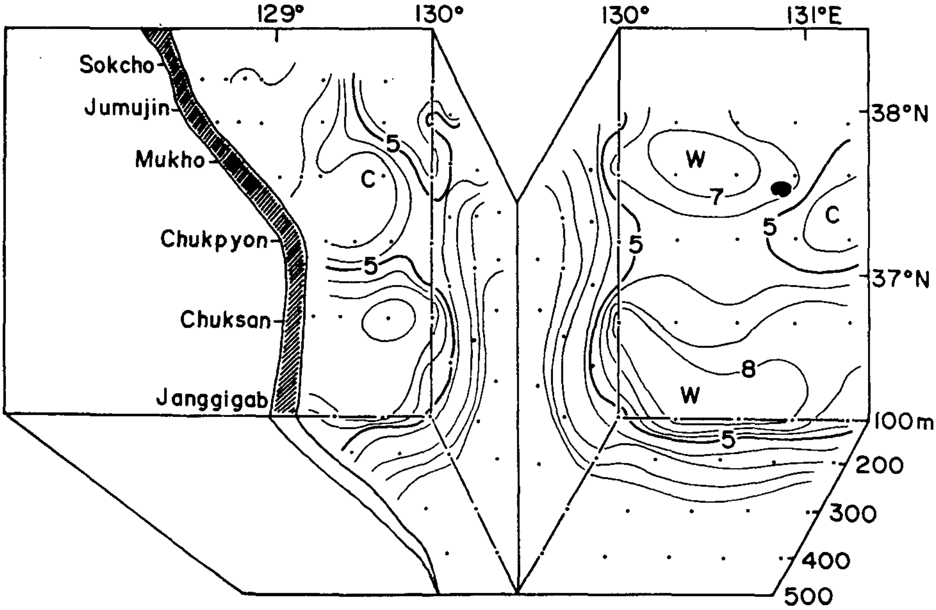

Fig. 9. Three dimension distribution of temperature in 100*m* of water depth in February, 1986.

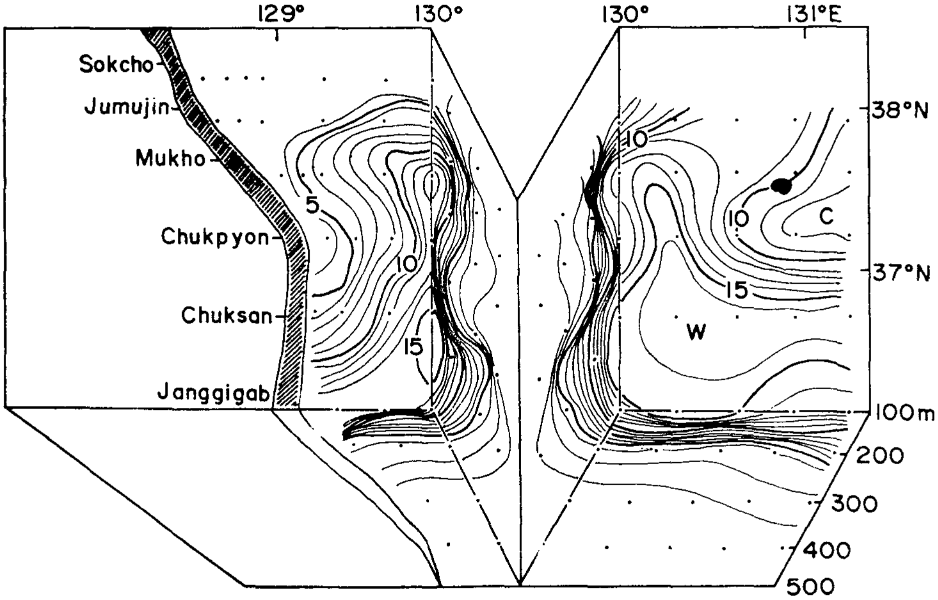

Fig. 10. Three dimension distribution of temperature in 100*m* of water depth in April, 1986.

When compared with one of June in Fig. 11, thermal front near the coast becomes weak.

Figures 13 and 14 also show the same for October and December, respectively, as in Fig. 9. In Fig. 13, the warm water mass with core of 11℃ or higher is found. The warm water mass with temperature of 8~9℃ shows elliptic, further south of which a thermal front with horizontal temperature gradient of 0.1℃/*km* appears. Temperature of the water south of the front is 15℃ or warmer. In contrast with other months, no warm water mass appears in December even though coastal thermal

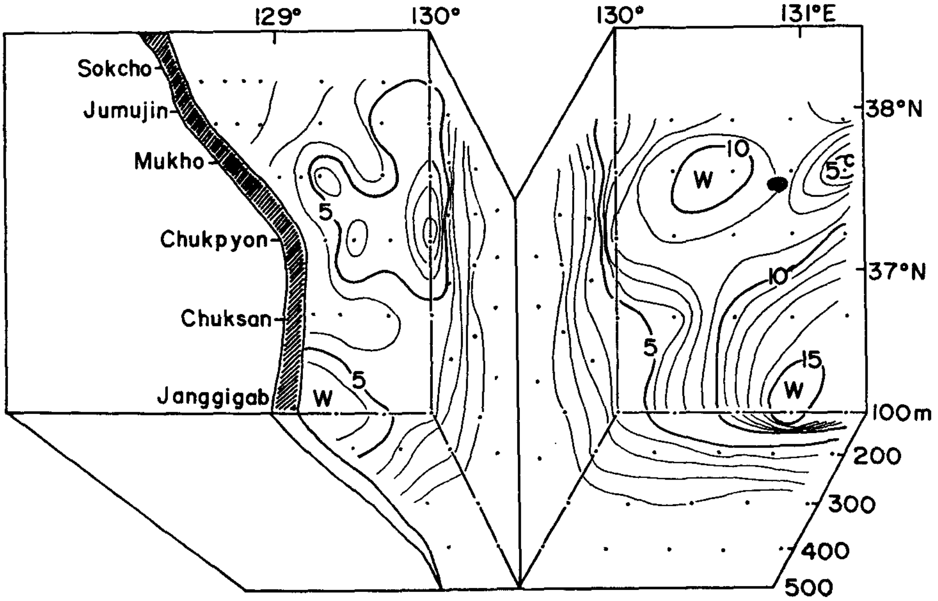

Fig. 11. Three dimension distribution of temperature in 100*m* of water depth in June, 1986.

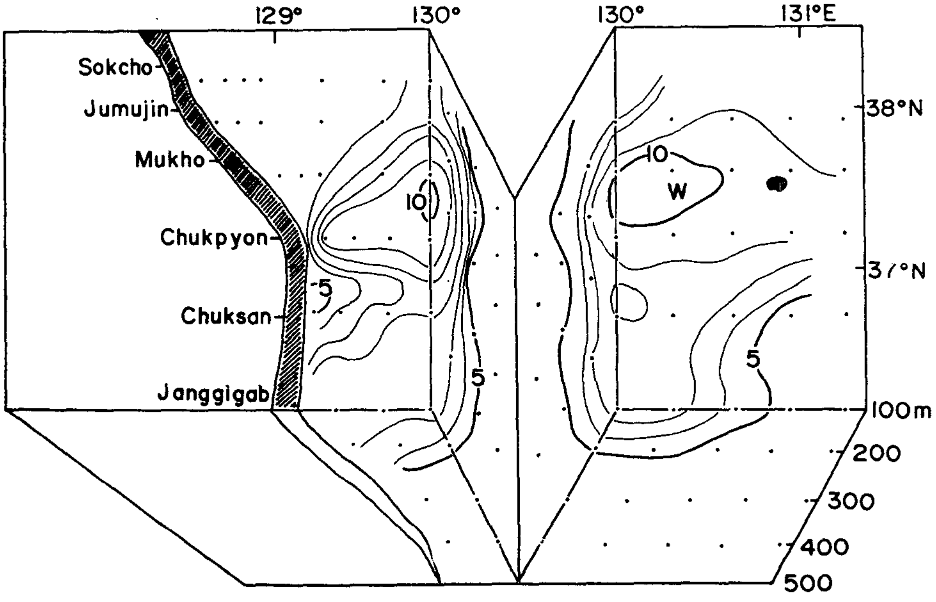

Fig. 12. Three dimension distribution of temperature in 100*m* of water depth in August, 1986.

front appears as before. The warm water mass, in summary from figures above, begins to appear near 37°N of latitude, moving to north near Ullung Island in June(~37.6°N of latitude) and to disappear after October. Appearence of the warm water mass may be attributed to the weakening or strengthening of the Tsushima Warm Current judged from the above analysis.

Hatakeyama et al.(1985) similarly reported that a warm water mass appears in the Sea of Okhotsk depending on the flow variability of the Soya Warm Current.

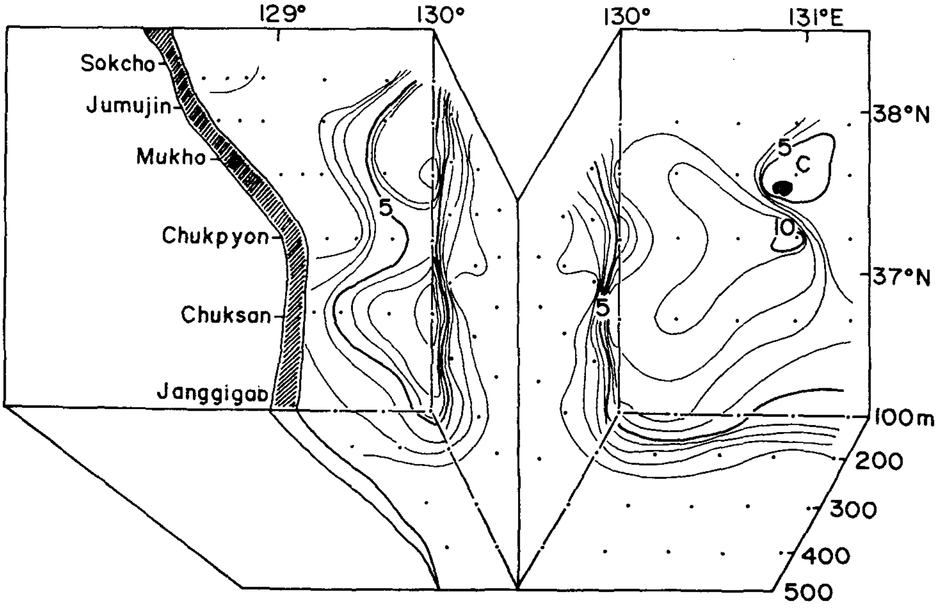

Fig. 13. Three dimension distribution of temperature in 100 *m* of water depth in October, 1986.

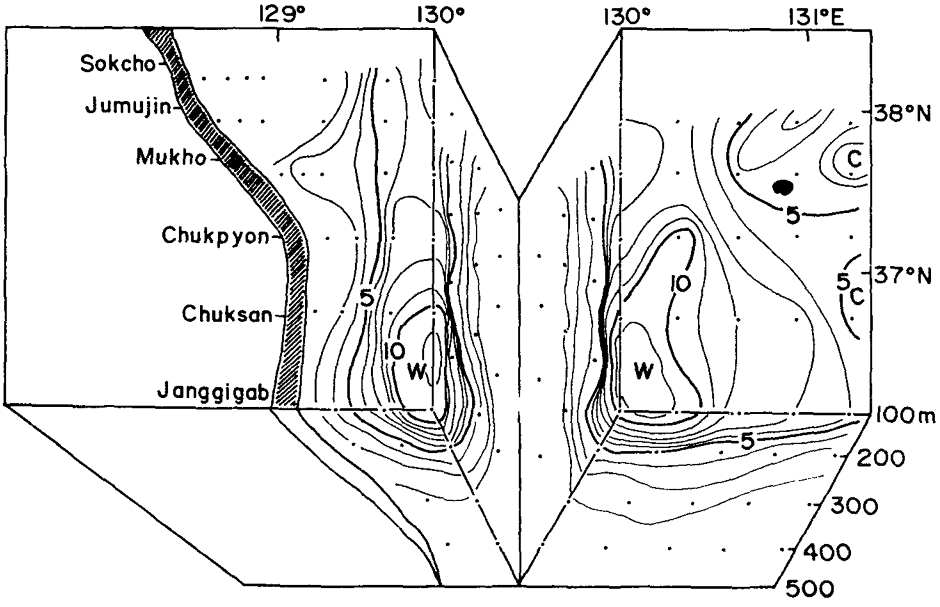

Fig. 14. Three dimension distribution of temperature in 100 *m* of water depth in December, 1986.

Discussions

1. Formation cause of warm water mass

Table 1. shows the characteristics of the warm water masses which appeared in the years '81, '82 and '86.

Fukuoka(1957) claimed that meandering of the Tsushims Warm Current is to obey the law of potential vorticity conservation on the varying bottom topography. Moriyasu(1972) explained that formation of the warm water mass is due to the meandering of the Tsushima Warm Current. Kang and Choi(1987) pointed out that appearence of the warm water mass over the basin south of the Ullung Island could be attributed to the topographic effect. Formation of the Ullung warm water mass may be also attributed to meandering of the Tsushima Warm Current which is influenced by the bottom topographic effect. The fact that most of the warm water mass appeared over the area 20~50 *km* southwest of Ullung Island with very slight change in size during August of '81, '82 and '86, is supporting the assumption above.

Influence of the Tsushima Warm Current itself may be considered next. According to Yoon(1982), the East Korea Warm Current(EKWC), a branch of the Tsushima Warm Current, flows to the north along the eastern coast of Korea until it meets with the NKCC and flows off the coast toward the east to form a meandering front. Kim and Legeckis (1986) mentioned that the warm water mass could be formed around the Ullung Island, which is associated with this meandering motion of the EKWC and NKCC. Bimonthly anlysis of data in 1986(Figures 9~14) showed that the warm water mass which had not been developed by Feburuary began to form as Tsushima Warm Current began to move northward in April, and was fully developed as Tsushima Warm Current also becomes the most influncial during August-October periods. It suggests that its appearnance and location are related with the seasonal variablity of the Tsushima Warm Current. In 1982 and 1986 when the northern limit of the Tsushima Warm Current was the farthest to the north, the warm water mass was convex lens shape and 20~50 *km* larger in diameter than in other years. This also suggests that variability of the Tsushima Warm Current, which is characterized by movement of the northern limit, may be correlated with the formation of the Ullung warm water mass.

However, the warm water mass also appeared in August, 1981 as shown in Fig. 3, even though EKWC was not developed in this year(Kim and Legeckis, 1986; Kim and Chung, 1984; Byun and Seung, 1984; Hong, Cho and Yang, 1984). No warm water mass appeared in August, 1980. A warm water mass began to appear in October and it lasted in August, 1980. A warm water mass began to appear in October and it lasted until December, 1980. The warm water mass found in 1981, therfore, would be a remnant of the warm water mass formed in 1980, seperated away from the Tsushima Warm Current. The one in 1981 may be classified into the last stage of eddy suggested by Tomosada (1975).

Causes for the warm water mass near Ullng Island, therefore, can be attirbute to the meandering and variability of the Tsushima Werm Current.

2. Annual variability of the warm water mass

Center of the warm water mass was of station 7~9 of the line 104 in 1981 and 1982, whereas it was on station 9~11 of the line 105 in 1986. This suggests that the farther from the coast the center of the warm water mass is, the farther to the north

Table 1. Charcteristics of the warm water masses

	Location of the center	Size(*km*)	Shape	Remarks
81	St. 6~ 9 of line 104	E-W : 50 N-S : 100	E-W : V N-S : V	weak TWC
82	〃	E-W : 80 N-S : 150	E-W : Diamond N-S : U	strong TWC (~40°N of lat.)
86	St. 9~11 of line 105	E-W : 90 N-S : 120	E-W : Diamond N-S : V	center moved from coast to northward

(TWC : Tsushima Warm Current)

the center of it moves.

The lengths of the warm water mass in E-W and N-S direction were 50 *km* and 100 *km* in Aug., 1981, and 80~150 *km* in Aug., 1982, respectively. That in 1981 was the smallest and one in 1982 was the largest during study periods. Again, the northern limit of the Tsushima Warm Current in 1981 was as low as 36°N of latitude(Kim and Legeckis, 1986), in which year no EKWC was developed(Kim and Chung, 1984). Whereas, the one in 1982 was as high as 40°N of latitude. It evidentally shows that size of the warm water mass has positive correlation with the strength or the nothern limit of the Tsushima Warm Current.

The warm Water mass was V-shape in 1981 and 1986 and U-shape in 1982 in N-S directional view, whereas V-shape in 1981 and diamond shape in 1982 and 1986 in E-W directional view. In 1982 when influence of Tsushima Warm Current was the strongest(Kim and Legeckis, 1986), the warm water mass was diamond shape and symmetric for the 100 *m* depth layer in E-W directional view, and U type in N-S directional view, decreasing its width as depth increased. Horizontal shape doesn't show much consistencies except elliptic shape with longer axis in N-S direction. No correlation can be found between shape and variability of the Tsushima Warm Current.

3. Kind of the warm water mass

A kind of the warm water mass appeared far off the main flow of the Tsushima Warm Current, which was associated with the lower northern limit of the Tsushima Warm Current, 36°N of latitude as in 1981. Another kind of the warm water mass appeared near the Tsushima Warm Current as in 1982 when the northern limit of the Tsushima Warm Current was as high as 40°N of latitude. Temperature differences from environmental of the warm water mass were as big as 5~8℃ in 1982, and temperature in the center of it is as high as 10~15℃. The warm water mass in 1982 is considered to be formed due to meandering of Tsushima Warm Current, from which the warm water mass is not separated.

4. Characteristics of the warm water mass

Two or theree dimensional structures showed contrast between warm water masses in 1981 and 1982 as shown in Table 1. The diameter of the warm water mass in 1982 was 150 *km* and 80 *km* long in N-S and in E-W directions, respectively, and shape of it was convex lens type in both upper and lower half, whereas convex type in lower part of the warm water mass with flat top in 1981. Thickness is 150~250 *m* on average. In August, 1981, the warm water mass in the layer between 100 and 250 *m* showed the thickest layer depth, which is composed of a single isothermal line of 5 ℃. Center of the warm water mass in 1981 and 1982, both of which were found at station 8 on the line 104, moved to northeast, station 9~11 of line 105 in 1986.

SUMMARY

In summary, as shown in Table 1, statistics based on data of 10 years show that isolated warm water mass appeared in 1981, and that attached warm water mass appeared in 1982 and 1986 in which years the northern limit of the Tsushima Warm Current was higher to the north than other years.

It is not certain that absence of warm water mass in some other years is true or is simply due to lack of data or other reasons. We, threfore, are encouraging scientists to solve these problems by long term, continuous and simultaneous observations and by proper anlaysis and interpretations of them.

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