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Two modes of the salinity-minimum layer water in the Ulleung Basin

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Abstract: CTD data taken bimonthly in 1991 show two modes of the salinity-minimum layer (SML) water less saline than 34.00‰ in the Ulleung Basin; the North Korean Cold Water (NKCW) and the East Sea Intermediate Water (ESIW). The NKCW was observed only along the east coast of Korea in summer, whereas the ESIW was observed around Ulleung Island in April and spreading southward in the Ulleung Basin subsequently. The depth of the SML is 100 to 200 m for the NKCW and 200 to 400 m for the ESIW. The temperature at the core of the NKCW is about 1.5℃, but that of the ESIW is higher than 2.0℃ in general during 1991.

1. Introduction

The East Sea has been divided into the warm water region and the cold water region (KAJIURA *et al.*, 1958; MORIYASU, 1972), since UDA (1934) found a polar front in the middle of the East Sea. MORIYASU (1972) defined water masses in the East Sea following this division; surface and subsurface water in each region, and the East Sea Proper Water (henceforth, ESPW) which is made of deep and bottom waters. Another water mass is situated between the Tsushima warm water and the proper water in the warm water region. This water is characterized by salinity-minimum and dissolved oxygen-maximum layer (KAJIURA *et al.*, 1958; MORIYASU, 1972). Despite of its distinct characteristics, detailed observation of salinity-minimum layer (henceforth, SML) water was scarce to understand its distribution and movement.

The SML has been also observed in the Ulleung Basin and became a subject of intensive investigation. KIM and CHUNG (1984) found an SML and dissolved oxygen-maximum layer in the southwestern region of the basin in September 1981 and named it the East Sea Intermediate Water (henceforth, ESIW) because of its distinct characteristic similar to that observed south of the polar front in the central part of the East Sea (KAJIURA *et al.*, 1958). KIM, LIE and CHU (1991) reported the widespread presence of the SML in the western half of the basin in August 1986. Previously KIM and KIM (1983) reported that the North Korean Cold Water (henceforth, NKCW) along the Korean coast has similar properties as the ESIW. Most of historical data used to identify the SML in the Ulleung Basin were taken with bottle casts at standard depths. Therefore, it is often difficult to distinguish the SML from the ESPW, and moreover the NKCW from the ESIW.

Recently KIM *et al.* (1991) indicated a possibility of two modes of waters for the SML, analyzing CTD data taken in the Ulleung Basin; three CTD sections across the Ulleung Basin show that the salinity-minimum water found at shallow depth off the Korean coast is less saline and warmer than similar waters observed widely in the basin. Although the NKCW and the ESIW are similar in their vertical structure, it is important to know whether their properties are different enough to imply different origin and passage into the Ulleung Basin.

Understanding of the circulation in the Ulleung Basin requires an in-depth investigation of physical characteristics and their temporal and spatial variations, for which bimonthly surveys were conducted in 1991, taking 60 CTD stations each time (Fig. 1). It should be noticed that the northernmost K-line running from the Korean coast to Dok Island is specially designed to find any indication of an inflow of the cold water from north. This is the first time that CTD sections were repeated between Ulleung Island and Dok Island. At each station SBE 19 profiler of Sea-Bird Electronics Inc. was

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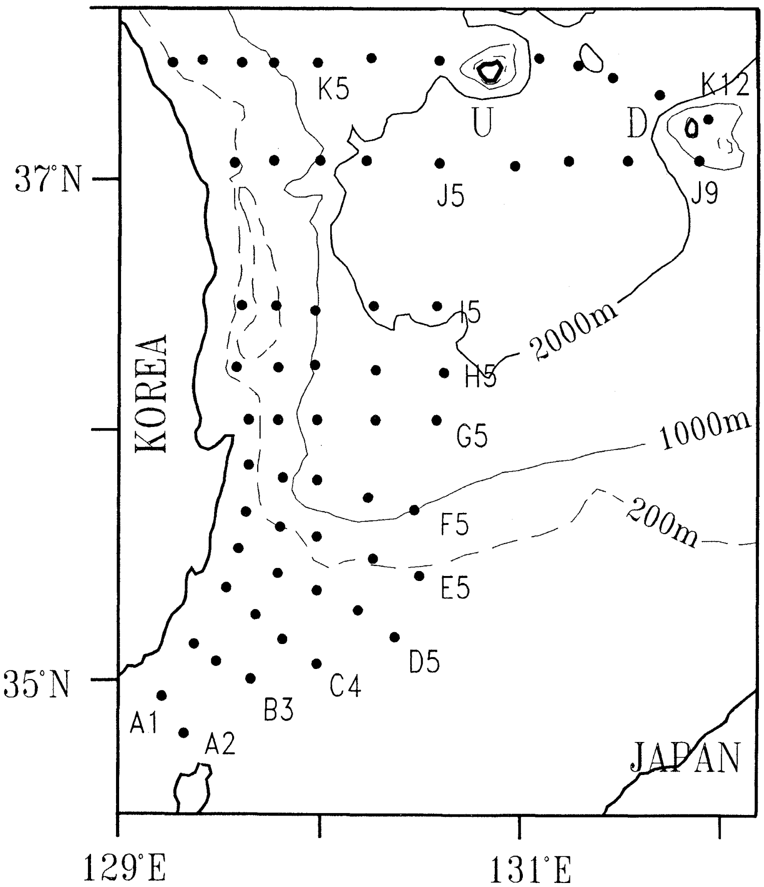

Fig. 1. CTD stations taken in April, June, August, October, 1991. Sections of K and J lines are presented in Figs. 2 and 5.

lowered to a nominal depth of 500 m at a speed of 60 m/min approximately, taking two samples of temperature, conductivity and pressure in one second, which give a vertical resolution of about 50 cm. Final data for analysis were obtained by averaging temperature and salinity data over two decibars.

The purpose of this paper is to report spatio-temporal variation of the characteristics of the salinity-minimum waters in detail, which renders clear distinction between the NKCW and the ESIW.

2. Vertical sections

Salinity sections shown in Fig. 2 illustrate a large change of salinity across the K-line from April through October 1991. In April salinity varies little between 34.1‰ and 34.0‰ in the upper 200 m except for the high salinity core near surface at stations K3 and K12. Below this the SML is observed across the section. In Fig. 2 the isohaline of 34.05‰ is chosen to indicate the minimum layer. Previously KIM and CHUNG (1984) used 34.05‰ as a criterion to define the layer in the southwestern region of the East Sea. It will be shown in the T–S diagram that this criterion is also useful in the present case. The SML in the K section is shaped like a bowl, deep and thick at the center near Ulleung Island and relatively shallow and thin away from the center. The diameter of the bowl is about 200 km. At stations K7 and K10 salinity in the minimum layer is even lower than 34.00‰. It is interesting to compare this section with another one taken at the same location in October, 1990 which is shown in Fig. 3. The SML defined by

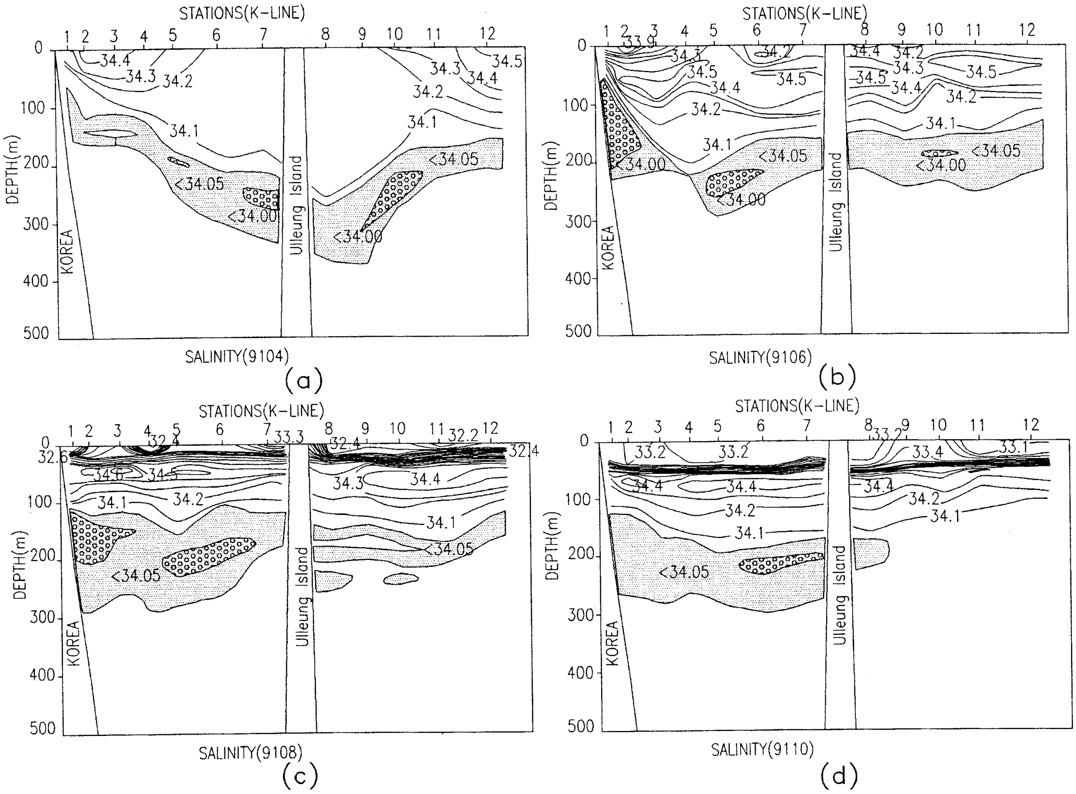

Fig. 2. K sections of salinity in April (a), June (b), August (c) and October (d), 1991. The waters with salinity less than 34.05‰ are shaded and salinity less than 34.00‰ is indicated with small circles.

34.05‰ was also observed six months before, but salinity is nowhere lower than 34.00‰. A period of six months is too long to speculate any specific process for the change from Fig.3 to Fig. 2. However, there is no doubt that the low salinity cores less than 34.00‰ in Fig. 2 represent a newly arrived water mass.

In June 1991 the salinity in the upper 100 m becomes higher than that observed in April. Despite this change, the SML remains, but relatively flat at about 200 m, losing its bowl-like structure. It is important to note that a new core of low salinity less than 34.00‰ appears at stations K1 and K2 near the Korean coast, leaning against the continental slope. Its shallow depth and triangular shape is separated from the rest of the SML. In August the SML becomes thicker between the Korean coast and Ulleung Island. However, two cores of low salinity are not connected closely. In October the core near the Korean side disappears as the thickness of the SML is reduced and its presence east of Ulleung Island is limited only at K8.

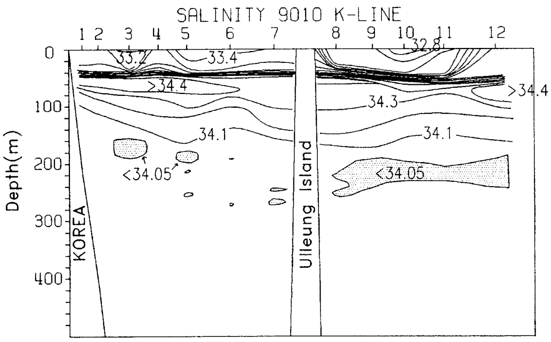

Fig. 3. Same as in Fig. 2 except for October, 1990.

We select stations K2 and K10, where cores of low salinity appear in August and April, to examine the variation of the T–S relation in time.

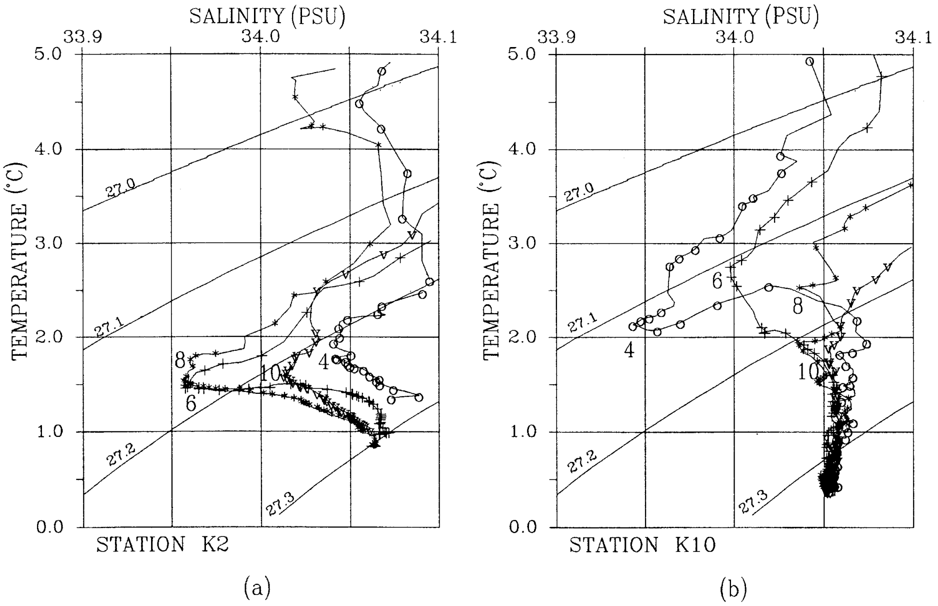

Fig. 4. Temperature-salinity diagrams for waters colder than 5℃ at stations K2 and K10. Numbers 4,6,8 and 10 represent months of observation.

Since the low salinity at intermediate depths is of our interest, Fig. 4 shows T–S diagram for temperature range of 0–5℃ only. The lowest salinity observed at K2 is about 33.96‰, nearly the same for June and August. This diagram indicates that below this layer salinity increases rapidly as temperature changes little, particularly so in June and August. Although the lowest salinities in April and October are higher than 34.00‰, all T–S curves clearly indicate the presence of the salinity-minimum.

At station K10 the lowest salinity is observed in April, which is less than that observed in June and August at K2 by 0.013‰. The minimum at K10 in June is substantially larger than that in April, but still very well-defined. In August multiple values of the minima appear as their salinities increase further, which is true at stations K8 and K9 as shown in Fig. 2. The minimum at K10 is not apparent in October. From T–S curves at K2 and K10 it is possible to distinguish the SML by S = 34.05‰, because of its relatively stable salinity for cold waters with T < 1℃ and the rapid increase of the salinity upward. Therefore salinity-minimum layers are indicated according to this criterion. It is also noticed in the T–S diagram that temperature of salinity-minima at K2 in June, August and October is about 1.5℃, but that at K10 is higher than 2.0℃ in general.

Salinity section along J-line taken in April also shows a bowl-shape structure of the SML in Fig. 5 which is similar to the SML along K-line. The depth of the bowl is between 300 m and 400 m, which is deeper than that shown for K-line (Fig. 2). It is interesting that the bowl-shaped minimum layer is imbedded at the base of permanent thermocline in the temperature range of 2–4℃ as can be seen in Fig. 5. Geostrophic current relative to 500 db is of the order of 5–10 cm/s into the section between J3 and J6 and out of it between J6 and J8. Together with a meridional section passing through J5 it is possible to show that these currents make a clockwise circulation around the bowl-like structure. In October the SML of J-line is in general flat at about 200 m without the core (S < 34.00‰). The temporal change of the salinity section from April to October is consistent with that of the temperature section.

3. Lateral spreading

Fig. 6 shows the horizontal distribution of the lowest salinity at stations with the SML. In April SML is observed extensively along K- and J-line in the northern part of the survey area.

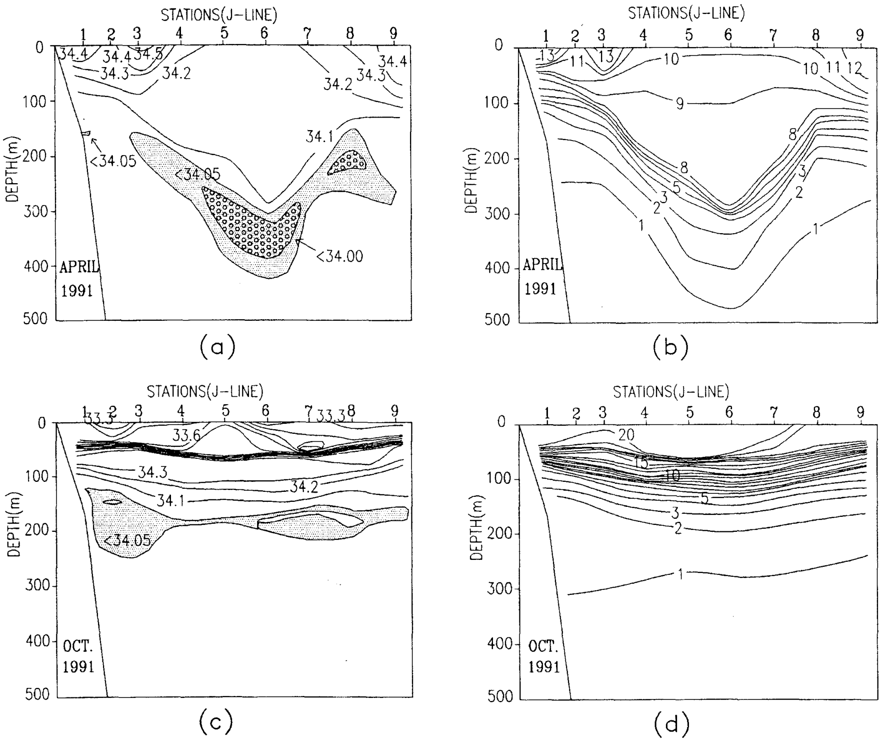

Fig. 5. J sections of salinity (a, c) and temperature (b, d) in April (a, b) and October (c, d), 1991.

Particularly it is noticed that the low salinity less than 34.00‰ is distributed around Ulleung Island. Except for two stations K11 and J9 temperature at the SML is higher than 2℃. It is important that temperature for salinity less than 34.00 ‰ is higher than 2℃ without any exception.

From April to June we notice several changes in the horizontal extent of SML. First, a new low salinity core less than 34.00‰ appears at K1 and K2 (see Fig. 1 for location) near the Korean coast, which is more than 100 m thick as shown in Fig. 2. Its temperature is lower than 2℃ unlike the core observed around Ulleung Island in April. Second, the SML is newly observed at H5 and I5 which are located almost due south of Ulleung Island. The high temperature core ($T > 3$℃) associated with the SML moves southward at the same time. It is important to note that this movement is not limited at depth of the SML, as can be seen in Fig. 7. Horizontal temperature at 200 m clearly indicates the presence of the warm bowl around Ulleung Island in April, although we cannot close isotherm due to insufficient data. In June the warm bowl is located south of Ulleung Island. As it is shown already in Fig. 5 that the SML is part of the bowl-like structure circulating clockwise with warm water inside, the SML spreads as the warm bowl moves southward.

In August the SML is observed at most stations. Particularly the core of the low salinity less than 34.00‰ is found along the Korean coast, contrasting its prevalence around Ulleung Island in April. The core which is observed only at K1 and K2 in June appears along the Korean coast as far south as G1. It should be noticed that the temperature of this core is close to 1.5 ℃ except for a couple of isolated stations. East and south of Ulleung Island temperature of SML is higher than 2.0℃ in August like in April, although it is not as high as 4℃ as observed at some stations in April and June. Since the warm bowl remains in this area through August (Fig. 7), it is quite likely that the SML southeast of Ulleung Island is of the same water as observed in April and June. In October the core along the Korean coast disappears, although the

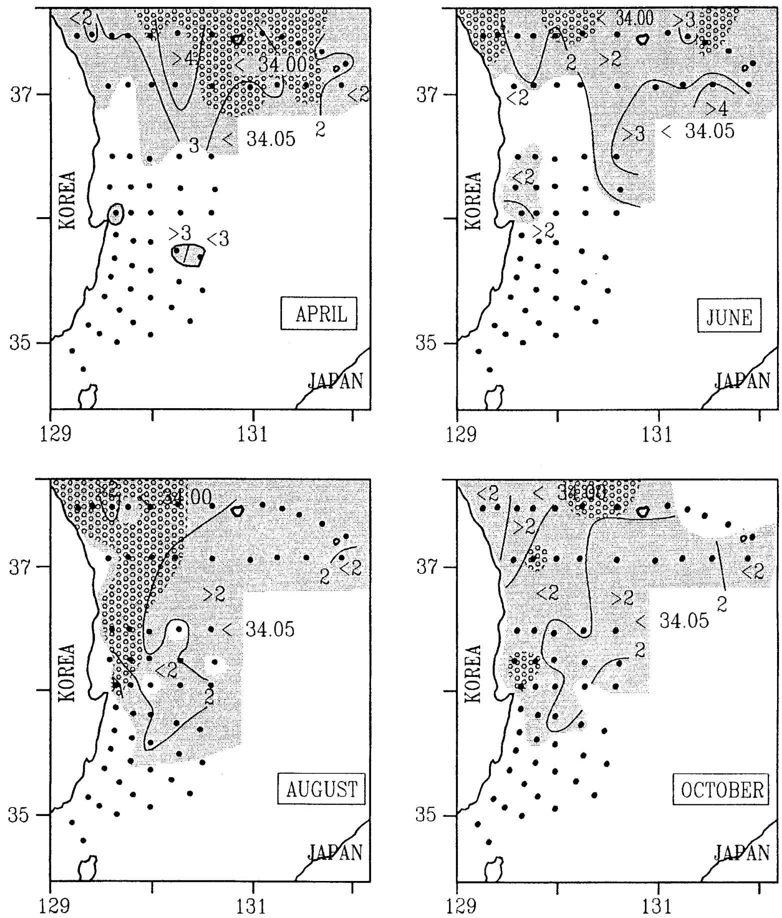

Fig. 6. Horizontal distribution of the lowest salinity in the salinity-minimum layer. The solid lines are the temperatures of the lowest salinity water in April, June, August and October, 1991. The waters with salinity less than 34.05‰ are shaded and salinity less than 34.00‰ is indicated with small circles as in salinity sections shown in Figs. 2 and 5.

SML is still observable widely in the Ulleung Basin.

4. Discussion and conclusion

In summary, the SML was observed in April, 1991 in the northern area of the Ulleung Basin with a low salinity core less than 34.00‰ around Ulleung Island. In August another core appeared along the coast of Korea. Salinities of SML cores are similarly as low as 33.95‰ as shown in Fig. 4, but they differ not only in the timing and location of observation in the basin, but their temperature and depth of observation. The former is warmer than 2℃ and observed deeper than 200 m and the latter is about 1.5℃ and shallower than 200 m. Since the latter was observed at K1 and K2 in June before its extensive presence along the east coast of Korea in August, it is reasonable to consider a current flowing southward along Korea, carrying this particular water. This water has been known as the NKCW (KIM and KIM, 1983), although there is no direct observation of this current yet.

It is very important to note that the former was observed extensively around Ulleung Island in April before the observation of the NKCW along the Korea coast. This indicates that there is another way for the SML to be introduced into the Ulleung Basin, as suggested previously by KIM and CHUNG (1984). As the SML is imbedded at the base of the warm bowl structure, it spreads into the basin as the bowl moves

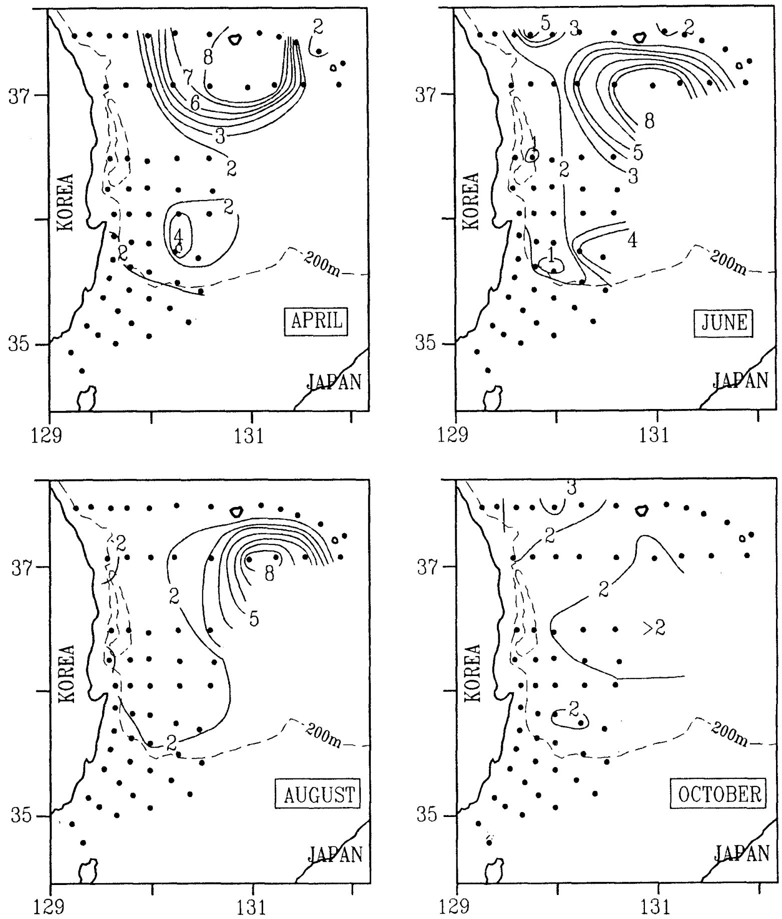

Fig. 7. Horizontal distributions of the temperature at 200 m in April, June, August and October, 1991.

southward in time. It seems that the presence of an anticyclonic (clockwise) circulation associated with the warm bowl is essential for the spreading of the SML.

The salinity of the SML water increases in time due to vertical mixing with neighbouring saline waters. However temperature changes little during this mixing process, because it has colder and warmer water above and below it. We can easily find an example of this process in Fig. 4. Temperature remains less than 2℃ at K2 and above 2℃ at K10 respectively over a period of six months, whereas the salinity increases in time.

The two cores of low salinity less than 34.00 ‰ with different temperatures suggest two different processes of their formation. First, it is possible that they represent different waters. There is no doubt that both of them are formed during winter due to cooling, most likely in the northwestern region of the East Sea. As temperature is in general low along the east coast of North Korea late winter, compared with offshore temperature, the two cores may originate from different locations; the NKCW along the Korean coast and the core around Ulleung Island from somewhere offshore. In this regard it is worthwhile to know that core temperature and salinity of the SML found at 37° 58′ N and 131° 00′ E, 60 km north of Ulleung Island on May 22, 1991 are 4.19℃ and 33.973‰ (Maizuru Marine Observatory, 1991). Similarly high temperatures of the SML were observed at a few stations nearby. These observations are consistent with the formation of the SML with temperature higher than 2℃.

Another possibility is that the two cores are formed in the same region, but at different time. As cooling continues throughout winter, part of water may leave the surface before the end of the cooling period, sinking and spreading at mid depth. On the other hand, the lower temperature of the NKCW implies that it is likely the final products of the cooling period along the coast of North Korea. At this point it is difficult to delineate the formation process any further without data taken in formation region during winter.

It is clear now that the NKCW is distinguished from the rest of the SML water in the Ulleung Basin, because of the separation in the temperature of the SML and its horizontal distribution in time. We postulate that the core of the SML around Ulleung Island found in April is different from the NKCW and term it the East Sea Intermediate Water (ESIW). When KIM and CHUNG (1984) introduced the ESIW based upon the data taken in 1981, its temperature range was 1–3℃ in the depth range of 100–300 m and no distinction was made for the NKCW. However, now it is certain that there are two modes of SML in the Ulleung Basin as observed in 1991, which spread in the basin following two different routes.

Recently there have been a couple of noteworthy investigations concerning this suggestion. KIM, LIE and CHU (1991) showed that in August, 1986 some of the SML water in the central part of the basin is lower than that along the Korean coast. KIM *et al.* (1991) showed two cores of the SML along the K-line in May, 1988; one near the Korean coast and the other near Dok Island which is the same location as station K11. These imply that the ESIW in the central part of the basin is not the extension of the NKCW, but has an independent route of southward flow in the basin.

It may be better at this point not to limit the temperature and salinity range of the ESIW. KIM, LIE and CHU (1991) showed a very significant interannual variation of T–S properties for the SML along a section which is identical to the K-line. The ranges of temperature and salinity which they showed are 1–4℃ and 33.80–34.05‰ respectively. Careful analysis of historical data is required in order to find any stable separation between the NKCW and the ESIW in their T–S properties such as found in 1991.

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