Ocean Science Journal, Vol. 41 No. 4, 227-234(2006)

Article

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Year-to-Year Variation of Cold Waters around the Korea Strait

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Received 20 November 2006; Revised 30 November 2006; Accepted 22 December 2006

Abstract – Year-to-year variation of bottom cold waters around the Korea Strait was investigated based on bottom temperatures measured by submarine telephone cable between Pusan, Korea and Hamada, Japan from 1982 to 1992. The characteristics of bottom temperatures could be divided into three different groups: the Korean side, the middle, and the Japanese side. Temperature drops in summer appeared in all the three regions implying the intrusion of cold waters into the Korea Strait. Significant decreases in the Korean side were observed in 1983, 1986, 1990, 1991, and 1992 when bottom temperatures were high in the middle. In contrast, bottom temperatures significantly decreased in the middle in 1985, 1988, and 1989 when the temperature drops in the Korean side were relatively small. This tendency for a negative relationship was also shown in the second mode of an EOF analysis. In the years when bottom temperatures significantly decreased in the Korean side, the cold water along the east coast of Korea expanded offshore and its temperature was low. On the contrary, cold water in the southern region of the Ulleung Basin developed in the years when bottom temperatures decreased considerably in the middle.

Key words – cold water, bottom temperature, Korea Strait, year-to-year variation, Ulleung Basin

1. Introduction

Oceanographic conditions in the Ulleung Basin of the East Sea are mainly affected by the distribution and characteristics of the Tsushima Warm Water (TWW) which is carried by the Tsushima Warm Current (TWC) into the East Sea through the Korea Strait. On the other hand, Cho and Kim (1996) observed the absence of the East Korean Warm Current (EKWC) in February 1991 and 1992 and suggested that the cold water underlying the TWW might play a role in the branching of the EKWC. Later, this suggestion was confirmed by a two-layer hydraulic model (Cho and Kim 2000). Furthermore, Isobe (1997) proposed that the circulation in the East Sea could change due to the intrusion of bottom cold water in the Korea Strait. Therefore, cold water combined with the TWW could be a major factor influencing circulation in the Ulleung Basin.

Cold water in the western side of the Korea Strait has been of considerable interest in many studies (Lim and Chang 1969; Park 1995; Cho and Kim 1998; Johnson and Teague 2002; Yun *et al.* 2004). Cold water has often been observed near the bottom in the Korean side in summer (Lim and Chang 1969) and it is known that the cold water has a maximum extent and lowest temperature in summer (Lim and Chang 1969; Yun *et al.* 1992). Using bi-monthly CTD surveys conducted in 1991 in the Korean side of the Korea Strait and the Ulleung Basin, Cho and Kim (1998) reported that the bottom cold water appeared within about 50 km of the Korean coast and its thickness was approximately 20-50 m. They also proposed that the salinity minimum layer (SML) water could form the bottom cold water in the Korean side.

Bottom cold water was found not only in the Korean side but also in the middle and Japanese side. In the middle, bottom cold water below 5°C was observed on the shelf northeast of Tsushima Island (Katoh 1993). In the Japanese side, bottom cold water exists in the north off Hamada all year round and becomes colder in the stratified period (Isoda and Murayama 1990). Meanwhile,

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Isoda an Oomura (1992) proposed that bottom temperature variation along a submarine telephone cable was related to the north-southward movement of bottom cold water.

Despite previous studies on bottom cold waters in the Korea Strait, year-to-year variations of the bottom cold waters are not well understood so far. Therefore, this study was performed to determine year-to-year variations of the bottom cold waters in the Korea Strait and to examine their relationship with the hydrographic conditions in the Ulleung Basin.

2. Data and Topography

We analyzed monthly bottom temperatures from 1982 through 1992 across the Korea Strait measured indirectly at the beginning of each month on a submarine telephone cable between Pusan, Korea and Hamada, Japan to examine variability of bottom cold waters around the Korea Strait. Since frequencies of 50 repeaters on the submarine cable varied according to surrounding temperatures, bottom temperatures at the location of repeaters (hereafter station) could be calculated using an empirical formula for each repeater.

To investigate bottom cold water, the distance between stations must be much shorter than the horizontal extent of the bottom cold water in the Korean side, for example 50 km (Cho and Kim 1998). Compared with most historical hydrographic data, bottom temperature data measured at stations which are spaced by 4.5-6.7 km have enough fine resolution. In addition, while there is the possibility that hydrographic data taken at standard depths of 25 m intervals near the bottom could not detect bottom cold water, bottom temperature data on the submarine cable are considered reliable.

Water depths of most stations were 120-150 m except around the trough in the western channel and near the coasts. Bathymetry shows a bank between St. 7 at the northern edge of the deep trough in the western channel and St. 10-13 in the shallow trough connected to the interior of the Ulleung Basin (Fig. 1). A bank around 132.2°E north of the submarine cable would be an obstacle preventing bottom cold water from moving southward and causing a different variation of bottom temperature between stations southeast and southwest of the bank.

Bi-monthly hydrographic data from the National Fisheries Research and Development Institute (NFRDI) were employed to examine the evolution of cold water by means of the temporal variation of T-S relationship along line N in Fig. 1. In addition to the NFRDI data, hydrographic data from the Japan Oceanographic Data Center (JODC) were also employed to describe horizontal distributions of water temperature at 100 m in August during 1982 to 1992.

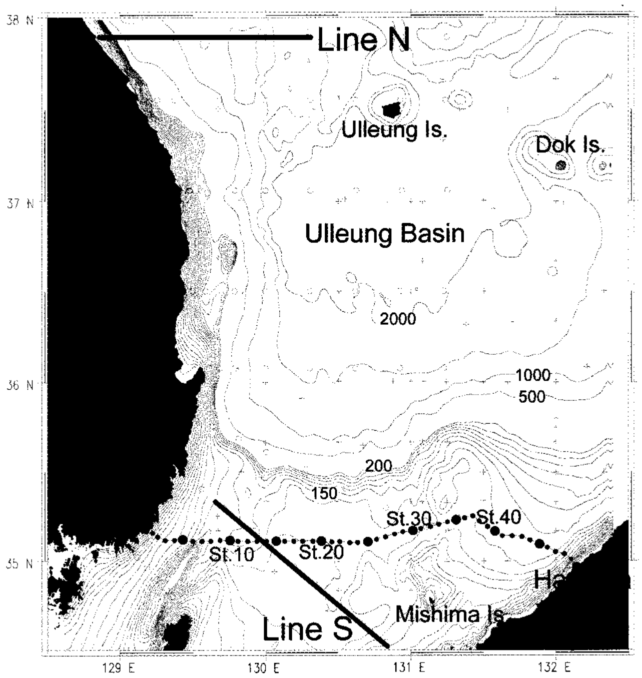

Fig. 1. Bathymetry in the Ulleung Basin and the Korea Strait and location of 50 repeaters (closed circle) along a submarine telephone cable located between Pusan, Korea and Hamada, Japan and hydrographic stations. Open circles represent the NFRDI stations and crosses represent stations of the JODC and other irregular observations.

3. Results

Annual variation of bottom temperature across the Korea Strait

In general, mean bottom temperatures on the submarine cable were higher as the water depths are shallower (Fig. 2). However, bottom temperatures were generally lower at St. 2-6 than other deeper stations. This is due to the uplift of bottom cold water to the Korean coast (Lim and Chang 1969; Yun *et al.* 1992; Cho and Kim 1998). Mean temperatures at St. 10-12 were lower than that at St. 9 by more than 2°C, which was larger than expected due to the difference of depths. It seems to be because that St. 10-12 were

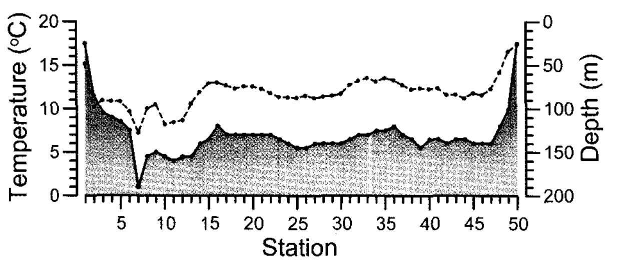

Fig. 2. Mean bottom temperature (dashed line) and water depth (solid line) at each station along the submarine cable.

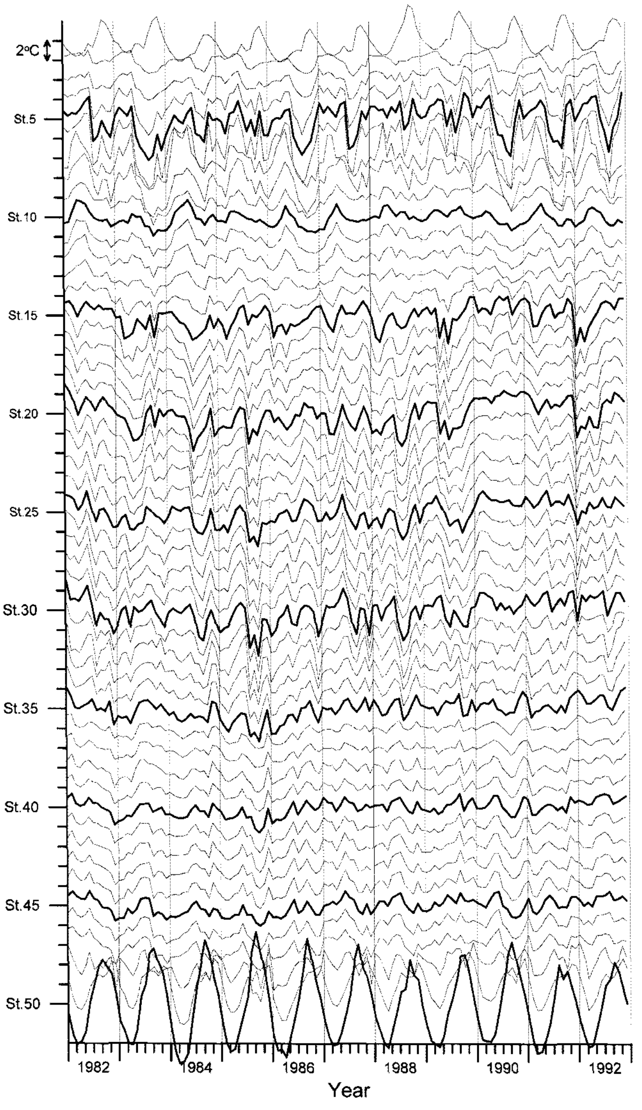

Fig. 3. Monthly bottom temperatures at 50 repeaters along the submarine cable.

located in the shallow trough connected to the interior of the Ulleung Basin.

Temporal variation in bottom temperature is shown in Fig. 3. Similar to surface water, bottom temperature at the nearest stations to the coast, *i.e.* St. 1 and St. 50, show dominant annual variation of low temperature in winter but high in summer. However, it is notable that bottom temperature at the second nearest station to the Korean coast was quite different with temperatures lower in summer than in winter. This implies that bottom cold water influences the Korean coast in summer. Such influences of bottom cold water near the coast were also detected near the Japanese coast (St. 49).

Bottom temperatures at stations around the western channel (St. 2-13) showed obvious seasonal variations. Temperatures started to drop around April and were lowest around September. This implied bottom temperature decreased in summer when bottom cold water intruded toward the western channel (Lim and Chang 1969; Lim 1973). In particular, in St. 4-8, annual variations were so great that bottom temperatures during September and October were as much as 3-8°C lower than April to June. Bottom temperatures around the western channel decreased continuously during approximately April-September, decreasing again around November. This implied that in addition to the primary development of bottom cold water in summer, secondary development took place again in winter.

Although seasonal variations of bottom temperature were obscure, drops in temperature in summer occurred in most years at other stations also in the middle and Japanese side, which implies the influence of cold water. It is remarkable that bottom temperatures at stations near the Japanese coast showed obvious semi-annual variations that were lowest in April and October.

Year-to-year variation of bottom temperature

Fig. 4 shows temporal and spatial variations in bottom temperature anomalies after removing the mean temperature at each station shown in Fig. 2. The anomalies clearly showed characteristics of temporal variation. From the anomalies, the characteristics of temporal variation could be divided into three different patterns with two boundaries, one near St. 13 corresponding to the eastern edge of the shallow trough and the other around St. 30-35 near the bank north of Mishima Island. Here, we define the Korean side, the middle, and the Japanese side from west to east, corresponding to three different patterns.

Long-term changes from 1982 to 1992 in bottom temperatures were significant in the middle and the Japanese side. While bottom temperatures in both the middle and

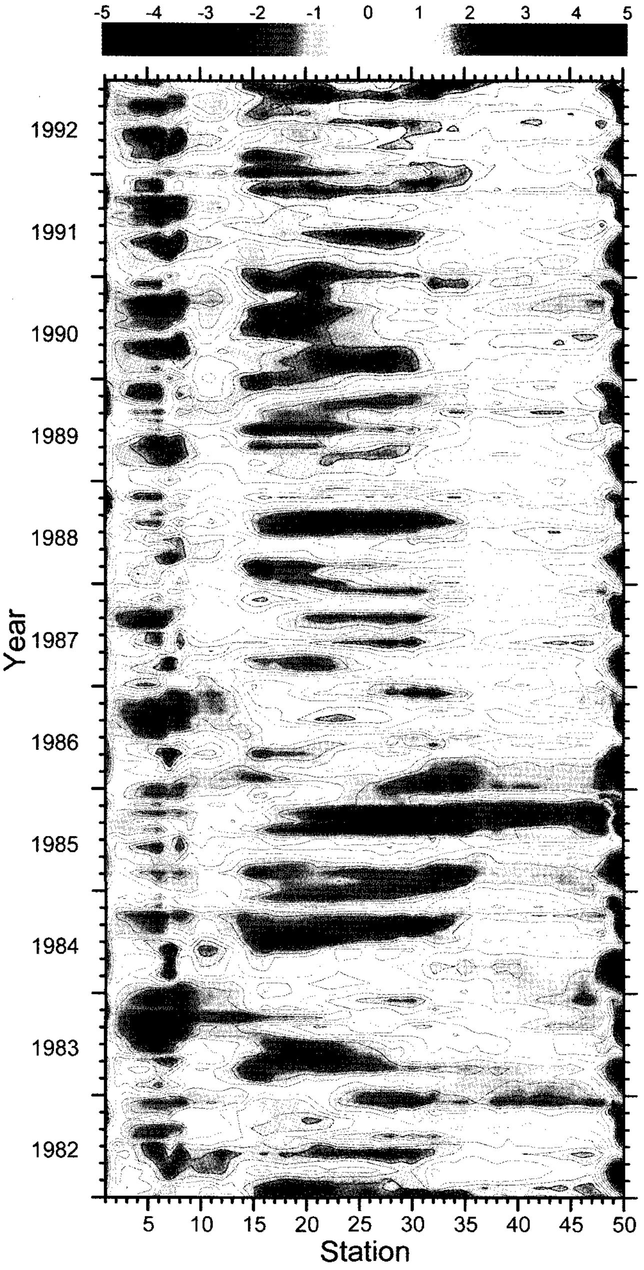

Fig. 4. Temporal and spatial variation of bottom temperature anomalies along the submarine cable. Anomalies were obtained by subtracting mean temperature at each station shown in Fig. 2.

Japanese side decreased since 1982 and reached a minimum in 1984-1985, temperatures changed differently since 1987. Temperatures in the middle were as low in 1988 as in 1985 and retained high since 1990, while temperatures in the Japanese side were high since 1987.

It is worth noting that bottom temperature anomalies in summer were much lower in 1984, 1985, 1988, and 1989 in the middle and in 1985 and 1990 in the Japanese side. However, anomalies were small in the Japanese side than the middle. Meanwhile, the large negative anomalies in the Korean side appeared in 1983, 1986, 1990, 1991, and 1992. There were tendencies that the negative anomalies in the Korean side were small in the years when those were large in the middle and vice versa.

These tendencies were also shown in hydrographic data across the Korea Strait. Fig. 5 shows the temperature section in September along Line S in Fig. 1 taken from 1988 to 1990 (Isobe 1994). The isolated cold water appeared around 130.5°E in 1988 and 1989 when large negative anomalies of bottom temperatures in the middle appeared. In contrast, the isolated cold water was absent and the temperature of cold water west of 130°E was lower in 1990 when negative anomalies of the bottom temperatures in the Korean side were large.

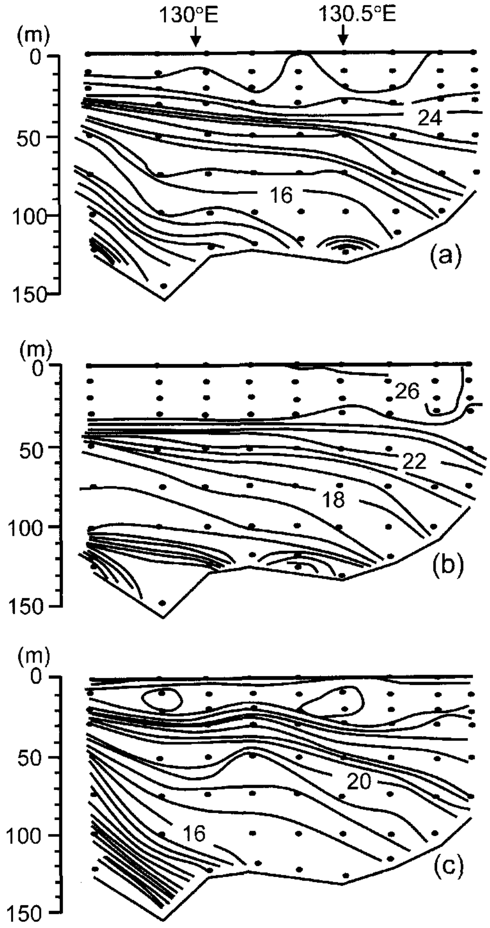

Fig. 5. Temperature section for September in 1988 (a), 1989 (b), and 1990 (c) along Line S shown in Fig. 1 (adapted from Isobe 1994).

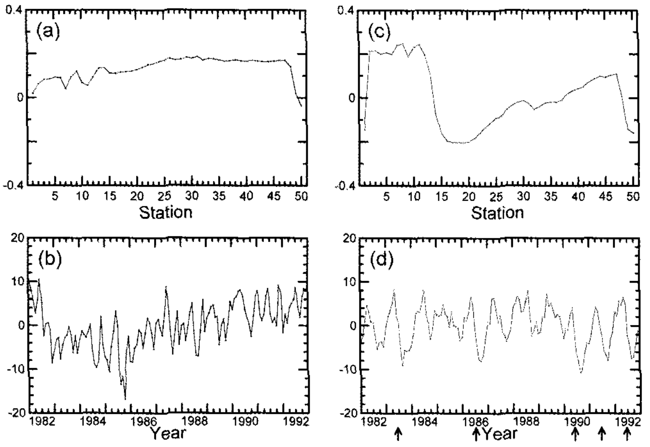

Fig. 6. Eigenvectors (a, c) and time coefficients (b, d) of the first (a, b) and second (c, d) mode of EOF based on a correlation matrix. The first and second modes explained 45% and 21% of total variance, respectively. Vertical arrows in (d) denote the years when the drops in summer were large.

First and second modes of empirical orthogonal function (EOF) analysis based on a correlation matrix manifest variability of bottom temperature anomalies (Fig. 6). Time coefficients for the first mode illustrate semi-annual variations in bottom temperatures having lower values in April and September including long-term variations with a decrease in temperature starting in 1982, reaching a minimum in 1985, and finally increasing again in 1986. However, the second mode shows a dominant seasonal variation with higher values in April and lower values in September. This seasonal variation could be related to the evolution of bottom cold waters in summer. In particular, large decreases in temperature in summer of 1983, 1986, 1990, 1991, and 1992 and small decreases in other years correspond well with year-to-year variations in the Korean side.

Components in the first mode eigenvector were larger in the middle and the Japanese side but small in the Korean side, indicating that the first mode explained the variation in the middle and the Japanese side rather than the Korean side. In contrast, components in the second mode eigenvector were large in the Korean side and the middle with opposite signs, indicating that the second mode explained the negative relationship between the Korean side and the middle.

The first and second modes contributed to the drop in bottom temperatures in summer in the Korean side. While the first mode also contributed to the drop in bottom temperatures in the middle, the second mode contributed to a rise in bottom temperature in summer. These imply that bottom temperature decreases in the Korean side are larger than those in the middle in summer. Furthermore, the opposite sign in the eigenvector for the second mode explains the negative correlation for the decreases in bottom temperature between in the Korean side and the middle. In other words, in the years when the decrease was large in the second mode, decreases in bottom temperatures in the Korean side were large while those in the middle were small and vice versa.

Relationship between cold waters in the Korea Strait and the Ulleung Basin

Distribution of water temperature at a depth of 100 m in August from 1982 through 1992 showed year-to-year variations of cold water (i.e. SML water) in the Ulleung Basin north of the Korea Strait (Fig. 7). Cold water below 10°C along the Korean coast was observed in all years, but its horizontal extent and temperature varied from year to year. The cold water contracted onshore around 37°N, which was probably due to the presence of warm water southwest of Ulleung Island, and expanded offshore around 36°N where the temperature of the cold water was below 5°C in most years except 1988 and 1989. South of 37°N, cold water occupied a wide region in 1983, 1986, 1990, 1991, and 1992 when bottom temperatures in summer were much low in the Korean side. In contrast, cold water was confined to the coast in 1985, 1988, and 1989 when bottom temperatures in summer were relatively high in the Korean side.

Meanwhile, cold water was clearly observed around 36°N and 131°E, in the southern region of the Ulleung Basin, in 1985, 1988, and 1989 when bottom temperatures in summer were relatively low in the middle. In particular, when cold water was less than 5°C in 1985, bottom temperatures were also quite low in the Japanese side. The distribution of cold waters at 100 m agreed with the year-to-year variation of bottom temperature in summer in the Korea Strait.

It is suggested that the North Korean Cold Water (NKCW), which is characterized by SML water, moves southward along the east coast of Korea in summer and the width of the NKCW becomes larger from April to August (Kim and Kim 1983; Yun *et al.* 2004). The relationship between the decrease in bottom temperatures

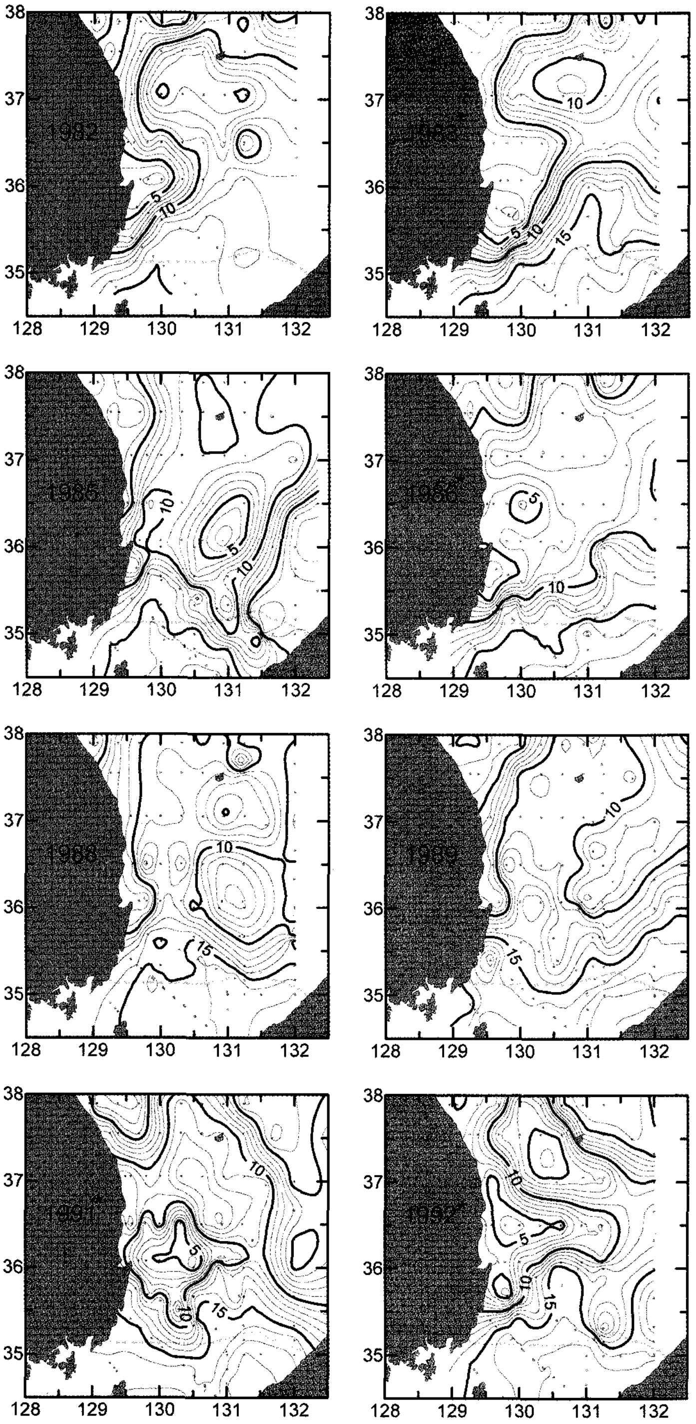

Fig. 7. Horizontal distribution of water temperature at a depth of 100 m in August from 1982 to 1992. Contour interval is 1°C. The symbol * denotes the years when bottom temperature drop was large in the Korean side.

in the Korean side and the evolution of the NKCW was examined indirectly as a temperature-salinity relationship along Line N in Fig. 1, by assuming that salinity would be lower when the NKCW was well evolved even though the salinity of the NKCW would depend on the winter condition when it was formed (Fig. 8). When the bottom temperatures were low in the Korean side in summers of 1983, 1986 and 1991, salinity was observed at less than

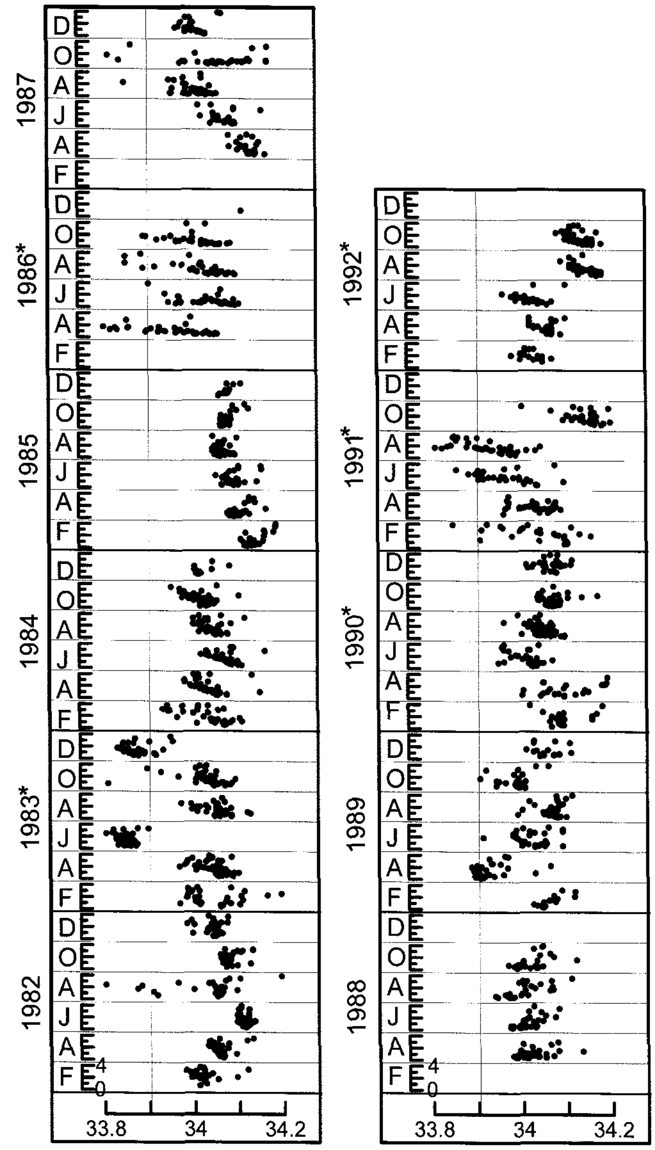

Fig. 8. Temperature-salinity relation in the temperature range of 0-4°C along Line N shown in Fig. 1 using bimonthly hydrographic data from NFRDI. The symbol * denotes the years when bottom temperature drop was large in the Korean side.

33.9 psu. Though the months when the lowest salinity appeared were different every year, low salinity less than 33.9 might be related with the year-to-year variation of the NKCW. This implied that bottom temperature in the Korean side was probably related to the evolution of the NKCW, although salinity less than 33.9 was not found in 1990 and 1992. On the other hand, there was no significant relationship between the decrease of the bottom temperature in the Korea Strait and the variation of salinity in the central Ulleung Basin, which might be due to inaccuracy of salinity data.

4. Concluding Remarks

Bottom temperature data taken at 50 stations along around 35°N provided substantial information regarding bottom cold waters in the Korea Strait. Stations situated closely were very helpful in defining cold water boundaries that appeared in the Korea Strait. Moreover, simultaneous measurements every month for 11 years made it possible to determine year-to-year variations of bottom cold waters in the Korea Strait and to examine the relationship between bottom cold waters in the Korea Strait and cold waters in the Ulleung Basin.

The decrease in bottom temperature in summer due to the southward expansion of cold waters was not only observed near coasts of Korea and Japan but also in the middle region of the Korea Strait. However, the decease in bottom temperature in the middle region was not influence by the cold water appearing near coasts. The influence of cold water in the Korean side was confined west of 130°E and that of cold water in the Japanese side was confined east of 131° 20'E near 35°N where the submarine cable was located.

It is worth noting that bottom temperature in the Korea Strait showed year-to-year variations in addition to seasonal variations. Bottom temperature in summer in the Korean side was quite low in 1983, 1986, 1990, 1991 and 1992 when the cold water along the east coast of Korea developed. Conversely, in the years when cold water developed in southern region of the Ulleung Basin (1985, 1988, and 1989) the bottom temperature in the middle dropped remarkably. These year-to-year variations imply that the decrease in bottom temperature in the Korean side results from the southward intrusion of cold water along the east coast of Korea while that in the middle is caused by the intrusion of cold water from southern region of the Ulleung Basin.

It was proposed that bottom cold water in the western region intrudes when geostrophic transport through the Korea Strait is low and is prevented from intruding when geostrophic transport is high (Johnson and Teague 2002). On the other hand, the density variation of the upper TWW and thickness of the SML water might be related to the intrusion of cold water into the Korea Strait (Cho and Kim 1998). However, previous studies on the intrusion of cold water into the Korea Strait were mainly focused on seasonal variations with observations performed over a short period.

It was shown that cold water near the coast of Korea tended to extend and to be colder in the years when the bottom temperature in the Korean side was lower. Meanwhile, salinity of SML water was relatively low in those years. This implied that the intrusion of cold water in the Korean side of the Korea Strait was closely related to the expansion of the SML water near the east coast of Korea. Although the relationship of cold waters in the Korea Strait with cold waters in the Ulleung Basin was examined, circulation in the Ulleung Basin and variation of the TWW should be precisely investigated in order to explain the mechanism related to year-to-year variations of the cold waters in the Korea Strait and the relationship between the cold waters.

The SML water has been proposed to originate from the northern region of the East Sea by local winter convection (Senjyu and Sudo 1994; Yun *et al.* 2004). Therefore, variability of the SML water in the East Sea might be closely related to the buoyancy flux through the sea surface boundary and inflow/outflow channel. In particular, since the TWW supplies heat and salt into the East Sea, it might be interesting to discuss the relation between the year-to-year variations of the bottom cold water in the Korea Strait and the TWW. Although we found that volume transport (Takikawa and Yoon 2005) through the Korea Strait calculated from sea level from 1982 to 1992 showed no significant relation with the bottom temperature in the Korean side in terms of year-to-year variations (not shown here), data are not enough to examine the relationship between the bottom cold water and the TWW. Therefore, long-term and synthetic observation should be required to fully understand the year-to-year variations of the bottom cold water in the Korea Strait.

Acknowledgement

This work was supported by the KORDI projects PE97005 and PP06401.

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