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Article

The Inflow Path of the East Sea Intermediate Water into the Ulleung Basin in July 2005

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Abstract : To investigate inflow path of the East Sea Intermediate Water (ESIW) into the Ulleung Basin, hydrographic data surveyed in July 2005 were analyzed. The ESIW was characterized by the Salinity Minimum Layer (SML) within a depth range of 100 to 360 meters. Averaged potential temperature and salinity of the SML were 1.835°C and 34.049 psu, respectively. Mean potential density (σ_θ) of the SML was 27.221 with a standard deviation of 0.0393. On isopycnal surfaces of 27.14 and 27.18 σ_θ which correspond to upper layers of the ESIW, the coastal low salinity water was separated from the offshore low salinity water by the relatively warm and saline water which might be affected by the Tsushima Warm Current Water. Relatively cold and fresh water, however, intruded into the Ulleung Basin from the region of Korean coast on isopycnal surfaces of 27.22 and 27.26 which was lower layer of the ESIW. The salinity distribution in the isopycnal layer of 27.14~27.26 with acceleration potential on 27.22 σ_θ surface also showed clearly that the low salinity water flowed from the coastal area and intruded into the Ulleung Basin. This implies that the ESIW flows from the north to the south along the east coasts of Korea and spreads into the Ulleung Basin in summer.

Key words : East Sea Intermediate Water, Ulleung Basin, isopycnal surface, salinity minimum layer, warm eddy

1. Introduction

There are three basins in the East Sea: that is, the Japan Basin, the Yamato Basin and the Ulleung Basin. The Ulleung Basin is located in the southwestern part of the East Sea and is surrounded by the continental shelves of Korea and Japan, the Korea Plateau and Oki Spur (Fig. 1). The basin is connected to the Japan Basin through a gap between Ulleung-do and Dok-do. Surface water in this basin is mainly affected by the Tsushima Warm Current (TWC). The TWC carries warm and saline water into the East Sea (Moriyasu 1972) and branches into the East Korean Warm Current (EKWC) and the Nearshore Current after passing the Korea Strait (Yoon 1982; Kato 1994). The EKWC flows northward along the Korean coasts. The current is separated from the coasts where it meets the North Korean Cold Current (NKCC) to form the sub-polar front together along the latitude about 38~40°N. The NKCC flows southward in the area off Vladivostok and

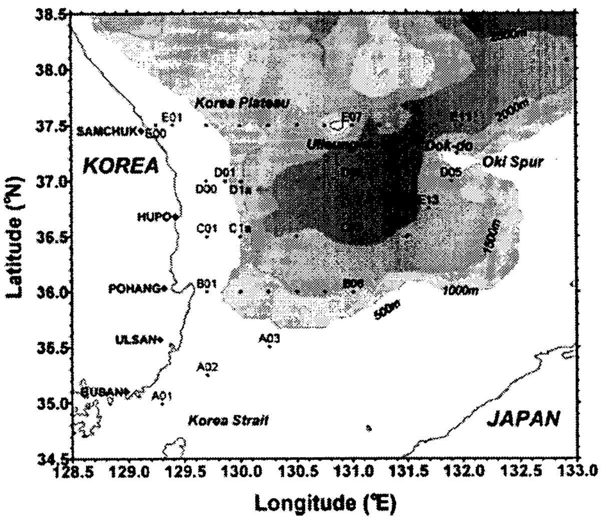

Fig. 1. Station map with bottom topography.

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along the east coasts of Korea.

Water masses in the Ulleung Basin are vertically classified by four parts (Kajiura *et al.* 1958; Moriyasu 1972). The uppermost part is the surface water which changes seasonally in its temperature and salinity. The second part is the Tsushima Warm Current Water (TWCW) which is below the surface water. Below the TWCW, there is the Salinity Minimum Layer (SML) water which was named East Sea Intermediate Water (ESIW) by Kim and Chung (1984). It is produced in the north of the sub-polar front, where the surface water has the characteristics of low salinity and temperature of 1-4°C (Kajiura *et al.* 1958). The last part is the East/Japan Sea Proper Water (ESPW) which has nearly homogeneous temperature and salinity. The ESPW can be subdivided into the upper portion of the Japan Sea Proper Water (UJSPW) and the deep water (Sudo 1986; Senjyu and Sudo 1993).

In the southwestern part of the East Sea, Kim and Chung (1984) found that the layer of a salinity minimum (<34.05) was coincident with that of a maximum concentration of dissolved oxygen (>6.5 m*l*/*l*) in a depth range of 100~300 meters. Kim *et al.* (1991) found the cores of the SML water appearing at the coastal and offshore regions in August 1986. Cho and Kim (1995) insisted that the salinity minimum water had two modes in the Ulleung Basinin 1991. One is a coastal mode which appears in the east coasts of Korea and originates from the water of the NKCC. The other is an offshore mode which appears around Ulleung-do and originates from the ESIW. The coastal mode exists at the depths from 100 m to 200 m and the temperature of it is about 1.5°C, but the offshore mode exists at deeper depths (from 200 m to 400 m) and its temperature is higher than 2°C. The author discussed the movement of two mode waters based on the analysis of horizontal distribution of the lowest salinity values at the stations within the SML. The lowest-salinity surface is not at a constant depth nor is an isopycnal surface. Moreover, the characteristics of the lowest salinity water can be modified by diapycnal and isopycnal mixing (Min *et al.* 2001).

Shin *et al.* (1998, 1999) insisted that the ESIW intruded from the north into the Ulleung Basin between the Korean coasts and Ulleung-do in summer of 1992 and 1993. Chang *et al.* (2004) also noted the possibility that the coastal mode water along the east coasts of Korea moves offshoreward by the anticyclonic warm eddy. Yun *et al.* (2004) hypothesized that the cold and relatively fresh water, formed in the northwestern East Sea, flows into the Ulleung Basin along three major paths: along the east coast of Korea, through the channel to the north of Ulleung-do, and through the channel between Ulleung-do and Dok-do. However, the flow path of the ESIW from the north to the Ulleung Basin is not yet clear because of a lack of direct observations of currents for the SML. Therefore, it is necessary to investigate the origin and movement of the ESIW in the southwestern part of the East Sea.

As mentioned above, two questions are proposed concerning the ESIW in the Ulleing Basin. One is: from where does the ESIW flow into the Ulleung Basin? The other is: what are the two modes of the SML water in the Ulleung Basin? In this study, hydrographic data surveyed in July 2005 are analyzed to investigate inflow path of the ESIW into the Ulleung Basin. The analyses are compared with the result of Shin *et al.* (1998) observed in July 1993. Finally, the two modes of the SML water are discussed.

2. Data and methods

An oceanographic survey was undertaken to investigate the water circulation of the SML in Ulleung Basin from July 19 to August 2 in 2005. Temperatures and salinities at 34 stations were observed by using a CTD (SBE 911 plus) on R/V Eardo (Fig. 1). The CTD system measures conductivity, temperature and pressure with 24 samplings per second. The raw data were processed by the standard method and averaged vertically by 1 dbar interval. To identify the water masses and the SML, T-S diagram was used. Vertical and horizontal sections of water property were depicted to analyze the thermocline and eddy structures.

Surface circulation pattern was obtained by geostrophic method with the reference level at 1,000 dbar. To draw dynamic topography in the coastal area where bottom depth is shallower than the reference level, the dynamic depth was extrapolated by its vertical gradient at the nearest station. This method was suggested by Shin *et al.* (1996).

To investigate the flow path of the ESIW, potential temperature and salinity were reanalyzed for isopycnal surfaces by density interval of 0.01 σ_θ. Potential vorticity and acceleration potential are also calculated to describe the flow path of the ESIW by using the same method as Shin *et al.* (1998).

3. Results

Salinity minimum layer

To identify water masses, the characteristics of potential temperature and salinity were presented in Fig. 2. Four major water masses can be identified by T-S diagram (Fig. 2a). The surface water is characterized by high temperature

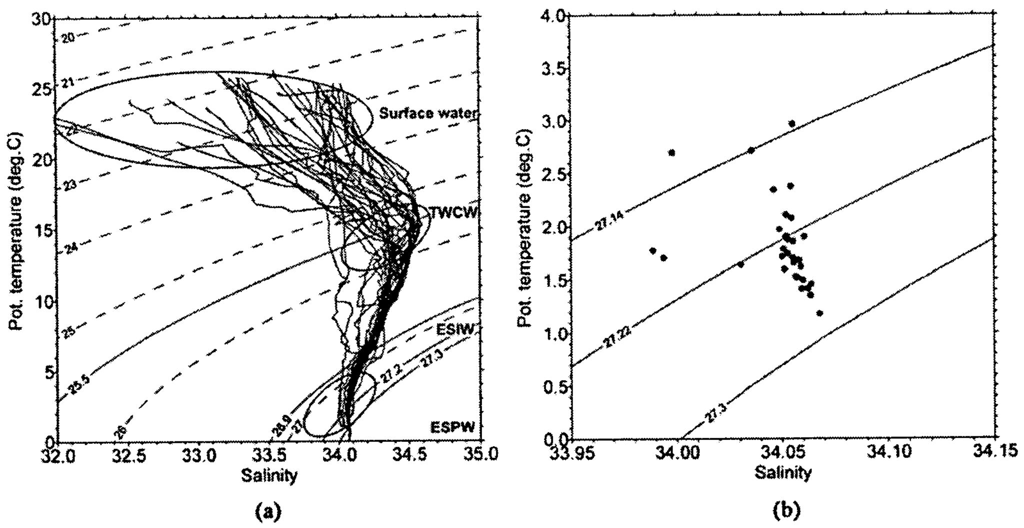

Fig. 2. T-S diagram with potential density contours for all the data (a) and for the minimum salinities in the SML (b) observed in July 2005.

and low salinity which appears only in summer season. At the isopycnal surface of 25.5, there was high salinity (S > 34.3) and high temperature (12°C < T < 16°C) water which was the TWCW. The ESIW is characterized by SML (S < 34.07) with an average density of 27.2 σ_θ. Below the ESIW, there is the ESPW which is very homogeneous in salinity (S ≃ 34.07 psu) and less than 1°C in temperature with potential density of 27.30~27.35.

The water in the SML is colder than 10°C (Fig. 2b). There were two exceptional data at stations A02 and C00, which were excluded in the statistical process. Station A02 is located in the Korea Strait, where the salinity and temperature in the salinity minimum layer were 34.277 psu and 6.638°C, respectively. The characteristic values were too high both in temperature and salinity so that the water could not be included in the ESIW. Station C00 is located in the coastal area where the TWCW did not appear in the upper layer. The depth of the water with salinity minimum at this station was very shallow (66 m) and its temperature was 4.413°C.

The average depth, potential temperature, salinity and potential density with their standard deviations in the salinity minimum layer were 194 ± 96 m, 1.835 ± 0.405°C, 34.049 ± 0.019 psu and 27.221 ± 0.039 σ_θ, respectively. Most of the water with salinity minimum belongs to the layer between 27.14 and 27.30 σ_θ, i.e., within 2 standard deviations from the average density.

Vertical section

Fig. 3 shows vertical distributions of potential temperature and salinity. The thermocline shows bowl shaped structure along the line D, where it deepens down to the depth of 300 meters at the station D03, the central location of the Ulleung Basin, where there is a warm eddy. This indicates that the left side of the eddy flows northward and the right side of it southward. At the center of the warm eddy, there were two thermoclines; that is, seasonal, and permanent ones. Well-mixed, homogeneous water occupies the layer between the two thermoclines, with a thickness of approximately 75 meters (from 75 m to 150 m). The temperatures and salinities in the homogeneous layer were about 10~11°C and 34.3~34.4 psu, respectively. This means that the warm eddy was made during the previous winter. This phenomenon was already reported by Shin *et al.* (2005).

The salinity minimum layer appears below the permanent thermocline. Potential density curves that are deduced from the statistics of the SML are overlapped in the vertical sections of salinity distribution. While the salinities of the SML in the coastal stations are relatively lower, the thickness is greater than in the offshore stations, especially along the line E. There are two cores of low salinity along the line D. This seems to support two modes of the SML which was suggested by Cho and Kim (1994).

Horizontal section

Fig. 4 shows horizontal distributions of potential temperature at the depths of 100 m and 200 m, respectively. A strong thermal front was developed from Pohang to Ulleung-do at 100 m depth, and an elongated core of warm water

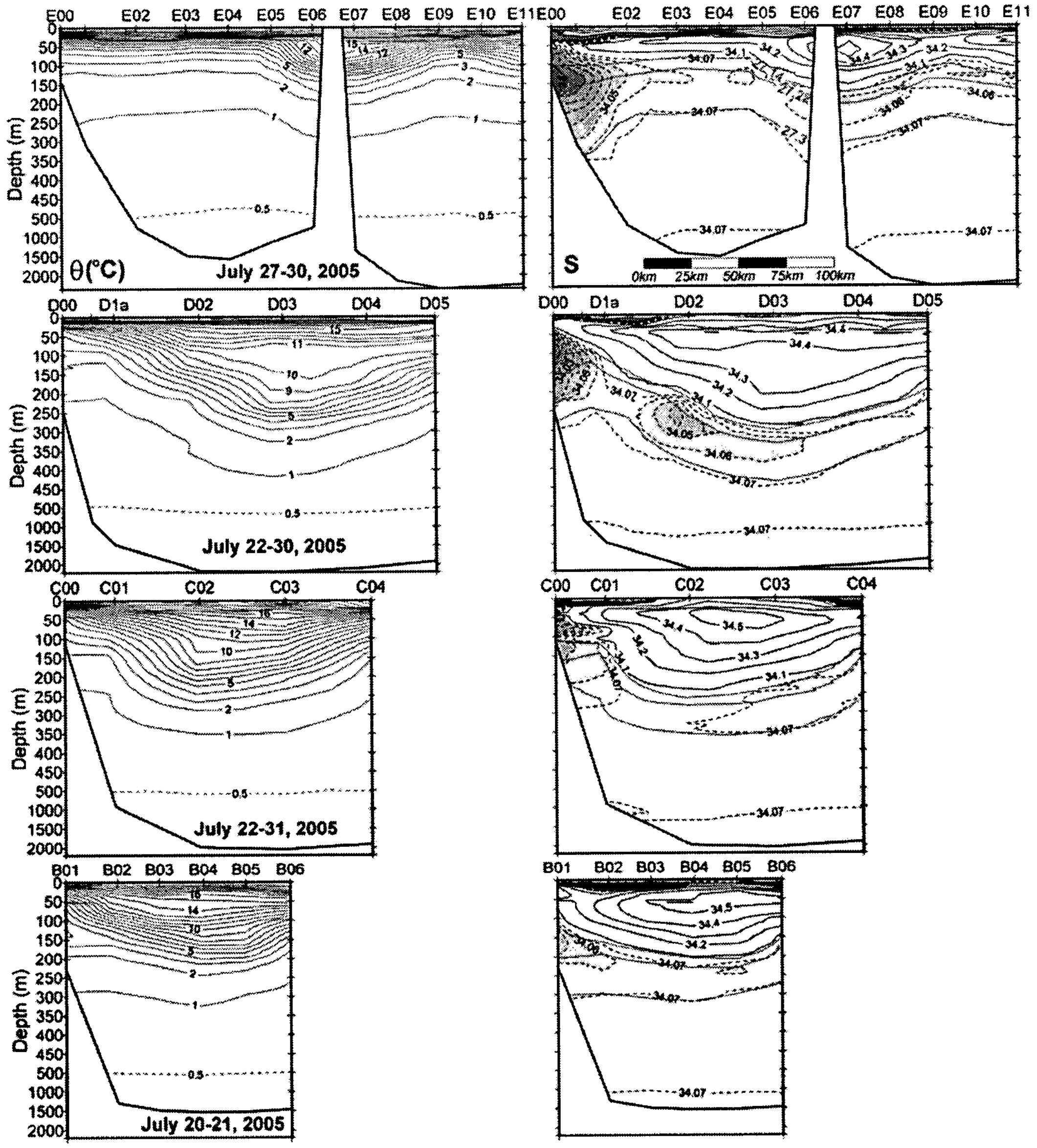

Fig. 3. Potential temperature (left) and salinity (right) sections. Red curves in the salinity sections indicate the isopycnals of 27.14, 27.2, 27.3 σ_θ, respectively.

was at 200 m depth. The vertical and horizontal distributions of potential temperature indicated that there was a meso-scale warm eddy and the surface flow pattern was anticyclonic in the Ulleung Basin.

Dynamic height

Fig. 5 shows the horizontal distributions of dynamic heights at 100 m and 200 m depths, with respect to 1000 m. Surface flow was anticyclonic because of a meso-scale warm eddy in the center of the Uleung Basin. Based on the distributions of dynamic heights and potential temperatures at 100 m depth, the EKWC was separated from the east coasts of Korea around Pohang and flowed offshorewards. The separation was about 1~2°N lower in latitude than that of the mean position, because the NKCC was very strong and flowed further down to the area around Pohang, as noted by Kim and Kim (1983). The EKWC flowed northeastwards from Pohang to Ulleung-do and added to the Ulleung Warm Eddy to make strong northeastward currents. Although the currents were weakened at 200 meters relative to those at 100 meters, their direction was unchanged.

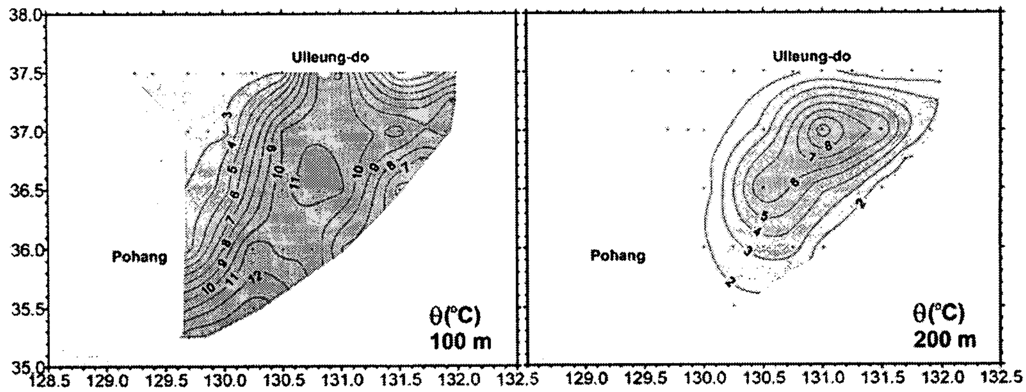

Fig. 4. Horizontal distributions of potential temperature at 100 m (left) and at 200 m (right) depths.

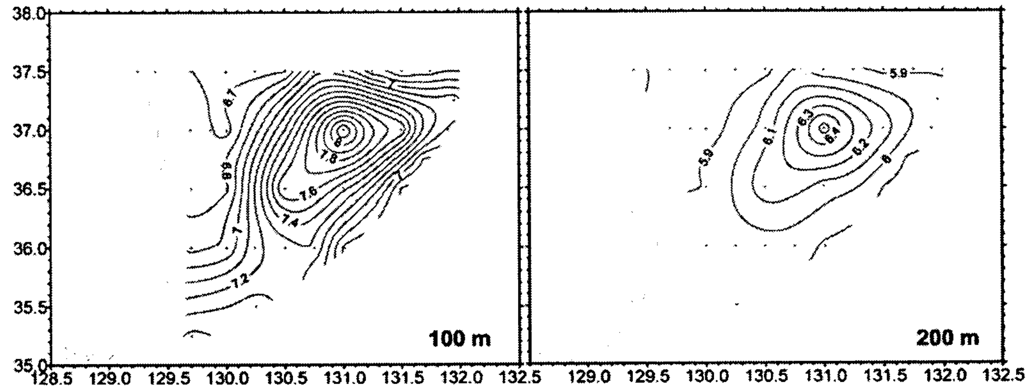

Fig. 5. Dynamic heights (10^2 J/kg) at 100 m and 200 m with respect to 1000 m.

Characteristics of ESIW on an isopycnal layer for 27.14~27.26 σ_θ

Fig. 6 shows the distributions of depth, potential temperature and salinity on the isopycnal surfaces of 27.14, 27.18, 27.22 and 27.26 σ_θ, respectively. They were arbitrarily determined by the multiples of a standard deviation (= 0.04) from the average of potential density, 27.22, in the salinity minimum layer. The distributions on the isopycnal surface of 27.30 were excluded in this analysis because of the small variations of potential temperature and salinity, compared with other isopycnal surfaces.

All the distributions represented the fact that a warm eddy existed in the Ulleung Basin. So, the deepest site was the center of the eddy. On the other hand, the shallowest area was located between Ulleung-do and the east coasts of Korea.

On the surface of 27.14, the relatively warm and saline water was stretched from the south to the north. So the cold and fresh water was divided into two cores, that is, coastal and offshore. It is possible to consider that the inflow path of the ESIW was assumed through two different ways. The warm and saline water might be affected by the TWC, because this isopycnal surface was close to the boundary between the TWCW and the ESIW. The coastal core was colder and fresher than the offshore one. The separation pattern, however, was weakened on the surface of 27.18. On the surfaces of 27.22 and 27.26, the cold and low salinity water spread from the east coasts of Korea into the Ulleung Basin, which was different from the pattern on the surface of 27.14.

To investigate the properties of ESIW which occupied the layer between the isopycnal surfaces of 27.14 and 27.26, the layer thickness and the characteristic values of potential temperature, salinity and potential vorticity were represented in Fig. 7. The characteristic values were averaged within the layer. The layer thickness is thicker and the water is colder and less saline in the coastal area. Potential vorticity is smaller in the coastal area than in the offshore area where the salinity is relatively higher. This implies that the low-salinity water is closer to the mode

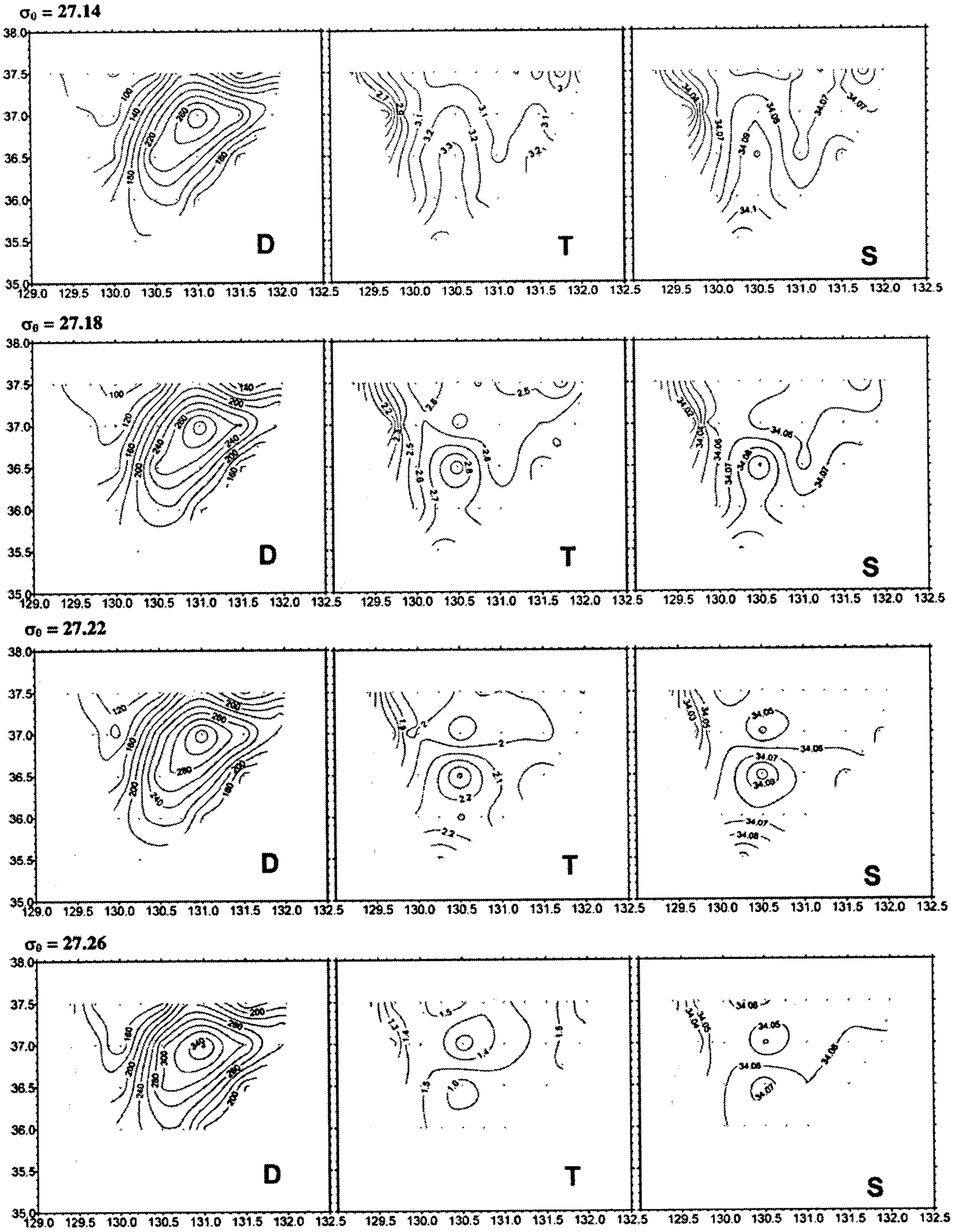

Fig. 6. Depth (m), potential temperature (°C) and salinity (psu) on the isopycnal surfaces of 27.14, 27.18, 27.22 and 27.26 σ_θ, respectively.

water of the ESIW than the high-salinity water (Shin *et al.* 1998; Kim and Seung 1999). The isolated low-salinity water in the southwest of Ulleung-do also had the same properties as the coastal one. This offshore low-salinity

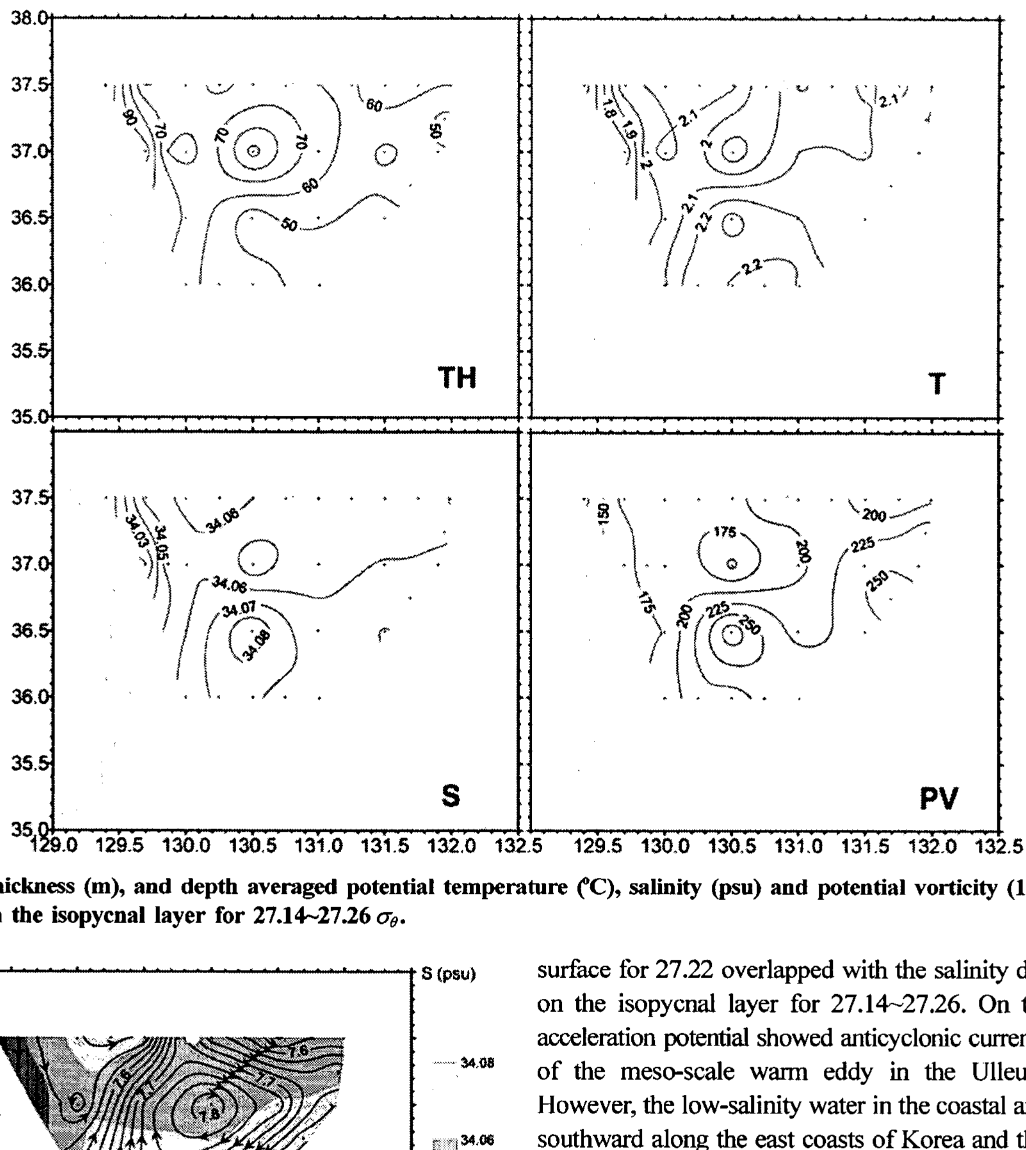

Fig. 7. Thickness (m), and depth averaged potential temperature (°C), salinity (psu) and potential vorticity ($10^{-12} \times$ 1/ms) on the isopycnal layer for 27.14~27.26 σ_θ.

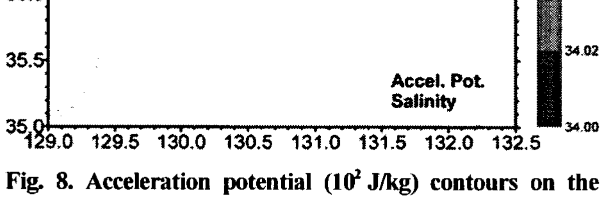

Fig. 8. Acceleration potential (10^2 J/kg) contours on the isopycnal surface of 27.22 σ_θ with the salinity (psu) in the isopycnal layer for 27.14~27.26 σ_θ.

water seemed to come from the coastal area, because there was no low-salinity water in this layer except in the coastal area.

Fig. 8 shows the acceleration potential on the isopycnal surface for 27.22 overlapped with the salinity distribution on the isopycnal layer for 27.14~27.26. On the whole, acceleration potential showed anticyclonic currents because of the meso-scale warm eddy in the Ulleung Basin. However, the low-salinity water in the coastal area flowed southward along the east coasts of Korea and then turned around northeastward and spread into Ulleung Basin. It seemed to appear that two modes of the SML existed in the vertical section. However, it was difficult to identify the two modes from the salinity distribution on the isopycnal surfaces. This result was very similar to that of Shin *et al.* (1998, 1999) in July 1993.

4. Summary and discussion

To investigate the inflow path of the ESIW into the Ulleung Basin, oceanographic data observed in July 2005 were analyzed. Water masses were clearly classified by temperature and salinity. The surface water that appear in summer season, the TWCW, the ESIW and ESPW (or JSPW), were major water masses. The EKWC flowed northeastward after it separated from Korean coasts around Pohang because the cold water mass which originated from the NKCC greatly affected conditions as far as near Pohang along the east coast of Korea. Temperature distribution at 200 m depth and vertical section along 37.0°N showed the existence of meso-scale warm eddy. Thus the flow pattern was anticyclonic in the Ulleung Basin. Below the TWCW, there was the ESIW characterized by the SML. A low-salinity core in the SML was separated from the coastal area to form another core in the offshore area. Acceleration potential showed that the ESIW flowed anticyclonically in the Ulleung Basin. The low-salinity water near the Korean coasts flowed southward along the continental shelf and then turned around northeastward, spreading into the Ulleung Basin. This suggests that the relatively fresh water flows mainly along the east coasts of Korea to the Ulleung Basin.

On the surfaces of 27.14 and 27.18 σ_θ, the relatively warm and saline water divided the cold and fresh water into two cores. From this, it is also possible to assume that there are two inflow paths of the ESIW: coastal and offshore. The latter is the path by which the ESIW intrudes into the Ulleung Basin from the east of Ulleung-do and flows anticyclonically with the warm eddy.

The major currents in the southwestern part of the East Sea are the EKWC and the NKCC. The EKWC in the Ulleung Basin often meanders and makes the Ulleung Warm Eddy. This warm eddy greatly affects the circulation in the basin from the surface to deep layer. The ESIW that exists below the TWCW must be transported from some other place to the basin. Hypothesized flow paths of the low-salinity ESIW are three (Yun *et al.* 2004). The first one is the east coast of Korea, and the others are the paths between Ulleung-do and the coast and the gap between Ulleung-do and Dok-do. In July 2005, there was a warm eddy in the Ulleung Basin and the NKCC flowed to the south down to the area near Pohang. Therefore, it is reasonably concluded that the low-salinity ESIW flowed southward along the east coast of Korea and then turned around northeastward into the Ulleung Basin. It is necessary to study further the flow path of the ESIW in the case of no warm eddy in the Ulleung Basin or of dependency upon the NKCC.

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