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Southward Intrusion of the East Sea Intermediate Water into the Ulleung Basin: Observations in 1992 and 1993

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Hydrographic data retrieved in the southwestern part of the East Sea in 1992—1993 were analyzed to investigate the probability of southward intrusion of the East Sea Intermediate Water (ESIW) into the Ulleung Basin. The ESIW showed the ranges of 1 to 4°C in potential temperature, 33.80—34.06 psu in salinity, and 26.9—27.3 kg/m^3 in potential density (σ_θ). The mean depth occupied by the ESIW was 170 m, where the characteristic values of the above three were 2.64°C, 34.02 psu, and 27.13 kg/m^3, respectively. One of the most prominent features of the ESIW was that its salinity changed not only seasonally but also interannually. It was low in summer and high in winter. The salinity within the isopycnal layer of 26.9—27.3 kg/m^3 was closely related with the potential vorticity ($\rho_\theta^{-1} f\, \partial\rho_\theta/\partial z$), being in direct proportion to the salinity. This implies that the low-salinity water was thicker than the high-salinity water. The flow path of the ESIW was investigated by tracking the low-salinity or the low-potential vorticity water and by referring to acceleration potential. Careful analysis of the flow path proves that the ESIW intrudes from the north between the Korean coast and Ulleung Island into the Ulleung Basin in summer. Existence of the high-potential vorticity water in the Ulleung Basin is associated with the interruption of the inflow of low-salinity water.

INTRODUCTION

The East Sea is a marginal sea of the North Pacific. The bottom of the East Sea may be divided approximately into two parts by 40°N parallel. The northern half, the Japan Basin, is comparatively flat-bottomed and deep. The bathymetry of the southern half is rather complicated. In addition to the shallow regions around the Ulleung, Dok, and Oki islands, there is conspicuous Yamato Bank isolated by deep troughs. The southern part of the East Sea has two basins. One is Ulleung Basin which is located in western side and the other is Yamato Basin. The former is connected with Japan Basin by an interchannel between Ulleung Island and Dok Island.

The East Sea is divided into warm and cold regions by the polar front. A major surface current of the warm-water region is the Tsushima Warm Current (TWC) which carries saline water (Moriyasu, 1972). The East Korean Warm Current (EKWC) branched from the TWC flows northward along the Korean coast and is separated from the coast near the polar front. In respect to the cold currents, there is the North Korean Cold Current (NKCC) flowing southward from the area off Vladivostok to the east coast of Korea (Hidaka, 1966).

Water masses in the warm-water region are divided into four parts (Kajiura *et al.*, 1958). The first part is the surface water. The second one is below the surface water and has high temperature and high salinity. Third, the proper water has nearly homogeneous temperature and salinity. The forth part is situated between the second water and the proper water. This water is produced in the cold-current with low-salinity surface water, and has temperatures of 1—4°C and is characterized by maximum oxygen content.

Kim and Chung (1984) analyzed hydrographic data along with dissolved oxygen data taken in the southwestern part of the East Sea in September 1981. They found the minimum salinity (< 34.05‰) coinciding with the maximum concentration of dissolved oxygen (> 6.5 ml/l) in a depth range of 100—300 m and they named the water as the East

Sea Intermediate Water (ESIW). Earlier than this, Kim and Kim (1983) searched for the origin of the cold water mass along the east coast of Korea, the water of NKCC. Kim and Chung (1984) suggested two possible origin of the ESIW. One is the extending of the the ESIW from the mouth of Tuman River southward along the east coast of Korea. The other is the spreading of the ESIW to the southwest between Ulleung and Oki islands on top of the East Sea Proper Water (ESPW) after sinking near the polar front in winter.

Kim *et al.* (1991) investigated the spatial and temporal variations of the ESIW and suggested that this water appears interannually. They found the cores of the salinity minimum water appearing at the coastal and offshore regions in August 1986. Cho and Kim (1995) reported that the salinity minimum water in the Ulleung Basin had two modes in 1991. One was the water of NKCC which was observed only along the east coast of Korea in summer and the other was the ESIW which was observed around Ulleung Island in April spreading southward at times. They discussed that the origins of the two modes differ from each other in space or time because the water of salinity minimum layer (SML) had different temperatures.

Recently, Kim (1996) found a low-salinity-intermediate water ($1<t<5$°C, $S<34.065$ psu, $27.10<\sigma_\theta<27.32$) prevailing in the western Japan Basin and a high-salinity intermediate water ($0.6<t<4$°C, $S>34.070$ psu, $27.0<\sigma_\theta<27.32$) in the eastern Japan Basin and extending westward to form a cyclonic gyre together with the low-salinity intermediate water.

The previous studies above are mainly about the distribution and characteristics of the ESIW. In the present study, successively surveyed CTD data were analyzed to find out the flow paths and temporal variations of the ESIW in the southwestern part of the East Sea. The ranges of depth, temperature, salinity and density of the ESIW were deduced from the data. The time and path of the ESIW intrusion into Ulleung Basin were discussed with the salinity and potential vorticity in the isopycnal layer.

DATA AND METHODS

The observations were conducted 12 times with a CTD (Neil Brown Mark IIIB) in the southwestern part of the East Sea from March 1992 to November 1993 by Korea Ocean Research and Development Institute. The number of CTD stations was 70 except in August 1992 (65 stations) and January 1993 (33 stations).

Survey area covered from 36°55'to 38°5'N in the meridional direction and from the east coast of

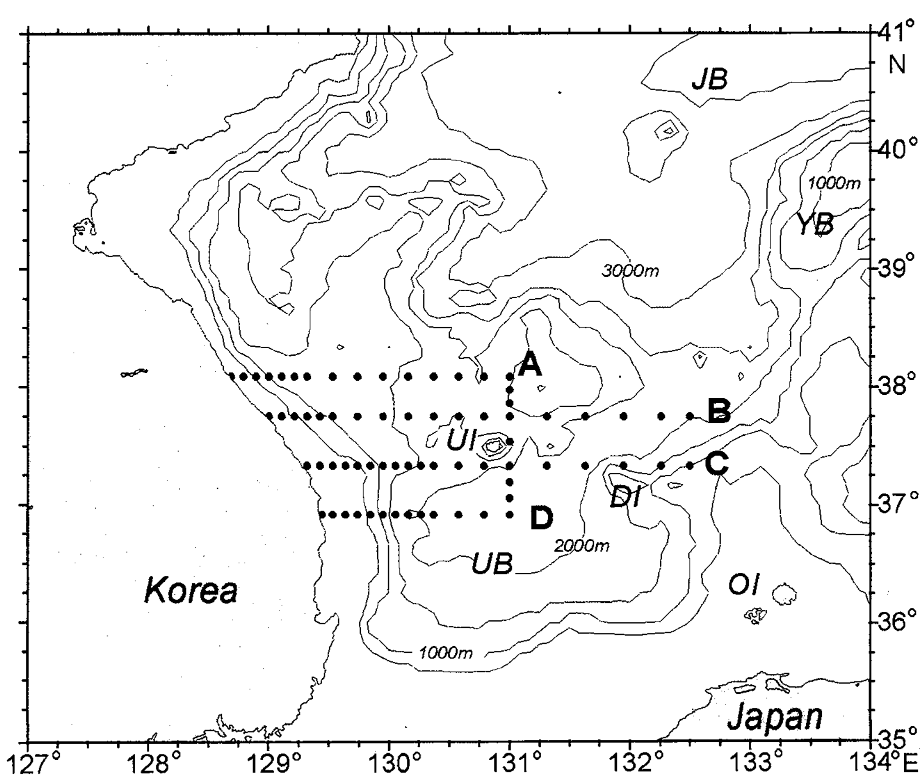

Fig. 1. Observation stations with bottom topography in meters. A, B, C and D indicate observation lines. JB=Japan Basin, UB=Ulleung Basin, DI=Dok Island, OI=Oki Island, UI=Ulleung Island, YB=Yamato Bank.

Korea to 132°30'E in the zonal direction (Fig. 1). The northernmost survey line A seems adequate to examine the crossing NKCC. Lines B and C were located across a trough connecting southern Japan Basin to Ulleung Basin. Line D runned from the east coast of Korea to the central part of Ulleung Basin.

The CTD system measured the conductivity, temperature and pressure with 33 sampling rates per second. The raw data were averaged vertically at every 1 decibar interval. Then, salinity and density were calculated using the formulas UNESCO determined (Fofonoff and Millard, 1983).

To investigate the flow path of ESIW in the isopycnal layer, potential density range was determined from the potential temperature-salinity relation of salinity minimum waters. The flow path was described by using the potential vorticity as a tracer in the density range. For weak horizontal current shears, the relative vorticity could be ignored, and the potential vorticity (Q) of a portion of water column in a continuously stratified ocean was calculated as

$$Q=-\frac{1}{\rho_\theta}\cdot f\cdot\frac{\partial\rho_\theta}{\partial z}=fE$$

where ρ_θ is potential density, f is the Coriolis parameter and E is stability parameter (UNESCO, 1991). Potential vorticity was calculated for a set of standard σ_θ surfaces with the interval $\Delta\sigma_\theta=0.01$ kg/m^3. Salinity and potential vorticity were averaged within the density interval $\Delta\sigma_\theta$.

The flow path determined by using the potential vorticity as a tracer (*e.g.*, Yasuda *et al.*, 1996) should be compared with the geostrophic streamlines on the isopycnal surface, *i.e.*, acceleration potential. The acceleration potential at the isopycnal surface is expressed such that $\Phi=\Phi_\alpha+\alpha_\alpha p$, where Φ_α and α_α are the anomalies of dynamic height and specific volume at the isopycnal surface, respectively, and p is the pressure (Montgomery, 1937; Kim, 1996).

DISTRIBUTION AND VARIATION OF EAST SEA INTERMEDIATE WATER (ESIW)

Vertical distribution of salinity minimum layer (SML)

A SML less saline than 34.06 psu was identified in the vertical salinity section along line A, except for some stations, in February, July, September and November 1993 (Fig. 2). In March 1992, a mesoscale warm eddy with a diameter of about 150 km was observed to the northwest of Ulleung Island (Shin *et al.*, 1995). The SML existed below the eddy with a bowl-shaped structure from March to August 1992. It had a low-salinity core just below the center of the eddy. This core water became more saline with time from 33.99 psu at Station A10 in March to 34.01 psu at Station A13 in August.

The bowl-shaped core moved away far from the shore in August 1992 and new low-salinity cores were developed near the coast at depth shallower than 100 m. These cores had temperature of 5—10°C so that they were not included in ESIW according to the definition as 1—4°C water by Kajiura *et el.* (1958) though the cores had low salinity less than 34.0 psu. In October and December 1992, the coastal low-salinity cores disappeared and tongue-shaped SML stretched to the east.

In June 1992, isotherms of 1—4°C were inclined downward near the coast. This trend was also observed in August 1992. This means that geostrophic current flowed southward along the Korean coast. In October and December 1992, the curved feature of the isotherms disappeared.

In January 1993, curved isotherms and shallow low-salinity cores with temperatures above 5°C again appeared in the coastal area. The tongue-shaped SML had remained since October 1992.

The water colder than 7℃ and fresher than 34.0 psu was obsevred in the layer above 100 m depth at stations A01 to A09 in late February 1993. The salinity increased with depth at these stations. This water was seen below the warm and saline water in April 1993. However, all of the low-salinity water was not ESIW because the water temperature was higher than 4°C in some cases.

In July 1993, the SML was not clear near the Korean coast at stations A01 to A05. The salinity increased downward and the isotherms were inclined downward near the coast at these stations. These mean that NKCC flowed southward. This pattern was partly maintained until September 1993.

In November 1993, the bowl-shaped temperature and salinity structure was seen around station All. The SML appeared again near the Korean coast; however, the SML was not clear around station All, where a low-salinity (< 34.0 psu) water appeared as a thick layer at the center of the bowl-shaped structure. This low-salinity water was warmer than ESIW. Thus this water was not considered as the ESIW.

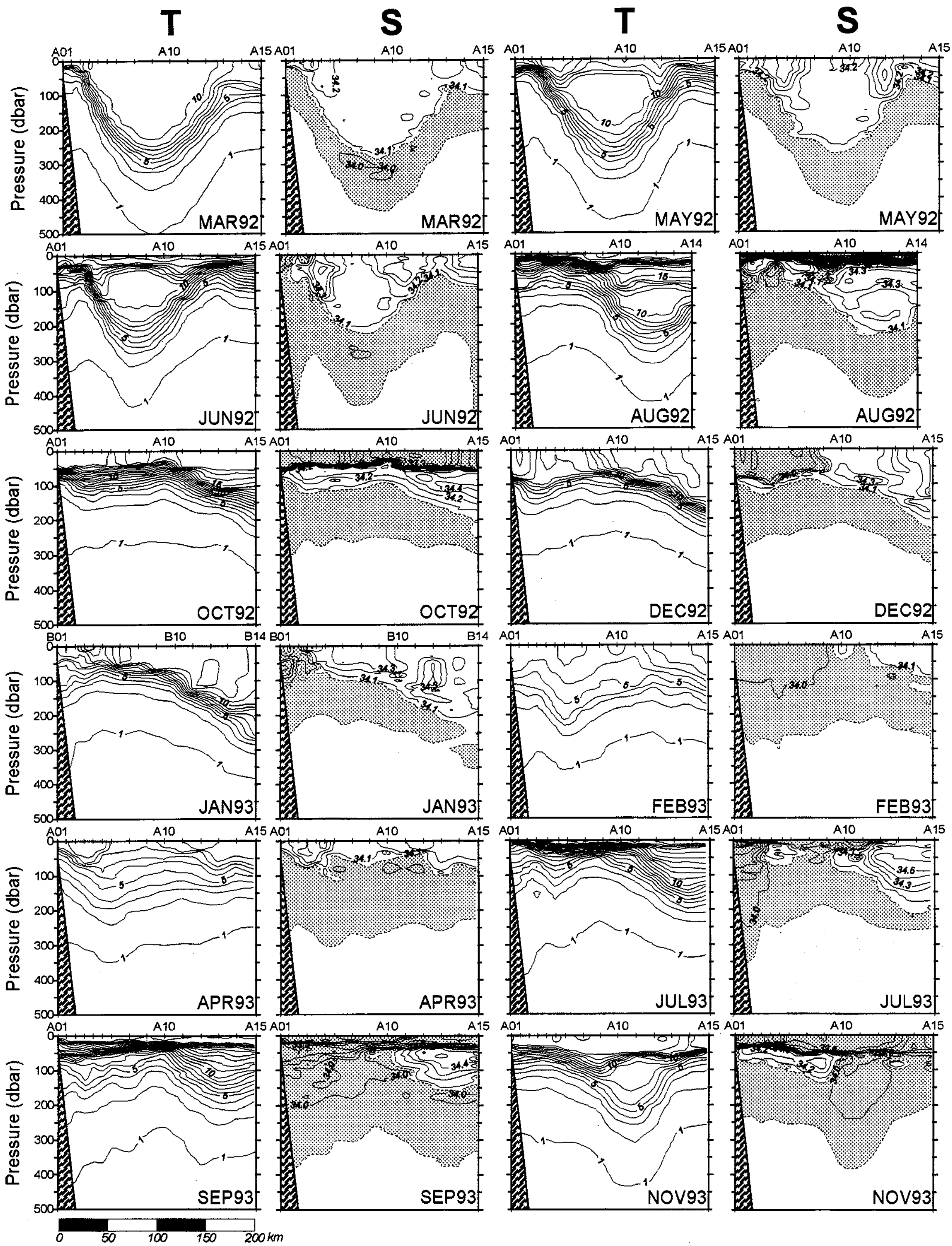

Fig. 2. Zonal sections of potential temperature (°C) (Column T) and salinity (psu) (Column S) along line A from March 1992 to November 1993 except February 1993 (replaced by line B). Contour intervals are 1°C in temperature and 0.1 psu in salinity. Shading is chosen to emphasize the low-salinity (less than 34.06 psu) water.

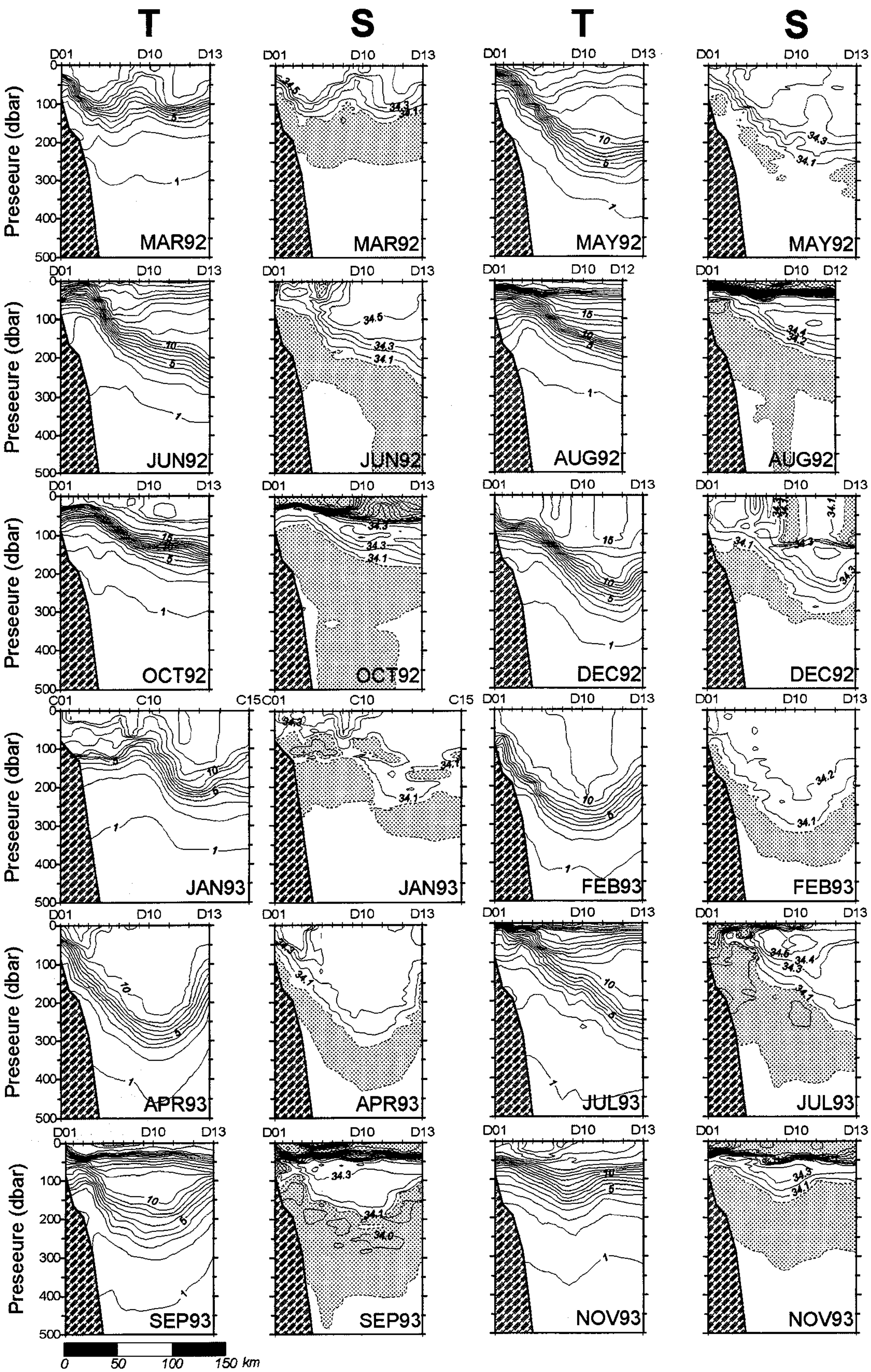

Fig. 3. Zonal sections of potential temperature (°C) (Column T) and salinity (psu) (Column S) along line D except February 1993 (replaced by line C).

In Ulleung Basin, the SML existed below warm and saline water in the section along line D (Fig. 3). The SML was thin in May and December 1992 and February and April 1993, but was thick from June to October 1992 and from July to September 1993 when the isotherms were curved to the bottom near the coast on line A except October 1992 (Fig. 2). In February, April and September 1993, the bowl-shaped structures of temperature and salinity correspond to the warm eddies (Lie *et al.*, 1995). The low-salinity cores appeared in July and September 1993 like line A.

Variation of salinity minimum water

To know the mean properties and variation of SML, potential temperature-salinity diagrams for the salinity minimum water of SML were drawn (Fig. 4). The salinity minimum was restricted to the water colder than 4°C in order to exclude the water which was warmer and fresher than ESIW. Most of the salinity minimum water was within the range of salinity of 33.80—34.06 psu and potential density (σ_θ) of 26.9—27.3 kg/m^3. The salinity minimum water did not follow the isopycnal surface because the temperature of the water varied within 1—4°C. Density of the water varied mainly with temperature rather than salinity except July and September 1993 when the salinity varied greatly.

The mean values and standard deviations of depth, potential temperature, salinity and potential density of salinity minimum waters are shown in Fig. 5. The total mean value of the salinity minimum depth is 170 m, although it was deeper than 300 m below the warm eddy in March 1992 (Fig. 2). There was no conspicuous seasonal variation in the salinity minimum depth. The maximum of the mean depth was 196 m in December 1992. In 1993, the mean depth became gradually shallower from 187 m in February to 142 m in November.

The average of the mean potential temperature of the salinity minimum water was 2.64°C. The salinity minimum water was warmer in 1993 than in 1992. The mean potential temperature was 2.2—2.7°C from March 1992 to January 1993, and 2.9—3.2°C from February to November 1993.

The variation pattern of the mean salinity differed from that of mean temperature. The range of the mean salinity was 33.98—34.04 psu and the average was 34.02 psu. The variance of salinity was maximum in July 1993 because of the difference in

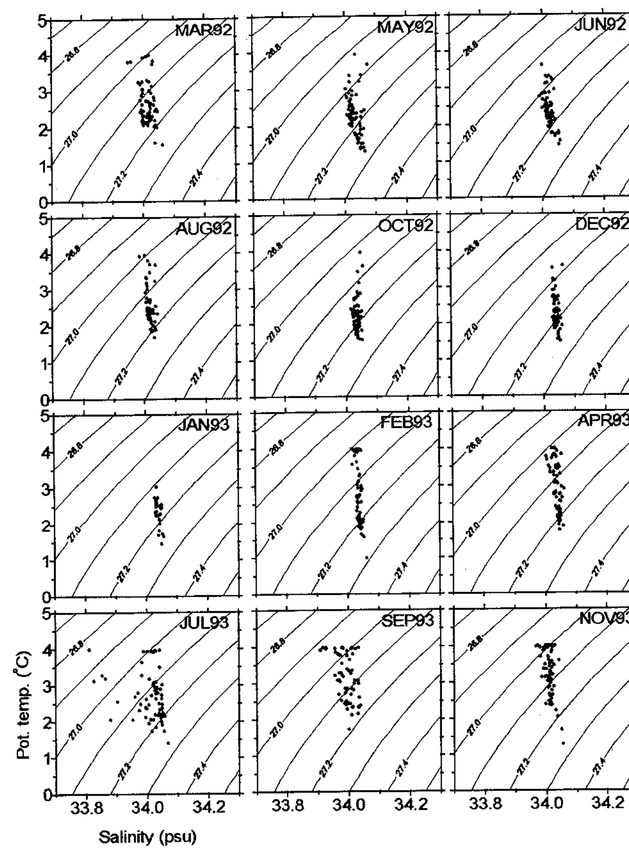

Fig. 4. Potential temperature-salinity diagrams of the salinity minimum waters from March 1992 to November 1993.

salinity of ESIW between the coastal and the offshore regions. The mean pattern varied seasonally. Salinity of SML was lower in summer than in winter. The interannual variation of the salinity was as large as seasonal one. This was probably related with the variation of cooling intensity in the source area of ESIW in the former winters. The monthly mean air temperature was −9.3°C in January 1992 but −16.3°C in January 1993 at Vladivostok (Japan Meteorological Agency, 1992, 1993). It seems that the salinity of SML in summer is largely controlled by the former winter temperature.

The mean potential density of salinity minimum water varied reversely with the mean temperature and the average was 27.13 kg/m^3.

Salinity and potential vorticity distribution along the isopycnal layer

As mentioned in the previous section, the salinity minimum water did not follow isopycnal surface but had potential density of 26.9—27.3 kg/m^3. This

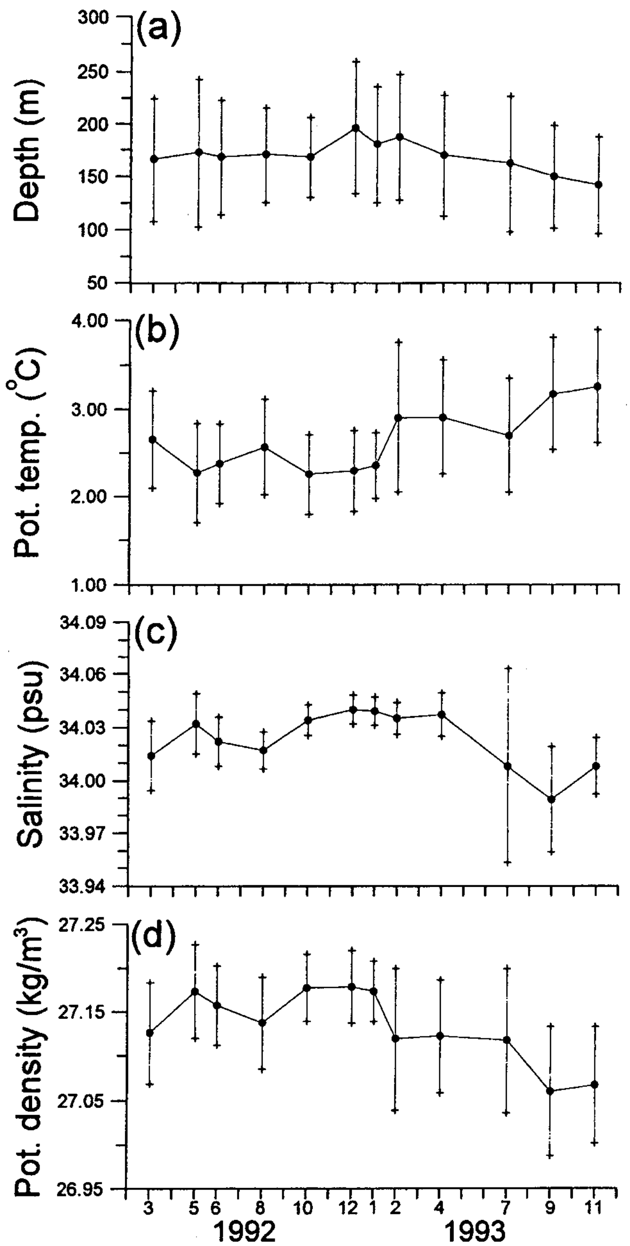

Fig. 5. Time variations of mean depth (**a**), potential temperature (**b**), salinity (**c**), and potential density (**d**) of the salinity minimum water from March 1992 to November 1993. Filled circles indicate mean values and "+" indicates mean ±1 standard deviation.

means that ESIW does not have a single potential density. Fig. 6 shows the relation of the potential vorticity and the salinity in the isopycnal layer. The potential vorticity increased with the salinity. This means that lower-salinity water was more homogeneous, relatively less affected by the surrounding waters. Fig. 7 shows the distribution of salinity and potential vorticity, each of which are classified into three classes. The lower the potential vorticity is,

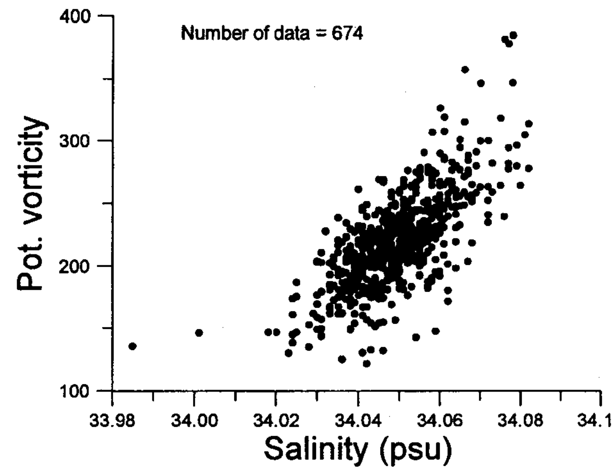

Fig. 6. Salinity vs. potential vorticity ($\times 10^{-12}$/ms) in the isopycnal layer σ_θ=26.9–27.3.

the thicker and younger the thickness of isopycnal layer is.

Generally speaking, the salinity and the potential vorticity were lower in the northern part than in the southern part of the study area, and the low-salinity area corresponded to the low-potential vorticity area. In March 1992, the low-salinity water existed to the northwest off the Korean coast. Area of the middle-salinity water extended to the Ulleung Basin. The middle-potential vorticity water was distributed to the west of Ulleung Island and in the Ulleung Basin. The salinity and potential vorticity in May were high in the Ulleung Basin, because the high-potential vorticity water kept ESIW from intruding southward into Ulleung Basin along the coast. This agrees also with the result of a simple layer model by Seung and Kim (1995).

In June 1992, the northern coastal area of East Sea became less saline than in May and the potential vorticity was low. The low-salinity and low-potential vorticity water spread to the southeast around Ulleung Island. But the potential vorticity in the Ulleung Basin was still high except in the coastal area. In August, the low-salinity and low-potential vorticity water occupied the northern coastal area. The water with intermediate salinity and potential vorticity intruded into Ulleung Basin as a narrow strip along the coast. Another low-salinity water appeared between Ulleung Island and Oki Bank. The salinity and potential vorticity in Ulleung Basin were high except in the coastal area.

In October and December 1992, the low-salinity water did not appear. The low-potential vorticity

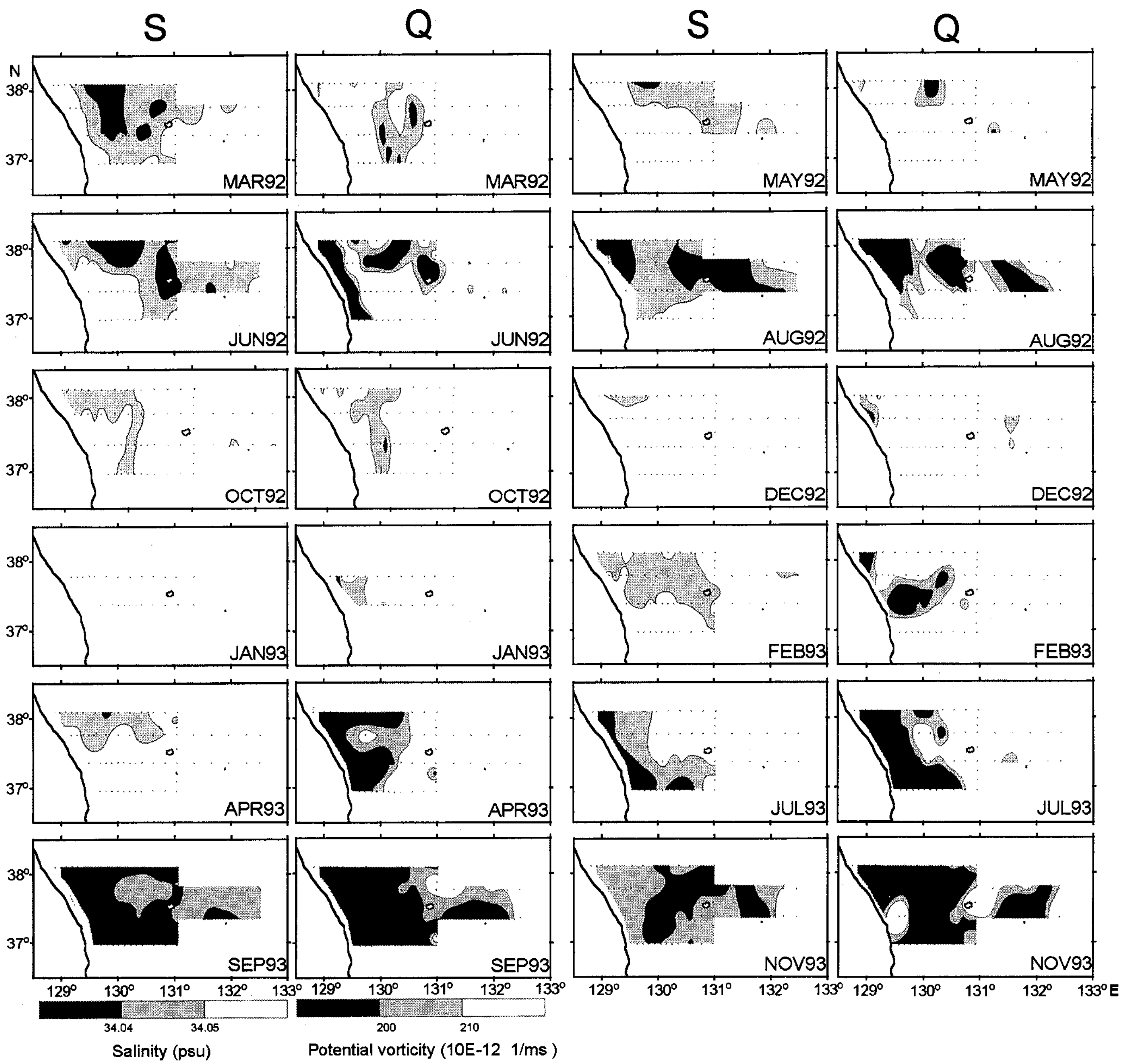

Fig. 7. Salinity (Column S) and potential vorticity (Column Q) along the isopycnal layer σ_θ=26.9—27.3.

water wardly appeared in both months, either. Salinity and potential vorticity were high in Ulleung Basin in October and December.

The salinity was high but the potential vorticity was middle in the coastal area of East Sea in January 1993. In February, the salinity was middle, and the potential vorticity was middle to low to the west of Ulleung Island.

The salinity was middle and the potential vorticity was low in the northern coastal area of East Sea in April 1993. The low-potential vorticity water existed along the coast. The salinity was high in Ulleung Basin. To the east of Ulleung Island, the salinity and the potential vorticity were high. In July, the salinity and the potential vorticity were low in Ulleung Basin. The low- and middle-salinity water existed along the coast. The potential vorticity of this water was low. This means that the low-salinity ESIW intruded into Ulleung Basin along the coast.

In September 1993, the area of the low-salinity and low-potential vorticity water extended from the coast to the east. The salinity and the potential vorticity were middle to the north but low to the

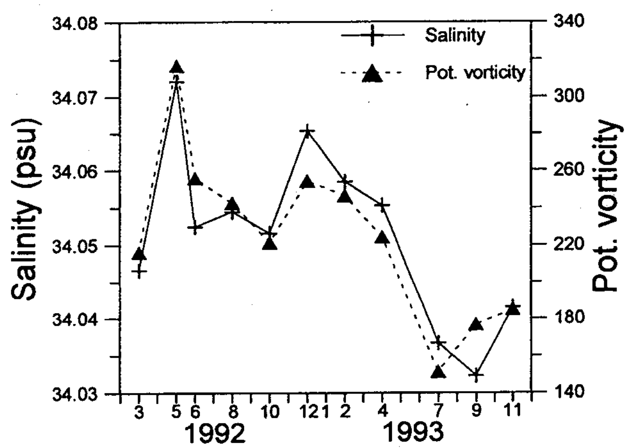

Fig. 8. Time variations of spatial mean salinity and potential vorticity ($\times 10^{-12}$/ms) of Line D in the isopycnal layer σ_θ=26.9—27.3.

southwest of Ulleung island. In November, the low-salinity water departed from the coast in the northern part, and the salinity in Ulleung Basin was middle except in the coastal area. The potential vorticity was still low except at some stations.

In summary, the salinity and the potential vorticity were lower in the northwestern part than in the southeastern part and the low-salinity ESIW intruded into Ulleung Basin between the Korean coast and Ulleung Island in summer. The high-potential vorticity water in the Ulleung Basin obstructed the inflow of the low-salinity water.

To investigate time variation of salinity in Ulleung Basin, the salinity on the isopycnal layer was averaged along line D (Fig 8). The potential vorticity was also averaged in the same way. The averaged salinity varied in phase with the potential vorticity. The salinity showed a seasonal variation that it was lower in summer than in winter except March 1992. Interannual variation was also as large as the seasonal one

Flow path of ESIW on the isopycnal surface

The ESIW has the range of potential density of 26.9—27.3 kg/m^3. The acceleration potential was calculated on the isopycnal surface of 27.2 σ_θ referring to 700 dbar to find out the flow path of ESIW.

Figure 9 shows the acceleration potential with the salinity on the isopycnal surface. In March 1992, the low-salinity water flowed southward along the east side of the warm eddy, and most of the water flowed northward but a part of the water entered the Ulleung Basin. In May, due to the strong northward current from the south near the east coast of Korea, the low-salinity water could not enter the Ulleung Basin but flowed eastward. In June and August 1992, the northward current became weak, and the low-salinity water could flow into the basin along the coast.

From October 1992 to April 1993, the low-salinity water did not flow into the Ulleung Basin. During this period, the potential vorticity was generally higher than other periods (Fig. 7). In July 1993 when the northward current dismished near the coast, the low-salinity water appeared in the northwest and flowed into the basin along the coast. The intruded low-salinity water spread over the basin in September and November 1993. This result corresponds with the previous description that the low-salinity and low-potential vorticity water intruded into Ulleung Basin between the Korean coast and Ulleung Island in summer.

CONCLUSIONS

The spatio-temporal variation of the ESIW with an SML were studied using the hydrographic data in the southwestern part of the East Sea from March 1992 to November 1993. The salinity of SML was lower near the Korean coast than to the east of Ulleung Island. Most of the salinity minimum waters were within the range of salinity of 33.80—34.06 psu and potential density of 26.9—27.3 kg/m^3. The salinity minimum waters did not follow the same isopycnal surface. Salinity of the salinity minimum water was lower in summer than in winter. Interannual variability of the salinity was as larg as seasonal one.

The salinity and the potential vorticity of the waters within the isopycnal layer of 26.9—27.3 in σ_θ were lower in the northwestern part than in other parts of the study area. The low-salinity area corresponded to the low-potential vorticity area and the potential vorticity was directly proportional to the salinity. The low-salinity water seemed to extend into the Ulleung Basin along the east of Korea in summer when the northward current was weak.

This proves that the ESIW intrudes into Ulleung Basin between the Korean coast and Ulleung Island in summer. When strong northward currents develops in the Ulleung Basin, the intrusion of the low-salinity water is interrupted.

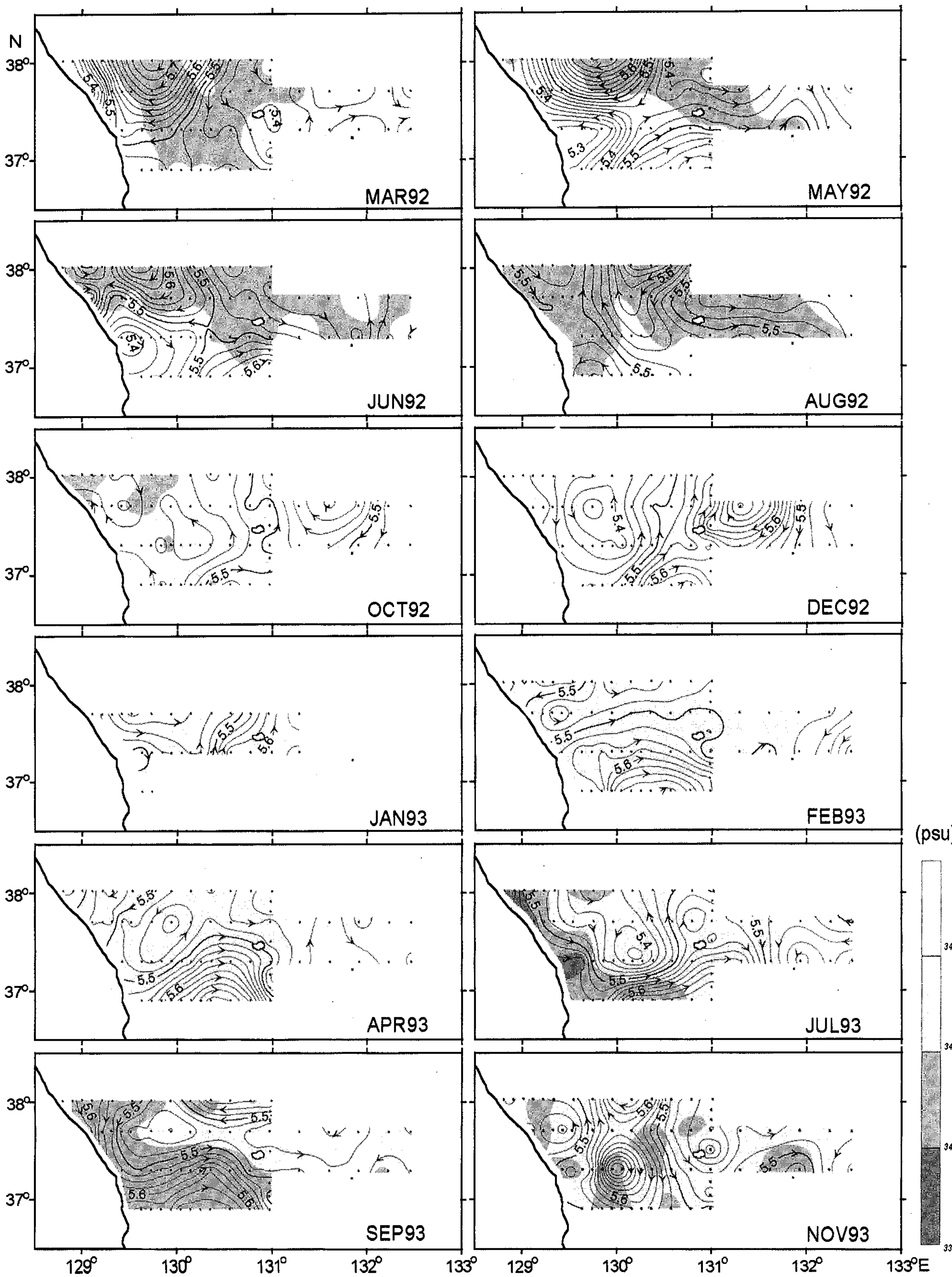

Fig. 9. Acceleration potential (contoured) and salinity (patterned) at the isopycnal surface $\sigma_\theta=27.2$.

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