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Seasonal variation of the East Korea Warm Current and its relation with the cold water

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Abstract: Hydrographic data and satellite images show the structure of the East Korea Warm Current (EKWC) and its seasonal variation. Satellite images taken in April with concurrent hydrographic data provide evidence of the branching of the Tsushima Current. However there is no evidence of branching in February. The EKWC flows north in summer when the cold water in the lower layer become thicker in the Korea Strait. Observed results and calculation of vorticity change suggest a possibility that the presence of the cold water, which can provide the negative relative vorticity for the EKWC, is more important than the planetary beta effect in the formation of the EKWC.

1. Introduction

The Tsushima Current (henceforth TC) carries heat and salt from the East China Sea to the East Sea throughout the year and determines the major hydrography in the East Sea (SVERDRUP, *et al.* 1942, p.734.)

UDA (1934) suggested that the TC leaving the Korea Strait splits into two branches (Fig. 1); one flows along the Japanese coast and the other along the Korean coast which is called the East Korea Warm Current (henceforth EKWC). Numerical experiments (YOON, 1982 *a*, *b*, *c*; KAWABE, 1982*b*) simulated the EKWC as a permanent feature due to the planetary beta effect and the branch along the Japanese coast due to the topographic effect.

Recently a couple of reports indicated the absence of the EKWC sometime. Firstly, based on satellite images and hydrographic surveys KIM and LEGECKIS (1986) showed that the EKWC was not formed in spring 1981 and suggested that the southward movement of the cold water was closely related with the branching of the TC. This suggestion is important, because in previous numerical models the cold water was assumed at rest as far as the branching was concerned.

Secondly, according to ISODA and SAITOH (1993) observation, the warm and saline water in the EKWC region is due to the seasonal episodic supply of the warm and saline waters through the northward intruding eddy process rather than the result of the persistent branching of the TC and they suggested the absence of the EKWC in winter. However they examined the data for only one year taken in 1987. Therefore it would be useful to examine the data for other years in order to understand whether the formation of the EKWC is indeed seasonal.

Most historical data were taken with bottle casts, so the depths of measurement were not accurate and it was often difficult to reveal the vertical structure of the EKWC. Moreover the meridional structure along the Korean coast was known poorly, because of inadequate spacing between stations.

The primary objective of this study is to understand the structure of the EKWC and its seasonal variation from recent CTD, hydrographic and satellite data.

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2. Data

To understand the physical characteristics in the Korea Strait and neighbouring sea and their temporal variation, surveys were

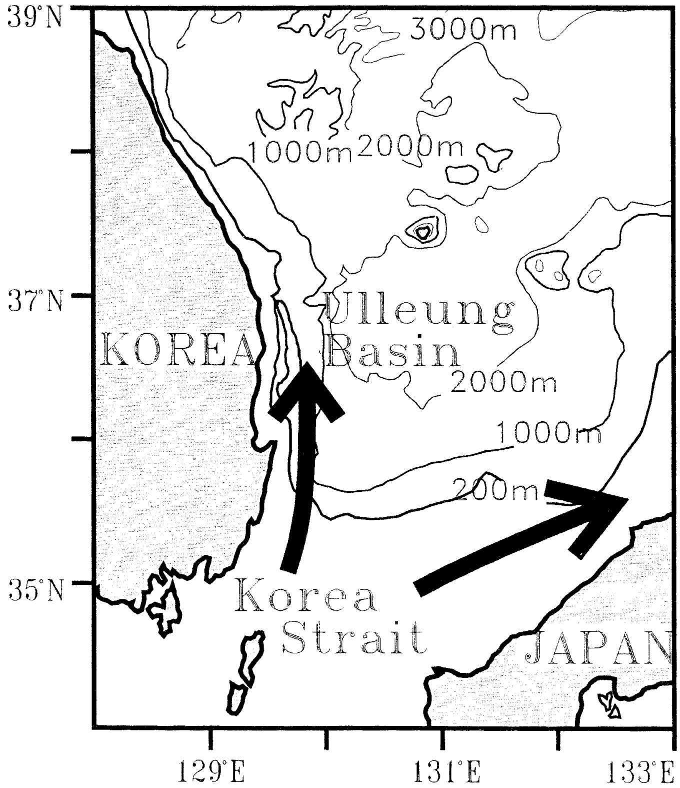

Fig. 1. Bathymetry of the East Sea. Arrows show schematically two branches of the Tsushima Current after Uda (1934). Depth are in meters.

conducted in April, June, August and October of 1991 and 1992 respectively, taking 60 CTD stations each time (Fig. 2). The stations are spaced every 10 miles approximately in the strait and CTD was lowered to near bottom at stations shallower than 500 m and about 500 m at stations deeper than 500 m. At each station SBE 19 profiler of Ser-Bird Electronics Inc. was lowered at a speed of 60 m/min approximately, taking two samples of temperature, conductivity and pressure in one second, which gives a vertical resolution of about 50 cm. Final data for analysis were obtained by averaging temperature and salinity data over two decibars.

To cover the eastern part of the strait, we used Japanese CTD data which were taken by Yamaguchi Prefectural Open-Sea Fisheries Experimental Station (▲marks in Fig. 2). The routine hydrographic data taken by the Korean Fisheries Research and Development Agency in February of 1991 and 1992 were also used. Satellite infrared image data from the Advanced Very High Resolution Radiometer on NOAA-9, NOAA-10 and NOAA-11 were processed at the Research Institute of Oceanography, Seoul National University to examine the branching of the TC.

3. Branching of the Tsushima Current

Since the sill depth of the Korea Strait is less than 150 m, the warm water flowing through the Korea Strait is limited to the upper layer as it spreads into the East Sea. Therefore, the major vertical and horizontal variation of temperature is also confined in the upper 200 m, which makes sea surface temperature (henceforth SST) particularly useful in investigating the branching. The path of the Tsushima Warm Water (henceforth TWW) is clear in winter and spring, because a thermal front is formed as the TWW meets the resident cold water. In summer and autumn, it is difficult to detect the path of the TWW by SST, because the surface front is not so clear due to the

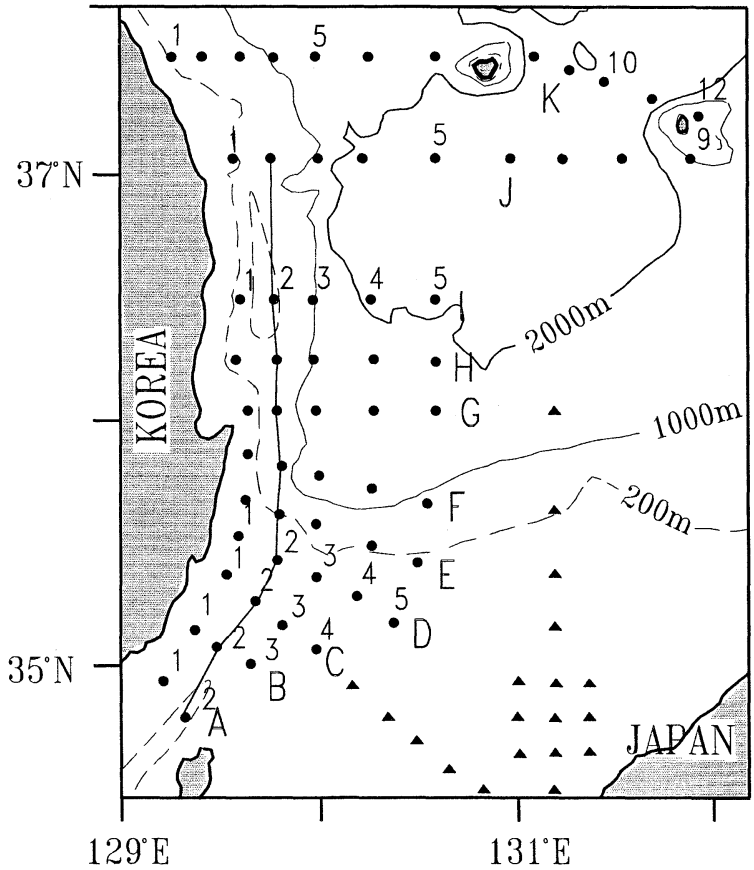

Fig. 2. CTD stations taken in April, June August, Octover, 1991 and 1992. Thick solid line represent the selected stations for vertical section. Depths are in meters. ▲ marks represent Japanese stations.

seasonal heating. Therefore satellite images of SST are useful in winter and spring only, illustrating nearly instantaneous distribution of the SST.

On February 25 1991, the SST was almost constant at 13℃ over a wide area, including the western and eastern channels of the Korea Strait (Fig. 3a). This uniformly warm water and the cold water to the north make a distinct thermal boundary in the east-west direction at 35° 30′ N. Across this boundary temperature dropped to the north by 3~5℃ in several kilometers. Similar front was reported previously by KIM and LEGECKIS (1986).

A partially cloud-free image taken on April 30 shows that warm inflow of 13~14℃ through the Korea Strait splits into two parts as it left the strait (Fig. 3b). The branch along the Japanese coast was similar to that observed in February. The other branch, the EKWC, flowed northward on separation, and part of it turned eastward at 38° N toward Ulleung Island.

On February 26 1992, the SST along the Korean coast was warmer than that on February 25 1991 (Fig. 3c). There is also thermal front in the east-west direction around 35° 30′ N.

The last image (Fig. 3d) taken on April 27, 1992 shows that the warm inflow of 13~14℃ through the Korea Strait clearly splits into two parts, developing two branches. The branch along the Japanese coast was similar to that observed in February 1992. The EKWC flowed northward on separation as in April 1991, and at 37° N most of it turned sharply eastward toward Ulleung Island and small part of it flowed northward along the coast.

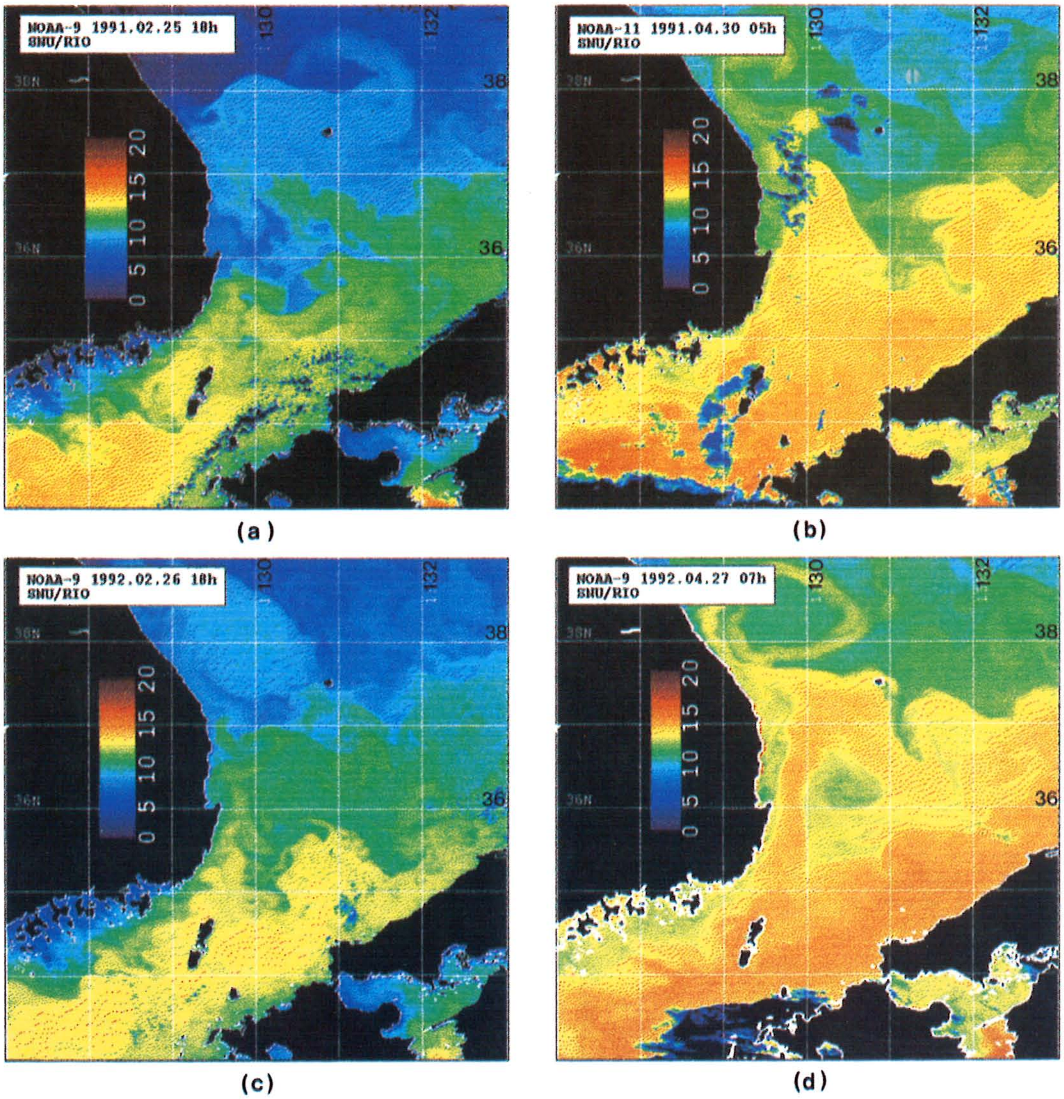

Fig. 3. SST images taken by satellite in (a) February 1991, (b) April 1991, (c) February 1992 and (d) April 1992.

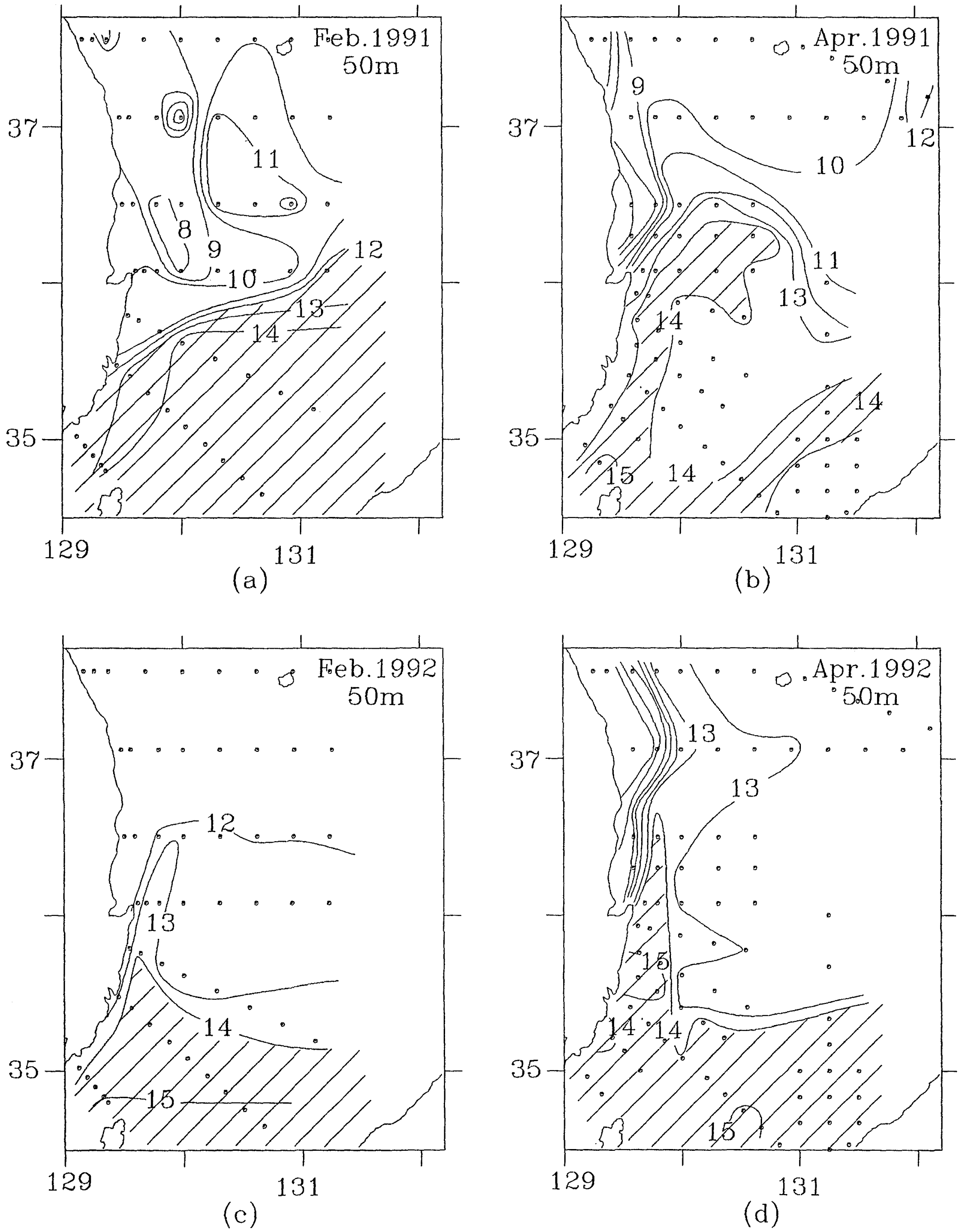

Fig. 4. Temperature distribution at 50 m depth from hydrographic survey in (a) February 1991, (b) April 1991, (c) February 1992 and (d) April 1992.

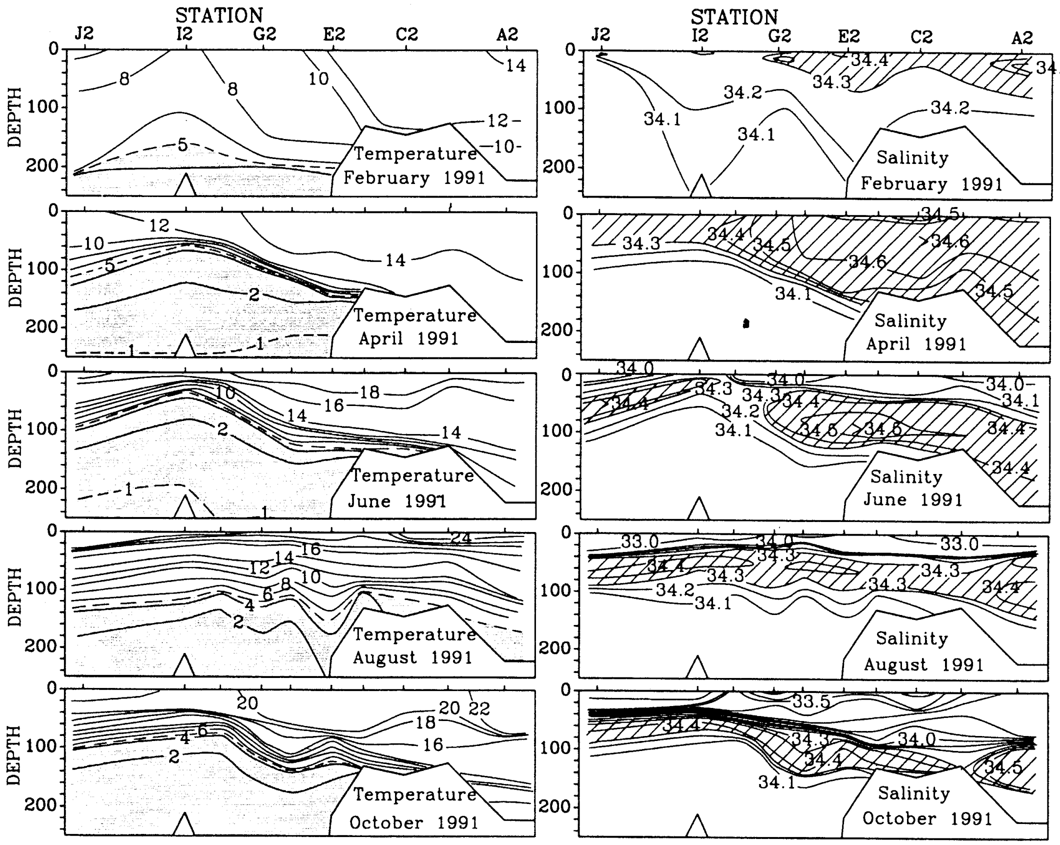

Fig. 5. Vertical sections of temperature and salinity along the Korean coast (see Fig. 2) in 1991. The waters colder than 5℃ are shaded and saline more than 34.3 psu are hatched.

Development of branching can be found also at 50 m depth in hydrographic data taken on February 2∼7, 1991 and February 17–23, 1992 by the Korean Fisheries Research and Development Agency. Hydrographic surveys were repeated on April 9∼27, 1991 and from 8 April to 4 May 1992.

In February, the water warmer than 12℃ in 1991 and 14℃ in 1992, passing the Korea Strait, was not observed north 36° N along the Korean coast (Fig. 4a, c). Although the survey was not conducted at the same time, it provided invaluable data to confirm the presence of the front in the east-west direction around 36° N which implies the absence of the EKWC. The formation of the EKWC was clear (Fig. 4b, d). The water warmer than 14℃ in 1991 and 15℃ in 1992 splits clearly into two parts as leaves the strait. One of it flowed north 36° N along the Korean coast, the other was along the Japanese coast as shown in SST (Fig. 3).

4. Vertical section along the Korean Coast

The section along the 2nd stations of each line was taken to examine seasonal variation of the EKWC (See Fig. 2 for stations). The most southern one is station A2 which is located at the deep trough of the Korea Strait. Those from B2 to D2 are on the sill whose depths are about 150 m (Fig. 5). Station E2 and I2 are on the southern slope and the bank respectively. The depth of the stations G2 and J2 is about 500m.

The cold water less than 5℃ which is consisted of the East Sea Proper Water and the salinity minimum layer water (CHO and KIM, 1994) is shaded and the saline water more than 34.3 psu which represents the TWW are hatched. The strong permanent thermocline with 5∼10 ℃ in temperature between the TWW and the water colder than 5℃, deepens towards the Korea Strait during entire period except February. In February, a mixed water with 8～10℃ in temperature is well developed, separating the TWW and the cold water. The thermal front between the mixed and the TWW around station E2 suggests the absence of the EKWC north of the continental slope in February. The saline water more than 34.3 psu, which can be used as another criteria for the TWW, is not observed north of station G2.

In April, the depth of 5℃ isotherm becomes shallow about 100 m in the Ulleung Basin, as the cold water expands into the Ulleung Basin from north. The isotherm of 12℃ moved near station J2 and the saline waters greater than 34.3 psu are observed at all stations. This indicates the formation of the EKWC along the Korean coast. The TWW whose thickness is about 140 m in the Korea Strait becomes thinner (less 60 m) around station I2, which is about 150 km apart from the strait. In June, the isotherm of 5℃ becomes further shallow and the cold water less than 5℃ appears on the sill. The surface water less than 34.3 psu in salinity appears at the surface. Therefore the saline TWW is present in the middle layer. The TWW becomes thinner to north as in April. The slope of the 10℃ isotherm is about 100 m/150 km from station C2 to I2.

The cold water moves further south in August. However the 5℃ isotherm becomes deeper in the northern area, which reduces the slope of the 10℃ isotherm. The temperature and salinity of the surface water is highest and lowest respectively during entire period. In October, the cold water on the sill retreats to slope, which increases the slope of the 10℃ isotherm. The slope is about 70 m/150 km. However the cold water less than 8℃ remains at station A2. The surface mixed layer is well developed, which makes the TWW deeper than in August. Although the surface layer becomes thicker than in August, it becomes colder and saline. Therefore the density increases compared with that in August. Salinity sections show that the EKWC which can be traced with the saline water more than 34.3 psu persists continuously except in February.

The same section in 1992 shows similar seasonal variation of the cold water and the TWW, although it is not shown here. The cold water becomes thicker in the strait in summer and thinner in winter. The TWW is not observed north of station G2 in winter but appears in other seasons.

Although we examine only one section, the fact that the temperature at 200 m depth in the Ulleung Basin for 1931–1940 is lower in August than in February (KANG, 1992), indicates that the lower layer in the Ulleung Basin and the Korea Strait is colder in summer than in winter generally. The sea water gets heat from the atmosphere in summer in this area (KANG, 1984). Therefore the decrease of the temperature can be explained only by the southward flow of the cold water from the East Sea which is the only place where the cold water lower than 10℃ is found. Directly measured results (ISOBE *et al.*, 1991; OMURA and KAWATATE, 1994) all show consistently southward flows of the cold water in the Korea Strait in summer.

5. Conclusion and Discussion

Satellite images taken in April of 1991 and 1992 with concurrent hydrographic data provide an evidence of branching of the TC. The distribution of SST clearly shows that the warm water flowing into the East Sea splits into two branches as it leaves the Korea Strait. One branch flows eastward along west coast of the Japan and the other one northward along the east coast of Korea, forming the EKWC. Contrast with April, non-branching were observed in February of 1991 and 1992.

ISODA and SAITOH (1993) suggests that the branching is not persistent, but episodic and the warm and saline waters are supplied by the northward intruding eddy process in spring and summer not in winter and autumn. Temperature distribution at surface in February of the 1989 and 1990 also show the absence of the EKWC (Fig. 6). Considering non-branching in February from 1989 to 1992 and the result of ISODA and SAITOH (1993) in 1987, it is believed that the absence of the EKWC is a permanent feature in winter.

Figure 7 shows schematically vertical distribution of the cold water (shadow area) and the TWW (hatched area) in each season. The cold water is defined by temperature lower than

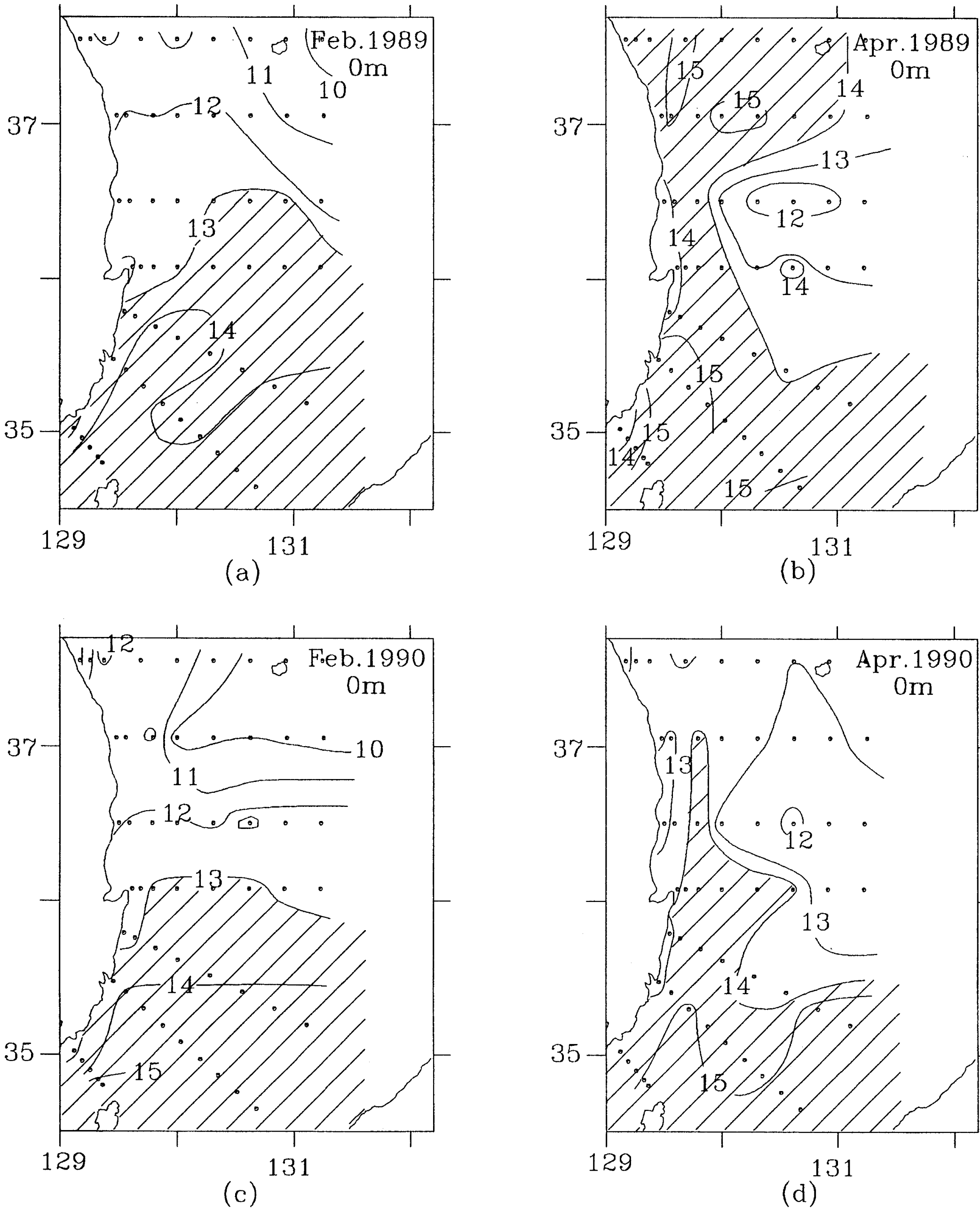

Fig. 6. Distribution of SST from hydrographic survey in (a) February 1989, (b) April 1989, (c) February 1990 and (d) April 1990.

5℃, the mixed water between 5℃ and 10℃ and the TWW higher than 34.3 psu and the surface water less than 34.3 psu. The cold water becomes thicker in the strait in summer when the density of the TWW decreases and retreats in winter when it increases. Further studies are necessary to reveal that the southward extension of the cold water is related with the density of the TWW or not. This study shows that the EKWC is formed when the cold water

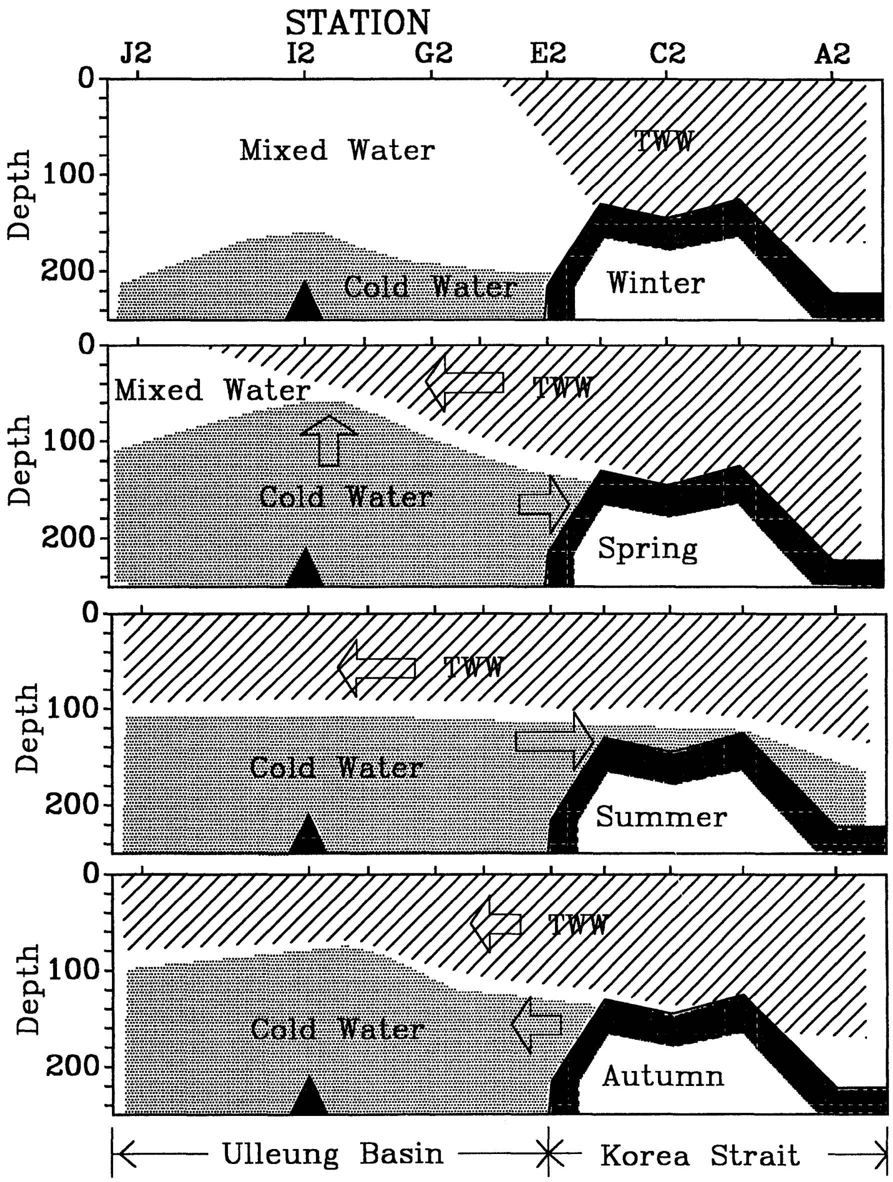

Fig. 7. Schematic distribution of the lower cold water (shadow area) and the Tsushima Warm Water (hatched area). Arrows indicate the direction of the water movement. The cold water represents the water colder than 5℃, and the TWW salinine more than 34.3 psu and the surface water less than 34.3 psu.

becomes thicker in the strait and it is absent when the cold water is located at a deeper depth in the basin.

The absence of the EKWC bears an exceptional importance in terms of not only the branching mechanism but also the circulation in the East Sea. YOON (1982 *a, b, c*) and KAWABE (1982b) treated the branching of the TC as dynamics of a warm current which is forced through a shallow strait into a deep basin of motionless cold water and reproduce the permanent branching numerically. However the absence of the EKWC in winter implies that the motion of the cold water is interlocked with the branching.

Concerning the formation of the EKWC, the planetary beta effect has been recognized as the cause of it. However simple calculation shows that the change of potential vorticity due to the shrinking of the TWW along the Korean coast is greater than the planetary beta effect. Neglecting external forcing and friction, we can show that quasi-geostrophic motion of uniform upper layer conserves the potential vorticity such as

$$\frac{f}{H}=\frac{f_0}{H_0}\left(1+\frac{\beta}{f_0}y-\frac{\alpha}{H_0}y\right)=\text{constant.}$$

Here β is the beta-effect, α is the slope of the bottom and H_0 is the mean thickness of the upper layer. In this case, let's assume the permanent thermocline as a bottom for the upper layer, because the upper TWW shrinks due to the presence of the lower cold water along the Korean coast. Locally $\frac{\beta}{f_0}=10^{-9}\text{cm}^{-1}$ (Kim *et al.*, 1991) and $\frac{\alpha}{H_0}=1.3\sim5.3\times10^{-8}\text{cm}^{-1}$ as the permanent thermocline changes 20~100 m over about 150 km as shown in along-strait section (Fig. 5). When the TWW experience shrinking due to the presence of the lower layer, it takes the negative relative vorticity which can induce the northward flow along the Korean coast. However the cold water which locates at deep depth in winter could not induce the negative vorticity. This simple calculation indicates that the effect of the cold water on the formation of the EKWC is important. Concerned with the effect of the cold water, Isobe (1994) argued that the Jebar effect in the Korea Strait which is mainly caused by the cold water along the Korean coast in summer, supplies the negative vorticity. His result in which the bottom cold water could supply the negative vorticity, is consistent with this study. However his interest is on the seasonal variation of the main axis of the TC in the strait. Our recent study to investigate the branching of the TC in the Korea Strait by the hydraulic model with two active layer, showed quantitatively the effect of the cold water in the formation of the EKWC (CHO, 1995).

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