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Two Branches of Tsushima Warm Current in the Western Channel of the Korea Strait

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韓國海峽 西水道에서 對馬暖流의 2個 枝流

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Abstract: On the basis of oceanographic observation conducted in summer 1982, the flow pattern of the Tsushima Warm Current definitely showed two branches with high surface velocity more than 70 cm/sec in the western channel of Korea Strait. One of the branches, the East Korea Warm Current, found about 8 km off Pusan flows northward along the east coast of Korea and the other branch, located at about 20km off Pusan flows east after passing the Korea Strait. The branching of two flows already occurred before the Tsushima Warm Current reaches the Pusan-Tsushima section, and the volume transport and the widths of the two branches are not much different from each other. The number of branches may be controlled by the width of western channel and the flow of two branches may also be related to the variation of layer depth and the widening ratio of widths between the western channel and the Japan Sea (East Sea).

要約: 1982년 여름에 실시된 해양관측자료에 의하면 대마난류의 흐름은 한국해협 서수도에서 70cm/sec 이상의 강한 표면유속을 갖는 두개의 분지 형태를 보였다. 부산에서 약 8km 부근에 나타나는 동한난류로 불리우는 한개의 분지는 한국동해안을 따라 북쪽으로 흐르며, 부산으로부터 약 20km 떨어져 나타난 제 2 분지는 한국해협 통과 후 동쪽으로 향한다. 두개의 흐름으로 분기되는 현상은 대마난류가 부산-대마도 단면에 이르기 이전에 형성되며, 두 분지의 용적수송량 및 흐름의 폭은 큰 차이를 보이지 않는다. 분지의 갯수는 서수도의 폭에 의해 좌우되는 듯하며, 두 분지의 흐름은 층두께의 변화와 서수도와 동해의 폭의 비율과 관련되는 것으로 보인다.

INTRODUCTION

It is well known that the Tsushima Warm Current supplies waters of high temperature and high salinty to the Japan Sea (East Sea) through the Korea Strait which is divided into two channels (the western channel from Korea to Tsuhima and the eastern channel from Tsushima to Kyushu: see Fig. 1). Suda and Hidaka (1932) first proposed from the study of flow pattern in the southern part of Japan Sea that the Tsushima Warm Current forms three branches : the East Korea Warm Current and the second branch are the extension of flow which enters the Japan Sea through the western channel and the first branch (the Japanese near-shore branch) through the eastern channel. Such a division into three branches has been recognized by many oceanographers, even though there is another view of meandering (Moriyasu, 1972).

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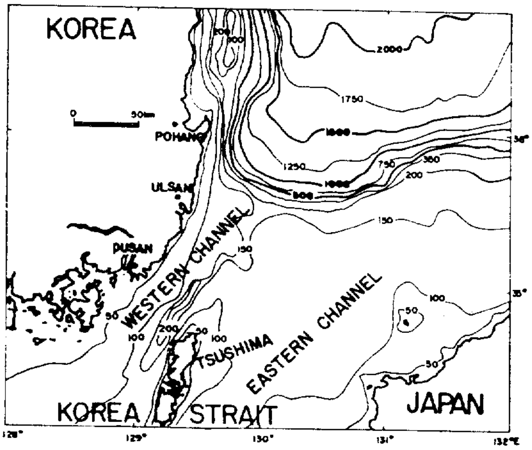

Fig. 1. Bottom topography near the Korea Strait.

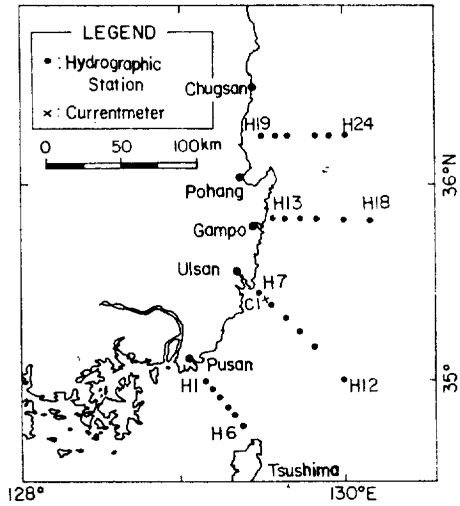

Fig. 2. Location of oceanographic stations.

Toba, Tomizawa, Kurasawa and Hanawa (1982) showed that the driving force for the Tsushima Warm Current is the sea level difference between the East China Sea and the sea area east of Tsugaru Strait. The variability of the Tsushima Warm Current in the Korea Strait was recognized by the change of hydrographical characteristics (Hahn, 1979; Kolpack, 1982; Hong and Cho, 1983) and also by the indirect current computation (Hidaka and Suzuki, 1950; Yi, 1966; 1970; Toba et al., 1982).

In the western channel of Korea Strait, the bottom cold water is found below the Tsushima Warm Current Water. Its intensity is strong when the Tsushima Warm Current becomes strong in August-September (Lim and Chang, 1969; Lim, 1973; An, 1974).

Near the Korea Strait, physical interpretation of branching mechanism of Tsushima Warm Current was tried. By numerical modeling, Yoon (1982a, b) showed that the East Korea Warm Current flows northward as a steady western boundary current. According to Tanioka (1968), the path of East Korea Warm Current is changed seasonally and almost 90% of its volume transport returns back Southward. Kawabe(1982a, b) examined the nature of three branches and showed in his numerical model that the second branch is a temporal current formed along the offshore side of Japanese continental shelf in association with the variation of Tsushima Wam Current. But the models of Yoon (1982a, b) and Kawabe(1982a, b) did not consider the variation of bottom topography and layer depth near the western channel of Korea Strait. The studies on the geostrophic adjustment in the sea strait (e.g., Nof, 1978a, b; Whitehead and Miller, 1979; Conlon, 1982; Ichiye, 1982) has an interest in the western channel of Korea Strait.

The purpose of this study is to reveal the flow structure of two branches observed in the western channel and to discuss the possible governing mechanism of two branches of Tsushima Warm Current in the western channel.

The data used for this study was collected in the southwestern part of the Japan Sea in summer 1982 (Fig. 2). The temperature and salinity were measured down to 300m depth at 24 stations by Nansen cast, and the current measurements at 15m and 82m depths respectively were carried out for about 50 hours.

DISTRIBUTION OF TEMPERATURE AND SALINITY

In order to see the water masses near the western channel of the Korea Strait, the temperature and salinity observed above 300m depth in summer 1982 are shown in Fig. 3. The three kinds of waters can be distinguished. The middle water characterized by high temperature of 15°C and high salinity more than 34‰ was found in the density range of 25. 0–26. 0. The surface water has wide ranges in temperature of 20~27°C and in salinity of 31–33‰. Below the middle water, the salinity decreased slightly with decreasing temperature. It can be easily seen that the middle water of high salinity is the Tsushima Warm Current Water flowing from the soutn of Korea Strait.

Fig. 4 shows the cross-sectional profile of temperature, salinity and densaty between Pusan and Tsushima. The seasonal and permanent thermoclines are located at about 20m and 100-160m depths respectively. Between the two thermoclines, the Tsushima Warm Current Water has a homogeneous layer with a density of 25-26. The vertical distance between 14°C and 16°C is 20m near Pusan and it increases

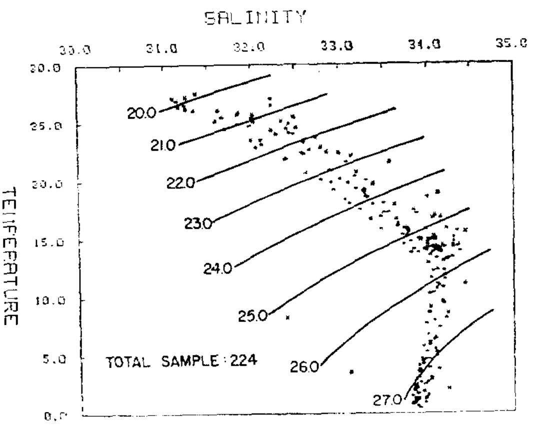

Fig. 3. Temperature-salinity relations near the Korea Strait during Aug. 6-10, 1982. The measurements were carried out above 300m depth.

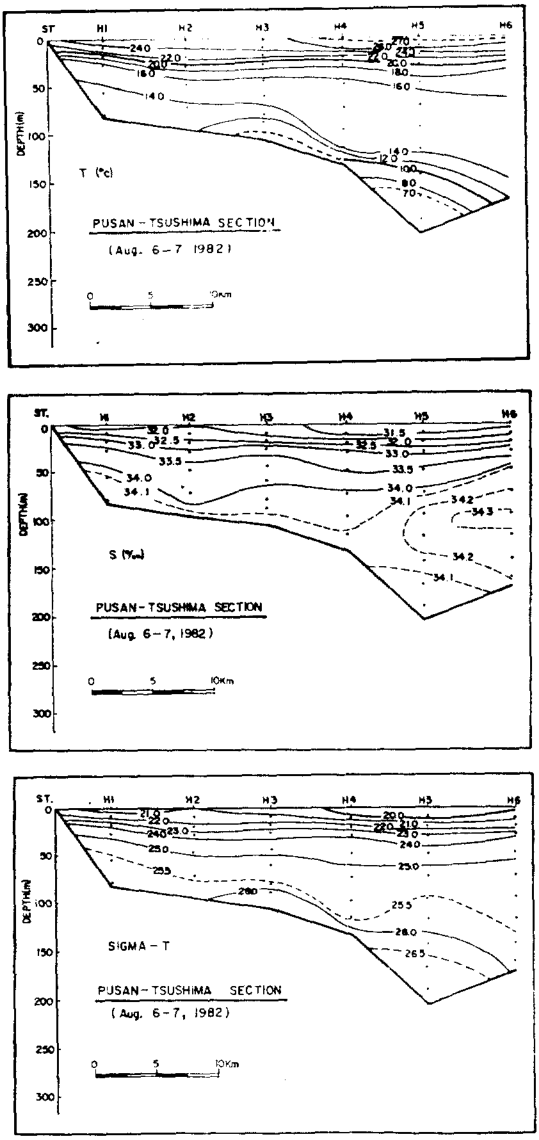

Fig. 4. Vertical distribution of (a) temperature, (b) salinity and (c) density between Pusan and Tsushima. in Aug. 1982 Pusan is in the left and Tsushima in the right.

to 80m in the western side of Tsushima. The fact that temperature and salinity near the bottom between Hl and H2 are more than 12°C and 34. 1‰ shows the influence of the Tsushima Warm Current Water near the bottom, but at the deepest station H5 in this section the bottom cold water is found.

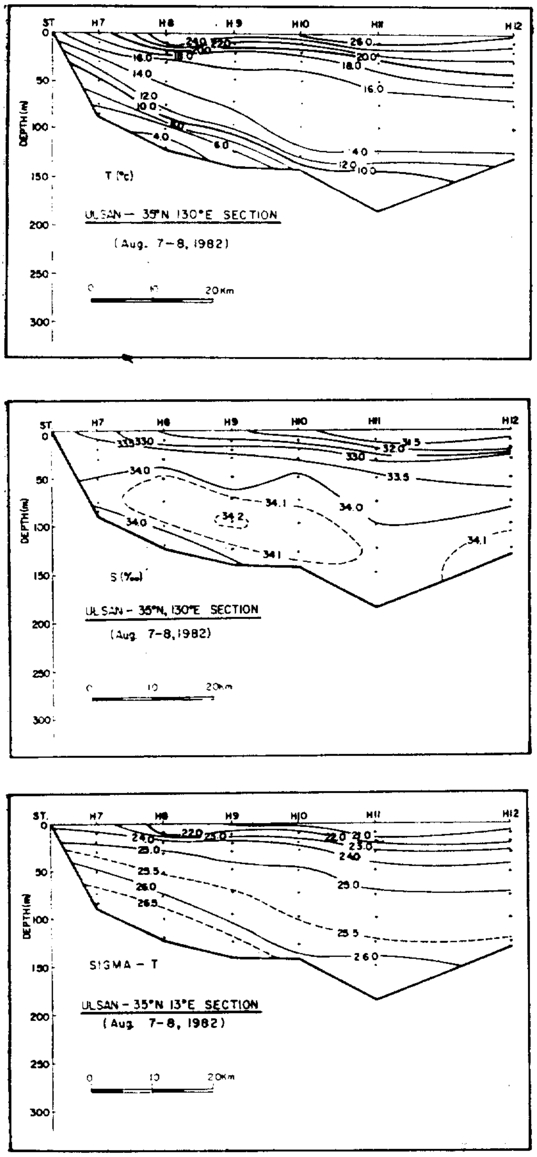

Fig. 5. Vertical distribution of (a) temperature, (b) salinity and (c) density southwards from Ulsan to 130°E in Aug. 1982.

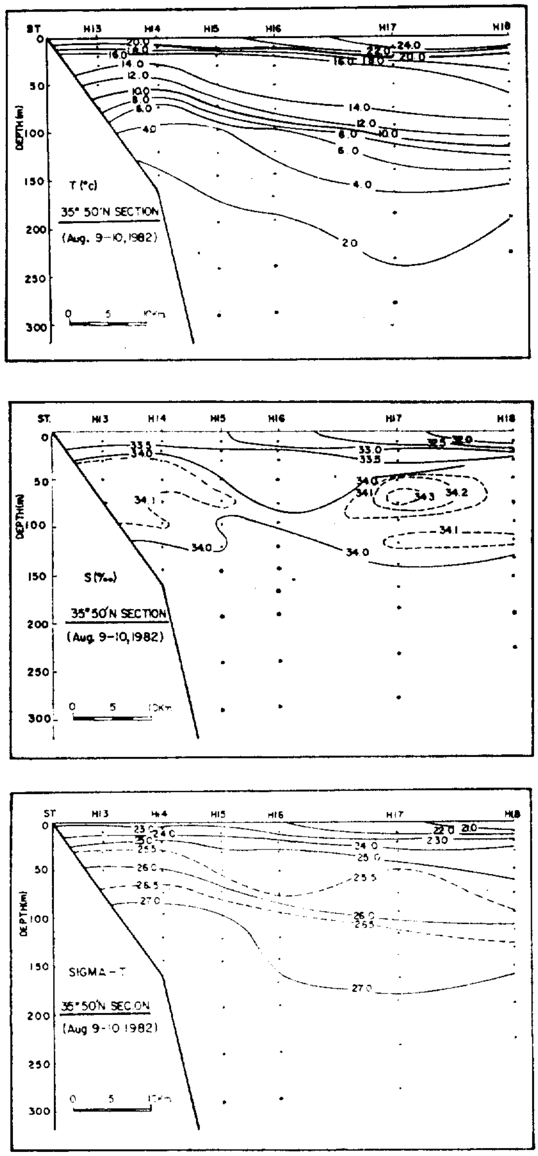

Fig. 6. Vertical distribution of (a) temperature, (b) salinity and, (c) density at 35°10′N eastward to 130°10′E in Aug. 1982.

The vertical profile of temperature, salinity and density observed southeastward from Ulsan to 130°E is shown in Fig. 5. As in Fig. 4, the Tsushima Warm Current water characterized by a homogeneous layer of temperature 14-16°C and salinity higher than 34.0‰ appears above the permanent thermocline located at 30-40m above bottom. A comparison between H11 and H8 shows that the bottom depth of H11 is 60m deeper but temperature is much higher and salinity and density is lower than in H8. This means that the bottom water flows mainly along the bottom topography of Korean side, and a strong stratification exists near the Korean side.

Fig. 6 shows the vertical profile of temperature, salinity and density at the latitude of 35°50'N eastward to 130°10'E. Between 20m and 100m depth, a homogeneous layer caused by the Tsushima Warm Current Water can be distinguished with temperature of 14-16°C and salinity higher than 34.0‰. Comparing H17 in Fig 6 with H10 in Fig. 5, the layer depth of 14°-16°C has decreased from 100m to 50m and the depth of 14°C has also decreased from 120m depth to 80m depth There are two maximum salinity cores (S>34.1‰) found near Korean coast and offshore side, and the depth of 14°C is shallower at H14. Below the permanent thermocline, a cold (T<4°C) and less saline (S<34.0‰) water which is generally accepted as the Japan Sea Proper Water (Uda, 1934; Lim and Chang, 1969; Shuto, 1982) or Japan Sea Intermediate Water (Kim and Kim, 1983; Lim, 1983; KORDI 1983) has the density higher than 27.0, and it can be expected that the bottom water of low temperature shown in Fig. 4 and Fig 5 is originated from this water in Fig. 6. The horizontal gradient of the depth ($\Delta z/\Delta x$) of 10°C isotherms between H18 is about 1/750 which has decreased to a half comparing to 1/40 between coast and H10 shown in Fig. 5.

The vertical distribution of temperature, salinity and density observed at the latitude of 36°15'N eastward to 130°E is shown in Fig. 7. The maximum salinity layer (S>34.0‰) is found at about 50m depth with layer depth of about 20m. The homogeneous layer with temperature 14~16°C shown in the previous figures does not appear in this section, and there is no distinction between seasonal and permanent thermoclines. The horizontal gradient of the depth of isotherms has decreased more slowly in comparison with the southern sections. The high salinity core (S>34.1‰) found near the Korean coast has a relation to the core shown in Fig. 6 and it seems to be originated from the Tsushima Warm Current Water because of its high salinity, although there the southward coastal jet was detected by drogue tracking (KORDI, 1982).

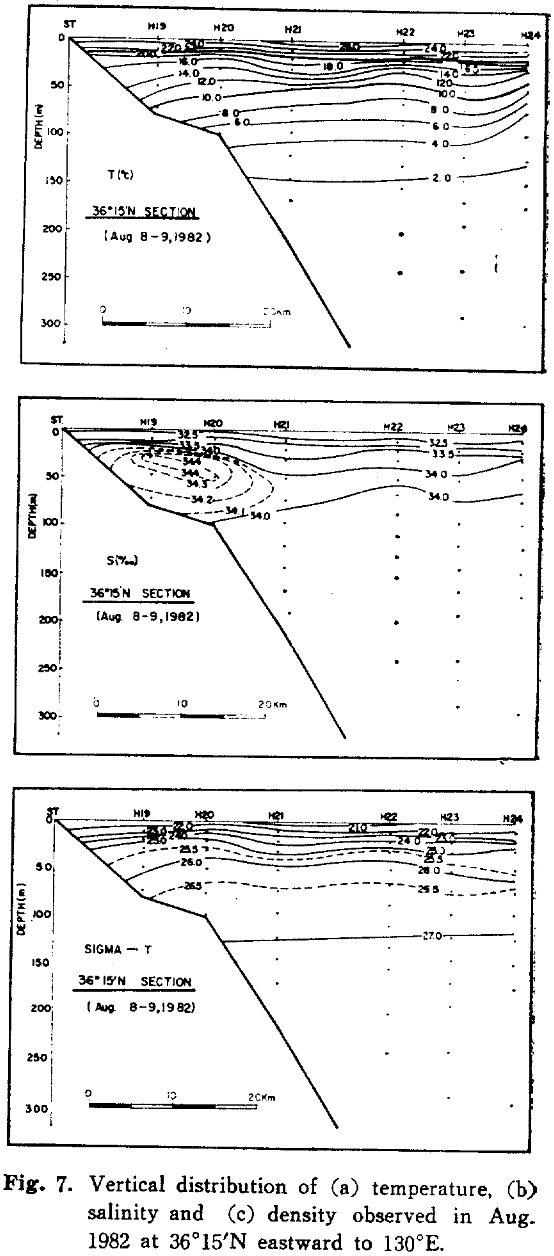

Fig. 7. Vertical distribution of (a) temperature, (b) salinity and (c) density observed in Aug. 1982 at 36°15'N eastward to 130°E.

DETERMINATION OF REFERENCE LEVEL

Fig. 8 shows the vertical profile of velocity obtained by an adjustment of direct current

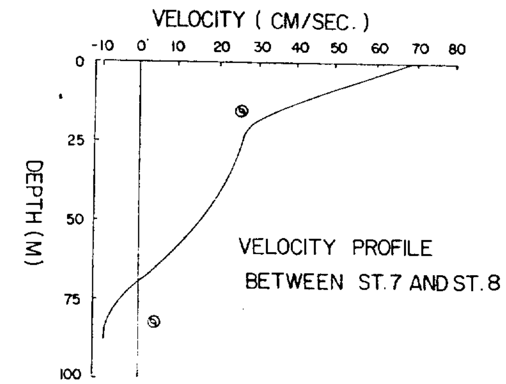

Fig. 8. Vertical profile of velocity between H7 and H8, adjusted to direct current measurements.

measurements to dynamic calculation between H7 and H8. The vertical shear of current speed directly measured is less than that of dynamic calculation, and there is a disagreement of ± 12 cm/sec. The vertical shear of current speed becomes larger at two thermoclines and the reference level can be placed at the permanent thermocline located at about 70m depth where the density of 26.5 is found in Fig. 5. The density surface of 26.5 lies in the boundary layer between the Tsushima Warm Current Water and the bottom cold water. Therefore, in the study area where two current systems exist with opposite directions, the choice of the reference level fixed at the boundary layer is reasonable also from a hydrographic point of view. With the data of summer 1981, Byun and Seung (1984) used the density surface of 26.0 as a reference level for caculating the current speed in the western channel of Korea Strait and they showed also that the surface of 26.0 lies in the boundary layer. In order to see the structure of the Tsushima Warm Current in summer 1982, the reference level of no motion is fixed to density surface of

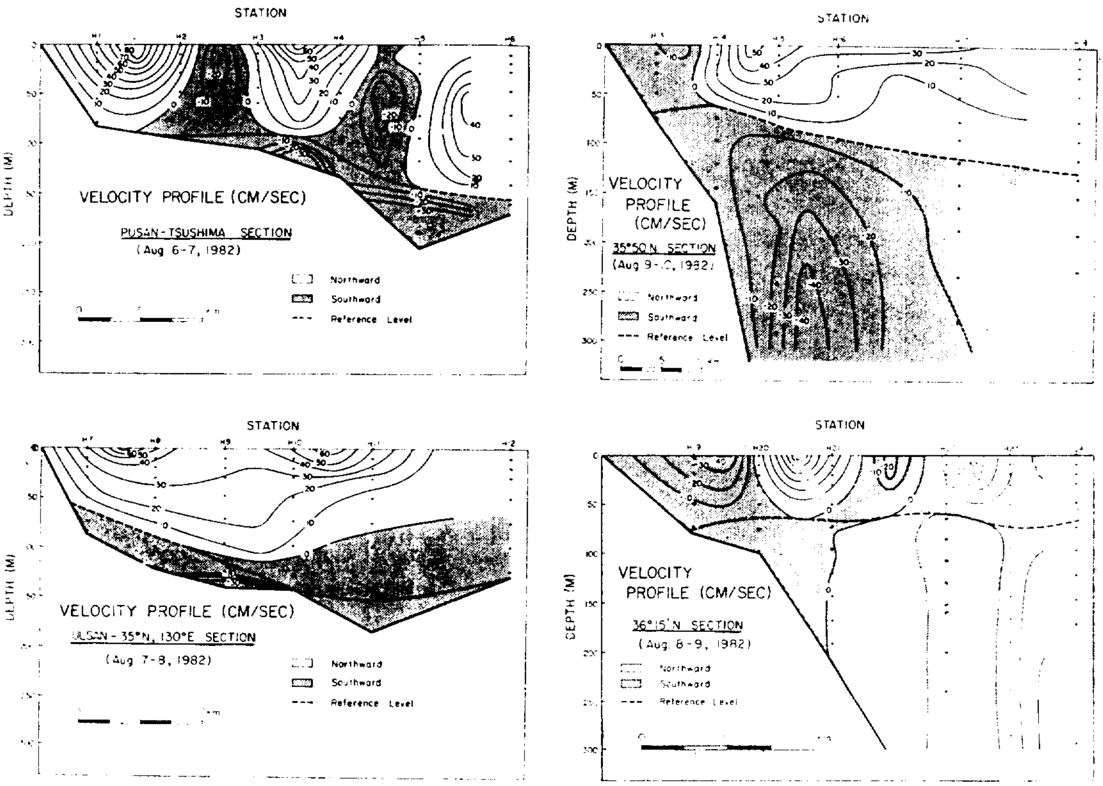

Fig. 9. Velocity profile of section (a) Pusan-Tsushima, (b) Ulsan-35°N, 130°E, (c) 35°50′N and (d) 36°15′N.

26.5, although this surface of 26.5 may not represent well the boundary layer in the two northern sections of 35°50′N and 36°15′N because of vertical mixing.

STRUCTURE OF TSUSHIMA WARM CURRENT IN THE WESTERN CHANNEL OF KOREA STRAIT

Fig. 9 shows the velocity profile of 4 sections shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7. The velocity was determined with a reference level placed at density surface of 26.5. In shallow region where the density is less than 26.5, the bottom was taken as a reference level. Generally the northward flow of Tsushima Warm Current is predominant. The strong surface currents with speed faster than 70cm/sec are found separately at two places in the southern sections of Pusan-Tsushima (Fig. 9-a) and Ulsan - 35°N, 130°E (Fig. 9-b). But in the northern sections of 35°50′N and 36°15′N there is only one strong current. In order to see the relation among the strong currents found in two southern sections and in the other two northern sections, the temperature and salinity measured at six stations near the strong flows are plotted on the T-S diagram as shown in Fig. 10. The characteristic of the Tsushima Warm Current Water is marked around temperature of 15°C and high salinity of 34‰ at

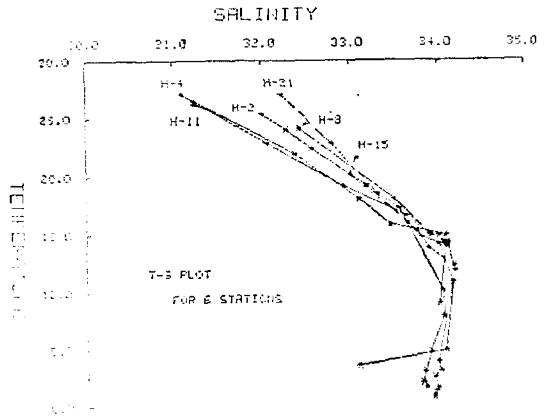

Fig. 10. Temperature-salinity relations for 6 different stations selected near the strong flow.

all 6 stations, but the temperature-salinity values at the surface layer can be grouped into two: one is found at stations of H2, H8, H15 and H21 located near the coast (coastal mode) and the other at H4 and H11 (offshore mode). The coastal upwelling centered near Ulsan area (see Fig. 5) influences the coastal mode which has wider ranges in temperature and salinity than the offshore mode. The different two modes show that the strong surface flow found in two northern sections of 35°50′N and 36°15′N is the continuation of the flow found near H2 and H8 in the western channel of Korea Strait. The offshore mode is not found at two northern sections and therefore it may be postulated that the offshore mode flows out eastward between Ulsan-35°N, 130°E section and 35°50′N section. The coastal mode flow corresponds to the East Korea Warm Current and the offshore mode to the 2nd branch of the Tsushima Warm Current (Suda and Hidaka, 1932; Kawabe, 1982a).

From Fig. 9, the East Korea Warm Current is found 8km off Pusan, 13km off Ulsan, 18km and 23km off coast. This results agree well with direct current measurement of drogue tracking which showed northward flow with 29cm/sec at about 20km off Korean coast(KORDI, 1982). As indicated by Lie(1984), the axis of East Korea Warm Current seems to shift a little away from the east coast of Korea as it flows northwards. The second branch is located at about 20km off Pusan and 45km off Ulsan. The branching seems to have already occurred before the Tsushima Warm Current reaches the Pusan-Tsushima section as shown in Fig. 9-a. The depth of $\sigma_t=26.5$ surface, which was taken as a reference level surface in this study, is decreasing along the path of the East Korea Warm Current and increasing along the second branch.

The volume transport of Tsushima Warm Current in summer 1982 was estimated to be $0.5\sim1.0\times10^6 m^3/sec$ in the western channel. Yi

(1966) showed, with a refrence level placed at 125m depth, the average volume transport of $0.96\times10^6 m^3/sec$ in the western channel and Tanioka (1968) calculated $3.0\times10^6 m^3/sec$ for the transport of East Korea Warm Current with 300 dbar surface as a reference level. Byun and Seung (1984) also showed the volume transport of $0.83\times10^6 m^3/sec$ in the western channel with a reference level of sigma-t 26.0. The volume transports of two branches were not much different from each other. The volume transports calculated at H1-H2 and H7-H8 are 0.23 and 0.24×10^6 m^3/sec respectively, and for the second branch $0.23\times10^6 m^3/sec$ is calculated at H3-H4 and H10-H11, respectively.

DISCUSSION ON THE FORMATION AND PATHS OF TWO BRANCHES

The Tsushima Warm Current carries the light water through the Korea Strait into the Japan Sea where the dense water is found in the lower layer. In the western channel of Korea Strait, the permanent thermocline differenciates the Tsushima Warm Current Water from the bottom cold water. In order to understand the behavior of the two branches seen in previous sections, it is necessary to see the dynamics of buoyant outflow from the sea strait in a rotating system.

Whitehead and Miller (1979) suggest from their hydraulic experiment of two layers without depth variations that an outflow can have several different flows, depending on the buoyancy, the geometry of the basin and the latitude. They show also that if internal Rossby radius is less than the width of the strait, a sharp shear zone would form within the strait, which would develop small eddies. The natural length scale associated with the buoyant flow is the internal Rossby radius, $R=(g\Delta\rho h/\rho f^2)^{1/2}$, where g is gravity, $\Delta\rho$ is density difference between two layers, h is water depth and f is Coriolis parameter. If the Tsushima Warm Current Water whose typical density is 25.5 is considered to represent the upper layer above permanent thermocline in the western channel, the internal Rossby radius, R, will be about 12 km with values of $g\sim980 cm/sec^2$, $\Delta\rho\sim1.0\times10^{-3}$ gr/cm^3, $h\sim100m$, $\rho\sim1.0265$ and $f\sim8\times10^{-5}$ rad/sec. This value of about 12km is fairly consistent with the widths of two branches shown in Fig. 9-a. The distance of 50km from Pusan to Tsushima is about 4 times larger than the Rossby radius, which may explain why two branches or two eddy-like flow patterns exist in the western channel of Korea Strait. The simple inertial theory (Stommel, 1966) predicts the maximum velocity of $(g\Delta\rho h/\rho)^{1/2}$ which coresponds to 98cm/sec in the western channel. The value of 98cm/sec is also consistent with the calculated speed of more than 70cm/sec shown in Fig. 9-a.

Nof (1978a) proposes a mathematical model of one layer which may give some qualitative explanation of the flow paths of the East Korea Warm Current flowing northward along the Korea east coast and of the second branch deflecting to the right after passing the western channel of Korea Strait. By solving the potential vorticity equation, an outflow from the strait with uniform velocity distribution can be predicted whether it will be deflected to the right or left depending on the depth of basin in which it debouches. There is a critical Rossby number, $Ro_c=C^2|\Delta H|(1+\Delta H)/2$, where C is relative widening of strait, $\Delta H=(H_1-H_0)/H_0$ (H_1: depth of basin, H_0: depth of strait), and below Ro_c the flow becomes to be narrow and veer to the right for $\Delta H>0$ and to the left for $\Delta H<0$. For our case, if we consider the branches as uniform flows with basin width of about 250 km (from Korean coast to Oki island), strait width of 50 km, $\Delta H=-0.2$ for the East Korea Warm Current (from 90m at Pusan-

Tsushima section to 70m at 36°15′N section) and $\Delta H=0.2$ for the second branch (from 90m at Pusan-Tsushima section to 110m at Ulgi-35°N, 130°E section), the relative widening will be 5 and then the critical Rossby numbers are 2 and 3 for the East Korea Warm Current and the second branch, respectively. The Rossby number, $Ro=V/fB$, where V is the speed in the strait and B is the width of current, is 0.8 in the western channel, taking the values of $v\sim100$cm/sec and $B\sim10$km. The fact of $Ro<Ro_c$ may explain the two narrow flows after passing the Korea Strait, and the fact of $\Delta H<0$ and $\Delta H>0$ may give some qualitative explanations that the East Korea Warm Current flows northward along the Korea coast (deflecting to the left) and the second branch deflects to the right.

CONCLUSION

Based on the oceanographical observation conducted in summer 1982, the Tsushima Warm Current Water in the western channel of Korea Strait shows two branches with high surface velocity more than 70cm/sec. One of the branches, the East Korea Warm Current, found about 8km off Pusan flows northward along the east coast of Korea (about 20km off coast at 36°N) and its characteristics of temperature and salinity seem to be related to the coastal upwelling near Ulsan. The other, the second branch, which is found about 20km off Pusan in Pusan-Tsushima section flows out to the east (deflecting to the right) after passing the Korea Strait, even though it was not traced far away from the Strait. The existence of two branches in Pusan-Tsushima section shows that the branching has occurred before the Tsushima Warm Current reaches the section. The volume transport and the width of the two branches do not show much difference between them.

The width of two branches is comparable to the internal Rossby radius of 12km calculated from the density difference between Tsushima Warm Current Water and the bottom cold water, and the width of the western channel may be related to the number of branches. The path and speed of the two branches after passing the western channel may be dependent on the variation of layer depth in the branches and on the widening ratio of widths between the channel and the Japan Sea (East Sea) near the strait.

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