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THE NORTHERN BOUNDARY OF THE TSUSHIMA CURRENT AND ITS FLUCTUATIONS

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ABSTRACT

The northern boundary of the Tsushima Current and its fluctuations are discussed in the Japan Sea in summer. This current was characterized with high salinity, and its path was traced by following the salinity maximum on the basis of oceanographical data collected during the period from 1963 to 1979. The salinity maxima (34.45~34.85 ‰) of the Tsushima Current in the areas between 29°N in the East China Sea and northern part of the Japan Sea were found at depths between 46m and 135m. The representative thermosteric anomaly corresponding to the salinity maximum was examined in order to analyze the advection of this current. In the Tsushima Current region in the Japan Sea, the thermosteric anomaly values in the layer of salinity maximum during the period of 1970 to 1979 was between 220 cl/t and 260 cl/t. In general, as the current moves northward its salinity decreases, its thermosteric anomaly decreases and the depth of salinity maximum becomes shallower.

The northern boundary of this current, which is indicated by 34.4‰ isohaline on 240 cl/t isanosteric surface during the study period of ten years, was confined to south of 40°N of the Japan Sea. The 34.4‰ isohaline revealed two types of flow: one of them flows northward along the eastern coast of South Korea and then meanders eastward, while the other flows basically northeastward along the coast of Japan. The meanders of northern boundary of this current identified by isohaline in this work were nearly similar to those studied by others on the basis of isotherm analysis.

INTRODUCTION

The Japan Sea is a relatively small marginal sea with a deep basin. The area of the Japan Sea is smaller than that of the East China Sea but the volume is greater than that of the East China Sea. The ratio of the area is 0.81, and that of the volume is 5.79. This means that the Japan Sea is deeper than the East China Sea. About 90% of the entire water of the Japan Sea is occupied by the Japan Sea Proper Water which is nearly homogeneous water of 0.5°C and 34.05‰, and the rest of the sea consists of the Intermediate Water (8°~16°C, 34.14~34.68‰) and the Surface Water (17°~20°C, 33.24~33.96‰) in summer (Yasui et al., 1967). On the other hand, it is known that the Tsushima Current, which is composed of relatively high temperature and high saline water, and similar to the properties of the Kuroshio, flows through the Korea Strait into the Japan Sea and then becomes the Intermediate Water. In partircular, Moriyasu (1972) discussed the relation of T-S, and of T-O_2 for the Intermediate Water in the Tsushima Current region of the Japan Sea.

Naganuma (1973) prepared the schematic diagram of the flow patterns of the Tsushima Current in the Japan Sea as shown in Fig. 1

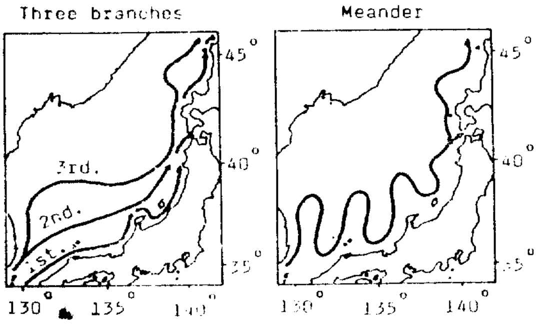

Fig. 1. Schematic patterns of the three branches' theory (left) and meander's theory (right) of the Tsushima Current in the Japan Sea (Naganuma, 1973).

(Kawai, 1974). Previously, Suda and Hidaka (1932) and Uda (1934) reported that this current is composed of three branches in the Japan Sea. Tanioka (1968) and Moriyasu (1972) presented that the warm current is composed of two branches: one flows along the Japanese coast and the other flows northward along the eastern coast of Korea as the East Korean Warm Current. Fukuoka (1957) presented that the Tsushima Current meanders due to the effect of bottom topography. Recently, Yoon and Suginohara (1977) reported that the role of the baroclinic instability can not be neglected in meanders of that current. At present, however, it would be appropriate to say that there is almost no definite theory that clearly demonstrates the flow patterns of the Tsushima Current.

In respect to the northern boundary of the Tsushima Current in the Japan Sea, some of previous investigator, including Uda (1934) and Tanioka (1968), mentioned this subject only on the basis of isotherm analysis. Fukuoka (1962) has been partly discussed about the change of flow pattern of the Tsushima Current. However, there are a few detailed studies on these subjects. After the introduction of the core layer method by Wüst (1936), salinity extremes have often been treated as a central part in the analysis of water mass. The salinity maximum which occurs in the Tsushima Warm Current region in summer may be not exceptional. Therefore, the northern boundary of the Tsushima Current and its fluctuations, which are the main study of this paper, will be discussed through the analysis of the salinity maximum.

DATA AND METHOD

The Tsushima Current has relatively high temperature and high salinity. These properties may be regarded as the characteristics of this current. Therefore, in order to analyze the advection of the Tsushima Current we traced the salinity maximum in the Tsushima Current region in summer.

Fig. 2 shows a schematic diagram of salinity profiles with the salinity maximum, a-type, and without the salinity maximum, b-tybe. We selected the profile of a-type as the salinity maximum type in which the salinity is low at the sea surface layer, reaches the maximum value at a certain depth, and then gradually decreases with depth. However, in our analysis we excluded the case when the salinity maximum is not clear (as b-type of Fig. 2) or when it appears at the surface and/or at the bottom. For convenience, the research area was divided into three regions as shown in Fig. 3.

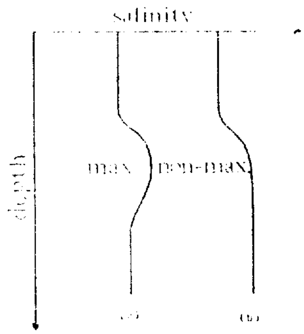

Fig. 2. Schematic diagram of s(z) with salinity maximum (a) and without salinity maximum (b).

The area S_1 is an area in the Tsushima Current region in which the influence of the Kuroshio is great, the area S_2 is the warm current region in the Japan Sea, and the area S_3 is an area in the Japan Sea where the influence of the Tsushima Current is very small.

The oceanographical data used in this study were obtained by Fisheries Research and Development Agency (FRDA) of Korea during 1965~1979, the Japan Meteorological Agency (JMA) during 1963~1979 and Fisheries Agency of Japan (FAJ) during 1963~1972.

The vertical changes of salinity maximum along the Tsushima Current were investigated on the basis of the oceanographical data of JMA during 1970 to 1979. The representative stations A,B and C for the areas S_1, S_2 and S_3 are shown in Fig. 3. The vertical distribution of salinity, and dissolved oxygen were discussed by the data of 1975.

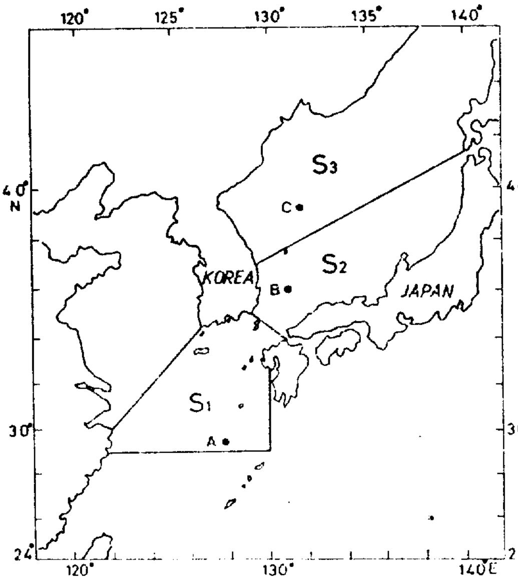

Fig. 3. The Tsushima Current region is divided into three areas; the areas S_1, S_2 and S_3 represent the area near the Kuroshio, the Tsushima Current region in the Japan Sea and the other region, respectively. The points A,B, and C indicate the representative station in the areas S_1, S_2 and S_3, respectively.

The northern boundary of the Tsushima Current and its fluctuations are discussed on the isanosteric surface by the salinity maximum value of high frequency occurrence.

RESULTS

1. The salinity maximum in the Tsushima Current region

Fig. 4 shows areas where salinity maximum occurs in the Tsushima Current. We divided the area into three parts by numbers of occurrence of salinity maximum at each stations. Salinity maximum was analysed at 6, 154 stations during 1963 to 1979. In the darkened areas of Fig. 4

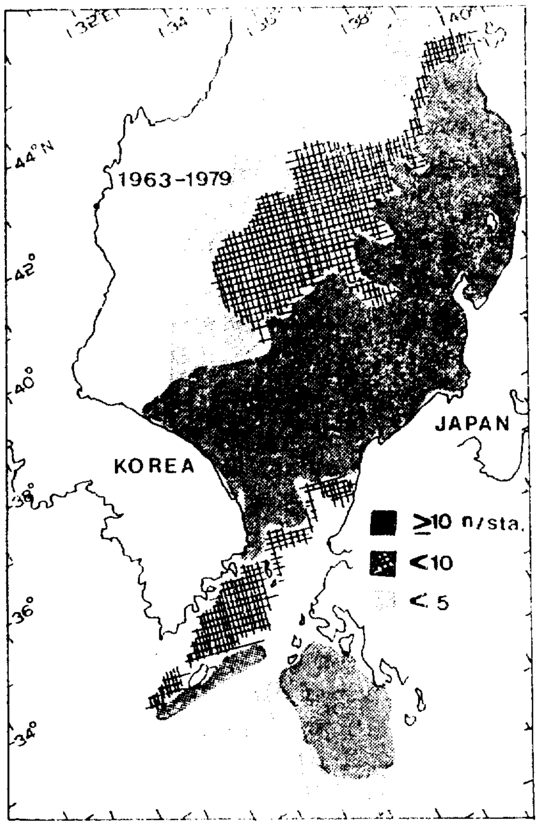

Fig. 4. Areas where the salinity maximum occurs in the Tsushima Current. Areas are divided into three parts by numbers of occurrence of salinity maximum at each station. All station numbers are 6154 in 1963~1979.

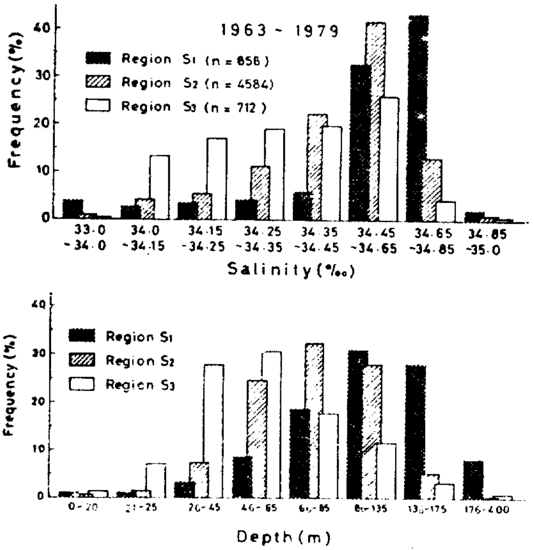

Fig. 5. Frequency distributions of the maximum salinity (upper) and the depth (lower) of the salinity maximum in the areas S_1, S_2 and S_3 in summer during 1963~1979.

the salinity maximum occurred more than 10 times and in the meshed and shaded areas the maximum occurs less than 10 and 5 times repectively. The salinity maximum usually appeared in the middle depths of each station except in the eastern path of the Korea Strait and the marginal continental shelf of the East China Sea. In these shallow areas the salinity maximum appeared at bottom. However, we did not examine the northern area of the eastern Korean coast because of insufficient data coverage.

Fig. 5 shows the frequency distributions of the maximum salinity and the depths of the salinity maximum in the areas S_1, S_2 and S_3 during 1963 to 1979 in summer. Usually all of the salinity maximum were found in salinity range of 34.45~34.65 ‰ and depth range of 46~135 m.

In general, as the current moves northward its salinity decreases, the depth of salinity maximum becomes shallower. It seems that after the Tsushima Current passes through the narrow

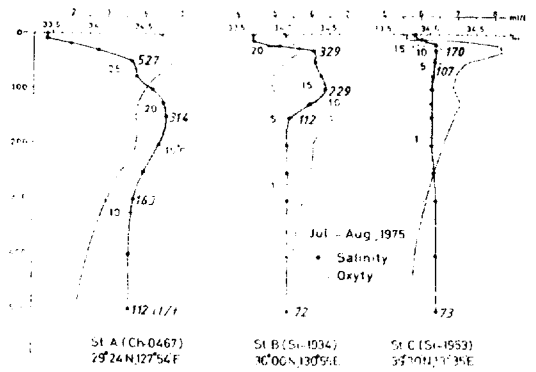

Fig. 6. Station graphs in each area S_1, S_2 and S_3 obtained by JMA in summer, 1975.

Korea Strait the thickness of the warm water becomes thiner and the width of it becomes gradually broader.

2. The relation between salinity and dissolved oxygen

In 1975, the observation was widely carried out by Japan Meteorological Agency in the almost entire area of the Japan Sea in summer. Fig. 6 shows the vertical distribution of the salinity maximum and dissolved oxygen in each area S_1, S_2 and S_3 in 1975. In the area S_1 the value of the salinity maximum was about 34.7 ‰, and in the area S_2 it was about 34.4‰. In the area S_3, however, the salinity maximum did not appear clearly. The depth of the salinity maximum becomes gradually shallower as the current flows from the area S_1 to the area S_3. The range of dissolved oxygen in the area S_1 is between 2 ml/l and 5 ml/l, while that in the area S_3 shows high values between 5.5 ml/l and 8.5 ml/l. In the area S_2 the dissolved oxygen is approximately between those observed in the area S_1 and S_3. Particularly, it is very interesting that minimum of dissolved oxygen occurred frequently at the layers of the salinity maximum. Thermosteric anomaly (δ_T) was large in southern area due to high temperature, but as the current moves northward, its values decreases due to temperature decrease.

In general, as the current flows from south to north, the salinity maximum gradually decreases as shown in Fig. 4, and the depth of the salinity maximum becomes shallower, while dissolved oxygen value becomes gradually increase.

3. The northern boundary of the Tsushima Current and its fluctuations

In order to analyze the advection of the Tsushima Current in summer, we investigated an isanosteric surface of the Tsushima Current in the Japan Sea. Fig. 7 shows the frequency distribution of δ_T on the surface of the salinity maximum during 1970 to 1979. The most of δ_T values are found between 220 cl/t and 260 cl/t and the highest frequency was 240 cl/t. On the 240 cl/t isanosteric surface we drew the isohalines of 34.4 ‰ which corresponds to the salinity

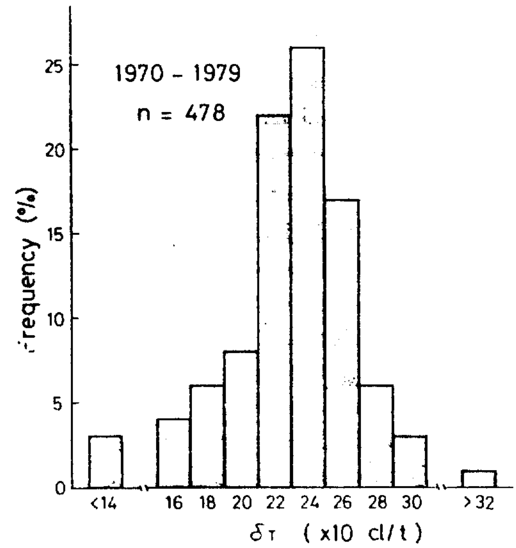

Fig. 7. Frequency distribution of thermosteric anomaly on the surface of the salinity maximum from the data of the Japan Meteorological Agency, in summer; 1970~1979.

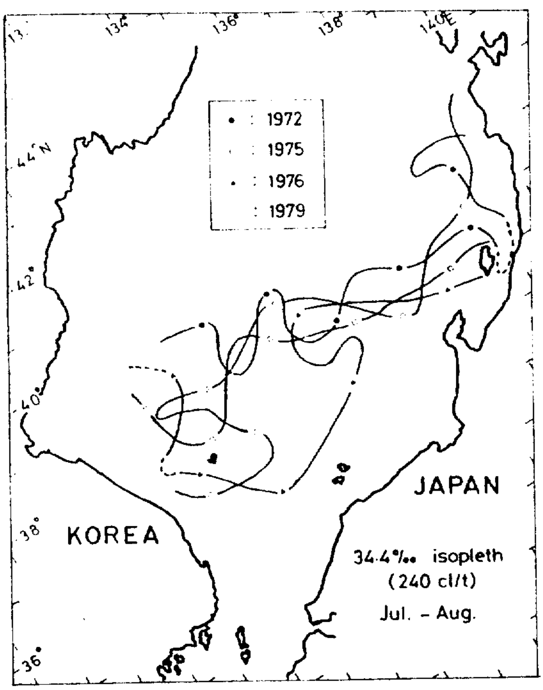

Fig. 8-a.

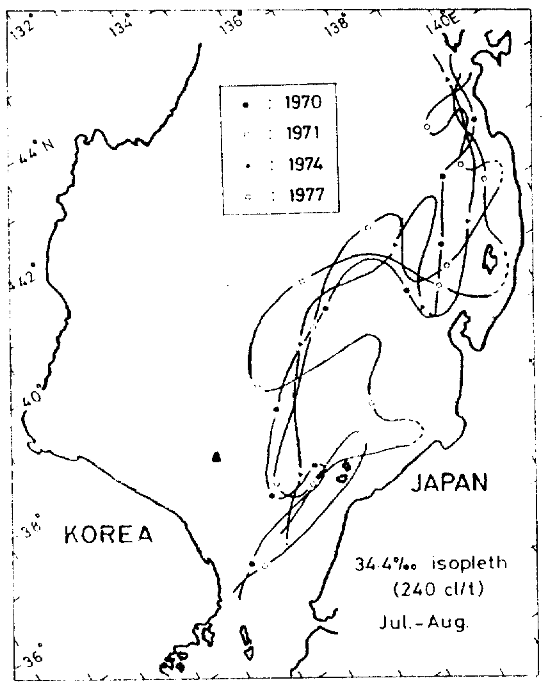

Fig. 8-b.

Fig. 8. Distribution of the isohalines of 34.4‰ on 240 cl/t isanosteric surface during 1970~1979. The isohalines are divided into two types: (Fig. 8-a) in a case of which the Tsushima Current flows northward along the eastern coast of South Korea and (Fig. 8-b) in a case of which this current flows basically northeastward along the coast of Japan.

maximum in Fig. 4. From the result we were able to obtain two types of flow patterns as shown in Fig. 8. Fig. 8-a indicates that the Tsushima Current flows northwars in the eastern coast of Korea and then meanders eastward. And the northern boundary of this current is confined to south of 40°N of the Japan Sea. Fig. 8-b indicates that the Tsushima Current flows basically northeastward along the coast of Japan.

DISCUSSION

1. The advection of high salt water

The surface water of the Tsushima Current which flows into the Japan Sea in summer is high in temperature and low in salinity but the intermediate water of this current is high in temperature and high in salinity. Therefore, in the Japan Sea in Summer, three layers of different properties are formed. One of them consists of the Japan Sea Proper Water. On the other hand, in the Tsushima Current region in the Japan Sea the salinity maximum appears although its value and the corresponding depth are different in comparison to that of the East China Sea near the Kuroshio region. Particularly, although dissolved oxygen is non-conservative property, the dissolved oxygens of the Tsushima Current (about 4.8 to 5.3 ml/l) are clearly distinguished from that of the Japan Sea Proper Water (about 5.5 to 8.5 ml/l) (Fig. 7). This means that the Tsushima Current originated from the Kuroshio advects to an upper layer above the Japan Sea Proper Water. Hence, it seems that the dissolved oxygen minimum is formed frequently in the layer of the salinity maximum in the Japan Sea.

We obtained the 210 cl/t isanosteric surface on which the salinity maximum is most frequent in the Tsushima Current region during 1970 to 1979. However, in 1978, the δ_T value showed 210 cl/t as shown in Fig. 9. It appears that the temperature and salinity of the Tsushima Current in the Japan Sea changes, as it was pointed out by Fukuoka (1961) and Tanioka (1962a).

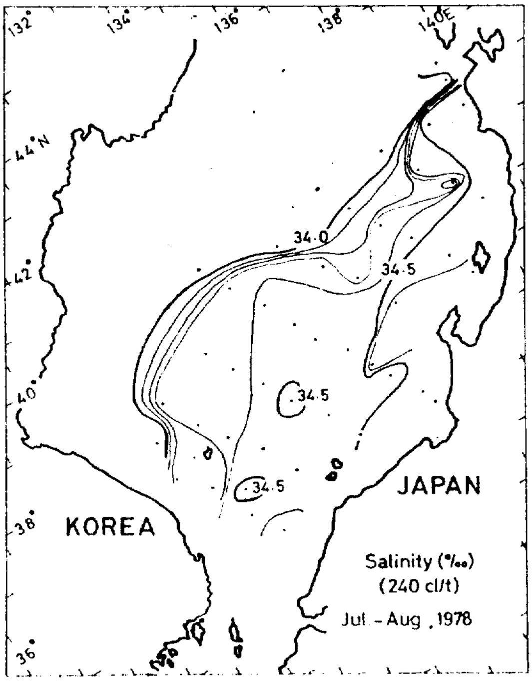

Fig. 9-a.

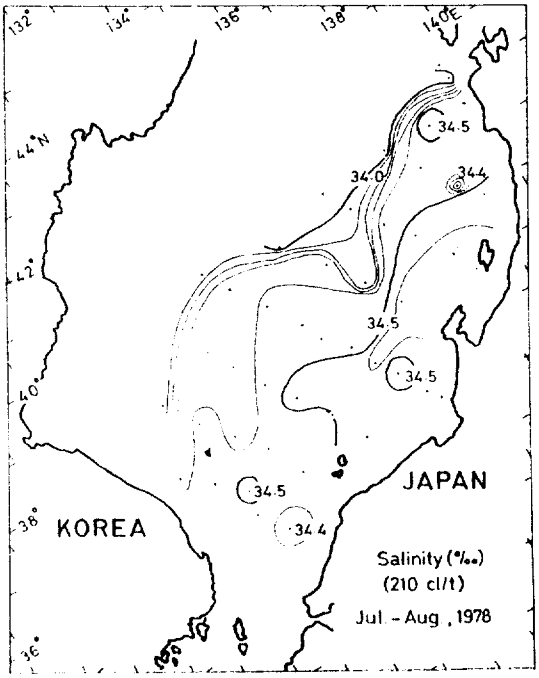

Fig. 9-b.

Fig. 9. Salinity distribution on 240 cl/t (Fig. 9-a) and 210 cl/t (Fig. 9-b) isanosteric surface, Jul.-Aug., 1978.

2. The northern boundary and its fluctuations

Uda (1934) and Tanioka (1968) mentioned the northern boundary of the Tsushima Current on the basis of isotherm distribution at some constant depth (e.g., 100m). However, since a current tends to advect through an isanosteric surface instead of a surface of constant depth we examined the northern boundary of the Tsushima Current on the isanosteric surface.

The result of our study investigated by 34.4 ‰ isohalines in the isanosteric surface shows that the northern boundary of the Tsushima Current appeared to the south of 40°N of South Korea (Fig. 8). This result is similar to that of Uda (1934) and Tanioka (1968) on the basis of isotherm analysis.

Fukuoka (1957, 1962) presented that the Tsushima Current meanders due to the effect of the bottom topography, and the local disturbances of this current seems to be due to small reliefs and meteorological conditions. Tanioka (1968, 1962b) and Yoon et al. (1977), however, proposed that the flow of the warm current is related to the cold water of the Japan Sea. This opinion seems to be appropriate. Although the great meanders near the offshore of Japan can be somewhat explained with the opinion of Fukuoka (1957), it is difficult to understand that about 90 % of the whole northward transport of the East Korean Warm Current flows back southward as a countercurrent (Tanioka, 1968) inspite of the great depth in the eastern sea of Korea and at the same time the countercurrent meanders. And also in our analysis it was shown that the pattern of the 34.4 ‰ isohaline on 240 cl/t isanosteric surface shows two main types (Fig. 8). Fig. 10 shows the temperature distributions at depth of 100 m in 1974 (Fig. 10-b) and in 1975 (Fig. 10-a). Fig. 10-a indicates the type in which the Tsushima Current flows northward in the eastern coast of South

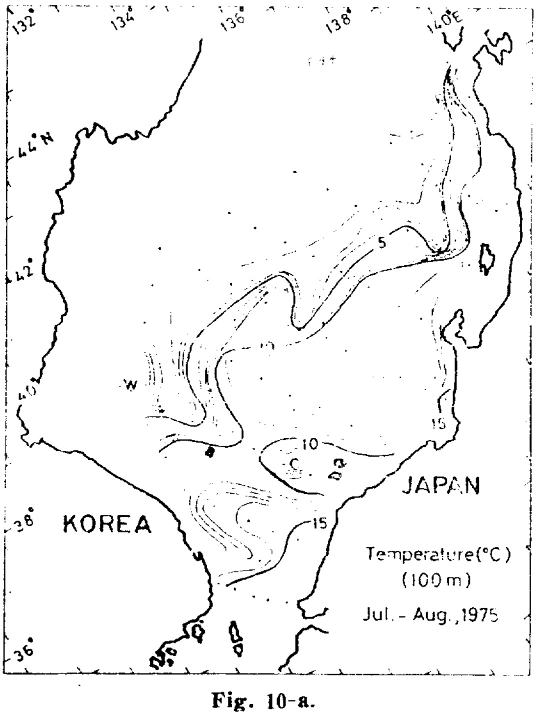

Fig. 10-a.

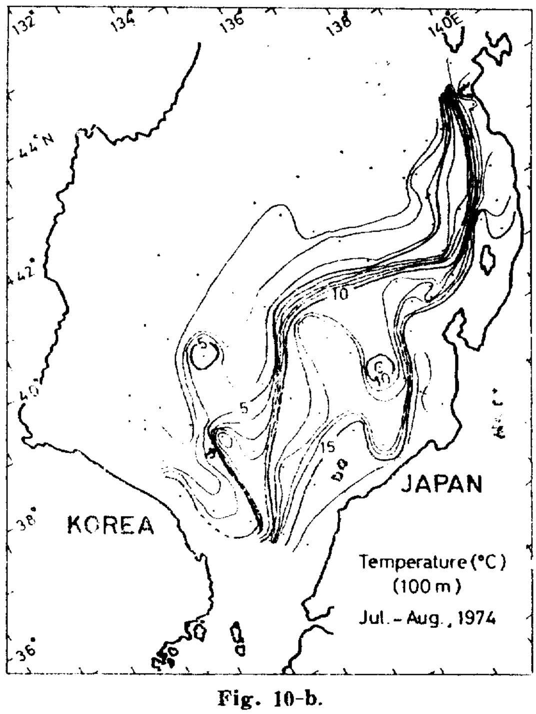

Fig. 10-b.

Fig. 10. Temperature distribution (°C) at the depth of 100 m in the Japan Sea; (Fig. 10-a) in 1975 and (Fig. 10-b) in 1974.

Korea. When 10°C isotherm is regarded as the southern boundary of the cold water of the Japan Sea (Uda, 1934; Ogawa, 1971), this isotherm in 1975 was more northward, while the Tsushima Current flows basically along the coast of Japan it was more southward as shown in Fig. 10-b. It may be said that the meanders is closely associated with the cold water mass of the Japan Sea. In other aspects the wind system of the Japan Sea is variable in summer and winter, and it seems that the changes of wind direction and wind stress would influence not only the path of the Tsushima Current but also the region of the distribution of cold water.

Consequently, we should like to point out that the main flow axis of the Tsushima Current is not constant but is variable according to the oceanographic conditions of the year.

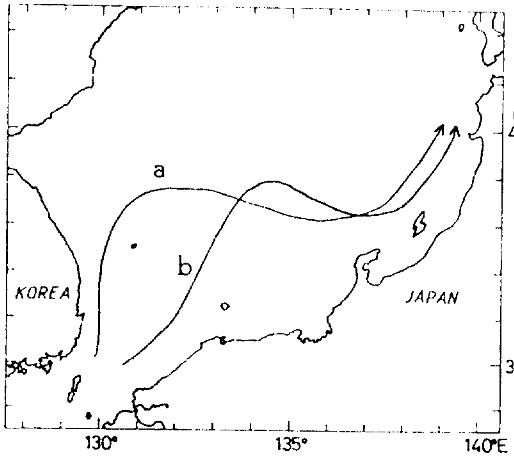

Fig. 11. Schematic chart showing the two types of the northern boundary of the Tsushima Current in summer during 1970 to 1979.

SUMMARY

In order to analyze the northern boundary of the Tsushima Current and its fluctuations, the path of this current was traced by following the salinity maximum and discussed on the isanosteric surface.

1. As the Tsushima Current moves northward, the salinity maximum becomes decrease, and the corresponding depth becomes shallower.

2. The range of thermosteric anomalies of high frequency at the salinity maximum in the Tsushima Current region during 1970 to 1979 was between 220 and 260 cl/t, and the highest frequency was found at 240 cl/t.

3. The northern boundary of the Tsushima Current obtained by 34.4 ‰ isohaline on the 240 cl/t isanosteric surface was confined to south of 40°N of the Japan Sea. The types of flows was as shown in Fig. 11 : one of them flows northward along the eastern coast of Korea and then meanders eastward (a-type), while the other flows basically northeastward along the coast of Japan (b-type).

4. The meanders of the northern boundary of this current identified by isohaline analysis are nearly similar to the results of the previous studies based on the isotherm analysis.

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하계 동해에 있어서 대마난류의 북상한계와 변동

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1970~1979년 기간중 하계의 동해에 있어서 대마난류의 북상한계와 연변동을 규명하기 위해서 염분최대를 추적하고, 이 값에 대한 δ_T(thermosteric anomaly)에 관하여 검토했다.

29°N 이북의 동지나해로부터 동해북부해역에 이르기까지 대마난류의 염분최대치 및 그 층의 심도는 각각 34.45~34.85 ‰, 46~135 m 범위였다. 일반적으로 남쪽에서 북쪽으로 갈수록 그 값은 낮아지는 경향을 보였으며, 그 층도 얕아졌다. 동해의 대마난류역에서 염분최대가 나타나는 층에 대한 δ_T의 값은 220~260 cl/t이었다.

240 cl/t 면상의 34.4 ‰ 등염선을 지표로 하여 조사한 대마난류의 북상한계는 한국 동해안측에서는 40°N 이남해역으로 한정되었으며, 등염선은 두가지 형태로 나타났다. 즉 동서방향인 한국 동해안쪽으로 치우쳐 북상하는 경우와 남남서—북북동 방향인 일본연안쪽으로 북상하는 경우였다.