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A Seasonal Circulation in the East China Sea and the Yellow Sea and its Possible Cause

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A seasonal circulation in the East China Sea and the Yellow Sea and its possible cause have been studied with CSK data during 1965–1989. Water mass distributions are clear in winter, but not in summer because the upper layer waters are quite influenced by atmosphere. To solve the problem, a water mass analysis by mixing ratio is used for the lower layer waters. The results show that the distribution of Tsushima Warm Current Water expands to the Yellow Sea in winter and retreats to the East China Sea in summer. It means that there is a very slow seasonal circulation between the East China Sea and the Yellow Sea: Tsushima Warm Current Water flows into the Yellow Sea in winter and coastal water flows out of the Yellow Sea in summer. By the circulation, the front between Tsushima Warm Current Water and coastal water moves toward the shelf break in summer so that the flow is faster in the deeper region. The process eventually makes the transport in the Korea Strait increase. The Kuroshio does not seem to influence the process. A possible mechanism of the process is the seasonal change of sea surface slope due to different local effects of surface heating and diluting between the East China Sea and the Yellow Sea.

INTRODUCTION

There are seasonal phenomena in the East China Sea and the Yellow Sea such as southward expansion of Yellow Sea Bottom Cold Water in summer (Asaoka and Moriyasu, 1966; Nakao, 1977; Lie, 1984; Park, 1985, 1986; Kim *et al.*, 1991; Youn *et al.*, 1991), northward intrusion of Yellow Sea Warm Water in winter (Uda, 1934; Byun and Chang, 1988; Pang *et al.*, 1992), and transport increase in the Korea Strait in summer (Miyazaki, 1952; Yi, 1966; Toba *et al.*, 1982). The phenomena have been basically understood by the efforts devoted so far, however, their mechanisms have not so well.

A main reason why we have difficulties in finding their mechanisms is probably that we have looked at them separately. They may be parts of a large circulation system. Some recent results (Pang *et al.*, 1992; Pang and Hyun, 1998) show a possibility that the seasonal circulation of the Yellow Sea is connected with the circulation of the East China Sea. Then, the seasonal phenomena are probably related with each other. In this paper, we are going to find their relations following the next questions. Is there a seasonal circulation connecting the East China Sea and the Yellow Sea? How does it influence the Tsushima Warm Current in the East China Sea? Does the process eventually influence the transport in the Korea Strait? And finally, what is its possible mechanism?

To do so, we should look at a wider area. Fortunately, we have CSK data to cover the East China Sea and the Yellow Sea. The CSK data during 1965 to 1989 are analyzed and the results are shown only for February and August, which represent winter and summer, respectively. Fig. 1 shows the locations of data in February and August during the CSK period. The locations are different in space and time so that the results are basically averages of data in space and time. Therefore, we need to look at them in large scale, rather than in details.

Seasonal variation of water characteristic distributions

Fig. 2 shows the T–S diagrams in February and August during 1965 to 1989. In February, they can be grouped into Kuroshio Water (high salinity water with a wide range of temperature in Fig. 2) and East China Sea Water (low temperature water with a wide range of salinity in Fig. 2). East China Sea Water

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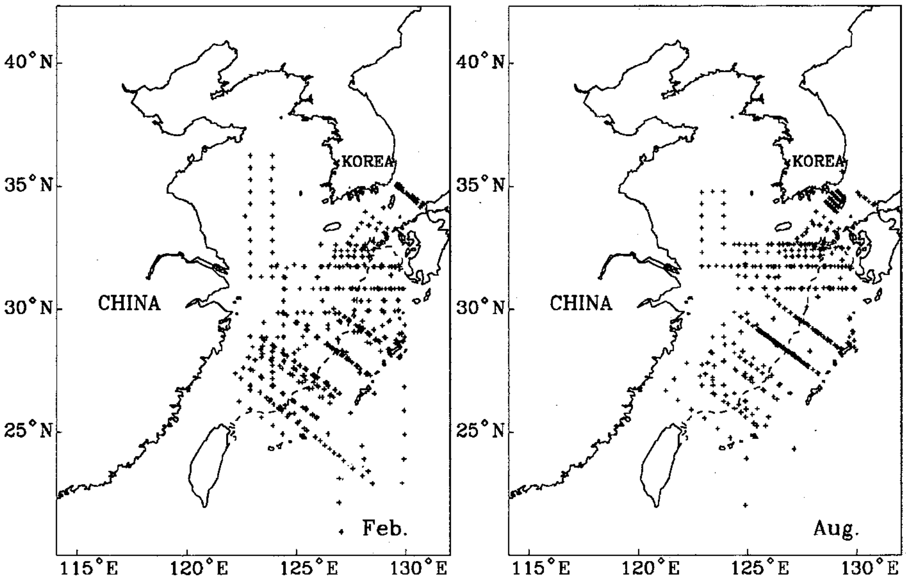

Fig. 1. Stations of the CSK data (Cooperative Study of the Kuroshio and Adjacent Regions) in February and August during 1965–1989.

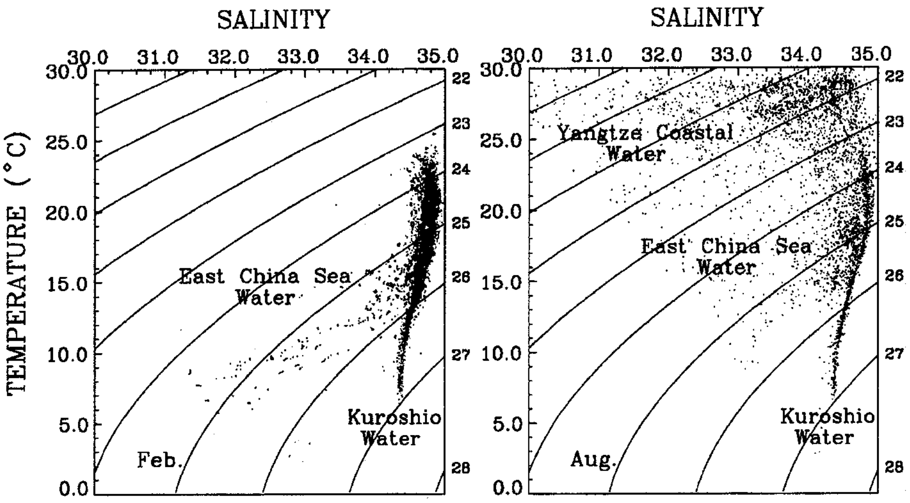

Fig. 2. T–S diagrams of the CSK data in February and August during 1965–1989.

is linked with Kuroshio Middle Water (water in the junction of Kuroshio Water and East China Sea Water in Fig. 2. It may be a little different from generally defined water.). It is interesting that Kuroshio Surface Water is not linked with East China Sea Water. It shows two possibilities. One is that when some of Kuroshio Water is branched, the surface water is significantly mixed with the deeper water. The other is that Kuroshio Water is not branched as suggested by Uda (1934). However, answering the question is beyond the subject of this paper. In August, East China Sea Water is heated and diluted a lot, but some of cold water is still shown in the East China Sea. Most Kuroshio Water keeps its characteristics except its surface water.

Fig. 3 shows the horizontal distributions of mean temperature and salinity at the depths of 0 and 50 m in (A) February and (B) August. Kuroshio Water of high temperature and high salinity distributes outside of the shelf break and coastal water of low temperature and low salinity distributes in the Yellow Sea. Tsushima Warm Current Water distributes between them. The water characteristics in the Korea Strait are mostly linked back to the adjacent sea of Taiwan along the inside of the shelf break. Such a basic structure is also maintained in August in the lower layer. In August, the distribution of water characteristics is quite different between the upper and lower layers. Surface water gets warm and diluted. The most diluted water appears between the Yangtze river and Cheju Island.

Water characteristic distributions of the lower layer in the boundary area between the East China Sea and the Yellow Sea show that the salinities of about 33.4–

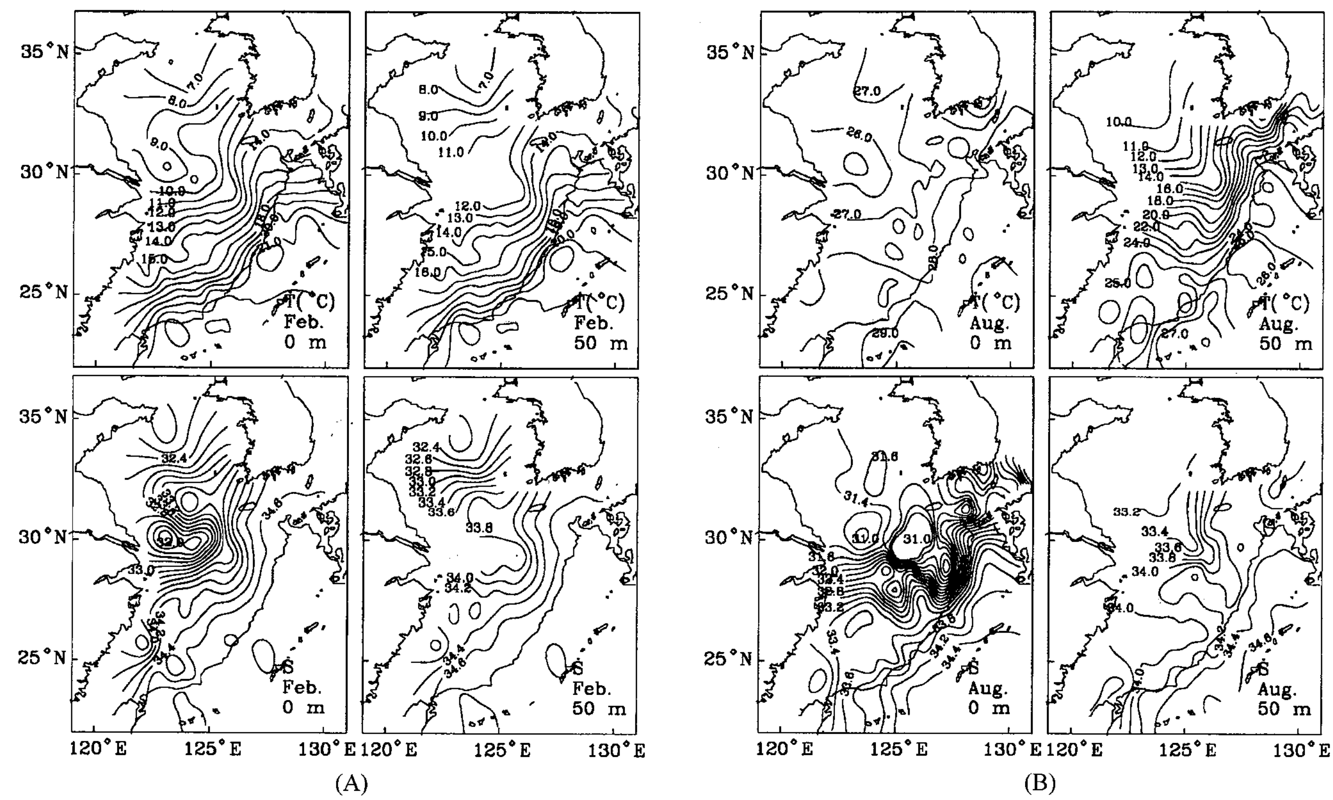

Fig. 3. Horizontal distributions of mean temperature and salinity in the depths of 0 m and 50 m. in (A) February and (B) August during 1965–1989.

33.8 move toward the Yellow Sea in February and toward the East China Sea in August. Such a seasonal variation coincides with the previous reports that Yellow Sea Warm Current Water flows into the Yellow Sea in winter and Yellow Sea Bottom Cold Water expands to the East China Sea in summer. However, temperature distributions hardly support it. It is probably due to heating in summer. Therefore, we need some more analysis to make sure of the seasonal movement of water mass.

Seasonal variation of water mass distributions

Since the study area is significantly influenced by the atmosphere and mixing, it is sometimes hard to define water masses directly from water characteristics. Water mass analysis by mixing ratio has been successively used in defining water masses to find the seasonal water mass movement in the south-eastern Yellow Sea (Pang and Hyun, 1998). To calculate mixing ratios, we need to determine the source water masses and their characteristic values. As shown in Fig. 2, all East China Sea Water can be formed by mixing between two water masses, Yellow Sea Cold Water (YSCW) and Kuroshio Middle Water (KMW), in February. In August, two more water masses are needed. They are Yangtze Coastal Water (YCW) and Kuroshio Surface Water (KSW). Their representative characteristic values can be determined in two ways for calculating mixing ratios. One is seasonally different values and the other is the same values all through the seasons. In this paper, the latter is chosen because the former is difficult to compare the results in different seasons. Table 1 is the representative characteristic values of the four source water masses. The four source water masses can be depicted as four corners in T-S diagram as shown in Fig. 4. The values are determined to wrap most waters in T–S dia-

Table 1. Four source water masses and thier characteristic values for calculating mixing ratios. They may be different from general definition.

Water Mass	T (°C)	S
Yangtze Coastal Water (YCW)	29.8	30.1
Yellow Sea Cold Water (YSCW)	6.0	31.4
Kuroshio Middle Water (KMW)	14.0	35.0
Kuroshio Surface Water (KSW)	29.9	34.8

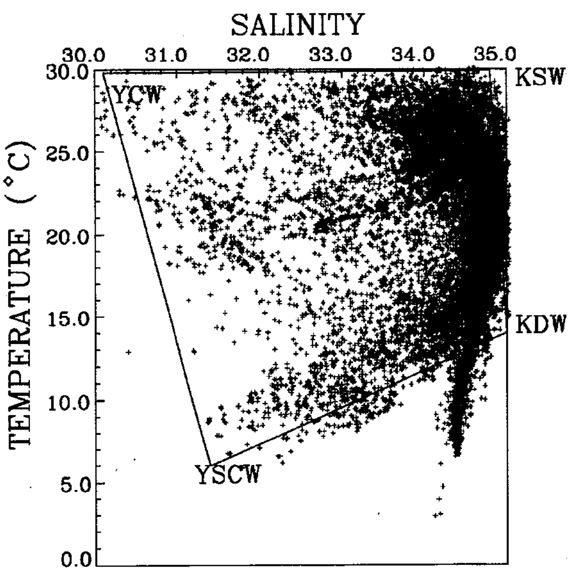

Fig. 4. T–S diagram of all CSK data during 1965–1989 and four source water masses. Their representative names and characteristic values are listed in Table 1.

gram so that they may be a little different from general definition. The way of determining mixing ratios of four source water masses with two properties, temperature and salinity, was suggested by Miller (1950) and developed by Mamayev (1975) and Chen *et al.* (1993). Detailed method is introduced in Pang and Hyun (1998).

Fig. 5 shows the mixing ratios (%) of the four source water masses at the depths of 0 m and 50 m in February and August. In February, Kuroshio Waters (KMW and KSW) are dominantly mixed in all the study area except in the surface layer of the coastal area off Yangtze river. Kuroshio Waters are still dominant (around 80%) in the southern Yellow Sea at the depth of 50 m. In August, surface waters (KSW and YCW) occupy the surface layer of all the area. YCW is dominant in the Yellow Sea while KSW is dominant in the East China Sea. Their boundaries (roughly, mixing lines of 50%) are shown along the area connecting from the Yangtze river to the Korea Strait. It probably shows that YCW flows to the East Sea along the area. At the depth of 50 m, Kuroshio Waters (KMW and KSW) are dominantly mixed (over 80%) in the East China Sea. However, YSCW is significantly mixed (about 40%) in the boundary area between the East China Sea and the Yellow Sea. Comparing the results in February and August shows that warm and saline waters (Tsushima Warm Current Water) expand toward the Yellow Sea in winter and cold and less saline waters (Yellow Sea Cold Water) expand toward the East China Sea in summer.

Seasonal circulation

The result in the previous section suggests that there is an oscillatory seasonal circulation between the East China Sea and the Yellow Sea. The circulation must be very slow (roughly 3 cm/sec) judging from the distance and time for variation. It can be interpreted as a secondary flow in this area as in Pang and Hyun (1998). Note that waters in the East China Sea primarily flow to the Korea Strait so that observed currents are basically northeastward (Lie and Cho, 1997). It is not easy to detect the secondary flow directly. However, we may indirectly detect it by its influence. So, we try to find the influence of a seasonal circulation on the Tsushima Current with dynamic topography.

In the East China Sea, dynamic topography may not be so helpful to detecting currents because of shallowness. If the depth of 200 m is used as a reference level, it covers only narrow area along the shelf break. If the depth of 50 m is used, it covers almost the whole area, but it tells about only the upper shallow layer. Nevertheless, dynamic depth anomalies calculated with the reference levels at 50, 100, and 200 m (not shown here) show that the Tsushima Current is significantly changed in season while the Kuroshio is not.

To see the whole area, the reference levels are chosen as the bottom for the stations shallower than 500 m and as the depth of 500 m for the stations deeper than 500 m. The calculated dynamic depth anomalies are shown in Fig. 6. Due to different reference depths, the anomalies do not have any meaning and we look at just their seasonal difference. The dynamic depth anomalies in the Kuroshio range from 0.3 to 1.5 dyn-m (the difference is 1.2 dyn-m) in February and from 0.5 to 1.6 dyn-m (the difference is 1.1 dyn-m) in August. So, the Kuroshio transport nearly keeps the same (actually slightly reduces in summer here). On the other hand, the dynamic depth anomalies in the East China Sea range from 0.1 to 0.3 dyn-m in February and from 0.2 to 0.5 dyn-m over a relatively shorter distance in August, which shows that the Tsushima Current increases in summer about twice as much as in winter.

Under the condition that the Kuroshio does not vary seasonally, increasing of the Tsushima Current in the East China Sea in summer can be interpreted as a

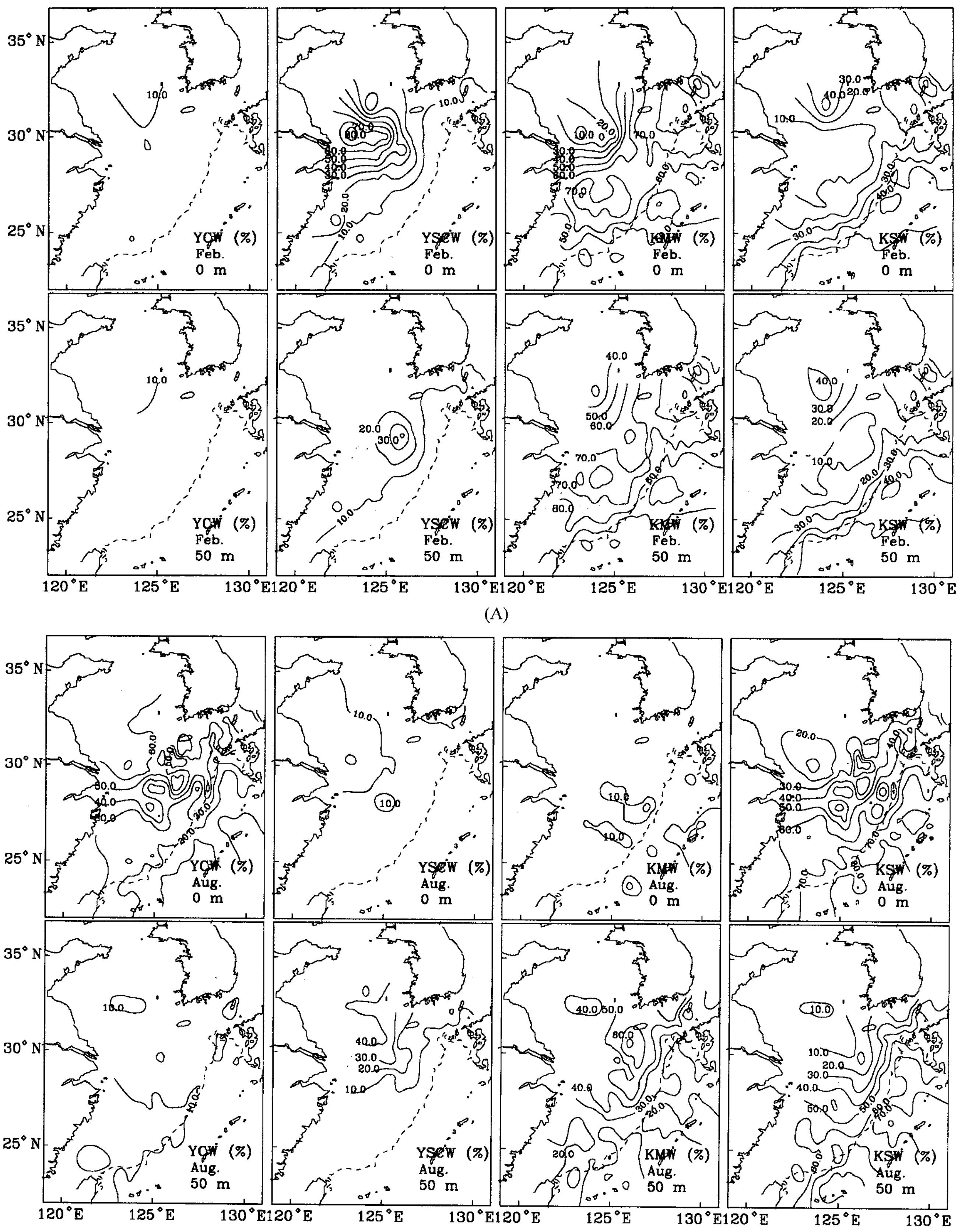

Fig. 5. Mixing ratios (%) of four source water masses (Table 1) in the depths of 0 m and 50 m in (A) February and (B) August during 1965–1989.

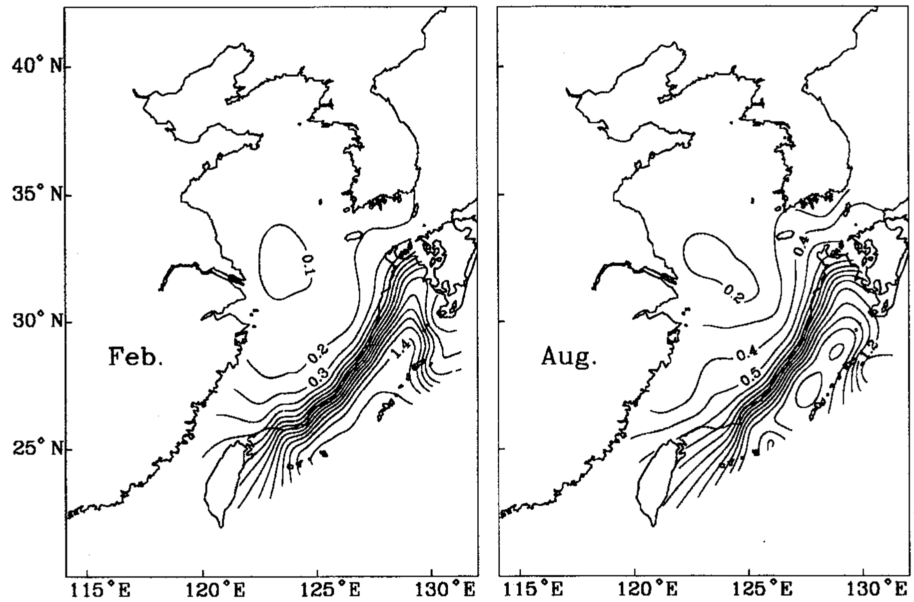

Fig. 6. Dynamic topographies (in dynamic meter) of the sea surface relative to the bottom for the region shallow than 500 m or to the depth of 500 m for the region deeper than 500 m in February and August during 1965–1989.

result of summer seasonal flow toward the East China Sea. Likewise, the opposite case happens in winter. They indirectly show the seasonal circulation between the East China Sea and the Yellow Sea. In this stage, we had better to confirm the condition that the Kuroshio does not play any significant role in the seasonal variation of the Tsushima Current.

A cause of transport variation

The Kuroshio transport hardly vary in season (Fig. 6; Nitani, 1972) while the transport in the Korea Strait significantly does (Miyazaki, 1952; Yi, 1966; etc.). Fig. 7 (Nishizawa *et al.*, 1982) shows that there is almost no seasonal transport variation in PN-Line which can influence the Korea Strait. Even if it varies, it should vary with the same ratio as in the Korea Strait to be a cause. The reault of a barotropic numerical experiment with the free flux boundaries in the Korea Strait and the Tokara Strait show that the transport in the Korea Strait varies with the same ratio as the Kuroshio transport as shown in Fig. 8 (Pang *et al.*, 1993). Such a high ratio of transport increase in summer as in the Korea Strait is hard to be expected in the Kuroshio. It means that the East China Sea is isolated from the Kuroshio in the sense of seasonal variation.

Then, we should find the cause of transport variation in the East China Sea. As shown in Fig. 6, the range of dynamic depth anomalies in the Korea Strait increases in summer by 0.1 dyn-m (from 0.2–0.3 dyn-m in February to 0.3–0.5 dyn-m in August).

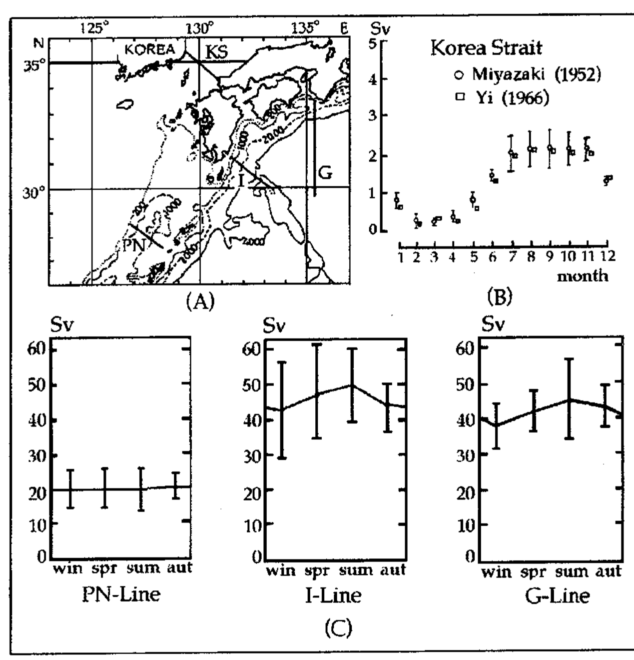

Fig. 7. Seasonal variations of volume transport across the sections KS, PN, I and G shown in (A) (depth in m). (B) comes from Toba *et al.*, 1982 and (C) comes from Nishizawa *et al.*, 1982.

It corresponds to about 1 Sv increase. In the East China Sea, the ranges of dynamic depth anomaly increases in summer by 0.1 dyn-m (from 0.1–0.3 dyn-m in February to 0.2–0.5 dyn-m in August), which corresponds to about 1.5 Sv increase. Although these are very rough estimation, the result shows nearly the same order as reported previously (Miyazaki, 1952; Yi, 1966). Therefore, it can be drawn a con-

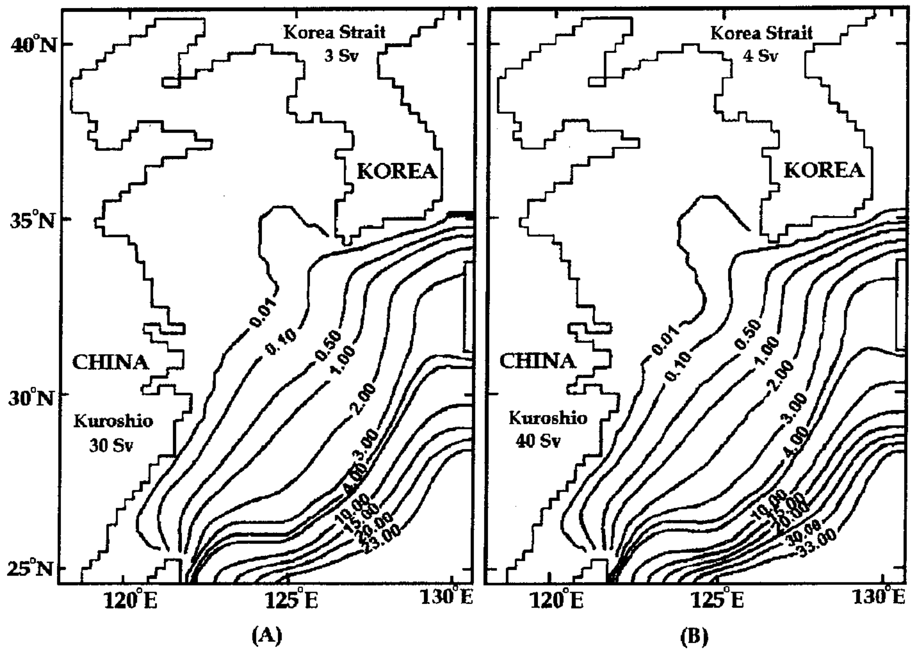

Fig. 8. Results of a barotropic numerical experiment with the free flux boundaries in the Korea Strait and the Tokara Strait for the input waters of (A) 30 Sv and (B) 40 Sv through the southern boundary. Stream lines are in Sv unit. (from Pang *et al.*, 1993).

clusion that the transport increase in the Korea Strait can be caused by that in the East China Sea which is driven by the seasonal circulation.

A possible mechanism of the seasonal circulation

Now, we know that three phenomena (seasonal circulation between the East China Sea and the Yellow Sea, seasonal variation of the Tsushima current in the East China Sea, and seasonal variation of transport in the Korea Strait) are related with each other and comprised in a large seasonal circulation system. In this section, we want to find a possible mechanism of the seasonal circulation.

Fig. 9 shows a sea surface slope obtained based on the dynamic depth anomaly along the S-Line in February and August. 'Inner' and 'outer' in Fig. 9 represent the inner and outer regions of the East China Sea, respectively. The sea surface is basically lower in the coast side. So, the basic pressure gradient force is toward the Yellow Sea and balanced with the Coriolis force by the northeastward (into the paper) Tsushima Current. In addition to the basic slope, a seasonal variation is added. In the inner region, the slope is stronger in February and weaker in August by more effects of heating and diluting in the Yellow Sea. In the outer region, the slope is reversely weaker in February and stronger in August.

Then, what makes the slope in the outer region steeper in summer? In the inner region, the additional pressure gradient force is toward the Yellow Sea in February and toward the East China Sea in August.

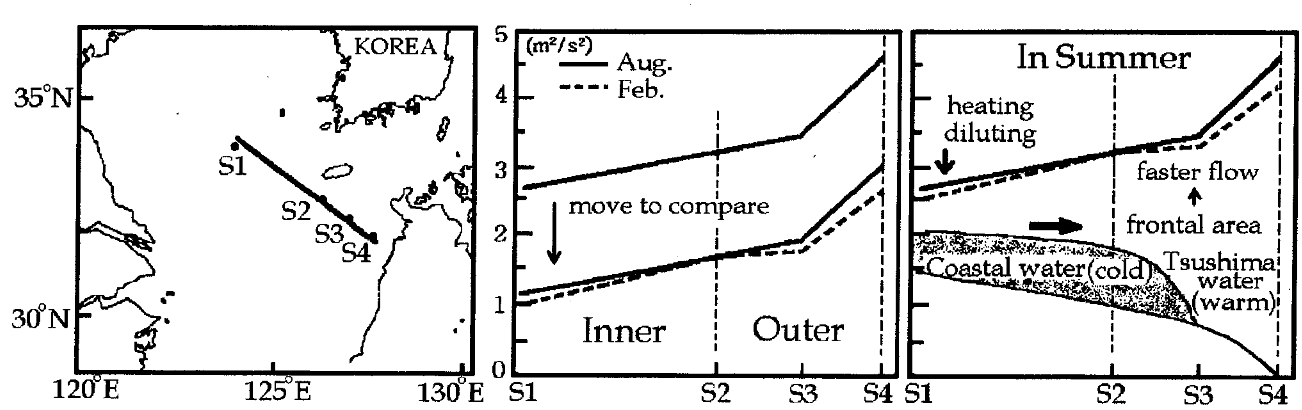

Fig. 9. Variations of sea surface slope obtained based on the dynamic depth anomaly across S-Line in February and August. Sea surface in summer is moved down to compare with that in winter. Right panel shows the process of transport increase by pushing the front between Tsushima water and coastal water to the outer deeper region in summer.

The force makes the seasonal circulation between the East China Sea and the Yellow Sea. In summer, the force pushes the waters (coastal water and Tsushima Warm Current Water) and their front toward the outer region so that the sea surface slope becomes steeper in the outer region as shown in the right panel of Fig. 9. It results in stronger flow in the outer region, which is deeper than the inner region, and so the increase of transport in summer.

CONCLUSION

In this paper, we have tried to find a seasonal circulation of large scale over the East China Sea and the Yellow Sea by studying the relation between the two seas. In the two seas, water masses are greatly divided into Kuroshio Water and East China Sea Water, and East China Sea Water can be divided into Tsushima Warm Current Water and coastal water. Water mass distributions are not so clear because of influence by atmosphere and mixing. To solve the problem, a water mass analysis by mixing ratio is used. The results show that the distribution of Tsushima Warm Current Water expands to the Yellow Sea in winter and retreats to the East China Sea in summer, which means that there is a seasonal circulation between the East China Sea and the Yellow Sea.

According to dynamic depth anomaly, the transport increases in summer both in the East China Sea and the Korea Strait by the similar amount. They are not caused by the Kuroshio, because its transport nearly keeps the same all the seasons. It turns out that they are caused by the seasonal circulation between the East China Sea and the Yellow Sea.

The pressure gradient force in the East China Sea is basically toward the Yellow Sea and balanced with the Coriolis force driven by the Tsushima Current. The additional pressure gradient force is seasonally toward the Yellow Sea in winter and toward the East China Sea in summer. It is due to more effects of heating and diluting in the Yellow Sea than in the East China Sea. It moves the front between the Tsushima Warm Current Water and the coastal water (Yellow Sea Bottom Cold Water) toward the Yellow Sea in winter and toward the East China Sea in summer. As a result, the Tsushima Current is faster in deeper region in summer so that the transport increases. The processes eventually make the transport in the Korea Strait increase.

In the mechanism, monsoon winds, which is suggested for the Yellow Sea circulation (Pang *et al.*, 1992), might be added to seasonal sea level change. For example, the latter mainly drives the summer circulation and the former the winter circulation. A seasonal circulation system in the East China Sea and the Yellow Sea is schematically depicted in Fig. 10, which is extended from the circulation model of the Yellow Sea suggested by Pang and Hyun (1998). In Fig. 10, the boundary of the Tsushima Current is symbolically chosen as the isohaline of 34‰, however, less saline waters are also included in the Tsushima Current transport.

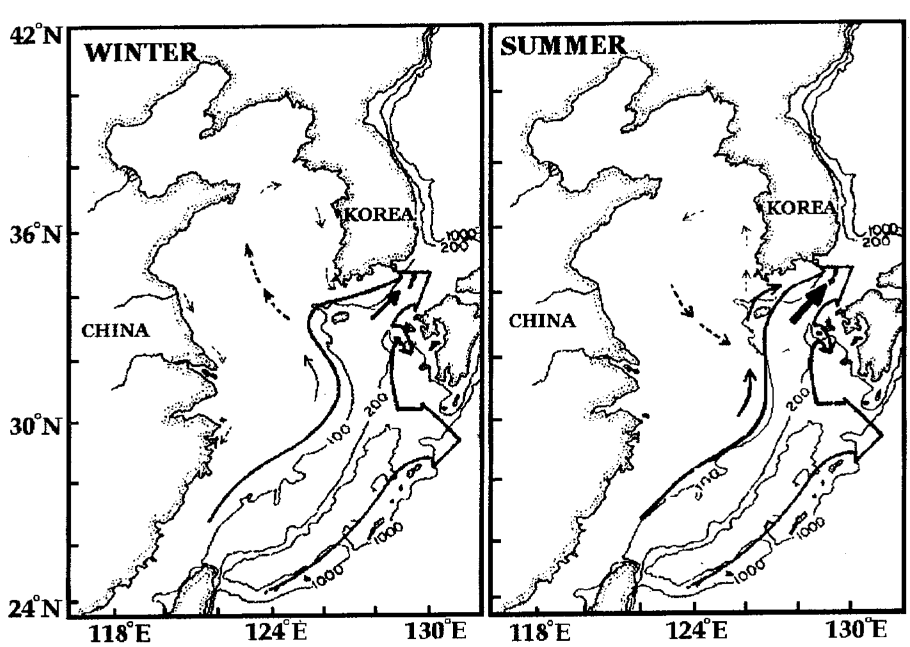

Fig. 10. Schematic representation of a seasonal circulation in the East China Sea and the Yellow Sea. Left line of the big arrow is the boundary of high salinity waters over 34‰ to illustrate the seasonal difference of water mass distribution, but not the boundary of Tsushima Warm Current.

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