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Seasonal Variation of Water Mass Distributions in the Eastern Yellow Sea and the Yellow Sea Warm Current

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A seasonal circulation pattern in the eastern Yellow Sea (EYS) is suggested from the water mass analysis and geostrophic calculation using the hydrographic data collected by National Fisheries Research and Development Institute during the years of 1970 to 1990. This research focuses on the presence of inflow of warm (and saline) waters into EYS in summer. EYS is divided into two regions in this paper: the west coast of Korea (WCK) and the central Yellow Sea (CYS). In CYS, waters are linked with warm waters near Cheju Island in winter, but with cold waters from the north in summer (in the lower layer). It is not simple to say about WCK because of the influences of freshwater input and tidal mixing. Nevertheless, water mass analysis reveals that along WCK, waters have the major mixing ratios (40—60%) of warm waters in summer, while the dominant mixing ratios (50—90%) of cold waters in winter. Such a seasonal change of water mass distribution can be explained only by seasonal circulation. In winter, warm waters flow northward into CYS and cold waters flow southward along WCK. In summer, warm waters flow northward along WCK and cold waters flow southward into CYS. This circulation pattern is supported by both statistical analysis and dynamic depth topography. Accordingly, Yellow Sea Warm Current may be defined as the inflow of warm waters to CYS in winter and to WCK in summer.

INTRODUCTION

For studying the circulations in the Yellow Sea, it is very important to know whether warm waters flow into the Yellow Sea or not. It has been generally believed that warm waters do not flow into the Yellow Sea in summer, being blocked by salt fronts formed along the southwestern coast of Korea (Lie, 1984, 1985; Kondo, 1985; Park, 1986; Kim *et al.*, 1991). However, this opinion seems to have two problems.

First, the distribution of water properties in the southwestern sea of Korea may be more influenced by tidal mixing than by circulation. Figure 1 shows the horizontal distributions of temperature and salinity of the area, which were observed in June 1994 (Pang *et al.*, 1996). As shown in Fig. 1, the strong tidal mixing off the southwest tip of the Korean Peninsula makes the temperature lower in the upper layer and higher in the lower layer, and makes the salinity higher in the upper layer and lower in the lower layer. As a result, Fig. 1 shows quite different water mass distributions in each property and in each layer. At the depth of 50 m, the waters off the southwest tip of the Korean Peninsula are linked with the waters in the adjacent seas around Cheju Island in temperature, but not in salinity.

Secondly, previous researchers have focused their efforts on a certain type of warm water. They have first defined the Yellow Sea Warm Water (YSWW) by salinity (or temperature), and then checked whether the water flows into the Yellow Sea or not. Saline waters over 34‰ have usually been defined as YSWW. As shown in Fig. 2, the saline waters are prevented from flowing into the Yellow Sea by salt fronts (Park, 1986). However, the figure also shows that less saline waters may flow into the Yellow Sea. If that is the case, the less saline waters should be defined as YSWW.

As described above, Yellow Sea Warm Current (YSWC) is still an unsolved topic. Then, is there really a warm and saline current to supply heat and salt to the Yellow Sea? Even if there is such a current, it may not be easy to detect from either hydrographic data nor current data because the general circulation of the Yellow Sea is very weak. This paper tries to detect the seasonal circulation patterns of the Yellow Sea and YSWC, based on hydrographic data using mixing ratios. Mixing ratios seem to be more reliable in studying water

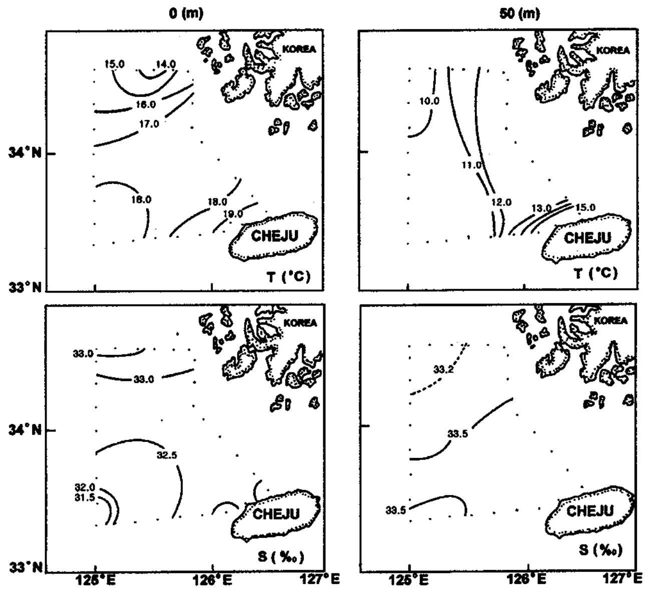


Fig. 1. Horizontal distributions of temperature and salinity at the depths of 0 and 50 m in northwestern sea of Cheju Island in June 20—22, 1994 (after Pang *et al.*, 1996).

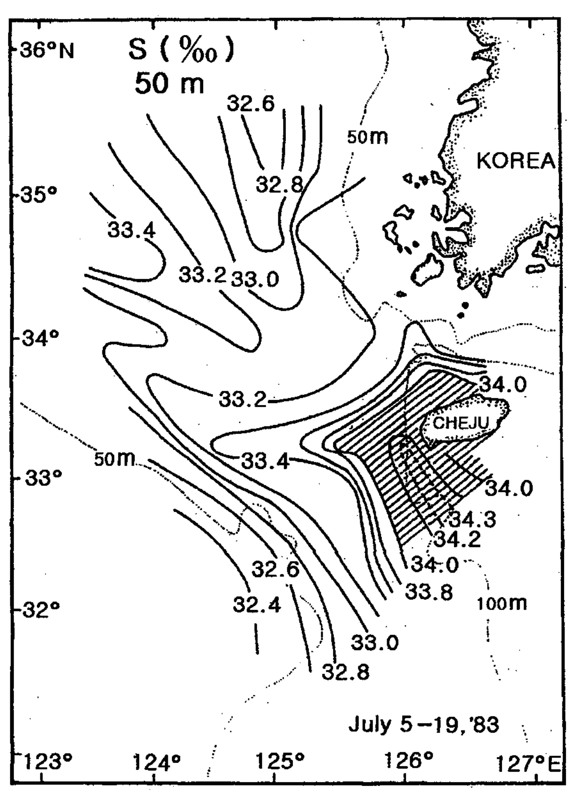


Fig. 2. Horizontal distribution of salinity at the depth of 50 m in the southeastern Yellow Sea in July 5—19, 1983 (after Park, 1986).

masses than temperature or salinity only. Whether warm water inflows are present in summer or not is specially focused on.

DATA AND METHODS

The hydrographic data used in this study were collected over 1970 to 1990 by the National Fisheries Research and Development Institute. The hydrographic stations are shown in Fig. 3. The study area includes eastern Yellow Sea (EYS) and the South Sea of Korea and is divided into squares of 1/2° latitude and 1/4° longitude. For spatial balance, the data of station line 313 are included in the squares just above the line. EYS is divided into 2 regions (CYS and WCK) (inset of Fig. 3).

The seasonal variation of water mass distributions is first studied by T-S diagram. The water mass analysis by mixing ratio is performed next, focusing on whether the waters along WCK are mixed with the warm waters from the south or with the cold waters from CYS. Four source water masses are chosen to calculate mixing ratios. T-S-time diagram and some statistical methods are also used to check the northward warm flows along WCK in summer. Finally, the seasonal circulations are deduced from water mass distributions and the dynamic topography.

Seasons are divided into the winter season (from December to April) and the summer season (from June to October).

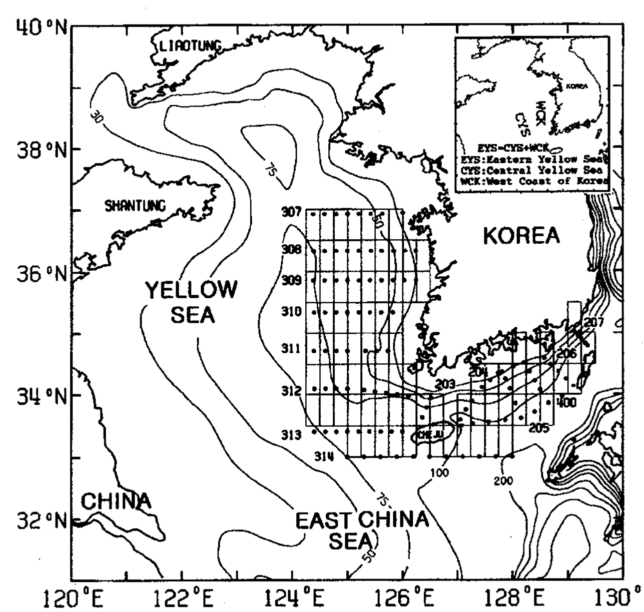


Fig. 3. Hydrographic stations of National Fisheries Research and Development Institutes and water depths in meters. The numbers of station lines are marked. Study area is divided into squares of 1/2° latitude and 1/4° longitude. Eastern Yellow Sea (EYS) is divided into 2 regions: central Yellow Sea (CYS) and west coast of Korea (WCK).

SEASONAL VARIATION OF WATER MASS DISTRIBUTIONS

The temperature and salinity data are plotted bimonthly in T-S diagrams (Fig. 4). In the winter season, they show the contrast of warm and more saline waters versus cold and less saline waters. Their characteristic ranges are shown in Table 1. The boundary values between them are roughly 10°C and 33.5‰. In the summer season, warm and diluted waters appear in the surface layer, and the cold waters in the lower layer get a little warmer than in winter. They are roughly classified into four water masses in the next section although it is hard to define their characteristic values. In Table 1, only the whole range of the water characteristics is given for summer. Figure 5 shows local T-S diagrams, where each square is the T-S diagram of water masses observed in the square area.

In winter, cold and less saline waters are distribut-

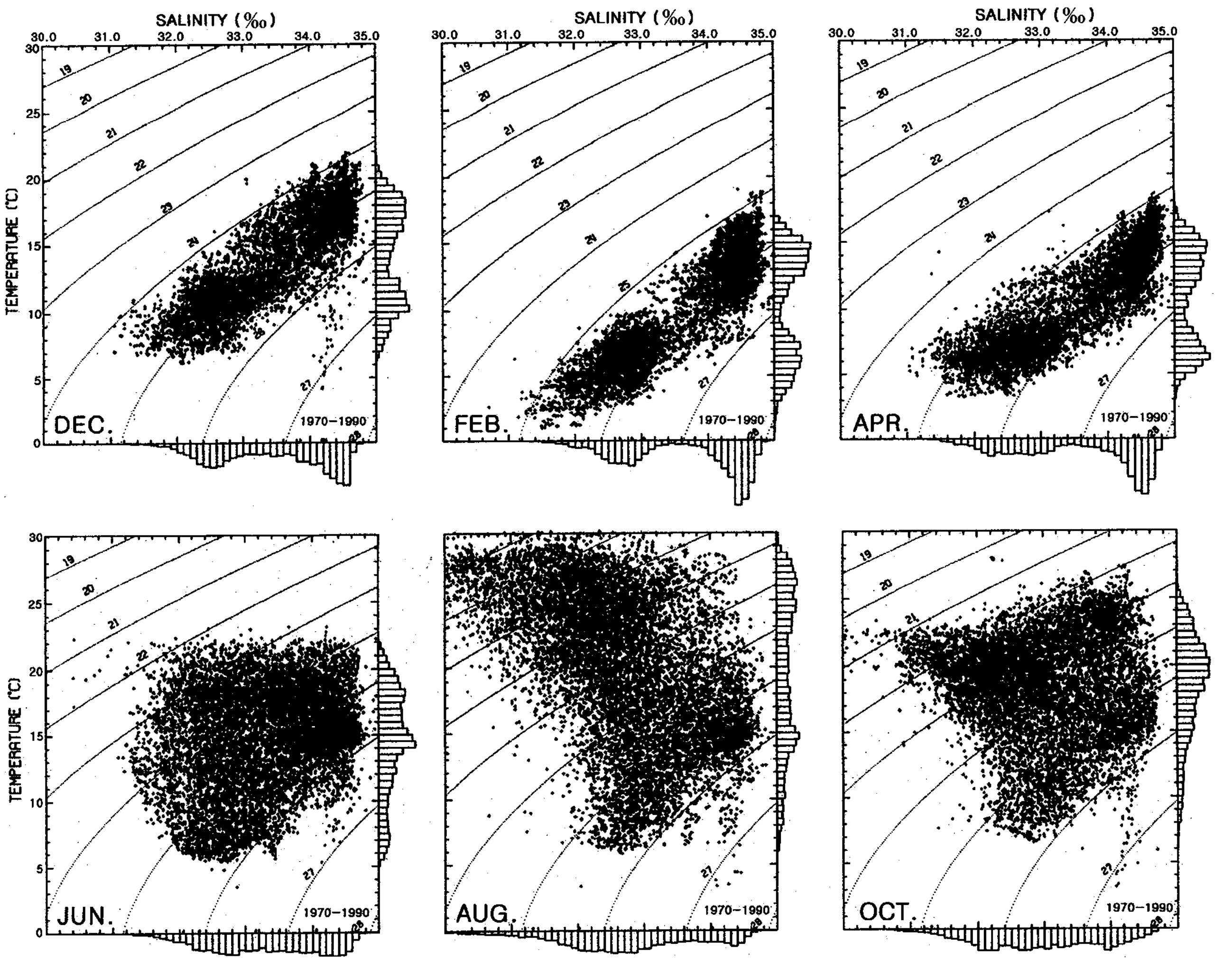


Fig. 4. Bimonthly T-S diagrams over 1970 to 1990. The numbers on curves are σ_t values. Stacks on the right and bottom sides in each diagram show the ratios of the number of data plotted within the strip of 0.1‰ or 0.5°C to the total number of data.

Table 1. The ranges of temperature and salinity in both the eastern Yellow Sea and the South Sea of Korea in winter and in summer from 1970 to 1990 (In summer, only the whole range of water characteristics is given)

	Water mass	Winter			Summer		
		December	February	April	June	August	October
T (°C)	Cold water	6—13	1—9	3—9	5.0—23.0	6.0—31.0	6.0—27.0
	Warm water	14—22	10—19	10—18			
S (‰)	Cold water	31.0—33.2	31.2—33.2	31.0—33.2	31.2—34.8	29.0—34.8	30.8—34.8
	Warm water	33.7—34.8	33.7—35.0	33.7—35.0			

ed in the Yellow Sea, and warm and more saline waters are distributed in the adjacent seas around Cheju Island and the South Sea of Korea. In the Yellow Sea, the waters are getting colder northward and toward WCK. This means that cold waters come from the north to WCK in winter. The waters in CYS are linked with the warm waters in the adjacent seas around Cheju Island.

In summer, high-temperature and low-salinity waters appear in the upper layer. In the lower layer, cold waters are still maintained in CYS while the waters along WCK get much warmer. In the lower layer, the waters in CYS are not linked with the warm waters in the adjacent seas around Cheju Island. Warm waters are confined around Cheju Island. The lower-layer waters in WCK have nearly the same salinity as in winter while they have much higher temperature than in winter. The waters in WCK seem to be mixed waters.

For the phenomenon of no salinity decrease in the lower-layer waters along WCK in summer despite significant freshwater input, there are two possible explanations. One is that input freshwaters do not influence salinity of the lower-layer waters. The other is that cold (less saline) waters distributed in WCK in winter retreat to CYS and warm (more saline) waters from the south replace them to compensate salinity decrease by freshwater input. These two possibilities propose completely opposite scenarios of water mass distribution. The former suggests the same structure as in winter, that is, the waters along WCK are linked with the cold waters from the north. The latter suggests the reverse structure, that is, waters along WCK are linked with the warm waters from the south. The two scenarios raise an important question. Which waters are

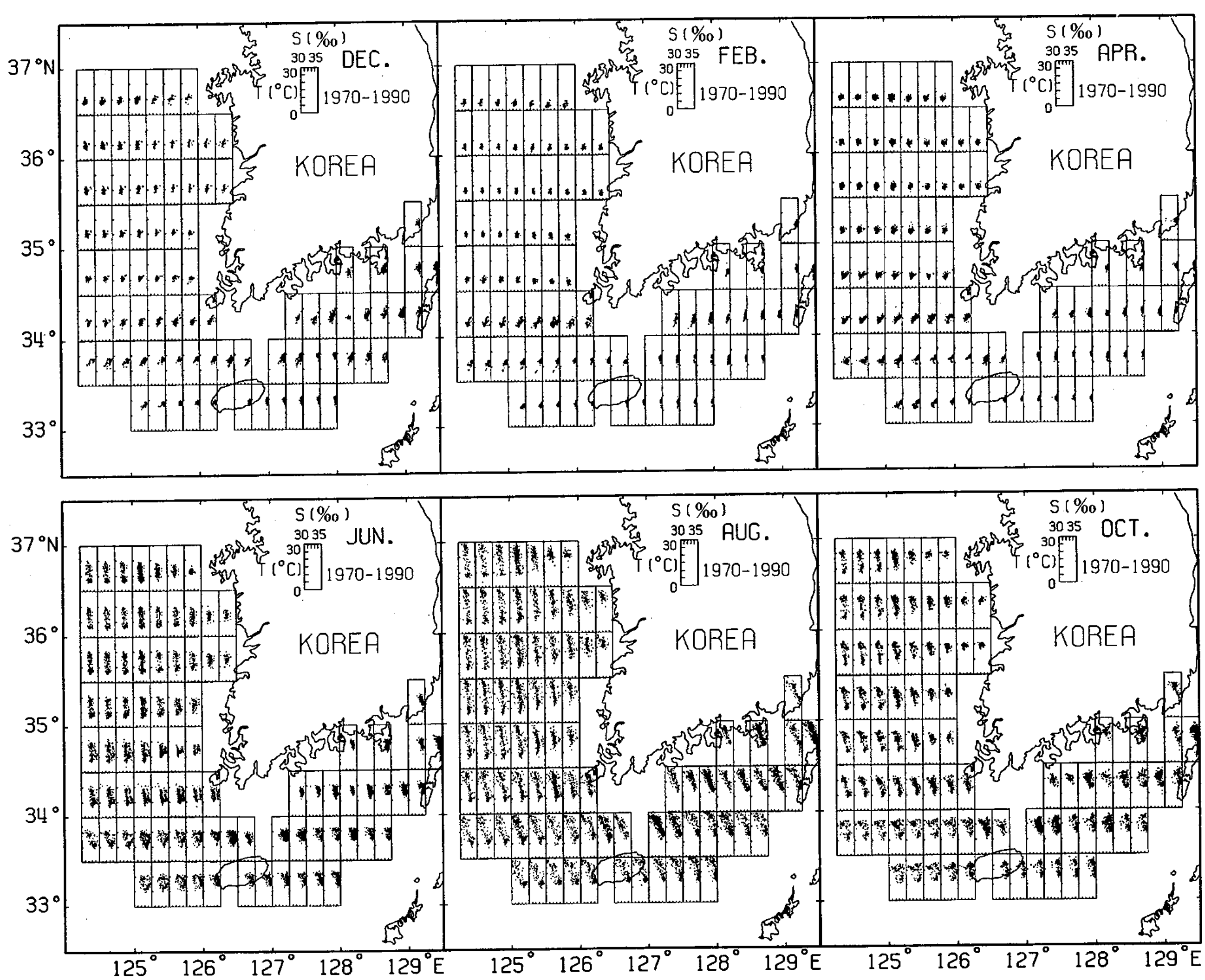


Fig. 5. Bimonthly spatial T-S diagrams over 1970 to 1990. *X* and *Y* axes in each square area represent salinity (30—35‰) and temperature (0—30°C), respectively.

dominant in the lower-layer waters in WCK in summer, cold (less saline) waters or warm (more saline) waters? The same question may be raised from the hoizontal distributions (Fig. 6) of mean temperature and salinity from 1970 to 1990 at the depths of 0, 30, and 50 m in February and August. In February, the waters in WCK are linked with the northern (cold and less saline) waters both in temperature and in salinity. However, in August, the lower-layer waters in WCK are linked with the southern (warm and more saline) waters in temperature though not in salinity. The next section aims to answer the question by calculating mixing ratios.

WATER MASS ANALYSIS BY MIXING RATIOS

To calculate mixing ratios, we need to determine the source water masses and their representative characteristic values. As shown in Fig. 4, there are two water masses in winter and two more water masses in summer in the study area. The four water masses can be defined as: Coastal Water (CW) with high temperature and the lowest salinity, Yellow Sea Cold Water (YSCW) with the lowest temperature and low salinity, Tsushima Deep Water (TDW) with low temperature and the highest salinity, and Tsushima Surface Water (TSW) with the highest temperature and high salinity.

Their characteristic values change by season. For calculating mixing ratios, their representative values can be determined in two ways. One is to use seasonally changing values and the other is to adopt

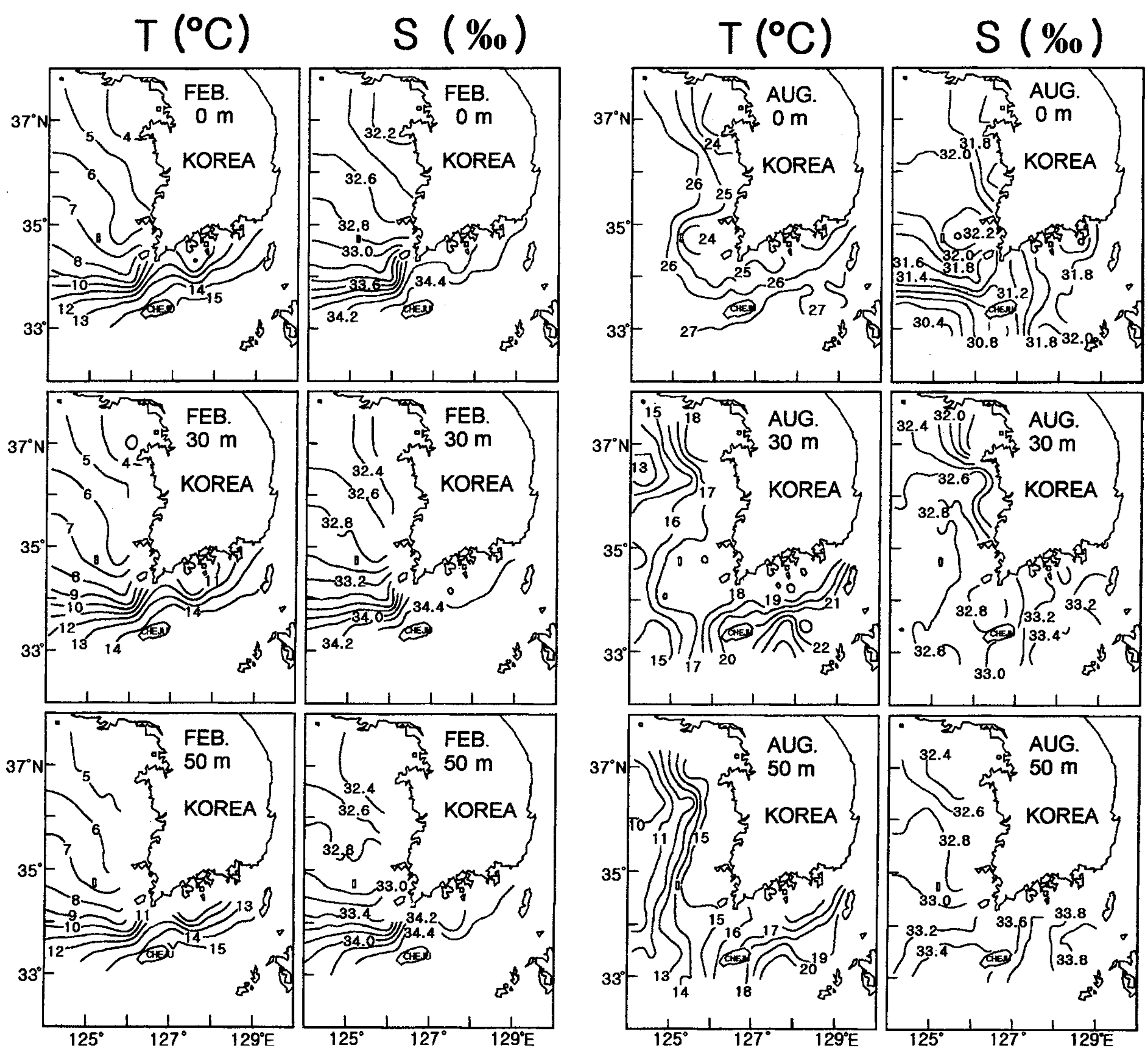


Fig. 6. Horizontal distributions of mean temperature and salinity over 1970 to 1990 at the depths of 0, 30, and 50 m in February and August.

the same values all through the year. If we use seasonally changing values, it is hard to compare the results of different seasons. For example, results from different bimonthly values may support the presence of warm (saline) waters flowing into WCK in summer; however, the results are also attributable to the difference in the representative values between seasons, that is, low salinity values in summer. To avoid such an ambiguity, the latter method was chosen. Table 2 shows the representative characteristic values of four water types. A T-S diagram (Fig. 7) of the mean data compiled over 21 years shows how the characteristic values are determined. Four source water types correspond to the four corners in the T-S diagram.

Strictly speaking, only two properties (temperature and salinity) are not sufficient to determine the mixing ratios among four source water masses. However, in a certain case of dominant horizontal mixing in layers and dominant vertical mixing in water columns (Fig. 8B), mixing ratios can be determined as suggested by Miller (1950). The method was developed by Mamayev (1975) and Chen *et al.* (1995), who applied it to the study of the northeastern sea of Taiwan.

Figure 8A shows how to determine the mixing ratios. Let the mixing ratios of four water types A, B, C, and D be f_a, f_b, f_c, and f_d. Let's divide Lines AB and DC by $m:n$ and Lines AD and BC by $k:l$, where $m+n=1$ and $k+l=1$. Then, $l(nf_a+mf_b)+k(mf_c+nf_d)=1$, and f_a, f_b, f_c, and f_d in Point P are $l \cdot n$, $l \cdot m$, $k \cdot m$, and $k \cdot n$, respectively. Detailed calculation methods are provided in Hyun (1996).

Figure 9 shows the mixing ratios of four source water masses at the depths of 0, 30, and 50 m in February and August. (The two months represent winter and summer seasons, respectively.) The unit of measure is percentage. In February, the distributions of mixing ratios are almost the same throughout the whole layer. YSCW is dominant in WCK, while TDW is dominant in the adjacent seas around Cheju Island. CW and TSW appear to be minor fractions. It should be noted that the ratios of TDW are higher in CYS than in WCK, while the ratios of YSCW are higher in WCK than in CYS.

In August, the distributions differ in layers. In the surface layer, CW and TSW are dominant. CW has very high ratios in the southwestern sea of Cheju Island, which shows the influence of Yangtze Coastal Water. In the layer of 50 m, cold waters (YSCW) have major mixing ratios (30—50%) in CYS, while warm waters (TSW+TDW) have major mixing ratios (40—60%) in WCK. It means that the waters in WCK are linked with the warm (saline) waters to the south. It is a reverse distribution to

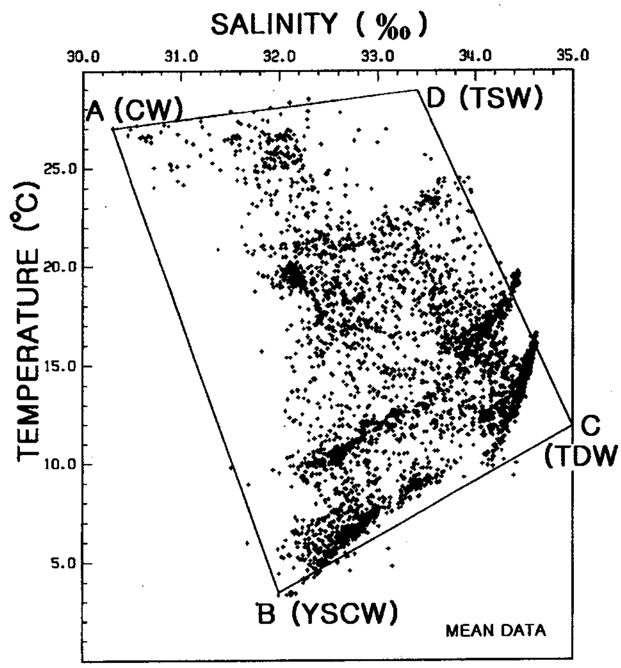


Fig. 7. T-S diagram of the mean data over 1970 to 1990. A, B, C, and D represent Coastal Water (CW), Yellow Sea Cold Water (YSCW), Tsushima Deep Water (TDW), and Tsushima Surface Water (TSW), respectively.

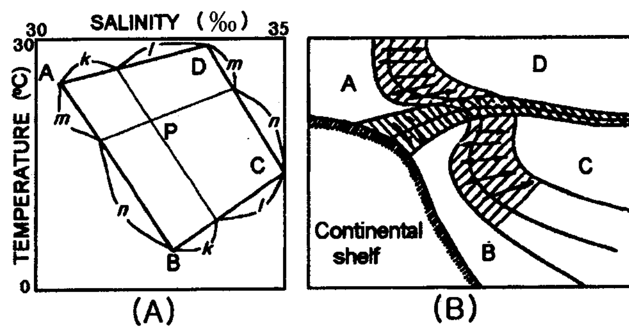


Fig. 8. (**A**) Diagram representing how to determine mixing ratios of four water masses under the circumstances of (B). (**B**) Stylized diagram of the distribution and interaction of water masses. The shaded regions correspond to the zones of horizontal and vertical mixing waters (after Miller, 1950).

Table 2. Temperatures and salinities of four water types for water mass analysis

Water mass	T (°C)	S (‰)	Water name
A	27.0	30.3	Coastal Water (CW)
B	2.5	32.0	Yellow Sea Cold Water (YSCW)
C	12.0	35.0	Tsushima Deep Water (TDW)
D	29.0	33.4	Tsushima Surface Water (TSW)

winter's.

The results of water mass analysis using mixing ratios provide an answer to the question posed in the previous section. That is, warm (saline) waters from the south are mainly linked with the waters along WCK in summer (in the lower layer). The seasonally reversed distributions may provide some information about seasonal circulations. Before the step, it may be the right time to confirm the seasonal reversal in water mass distributions.

Figure 10 is a spatial T-S-time diagram with mean temperatures and salinities for 21 years at the depth of 50 m. It shows that salinity maintains almost the same level in WCK all years round. Considering the significant freshwater input in summer, there should be salt supply from the south in summer. Figure 11 shows the appearance percentage of 33.7‰ or more saline waters to the total data at each station over 21 years. The value of 33.7‰ was chosen from the distinction between warm and cold waters (Table 1). As shown in Fig. 11, there is no appearance of 33.7‰ or more saline waters north of 35°N in winter, but they appear as north as 37°N in summer in spite of significant freshwater inputs. This is further evidence that warm and saline waters are supplied into WCK from the south in summer.

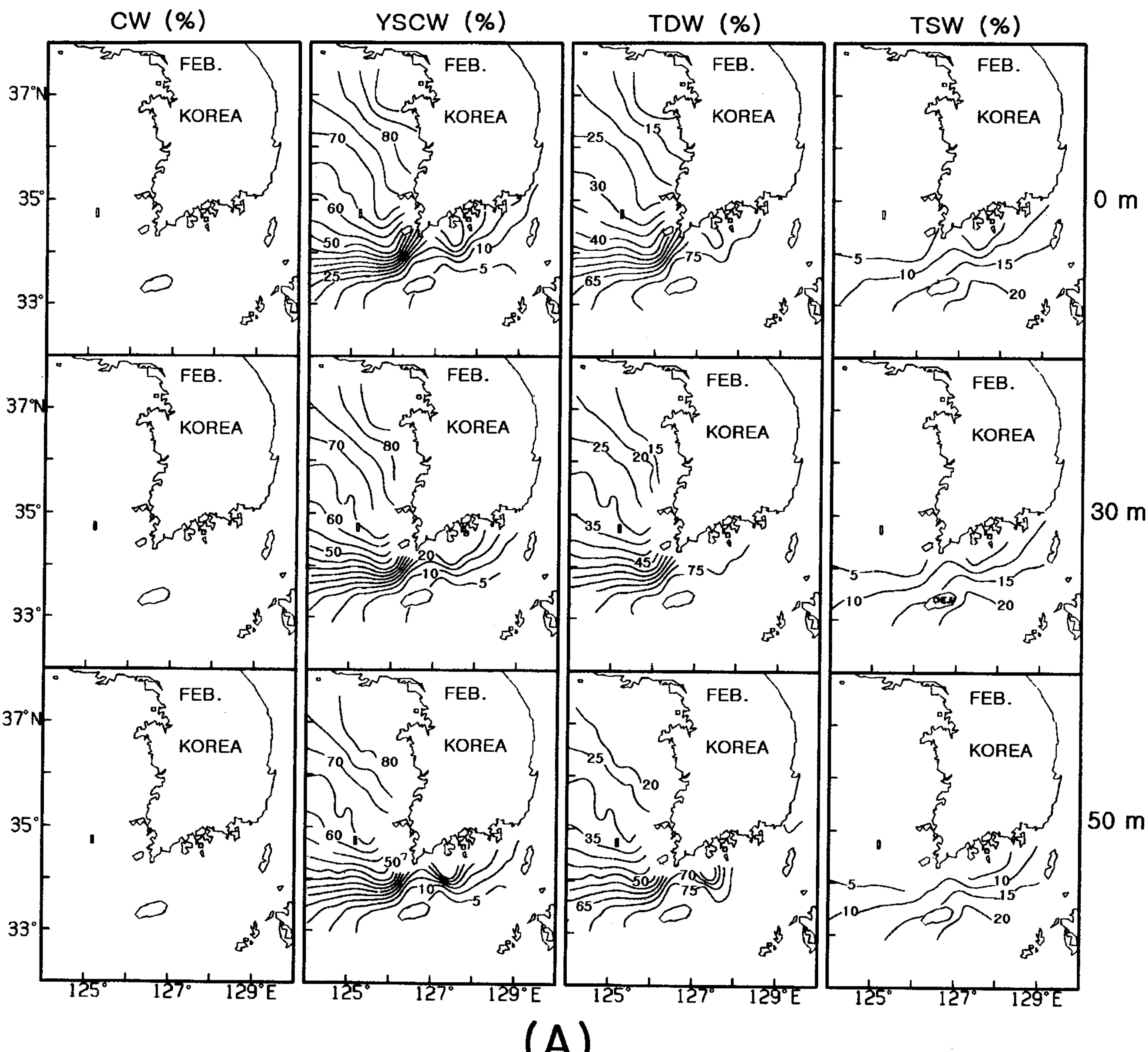
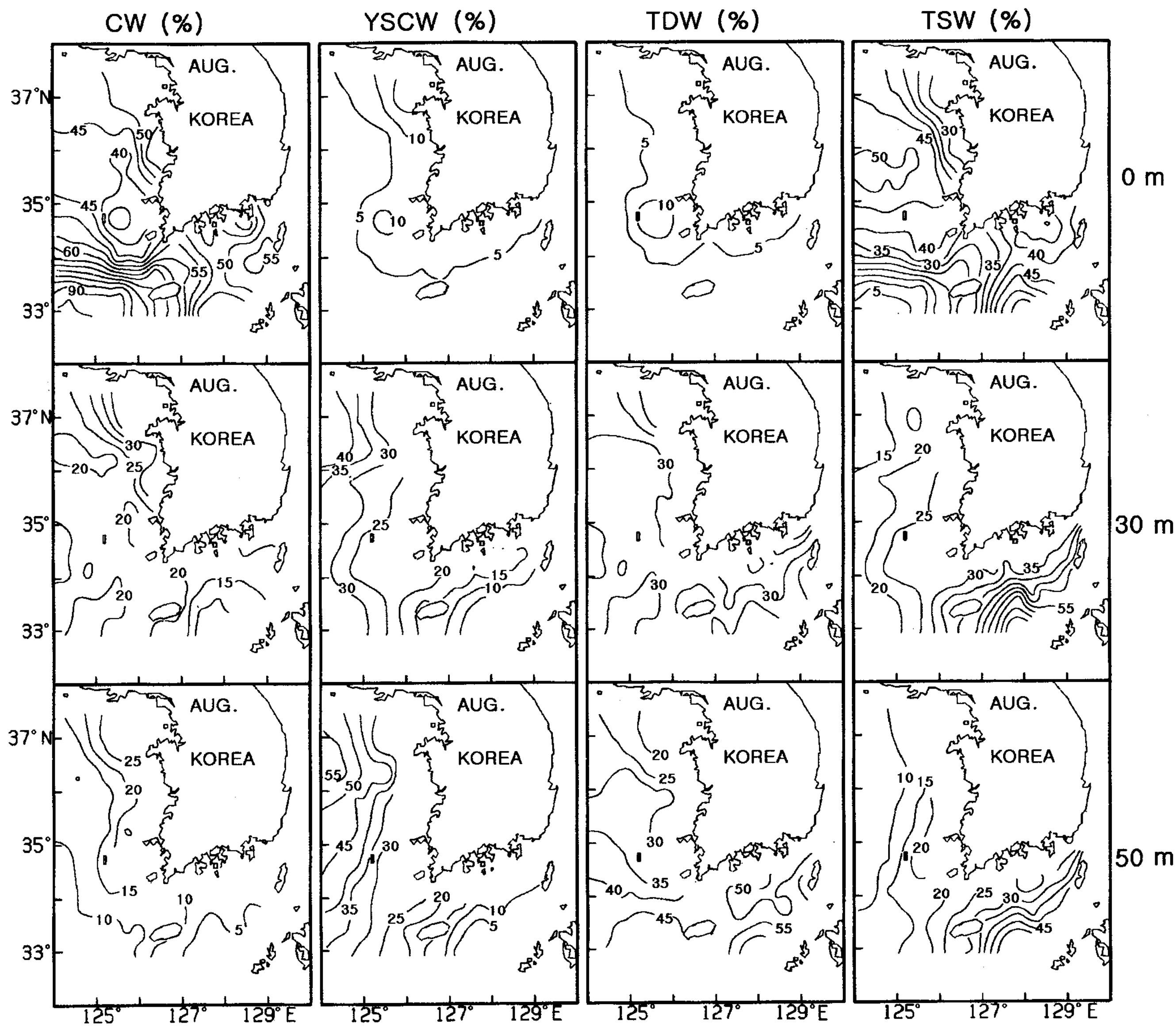


Fig. 9. Mixing ratios (%) of four source water masses shown in Fig. 7 in February (A) and August (B).



(B)

Fig. 9. Continued.

SEASONAL CIRCULATIONS

In the previous section, the water mass analysis shows seasonally reversed structures of water mass distributions. Now, we want to get some information of the seasonal circulation from them. Such water mass distributions can be influenced by various factors such as meteorology, diffusion, and circulation. However, the meteorological influence cannot explain why waters in WCK are equally or even a little more saline than waters in CYS in summer. Diffusion was introduced to explain the salt supply to the Yellow Sea (Lee and Kim, 1989); however, it cannot explain the reverse water mass distributions. The reverse water mass distributions can be explained only by circulation: in winter, warm waters intrude into CYS and cold waters expand southward along WCK and in summer, warm waters intrude northward along WCK and cold waters expand southward in CYS.

Such seasonal circulations have been known or easily acceptable except for the northward flow along WCK in summer. The southward expansion of cold waters in CYS in summer is well known (Asaoka and Moriyasu, 1966; Nakao, 1977; Lie, 1984; Park, 1985, 1986; Kim *et al.*, 1991; Youn *et*

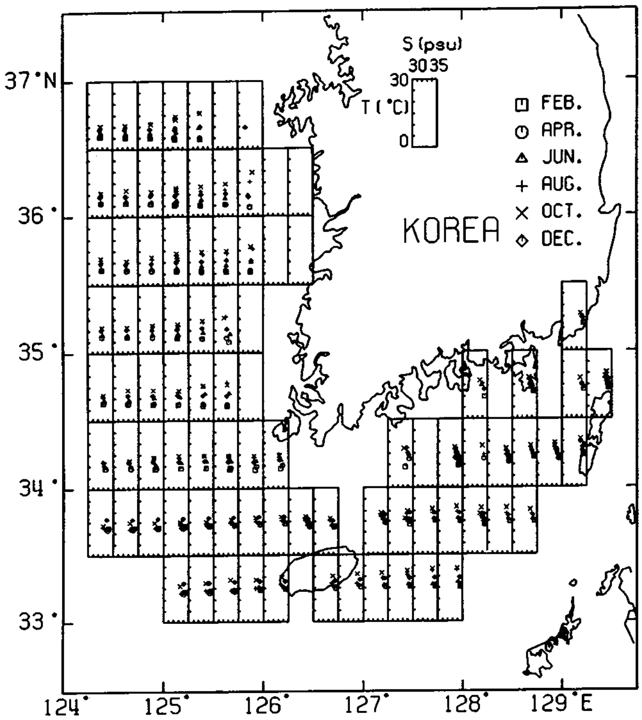


Fig. 10. Spatial T-S-time diagrams with mean temperatures and salinities over 1970 to 1990 at the depth of 50 m.

al., 1991). The northward intrusion of warm waters in CYS in winter is also recognized (Uda, 1934; Byun and Chang, 1988; Pang *et al.*, 1992). The southward expansion of cold waters along WCK in winter has not yet been formally reported, but it is easily acceptable. However, for the northward flow of warm waters along WCK in summer, negative opinions (Nakao, 1977; Lie, 1984, 1985; Kim *et al.*, 1991) have dominated positive ones (Pang, 1987; Pang *et al.*, 1992). Strong salt fronts formed in summer are believed to keep saline waters from flowing into WCK. Contrary to this belief, there are biological and chemical evidence of northward warm flows in summer (Sim *et al.*, 1988). We can also find some long-term current data to show such flows. Figure 12 shows low-pass filtered current data collected hourly at the depth of 20 m near Taeheuksan-do from June 22 to August 6, 1983 (KORDI, 1987). They show northward flows.

Figure 13 shows the dynamic depth topographies with the reference levels of 30 m and 50 m in February and August. We can see northward flows along WCK at the reference level of 50 m in August.

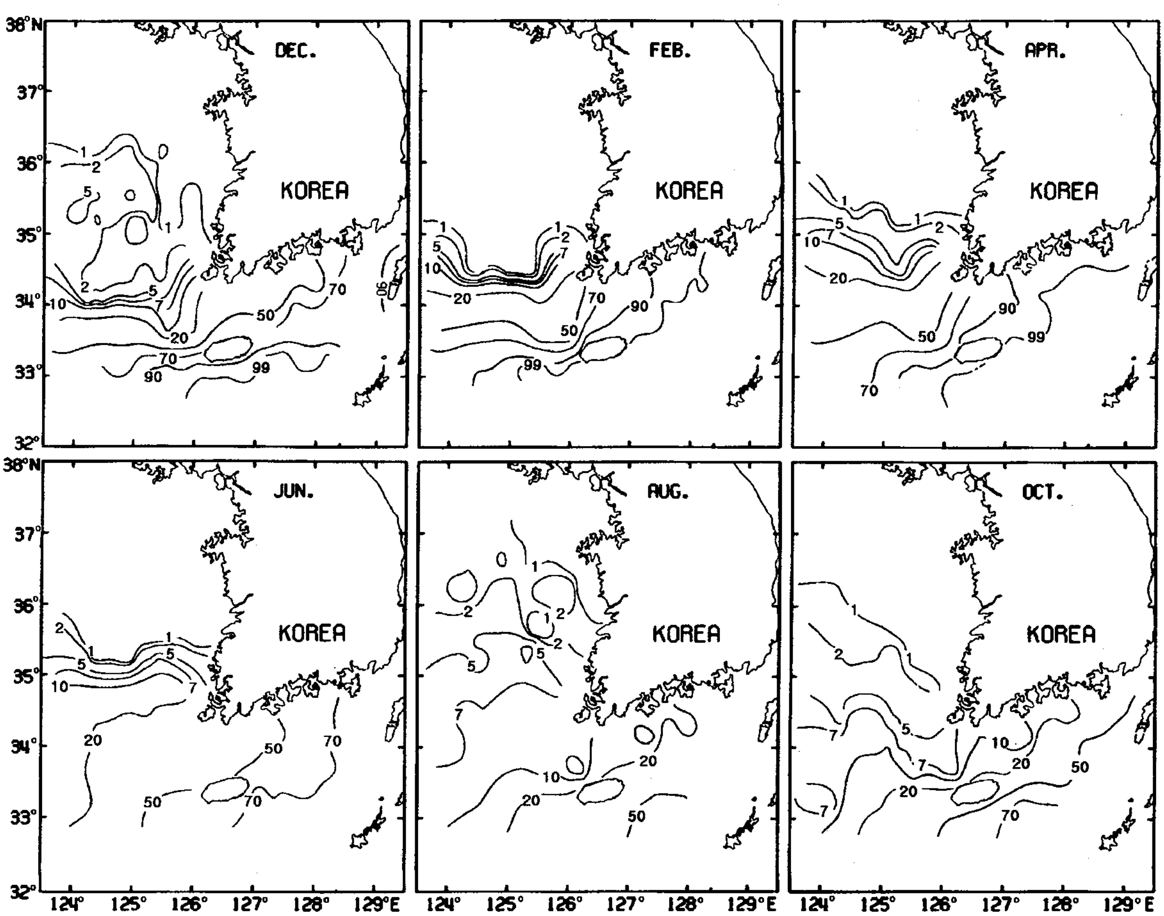


Fig. 11. Appearance percentages of 33.7‰ or more saline waters over 1970 to 1990.

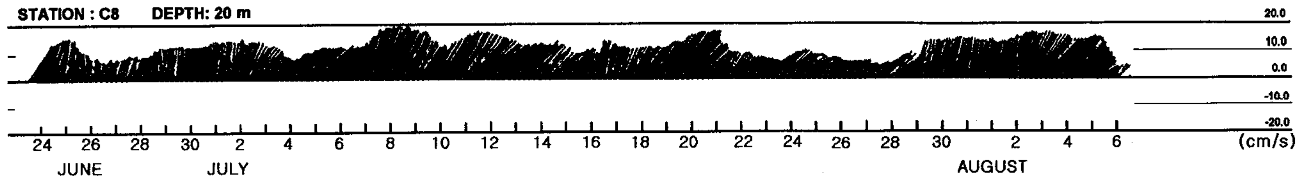


Fig. 12. Low-pass filtered velocity vectors plotted every hour from June to August, 1983 at the place of 34°35'N and 125° 15'E at the depth of 20 m (after KORDI, 1987).

They do not appear at the reference level of 30 m and we are not sure why. We can only tell that there are northward flows in the lower layer. It should be noted that the southward expansion of cold waters along WCK in February is not clear. This is probably because the flows are barotropic and are driven by winds in winter (Pang *et al.*, 1992). The northward flows along WCK in summer are comprised in the seasonal circulations.

We can find some reports to support the seasonal circulations. Figure 14A shows the geostrophic currents estimated from the satellite altimetric data (Yanagi *et al.*, 1996). Figure 14B displays the diagnostically calculated sea surface circulations (Yanagi and Takahashi, 1993). The figures show a clockwise circulation in winter and an anti-clockwise circulation in summer in EYS. The Yellow Sea circulation may be schematically depicted as Fig. 15. The figure shows the primary and secondary circulations. The secondary circulation corresponds to the seasonal circulation.

YELLOW SEA WARM CURRENT (YSWC)

In terms of the seasonal circulations, YSWC seems to be different from the current suggested by Uda (1934). It seems to flow into the Yellow Sea through

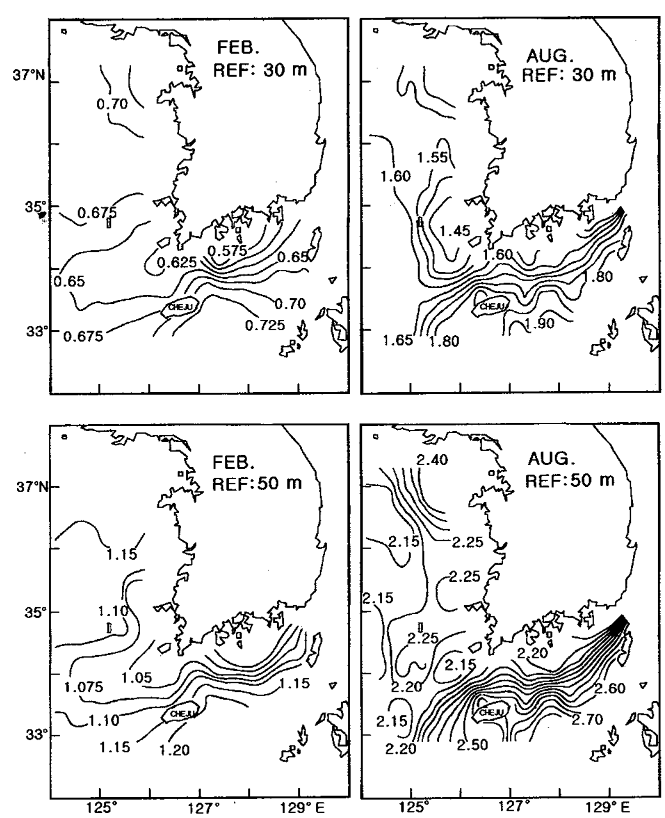


Fig. 13. Dynamic depth topographies with the reference levels of 30 and 50 m in February and August. Contours are in dynamic meters.

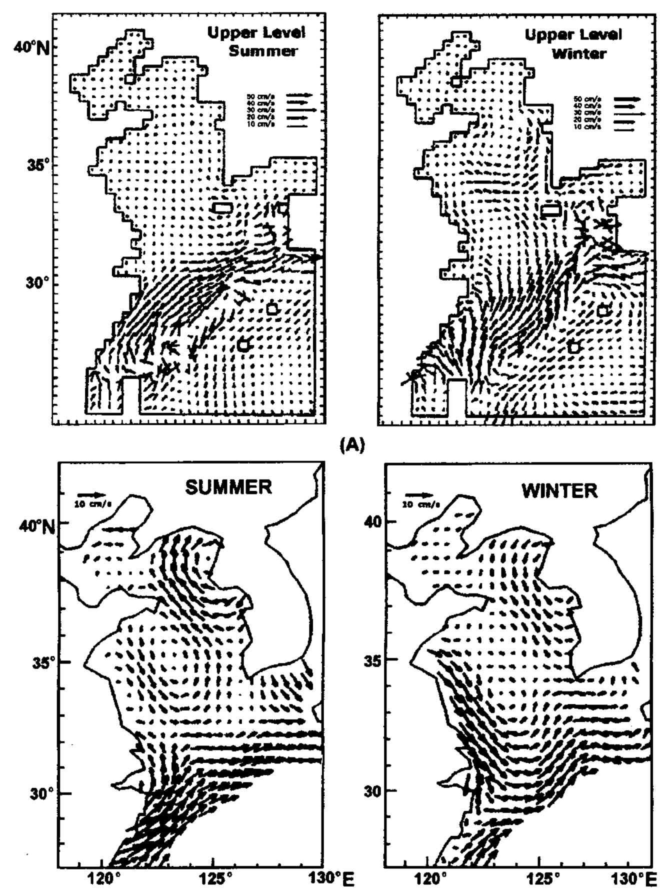


Fig. 14. (**A**) The diagnostically calculated sea surface circulation by Yanagi and Takahashi (1993). (**B**) The surface geostrophic current estimated from altimetric data by Yanagi *et al.*, (1996).

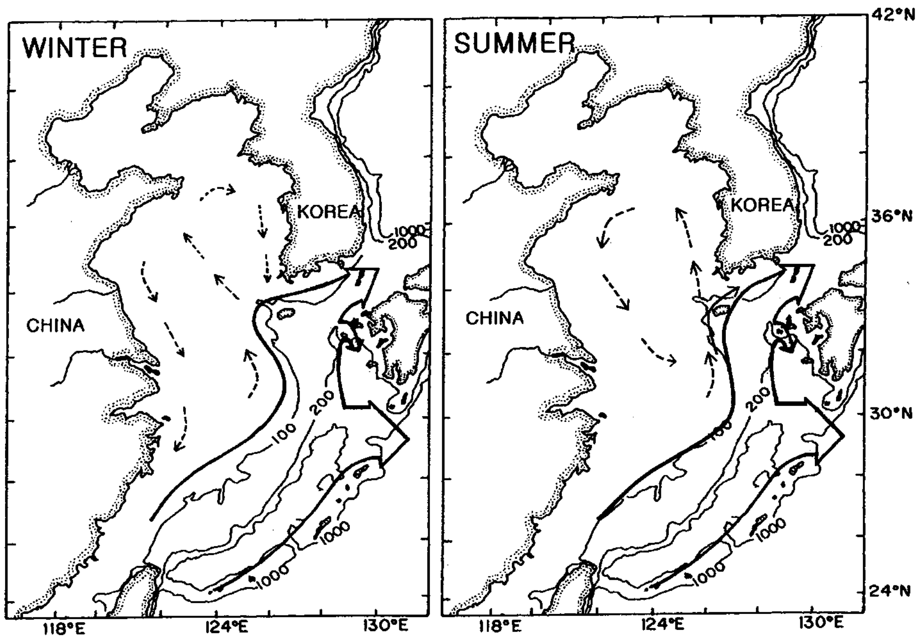


Fig. 15. Schematic circulation diagrams in the Yellow Sea and the East China Sea in winter and in summer (modified from Pang *et al.*, 1992). Contours are in meters.

CYS in winter and along WCK in summer. The summer inflow waters are mixed waters and not so high saline as defined previously. In this circumstance, YSWC should be defined as the inflows supplying heat and salt to the Yellow Sea, no matter what its temperature and salinity are. According to water mass analysis, its characteristic values might be defined as Table 3. Table 3 shows the characteristic ranges of YSWW in winter and summer. The lower limits of salinity are selected by the salinity of the waters having the 50% mixing ratio of warm waters. The upper limits of salinity are not so clear, but are selected by the salinity of the waters that are not connected with WCK. It should be noted that all salinities are less than 34‰, which was previously considered the lower limit of YSWW.

CONCLUSIONS

It has been generally believed that warm waters do not flow into the Yellow Sea in summer because of strong salt fronts. However, the salt fronts can be formed by tidal mixing with freshwater runoffs. On the other hand, the waters around Cheju Island are connected with the waters along WCK in temperature. This study aims to solve the discrepancy using mixing ratios.

For calculating mixing ratios, four source water masses are selected, that is, CW, YSCW, TSW, and TDW. Results show that the waters in WCK have dominant mixing ratios (50—90%) of cold waters (YSCW) in winter, and major mixing ratios (40—60%) of warm waters (TSW+TDW) in summer (in the lower layer). The waters in CYS are connected with warm waters from the south in winter (with the mixing ratios of more than 50%), and with cold waters (in the lower layer) from the north in summer (with the mixing ratios of more than 40%). These mean that water mass distributions reverse by season. Cold waters are distributed mainly in WCK in winter and in CYS in summer, and warm waters are distributed mainly in CYS in winter and in WCK in summer.

These seasonally reversed water mass distributions can be explained only by seasonal circulations. In winter, warm waters flow into CYS and cold

Table 3. The characteristic ranges of Yellow Sea Warm Water (YSWW)

Season	Month	T (°C)	S (‰)	Depth	Area
Winter	February—April December	9—10 13—14	33.2—33.7	all layers	central Yellow Sea
Summer	June August October	12—15 14—15 14—16	33.0—33.7 33.0—33.4	lower layer	west coast of Korea

waters flow southward along WCK. In summer, warm waters flow northward along WCK and cold waters flow southward in CYS. Mixing ratios prove northward warm flows along WCK (in the lower layer) in summer. Other statistical results also confirm these flows. Spatial T-S-time diagrams show that salinities in WCK are almost constant all year round. From 1970 to 1990, 33.7‰ or more saline waters did not appear north of 35°N in winter, but appeared as north as 37°N in summer. These statistical results show that there should be salt supply from the south in summer to compensate significant river runoff. Geostrophic calculations finally confirm the flows. In these circumstances, YSWC should be defined as the warm (saline) inflows toward CYS in winter and along WCK in summer no matter what its temperature and salinity are.

ACKNOWLEDGEMENTS

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