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Article

Water Masses and Salinity in the Eastern Yellow Sea from Winter to Spring

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Abstract : In order to understand the water masses and their distribution in the eastern Yellow Sea from winter to spring, a cluster analysis was applied to the temperature and salinity data of Korea Oceanographic Data Center from 1970 to 1990. From December to April, Yellow Sea Cold Water (YSCW) dominates the eastern Yellow Sea, whereas Eastern Yellow Sea Mixed Water (MW) and Yellow Sea Warm Water (YSWW) are found in the southern part of the eastern Yellow Sea. MW appears at the frontal region around 34°N between YSCW in the north and YSWW in the south. On the other hand, Tshushima Warm Water (TWW) is found around Jeju Island and the South Sea of Korea. These water masses are relatively well-mixed throughout the water column due to the winter monsoon. However, the water column begins to be stratified in spring due to increased solar heating, the diminishing winds and fresh water discharge, and the water masses in June may be separated into surface, intermediate and bottom layers of the water column. YSWW advances northwestward from December to February and retreats southeastward from February to April. This suggests a periodic movement of water masses in the southern part of the eastern Yellow Sea from winter to spring. YSWW may continue to move eastward with the prevailing eastward current to the South Sea from April to June. Also, the front relaxes in June, but the mixed water advances to the north, increasing salinity. The salinity is also higher in the nearshore region than offshore. This indicates an influx of oceanic water to the north in the nearshore region of the eastern Yellow Sea in spring in the form of mixed water.

Key words : water mass, salinity, Yellow Sea Warm Water, Yellow Sea Cold Water, Eastern Yellow Sea Mixed Water, Tsushima Warm Water

1. Introduction

Water from oceanic origin meets various coastal waters with freshwater discharges from Korea and China in the eastern Yellow Sea (Fig. 1). In addition, seasonal variations of solar heating and winds add complexities to the water mass distribution in this shallow coastal ocean. One of the important aspects of the study on water masses of the eastern Yellow Sea is to know how they maintain their salinity over a year despite inflow of immense fresh water discharge (Schubel *et al.* 1986) from Korea and China in summer. It is well known that warm and saline water intrudes into the central portion of the Yellow Sea in winter. However, the inflow of warm and saline water in other seasons has not been conclusive and needs to be understood better. There have been efforts (e.g. Lie 1986; Park 1986; Kim *et al.* 1991; Liu *et al.* 1992; Su and Weng 1994; Lee 1998; Pang and Hyun 1998; Hur *et al.* 1999; Park and Oh 2001; Kim *et al.* 2003) to understand the water mass distribution in the Yellow Sea. It is generally known from previous studies that water masses of Yellow Sea Cold Water, Yellow Sea Warm Water, Mixed Water, Korean Coastal Water and Chinese Coastal Water exist in the Yellow Sea. In addition, Yellow Sea Bottom Cold

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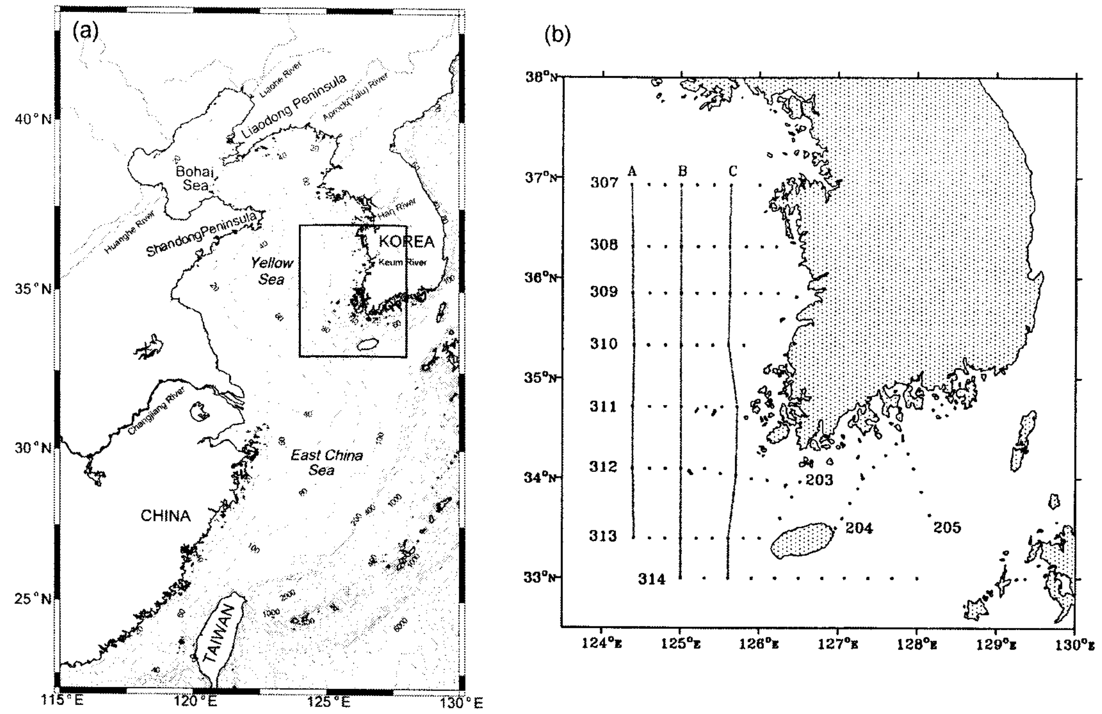

Fig. 1. Study area in the Yellow Sea (a) and KODC stations with longitudinal sections (b).

Water and Changjiang Diluted Water are found in the Yellow Sea in summer. Studies so far, however, examined water masses in summer and winter months or annual water mass variation without detailed information on the annual variation of water mass distribution in the eastern Yellow Sea. Kim *et al.* (1991) analyzed water masses in the Yellow and East China Seas based on observed data in January and July, 1986, and the analysis is limited to winter and summer. Liu *et al.* (1992) and Su and Weng (1994) studied water masses in the Yellow and East China Seas, but the eastern Yellow Sea were out of their study area. Hur *et al.* (1999) showed annual water mass variation in the Yellow and the East China Seas, but they focused their study on winter and summer. Detailed knowledge of how the water masses and their salinities in the eastern Yellow Sea change from winter to spring has not been available. This study intends to examine the variation of water masses and their salinities in the eastern Yellow Sea (Fig. 1) from winter to spring when the fresh water discharge is low (Schubel *et al.* 1986), using the bimonthly salinity and temperature data of the Korea Oceanographic Data Center (KODC) from 1970 to 1990.

2. Analysis of KODC Data

A cluster analysis was applied to the KODC data to identify the water masses in the eastern Yellow Sea and the South Sea of Korea objectively. Since we are interested in the mean properties of the water mass in this study, the mean temperature and salinity were used in this analysis. Standard depths used are 0, 10, 20, 30, 50, 75, 100 and 125 m. A brief description of the cluster analysis will be made here and further information can be found in previous studies using this method (Kim *et al.* 1991; Hur *et al.* 1999). A cluster is composed of data and merged into a new cluster with other data that is closest in proximity. It was shown previously that the water masses at the surface are different from those in deeper layers when the water column is stratified in the Yellow Sea. Also, geographic proximity is important in clustering the water masses. Thus, the distance function is made up of temperature, salinity, depth and geographic distance. The temperature, salinity, and depth are normalized since they have different units and variable ranges as follows (Hur *et al.* 1999).

$$T_n = DT/M_T,\quad S_n = DS/M_S,\quad d_n = Dd/M_d$$

where DT, DS, and DD are temperature, salinity and depth differences between two clusters, and M_T, M_S, and M_d are the standard deviations. The distance function,

$$F_D = T_n^2 + S_n^2 + W_d d_n^2 + W_D D$$

where W_d and W_D are weighting factors for depth and geographic distance D, respectively. W_d is 1.0 from December to April and 0.75 for June. W_D is 10^{-4} (m^{-1}) to give clusters 10 km apart the same weight as other parameters with one standard deviation. For the computation of F_D, average values for the temperature, salinity and depth of each cluster are used. However, for geographic distance, the shortest distance between two clusters is used to allow one cluster to merge with another of similar temperature, salinity and depth nearby.

3. Water masses and salinity in the eastern Yellow Sea from winter to spring

It is well-known from the previous works that the warm and saline water intrudes into the southern Yellow Sea where it meets colder and less saline water in winter. The results of the water mass analysis for December shows that there are water masses of Yellow Sea Cold Water (YSCW), Yellow Sea Warm Water (YSWW), Tshushima Warm Water (TWW), Eastern Yellow Sea Mixed Water (MW) and Korea Southern Coastal Water (KSCW) in the eastern Yellow Sea and the South Sea of Korea (Fig. 2a). YSCW and YSWW dominate the region with MW in the frontal zone between YSCW and YSWW along 34°N (Fig. 3). YSWW appears to the west of Jeju (or Cheju) Island, and warmer, more saline TWW with temperatures of 17.0-19.7°C and salinity of 34.1-34.5 psu appears south and east of Jeju Island. YSWW and TWW are influenced by warm and saline water originating from the Kuroshio. Appearance of MW between YSCW and YSWW and its temperature and salinity suggest that MW is produced through the mixing of two water masses, YSWW and YSCW. KSCW is found near the southern coast of Korea.

In February, water masses found in December appear again, but their temperatures are lower and their salinities higher as shown in Fig. 2(b). Also, the water masses show a more cohesive pattern than those in December reflecting the well-mixed water column in the study area. The strong northwesterly monsoon in the study area and diminishing fresh water discharge may have contributed to these changes. The water mass distribution in Fig. 4 clearly shows that it is essentially depth-independent. The water mass distribution in February is very similar to that of December (Fig. 3). However, in February, TWW advances to the west of Jeju Island, enforcing its influence in the southern Yellow Sea.

Kim *et al.* (1991) analyzed temperatures and salinity obtained in the region deeper than 50 m in the Yellow and East China Seas and identified four water masses in January for this study area. Group 2 and 3 representing cold and less saline water is found in the eastern Yellow Sea, while Group 4, representing warm and saline water appears in the South Sea. Group 4 corresponds to TWW in this study. Group 5, which corresponds to KSCW, also appears in the South Sea. Although Group 2 and 3 appear in the eastern Yellow Sea, they do not correspond to YSCW and YSWW considering their temperature and salinity characteristics and distribution patterns. Also, water mass corresponding to MW does not exist in their study. Discrepancies between the two results may have risen as a result of different data sets and classificaion schemes.

On the other hand, Hur *et al.* (1999) identified five water masses for the eastern Yellow Sea and the South Sea in

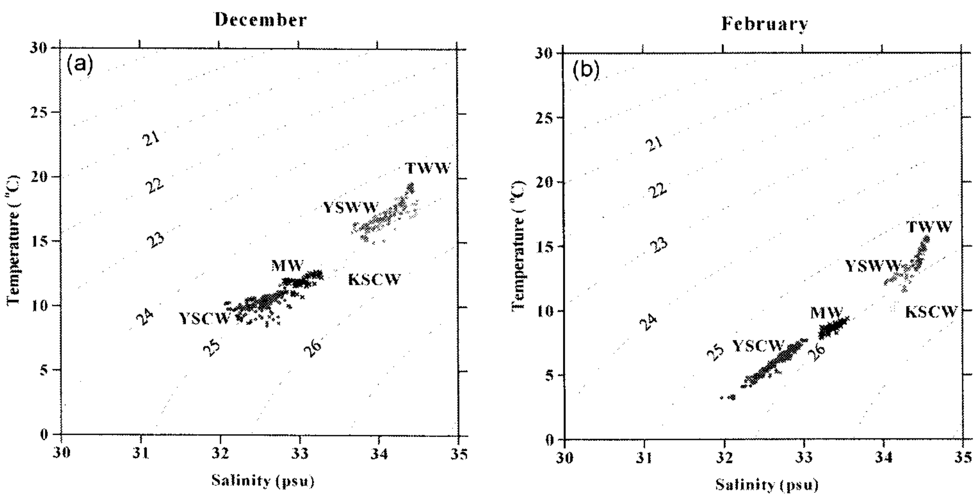

Fig. 2. Water masses in the eastern Yellow Sea and the South Sea of Korea in December (a) and February (b).

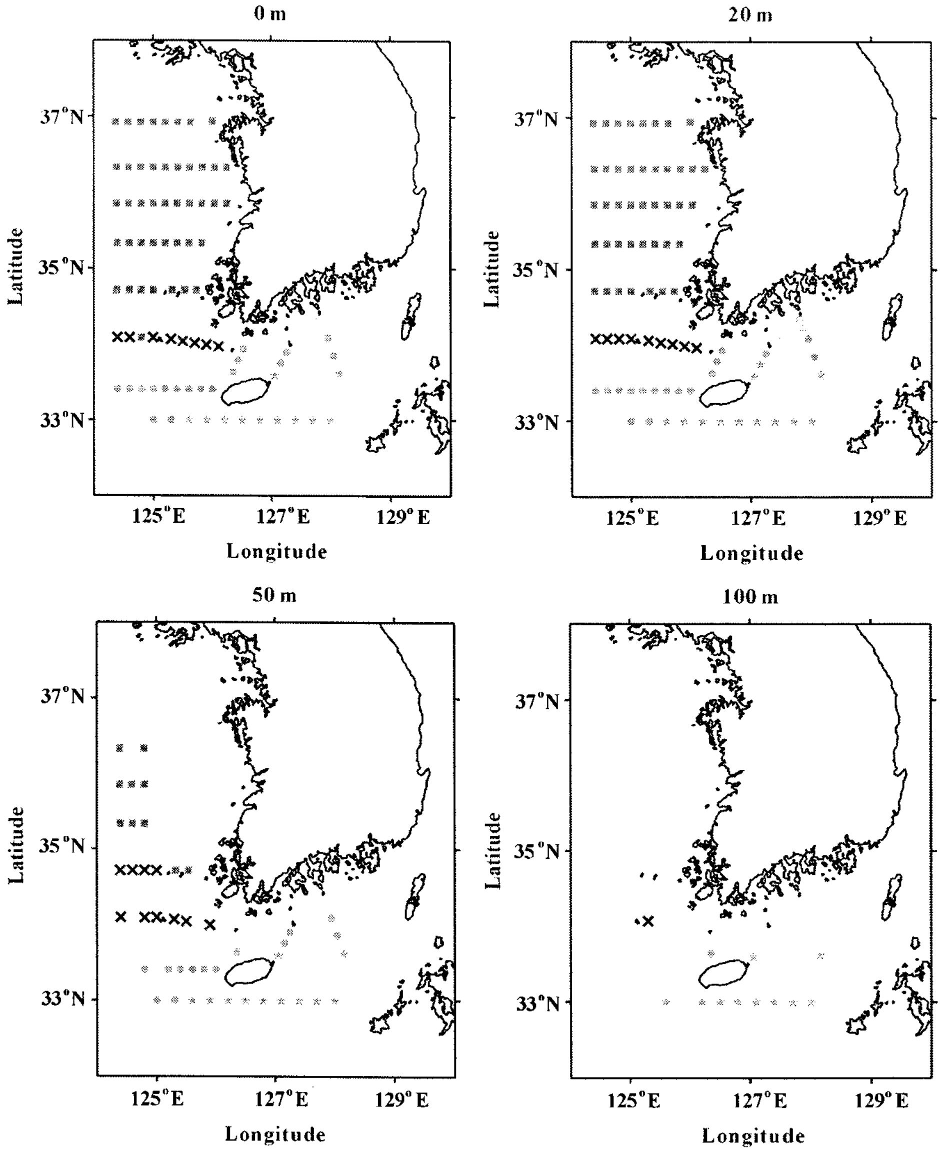

Fig. 3. Horizontal distribution of water masses in the eastern Yellow Sea and the South Sea of Korea in December.

January, namely the surface (YSS) and bottom (YSB) water masses of the Yellow Sea, mixed water (MW), Kuroshio and East China Sea Water (KE) and Korea Strait Water (KS). YSS and YSB may correspond to YSCW, while KE corresponds to YSWW and TWW. In this study, the water column is considered well-mixed, yielding YSCW in the eastern Yellow Sea, whereas warm and saline water is differentiated into YSWW and TWW. On the other hand, MW of Hur *et al.* (1999) appears along 34°N in the eastern Yellow Sea as shown in this study. KS appears around Jeju Island and the Korea Strait.

In April, YSCW, YSWW, MW, and TWW appear as in December and February, but KSCW disappears (Fig. 5a). YSWW, MW and YSCW show a dispersed pattern as the water column becomes stratified with increased solar heating, reduced winds and fresh water discharge. Comparing water masses in February (Fig. 2b) with those in April, we find that MW becomes more saline, while YSWW becomes less saline, narrowing the salinity differences between the two water masses. In addition, YSWW shows a decrease of temperature, while MW shows a temperature increase. These phenomena suggest vigorous mixing of two water masses, YSWW and MW in spring. The water mass distribution (Fig. 6) shows a similar pattern as in February, but YSWW instead of TWW appears to the west of Jeju Island.

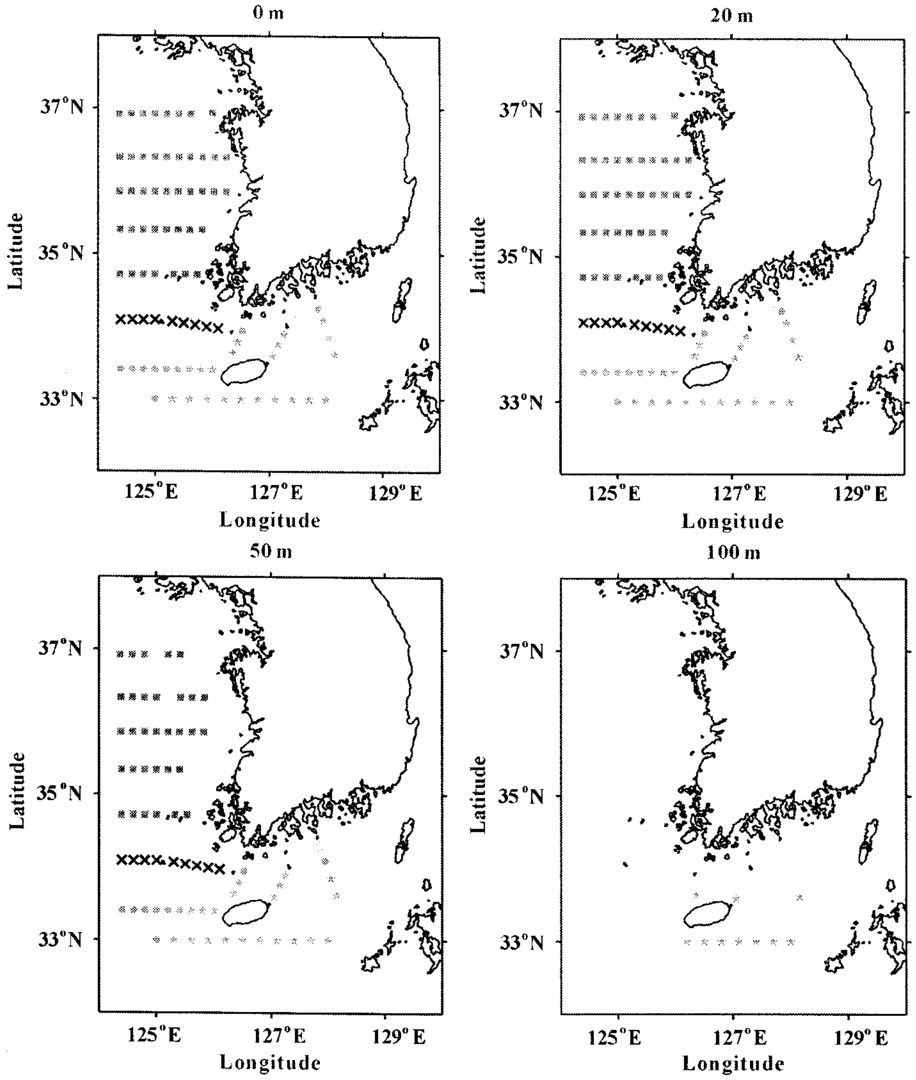

Fig. 4. Horizontal distribution of water masses in the eastern Yellow Sea and the South Sea of Korea in February.

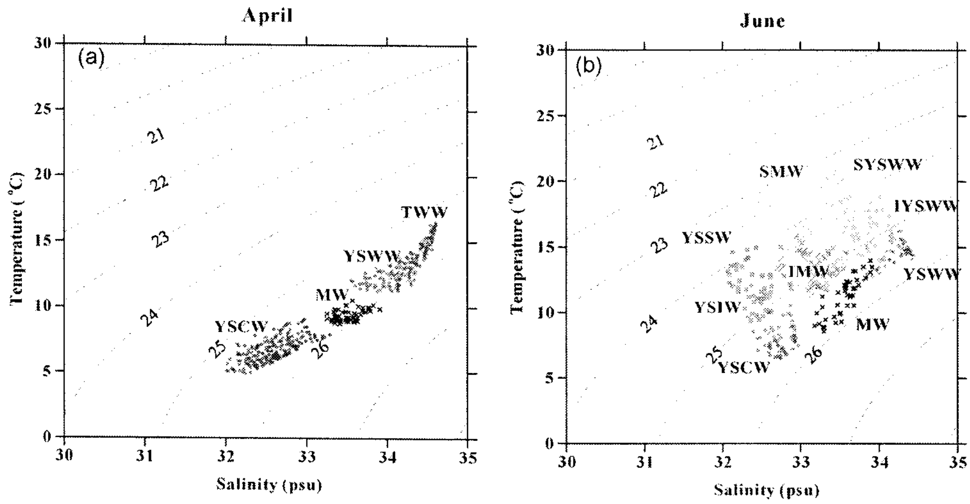

Fig. 5. Water masses in the eastern Yellow Sea and the South Sea of Korea in April (a) and June (b).

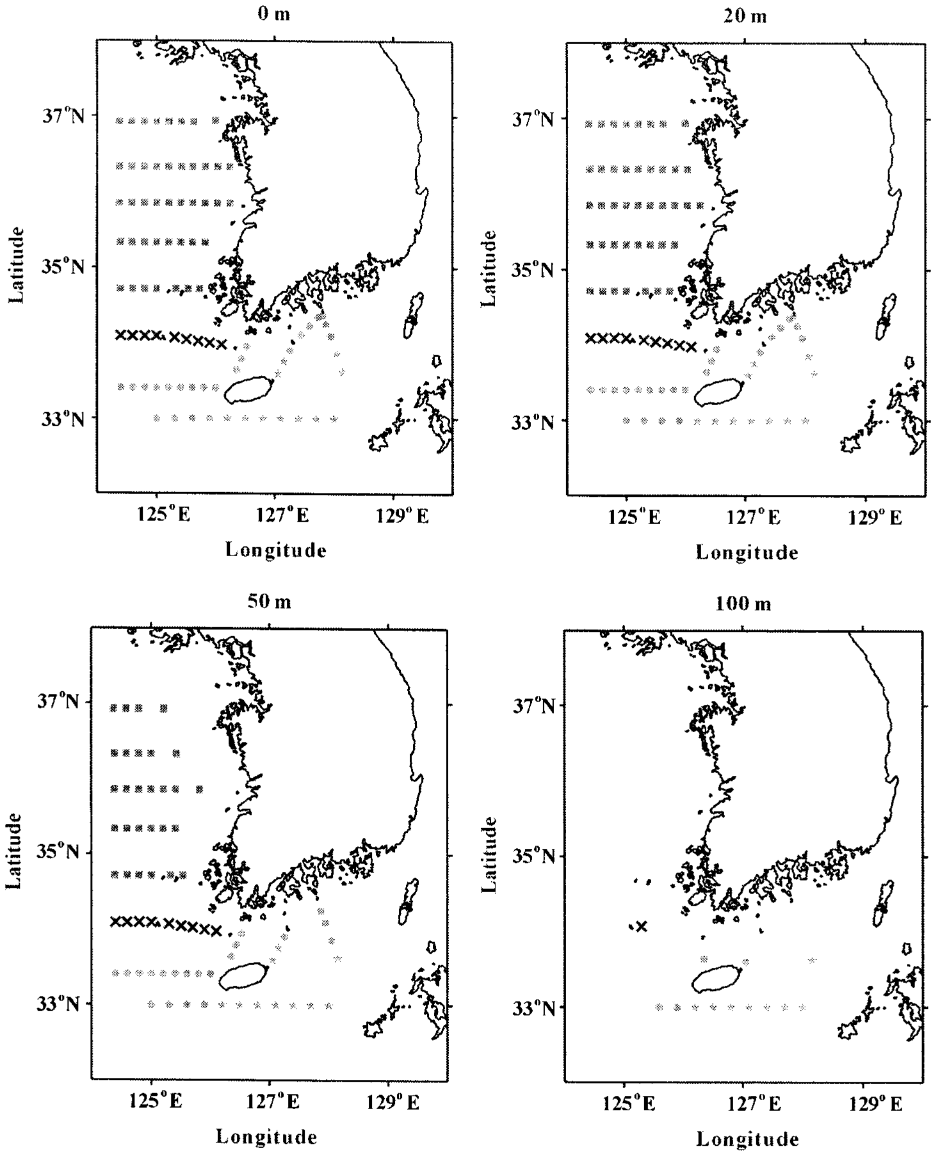

Fig. 6. Horizontal distribution of water masses in the eastern Yellow Sea and the South Sea of Korea in April.

Comparing water mass distribution in April with that of December (Fig. 3), we find that they are almost identical, except that KSCW in December changes to YSWW in April. This suggests northwestward advance of TWW to the southern part of the eastern Yellow Sea in February from its position in the south and east of Jeju Island in December and a retreat in April to its previous position in December. YSWW is colder and less saline than TWW and appears northwest to TWW. This means that YSWW advances to the central Yellow Sea in February from its position in December, and retreats back in April to its position in December. This suggests a periodic movement of water masses in the southern part of the eastern Yellow Sea from winter to spring, which has the maximum northwestward displacement of water masses in February.

Due to increased solar heating, weak winds and fresh water discharge, the water column becomes more stratified, the water masses displaying a complex pattern in June (Fig. 5b). Kim *et al.* (1991) separated water masses at surface from those in 50 m in July. Hur *et al.* (1999) also indicated the existence of a three layer system in the Yellow Sea from May to November. Considering the strong stratification of temperature and salinity in the water column of the eastern Yellow Sea in June (Fig. 9), the water column may be separated into surface, intermediate and bottom layers. YSWW, which appears again west of Jeju Island in

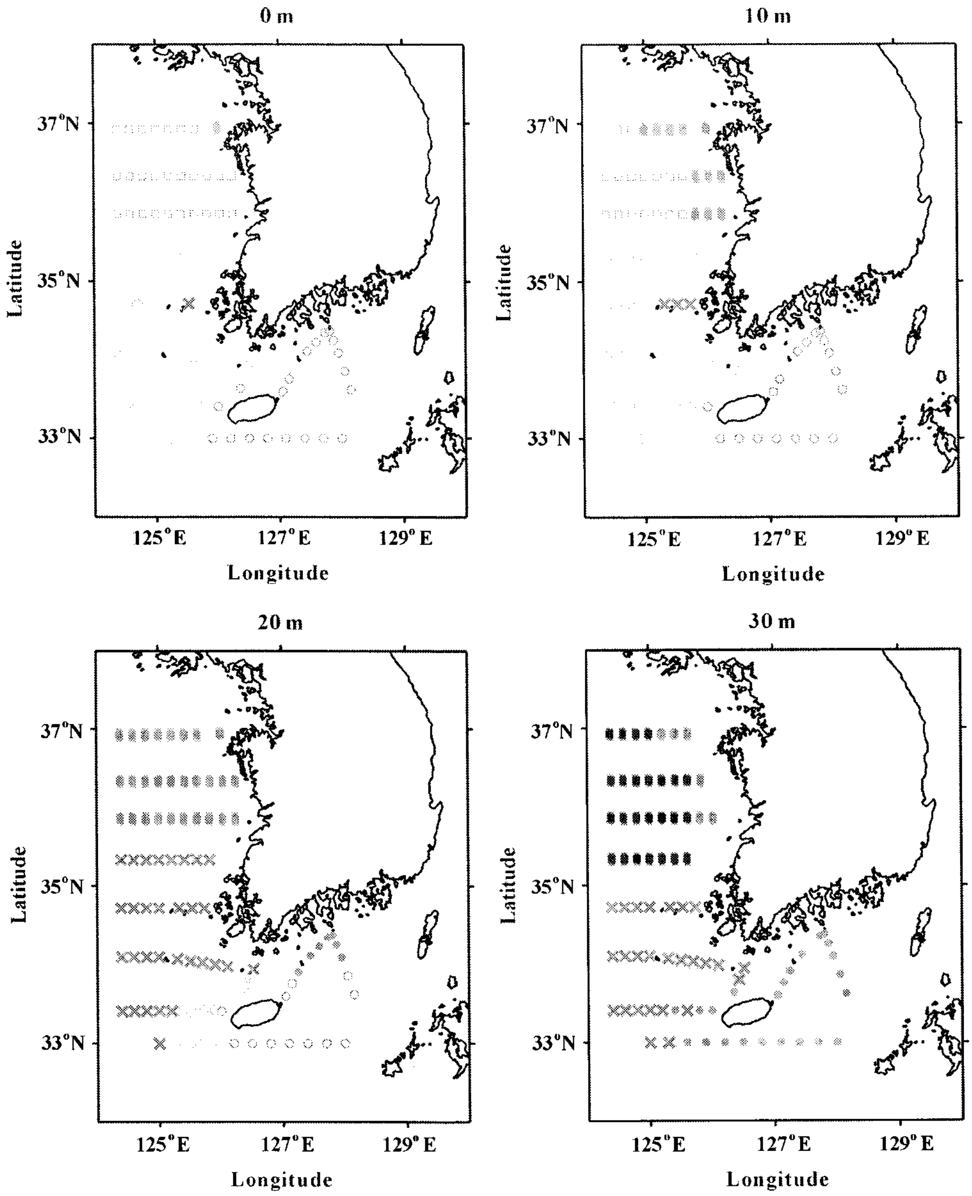

Fig. 7(a). Horizontal distribution of water masses in the eastern Yellow Sea and the South Sea of Korea in June.

April due to the periodic movements as discussed previously, may continue to move eastward with the prevailing eastward mean current (e.g. Chang *et al.* 1995) to the South Sea of Korea.

Accordingly, water masses in the eastern Yellow Sea and the South Sea of Korea consist of surface, intermediate and bottom layers of YSCW, MW and YSWW (Fig. 5b). YSCW, which existed from December to April throughout the water column, is now separated to Yellow Sea Surface Water (YSSW), Yellow Sea Intermediate Water (YSIW), and YSCW. YSWW becomes Surface Yellow Sea Warm Water (SYSWW), Yellow Sea Intermediate Warm Water (IYSWW) and YSWW. MW is also separated into Eastern Yellow Sea Surface Mixed Water (SMW), Eastern Yellow Sea Intermediate Mixed Water (IMW) and MW. This shows that YSCW, MW and YSWW appear again, but they are confined to the bottom layer of the water column. YSCW, which appears from 30 m with temperatures less than 10°C, may correspond to Yellow Sea Bottom Cold Water. Hur *et al.* (1999) also classified the water masses in the Yellow Sea in June as the three-layer system, i.e. Yellow Sea Surface Water (YSSW), Yellow Sea Cold Water

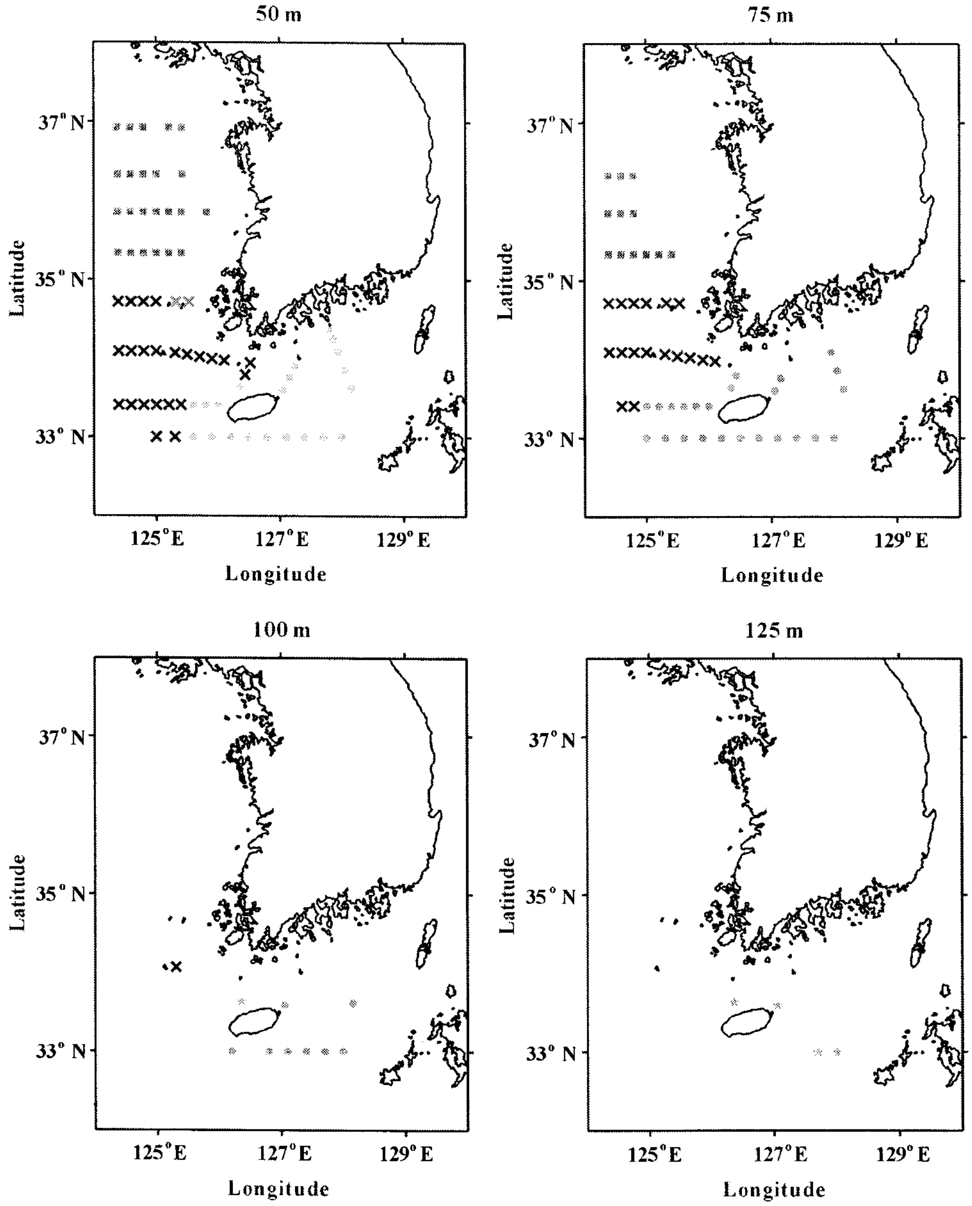

Fig. 7(b). Horizontal distribution of water masses in the eastern Yellow Sea and the South Sea of Korea in June.

(YSCW) and Yellow Sea Bottom Water (YSB). In this study, we used YSSW, YSIW, and YSCW in order to be consistent with the water mass, YSCW, in previous months from December to April. On the other hand, Hur *et al.* (1999) did not separate the water masses in the South Sea in June, but classified them as Kuroshio-East China Sea Water (KE).

YSSW, YSIW and YSCW in the north and SMW, IMW and MW in the south dominate the eastern Yellow Sea in June, while SYSWW, IYSWW and YSWW dominate the South Sea (Fig. 7). Comparing water mass distribution in April (Fig. 6) with that in June (Fig. 7), it is noticeable that there is a northward retreat of water masses associated with YSCW, i.e. YSSW, YSIW and YSCW and expansion of water masses associated with MW, i.e. SMW, IMW and MW. All the mixed waters, SMW, IMW, and MW expand south and north. This suggests a relaxation of the front along 34°N, and the advance of saline water to the north of 34°N.

As the saline YSWW continues to intrude into the central Yellow Sea in winter, the salinity of seawater in the offshore region of the eastern Yellow Sea increases by

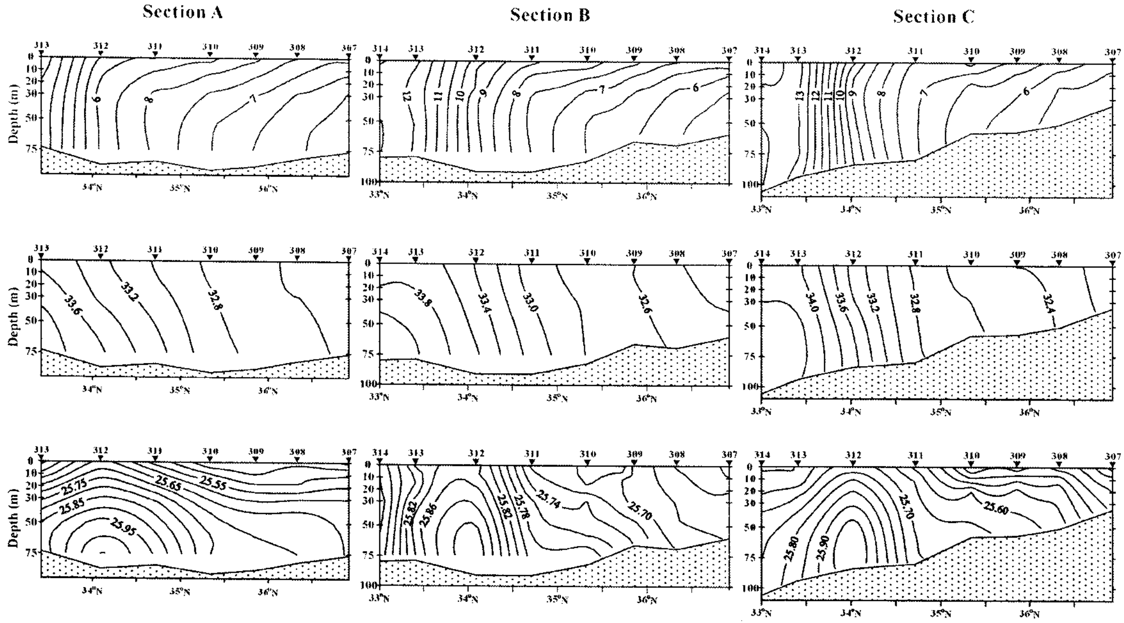

Fig. 8. Vertical profiles of temperature, salinity and sigma-t along the longitudinal sections in the eastern Yellow Sea in April.

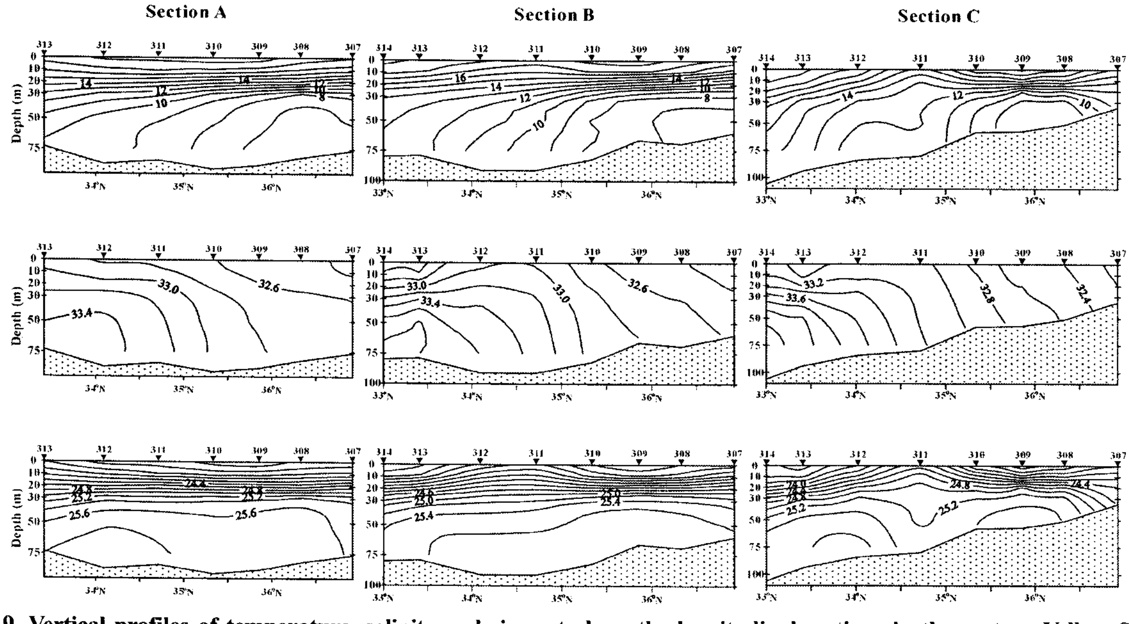

Fig. 9. Vertical profiles of temperature, salinity and sigma-t along the longitudinal sections in the eastern Yellow Sea in June.

about 0.2 psu from December to February, while it does not show much variation in the inshore region. The temperature decreases by 2-5°C in the whole area of the eastern Yellow Sea. The water column also becomes more homogeneous due to intense mixing as a result of the winter monsoon.

In April, the surface water temperature increases by 1-2°C from that of February in general and the water column becomes stratified. On the other hand, the salinity of YSWW in the southeastern Yellow Sea decreases, while that of MW in the frontal zone increases (Fig. 5a). The salinity increases by 0.1-0.2 psu along 34°N (312 Line of KODC,

Fig. 1b) in this period in the lower layer of the water column. This may be due to the mixing of saline YSWW with less saline YSCW by the strong tidal current in the frontal zone of the southeastern Yellow Sea. On the contrary, the salinity to the north of 35°N decreases apparently due to the fresh water discharge from the Korean rivers.

From April to June, the salinity in the south of 34°N of the eastern Yellow Sea continues to decrease, while the salinity to the north of 34°N increases in the lower layer of the water column. The 33.0 psu isoline advances from 34°30'N (Fig. 8) to the north of 35°N along Section C (Fig. 9).

4. Discussion and conclusions

From December to April, Yellow Sea Cold Water (YSCW) dominates the eastern Yellow Sea, whereas Eastern Yellow Sea Mixed Water (MW) and Yellow Sea Warm Water (YSWW) are found in the southern part of the eastern Yellow Sea. MW appears at the frontal region around 34°N between YSCW in the north and YSWW in the south. On the other hand, Tshushima Warm Water (TWW) is found around Jeju Island and the South Sea of Korea. The water column is nearly homogeneous and water mass distribution is similar from December to April. However, due to the increase of solar heating and fresh water discharge, the water column in June becomes stratified as surface, intermediate and bottom layers and YSWW, YSCW and MW appears only in the bottom layer in the eastern Yellow Sea and the South Sea of Korea.

YSWW advances to the central Yellow Sea in February from its position in December, and in April it retreats back to its previous position in December. This suggests a periodic movement of water masses in the southern part of the eastern Yellow Sea from winter to spring, which has the maximum northwestward displacement of water masses in February. YSWW may continue to move eastward from west of Jeju Island to the South Sea by the prevailing eastward current from April to June, and may also be related to the expansion of MW. Pang *et al.* (1992) indicated that warm and saline water extended northwestward into the Yellow Sea in winter and retreated southeastward in summer due to the monsoonal winds.

Water masses found in the South Sea may eventually flow into the Korea Strait and the East (Japan) Sea by the eastward current (e.g. Chang *et al.* 1995; Byun 2000; Lie *et al.* 2000; Pang *et al.* 2003; Lee *et al.* 2003) to form the Tsushima Current water. However, water masses found in the South Sea in summer have been named differently by various authors; Gong (1971) suggested that surface and intermediate waters of the Tsushima Current are influenced by the Chinese Coastal Water and flow into the East Sea. The Tshushima Current water was also considered a mixture of Kuroshio surface water and East China Sea water (Lim, 1971). On the other hand, Rho (1985) showed that YSWW and TWW appear in the South Sea in June. Kim *et al.* (1991) suggested that the surface water (Group 10) in the South Sea is affected by the Kuroshio, and the deep water found at 50 m is named the East China Sea Water. Hur *et al.* (1999) showed that the water mass in the South Sea changes significantly over a year and named it the Kuroshio-East China Sea Water in June.

The strong salinity front between YSWW and YSCW forms along 34°N from December to February. During this period, the salinity of YSWW and MW increase suggesting an influx of saline oceanic water into the study area. An increase of salinity is especially noticeable in the offshore region of the eastern Yellow Sea. On the other hand, the salinity of YSWW decreases from February to April, while that of MW continues to increase, and as a result, the salinity front between MW and YSWW weakens. From April to June, while the salinity in the south of 34°N of the eastern Yellow Sea continue to decrease, the saline water in the subsurface layer of the water column in the north of 34°N advances northward. MW continues to exist and expand in the study area unlike the results of Hur *et al.* (1999), which suggested a cease of MW after April. Water mass analysis also showed the northward advance of MW in the study area. This indicates that the salinity increase in the eastern Yellow Sea in spring is due to the northward advance of MW.

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