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The temporal and spatial variability of the Yellow Sea Cold Water Mass in the southeastern Yellow Sea, 2009–2011

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Abstract

The Yellow Sea Cold Water Mass (YSCWM) is one of the important water mass in the Yellow Sea (YS). It is distributed in the lower layer in the Yellow Sea central trough with the temperature less than 10°C and the salinity lower than 33.0. To understand the variability of the YSCWM, the hydrographic data obtained in April and August during 2009–2011 are analyzed in the southeastern Yellow Sea. In August 2011, relatively warm and saline water compared with that in 2009 and 2010 was detected in the lower layer in the Yellow Sea central area. Although the typhoon passed before the cruise, the salinity in the Yellow Sea central trough is much higher than the previous season. It means that the saline event cannot be explained by the typhoon but only by the intrusion of saline water during the previous winter. In April 2011, actually, warm and saline water ($T>10$°C, $S>34$) was observed in the deepest water depth of the southeastern area of the Yellow Sea. The wind data show that the northerly wind in 2011 winter is stronger than in 2009 and 2010 winter season. The strong northerly wind can trigger the intrusion of warm and saline Yellow Sea Warm Current. Therefore, it is proposed that the strong northerly wind in winter season leads to the intrusion of the Yellow Sea Warm Current into the Yellow Sea central trough and influenced a variability of the YSCWM in summer.

Key words: Yellow Sea Cold Water Mass, interannual variation, saline event, atmosphere variability, Yellow Sea

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1 Introduction

The Yellow Sea (YS), a semi-enclosed marginal sea in the northwestern Pacific, is bounded by the Korean Peninsula to the east and China to the west and opens to the Bohai Sea to the north and the East China Sea (ECS) to the south (Fig. 1). The YS lies entirely over the shallow continental shelf (mean depth of 44 m) and includes a central trough extending north-south (deeper than 75 m in Fig. 1b). The characteristics of seawater in the shallow YS are sensitive to changes in the seasonal monsoon. In winter, the strong northerly wind and the net heat loss from sea surface to atmosphere cause vigorous vertical mixing, and the water column becomes almost vertically uniform. In general, the surface water in the offshore area becomes hotter and fresher than the water below it during spring and summer due to surface heating and freshwater input, while the water below the seasonal thermocline maintains the properties of the previous winter (Park et al., 2011). The lower layer water in summer is generally referred to as the Yellow Sea bottom cold water (YSBCW) because of its low temperature (Hur et al., 1999; Lie, 1984; Nakao, 1977; Uda, 1934). The surface cooling during late autumn induces thickening of the surface mixed layer and consequently deepening and weakening of the thermocline. Eventually the water column becomes uniform again during winter. In this distinct seasonal cycle, the Yellow Sea Cold Water Mass (YSCWM), including the YSBCW, is the most dominant water mass in the YS and is present throughout the whole year.

The previous studies (Chu et al., 1997; Hur et al., 1999; Lie, 1986; Park et al., 2011; Zhang et al., 2008) have suggested slightly different definitions of the YSCWM. In this study, we use the relatively broad definition of the YSCWM being water colder than 10°C and with salinity values in the range of 32.0–33.0, following Lie (1984). The distribution of the YSCWM is associated with the circulation of waters in the YS and ECS generated by the monsoon and the tidal currents (Moon et al., 2009). The dominant northerly wind in winter generates an upwind flow system and the warm water, known as the Yellow Sea Warm Current (YSWC), flows into the YS along the Yellow Sea central trough (YSCT) from the ECS (Nitani, 1972). The YSWC is considered to be the main source of salt and heat into the YSCWM during winter. The YSWC intrusion is occurrs as a sporadic event in winter when the strong northwesterly monsoon prevails over the YS (Hsueh, 1988; Lie et al., 2009).

The YSCWM has an important effect on marine ecosystems (Hur et al., 1999; Lie et al., 2001). For example, the copepod *Calanus sinicus*, the most dominant and important zooplankton in the YS, prefers cold water and stays in the YSCWM during summer (Kang and Kim, 2008). Wang et al. (2003) also reported that the YSCWM is an oversummering site for *C. sini-*

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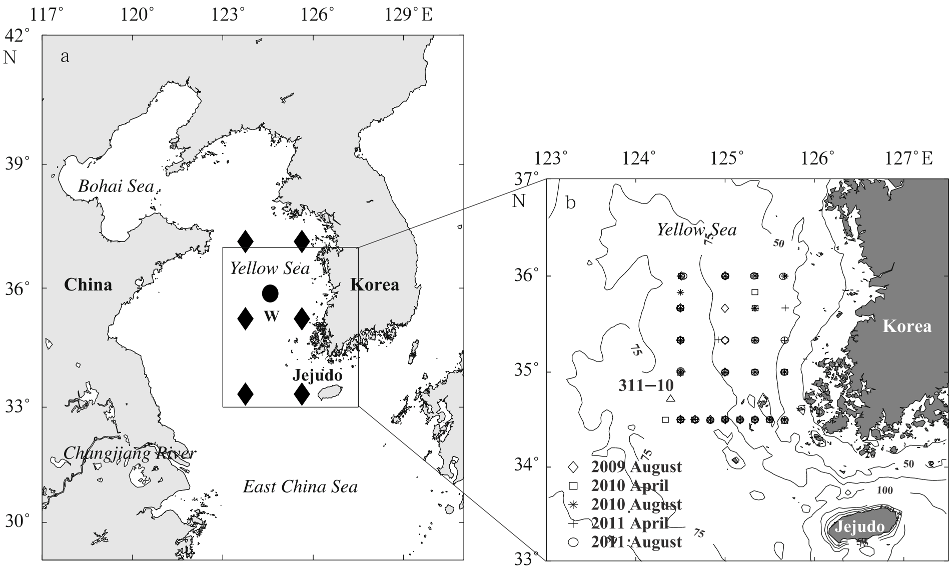

Fig.1. Study area with positions of wind stations (diamonds and circle) (a) and CTD stations for the five surveys by the KIOST during 2009–2011 (b). Hydrographic data for 1990–2010 at Sta. 311–10 (triangle) were obtained from the KODC. Depth contours are shown in meters in b.

cus in summer. Therefore, the understanding of the factors' influencing the YSCWM is the key to understanding variations in the YS marine environment. In this study, we examine the temporal and spatial variability of the YSCWM mainly using the hydrographic observation data collected in the southeastern YS during the period, 2009–2011.

2 Data

Five hydrographic surveys were conducted in the southeastern YS by the Korea Institute of Ocean Science and Technology (KIOST) using the R/V *Eardo* (see Fig. 1) in April and August during the period 2009–2011 (Table 1). The observation area in Fig. 1b does not cover the whole area of the YSCWM. This area, however, is the important area for the studies of the YSCWM because that it is the pathway connecting the YS and the ECS. Lie et al. (2009) show that the intrusion of warm and saline water from the ECS to the YS forms a tongue-shaped thermohaline front in the south of the study area in the winter season when the northerly wind prevails over the Yellow and East China Seas (YECS). A well-developed tidal front is usually detected in this study area from spring to autumn. The tidal front of north-south direction is formed between the deep central area and the shallow coastal area where a strong tidal current vertically mixes the whole water column (Lie, 1989).

Table 1. Summary of the CTD surveys in the Yellow Sea by KIOST during 2009–2011

Observed date	R/V	CTD	Station
August 5–9, 2009	Eardo	SBE 911 plus	14
April 15–17, 2010	Eardo	SBE 911 plus	21
August 17–20, 2010	Eardo	SBE 911 plus	21
April 9–12, 2011	Eardo	SBE 911 plus	23
August 9–12, 2011	Eardo	SBE 911 plus	21

Table 2. Bimonthly mean temperature and salinity at Sta. 10 of Line 311 from the KODC

	Feb.	Apr.	Jun.	Aug.	Oct.	Dec.
Mean temperature/°C	8.42	8.28	8.92	9.94	9.97	11.34
Mean salinity	32.94	32.93	33.01	32.99	33.13	32.85

The observations of this study focus on April and August. In April, the sea surface warming is initiated by the increase in a solar radiation, leading to the spring bloom of phytoplankton. In August, the YSCWM is distinctly restricted to the bottom layer by the strong thermocline (Uda, 1934). The information provided at each seasonal observation point is very similar to that shown in Fig. 1b. For consistency within the conductivity-temperature-depth (CTD) measurements in the YS, surveys were completed within 4 days and the stations were within 50–80 km from each other (Chu et al., 1997). We also analyzed the CTD data from the Korea Oceanographic Data Center (KODC) collected from 1990 to 2010 in the southeastern YS. These KODC data are bimonthly (i.e., every two months) from February to December. Two types of wind data are used here. (1) The simulated wind data of 3 hour interval using the high resolution weather research and forecast (WRF; Skamarock, 2005) model. The wind simulation performed on a domain covering East Asia including eastern China, Korea and Japan with (1/5)° grid spacing on a 211×211 horizontal grid with 27 vertical levels and a model top at 50 hPa. The initial and lateral boundary conditions were obtained by adding perturbations to the National Centers for Environmental Prediction (NCEP) "Final" analysis (FNL; see online at http://dss.ucar.edu/datasets/ds083.2). (2) the monthly mean satellite wind data from the NCEP/department of energy reanalysis 2 (NCEP2) represented by diamonds in Fig. 1a.

3 Spatiotemporal variations in water properties

3.1 *April*

Generally, the water column in early spring in the YS maintains the general features of the winter season and is almost vertically homogeneous from the surface to the bottom due to the strong vertical mixing induced by the strong northerly wind (Lie, 1984, 1985). The northerly wind prevails over the YS from late November to early April (Yuan and Su, 1984). It is intensified in February and fades away in April in this region (Kawai, 1998). In April 2010, the distribution of the seawater properties in Fig. 2 shows the typical features of early spring. The seawater with temperature less than 9°C and salinity in the range of 32.6–32.7 occupies the study area. The horizontal distributions of the temperature and salinity in the surface and at 50 m depth are almost similar due to the vertical mixing. Temperature shows a decreasing trend from south to north, whereas the salinity is almost uniform over the whole study area.

In April 2011, however, the distributions of temperature and salinity are quite different to those in 2010 as seen in Fig. 3. In the surface layer, the temperature and the salinity increase from east to west, and relatively high temperatures and high salinities compared with those in 2010 are present in the central trough around 34.5°N. At the depth of 50 m, warmer and more saline water (over 10°C and 34.0) is present along the 75 m isobath in the YSCT. This water at the depth of 50 m has higher temperature and salinity than the surface layer and expands to north of 35°N.

The temperature at 50 m depth in 2011 is colder by about 0.5–1.0°C than that in 2010 in the northern area of 35°N, but is higher by approximately 0.5–2.0°C in the southern area of 35°N. Similarly, the salinity in 2011 is lower by about 0.2 than that in 2010 in the area northern of 35°N, but is higher by approximately 0.4–1.4 in the area south of 35°N. In other words, the water properties in 2011 have larger spatial variability.

This distribution pattern of warm and saline waters in 2011 is slightly different from the general features of spring. The tongue-shaped water mass (T >10°C, S >33.5) mainly follows the topographic contours of the YS between 33°N and 35°N, 122°E and 124°E and generally exists until April (Zhang et al., 2008). This tongue-shaped front band is lopsided to the western flank of the trough west of 124°E (Lie et al., 2009). Lin et al. (2011) also mentioned that the YSWC exists on the western side of the YSCT. In 2011, however, the warm and saline water extends eastward to the YSCT between 34.5°N and 35°N, 124.5°E and 125°E. In the southern area, the water at 50 m depth is warmer than the surface water, and the temperature profile shows a reverse structure. In fact, the warmer lower layer water is more saline and eventually becomes denser than the cold surface water and is thought to have originated from waters, the warmer and more saline YSWC.

3.2 *August*

In general, high-temperature and low-salinity water resulting from the increase and solar radiation and expansion of the Changjiang diluted water (CDW) toward Jeju Island is distri-

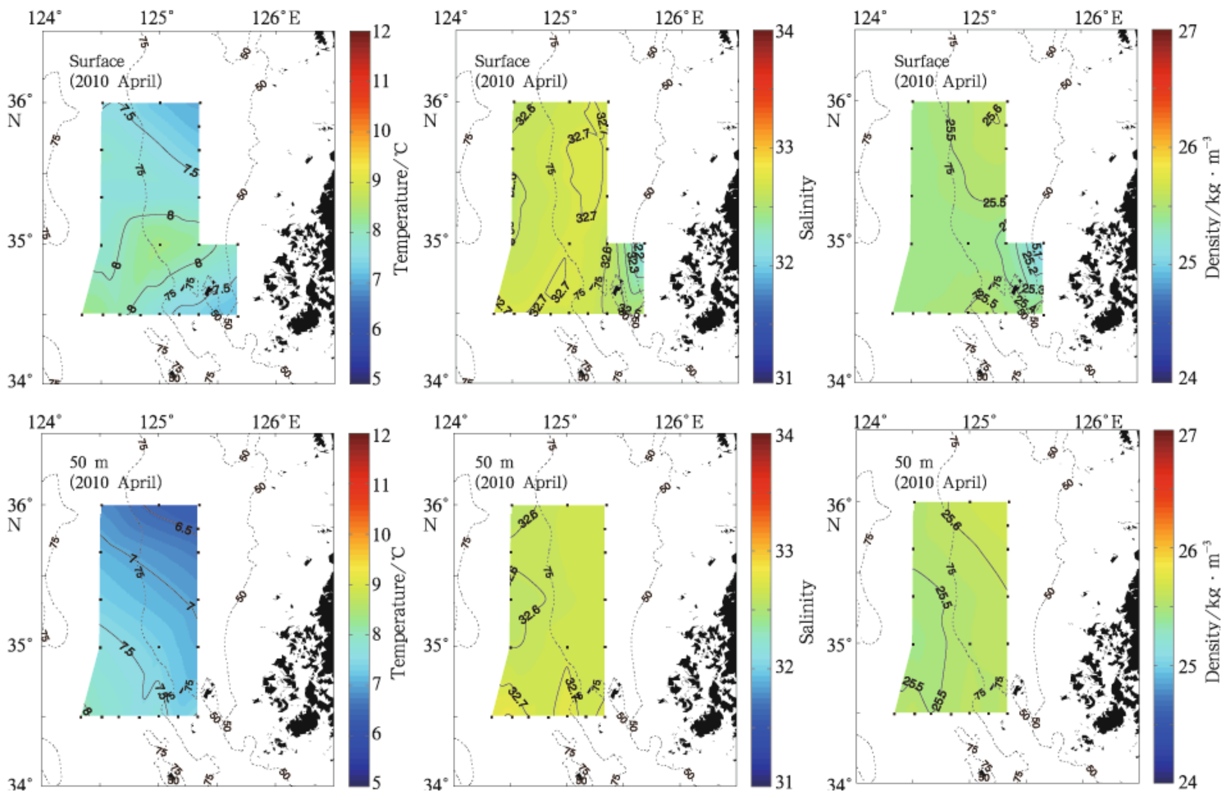

Fig.2. Horizontal distributions of temperature, salinity, and density on the surface and 50 m depth layer in the southeastern Yellow Sea in April 2010. Dots denote CTD stations. The contour interval is 0.5°C, 0.1 and 0.1 kg/m^3, respectively.

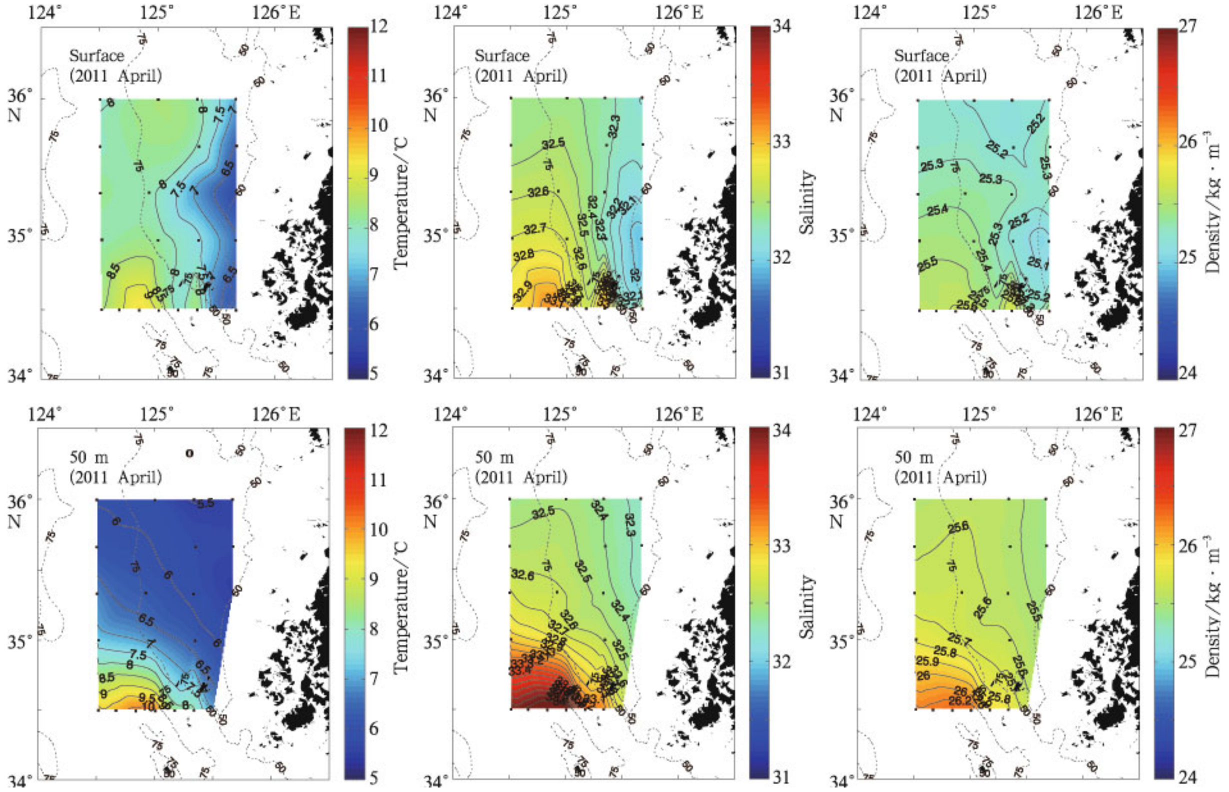

Fig.3. Horizontal distributions of temperature, salinity, and density on the surface and 50 m depth layer in the southeastern Yellow Sea in April 2011. Dots denote CTD stations. The contour interval is 0.5°C, 0.1 and 0.1 kg/m^3, respectively.

buted in the surface layer of the YS in the summer season. In the bottom layer, on the other hand, the YSCWM is dominant water and exists in the YSCT (Lie, 1984). Figure 4 shows horizontal distributions of temperature, salinity, and density in August 2010. The water with temperatures greater than 25°C and salinity of 31.0–32.2 occupies the central part of the surface layer. Water with relatively low salinity (31.0) appears in the area near 125°10′E, 34°30′N and believed to be part of the CDW. The water in the lower layer is generally colder and more saline than the water in the surface layer. In the 50 m layer, the YSCWM with temperatures less than 10°C and salinity of 32.6–32.8 exists along the 75 m isobath in the YSCT. The distributions of the temperature and the salinity in August 2009 (not shown here) show very similar patterns to those of 2010.

Figure 5 shows the horizontal distributions of the water properties in August 2011. Unusually cold water (colder than 21°C) occupies the surface layer. The sea surface temperature in August 2011 is over 5°C colder than the typical temperatures property in this area. Meanwhile, the salinity is just difference less than 0.5 compared with that in August 2010. This cold and saline surface event may have been caused by the effect of a passing typhoon. During the passage of the typhoon, water properties changed due to the vertical mixing by the strong typhoon winds. Conjugated satellite images also show that this cold event in the surface water continued for several days (not shown here). Typhoon-induced fluctuations in seawater properties are usually maintained for 4–5 days in the ECS (Lee et al., 2008). This survey in August 2011 was conducted on the third day after the typhoon passage.

The water in the 50 m layer in August 2011 is colder and more saline than the water in the surface layer, but is warmer and much more saline (>33.6) than the water at the depth of 50 m in August 2010. As compared with the observations made in 2010, the 2011 temperature is about 3°C lower in the YSCT, and the maximum difference of temperature is about 7°C in the coastal area. The cold water (< 10°C) only exists in the YSCT and it is limited to the area west of 125°E. The distribution pattern of salinity in August 2011 also differs from that in August 2010. Waters with high salinity (> 33.0) are present in the central part of the YS, in comparison with the value of 32.8 recorded in August 2010. The maximum salinity difference is about 1.2 in the YSCT and 0.2 in the coastal area. This is higher than the previous findings of 32.0–33.0 by Lie (1984) and less than 33.5 by Park et al. (1985) and Hur et al. (1999).

Such high salinity (> 33.0) cannot be attributed to the influence of the typhoon because the salinity in the lower layer would decrease due to the typhoon-induced vertical mixing. Therefore, we can expect that the water with higher than usual salinity already had intruded into the YSCWM region during the previous season, winter or spring.

4 Distribution of the warm and saline water

Temperature-salinity (T-S) diagrams (Fig. 6) show the relatively narrow ranges of the temperature and salinity in April 2010, indicating almost uniform water properties in the whole study area. In April 2011, by contrast, the temperature and the salinity vary more widely, and the water masses roughly consist of relatively higher temperature and salinity water and lower temperature and salinity water. This warm and saline water (with salinity over 1 higher than that in April 2010) existed in the

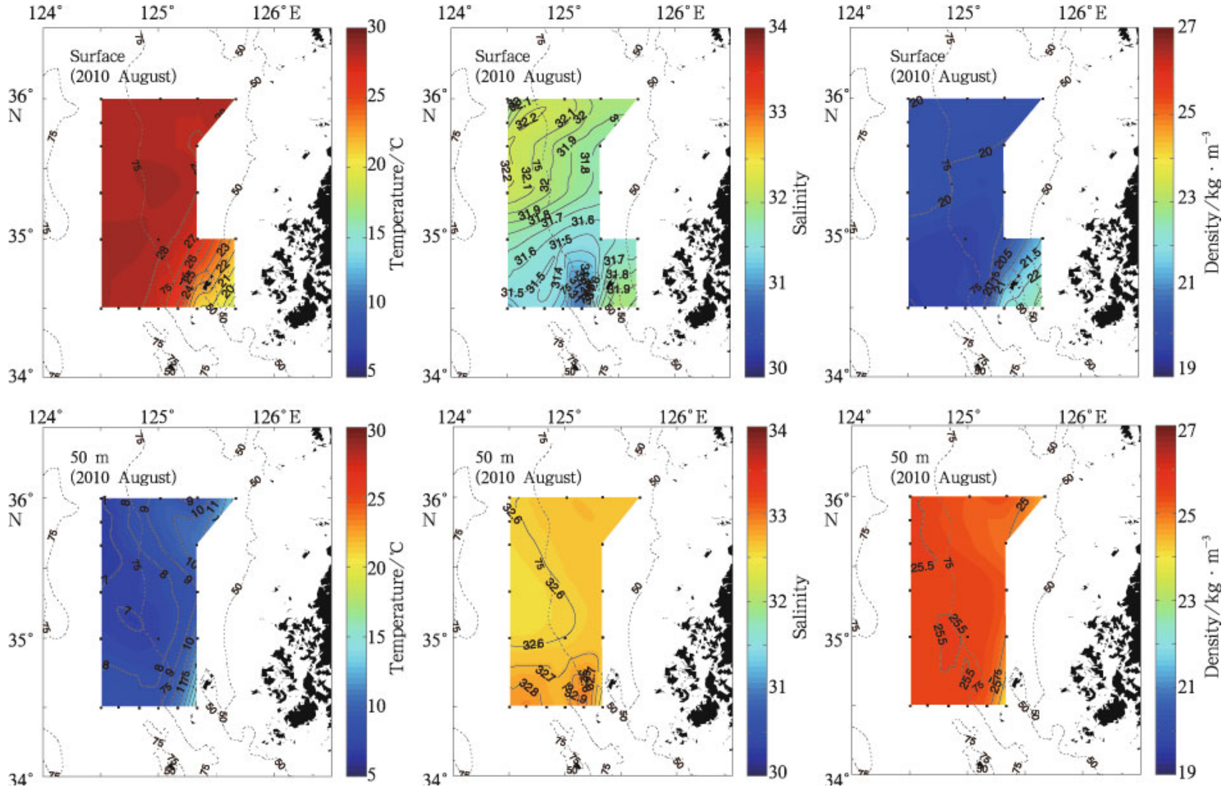

Fig.4. Horizontal distributions of temperature, salinity, and density on the surface and in 50 m depth layer in the southeastern Yellow Sea in August 2010. Dots denote CTD stations. The contour interval is 1°C, 0.1 and 0.5 kg/m^3, respectively.

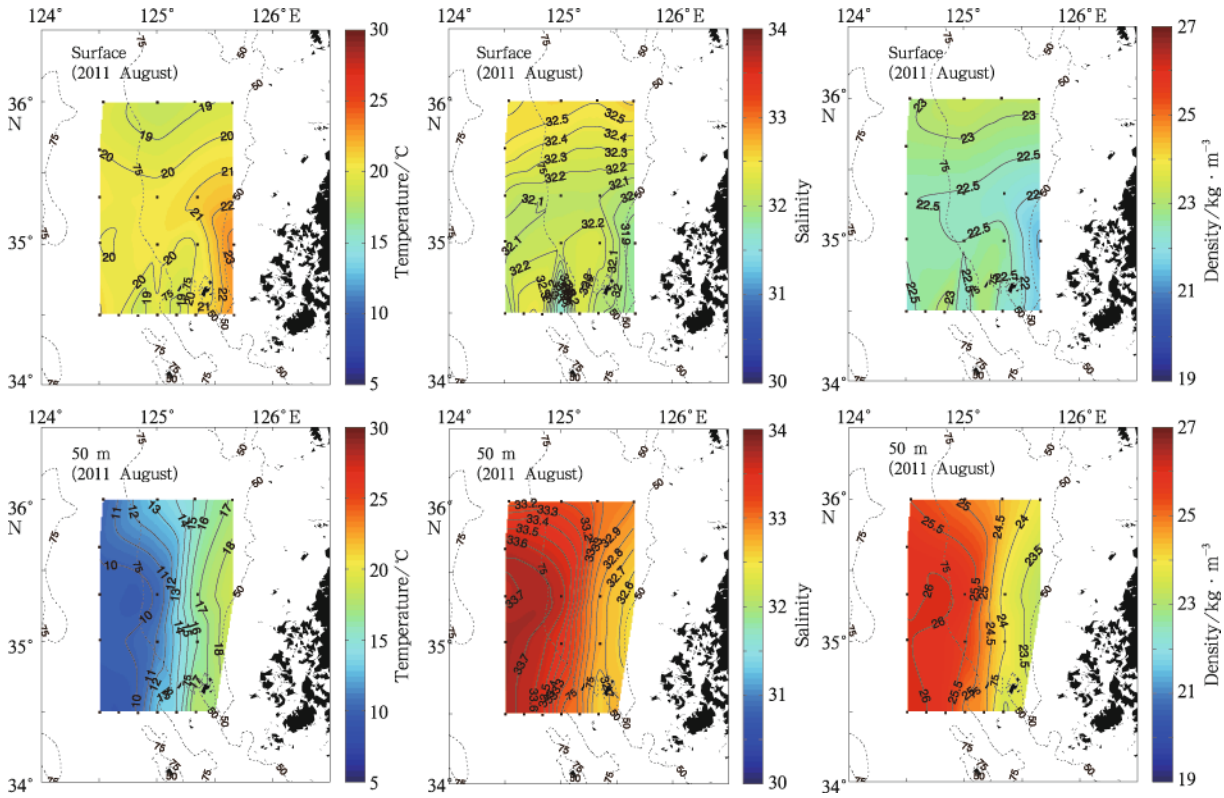

Fig.5. Horizontal distributions of temperature, salinity, and density on the surface and in 50 m depth layer in the southeastern Yellow Sea in August 2011. Dots denote the CTD stations. The contour interval is 1°C, 0.1 and 0.5 kg/m^3, respectively.

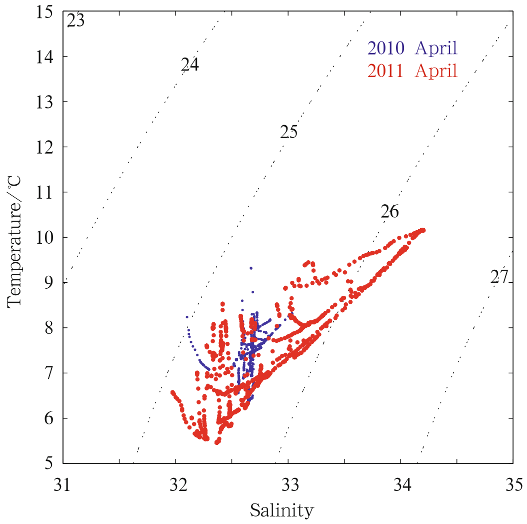

Fig.6. Temperature-salinity diagram for all CTD stations shown in Fig. 1b in April 2010 and 2011.

bottom layer of the study area. Figure 7 shows the vertical structures of the temperature, salinity, and density along the section at 34.5°N. The warm and saline water exists in the bottom layer near the YSCT (124.5°–125.0°E). The core of the warm and saline water is slightly shifted into the eastern side of the YSCT. This is different from the known pattern of the YSWC. The recent findings mention that the YSWC is located at the west edge of the YS central trough (Lie et al., 2009; Yu et al., 2009; Lin et al., 2011).

Figure 8 shows the T-S diagrams for August 2009, 2010, and 2011. The water properties in 2009 and 2010 are almost similar. Water with high temperatures (> 25°C) and low salinity (< 32.5) is found in the surface layer, and the YSCWM (< 10°C) is in the bottom layer. However, in August 2011 the surface water is much colder whereas the bottom water is warmer and more saline than that in the previous two years. This change in the temperature is attributable to the typhoon-induced vertical mixing as mentioned above. Eventually, as seen in Fig. 9, the cold water, less than 10°C with salinity over 33.5, only remained under 40 m depth near the YSCT (124.5°–125.0°E). It is remarkable that the salinity occupying the whole bottom layer in 2011 is higher than that in the previous years.

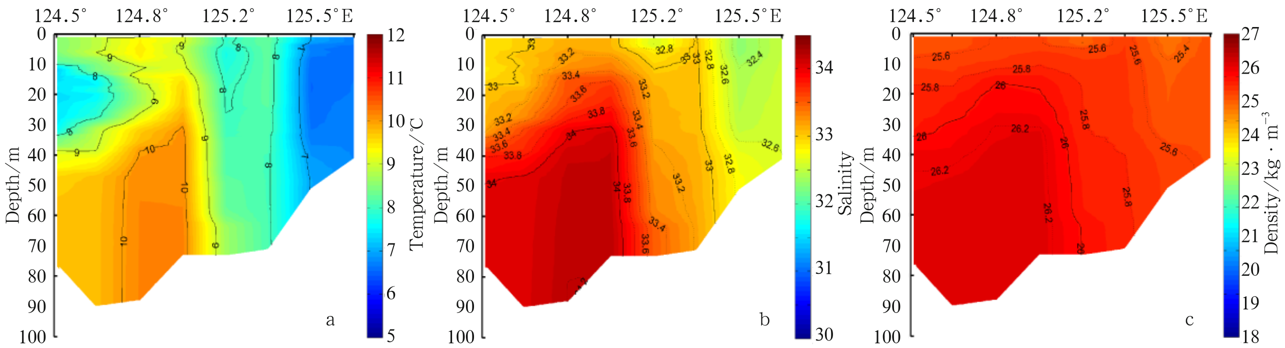

Fig.7. Vertical distributions of temperature, salinity, and density along a section at 34.5°N in April 2011. Each contour interval is 1°C, 0.2 and 0.2 kg/m^3, respectively.

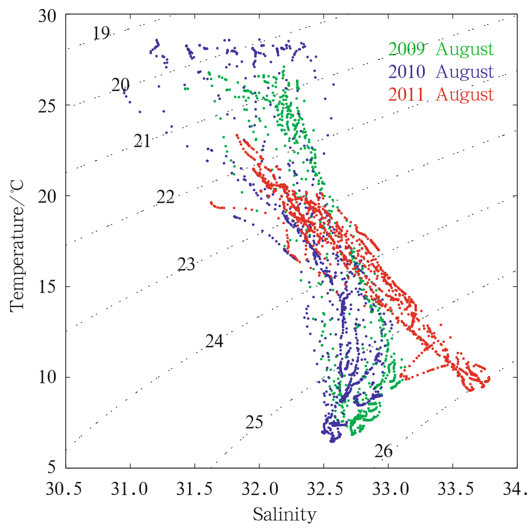

Fig.8. Temperature-salinity diagram for all CTD stations shown in Fig. 1b in August 2009, 2010, and 2011.

5 Intrusion of the saline water and variability of YSCWM

Although the observations examined here were made in April and August during only three years, the results clearly show that there was a high saline event in 2011. It may be one of the interannual variability of the YSCWM.

To examine the previous high saline events, we analyzed another subset of CTD data by the KODC during 1990–2010. Figure 10 shows the temporal variation in the temperature and salinity anomalies at the depth of 50 m at Sta. 311–10 (see Fig. 1b for the station location). In April (red line in Fig. 10), there are two saline events (the salinity over 33.8) in 1992 and 2006 during the period of 20 years. The saline trend in 1992–2006 continues in June and August (green and purple lines in Fig. 10, respectively). That is, the saline events are closely connected to each month and it is supposed that the saline water can occasionally intrude into the YS interior in spring.

We also compared the simulated wind data at Sta. W (Fig. 1a) in the central part of the YS. Figure 11 shows the time series of the daily mean north-south component of the wind data during three winter seasons: January to March, 2009 (2009 winter), January to March, 2010 (2010 winter), and January to March, 2011 (2011 winter). The mean wind speed of each season is, respectively, –3.75 m/s, –3.61–4.86 m/s. In the winter of 2011, the wind speed of northerly wind is increasing about 30% more than two winter seasons. As compared with the wind data just January to February at each season, the wind speed of nor-

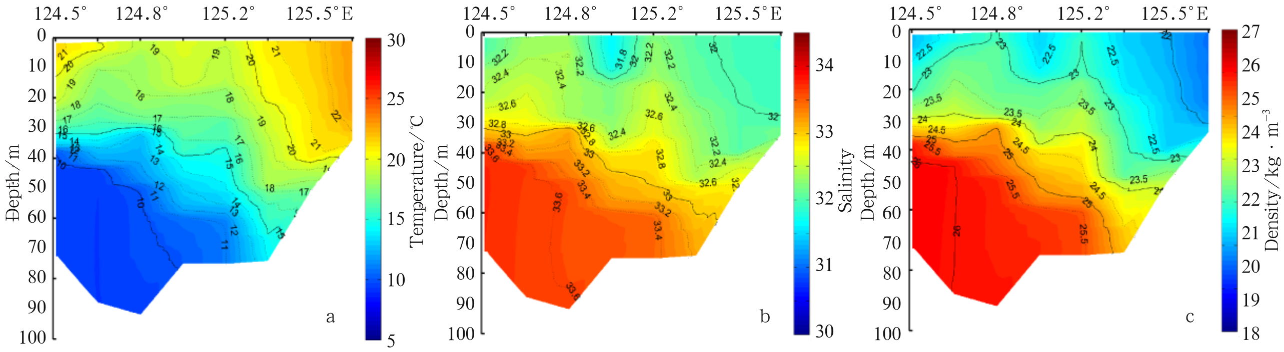

Fig.9. Vertical distributions of temperature, salinity, and density along a section at 34.5°N in August 2011. Each contour interval is 1°C, 0.2 and 0.5 kg/m^3, respectively.

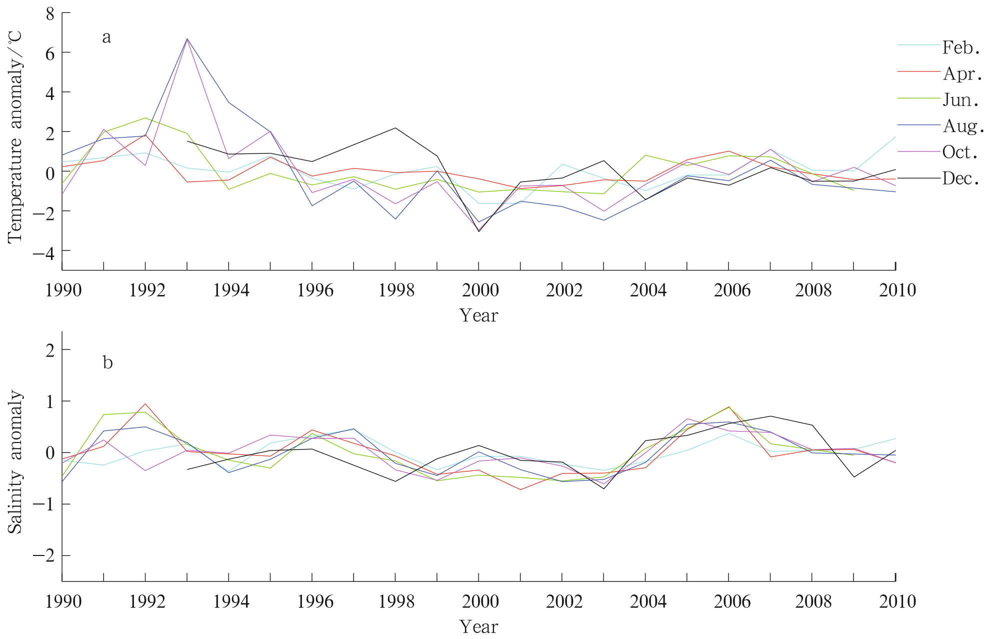

Fig.10. Bimonthly time series of temperature and salinity anomalies at Sta. 311–10 from 1990 to 2010.

therly from wind is stronger about 50% than the other seasons. The period of northerly wind is much longer than that of southerly wind. In other words, the stronger northerly wind, which dominates in 2011 winter, strengthens the northward intrusion of the warm and saline water into the YS from the ECS, which can explain the saline event in April 2011.

Figure 12 shows the correlation between the salinity at 50 m depth at Sta. 311–10 in April during 1990–2010 and the north-south component of wind data. The wind is spatially averaged over the whole YS area (at the six diamond points in Fig. 1a) and temporally averaged during January to March, the three months prior to April. The correlation in Fig. 12 means that the higher salinity in the southeastern YS area is related to the strong northerly wind during winter. The correlation coefficient is about 0.56 and the r^2 is about 0.32. Although the correlation coefficient is not high, it supports the upwind theory regarding the saline event in the YSCWM.

The results show that the intrusion of the warm and saline water by the northerly wind causes variations in the YSCWM in the southeastern YS. First, the spatial distribution of the YSCWM is dependent on the intrusion of the warm and saline water. In August 2010, the YSCWM occupies the 50 m depth layer throughout almost the entire study area in the southeastern YS as shown in Fig. 4. In August 2011, however, the YSCWM is limited to the southwestern side of our study area in the YSCT between 34.5° and 35.5°N, 124.5° and 125°E, (see Fig. 5). Second, the characteristics of the YSCWM are closely related to the intrusions of warm and saline water of the previous winter season. In August 2011, the lower layer water has a unique water characteristic. The salinity of the water colder than 10°C in the study area is higher than the well- known feature of the YSCWM (see Fig. 8).

It is difficult to clearly define the variability of the YSCWM in this study. The YSCWM, however, is obviously influenced from the movement of the warm and saline YSWC. The previous studies have shown annual variations in the YSCWM (Cho,

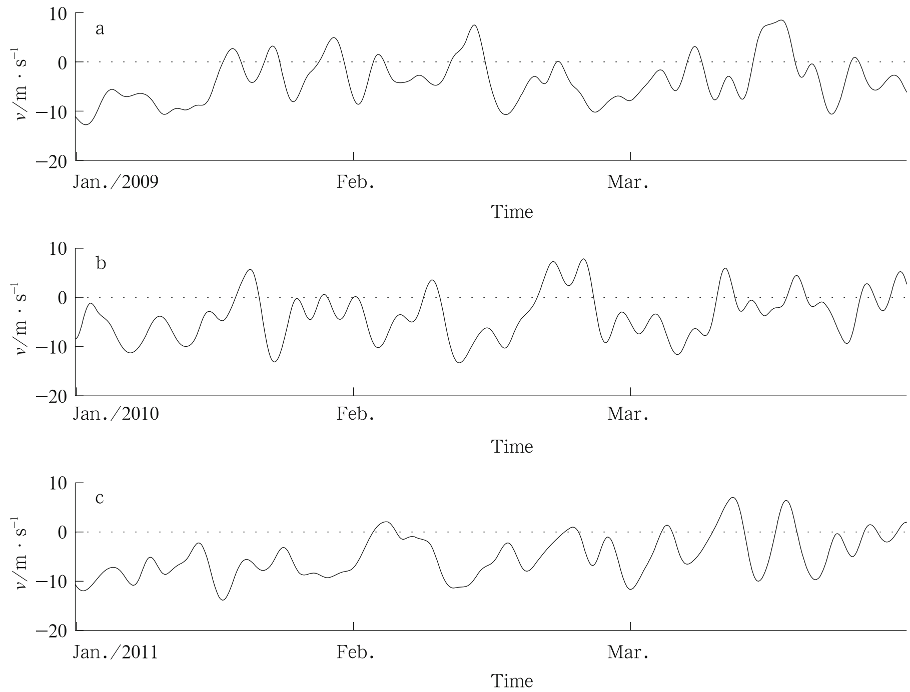

Fig.11. Daily mean of the north-south component (v) of wind speed at Sta. W in Fig. 1a during the three winter seasons: January 2009 to March 2009 (upper), January 2010 to March 2010 (middle), and January 2011 to March 2011 (lower).

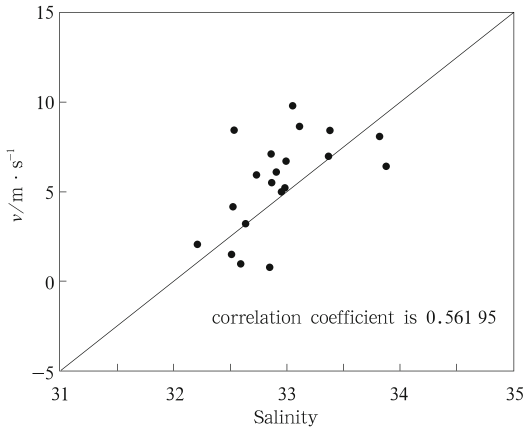

Fig.12. Scatter diagram of salinity shown in Fig. 10 and the north-south component of NCEP2 wind data. The wind data are averaged from the six points denoted by diamond symbols in Fig. 1a for the period 1992–2010.

1982); this period of variation is much longer than that in any other water masses in the YS (Su and Weng, 1994). Park et al. (2011) analyzed the interannual variation of the YSCWM using KODC temperature data and identified three cold events (1967–1971, 1983–1988, and 1996–2008) and two warm events (1972–1980 and 1990–1995) during the period 1967–2008. The saline event in 1992 (see Fig. 10) coincides with the warm events described by Park et al. (2011), but the saline event in 2006 coincides with a cold event.

6 Discussion and conclusions

We investigated the spatio-temporal variability in the YSCWM in the southeastern YS using hydrographic observation data collected during 2009–2011 (with a subset of the hydrographic data collected by the KODC during 1990–2010) and available wind data. A distinct warm and saline event occurred in the southern part of the YS in April 2011 due to the intrusion of warm and saline water from the ECS. This warm and saline event was also detected in the lower layer of our study area in August 2011. The warm event in the bottom layer is related to the vertical mixing by a typhoon that passed over the study area several days before the observations. The saline event in the bottom layer, however, cannot be explained by the typhoon-induced vertical mixing. It can only be explained by the influx of saline waters. There is no known about the inflow of the saline waters along the YS central trough in the lower layer from the ECS to YS in summer. We, however, can infer the mechanism of the saline event from the previous reports. The YSWC is inflow the YS in winter along the western side of the YSCT (Lin et al., 2011; Lin and Yang, 2011; Yu et al., 2009), and the remnant of the Yellow Sea Warm Current Water in winter remains in the YSCT (Lie et al., 2001). The YSCWM in summer season is determined by the weather conditions of the previous winter season (Guan, 1963; He et al., 1959; Jang et al., 2011; Kang and Kim, 1987). In such dynamics, the YSWC is the only source of salt for the YSCWM from the ECS. Therefore, we can expect that the saline event in the bottom layer in August 2011 was induced by the saline water intrusion from the ECS during the previous winter and spring.

The strong northerly wind, that dominates the YS in winter, is considered to be a main driving force of the warm and saline water intrusion into the YS. This northerly wind generates the upwind flow moving northward from the ECS to the YS (Lie et al., 2009; Lin and Yang, 2011b). Hsueh (1988) suggested that northerly wind pulses in the winter monsoon give rise to the northward current bursts along the deep region of the YS.

Lie et al. (2001) stated that the YSWC is not a persistent mean current and suggested that the northerly wind induces the intermittent northward flow along the YSCT. Yu et al., (2009) also mentioned that the YSWC is strongly influenced by cold wind surges in the upper layer in winter but remains quite stable near the bottom layer. The wind data show that the northerly wind in 2011 winter season was much stronger and lasted for longer than that in the previous two winter seasons. It reveals that saline events are induced by the strong northerly wind in winter. The reason of the strong northerly wind in 2011 winter season could be confirmation by the variation of the Arctic Oscillation (AO) index. In the winter of season, the AO index shows the strongest negative index during the recent decades. The high correlation between the winter sea surface temperature over the YS and the ECS and the AO index reported recently (Jang et al., 2011; Park et al., 2011).

The hydrographic data for 1990–2010 show that the several saline events occurred in the lower layer in April at 4 to 10 years intervals in the southeastern YS. This means that there is a distinct interannual variation in the lower layer water and it affects the variability of the YSCWM in summer. Park et al. (2011) reported that the warm/cold events of the YSCWM are closely related to the atmospheric variability in the western north Pacific and East Asian area. The saline events in this study, however, do not exactly coincide with the warm/cold events detected by Park et al. (2011) because of the difference in the mechanisms involved. The saline event of the YSCWM is directly related to the saline water intrusion from the ECS, whereas the warm/cold event is a result of heat exchange between the sea surface and atmosphere.

The details of the spatio-temporal dynamics of the YSCWM are still unclear because of limitations of our observations, which covered only a three year period (2009–2011) in the southeastern area of the YSCWM, and cruises were conducted only in April and August. In spite of the limitations, we can suggest that the salinity and temperature of the YSCWM are closely related to the atmospheric variability on the sea surface. In other words, variations occurring due to global climate change can affect the characteristics of the YSCWM. The YSCWM plays an important role in determining ecosystem change in the YS (Kang and Kim, 2008; Song et al., 2007; Wang et al., 2003). Therefore, an investigation of the interannual variations in the YSCWM using the numerical models would be an important future study for understanding the marine environmental response by long-term climate change.

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