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Southwestward Intrusion of Korea Strait Bottom Cold Water Observed in 2003 and 2004

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Abstract – Hydrographic surveys were carried out four times in the western channel of the Korea Strait in March and August 2003 and in June and November 2004. The bottom cold water, which was lower than 10°C, appeared in the channel trough except in March 2003. It flowed southwestward along the shelf of Korean coasts in August 2003 and in November 2004. The width and the maximum speed of the intrusion current were about 20 km and approximately 25 cm s^{-1}, respectively, off Ulsan, Korea. The volume transport of the bottom cold water was estimated 0.019 Sv (Sv≡ 10^6 m^3 s^{-1}) in August 2003 and 0.026 Sv in November 2004.

Key words – Korea Strait Bottom Cold Water, intrusion, ADCP, bottom current, Tsushima Current

1. Introduction

The Korea Strait is located in the southwestern corner of the East Sea, which is a semi-enclosed marginal sea of the northwestern Pacific Ocean. The strait connects the East Sea with the East China Sea and is the only route for warm current to enter the East Sea. The strait, about 140 km wide with an average depth of approximately 100 m, is divided into two channels by the Tsushima Island. In its western channel, there is a trough deeper than 200 m, where the surface and middle waters are occupied by the Tsushima Warm Current Water. Although both the surface and bottom temperatures change seasonally, the water temperature near the bottom varies inversely to the temperature of the surface water; it is warm in winter and cold in summer (Yun *et al.* 2004).

A number of studies have reported the bottom cold water in the Korea Strait (Nishida 1926; Cho and Kim 1998; Chang *et al.* 2004). In summer, the bottom cold water intrudes into the trough over the sill (139 m deep) between the Ulleung Basin and the Korea Strait (Lim and Chang 1969; Lim 1973; Yun *et al.* 1992; Yun *et al.* 2004). Generally, the Korea Strait Bottom Cold Water (KSBCW) is defined as the water mass of lower than 10°C appearing in the western channel of the strait (Lim and Chang 1969; Lim 1973; Cho and Kim 1998). The origin of the water is the East Sea Intermediate Water, rather than the East Sea Proper Water (Cho and Kim 1998; Yun *et al.* 2004). The sub-tidal southwestward velocity of the KSBCW is approximately 5–15 cm s^{-1} near the coast of Korea (Lim 1973). Park *et al.* (1995) introduced a hydraulic model to study the flow dynamics of the cold water and showed that the sloping sea floor to the Korean coasts makes the cold water only appear over the continental slope away from the trough of the strait. Cho and Kim (2000) insisted that the KSBCW is important to branch the East Korean Warm Current from the Tsushima Current.

Johnson and Teague (2002) reported the results of monitoring the Korea Strait with an array of bottom-mounted acoustic Doppler current profilers (ADCP) with temperature and pressure sensors for 11 months (1999–2000). They did not find a yearly cycle of the KSBCW in its appearance with a maximum temperature in summer and a minimum temperature in winter. They observed sustained intrusions of the cold water in May and June and again in December and January. They also noted that the advective intrusion of the bottom currents from the

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East Sea to the Korea Strait occurred only on a daily-averaged scale, not on a monthly-averaged scale. Their results did not agree with the seasonal variation of KSBCW (Lim and Chang 1969).

On the other hand, Takikawa *et al.* (2005) analyzed the Tsushima Current estimated from ferry boat ADCP data in the Korea Strait. They found the deep countercurrent, considered as an advection of the KSBCW, from April to January with two maxima in September (16 cm s^{-1}) and December (12 cm s^{-1}) at the center of the trough in the western channel. Park *et al.* (1999) also observed the deep countercurrent in winter from Dec. 9, 1995 to Jan. 17, 1996. However, water temperature data was not included in their studies.

Therefore, the intrusion of the KSBCW should be reconfirmed and studied quantitatively. In this study, we analyzed oceanographic data obtained from the southwestern East Sea from 2003 to 2004, including the western channel of the Korea Strait, to investigate detail structure and transport of the KSBCW intrusion.

2. Observations

Four oceanographic surveys were conducted in the southwestern East Sea, including the western channel of the Korea Strait, by the Korea Ocean Research and Development Institute (KORDI) in March and August 2003 and June and November 2004 (Fig. 1). Temperature, salinity, and current were measured using a CTD (conductivity-temperature-depth) sensor (SBE911plus, Seabird Electronics, Inc., Bellevue, WA) and a vessel-mounted ADCP (acoustic Doppler current profiler) (Teledyne RD Instruments, San Diego, CA, 150 kHz), respectively, on the R/V Eardo. CTD castings were carried out from the surface to 2~5 m above the seabed to detect the bottom cold water. Temperatures and salinities were averaged by 1-m interval. Currents were measured and averaged by every 8 meters. Current data taken too close to the bottom were rejected because of contamination by the strong bottom echo (RD Instruments 1996). The ADCP used had a 30° transducer beam angle oriented from the vertical. Therefore, current data were obtained 85% of the total range.

In the Korea Strait, tidal flows are the dominant current activities (Park *et al.* 1999; Takikawa *et al.* 2003). Thus, to eliminate tidal currents, we selected a line across the Korea Strait from Ulsan to the southeast, 24 nautical miles in length. Measurement of current speed was made on four roundtrips in a 25-hour period along the line with a ship speed of 8 knots and 7 min of turning time at the end of the line. We completely surveyed the currents, except in March 2003. At that time, we performed only two roundtrips because of bad weather. Thus, a diurnal component of the tidal currents might remain in the averaged currents along the line. We eliminated the tidal component from the current data of the four roundtrips using averages for every 0.01° in latitude interval (about 1.1 km). To secure evidence of the southwestward intrusion of the KSBCW along the strait, the averaged currents were transformed from the north to 45° to the right and divided into along-strait and cross-strait components.

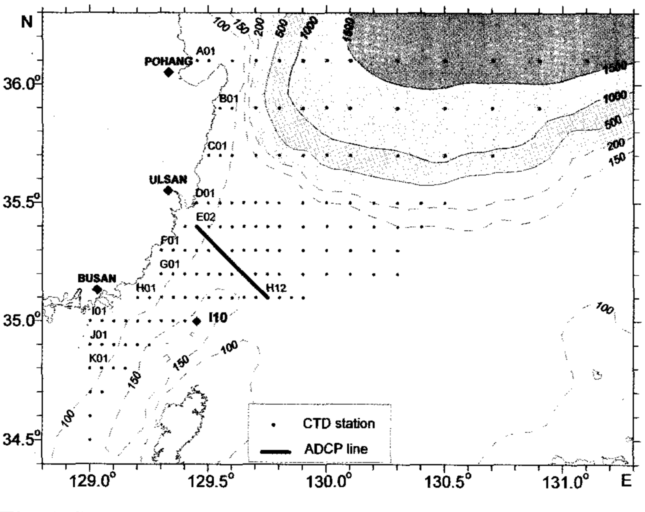

Fig. 1. Station map with bottom topography in meters.

3. Results

The characteristics of the bottom water in the middle of the western channel of the Korea Strait and the north of the Tsushima Island were examined at the station I10 by T-S curves and vertical temperature profiles (Fig. 1), in order to verify the existence of the KSBCW. Thermocline seems to persist from spring to fall, but not in winter. The KSBCW was not present in the trough in March 2003, when defined that the temperature of the KSBCW should be below 10°C (Lim and Chang 1969). The near-bottom temperature was the warmest (11.85°C) in March 2003 and the coldest (2.85°C) in November 2004 (Table 1). The variation of the bottom temperature (9.0°C) was comparable to that of the surface (11°C). The variation in

Table 1. Characteristics of surface and near bottom water at station I10 located in the trough of Korea Strait. Water depth of the station is 219 m.

	Layer	T (°C)	S (psu)	D (σ_t)
Mar. 25, 2003	Surface	14.201	34.547	25.795
	Bottom	11.849	34.237	26.026
Aug. 2, 2003	Surface	25.443	31.844	20.827
	Bottom	3.793	34.102	27.093
June 26, 2004	Surface	22.736	34.086	23.318
	Bottom	5.884	34.217	26.949
Nov. 9, 2004	Surface	21.400	34.267	23.828
	Bottom	2.853	34.107	27.186

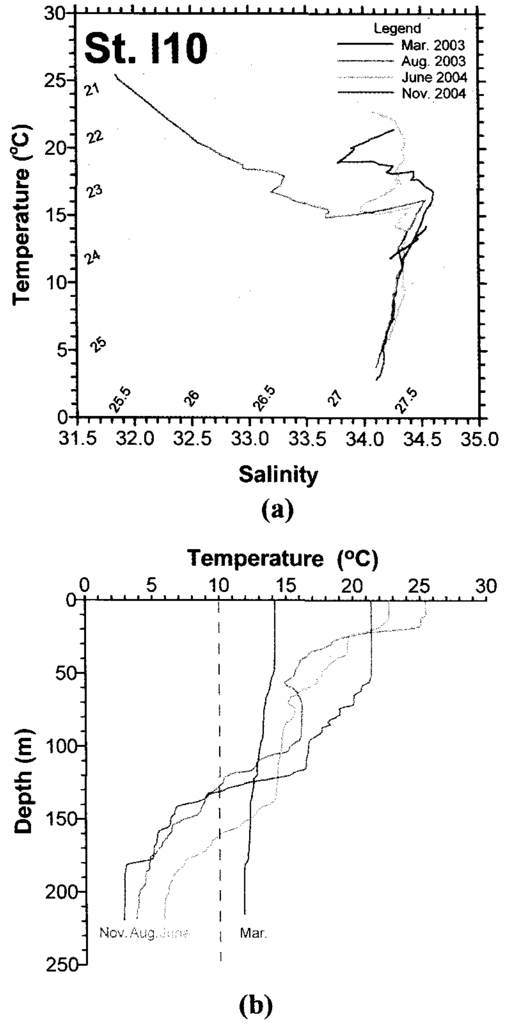

Fig. 2. T-S curves (a) and vertical temperature profiles (b) of station I10 observed in Mar. 25, 2003 (blue line), Aug. 2, 2003 (red line), June 26, 2004 (green line) and Nov. 9, 2004 (violet line).

the bottom salinity (0.1), however, was very small compared to that of the surface (2.7). Salinity was low in August and November, but high in March. The Korea Strait is the unique passage of the Tsushima Warm Current, a warm and saline branch of the Kuroshio to the East Sea (Moriyasu 1972). Thus, the bottom cold water observed at this station should be of northern, not of southern, origin.

Fig. 3 shows the horizontal distributions of near bottom temperature. The cold water below 10°C flowed over the sill of the Korea Strait except in Mar. 2003. This figure indicates that the KSBCW is originated from the East Sea as previous studies show (An 1974; Cho and Kim 1998; Lim 1973; Lim and Chang 1969; Yun *et al.* 1992; Yun *et al.* 2004). In June 2004, the cold water below 5°C did not flow into the middle of the western channel but in August 2003 and November 2004.

The residual currents are shown in Fig. 4, after elimination of the tidal currents along the ADCP line, as shown in Fig. 1. Current data near the bottom were not used because of contamination by the strong bottom echo. Except in March 2003, vertical shear of the along-strait currents was strong, and the speed was higher than that of the cross-strait; the maximum northeast current was approximately 70 cm s^{-1} in August 2003 and June 2004, which was in good agreement with findings by Teague *et al.* (2002). Opposite currents were measured in the along-strait component, except in June 2004. In March 2003, the southwestward currents were vertically homogeneous in the offshore area. In August 2003 and November 2004, however, the southwestward currents appeared near the bottom in the onshore area. The maximum speed of the southwestward current was approximately 25 cm s^{-1} in November 2004.

To examine the relationship between the southwestward currents and the bottom cold water, vertical temperature sections overlying the southwestward currents (shaded areas) are shown in Fig. 5. In March 2003, water temperatures across the section were above 10°C; therefore, the southwestward current did not indicate intrusion of the

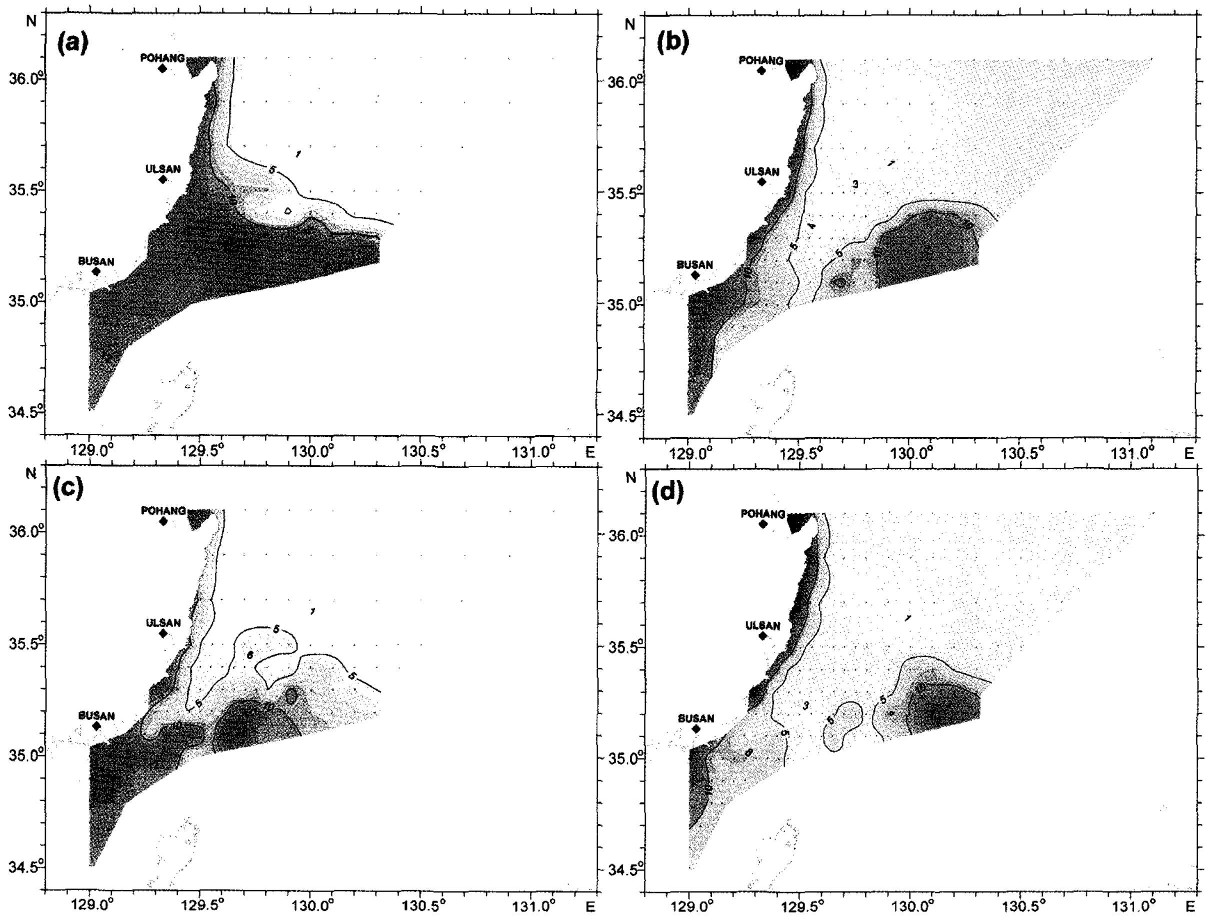

Fig. 3. The horizontal distributions of near bottom temperature observed in Mar. 2003(a), Aug. 2003(b), June 2004(c) and Nov. 2004(d).

cold water and may be considered a recirculation current of the Tsushima Current or a diurnal tidal component; this because of insufficient observation time for eliminating the diurnal component. However, in August 2003 and November 2004, an area of southwestward current appeared roughly below the 10°C isotherm. The southwestward intrusion of KSBCW only occurred over the continental slope on the Korean side of the strait, as shown in the hydraulic model proposed by Park *et al.* (1995).

It is notable that the southwestward currents did not develop in all areas below the 10°C isotherm, but only in the coldest water and around the area. This implies that the intrusion occurred around the coldest area, and that the other cold water flowed back to the East Sea. In June 2004, the near-bottom temperature was also below 10°C in onshore areas, but there was no southwestward current detected because this area of bottom cold water was very thin and the vessel-mounted ADCP current measurements were limited near the bottom.

To investigate near bottom current in dynamical calculation, we calculated geostrophic currents referred to 12 m depth. Then, the geostrophic currents were corrected by measured currents with ADCP at 12 m depth. Fig. 6 shows the vertical distributions of corrected geostrophic current speed. Bottom countercurrent was calculated in June when the bottom counter current was not observed by ADCP and November 2004. In August 2003, the counter current was very weak compared with ADCP measured current. This was the reason for the long distance between stations in the KSBCW intrusion area and other effects.

The volume transport was calculated from the corrected geostrophic current and the current data gathered along the ADCP section (Table 2). In processing the measured data, the surface and bottom current values were extrapolated from (given the same values as) the uppermost measured

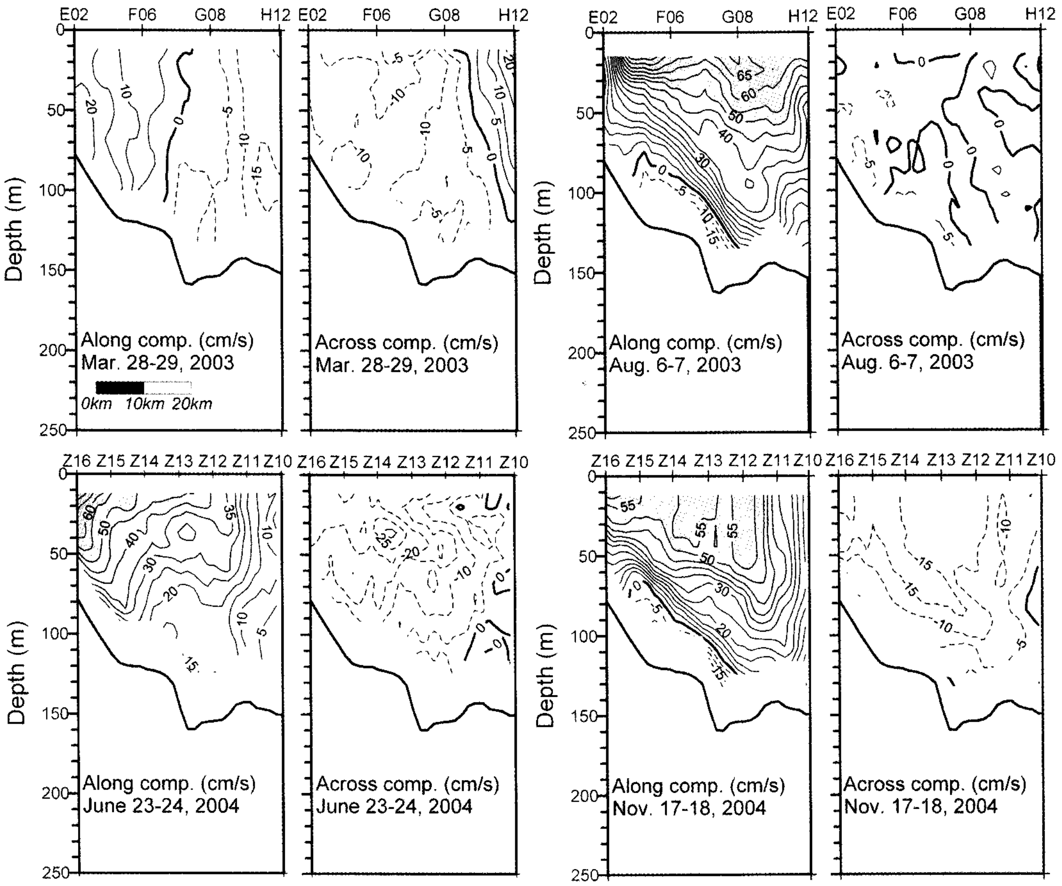

Fig. 4. Vertical sections of current which flowed along and across the channel observed in March, August 2003 and June, November 2004.

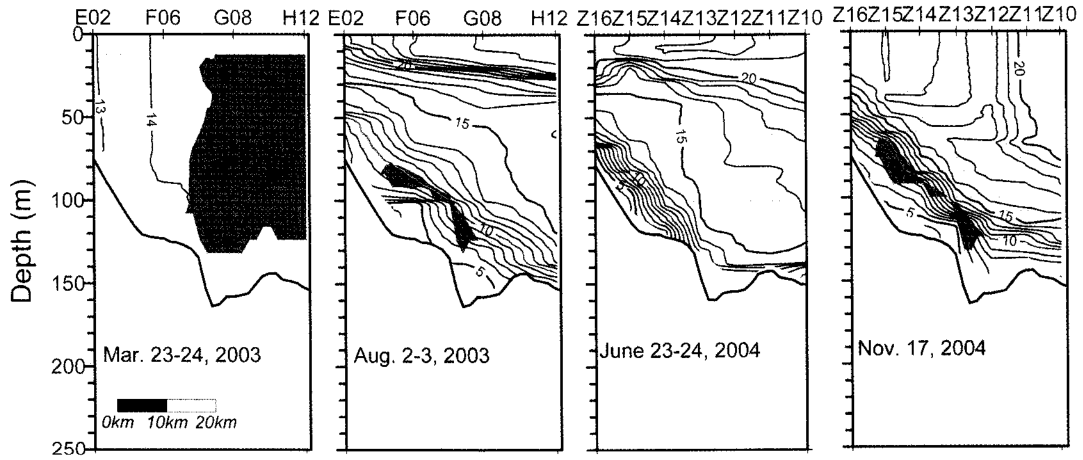

Fig. 5. Vertical sections of temperature along the ADCP line. The blue shaded area indicates that the current flowed southwestward. Red dots are data points of ADCP.

point and the lowermost data point, respectively.

Northeastward inflow transports of Tsushima Warm Current Water on the west side of the Korea Strait were greater in August (1.68 Sv (Sv 10^6 $m^3 s^{-1}$)) and November (1.49 Sv) than in March (0.19 Sv) and June (1.21 Sv) in ADCP data. Southwestward transports of KSBCW, however, were very small compared with the transport by the Tsushima Warm Current. The southwestward transport in March was not KSBCW because of the temperature above 10°C. The transport of KSBCW was 1.90 x 10^{-2} Sv

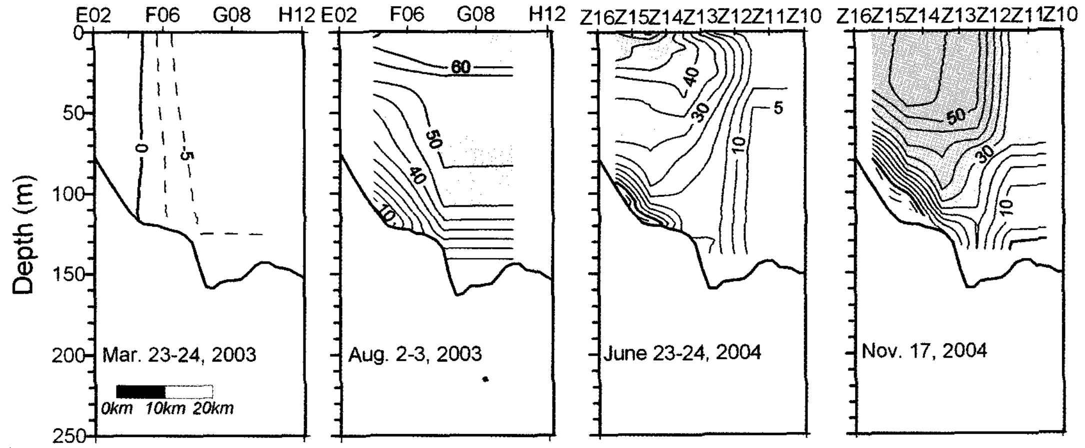

Fig. 6. The vertical distributions of geostrophic current speed (cm/s) referred to ADCP along current speed at 12 m depth along the ADCP line. Positive value indicates the current to the northeastward.

Table 2. The inflow (northeastward) and out flow (southwestward) volume transports calculated by corrected geostrophic currents and measured currents using ADCP along the ADCP line.

	Inflow (Sv)		Outflow (Sv)	
	Corrected Geostrophic	ADCP	Corrected Geostrophic	ADCP
Mar. 2003	0.139	0.185	0.142	0.207
Aug. 2003	1.980	1.675	0.051×10^{-4}	0.019
June 2004	1.477	1.207	0.012	-
Nov. 2004	1.172	1.493	0.034	0.026

in August and 2.58 x 10^{-2} Sv in November in ADCP data. These values are comparable with 1.7 x 10^{-2} and 3.2 x 10^{-2} reported by Lim (1973) and Cho *et al.* (1997), respectively. In June 2004 when the southwestward current was not observed, the outflow corrected geostrophic transport was 1.17x 10^{-2} Sv. In August 2003, however, the outflow corrected geostrophic transport was nearly zero.

Figure 7 shows the horizontal distributions of near-bottom temperatures and current vectors. Cold water with temperatures below 5°C intruded into the trough except in March and June, indicating that intrusion occurred around the coldest water and that other outside cold water flowed back to the East Sea. There was no cold water below 10°C in the trough in March. Although the cold water intruded into the trough in June, the southwestward current was not observed because of the extreme thinness of the cold-water layer relative to that in the other seasons. This implies that June is the first stage in the cold-water intrusion. The thickness of the KSBCW from the sea bottom to the 10°C isotherm was less than 25 m at station Z15 (Fig. 5). The KSBCW existed very close to the bottom, so the vessel-mounted ADCP could not detect the southwestward current in June.

The KSBCW flowed into the strait with a width less than 20 km off Ulsan in August and November (Fig. 7). The maximum intrusion current to the southwest was 20 cm s^{-1} in August and 25 cm s^{-1} in November. Although observation times differed, the intrusion currents appeared in the same location, 30 to 50 km to the southeast of Ulsan. In August and November, the intrusion area was located between the coastal ADCP mooring stations of Johnson and Teague (2002) (black triangles in Fig. 7). This indicates that the ADCP stations of Johnson and Teague (2002) were located in the boundary of the intrusion area and they missed the intrusion main current because their station interval was too wide to detect the southwestward intrusion of the KSBCW.

4. Summary and Discussion

To investigate intrusions of the KSBCW, four oceanographic surveys were carried out in the southwestern East Sea,

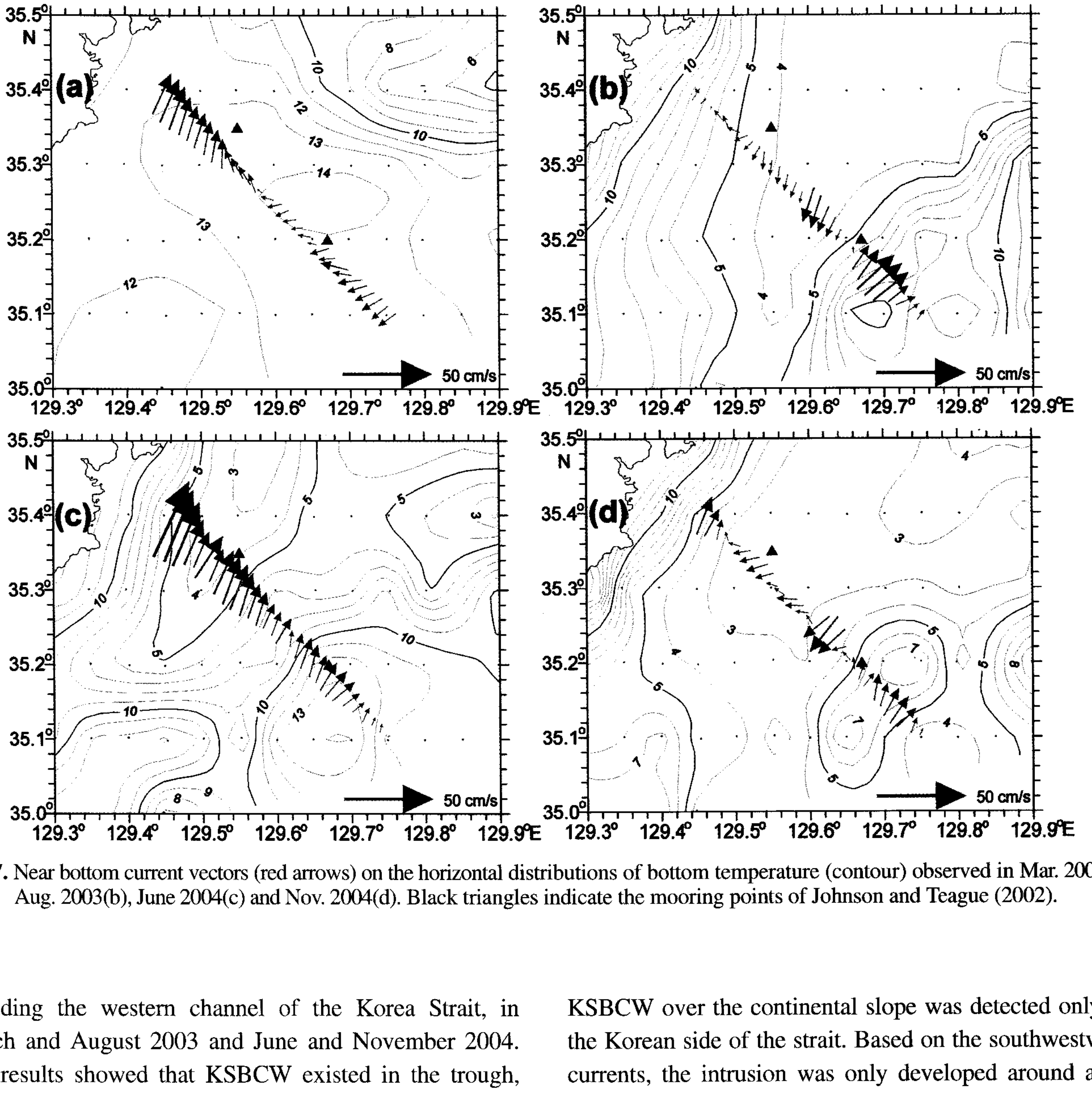

Fig. 7. Near bottom current vectors (red arrows) on the horizontal distributions of bottom temperature (contour) observed in Mar. 2003(a), Aug. 2003(b), June 2004(c) and Nov. 2004(d). Black triangles indicate the mooring points of Johnson and Teague (2002).

including the western channel of the Korea Strait, in March and August 2003 and June and November 2004. The results showed that KSBCW existed in the trough, except in March 2003. The current, corrected for tidal flow, reached a maximum of 70 cm s^{-1} to the northeast in the upper layer in August 2003 and June 2004. The southwestward current near the bottom was detected except in March 2003 and June 2004 and it flowed along the strait. In March 2003, there was no KSBCW; therefore, the southwestward current was not the intrusion of the KSBCW. In June 2004, the near-bottom temperature were below 10°C in onshore areas, but the southwestward current could not be detected because of the thinness of the bottom cold water. The southwestward current and bottom temperature were evidence that the KSBCW intruded over the sill into the trough. The intrusion of the KSBCW over the continental slope was detected only on the Korean side of the strait. Based on the southwestward currents, the intrusion was only developed around areas occupied by the coldest water, and the other cold water flowed back to the East Sea. Volume transports of the KSBCW were 1.90×10^{-2} Sv in August 2003 and 2.58×10^{-2} Sv in November 2004. Although the southwestward bottom counter current was not detected in June 2004, the corrected geostrophic current showed the bottom counter current and southwestward outflow transport. The maximum intrusion current was 25 cm s^{-1} to the southwest in November 2004. The KSBCW flowed narrowly into the strait with a width of less than 20 km off Ulsan in August 2003 and November 2004. Therefore, to detect the intrusion current of the KSBCW, station intervals would have to be less than 20 km.

Previous studies based on the analyses of historical hydrographical data show that the near-bottom temperature in the Korea Strait varies seasonally (Lim 1973; Yun *et al.* 1992; Yun *et al.* 2004). The southwestward current near bottom was observed below about 130 m in the western channel from summer to winter but was absent in spring (Takikawa *et al.* 2005). In this study, the horizontal distribution of near-bottom temperature showed a variation, that the cold water below 5°C flowed into the middle of the western channel in August 2003 and November 2004 but in June 2004 (Fig. 3). The thickness of KSBCW from the sea-bed to 10°C isotherm in June 2004 was very thin compared with other two seasons, August 2003 and November 2004 (Fig. 6). This implies that the KSBCW varies seasonally and June is the first stage of the KSBCW intrusion. However, the bottom temperature records from the moored current meter showed no obvious yearly cycle and large variance in daily averaged data (Johnson and Teague 2002). Data used in this study were obtained four times during two years. Thus, it is difficult to generalize the intrusion time in this study and it will be necessary to observe the bottom temperature and current for a long time at the point of intrusion.

To investigate current structure and transport of the KSBCW, current velocity was observed by the vessel-mounted ADCP in a 25-hour period along the line and was averaged simply to eliminate the tidal component. In the study area, the near-inertial component, which has 1.1 cycles per day, is also significant (Jacobs *et al.* 2001). The near-inertial oscillations are highly intermittent and baroclinic. Moreover, low-frequency current variability in the region could be strong enough to smear the seasonal variability according to the results of Teague *et al.* (2002). In this study, the observation periods of current were too short to eliminate long period current components. The interannual variability of KSBCW also affects both the transport variations through the Korea Strait (Lyu and Kim 2005) and the path variations of the Tsushima Warm Current (Choi *et al.* 2004). Therefore, to estimate transport and variation of the KSBCW, more detail and long term current and temperature observations are necessary.

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