Journal of the Korean Society of Oceanography
Vol. 35, No. 4, pp. 170 — 178 December 2000

Structure and Source of Low Salinity Water Observed During May in the Cheju Strait

SANG-KYUNG BYUN*
Marine Environment and Climate Change Laboratory, Korea Ocean Research and Development Institute
Ansan P.O. Box 29, Seoul 425-600, Korea

Low salinity water was observed during May in the Cheju Strait. Its structure and source were studied by using both the hydrographic data collected not only in the Cheju Strait during 1987–1989 but also in the wider area around Cheju Island extending to the Bank of Changjiang river in 1994 and the current data taken in the Strait during 1987–1989. The water had lower values of temperature, salinity, and density compared with the surrounding water and it was found in the surface layer outside of Tsushima Current Water 10–50 km off Cheju coast. The density of low salinity water was more dependent on salinity than on temperature. The low salinity water flowed into the Strait from the west as a series of intermittent waters whose size was variable in width and in thickness. The low salinity water was originated from the Changjiang River Diluted Water. In the Cheju Strait, the water showed changes within 3 days on time and 30–50 km on space, and its sudden appearance was marked especially in May. Such strong variability and sudden appearance may be attributed to the beginning stage in May when the fresh water of Changjiang River Diluted Water starts to arrive in the Cheju Strait.

INTRODUCTION

The Cheju Strait, located between the southern coast of Korean peninsular and Cheju Island, has the dimension of about 80 km in length and 50 km in width. The bottom topography shows isobaths running in the east-west direction and asymmetric bathymetry in the north-south direction. A trough deeper than 100 m is found 5–20 km off the northern coast of Cheju Island, farther distanced from the southern coast of Korea.

There have been a few works directly associated with the low salinity water in the Cheju Strait. Kim *et al.* (1991), with the hydrographic data gathered in the Cheju Strait and the southeastern part of the Yellow Sea in June of 1980 and August of 1981, found the water of salinity lower than 33.0 to extend from the area south of Soheuksan Island to the Cheju Strait as a tongue-like shape in summer. The water was considered to be rooted in the river plume over Changjiang River Bank and to move eastwards into the Cheju Strait. Chang *et al.* (1995) made an observation of low salinity core water (<33.7) located in the surface layer of the Cheju Strait during May of 1983. They speculated that the southward extension of Korean Coastal Water (KCW) might be related with the appearance of low salinity water in May. Suk *et al.* (1996) reported an observation of low salinity core water (<34.38 psu) in the sub-surface layer up to 50 m depth of the Cheju Strait on April 25, 1995 which was flowing eastwards with speed of about 10 cm/s. Recently some direct current measurements in the Cheju Strait revealed the eastward flow existing year round, and the flow was called specifically Cheju Warm Current (Chang *et al.*, 1995; Lie *et al.*, 2000; Chang *et al.*, 2000).

They are not known when and how KCW influences the waters in the Cheju Strait. At the western part of Cheju Strait and near the eastern entrance of the Yellow Sea, the horizontal distribution of historical hydrographic data shows a strong thermohaline front existing in winter (NFRDI, 1998). The front might be formed in winter when the alongshore cold current driven by prevailing northerly wind encountered the warm water advected from the south by Tsushima Current (Seung *et al.*, 1996). The front was believed to play a role of wall in suppressing the water exchange over that area. This front becomes

*Corresponding author: skbyun@kordi.re.kr

to disappear and the water starts to freshen at sea surface as time goes on from February to April and June.

Most research works on hydrography near Cheju Island were based on the data of temperature and salinity which National Fisheries Research and Development Institute (NFRDI) of Korea had collected bimonthly in even months, e.g., April and June for spring season, as a serial oceanographic observation at predetermined stations. Although the data has contributed to revealing the general distribution of water masses and their circulations, there is still the uncertainty of low salinity water because of its high variability in May. In this study, I tried to describe the structure of low salinity water observed in May in the surface layer of the Cheju Strait and to clarify its possible source, with the help of current data.

DATA AND METHODS

For studying on the low salinity water appearing in the Cheju Strait in May, the data of temperature, salinity, and current measured by CTD and Aanderaa currentmeter were used. The main part of data was collected during the first half of May in 3 consecutive years of 1987, 1988, and 1989. They were used to form 10 sections as shown in Fig. 1. Hydrographic measurement was repeated with the interval of 3 days on 4 lines located near the northeastern Cheju coast in May, 1987 and on a line located in the middle part of Cheju Strait in May, 1989. Temperature and salinity collected during May 4–9, 1994 were also used in order to trace the source of low salinity water in wider area around Cheju Island (sampling location marked in Fig. 10). Because of strong homogeneity in the surface layer due to seasonal heating, the depth of 20 m was selected for demonstrating horizontal distributions of salinity. Some detailed informations of the data used in this study were summarized in Table 1 including the mean values of current averaged over the whole period of measurement.

RESULTS

Structure of low salinity water in the Cheju Strait

Fig. 2 shows the values of temperature and salinity observed in the Cheju Strait during May 1987, 1988, and 1989. It shows temperatures range between 12°C and 18°C and salinities between 32.6 and 34.6. Tsushima Current Water (TCW) originating from the Kuroshio is well known to be the source of high tem-

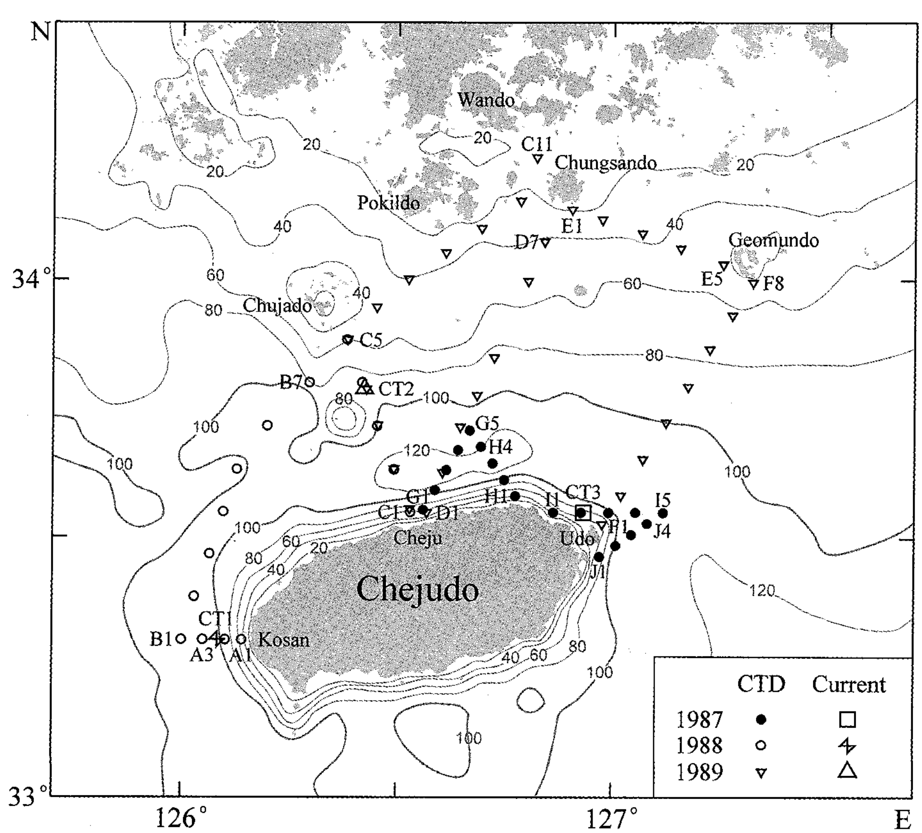

Fig. 1. Map of stations in the Cheju Strait in May 1987, 1988, and 1989 with bottom depth.

Table 1. Summary of data set for
(a) hydrography and

Period		Occupied Line	Area	Instrument
Year	Date			
1987	May 12	G, H, I, J	Western part of Cheju Strait	CTD
	May 15	G, H, I, J	"	"
1988	May 11	A, B, C	Eastern part of Cheju Strait	CTD
1989	May 4	C	Western part of Cheju Strait	CTD
	May 7–9	C, D, E, F	"	"
1994	May 8–14		Wide area around Cheju Island	CTD

(b) current with mean speed and direction

Period		Measuring/Total Depths	Speed		Instrument
Year	Date (Duration)		Mean (cm/s)	Direction (°)	
1987	May 1215 (68 hrs)	20/93	3.7	120	RCM
		70/93	6.6	48	"
1988	May 511 (142 hrs)	15/103	5.7	338	RCM
		50/103	5.2	350	"
		90/103	2.5	5	"
1989	May 49 (124 hrs)	20/100	10.8	76	RCM
		80/100	4.6	63	"

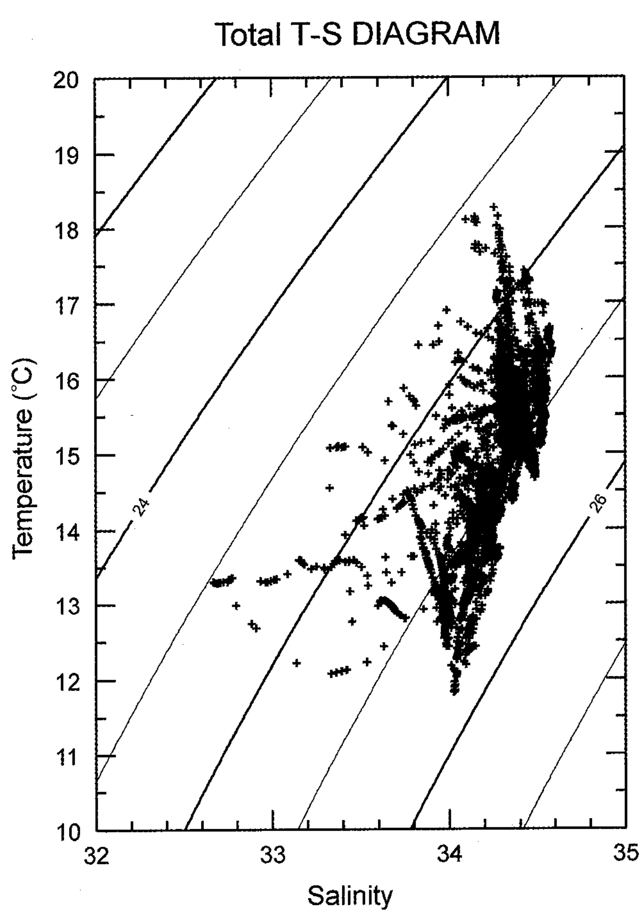

Fig. 2. T–S diagram of data in the Cheju Strait in May 1987, 1988, and 1989.

perature and high salinity in the study area (Byun and Chang, 1988). In this figure the water having temperature higher than 15°C and salinity higher than 34.0 was considered as the TCW. There appeared a water whose salinity was lower than 34.0 with temperature lower than 15°C. We call it low salinity water (LSW) in May for the study.

Fig. 3 is the vertical profiles of temperature, salinity, and density measured on May 12 and 15, 1987 in the section G which was in the middle part of Cheju Strait. TCW of high temperature and high salinity was found in the area of stations G01-G02 (near Cheju coast). During the first cruise of May 12, the LSW of salinity lower than 34.0 psu occupied the surface layer and it formed a front of salinity against TCW. This LSW had the characteristics of low temperature and low density as well. The density of LSW was dependant mainly on salinity rather than on temperature. At station G03 where LSW was thicker than at the other stations, the lowest temperature (<13°C) was seen at the depth of 10–20 m as a core part and this core water of lowest temperature was not necessarily corresponding to the water of lowest salinity (<33.4). The LSW seemed to be confined within 30 m depth from the sea surface. Three days later, however, this LSW disappeared from the section G. The water in the surface layer showed the characteristics of the TCW of high temperature and high salinity. In the horizontal distrib-

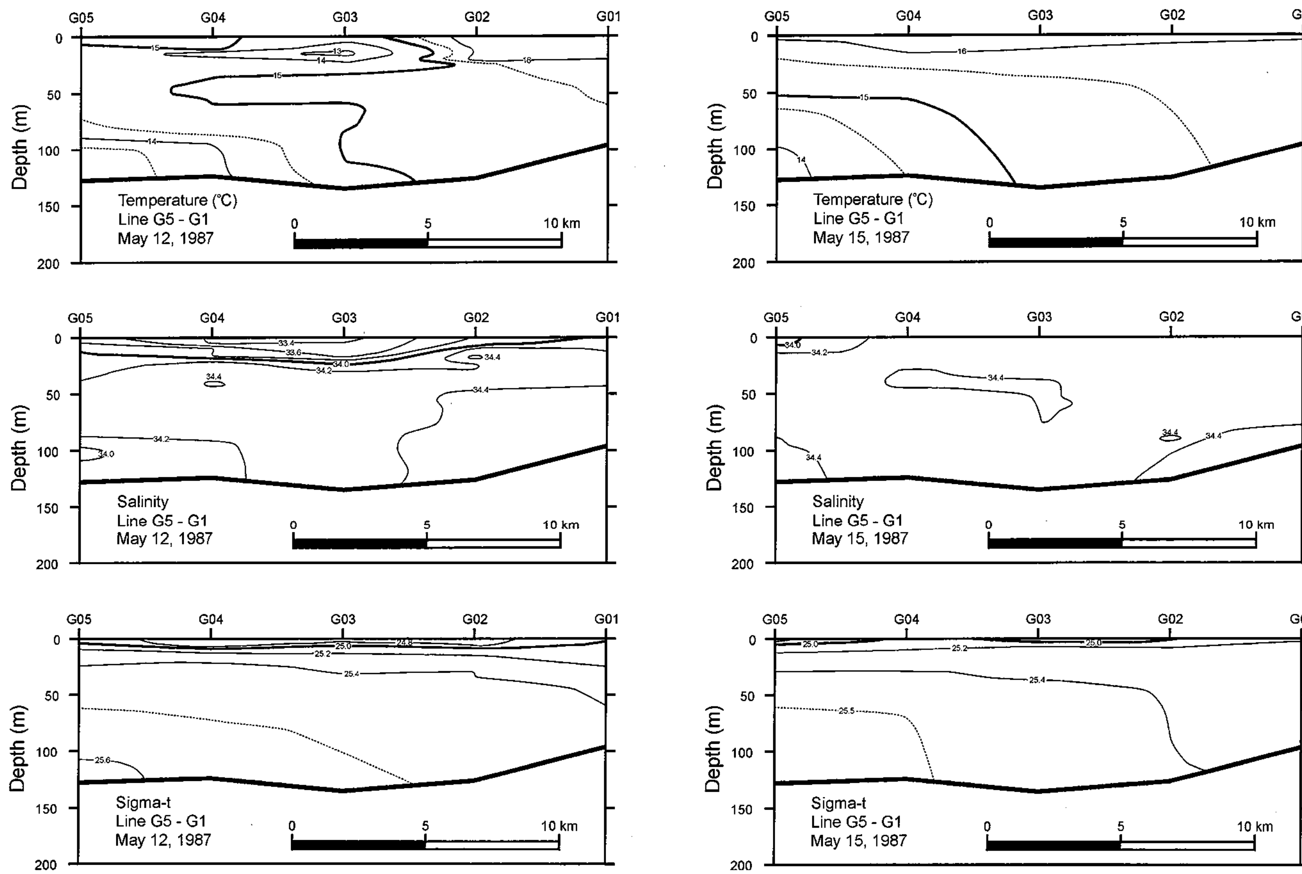

Fig. 3. Vertical profiles of temperature, salinity, and density in the section G on May 12 and 15, 1987.

ution of salinity at 20 m depth (Fig. 4), the LSW was seen on May 12, 1987 at a small region off Cheju coast. After 3 days the LSW disappeared and was replaced by the high salinity water. We saw an increase in salinity at whole area.

Fig. 5 shows the vertical profiles of temperature, salinity, and density obtained on May 11, 1988 in the section B which was situated at the western entrance of Cheju Strait. The LSW with minimum salinity value reaching 32.8 psu at station B06 was found in the surface layer outside of the TCW. There was thermo-haline front formed in the surface layer between TCW and LSW. Because of low density which was much influenced by salinity as in 1987 (Fig. 3), the LSW was introduced above the water of relatively high salinity and high density as a shape of bowl floating in water. The width of LSW was about 30 km and its thickness was about 30 m. This LSW appeared also at the section C although its size became smaller as shown in the horizontal distribution of salinity at 20 m depth in Fig. 6. In the region within about 20 km from Cheju coast there existed TCW of salinity higher than 34.0 psu. The LSW was considered to exert its influence eastwards. The eastward movement of LSW could be seen also in direct measurements of current as in Table 1.

In Fig. 7 are shown temperature, salinity, and density on May 4 and 9, 1989 in the section C running through the middle part of Cheju Strait. The general feature of water distribution maintained except slight decrease in temperature and salinity during 5 days. On May 4 there was found LSW in the surface layer at station C04 with temperature inversion at the depth of 10–30 m. Five days later the LSW still existed at stations C03–C04 and its core part moved southwards from stations C04 to C03. This LSW showed low temperature of 13–15°C and it was localized outside of the TCW situated near the Cheju coast as shown in 1987 and 1988 (Figs. 3 and 5). This section was also occupied partly in the previous year (sectional profile not shown here). In 1988 the core of LSW was observed at the sea surface of station C03 with the value lower than 33.2 psu and the LSW was found in the surface layer of wider area to the north of station C03. But in 1989 LSW with salinity lower than 34.0 psu appeared on smaller area of the section

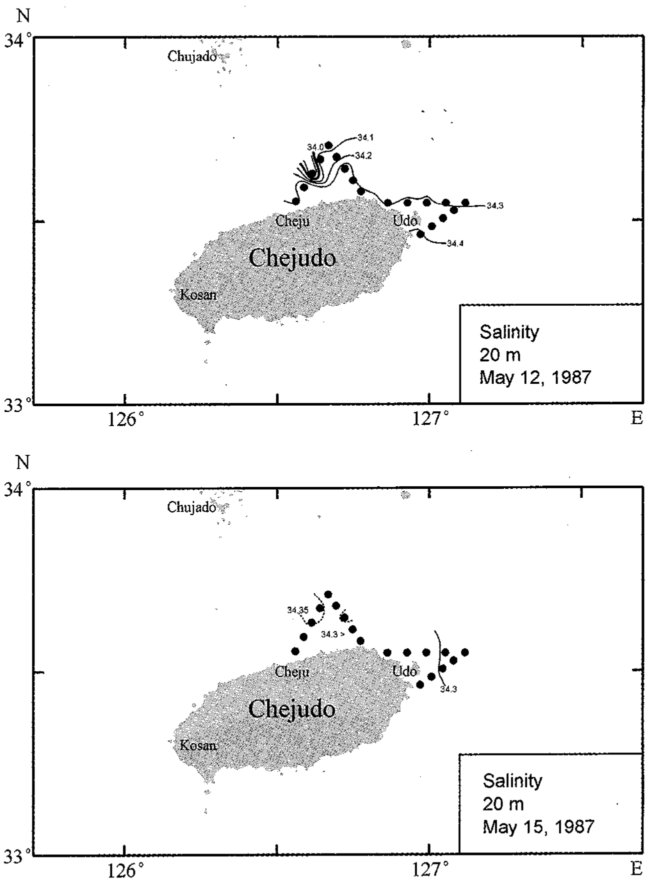

Fig. 4. Horizontal distribution of salinity at 20 m depth on May 12 and 15, 1987.

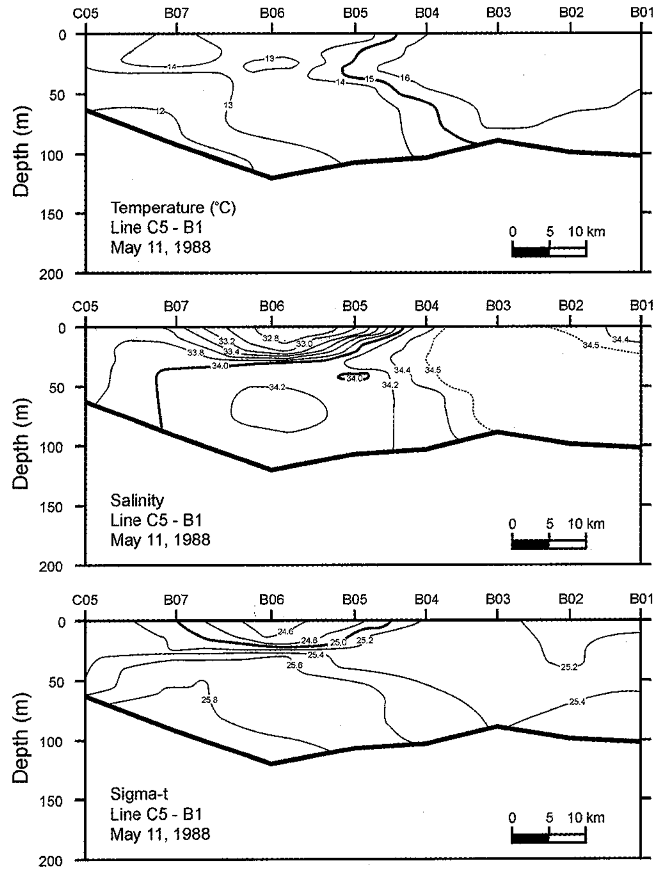

Fig. 5. Vertical profiles of temperature, salinity, and density in the section B on May 11, 1988.

than in the previous year. From Fig. 8 showing the distribution of temperature, salinity, and density on May 7, 1989 in section D which was located in the middle part of Cheju Strait, we can see also the core water of salinity minimum lower than 34.0 at about 25 m depth of station D04 in reduced size. If comparing with section G surveyed in 1987 (Fig. 3), we can notice that in 1989 the core part of LSW was found 15–20 km off to the northeast from station G03. The horizontal distribution of salinity at 20 m depth is shown in Fig. 9. The lowest salinity was found along the northern flank of trough (100 m isobath) and its value increased eastwards. The LSW seemed to be confined only in the central part of the Strait, not in the whole area. The current measurement as summarized in Table 1 showed the LSW flowing toward the east. The results for the location of LSW and the measurement of current can give an interpretation for an eastward flow of LSW along the deep trough of Cheju Strait.

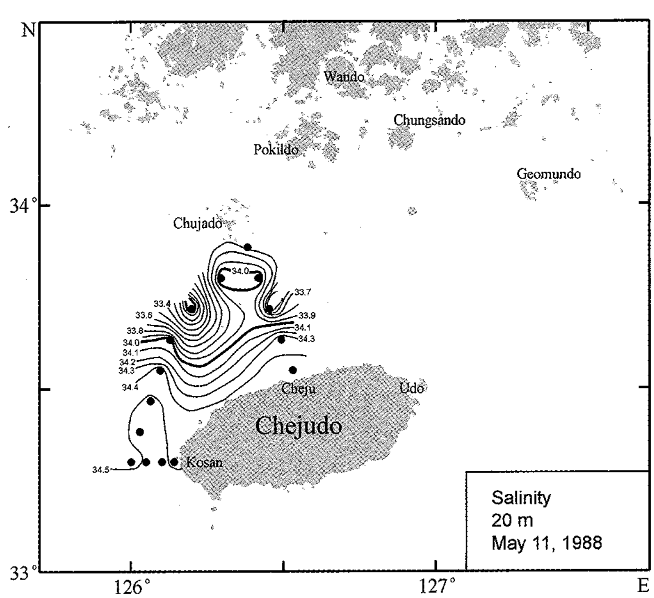

Fig. 6. Horizontal distribution of salinity observed at 20 m depth on May 11, 1988.

Source of low salinity water in May

In order to investigate the origin of LSW which appeared in the Cheju Strait especially in May, the

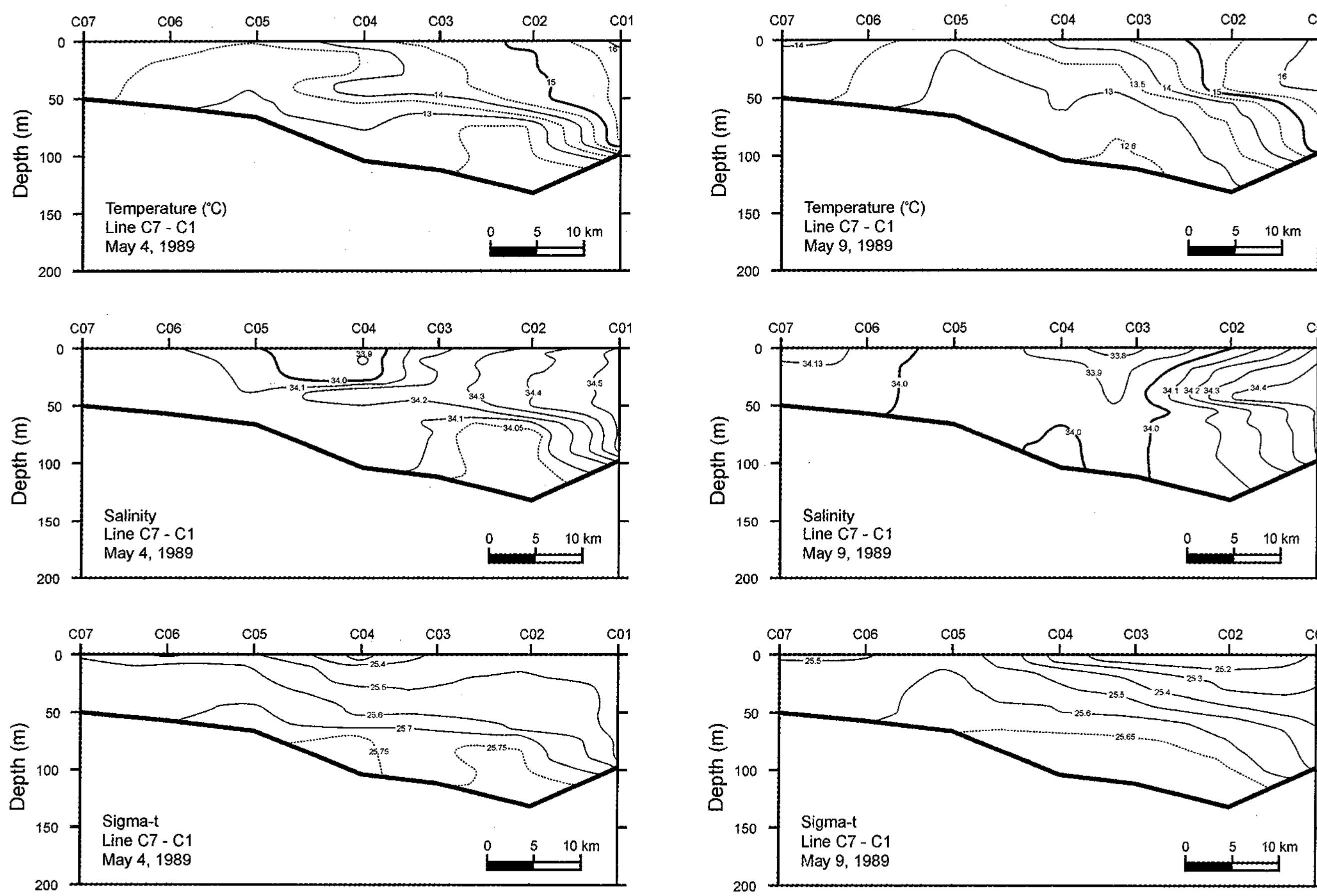

Fig. 7. Vertical profiles of temperature, salinity, and density in the section C on May 4 and 9, 1989.

salinity data collected in wider area was examined. Fig. 10 shows the horizontal distributions of temperature, salinity, and density at the depth of 20 m during May 8–14, 1994. The survey area was extending to cover the whole Cheju Strait to the north, the mouth of Changjiang river to the west, and Soheugsan Island to the northwest. We can find 3 different waters from the figure: TCW in the southeastern part of survey area, Changjiang River Diluted Water (CRDW) in the southwestern part, and KCW in the northwestern part. In the southwest of Cheju Island, salinity front between TCW and CRDW was formed and it ran through the Cheju Strait toward the northeast. To the eastern side of this front, high temperature of the TCW was found in wide area. In the region of 125.5–126.0°E the salinity front was coincided with the thermal front. Those two fronts of salinity and temperature were not shown in the density distribution because of compensating effect. To the west of 125.5°E there was an another salinity front formed between CRDW and KCW at 33.0–33.5°N. This front was not clearly shown in the temperature distribution. From the distribution of salinity in the Cheju Strait we can see two core waters of low salinity centered at 33.6°N, 126.0°E and 33.7°N, 126.5°E respectively. The LSW appeared like a series of eddies and they had a diameter of 40–50 km. This water showed salinity lower than 33.6 psu, temperature lower than 14°C, and the density lower than 25 sigma-t. Those characteristics of LSW are similar to the values which we already found during the measurements of 1987, 1988, and 1989 (Fig. 2). In Fig. 10 we can realize that at the location where LSW was found the temperature and density showed also low values as seen in 1987, 1988, and 1989 (Figs. 3, 5, 7, and 8). Considering the water of lowest salinity found at the southwestern part of survey area, the LSW appearing in the Cheju Strait can be traced for its origin as far as to the mouth of Changjiang river.

The spread of CRDW toward the Cheju Strait in spring was also detected by the distribution of suspended sediment. Fig. 11 is the satellite image of suspended sediment constructed from SeaWIFS ocean color data of April 14, 1999 after Ahn *et al.* (1999). In general, the distribution of suspended sediment shows a very similar pattern to that of salinity seen

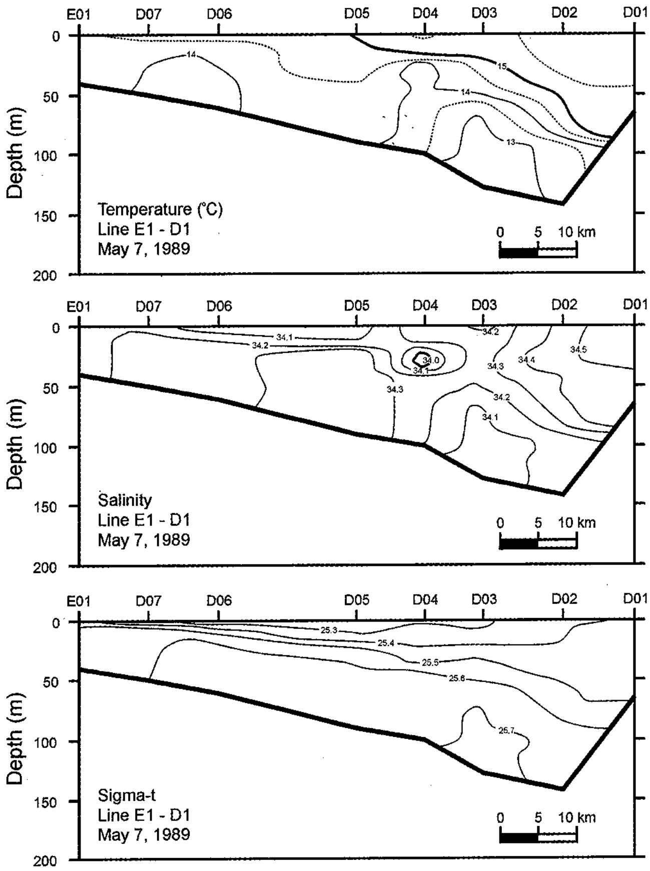

Fig. 8. Vertical profiles of temperature, salinity, and density on May 7, 1989 in the section D.

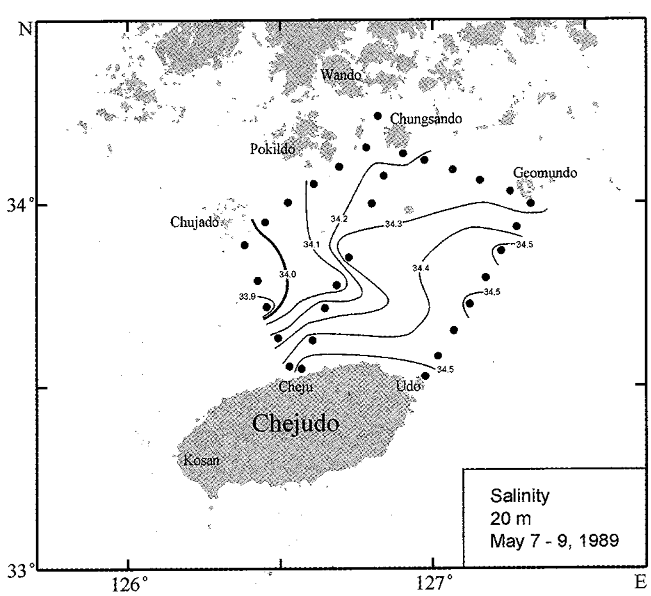

Fig. 9. Horizontal distribution of salinity observed at 20 m depth during May 79, 1989.

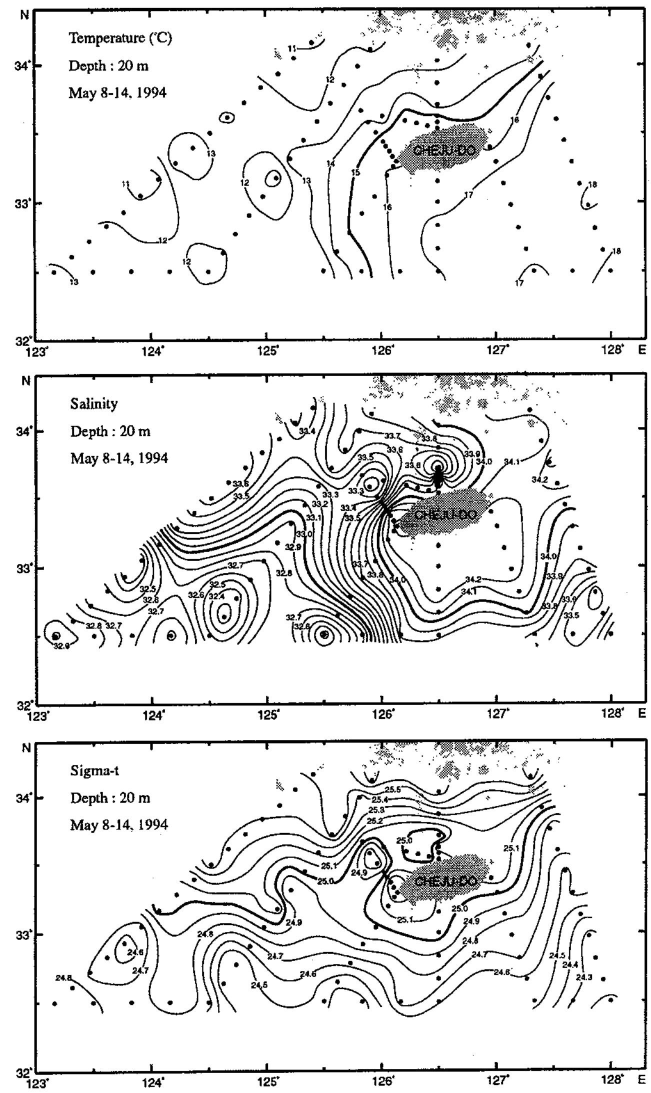

Fig. 10. Horizontal distributions of temperature, salinity, and density at 20 m depth during May 8–14, 1994.

in 1994 (Fig. 10) even if they were measured at different time. Turbidity formed two fronts to the south and to the west of Cheju Island where salinity also showed the fronts. Highly turbid waters was found not only near the mouth of Changjiang river but also near the southwestern coast of Korea. The former, originated from the discharged Changjiang river water which was mixed by local tide, showed the turbidity higher than the latter known to be formed by tidal mixing. They were separated each other in the Cheju Strait by less turbid water. The former, with a range of 10–25 g/m^3 according to Ahn *et al.* (1999), extended eastwards as a tongue-like shape from the Chinese coast and then a part of it turned its direction toward the northeast before being introduced into Cheju Strait. The gradual attenuation of the turbidity can give a high possibility that the origin of the turbid

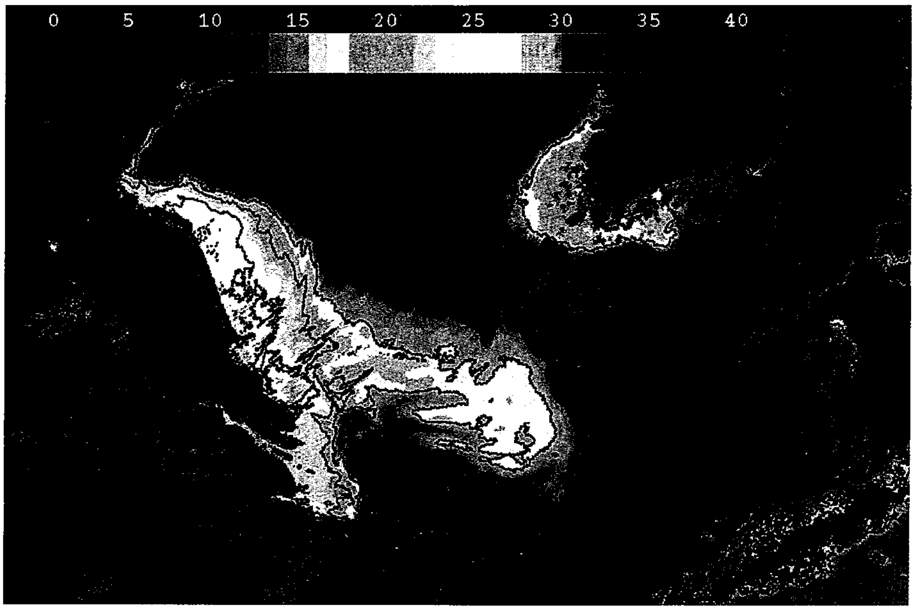

Fig. 11. Suspended sediment distribution on April 14, 1999 obtained from SeaWiFS (in g/m^3; after Ahn *et al.*, 1999).

water appearing in the Cheju Strait was from the CRDW, not from the KCW. This result coincides very well with the conclusion derived from salinity distribution as in Fig. 10.

DISCUSSIONS

We observed the LSW in the Cheju Strait in May. The LSW can be differentiated from Cheju coastal water discharged from Cheju Island because it was found 10–50 km off, not very near, the Cheju coast and appeared outside of TCW which encompasses the Island. The gradual increasing of salinity from the core of LSW toward the north suggested that the LSW was not associated with the KCW which found near the southwestern coast of Korea, i.e., in the northern part of study area.

The eastward movement of the LSW in the Cheju Strait was supported from the facts that its salinity increased from the western entrance of the Strait toward the east and the result of direct current measurements summarized in Table 1 indicated the eastward flow in the Cheju Strait. On the other hand, the hydrographic survey extending beyond the Cheju Strait to the mouth of Changjiang river showed that the LSW was originated from the CRDW. If combining two facts together, we can imagine that the CRDW extends toward the east and exerts its influence in the Cheju Strait as LSW.

The LSW showed high variability in time and in space as seen in Figs. 3, 7, and 10. With 30–50 km for the width of LSW and 10 cm/s for current speed we can estimate 4–5 days for the water to be changed in time. If considering the length of the Strait to be 80 km, we have 9 days which the LSW may take for passing through the Cheju Strait.

The historical hydrographic data in the Cheju Strait was measured mostly in even months and therefore there is the lack of works on May. We can notice, from historical salinity data (NFRDI, 1998), that in June the water of salinity lower than 34 psu covers the whole southern sea of Korea including the Cheju Strait even though in April it appears only in small area. In May we found the LSW in the Strait. Such sudden appearance of LSW can be explained by the change of wind direction and the increase of freshwater discharge. In May, the wind system is known to change its direction from north to south. Moreover, the discharge of Changjiang river increases in volume very quickly from the dry season of November–April to rainy season of May–October (Shen *et al.*, 1998). Bang and Lie (1999) noted, from a numerical experiment on the dispersion of the Changjiang river discharge, that the southerly wind was responsible for the eastward expansion toward Cheju Island rather than the variation of Changjiang river discharge and the appearance of the LSW near the Island in summer was mainly a result of Ekman transport. We can estimate 46 days for the arrival time of the CRDW to the Cheju Strait simply with 400 km for the distance from the Changjiang estuary to the Strait and 10 cm/s for average current speed of this water. The month of May is the beginning period in which the CRDW starts to arrive in the Cheju Strait as LSW. But the scarcity of salinity data collected in May cause it insufficient for depicting precisely the LSW. We need further data in order to fully understand the beginning stage of introducing CRDW into the Cheju Strait.

CONCLUSION

The LSW was observed in the Cheju Strait in May of 1987, 1988, and 1989 and also in 1994. It was found 10–50 km off the Cheju coast outside of the TCW, and it was located mainly on the sea surface, but sometimes at certain depth of the surface layer as an isolated core water. In the Cheju Strait it had temperature lower than 15°C, salinity lower than 34.0 psu, and density lower than 25.5 sigma-t. The density of LSW was more dependent on the salinity than the temperature. The low salinity water appeared as a series of intermittent waters whose size was very variable in width and thickness.

The LSW was originated neither by the KCW located near the southwestern coast of Korea, nor by the fresh Cheju coastal water found just near the Cheju coast. The eastward movement of LSW in the Cheju Strait and the horizontal distributions of salinity and suspended sediment in wider area showed that the CRDW was the source water for LSW and it exerted its influence to the Cheju Strait after extending eastwards.

The LSW demonstrated the strong variation on time scale of a few days and space scale of a few tens of kilometer. The sudden appearance of LSW was noted especially in May. The high variability and sudden appearance of LSW can give an interpretation that the month of May is the beginning period in which the CRDW starts to arrive in the Cheju Strait as LSW.

ACKNOWLEDGEMENTS

This work was supported by the inhouse research project of Korea Ocean Research and Development Institute (BSPE 00366-699-1). The author is very grateful to Mr. P.-J. Kim for drawing the figures, Dr. Y.-H. Ahn for providing the satellite image of suspended sediment, and Profs. I.-C. Pang and S.-H. Lee for the helpful comments. He also appreciate the efforts of Naval Oceanography Research Team for collecting the data of May, 1994.

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Manuscript received October 12, 2000
Revision accepted November 13, 2000
Editorial handling: Dong-Kyu Lee