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Hydrography and Sub-tidal Current in the Cheju Strait in Spring, 1983

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1983년 춘계 제주해협의 해황과 해류

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Two hydrographic surveys along with direct current measurements using drogues and moored current meters were conducted in the Cheju Strait during April and May, 1983. The data clearly demonstrate that a branch of the Kuroshio characterized by high temperature and high salinity enters the Cheju Strait after turning around the western coast of Cheju-Do. The width of the current turning west of Cheju-Do is about 60 km and reduces to 20~30 km in the strait, resulting in a high speed (>10 cm/s) at the western entrance and in the middle of the strait, compared with a low speed (<5 cm/s) west of Cheju-Do. The Tsushima Current water also originating from the Kuroshio shows its influence in the eastern part of the Cheju Strait. Thermohaline fronts formed between the warm current waters and the coastal waters suggest the southward extension of the Yellow Sea Coastal Water west of the Cheju Strait. A warming of the warm current waters occurs in May, while a cooling takes place in other areas. The major freshening and cooling of water take place in the middle of the Cheju Strait in May due to the intrusion of cold and low salinity water from the west of the Cheju Strait.

1983년 4월과 5월에 걸처 제주해협에서 부표와 해류계를 이용한 해류관측과 함께 2회에 걸처 수온-염분관측을 실시하였다. 관측자료로부터 고온, 고염인 흑조의 한 지류가 제주도 서쪽을 돌아 제주해협으로 유입됨을 명확히 보였다. 제주도 서쪽을 우회하는 해류는 제주도 서쪽에서는 그 폭이 약 60 km이며 제주 해협내에서는 20~30 km 이내에 존재하여 제주도 서쪽에서는 5 cm/s 미만으로 유속이 작은 반면에 제주해협의 서쪽입구와 해협 내에서는 10 cm/s 이상의 큰 유속을 갖는다. 제주해협의 동쪽에는 역시 흑조로부터 기원된 대마난류의 영향이 인지되었다. 난류수와 연안수사이에 형성되는 수온, 염분전선의 변화는 제주 해협의 서쪽에서 황해연안수가 남하함을 제시하였다. 난류수역에서는 5월에 수온이 상승한 반면에 다른 해역에서는 수온이 감소하였다. 5월에 제주해협 중앙부에서는 해협의 서쪽으로부터 저온, 저염의 해수가 유입되어 4월에 비해 수온과 염분이 급격히 감소하였다.

INTRODUCTION

The Cheju Strait located between Cheju-Do and the southwestern coast of Korea is relatively wide strait with its length and width about 70 km. The mean water depth in the strait is about 100 m and the isobaths run mainly parallel to the east-west direction as shown in Fig. 1. A trough deeper than 120 m exists in the southern part of the strait and the bottom topography is characterized by a rapid deepening off the coast of Cheju-Do and a slow shoaling north of the trough towards the southwestern coast of Korea.

The Cheju Strait has received much attention since Kim$_k$ (1980) suggested that a branch of the Kuroshio enters the Cheju Strait after turning around the western coast of Cheju-Do and flows eastward in the strait based upon closely spaced summertime hydrographic and dissolved oxygen data. Kim$_k$'s suggestion refutes the belief since Uda (1934) that the Yellow Sea Warm Current (YSWC) originating from the Kuroshio penetrates deep into the Yellow Sea along the western coast of Korea. A schematic circulation pattern proposed by Uda has been cited with little modification in describing a general circulation pattern in the East China Sea and the Yellow Sea until recently (e.g. Tomczak and Godfrey, 1994). The turning current suggested by Kim$_k$ is probably confined within 20 km from the northern and western coast of Cheju-Do (Kim$_k$, 1980; Kim, 1982; Kim and Lee, 1982; Rho and Kim, 1983; Kim et al., 1991). The magnitude of the turning current calculated by the dynamic method was about 10 cm/s at 30 m relative to 75 m (Lee, 1982). Kim$_k$'s suggestion was further supported by results of other summertime hydrographic surveys (Lie, 1986; Park, 1986).

Kim et al. (1991) analyzed summertime hydrographic data taken in the area covering the entire length of the entrance of the Yellow Sea between Cheju-Do and the mouth of Changjiang river. They showed that a low salinity water on the Changjiang bank originating from the river plume extends northeastward to Cheju-Do and separates oceanic water of high temperature and high salinity around Cheju-Do from the surface water of the Yellow Sea. Below the seasonal thermocline a thermal front is formed between the oceanic water and the Yellow Sea Cold Water. A series of ships-of-opportunity SST (sea surface temperature) data taken in the Cheju Strait for one year indicates that the warm water appears also in the strait during winter and spring (Rho and Kim, 1983). The above hydrographic results are suggestive of the existence of the warm oceanic water in the Cheju Strait all the year round.

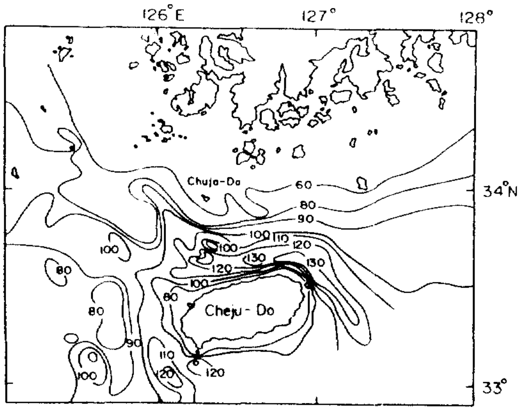

Fig. 1. A topographic map for the Cheju Strait. Isobaths are in meters.

Lee (1968), Lee and Bong (1969), Dong (1970), Lee (1974) and Kim$_b$ (1980) described a surface current pattern in the seas around Korea using drift bottles and reported northward currents west of Cheju-Do and eastward currents in the Cheju Strait every year. Sub-tidal currents based upon the various sources of direct current measurements in the Cheju Strait (Kim, 1979; Kim, 1982) also showed that the mean currents flow northeastward in the Cheju Strait. Trajectories of Argos drifters deployed in the area west of Cheju-Do demonstrated the flow turning around Cheju-Do (Beardsley et al., 1992) as suggested previously from the hydrographic data by Kim$_k$ (1980).

The previous suggestions of the existence of the turning current around the western coast of Cheju-Do are largely based upon the distributions of temperature and salinity. However, direct measurements of such currents have been scarce in the west of Cheju-Do and all the current measurements in the Cheju Strait spanned less than a week.

A moored current measurement was conducted for the first time at a single location in the Cheju Strait for a 20-day period to investigate the sub-tidal flow variability in the strait. During the current measurement drogue trackings and hydrographic surveys were also made around Cheju-Do to identify the turning current, carrying waters originating from the Kuroshio. In this paper we describe the results of the hydrographic surveys together with the observed mean currents.

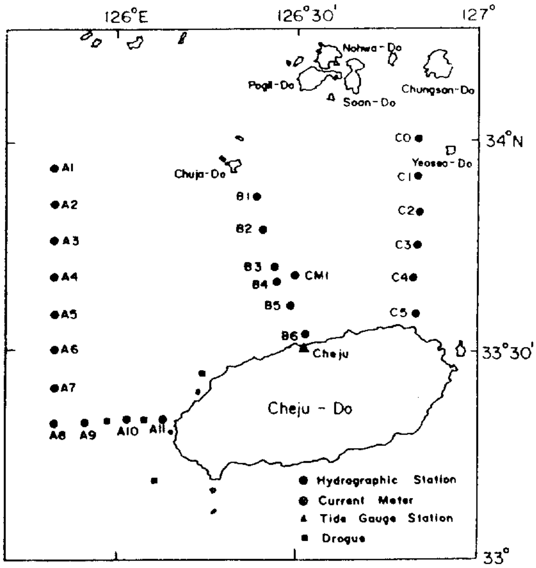

Fig. 2. Positions of hydrographic (●) and current (⊗, ☒) stations occupied in the Cheju strait, 11 April-10 May 1983. ⊗ and ☒ denote the location of moored current measurement and locations of deployment of drogues respectively.

DATA

From April 11 to May 10, 1983 hydrographic surveys, drogue trackings and moored current measurements were made in the Cheju Strait and west of Cheju-Do. Each station of various measurements is shown in Fig. 2.

The moored current measurements were conducted 10 miles north of Cheju harbour at two nominal depths (30 m and 60 m) in 100 m of water with Aanderaa current meters suspended beneath the surface floats. The Aanderaa current meters recorded speed, direction, temperature and conductivity at 5 minutes interval from April 11 to May 3, 1983. The measured currents were decomposed to along-strait (east-west) and cross-strait (north-south) components and each component was plotted to check the erroneous data. The 5 minutes data were first smoothed by a filter with a half power at 0.3 cph (cycle per hour) to remove high frequency fluctuations and to obtain hourly time series. Hourly values of current were then filtered to eliminate tidal and inertial frequencies using a Doodson's Xo-filter (Doodson and Warburg, 1941). The Xo-filter has 39 weights with a half power point of 0.456 cpd (cycle per day) and is highly effective in removing tidal energy in the diurnal, semidiurnal, quarter- and sexto-diurnal bands (Prandle, 1987).

Lagrangian current measurements were conducted within 20 km off the southwestern, western and northwestern coast of Cheju-Do using window-shade drogues at 5 m and 50 m depths. The position of each drogue was measured by ship's radar. Each drogue 2.5 m in width and 3.6 m (5.4 m for deeper one) in length with a 25 kg weight was hung below a float with a bamboo pole. The pole had a weight at its lower end to hold the surface assembly vertical in the water, and a radar-reflector (aluminium net), flag and flash on its upper part to aid the tracking by ship. The drogues were designed to secure for the 4 m wave height and estimated speed error is below 1 cm/s for wind speed of 15 m/s.

Two hydrographic surveys were completed on a two-week basis during the deployment of Aanderra current meters. Due to bad weather the first survey during April 12-17 was broken into two parts; section A and stations B1-B4 during April 12-13 and stations B5-B6, section C during April 16-17. The second hydrographic survey was conducted during May 1-2. An additional survey was carried out along section B on April 20. The hydrographic stations were chosen to be closely spaced in north-south direction (about 5 miles) and close to the coast of Cheju-Do (about 2 miles from the coast). Nansen and Ekman water samplers with reversing thermometers were used to measure water temperature and salinity at standard depths and 5 m above the bottom. Surface temperature was measured with pole-shaped thermometer after bucketing surface sea water. Salinity was measured in laboratory with Autosal Salinometer (Guildline Model 8400). Accuracies of temperature and salinity are ±0.02°C and ±0.003‰, respectively.

RESULTS

APRIL, 1983

Vertical Sections

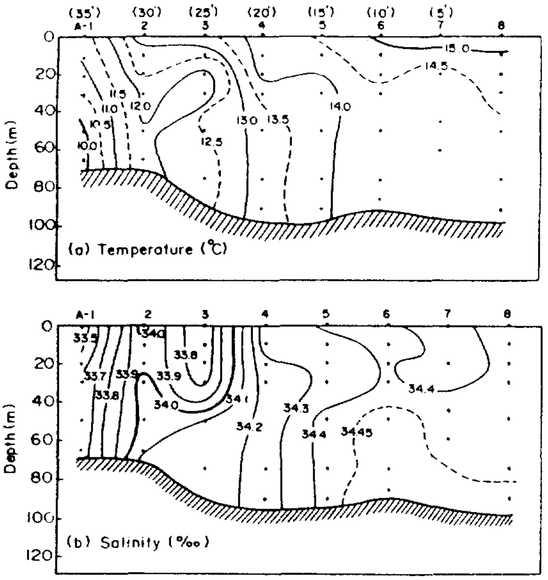

Fig. 3. Vertical distributions of temperature and salinity for section A1-A8 in April. The distance from station A1 to each station in nautical miles is shown in parentheses above the station number.

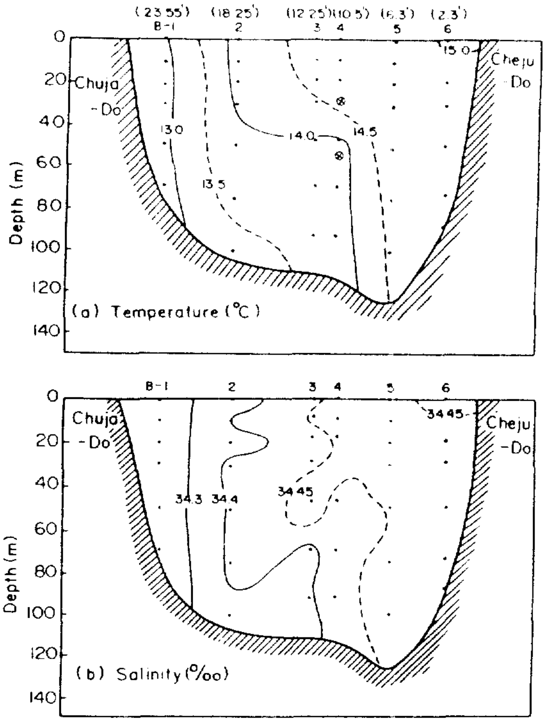

Fig. 4. Vertical distributions of temperature and salinity for section B1-B6 in April. The distance from the Cheju-Do to each station in nautical mile is shown in parentheses above the station number. Moored current measurement was conducted about 3 miles east of station B4 at two depths denoted by ⊗.

Vertical profiles of temperature and salinity on sections A1-A8, B1-B6 and C1-C6 are shown in Figs. 3, 4 and 5, respectively.

Section A1-A8 Temperature and salinity vary mainly horizontal and decrease towards the north. Homogeneous water of temperature higher than 14.0°C and salinity higher than 34.4‰ is found at Sts. A6, A7 and A8 except the slightly lower salinity at the surface layer of St. A7. Though not shown, high temperature (>14.0°C) and high salinity (>34.4‰) water entirely occupies Sts. A9, A10 and A11 near the western coast of Cheju-Do. From St. A5 temperature and salinity gradually decrease and water properties change abruptly between Sts. A1 and A2 at all depths. Minimum temperature (<10°C) was found at St. A1 below 50 m depth. Water of the lowest salinity (<33.5‰) was also found at St. A1 in the upper layer. The surface layer of St. A3 is less saline than its southern and northern stations and temperature inversion appears at 20 and 30 m depths.

Section B1-B6 Section B1-B6 runs northwest from Cheju-Do towards Chuja-Do. Both temperature and salinity decrease towards Chuja-Do and a relatively sharp change of temperature and salinity occurs above 30 m depth between Sts. B1 and B2 near Chuja-Do. Homogeneous water characterized by high salinity (>34.4‰) and high temperature (>14.0°C) appears from the coast of Cheju-Do to St. B2 above 30 m depth and to St. B5 below 50 m depth. The water properties are identical to those of water which appears at Sts. A6, A7 and A8 in section A1-A8 in the area west of Cheju-Do. A relatively cold and fresh water occupies the whole depth at St. B1 close to Chuja-Do and the influence of this water extends to St. B4 below 50 m depth.

Section C1-C5 Section C1-C5 located at the eastern side of the Cheju Strait runs north from the northeast of Cheju-Do to Chungsan-Do. Except for St. C1, homogeneous water having a temperature range between 14.0 and 15.0°C and a salinity between 34.4 and 34.6‰ occupies the whole stations. Salinity of water off Cheju-Do is slightly high-

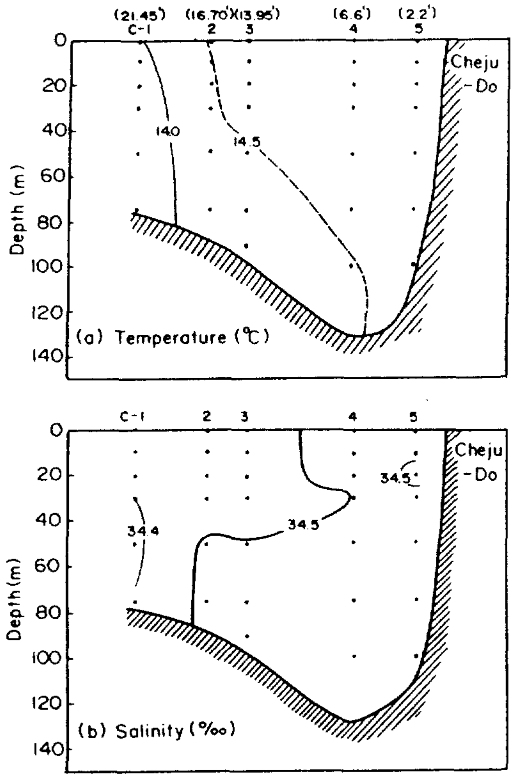

Fig. 5. Vertical distributions of temperature and salinity for section C1-C5 in April. The distance from the Cheju-Do to each station in nautical miles is shown in parentheses above the station number.

er than that of which appears at section B1-B6.

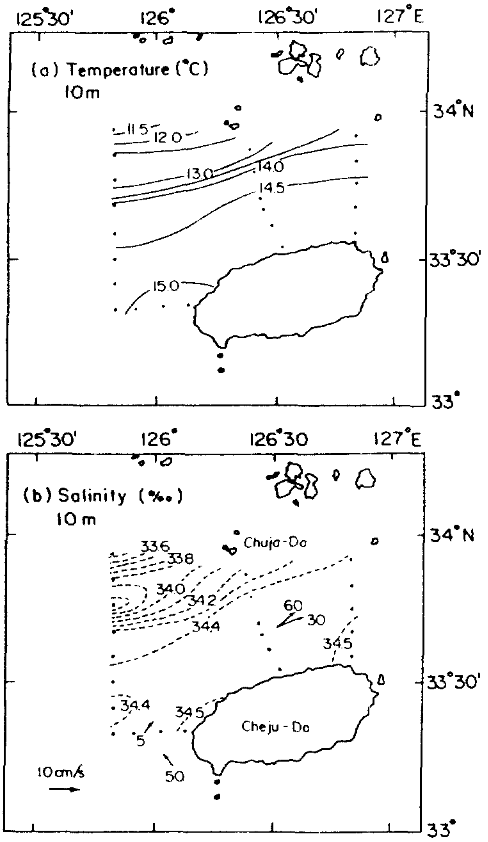

Fig. 6. Distributions of temperature and salinity at 10 m depth. Observed mean currents around Cheju-Do computed from the moored current measurement during the first hydrographic survey and drogue trackings made in April are superimposed on the horizontal distribution of salinity. Measurement depths of the currents are shown in meters near current vectors.

Horizontal distribution

Horizontal distributions of temperature and salinity at 10 m depth are shown in Fig. 6. The maps are contoured at 0.5°C interval for temperature with solid lines and 0.1‰ interval for salinity with dotted lines. The observed mean current distribution around Cheju-Do is superimposed on the horizontal distribution of salinity. The direction and magnitude of mean currents are computed from the results of drogue trackings made for more than one day in April and a moored current measurement during the first hydrographic survey as shown in Table 1.

Each isoline runs nearly parallel to the southwest-northeast direction and temperature and salinity decrease towards the southwestern coast of Korea. Relatively homogeneous water having a temperature above 14.0°C and a salinity above 34.4‰ is found around Cheju-Do and this water mass appears within 30 km from the coast of Cheju-Do in the strait at 10 m depth. At 50 m depth relatively cold water (<14.0°C) extended further southward in the strait than that in the upper layer (see the vertical section of B1-B6 in Fig. 4). In the warm water area with temperature higher than 14.0°C temperature is higher in the area west of Cheju-Do than that in the eastern part of the Cheju Strait. However, water of high salinity (>34.5‰) appears more broadly in the eastern part of the strait than that in the region of high salinity west of Cheju-Do. Water of high sa-

Table 1. Summary of mean currents around Cheju-Do observed during April 9~May 10.

Location	Type of measurement	Depth	Measurement period	Current	
				direction	magnitude
southwestern coast of Cheju-Do	drogue	50 m	April 8, 14:30~ April 12, 13:30	northwest	4 cm/s
western coast of Cheju-Do (between stations A9~A10)	drogue	5 m	April 23, 13:00~ April 25, 08:00	northeast	3~5 cm/s
western coast of Cheju-Do (between stations A10~A11)	drogue	5 m	May 8, 12:00~ May 9, 14:40	northeast	2 cm/s
northwestern coast of Cheju-Do	drogue	5 m	May 9, 16:00~ May 10, 16:30	east	19 cm/s
	drogue	50 m	May 9, 16:25~ May 10, 16:20	east	14 cm/s
Cheju strait	current mooring	30 m	April 12, 14:00~ April 18, 23:00	27.3°*	12.1 cm/s
	current mooring	60 m	April 12, 14:00~ April 18, 23:00	34.2°*	9.3 cm/s
Cheju strait	current mooring	30 m	April 29, 00:00~ May 2, 16:00	35.4°*	12.5 cm/s
	current mooring	60 m	April 29, 00:00~ May 2, 16:00	44.8°*	9.6 cm/s

*The direction is measured counter-clockwise from the east.

linity at the eastern entrance of the Cheju Strait is regarded as the Tsushima Current water (Rho and Hirano, 1983). In the middle of the strait, salinity does not exceed 34.5‰.

Vertical and horizontal distributions of water properties show that homogeneous water characterized by high temperature (>14.0°C) and high salinity (> 34.4‰) appears around Cheju-Do. This water belongs to group 4 representing the mixture of shelf water and the Kuroshio water according to Kim et al. (1991) and the Kuroshio water according to Sawara and Hanzawa (1979). Fig. 6 clearly shows that the observed high temperature and high salinity water which appears off the western and northern coast of Cheju-Do is carried by a current turning around the western coast of Cheju-Do. The speed of the current is less than 5 cm/s in the area west of Cheju-Do and about 10 cm/s in the middle of the Cheju Strait.

A part of the Kuroshio makes a northerly branch in the southwestern sea region of about 200 km offshore from Kyushu (Uda, 1934; Nitani, 1972; Zheng and Klemas, 1982; Lie and Cho, 1994). This northerly branch again divides into two tributaries; one flows into the East Sea through the Korea Strait, which is called the Tsushima Current (TC) and the other, after having passed south of Cheju-Do, runs towards the Yellow Sea (Uda, 1934; Koizumi, 1957; Nakao, 1977), which is called the YSWC. So it is expected that the area east of Cheju-Do is affected by the TC while the area west of Cheju-Do by the YSWC. The YSWC has been referred to as a branch of the Kuroshio which penetrates deep into the Yellow Sea. While the existence of the YSWC is still in controversy, the existence of the current turning around the western coast of Cheju-Do has been recognized as a year-round feature based mostly upon the hydrographic data since Kim$_k$ (1980). As our simultaneous hydrographic and current data clearly demonstrate that a branch of the Kuroshio enters the Cheju Strait after turing around the western coast of Cheju-Do, this current may deserve a name other than the YSWC. The current is called the Cheju Warm Current (CWC) hereafter in this paper. According to our hydrographic and current data, water of high temperature and high salinity which appears off the western and northern coasts of Cheju-Do is carried by the CWC.

In view of the expected complex hydrographic structure, the area covered by the hydrographic survey is rather small to understand the general oceanographic condition in space. To supplement this, hydrographic data obtained by Fisheries Research and Development Agency of Korea

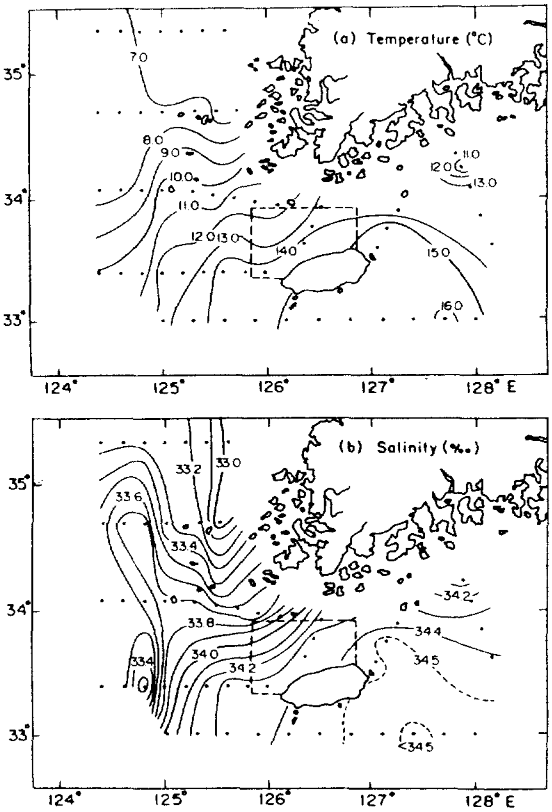

Fig. 7. Distributions of temperature and salinity at surface around Cheju-Do in April produced using hydrographic data obtained by Fisheries Research & Developmeht Agency of Korea during 9~18 April. Two hydrographic surveys were conducted in the dotted area.

(FRDA) around Cheju-Do and in the southeastern Yellow Sea during 9~18 April, 1983 were analysed. Fig. 7 shows horizontal distributions of temperature and salinity at surface produced using the FRDA data. During this period seasonal thermocline was not formed yet and property distributions showed little difference between depths. Temperature and salinity decrease from the area southeast of Cheju-Do to the north and to the northwest. High temperature (>14.0°C) and high salinity (>34.3‰) water appears around Cheju-Do and water properties decreased rapidly from the isolines of 14.0°C and 34.2‰ to the northwest. Although salinity of this water is slightly lower than that of our data, the above water is regarded as the CWC water originating from the Kuroshio. The influence of the TC water in the eastern part of the Cheju-Do can also be seen. Strong thermohaline fronts are formed between the warm and saline CWC water and relatively cold and fresh waters in the northwest and west of the front as other studies documented (Gong, 1971; Nakao, 1977; Lie, 1984). The location of the thermohaline front formed in the area northwest of Cheju-Do in Fig. 7 corresponds to that observed in this study. There is little indication of the existence of the YSWC water, although wintertime satellite images showed a warm tongue towards Shangdong Peninsula, the main axis of which lies slightly to the west of the deep Yellow Sea trough (Zheng and Klemas, 1982) further offshore of the observation area of the FRDA. It is interesting to note the tongue-like distribution of relatively saline water (33.7~33.8‰) towards the northwest in Fig. 7. According to the figure the tongue-like distribution seems to result from the intrusion of a part of water in the northern portion of the front between the CWC and coastal waters.

The CWC water of high temperature (>14.0°C) and high salinity (>34.3‰) extended over 60 km offshore from the western coast of Cheju-Do according to Fig. 7. Kim$_K$ (1980) reported the width of the CWC water to be about 15~30 km based upon hydrographic data obtained in June and August, but in our case it is about 60 km west of Cheju-Do and 20~30 km in the Cheju Strait. It is generally known that Yellow Sea Cold Water extends southward in summer (Nakao, 1977; Park, 1985; Youn, 1986; Kim et al., 1991) and the width of the CWC would vary seasonally west of Cheju-Do depending on the strength of the Yellow Sea Cold Water. The South Korean Coastal Water (SKCW, Lim, 1976) near Geomun-Do northeast of the Cheju Strait can be seen, which is distinguished from both the CWC water and the TC water as well as water in the southeastern Yellow Sea, which is referred to as the Yellow Sea Coastal Water (YSCW, Gong, 1971; Kang, 1971). There exists another low salinity water west of 125° E, water temperature of which is higher than that of the YSCW according to Fig. 7.

MAY, 1983

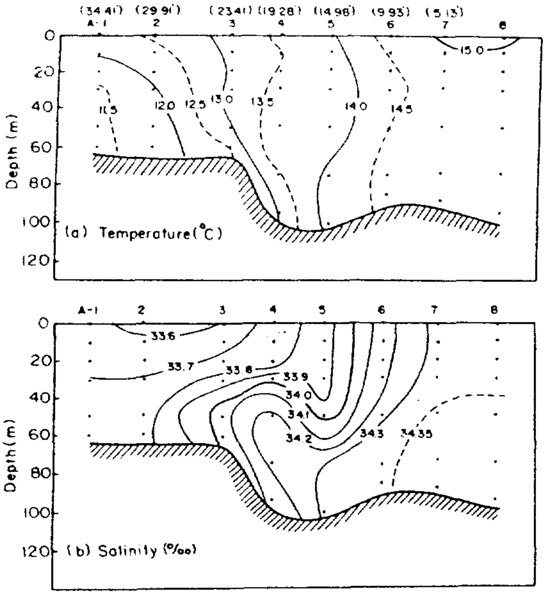

Fig. 8. Same as Fig. 3 except in May.

Vertical sections

Shown in Figs. 8, 9 and 11 are vertical profiles of temperature and salinity on sections A1-A8, B1-B6 and C0-C5, respectively, during May 1-2 after about half a month from the first cruise.

Section A1-A8 Vertically homogeneous water of high temperature and high salinity appears at Sts. A7 and A8 and temperature and salinity decrease northward. A boundary zone between two different water masses is conspicuous in vertical salinity profile. Maximum horizontal gradient of salinity as large as 0.3‰ is found between Sts. A5 and A6 above 50 m depth, and between Sts. A2 and A3 below 50 m depth. The salinity front is located more to the south (about 18 km) than that in mid-April.

Section B1-B6 Remarkable changes in hydrographic structure took place in the Cheju Strait over a period of only about 15 days. A low salinity core (<33.7‰) was observed from surface to 30 m depth at St. B3 in the middle of the section. Surface salinity at St. B3 is lower by about 0.7‰ than that in mid-April and temperature also decreased at this station compared with the value in mid-April. This salinity value is even lower than that at station B1 located further north near Chuja-Do, so the isohalines form a concave shape in the surface layer of this section as shown in Fig. 9. Salinity increases rapidly (0.7‰/10 miles) from the low salinity core to the coast of Cheju-Do and increases (0.3‰/10 miles) slowly towards Chuja-Do. In temperature profile, this fresh water is not distinguished from the water which appears near Chuja-Do, but it is clearly distinguished from the warm water near Cheju-Do. According to Fig. 7, water properties of this low salinity core are similar to those of waters in the frontal regions northwest of Cheju-Do between the CWC water and the YSCW, and west of Cheju-Do. An additional hydrographic survey was conducted along section B1-B6 on April 20 between the first and second hydrographic surveys and the low salinity core was not observed at that time as shown in Fig. 10. Water of relatively cold and fresh water off the coast of Chuja-Do extended further to the south on April 20 compared to the results of the first hydrographic survey taken before one week.

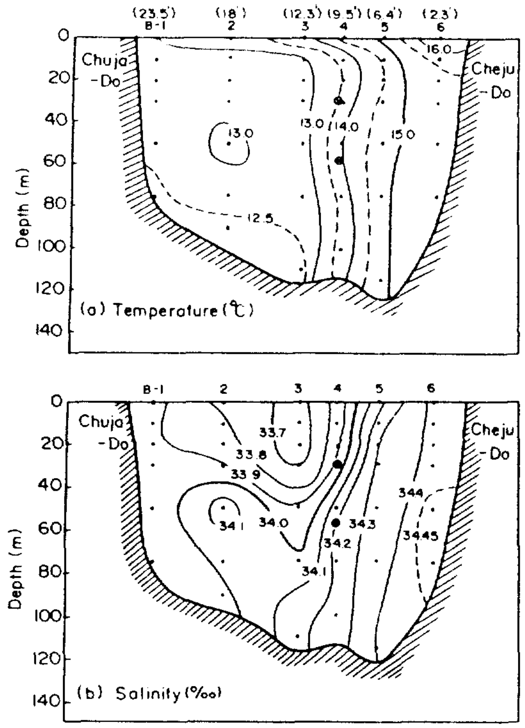

Fig. 9. Same as Fig. 4 except in May.

Hydrographic data taken in the Cheju Strait in May 1987~1989 also showed the appearance of the

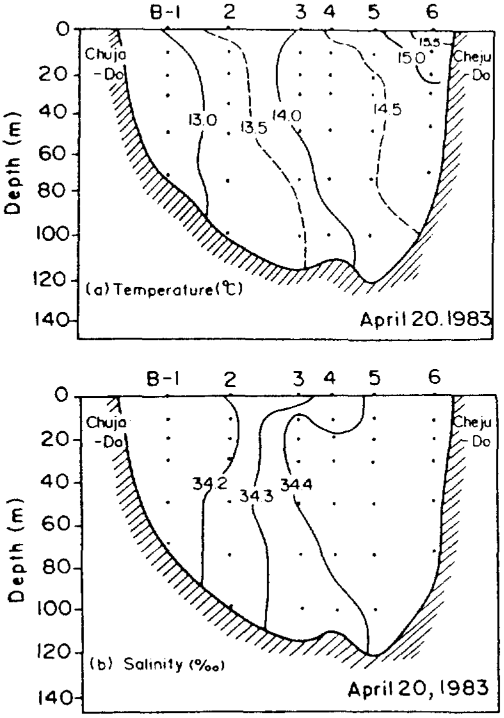

Fig. 10. Vertical distributions of temperature and salinity for section B1~B6 occupied on April 20 between the first and second hydrographic surveys.

low salinity core in the middle of the strait (KORDI, 1994). The minimum salinity value of the core, however, varied from year to year ranging from 32.7‰ to 33.8‰, and a short term variability of the core was noted from repeated hydrographic measurements along a section. The appearance of the low salinity core is due to an advection of the low salinity water into the strait since the rainfall and/or the freshwater discharge from the south coast of Korea cannot account for the localized freshening of the seawater. The source of the low salinity water can be either the YSCW or the low salinity water found in the area west of Cheju-Do as shown in Fig. 7. At this stage it cannot be said explicitly where the low salinity core originated from due to the lack of hydrographic data taken in a wider area in May. Satellite images in February and April, however, showed a wave-like thermal front in the Cheju Strait formed between the CWC water and the YSCW, the latter expands southward and enters the Cheju Strait due to northerly wind and the eastward flowing residual currents (Han, 1989). Kim et. al. (1991) suggested a possibility that the Yellow Sea Cold Water flows into the South Sea passing through the northern part of the Cheju Strait. Cho and Kim (1994) also reported the intrusion of water from the Yellow Sea to the South Sea through the Cheju Strait. As previously mentioned, the salinity front which is regarded as the boundary between the CWC water and the YSCW was located about 18 km more to the south in May than that in mid-April as shown in Fig. 8. This southward extension of the YSCW seems to be related with the appearance of the low salinity core in the Cheju Strait in May.

The CWC water was also clearly identified in the second survey not only by its properties but also by the strong thermohaline fronts (2.0°C/10 km, 0.5‰/10 km) between Sts. B3 and B5. The width of the CWC was limited within 10 km from the coast of Cheju-Do, which is about a half of that in mid-April.

Section C0-C5 Temperature and salinity decrease from St. C4 to the north the same as in mid-April. Horizontal gradients of temperature and salinity are, however, more intensified than those in mid-April. Temperature and salinity differences between station C1 and C5 are 2.0°C and 0.4‰, respectively, but they were 1.0°C and 0.2‰, respectively in mid-April. The area of high temperature (> 14.0°C) and high salinity (>34.4‰) water was shrunk in May than that in April and confined to about 15 km from the coast of Cheju-Do. Low salinity core which appears in section B1-B6 was not observed in this section.

Horizontal distribution

Distributions of temperature and salinity at 10 m depth are shown in Fig. 12. The observed mean current distribution around Cheju-Do is superimposed on the horizontal distribution of salinity. The direction and magnitude of mean currents are computed from the results of drogue trackings made for more than one day in May and a moored current measurement during the second hydrographic survey.

The intrusion of low salinity water from the west of the Cheju Strait to the middle of the strait can be

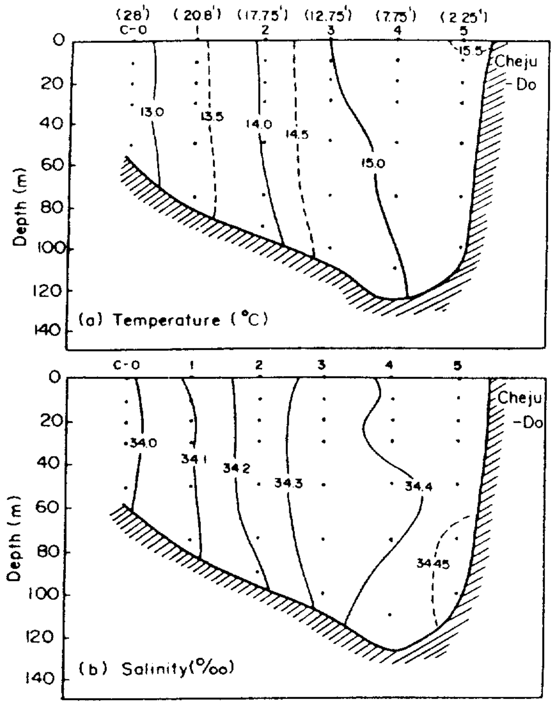

Fig. 11. Same as Fig. 5 except in May for section C0~C5.

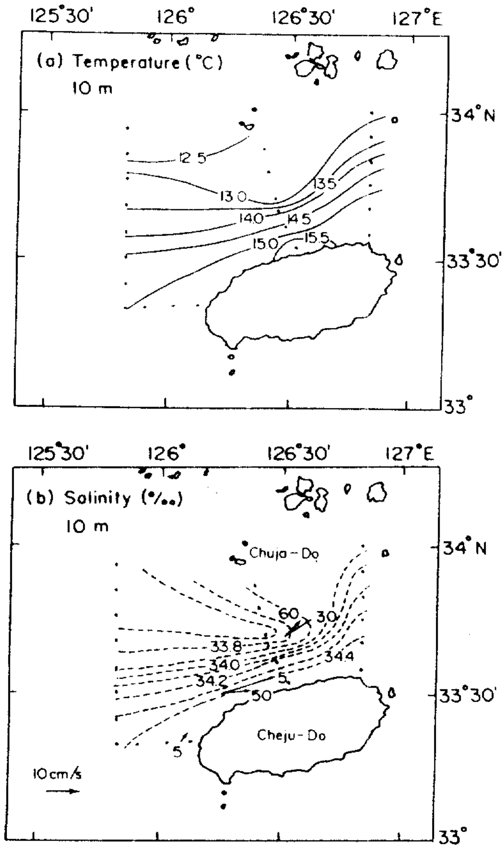

Fig. 12. Same as Fig. 6 except in May.

seen clearly from the salinity distribution. The CWC water having a temperature above 15.0°C and a salinity above 34.4‰ appears around Cheju-Do over the whole depth though its width in the strait (approximately 10 km) became narrower compared with that in mid-April presumably due to the intrusion of low salinity water from the west. The orientation of isolines tilts more to the north toward the eastern part of the strait, which is suggestive of the influence of the TC water. The current vectors are parallel to the isohalines off the northwest coast of Cheju-Do, while the mean currents in the strait deflect more to the north from the east presumably resulting partly from the influence of the TC in the southeastern part of the Cheju Strait.

Temporal changes of water properties

In order to examine the short-term variations of temperature and salinity in the Cheju Strait during a period from mid-April to early-May, temporal changes of water properties are computed at standard depths of each station as follows,

$$X=(P2-P1)/t,$$

where

P2: values of temperature or salinity obtained in early-May

P1: values of temperature or salinity obtained in mid-April

t : time interval between the two measurements.

Arithmetic mean values ($Y=X/N$, where N is the number of standard depths) of water properties at each water column are estimated from surface to 30 m and from 50 m to 75 m or 100 m as representative values of upper and lower layers, respectively. Despite of the vertically homogeneous structure at many of the stations, the water column is divided into the upper and lower layers since a two-layer structure was also observed at some stations as can be seen in Figs. 8 and 9. Figs. 13 and 14 show the

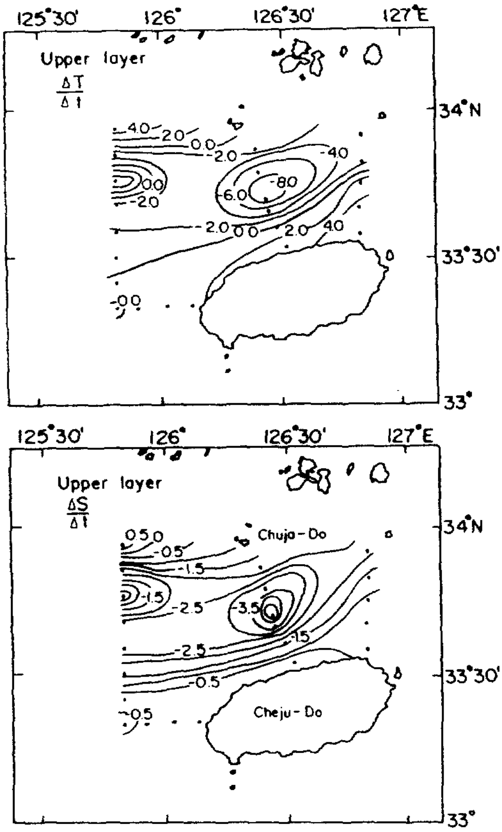

Fig. 13. Temporal changes of temperature ($\times 10^{-7}$ °C/s) and salinity ($\times 10^{-7}$ ‰/s) in the upper layer between mid-April and early-May.

temporal changes of temperature and salinity between mid-April and early-May in upper and lower layers, respectively.

As the spring progresses several changes occur in the water column. The salinity of the water column in early-May decreases both in the upper and lower layers over the whole area except for the station A1. The most freshening and cooling of the water column occurs in the middle of the Cheju Strait, especially in the upper layer resulting from the intrusion of the coastal water from the western part of the Cheju Strait. The order of magnitude of the along-strait flow in the Cheju Strait is about 10 cm/s assuming a balance between the local time changes of water properties and the advection, which corresponds to the observed along-strait velocity scale in the Cheju Strait.

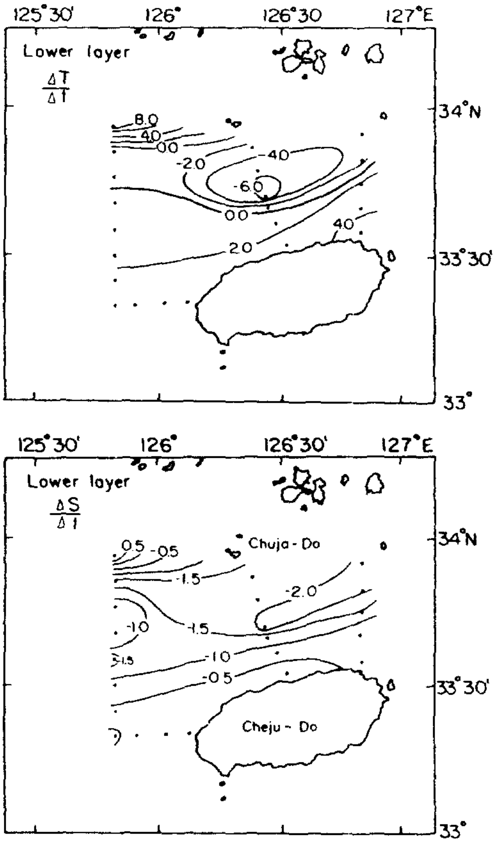

Fig. 14. Same as Fig. 13 except in the lower layer.

A warming and relatively slight freshening of the whole water columns occur in the area around Cheju-Do, affected by the branch of the Kuroshio, which differs from those of the other areas. More warming and freshening take place in the eastern part of the Cheju Strait influenced by the TC water than in the area west of Cheju-Do influenced by the CWC water.

The temporal variations of temperature and salinity at stations in the frontal region north of section A1-A8 are complicated. Both temperature and salinity increased in the upper and lower layers at St. A1. The temporal variations of temperature in the upper layer of stations A3~A6 differ from those in the lower layer. These changes seem to be related with the short-term variability of complex frontal structure.

SUMMARY AND DISCUSSION

Simultaneous hydrographic and current observations in the Cheju Strait clearly demonstrate that a branch of the Kuroshio characterized by high temperature and high salinity enters the Cheju Strait after turning around the western coast of Cheju-Do as previously suggested by Kim_k (1980) based upon hydrographic data only. We proposed to call this current the Cheju Warm Current, which can be defined as a current flows into the Cheju Strait after turning around the western coast of Cheju-Do and carries water of high temperature and high salinity originating from the Kuroshio water. The speed of the current is larger (~10 cm/s or larger) at the western entrance and in the middle of the Cheju strait than that in the western coast of Cheju-Do (<5 cm/s). This seems to be due to the continuity of transport at the entrance of the strait, which concentrates the mean flow in the smaller cross-sectional area of the strait. Hydrographic data obtained by the FRDA in a wider area showed that the width of warm (>14.0°C) and saline (>34.3°C) water carried by the Cheju Warm Current is about 60 km in the area west of Cheju-Do as shown in Fig. 7. The width of warm (> 14.0°C) and saline (> 34.4) water along section B1-B6 in Fig. 4, however, is only about 20~30 km.

The tilting of isolines more to the north towards the east in the Cheju Strait suggests that the Tsushima Current water also originating from the Kuroshio exerts its influence in the eastern part of the strait. The Tsushima Current does not reach deep into the strait but seems to turn anticyclonically in the eastern part of strait after joining the Cheju Warm Current. The detailed interaction between the two currents in the Cheju Strait deserves further study.

Thermohaline fronts are formed between the warm current waters and the coastal waters. The fronts are located more to the south in May suggesting the southward extension of coastal waters west of the Cheju Strait and the intrusion of coastal water into the strait. A warming of water columns occurs in May in the area influenced by both the Cheju Warm Current water and the Tsushima Current water in contrast to a cooling of water in other areas. The warming of the Tsushima Current water is more pronounced than that of the Cheju Warm Current water. The major freshening and cooling occurs in the middle of the Cheju Strait in May which is attributed to the intrusion of cold and low salinity water from the west of the Cheju Strait. Changes in water properties in the Cheju Strait should be explained in a manner consistent with the observed mean eastward current. The width of the Cheju Warm Current water is reduced in the Cheju Strait in May due to this intrusion.

There is a possibility that eastward propagating wave-like frontal features in the Cheju Strait observed in satellite images (Han, 1989) may be responsible for the appearance and disappearance of the surface low salinity core at a section cross the strait observed in this study and the other (KORDI, 1994) in May. A routine hydrographic measurement by FRDA is being conducted every even months. While the mean hydrographic conditions in April and in June are notably different in the South Sea (eg. KORDI, 1993), the transition between the two months is little known. Although our hydrographic stations are closely spaced mainly in the north-south direction, they are not enough to resolve the mesoscale features observed in satellite images. More closely spaced hydrographic surveys in a wider area for a period of transition from winter to summer are needed to elucidate the water exchange between the Yellow Sea and the South Sea through the Cheju Strait.

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