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Monthly Variation of Water Mass Distribution and Current in the Cheju Strait

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The monthly observations of hydrography in the Cheju Strait from September 1995 to June 1998 show that the Cheju Strait is occupied mostly by Tsushima Current Water in winter and coastal waters in summer. In summer, the Yangtze Coastal Water appears in the upper layer and cold water in the lower layer. Especially, the Yellow Sea Bottom Cold Water appears in August 1997, and the clockwise flow of warm water along the northwestern coasts of Cheju Island is disturbed by an eastward expansion of the cold water from the northwest. The cold water expansion seems to be partly associated with strong southeasterly winds. Current measurements in the Cheju Strait suggest that there exists steady eastward barotropic component of about 5 cm/sec, which corresponds to 0.2 Sv barotropic transport in the Cheju Strait. Geostropic transport (baroclinic component) ranges from 0.1 Sv in winter to 0.4 Sv in summer. By adding the barotrophic component of 0.2 Sv, the total transport varies from 0.3 Sv to 0.6 Sv, which is consistent with previous estimations. The transport increase in summer seems to be caused by the expansion of coastal water to the Cheju Strait.

Key words: Cheju Strait, Yangtze Coastal Water, Yellow Sea Bottom Cold Water

INTRODUCTION

The Cheju Strait has become an interesting area to understand the circulation in the East China Sea and the Yellow Sea, since it has been realized that the warm water enters the Cheju Strait from the west of Cheju Island (Kim, 1980, 1982; Lie, 1986; Park, 1986; Beardsley *et al.*, 1992; Lie, *et al.* 1998, 2000; Chang *et al.*, 1995) instead of flowing to the Yellow Sea as was suggested by Uda (1934), and that the Yangtze Coastal Water flows into the Cheju Strait in summer (Kim *et al.*, 1991; Kim and Rho, 1994). Typical phenomena related with seasonal variations are southward expansion of Yellow Sea Bottom Cold Water in summer (Asaoka and Moriyasu, 1966; Nakao, 1977; Lie, 1984; Park, 1985, 1986; Kim *et al.*, 1991; Youn *et al.*, 1991), northward intrusion of Yellow Sea Warm Water through the central Yellow Sea in winter (Uda, 1934; Byun and Chang, 1988; Pang *et al.*, 1992), northward intrusion of warm water along the west coasts of Korean Peninsula in summer (Pang and Hyun, 1998), and northeastward flow of Yangtze Coastal Water towards the Cheju Strait (Yu *et al.*, 1983; Beardsley *et al.*, 1983; Zhao *et al.*, 1983; Kim, 1986, Pang *et al.*, 1999). The Cheju Strait is influenced by those waters due to the mean eastward flows in the strait (Chang *et al.*, 2000). Therefore, seasonal variations occurring in the Cheju Strait can be an indicator of the circulation in the East China Sea and the Yellow Sea.

A recent study has suggested that the seasonal variation of the volume transport in the Korea Strait is determined by the circulation between the East China Sea and the Yellow Sea (Pang and Oh, 2000). Since the variations in the Cheju Strait are probably transmitted to the Korea Strait, the Cheju Strait is also an interesting area in understanding the variations in the Korea Strait. Although the basic structure of hydrography and currents in the Cheju Strait has been documented by recent studies (Chang *et al.*, 1995, 2000; Suk *et al.*, 1996; Kim and Rho, 1997), seasonal variations of them with possible dynamics need to be further investigated. Monthly CTD observations and current measurements using TGPS buoys and

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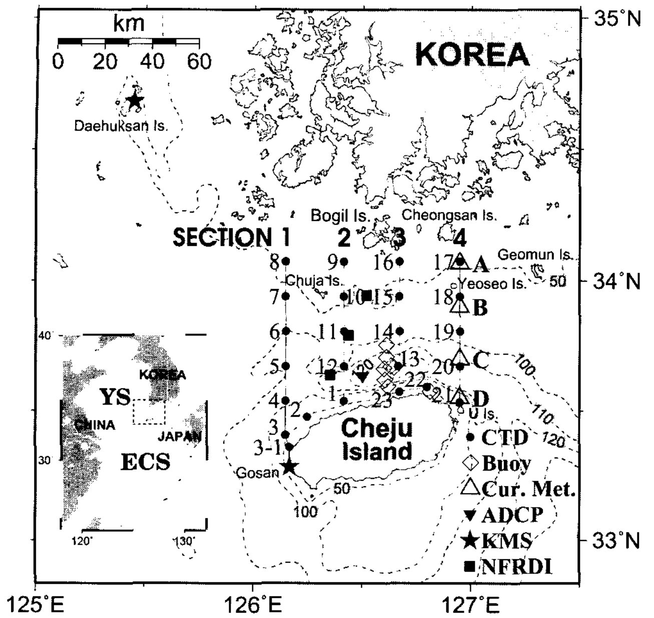

Fig. 1. Map of the Cheju Strait with isobaths in meters. CTD stations (●), release locations of TGPS buoys (◇), and locations of current meter moorings (△) are shown. Locations of hydrographic stations (203 line) of National Fisheries Research and Development Institute in the Cheju Strait (▣), long-term ADCP mooring (▼), and Korea Meteorological Station (KMS, ★) are also shown.

current meters were conducted between September 1995 and June 1998 to examine monthly variations of water mass distribution and currents in the Cheju Strait, and to relate them with the circulation in the East China Sea and the Yellow Sea (Fig. 1).

WATER CHARACTERISTICS

The monthly T-S diagrams (Fig. 2) can be divided into two types, winter and summer types. The winter type between December and April forms a straight line nearly parallel to isopycnals from high temperature and salinity to low temperature and salinity. The summer type from June to October forms also a straight line but across isopycnals from high temperature and low salinity to low temperature and high salinity. Transient pattern occurs in May and November.

The straight lines in T-S diagram indicate the mixing of water masses. In the Cheju Strait, the ways of mixing are different for the two types. In winter, vertical mixing makes the stratification weak so that the data points become nearly parallel to isopycnals on the T-S diagram. On the other hand, crossing the isopycnals indicates the development of quite strong vertical stratification in summer. Therefore, waters need to be mixed horizontally in some way upstream of the Cheju Strait in summer. Horizontal mixing may be possible for different waters by flowing together for a long time in the presence of strong tidal stirring. For example, it takes more than one month for the low salinity water to reach the Cheju Strait from the mouth of Yangtze River (Pang *et al.*, 1999).

The two types of T-S diagram can be used to understand the current conditions. Horizontal gradient of dynamic depth anomaly can not be large for the winter type so that the baroclinic current is small in winter while it is opposite for the summer type. Therefore,

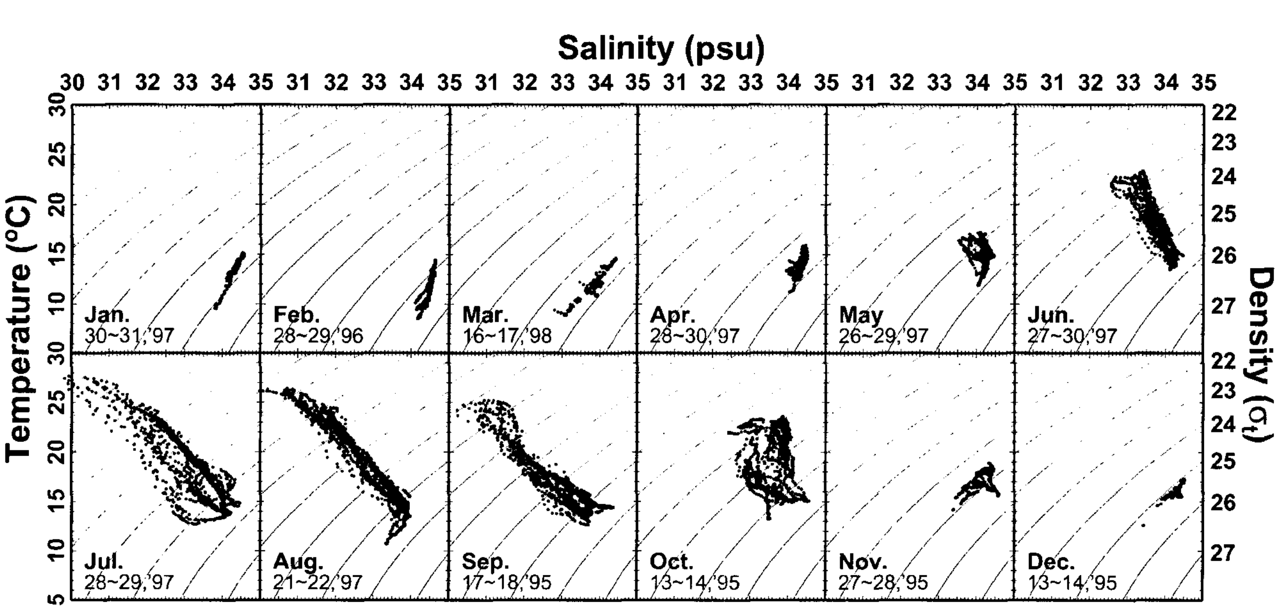

Fig. 2. Monthly T-S diagrams for CTD data obtained between September 1995 and June 1998 in the Cheju Strait.

the two types could be related with the seasonal variation of volume transport through the Cheju Strait. Water masses in winter can be easily classified into warm and saline Tsushima Current Water (TCW) and relatively cold and fresh coastal water. The distinction between the two water masses, however, is not so clear in summer only with the T-S diagram. They may be distinguished with the help of the spatial distribution of water properties.

WATER MASS DISTRIBUTIONS

Figs. 3 and 4 show monthly horizontal distributions of temperature and salinity at surface and 50 m depth. The lower layer shows relatively simpler distributions than the surface layer. Generally, the highest temperature and salinity appears in the southeast of the Cheju Strait due to the influence of the Tsushima Current coming from the East China Sea. It makes isotherms and isohalines run slightly northeastward in the Cheju Strait. However, the highest temperature and salinity also appears southwest of the Cheju Strait in winter. Isotherms and isohalines running slightly southeastward in December indicate that the Tsushima Current expands up to higher latitude west of the Cheju Strait in winter. Salty water with salinity greater than 34.0‰ occupies the whole area in the Cheju Strait in winter from December to April.

In March 1998, however, salinity less than 34.0‰ was shown. In particular, cold (T<11.0°C) and less saline (S<33.4‰) water appeared in the southwestern Cheju Strait. This is due to the southeastward intrusion of a cold tongue spreads into the Cheju Strait as is also identified by the satellite image (Fig. 5).

Figures 6 and 7 show the vertical distribution of temperature and salinity at Section 1 and 4, respectively. Upper layer is occupied by very fresh water and lower layer by very cold water in the western Cheju Strait (Fig. 6). The salinity of the upper fresh water is about 30.0‰ in July and August, which originates from the Yangtze Coastal Water (Lie, 1986). The Yangtze Coastal Water is wide-spread in the southwest of Cheju Island according to the data observed by National Fisheries Research and Development Institute (NFRDI) in August 1997. The temperature of the bottom cold water in August is below 11.0°C with salinity less than 33.4‰ in the western Cheju Strait. Such a low temperature water in summer is called Yellow Sea Bottom Cold Water (YSBCW) (Lie, 1984; Park, 1985, 1986; Kim *et al.*, 1991; Youn *et al.*, 1991). It is interesting that such a low temperature water appears in summer in the Cheju Strait. Due to the cold water, warm water columns off Cheju Island is not clear in Section 1 in August (Fig. 6). As will be shown later, a westward flow was observed along the northern coast of Cheju Island at that time. It suggests that the clockwise flow of warm water along the northwestern coast of Cheju Island may be disturbed by the eastward expansion of cold water.

COLD WATER IN SUMMER

On the origin of the cold water shown in the western Cheju Strait in summer, there have been two views. One is that the cold water originates from the YSBCW observed northwest of Cheju Strait (Kim *et al.*, 1991; Cho and Kim, 1994). The other, based on trajectories of satellite-tracked drifters, is that the cold water enters the Cheju Strait from an area southwest of Cheju Island together with saline water (Lie *et al.*, 2000). Chang *et al.* (2000) also suggest the cold water in the Cheju Strait originates from an area southwest of Cheju Island by analyzing hydrographic data.

Tsushima Current Water and coastal waters are in contact with each other in the Cheju Strait, and the front between the two different waters moves to north and south seasonally. As shown in Figs. 3 and 4, the front is located close to Bogil Island in winter, and close to or attached to Cheju Island in summer. The movement of the front means that the Cheju Strait is mostly occupied by TCW in winter and coastal water in summer. NFRDI data obtained in a wider area for the same periods showed that the front runs northeastward from the southwest of Cheju Strait in summer (not shown here). Thus, (a little warmer) cold water influenced by warm water could flow into the Cheju Strait from the southwest along the front with warm water. However, the cold water in August 1997 does not seem to follow this route.

The cold water less than 11°C shown in August 1997 (Fig. 6) appears to flow into the Cheju Strait from the northwest but does not reach the eastern section (Fig. 7). One of the reasoning for this phenomenon is that the clockwise flow along the northwestern coast of Cheju Island seems to be disturbed as shown in water mass distribution (in the previous section) and geostrophic current (in the next section, Fig. 14). Another reasoning is that temperature of the cold water appeared in the Cheju Strait is too low to come from the southwest of Cheju Island together with warm water. Then, how does the cold water come directly from the west? Very strong southeasterly winds over

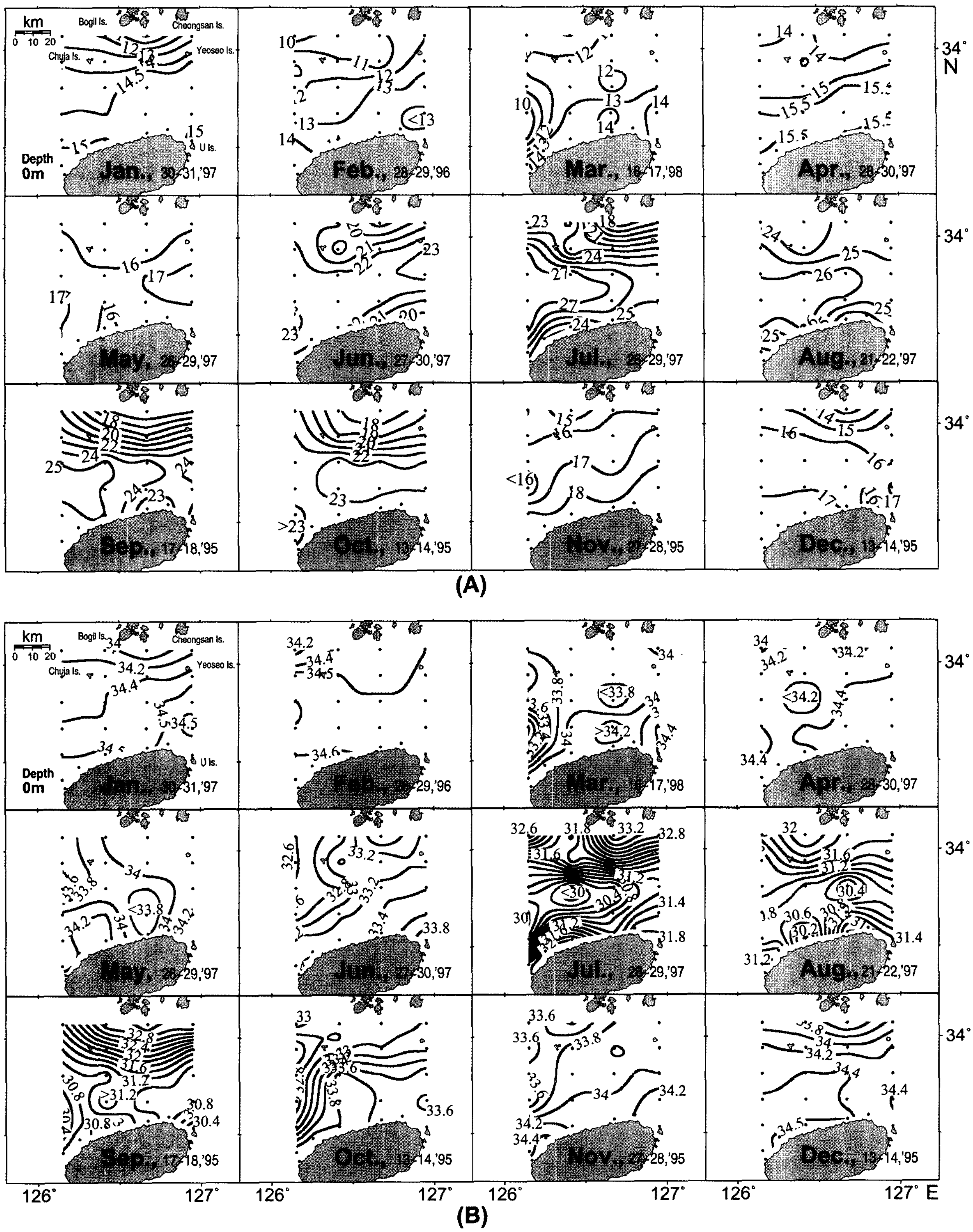

Fig. 3. Monthly horizontal distributions of (A) temperature and (B) salinity at surface in the Cheju Strait between September 1995 and June 1998.

10 m/sec had lasted three days just before the observation (Fig. 8). Such winds can drive sufficiently strong up-wind and down-wind flows in the Yellow Sea and the Cheju Strait. One possible interpretation

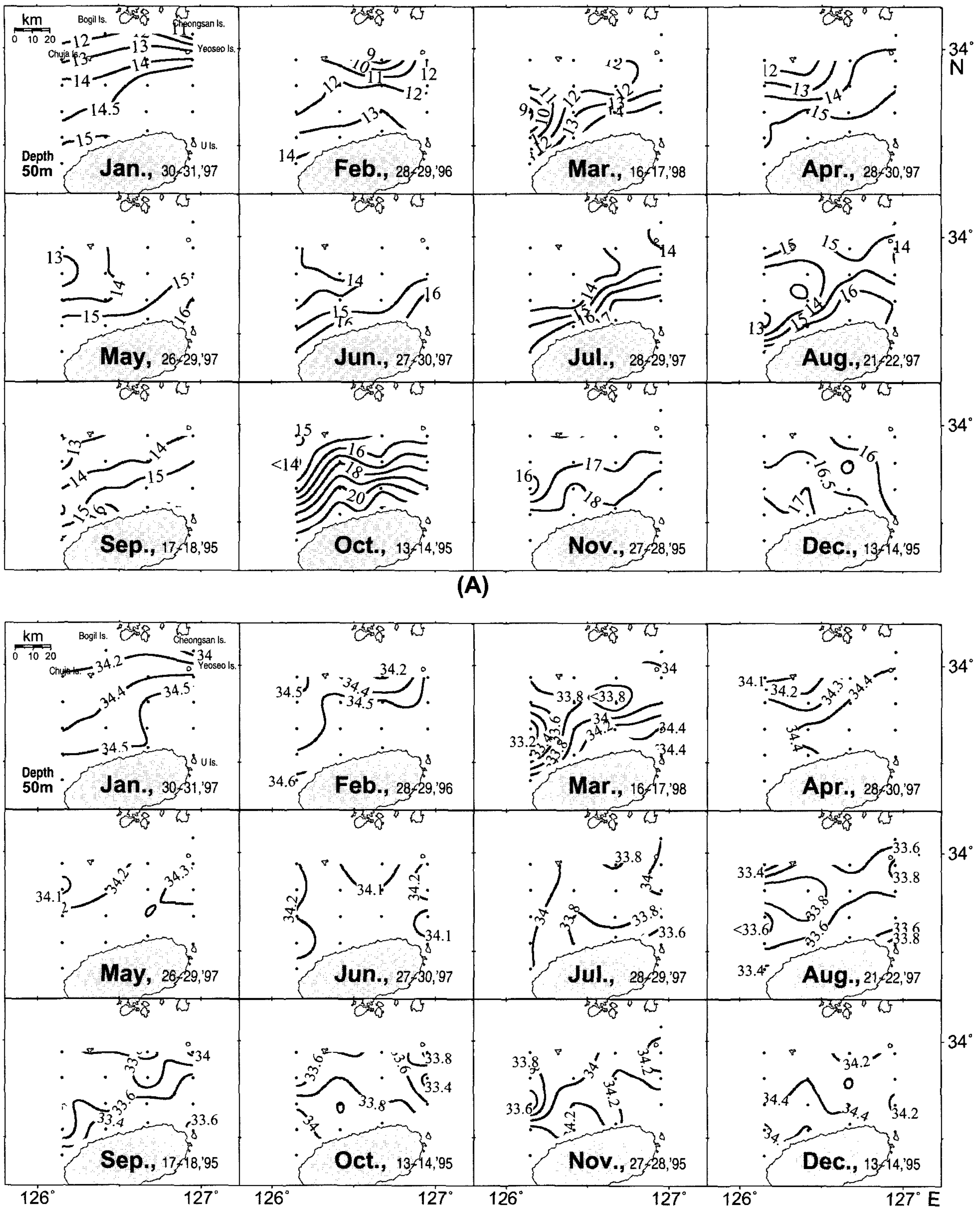

Fig. 4. Monthly horizontal distributions of (A) temperature and (B) salinity at 50 m in the Cheju Strait between September 1995 and June 1998.

is, as proposed by Pang and Oh (2000), that southeastward up-wind flow in the central Yellow Sea pushes the YSBCW eastward to the Cheju Strait, while northward and westward down-wind flows occur along the west

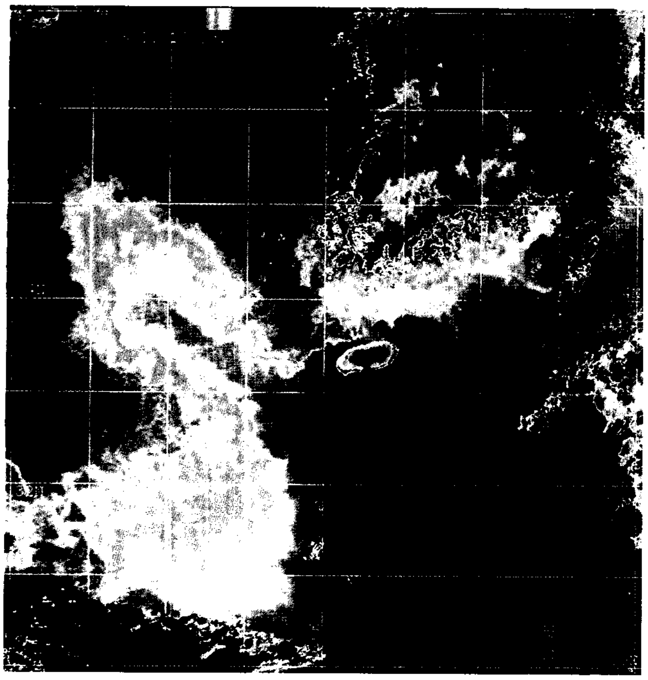

Fig. 5. NOAA AVHRR image on March 17, 1998.

and south coasts of Korean Peninsula, respectively.

General circulation west of Cheju Island is characterized by clockwise flow around Cheju Island and northward flow to the eastern Yellow Sea in the margin of the clockwise flow (Pang and Hyun, 1998). The circulation pattern could be confirmed by trajectories of satellite-tracked drifters, which were released west of Cheju Island (33.088°N-124.102°E and 33.070°N-124.074°E) and flowed northward along the west coast of Korean Peninsula at 15 m depth and eastward to the Cheju Strait at 45 m depth (Pang *et al.*, 2001).

Bottom temperature and salinity at three hydrographic stations along the Line-203 of NFRDI in August are shown in Fig. 9. The Line-203 is located east of Section 1 (see Fig. 1). The bottom cold water (T<12.0C) in Fig. 6 does not appear in Section 2, where bottom temperature ranges 12.0-13.0°C (not shown here). Hence, the cold water below 12.0°C did not penetrate deep into the Cheju Strait in August 1997, that can also be seen in Fig. 9. Abnormally cold water with temperature less than 12.0°C appeared in the Cheju Strait in 1977, 1982, 1984, and 1996. Hence, the cold water intrusion occurred only 4 times in 38 years. The occurrence may be more frequent in the westernmost Cheju Strait as for the case in 1997.

The lowest bottom temperature occurred in 1977 at stations 2 and 3, while bottom temperature was abnormally high at the northern station 1. Winds at Cheju in August 1977 and 1984 are shown in Fig. 10. Hydrographic observations were conducted on 29 August in 1977 and on 7 August in 1984. In 1977, southeasterly wind persisted for about 8 days (16~23) prior to the observation, similar to the case in 1997. On the other hand, wind was weak and variable prior to the observation in 1984. So, the penetration in 1984 may be hard to be explained by wind. It appears that the deep penetration of the YSBCW into the Cheju Strait in summer is not solely wind-driven although the wind may be partly responsible for the penetration. The reason for the abnormally cold water penetration is yet to be studied.

CURRENT AND TRANSPORT

Currents in the Cheju Strait were obtained by tracking TGPS buoys, current meter moorings, and geostrophic calculation. Fig. 11 shows the trajectories of eight TGPS buoys released in the Cheju Strait in 1996 and 1997. Their mean current is 21.4 cm/sec at 76° (measured clockwise from the north). The minimum and maximum speeds are 8.7 cm/sec in April and 52.0 cm/sec in August, respectively. During the periods of buoy tracking, wind speeds were less than 5 m/sec. In the Cheju Strait, currents are generally to the ENE direction and northward components increase in summer as well as eastward components. On the other hand, currents are generally southeastward near Cheju Island. Fig. 12 shows progressive vector diagrams based on currents measured with moored current meters in the eastern Cheju Strait in 1997. The instrument depths are given on the figure. While currents near the central Cheju Strait are steadily eastward, current directions are variable in the eastern part of the strait.

Geostrophic currents, calculated referred to bottom and averaged over all of the four sections, are comparable to directly measured currents around the trough of the Cheju Strait as shown in Fig. 13. Average difference between measured and calculated currents is about 5 cm/sec. According to ADCP (Acoustic Doppler Current Profiler) data deployed at 124 m depth in the trough from March to December, 1998 (see Fig. 1), monthly mean eastward current is about 10 cm/sec in winter and 15 cm/sec in summer at 70 m depth and about 5-6 cm/sec in both seasons at 100 m depth (Teague *et al.*, 2002). Eastward currents measured by our current meter in 1997 are also about 5 cm/sec at around 100 m depth. These fairly constant velocities of 5 cm/sec at about 100 m depth outside the bottom boundary layer can be accepted as the barotropic component. If the barotropic current

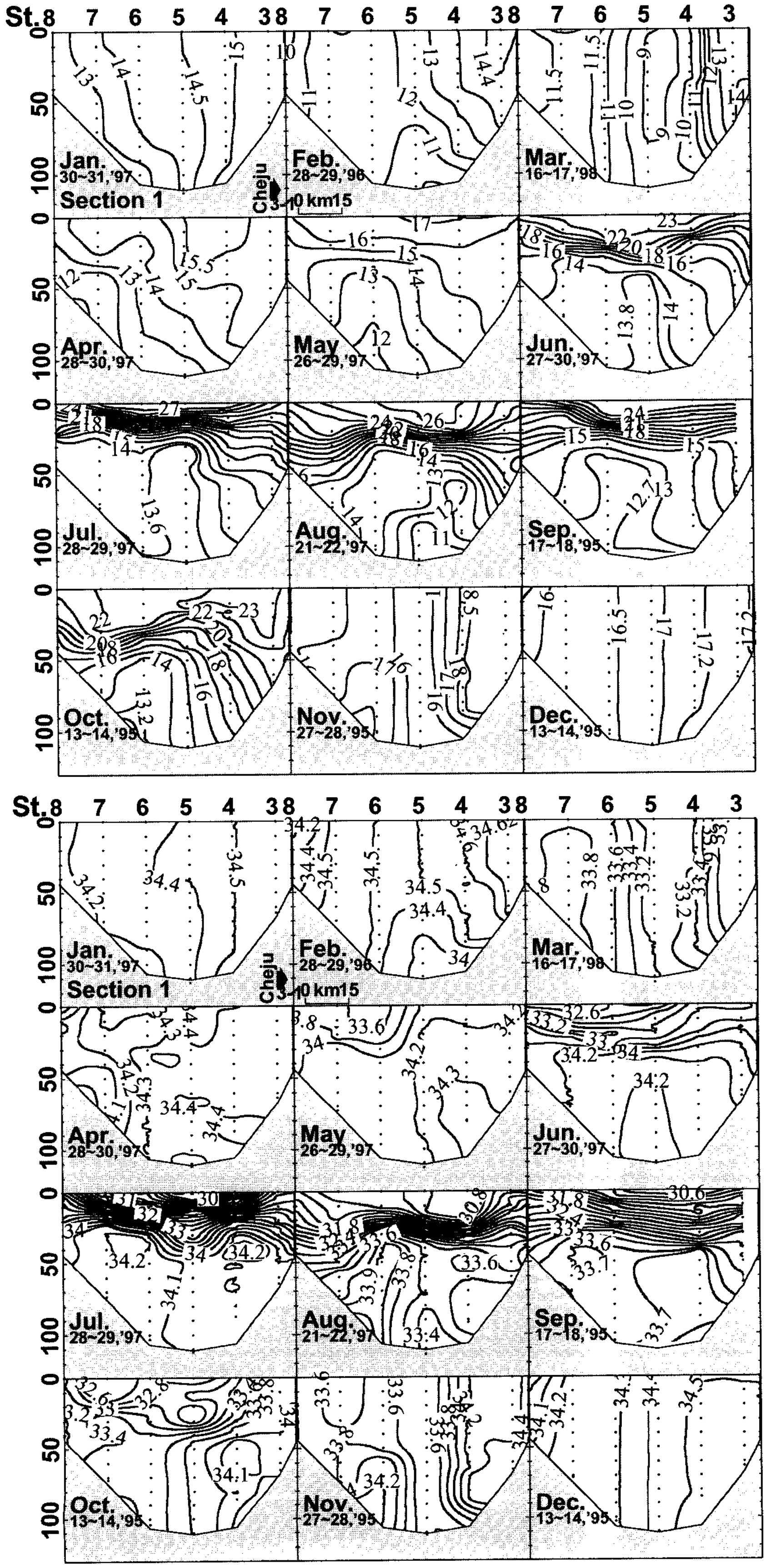

Fig. 6. Monthly vertical profiles of (A) temperature and (B) salinity between September 1995 and June 1998 along Section 1.

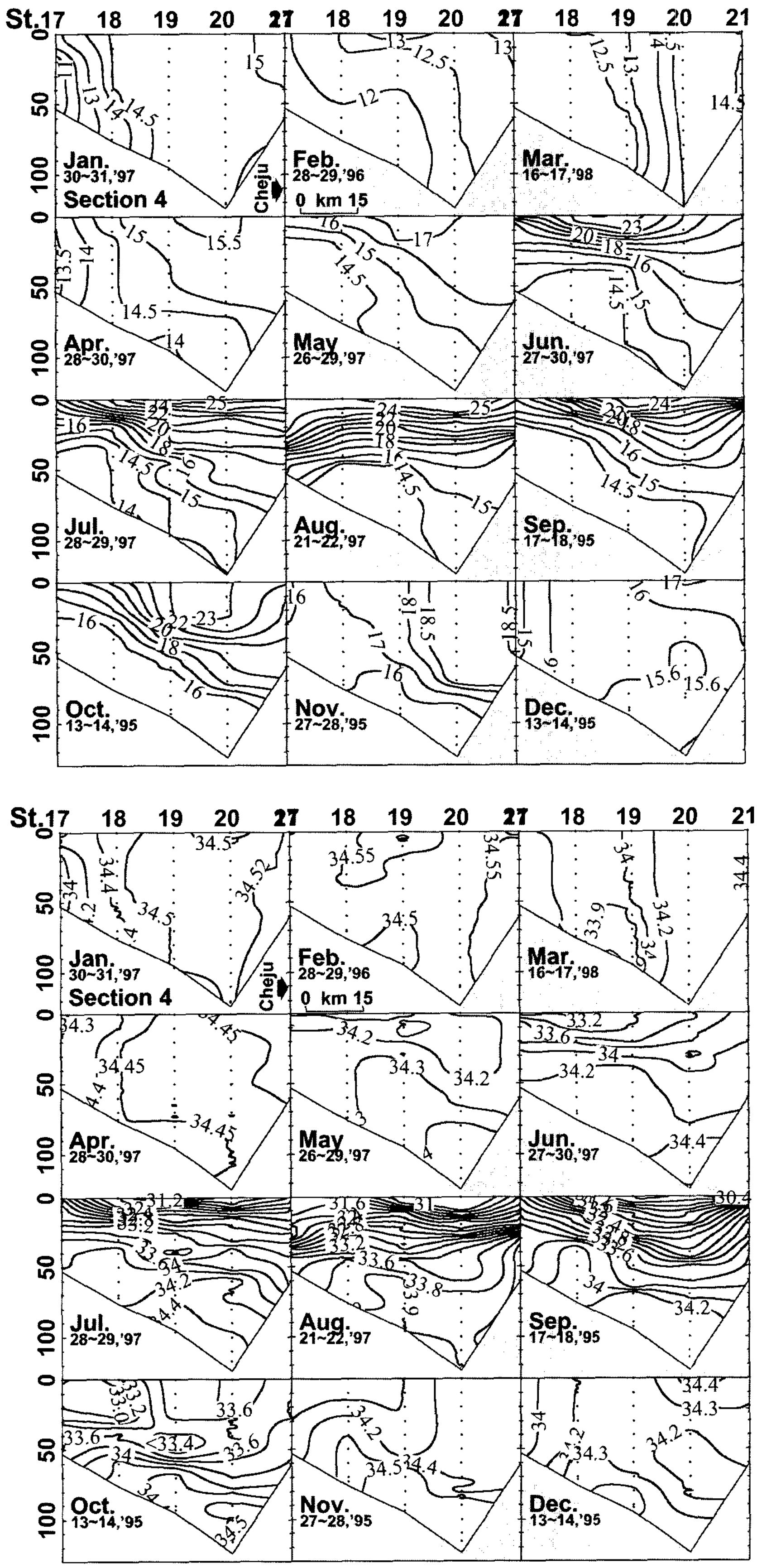

Fig. 7. Monthly vertical profiles of (A) temperature and (B) salinity between September 1995 and June 1998 along Section 4.

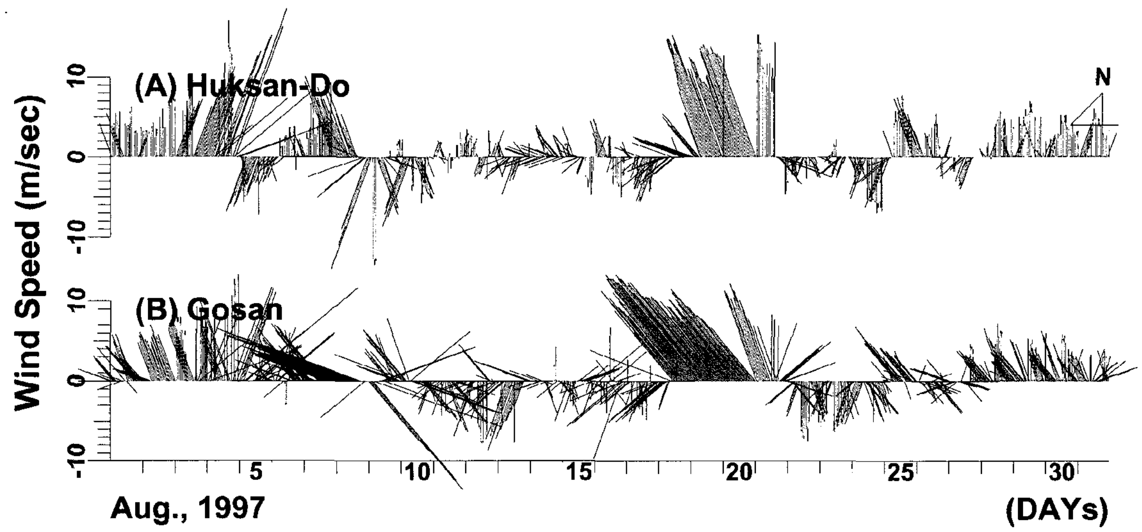

Fig. 8. Wind vectors at (A) Huksan Island and (B) Gosan in August 1997. Strong southeasterly winds lasted about 3 days just before the CTD observation.

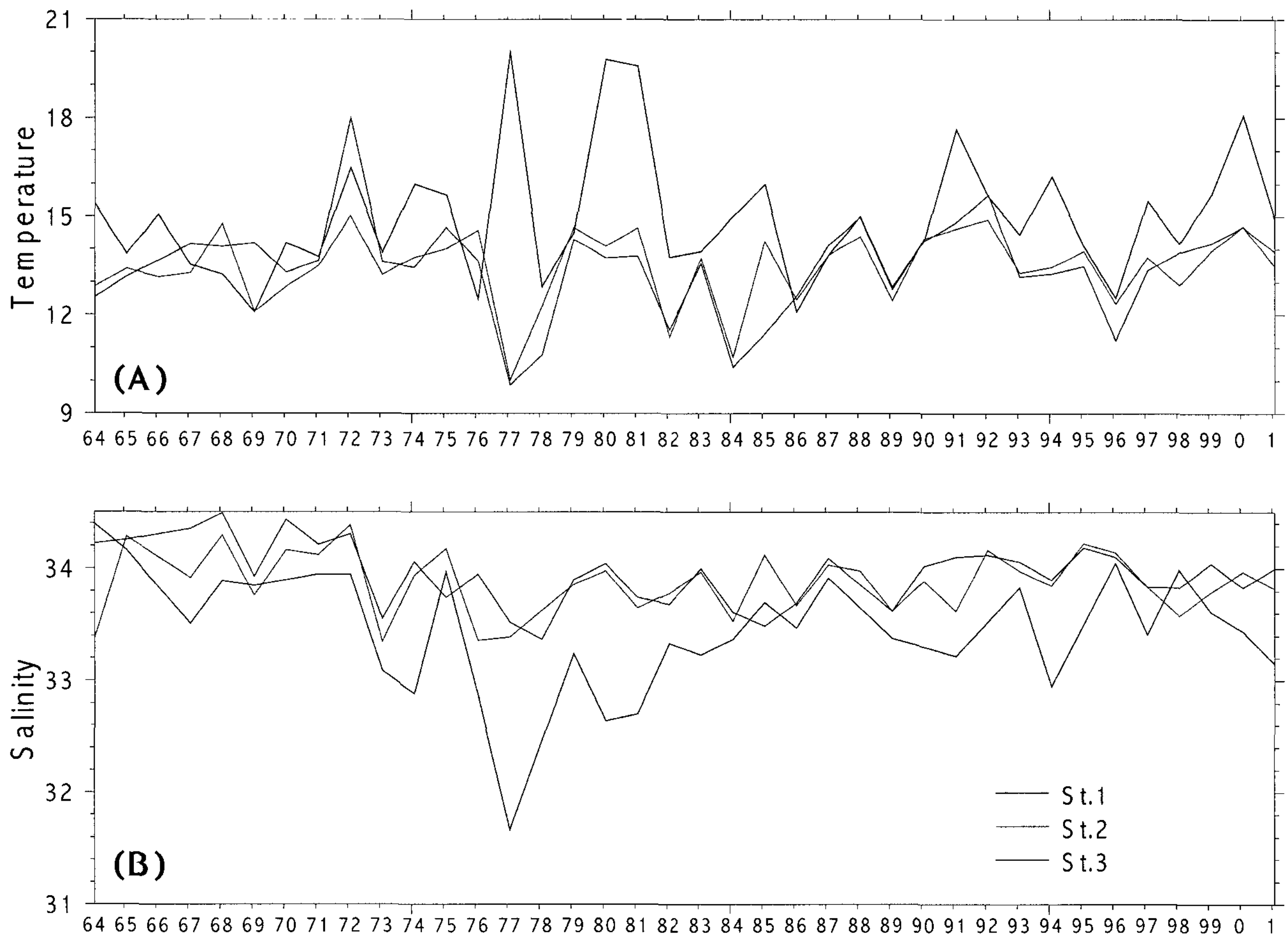

Fig. 9. Bottom (A) temperature and (B) salinity at three NFRDI's stations along 203 line in the Cheju Strait in August between 1964 and 2001.

is assumed roughly the same in the whole section of the Cheju Strait, the barotropic transport would become about 0.2 Sv (Sv=10^6 m^3/s) in the Cheju Strait with the width of 80 km and the averaged depth of 50 m.

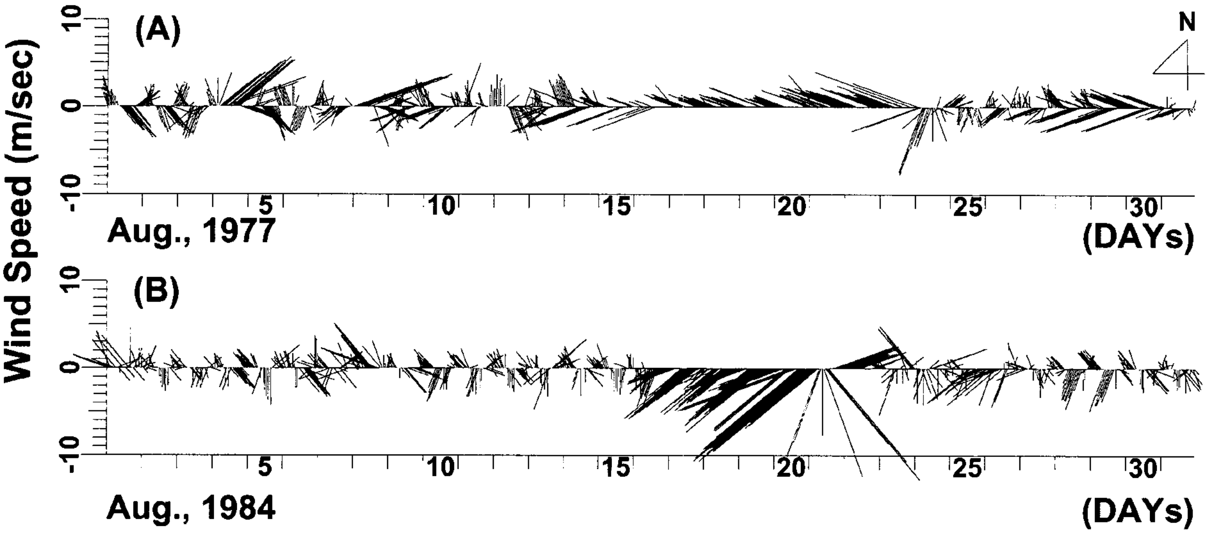

Fig. 10. Winds at Cheju meteorological station in August (A) 1977 and (B) 1984.

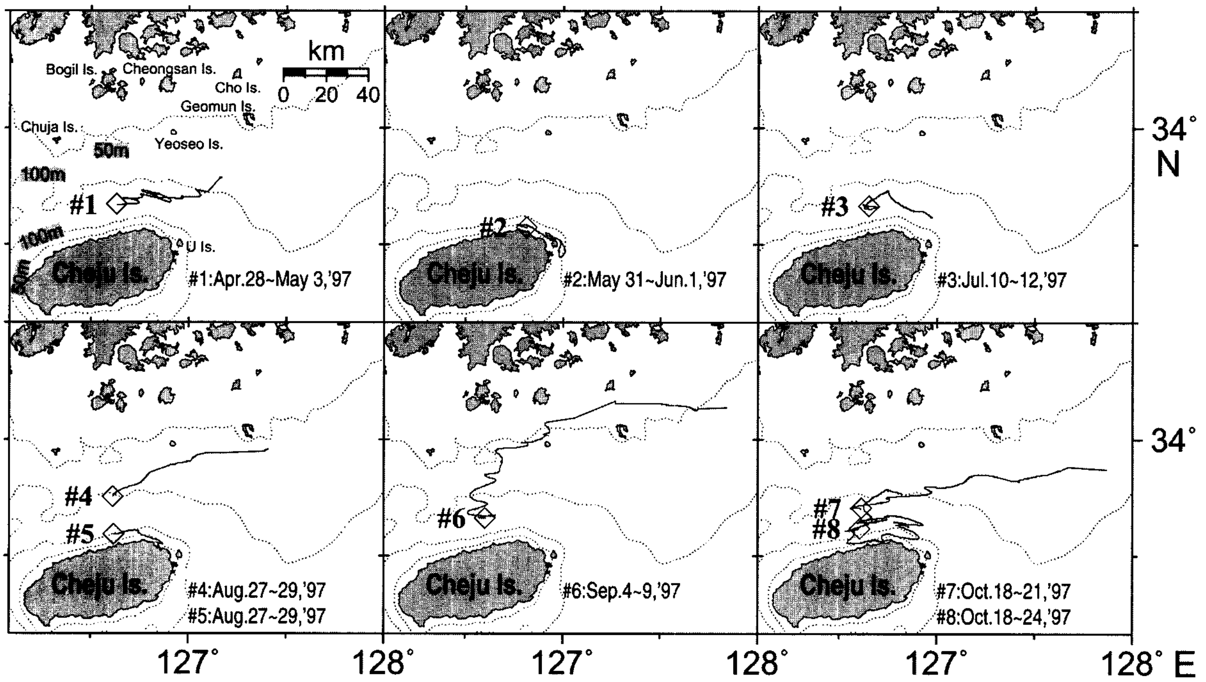

Fig. 11. Trajectories of TGPS buoys released in the Cheju Strait in 1996 and 1997. The locking depths are all 15 m.

Fig. 14 shows vertical profiles of eastward geostrophic current across Section 4. The strong westward currents along the northern and southern coasts of Cheju Strait in August are due to the down-wind flows as mentioned previous section. Northward Ekman transport by southeasterly wind causes sea level rise toward the northern coast of the strait while an process similar to the coastal upwelling would occur on the Cheju Island side, both effects induce a westward current. Particularly strong wind of August 1997 (Fig. 8) would play a significant influence of the circulation in the strait. However, the direction of eastward Tsushima Current in the central region of the strait is not easily reversed by the opposing wind.

Fig. 15 shows the monthly variation of mean geostrophic transport across the four sections in the Cheju Strait. The geostrophic transport in August is smaller than the transports in other summer months because of strong westward flows near the coasts. As mentioned previously, the strong westward flows

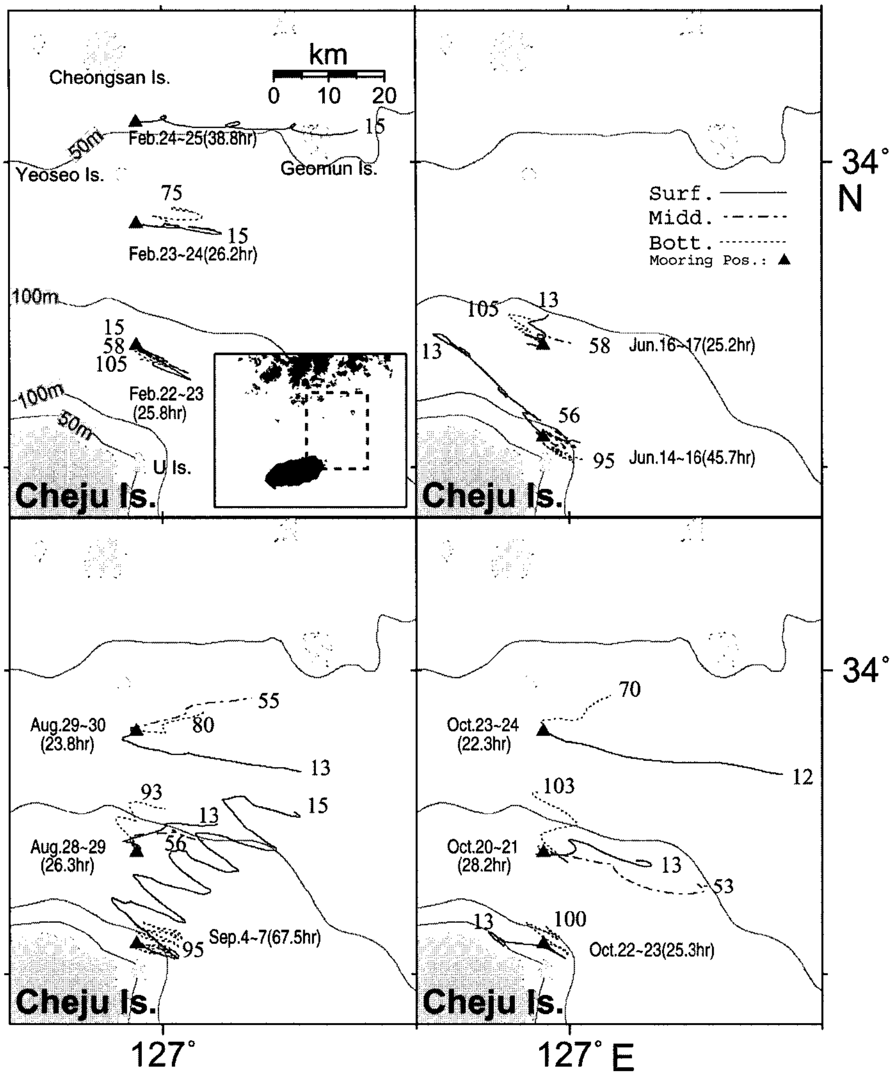

Fig. 12. Progressive vector diagrams for moored current data obtained in the eastern Cheju Strait in 1997.

are driven by strong southeasterly winds over 10 m/sec for three days just before the observation. Long-term ADCP measurement shows that strong easterly winds due to the passage of typhoon induces a full-depth westward flow in the southern Cheju Strait (Teague *et al.*, 2002). Monthly transport of geostrophic current (baroclinic component) varies roughly from 0.1 Sv in winter to 0.4 Sv in summer. When we add the barotrophic component of 0.2 Sv, the total transport varies from 0.3 Sv to 0.6 Sv, which is close to the previous results (Pang and Oh, 1994; Chang *et al.*, 2000). Average volume transport between October and December 1999 based on concurrent current measurements are 0.14 Sv through the Taiwan Strait, 0.59 Sv for the Cheju Strait, and 3.17 Sv for the Korea Strait (Teague *et al.*, 2003). Hence, about 20% of total transport through the Korea Strait comes from the Cheju Strait, while remaining 80% from an area between Cheju Island and Kyushu.

SEASONAL VARIATION OF TRANSPORT

The seasonal variation of current in the Cheju Strait occurs mainly in the baroclinic component. Hence, the variation is thought to be associated with water mass distribution. As shown in Fig. 2, the spatial range of density, hence the dynamic depth anomaly, is small in winter and large in summer. The large spatial density range means the co-existence of different water masses. It also means that coastal water off the southwest coast of Korea expands to the Cheju Strait in summer. Due to the expansion of coastal water, a stronger thermal front is formed near Cheju Island in the lower layer between colder water in the central Cheju Strait and warmer water near Cheju Island in summer, as shown in Figs. 3 and 4. The thermal front runs northeastward to Yeoseo Island. The front makes current strong and leads to an increase in the transport in summer. On the other

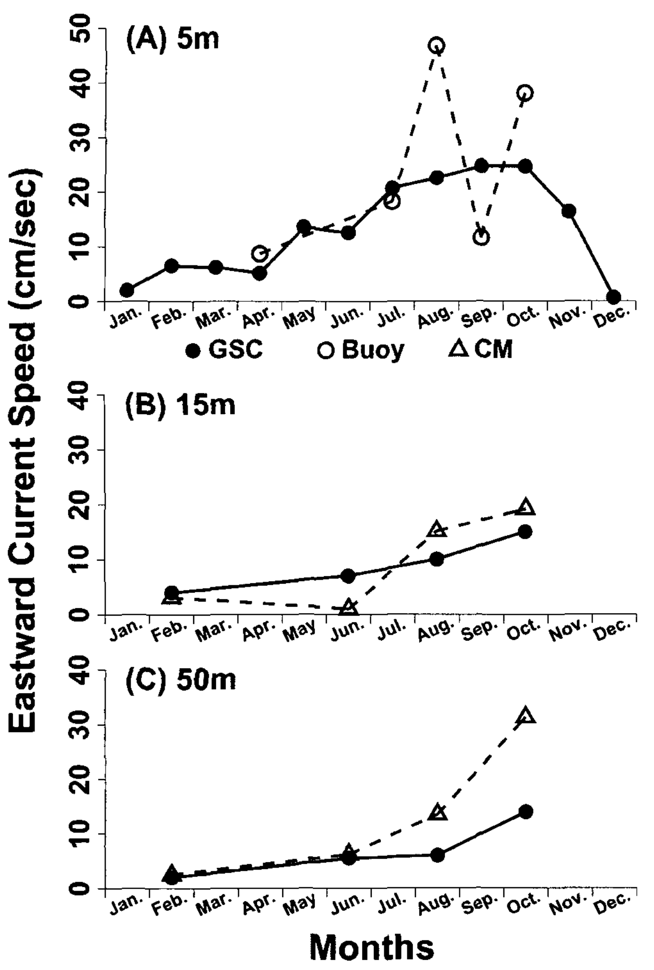

Fig. 13. Comparisons of the eastward geostrophic current (GSC) with the eastward currents measured by TGPS buoys (Buoy) and moored current meters (CM) in the Cheju Strait. Positions of TGPS and current meters are the same as Fig. 11 and Fig. 12, respectively.

hand, small density range in winter means that similar water masses are prevalent. It can be explained by the expansion of TCW in this area in winter.

Temperature and salinity of TWC at Section 1 are generally higher in winter and lower in summer than those at Section 4 (Figs. 6 and 7). It suggests that warm and saline water is supplied to the Cheju Strait from the west in winter and from the east of Cheju Island in summer. It supports the expansions of TCW toward the Yellow Sea in winter and coastal water toward the East China Sea in summer. In winter, TCW expands to the Yellow Sea and flows eastward to the Cheju Strait. In summer, coastal water expands southward to the East China Sea from the Yellow Sea to increase the transports in the Cheju Strait, and the Tsushima Current flows northeastward through the east of Cheju Island. So, the seasonal variation of transport in the Cheju Strait can be interpreted to be caused by the seasonal circulation between the East China Sea and the Yellow Sea.

CONCLUSION

The monthly hydrography in the Cheju Strait between September 1995 and June 1998 shows that the Cheju Strait is occupied mostly by TWC and coastal waters in winter and summer, respectively. The highest temperature and salinity water appears in the region southwest of the Cheju Strait in winter and in the region southeast of the Cheju Strait in summer. Temperature and salinity in the western Cheju Strait (Section 1) are higher in winter and lower in summer than in its eastern part (Section 4), suggesting that TWC and coastal waters are dominant in the region west of the Cheju Strait in winter and summer, respectively.

In summer, low salinity water with salinity down to 30‰ (Yangtze Coastal Water) appears in the upper layer and cold water in the lower layer west of the Cheju Strait. Especially, very cold water ($T<11°C$, Yellow Sea Bottom Cold Water) appeared in the lower layer in August 1997, and a warm water column usually shown off Cheju Island in the western Cheju Strait was not obvious. It suggests that the clockwise flow of warm water along the northwestern coasts of Cheju Island could be disturbed by an eastward expansion of cold water from the northwest of the Cheju Strait. According to geostrophic currents, a strong westward flow appeared along the northern coast of Cheju Island in August 1997, which seems to be driven by wind. Very strong southeasterly winds over 10 m/sec had lasted for three days just before the observation. Such strong winds can drive sufficiently strong up-wind and down-wind flows. It might explain how very cold water appeared in the Cheju Strait can be linked with the Yellow Sea Bottom Cold Water that distributes northwest off the Cheju Strait in summer.

Currents in the Cheju Strait obtained by TGPS buoys, current meters, and geostrophic calculation are generally eastward. The eastward currents increase in summer as well as northward components. Current directions are steadily eastward in the central area, but largely variable near Cheju Island. According to ADCP data gathered in the trough from March to December, 1998, the eastward barotropic component is nearly steady in the whole period with a speed of about 5 cm/sec. The barotropic transport is esti-

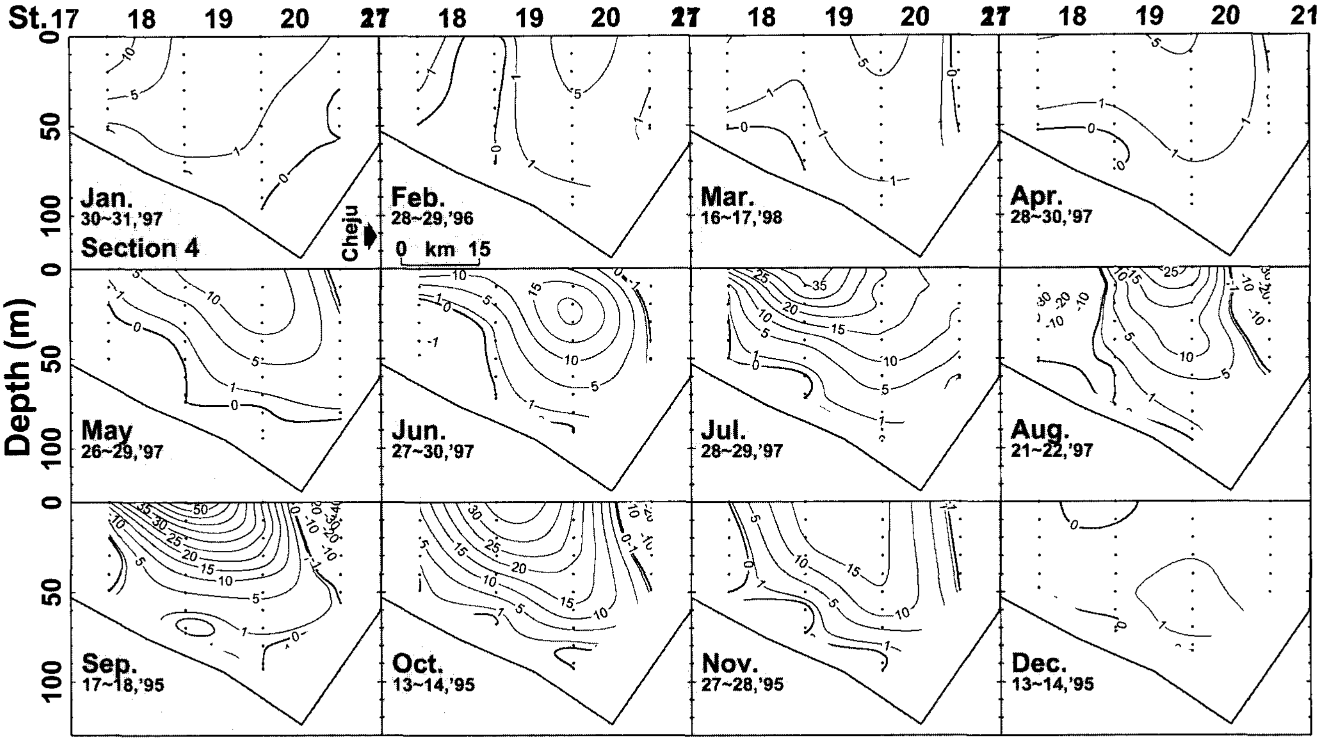

Fig. 14. Monthly vertical profiles of geostrophic currents along Section 4.

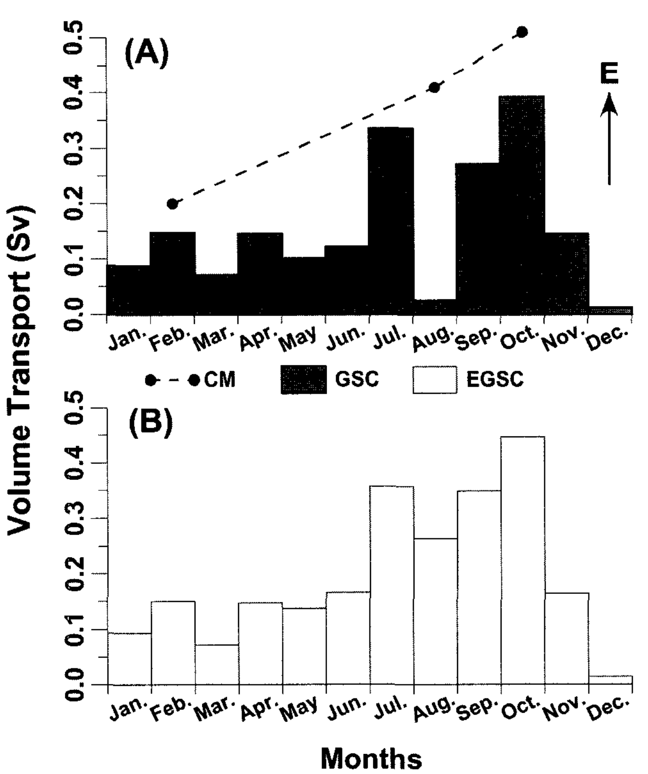

Fig. 15. Monthly variation of total (GSC) and eastward (EGSC) volume transports across the Cheju Strait calculated by averaging the geostrophic transports across the four sections. Volume transports based on directly observed current data are also shown (●).

mated to be about 0.2 Sv in the Cheju Strait based on the ADCP data, assuming the barotropic component has a similar magnitude over the entire Cheju Strait. Geostrophically calculated currents referred to bottom are close to directly measured currents with an averaged difference of about 5 cm/sec. The monthly geostrophic transport varies 0.1 Sv in winter to 0.4 Sv in summer. Adding the barotrophic component of 0.2 Sv, the total transport variation ranges from 0.3 Sv to 0.6 Sv, which is consistent with previous results.

The baroclinic component seems to contribute mainly to the seasonal variation of current in the Cheju Strait, while the barotropic component is nearly constant in the seasonal time scale. Then, the variation can be explained by water mass distribution. Water mass groups in T-S diagram form straight lines parallel to isopycnals in winter and perpendicular in summer. Hence, the horizontal gradient of dynamic depth anomaly is large in summer and small in winter, that is caused by the expansion of Tshshima Current water in winter and coastal water in summer to the Cheju Strait. In summer, coastal water expands southeastward from the Yellow Sea to increase transports in the Cheju Strait and the East China Sea. The variation of transport in the Cheju Strait may be caused by the seasonal circulation between the East China Sea and the Yellow Sea.

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