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Distribution and Transport of Suspended Particulate Matter, Dissolved Oxygen and Major Inorganic Nutrients in the Cheju Strait

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Distribution of suspended particulate matter, dissolved oxygen and major inorganic nutrients along a meridional section (126° 33' E) in the Cheju Strait is described along with the hydrographic and current data obtained during April 25-27, 1995. The current measurements was conducted using a vessel-mounted Acoustic Doppler Current Profiler (ADCP). Repeated coverage along an ADCP transect during 25 hours allows to calculate the daily mean along- and cross-strait currents. Measured material concentrations and the mean current speed were used to estimate the flux density (concentration times current speed) of materials. Two types of depth distribution of flux densities were observed. For nitrate and suspended particulate matter, the depth distribution pattern of materials determines those of flux densities. However, flow patterns determine those of flux densities for dissolved oxygen, phosphate and silicic acid. The total along-strait water volume transport is about 0.3 Sv (1Sv 10^6 m^3/s^{-1}). The total along-strait material transports are estimated to be 3.1×10^5 g/s^{-1}, 2.4×10^6 g/s^{-1}, 7.1×10^2 mol/s^{-1}, 3.1×10 mol/s^{-1}, 1.7×10^3 mol/s^{-1} for suspended particulate matter, dissolved oxygen, nitrate ion, silicic acid and phosphate ion, respectively.

INTRODUCTION

The Cheju Strait located between Cheju-Do (Island) and the southwestern coast of Korea is about 70 km long and 70 km wide. The isobaths run mainly parallel to the east-west direction and the bottom topography rapidly deepens toward Cheju-Do and forms the "Cheju Trough" and slowly shoals towards the Korean coast. A mean eastward flow has been documented in the Cheju Strait (Kim, 1979; Kim *et al.*, 1991; Beardsley *et al.*, 1992; Chang *et al.*, 1995), so it serves as a conduit for the transport of chemical materials from the Yellow and East China Seas to the southern shelf of Korean Peninsula and ultimately to the East Sea (Japan Sea). A branch of the Kuroshio characterized by warm and saline waters enters the Cheju Strait after turning around the western coast of Cheju Island and appears in the southern part of the Cheju Strait (Kim *et al.*, 1991; Chang *et al.* 1995). However, in the northern part, the current regime is not clearly understood, although it has been suggested that a coastal current transports water (Cho and Kim, 1995), suspended particulate matter (Wells and Huh, 1984) and the fine sediments (Chough, 1983) from the Yellow Sea into the South Sea. Highly turbid waters hugging the Korean coast can be readily distinguished from the less turbid offshore waters in satellite images (Yoo, 1986).

While quantification of fluxes of water and chemical materials across the Cheju Strait is essential to estimate chemical mass balances on the southern shelf of the Korean Peninsula, no data have been available to quantify the fluxes so far. Spatial distribution of daily mean currents across a meridional section in the Cheju Strait was therefore obtained in this study through repeated coverage of a fixed ADCP transect for 25 hours in April 1995. The data along with simultaneous chemical casts provide a unique opportunity to estimate fluxes of chemical components. The principal objectives of this study are to describe the depth distribution of suspended

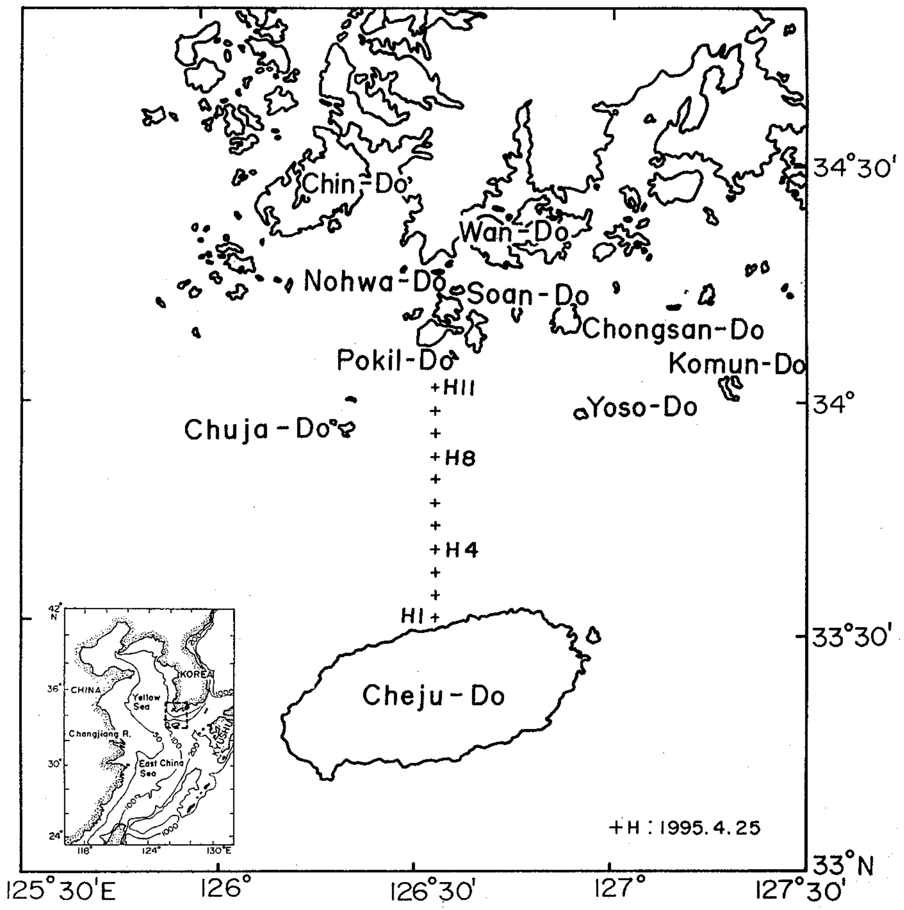

Fig. 1. Positions of hydrographic stations occupied in the Cheju Strait on 25, April 1995. ADCP observations were repeated 8 times along a 30 mile-long line between stations H1 and H11 during 25 hours from 26 to 27, April.

particulate matter and major inorganic nutrients, and to estimate water and material transport rates across the Cheju Strait.

MATERIALS AND METHODS

ADCP observations were repeated 8 times during 25 hours along a 48 km-long line between Cheju-Do and Pogil-Do(Island) in order to remove dominant tidal current components and to obtain daily mean currents (Fig. 1). Ship's velocity was maintained constant during these observations. Daily mean currents are computed at each hydrographic station by a simple averaging method. More details of the observation method and data analysis are given by Suk (1996).

Eleven hydrographic stations (every 4.8 km interval) were occupied along the same section as the ADCP transect approximately one day before the first ADCP observation. Continuous temperature and salinity (conductivity) profiles and discrete water samples were obtained using a MARK IIIB CTD - Rossette assembly fitted with twelve 10-liter Niskin bottles. While the assembly was lowered to the near-bottom, water samples were taken only up to 50 m depth due to the malfunction of Rossette triggering unit. During the observational periods, the sea state was very calm with only a weak wind.

Accuracy of the conductivity probe of the CTD was checked by determining conductivity using an AUTOSAL salinometer calibrated with IAPSO standard seawater. The precision of the measurement was ±0.005. Dissolved oxygen was determined in discrete samples using the Winkler titrimetric method (Carpenter, 1965) with a precision of ±0.5% at 250 mmol kg^{-1} level. Water samples for nutrient analysis were filtered through Whatman GF/F glass fiber filters and deep frozen for later analysis. Nitrate, reactive phosphate, and silicic acid were determined using an autoanalyzer (Technicon II). Nitrate was determined by the Greiss reaction. Phosphate was determined by the molybdenum blue method. Silicic acid was determined by the silicomolybdenum blue method (Parsons et al. 1984). Suspended particulate matter (SPM) concentration was determined with a precision of ±0.02 mg l^{-1} by water bottle sampling and immediate filtering through pre-weighed 0.4 mm pore-size Nucleopore filters.

Along-strait fluxes were calculated by multiplying the mean current speed by the chemical concentrations (Wunch *et al.* 1983; Brewer *et al.* 1989; Rintoul and Wunsch, 1991; Chen *et al.*, 1994; Chen, 1995).

RESULTS

Hydrography

Temperature and salinity varied from 12.5 to 15.0°C and 34.25 to 34.55, respectively (Fig. 2). Seasonal thermocline had not developed yet and the water column was weakly stratified. Temperature and salinity decrease and the density increases from the south to the north. Horizontal temperature gradient is relatively strong in the south of the Cheju Trough while salinity changes sharply between stations 10 and 11 near Pogil-Do. Water of high salinity (> 34.4) and high temperature (> 13.0°C) south of station 10 is thought to originate from the Kuroshio, which enters the Cheju-Strait after turning around the west coast of Cheju-Do (Chang *et al.*, 1995; Chang and Kim, 1996). This water belongs to group 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). Isopleths of temperature and density deepen toward the Cheju Trough from the north. A low salinity core appears at station 5 up to 50 m depth which has been documented in the middle of the strait in spring (Chang *et al.*, 1995). However, the value of the core in this study is higher by about 0.6 than that in the previous one by Chang *et al.* (1995). The low salinity core which appears in the middle of the strait in spring was attributed to the intrusion of low salinity water from the west of the Cheju Strait (Chang *et al.*, 1995). However, mesoscale phenomena such as frontal features (Han, 1989) and/or eddies may be responsible for the appearance of the isolated core in a section like Fig. 2. Since density of seawater is largely determined by the temperature in the temperate climate of the study area, vertical profile of density (Sigma-t) is similar to that of temperature. Water properties are relatively homogeneous between stations 6 and 8 and in the upper layer between stations 3 and 4.

Current Structure

Basically the flow is mainly eastward (along-strait direction) as documented (Fig. 2). Isopycnal slopes are consistent with the mean flow direction suggesting a geostrophic balance. The maximum vertical speed difference of the along-strait flow is about 20 cm s^{-1} in the deeper part of the strait where the horizontal density gradient is large, indicative of the strong baroclinicity. Two high speed cores of along-strait flow appear in the upper 50 m depth where the physical properties are relatively homogeneous. The southern warm core, the maximum speed of which is higher than 16 cm s^{-1}, is located 15 miles off Cheju-Do. The northern cold core with speed of about 10 cm s^{-1} is located at 27 miles from Cheju-Do. Near the bottom of the Cheju Trough, water flows to the west very slowly. This westward bottom flow was also observed from the bottom tethered moored current meter during the same period as the ADCP observations (Suk, 1996). Cross-strait flow is relatively weak (< 8 cm s^{-1}) and is mainly northward. Maximum northward flow was observed in the lower layer of station 10. In the upper 50 m where low salinity

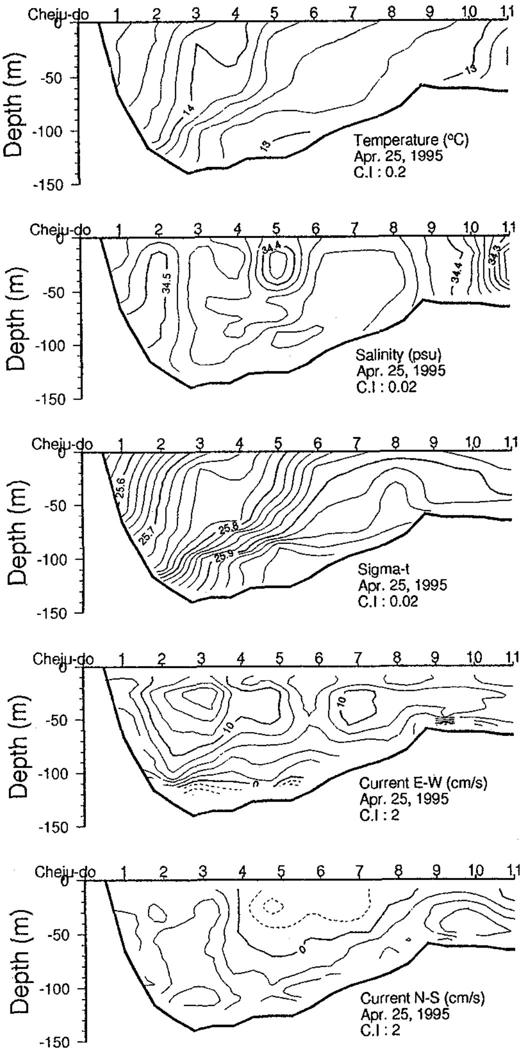

Fig. 2. Vertical profiles of temperature, salinity, density (σ_t), along-strait and cross-strait daily-mean current components from the top. Positive values in the current profiles represent eastward and northward flows for the along- and cross-strait currents respectively.

lens appears, a very weak southward flow was also observed. Relatively long-term moored current measurement for twenty days roughly between stations 3 and 4 in Fig. 2 in April, 1983 gave a mean along- and cross-strait currents of 11 cm s^{-1} and 6 cm s^{-1}, respectively, at 30 m depth (Chang and Kim, 1996), which is comparable to the present results.

After Chang *et al.* (1995), we call the southern warm water flow the Cheju Warm Current and northern cold water flow the Cheju Cold Current. We call the eastward water flow across the Cheju Strait as the Cheju Current.

Depth distribution of chemicals

Distributions of suspended particulate matter, dissolved oxygen and major inorganic nutrients are shown in Fig. 3. Suspended particulate sediment (SPM) content is high in the north (4.8 mg l^{-1}) near Pokil-Do and low in the south (0.5 mg l^{-1}). The SPM content is smaller than that observed in the Cheju Strait in November 1980 and 1981 (5 mg l^{-1} to 20 mg l^{-1}, Wells and Huh, 1984), which is suggestive of seasonal and/or interannual variability. A turbidity front is present between stations 9 and 11 in the upper layer, while it is located farther to the south in the bottom layer. A tongue of relatively high SPM content extends from the middle layer of station 7 to the surface layer toward the south where a weak southward mean flow is seen.

Dissolved Oxygen (DO) concentrations are generally high in the north and low in the south, and vertically homogeneous in the central part of the strait. Subsurface concentration maximum occurs at 10 m depth in the north and 20-30 m depth in the south, probably due to the phytoplankton bloom.

Nitrate ion concentrations are high in the north (4.0 μmol l^{-1}) and low in the south (1.1 μmol l^{-1}). Nitrate concentrations are vertically homogeneous in the warm south and peak at subsurface in the cold northern region. A high nitrate tongue stretches down from the surface of the northern part (station 11) to the 50 m depth toward the south (station 7) Phosphate ion concentrations are high in the north (0.25 μmol l^{-1}) and low in the south (0.1 μmol l^{-1}). A very low concentration was observed in the saline (salinity >34.45) waters. Silicic acid concentrations are high in the north and low in the south, however, the meridional concentration difference is relatively weak compared to other chemicals determined.

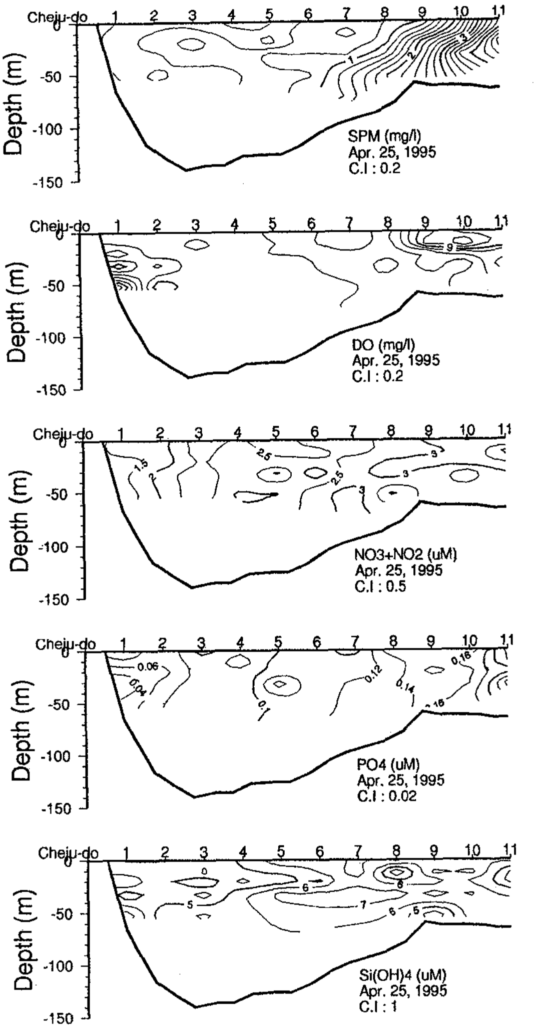

Fig. 3. Vertical profiles of suspended particulate matter, dissolved oxygen, nitrate, phosphate and silicic acid concentrations.

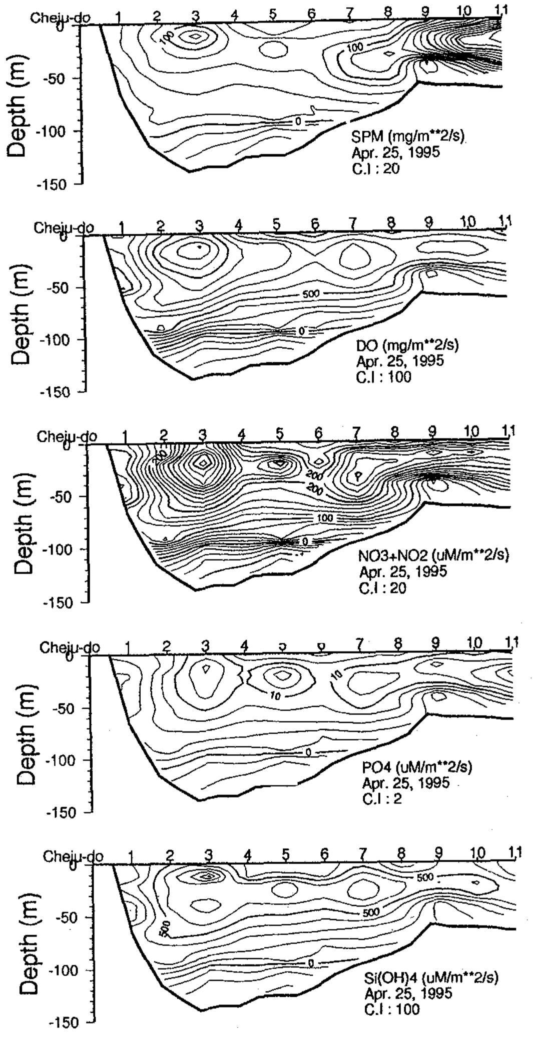

Fig. 4. The along-starit material fluxes per unit area (flux-density) of suspended particulate matter, dissoved oxygen and nutrients in the Cheju Strait calculated by multiplying mean current speed by concentration.

Along-strait transports of SPM, oxygen and nutrients

The along-strait fluxes of water, SPM, oxygen and nutrients in the Cheju Strait were calculated by multiplying the mean current speed by their concentration. Fig. 4 shows material fluxes per unit area (flux-density). The ADCP data is available from 13 m depth and shallower depth values are extrapolated to calculate fluxes. As the chemical casts were conducted only to 50 m depth, the concentration of chemicals is also extrapolated down to the bottom and then multiplied by the mean current speed to calculate fluxes. Table 1 summarizes the gross and annual fluxes of each material. The calculated annual flux should be regarded only as the first order of magnitudes since the temporal variability was not taken into account. At present, there exist not enough data to calculate the water and material fluxes through the Cheju Strait with a resonable accuracy. According to Chang and Kim (1995), the

Table 1. Along-strait material fluxes in the Cheju Strait.

chemicals	fluxes			
	full depth		50 m depth	
	gross flux	annual flux	gross flux	annual flux
suspended matter	3.1×10^{8} mg s^{-1}	9.9×10^{6} ton yr^{-1}	2.7×10^{8} mg s^{-1}	8.4×10^{6} ton yr^{-1}
diffolved oxygen	2.4×10^{9} mg s^{-1}	7.6×10^{7} ton yr^{-1}	1.9×10^{9} mg s^{-1}	6.1×10^{7} ton yr^{-1}
nitrate	7.1×10^{8} μmol s^{-1}	2.3×10^{10} mol yr^{-1}	5.8×10^{8} μmol s^{-1}	1.8×10^{10} mol yr^{-1}
phosphate	3.1×10^{7} μmol s^{-1}	9.9×10^{8} mol yr^{-1}	2.6×10^{7} μmol s^{-1}	8.1×10^{8} mol yr^{-1}
silicate	1.7×10^{9} μmol s^{-1}	5.3×10^{10} mol yr^{-1}	1.4×10^{9} μmol s^{-1}	4.3×10^{10} mol yr^{-1}

standard deviation of along-strait currents both at 30 m and 60 m depths is about 50% of the 20-day mean currents in spring, 1983. One day mean currents at three locations in the Cheju Strait in March and August, 1973 show maximun seasonal difference of about 20% at 5 m depth (Kim, 1979). Standard deviation of depth-integrated nitrate concentration is about 20% of the annual mean concentrations in the mouth of the Yellow Sea (Hong *et al.* 1994). Hong *et al.* also showed that the standared deviations of nitrate, phosphate, and silicate concentration in the Yellow Sea are about 60, 60 and 50 to 80% of the regional means of nutrient concentraions in the well mixed coastal and stratified central regions during September 1992, respectively. Therefore, we think that the calculated annual flux in Table 1 contains an error of about 50% or less due to the neglect of any temporal variability of flows. For comparison, the fluxes down to 50 m depth are also shown together with extrapolated full depth fluxes. Along-strait transports of materials to the east appear to be dominated by the upper 50 m layer due to the rapid decrease in the flow with depth below 50 m.

Total water volume transport is estimated to be about 0.3 Sv, which is nearly the same as the baroclinic volume transport through the Korea Strait in April (Yi, 1966) and about 30% of the total transport measured by ADCP in April, 1990 (Isobe *et al.*, 1994). The mean volume transport through the Cheju Strait calculated using historical current meter data was 0.5 Sv (Miita and Ogawa, 1984), which is about 40% larger than the present calculation.

Flux-density of SPM varies from -60 to 340 mg m^{-2} s^{-1}. Depth distribution of flux density is largely dominated by the concentration structure. The annual flux of SPM in the Cheju Strait estimated to be 9.9×10^{6} ton yr^{-1} eastward, is only a small fraction of SPM flux transported to the south by the Yellow Sea Coastal Current ($60\text{-}600\times10^{6}$ ton yr^{-1}; Wells and Huh, 1984). Since our sampling stations did not include the area north of Pokil-Do where the extreme turbid water prevails, the present estimate on the flux-densities of materials should be regarded as a lower limit. If a major SPM flux comparable to Wells and Huh's estimate takes place through a narrow passage (~10 km) between Pogil-Do and the southwestern coast of Korea, the mean concentration in the passage should be two or three times higher than the maximum surface value (~100 mg^{-1}) observed in the southeastern part of the Yellow Sea, which is unlikely to happen. A significant reduction of SPM carried by the southward flowing Yellow Sea Coastal Current seems to take place during its passage into the Cheju Strait.

Flux-density of DO varies from -500 to 1300 mg m^{-2} s^{-1} and peaks in the upper layer of stations 2 and 3. Although the flux-density is dominated by concentration and velocity, the flux-density structure of dissolved oxygen was similar to the velocity structure. Flux-density of nitrate varies from -140 to 440 mmol m^{-2} s^{-1}. In the Cheju Warm Current region, the flux-density is dominated by the velocity structure, while in the Cheju Cold Current region, the flux-density is dominated by the concentration structure. Flux-density of phosphate ranges from -6 to 16 mmol m^{-2} s^{-1}. The depth distribution of the flux-density of phosphate is similar to that of nitrate. Flux-density of silicic acid varies from -500 to 1000 mmol m^{-2} s^{-1}. Depth distribution of the flux-density of silicic acid is similar to that of dissolved oxygen.

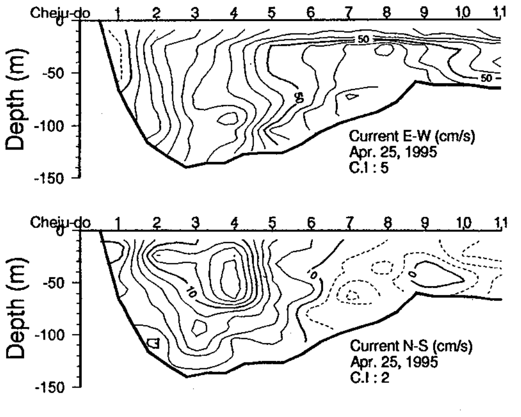

Fig. 5. Vertical profiles of the along- and cross-strait components of instantaneous currents obtained during the period of hydrographic and chemical casts.

SUMMARY AND DISCUSSIONS

Simultaneous hydrographic, chemical and current measurements were made in the Cheju Strait in April, 1995. Repeated coverage of a fixed ADCP transect allowed elimination of tidal contribution to total flow effectively and estimation of water and material fluxes cross the strait.

Main conclusions of present study are as follows:

1. In the Cheju Strait, cold, turbid and nutrient-rich water in the north and warm, clear and nutrient-depleted water in the south are separated by the turbidity front at 48 km from Cheju-Do.

2. The eastward flowing along-strait flow is dominant as previously documented and isopycnal slopes are consistent with the mean flow direction in a geostrophic sense. The vertical shear of the along-strait flow is large in the deeper part of the strait where the horizontal density gradient is large. The along-strait flow has two cores in the upper 50 m depth. The southern warm core, with a maximum flow of more than 16 cm s^{-1}, is located 24 km from Cheju-Do. The northern cold core, whose maximum flow speed is 10 cm s^{-1}, is located 43 km from Cheju-Do.

3. It appears that materials in the cold and turbid water are transported from the upstream region in the coastal band of the southeastern Yellow Sea, but with a significant reduction for the case of suspended matter, compared with previous results by Wells and Huh (1984).

4. The total volume transport is estimated to be 0.3 Sv. The total along-strait transport of materials are estimated to be 3.1×10^5 g s^{-1}, 2.4×10^6 g s^{-1},, 7. 1×10^2 mol s^{-1}, 3.1×10 mol s^{-1}, 1.7×10^3 mol s^{-1} for suspended particulate matter, dissolved oxygen, nitrate, silicate and phosphate respectively in April 1995.

5. Two types of the depth distribution of flux density were observed. For nitrate and suspended particulate matter, the depth distribution pattern of materials determine those of flux densities. However, flow patterns determine those of flux densities for dissolved oxygen, phosphate and silicic acid.

Although the above conclusions are based on mean current averaged over a day, the along-strait fluxes of water and materials have been estimated for the first time in the Cheju Strait, which may provide a guide for future studies on material exchanges between the Yellow Sea and the South Sea of Korea. Since the low-frequency variability of the sub-tidal flow was found in the Cheju Strait (Chang and Kim, 1996), a long-term observational plan needs to be established.

A mechanism for the material exchange across the turbidity front is also very important to understand the land-ocean interaction in the Yellow and East China Seas due to the presence of turbidity front along the coast of Korean Peninsula. In the Cheju Strait the turbidity front is located farther to the south in the lower layer. In general, the density of SPM varies from 1.03 to 2.65 g cm^{-3} (Hong, 1986). SPM is heavier than seawater and tends to sink to the bottom. Since the distribution pattern of SPM is very similar to that of sigma-t in the northern part of the Cheju Strait, the along-isopycnal diffusive flux of SPM to the south may be possible in the cross-strait direction against the mean northward advective flux (Fig. 2). A rough estimate of eddy diffusivity for this case ($K_h > U_d \times L_d$, where U_d is the northward velocity scale (5 cm s^{-1}) and L_d is the width of the turbidity front (20 km)) yields $K_h >$ 1000 m^2 s^{-1}, which is not an unrealistic value and comparable to the value by Lee and Kim (1989) who estimated eddy diffusivity in the Yellow Sea. For the value of $K_h = 1000\ m^2\ s^{-1}$, the associated diffusion time scale ($T_d \sim L_d^2 \times K_h^{-1}$) is about 4.5 days over which the along-strait excursion of a particle ($L_a \sim T_d \times U_a$, where U_a is the along-strait velocity scale (10 cm s^{-1})) is about 40 km. Therefore, it is unlikely that the observed pattern of SPM is maintained through a purely cross-strait diffusive process.

Though the ADCP observations were repeated 8 times to remove tidal components, the vertical profiles of materials in Fig. 3 are the results of one chemical cast. Fig. 5 shows distribution of the along- and cross-strait components of the instantaneous currents obtained during the period of hydrographic and chemical casts. A weak southward flow is evident in the northern part of the Cheju Strait where the SPM concentration is high. However, the along- and cross-strait tidal excursions for 12 hours are estimated to be about 20 km and 2 km respectively; so the 20 km wide turbidity front cannot be formed for 12 hours by the cross-strait component of tidal currents. Rough estimates suggest that the observed southward extension of turbidity front in the bottom layer may not result from the diffusive process along isopycnals and tidal motion. Instead, the observed feature seems to be advected from the upstream region. It should, however, be noted that for a larger K_h, say $K_h = 5000\ m^2\ s^{-1}$, the cross-frontal flux is dominated by the diffusion term with the diffusion time scale of about 1 day during which particles are transported 8 km in the along-strait direction. Hence, the cross-frontal diffusive flux becomes not negligible as materials are transported to the downstream. Since the isopycnals deepen toward the south, the diffusive cross-frontal material fluxes are more likely to take place in the Cheju Strait than in the southeastern area of the Yellow Sea, where water is vertically homogeneous during the unstratified season (Wells, 1988) and lighter water stays in the shallow coastal area (Cho *et al.*, 1994), and therefore, materials are trapped in the landward side of the front.

More observational efforts should be put forth to investigate cross-frontal material exchanges and temporal variability of fluxes.

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