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Tidal and Nontidal Fluctuations of Currents in the Western Channel of the Korea Strait

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We carried out simultaneous and long-time observations of currents across the western channel of the Korea Strait during the period of May, 1994 to September, 1996 in order to understand the spatial and temporal variability of tidal and nontidal currents in the Strait. Results show that currents in the Strait are quite variable in space and time, and they largely consist of mean current and diurnal and semidiurnal tidal currents of about equal magnitudes. The mean currents include the Tsushima Current and the Korea Strait Undercurrent at the center of the channel. The former occupies the upper two-thirds and the latter the lower one-third of the water column. The semidiurnal and diurnal currents are largely rectilinear in the direction of NE-SW and their amplitude variation across the channel appears to be small. However, the diurnal currents at some locations show rotational characteristics with significant nontidal effects. The station close to the Korean coast leads the phase and the phase difference of the semidiurnal current across the channel appears to be less than half an hour while that of the diurnal current is over five hours.

INTRODUCTION

The Tsushima Current which flows off the southern coast of Korea and enters the East Sea (Sea of Japan) through the Korea Strait is a main source of heat and salt of the East Sea, and it is one of the major factors that control the circulation of the East Sea. The Tsushima Current (TC) was believed to be separated from the Kuroshio around the relatively deep, southwestern valley off the Kyushu Island of Japan (Uda, 1934). Recently, however, a drifter study has revealed that the flow in the valley does not penetrate to the Korea Strait but flows out of the valley, and rejoin the Kuroshio (Lie and Cho, 1994). It is also speculated that the TC is originated through a broad mixing process along the continental slope in the East China Sea (Huh, 1982). On the other hand, Beardsley *et al.* (1985) and Seung and Nam (1992) argued that the TC is an extension of the Taiwan Warm Current which flows out of the Taiwan Strait after branching off from the Kuroshio.

In general there are two approaches in understanding the circulation dynamics of the East Sea; observation and modeling. Observations have, however, been limited to specific areaswith specific duration due to difficulties and large expenses in field works, and more efforts should be made. Numerical models have also been used to understand the circulation dynamics of the East Sea, but they either assumed the East Sea to be a closed basin (e.g. Kim and Chung, 1989) or specified the constant transport at the open boundary (e.g. Kang, 1988, Bang *et al.*, 1996). This results from the fact that the volume transport of the TC has not been known clearly, although it is thought to be one of the major factors that control the circulation of the East Sea.

The volume transport of the TC have been computed with the geostrophic current estimated from temperature and salinity distribution or mean seal level (e.g. Yi, 1966). Recently, Byun *et al.* (1988) and Kaneko *et al.* (1991) estimated the volume transport of the TC in the Korea Strait through a few cross-sectional surveys with Acoustic Doppler Current Profiler (ADCP). However, it has been pointed out that the currents and the volume transports are greatly influenced by the tidal currents in the Korea Strait (e.g. Ro *et al.*, 1995), but observational evidences of tidal currents in the Korea Strait are, however, scarce. Odamaki (1989) analyzed the data from 25 hour current observations and showed semidiurnal and diurnal tidal currents in the Strait. However, the observations were made at a few depths at different times and we lack simultaneous and long-time observations of currents over the entire water column across the Strait. Thus, a detailed current structure in the Strait has been largely unknown so far. In this study, we attempted simultaneous and long-time observations of currents and present detailed horizontal and vertical structures of the tidal and nontidal currents in the western channel of the Korea Strait.

OBSERVATION AND ANALYSIS OF CURRENTS

In order to understand the tidal and nontidal fluctuations of the transport in the Korea Strait, it is essential to know the spatial and temporal variability of tidal and nontidal currents in the Strait. To this end, we selected a cross-section with six stations across the western channel of the Korea Strait (Fig. 1) and their locations are listed in Table 1. In order to understand the amplitude and phase relationships of the tidal currents across the Strait, simultaneous observations of currents were made using two ADCPs at Stations 2 and 3 for 25 hours on May 12–13 and May 19–20, 1994 and March 19–20, 1996. At Stations 3 and 5, 50 and 25 hours of observation were made on June 3–5 and September 17–18, 1996, respectively. However, we failed to recover the data from observation at St. 3 in September, 1996. The most important effort made was to observe the currents near the deepest point of the Korea Strait (Station 4) for the period longer than a lunar month to understand the detailed characteristics of tidal and nontidal currents in the Korea Strait. An ADCP was deployed on a large buoy for 39 days from December 9, 1995 to January 17, 1996 at the depth of 225 meters near the center of the western channel of the Strait, and the data were successfully obtained every 20 minutes with the depth interval of 4 m from 10 m to 214 m. The summary of observations is listed in Table 2.

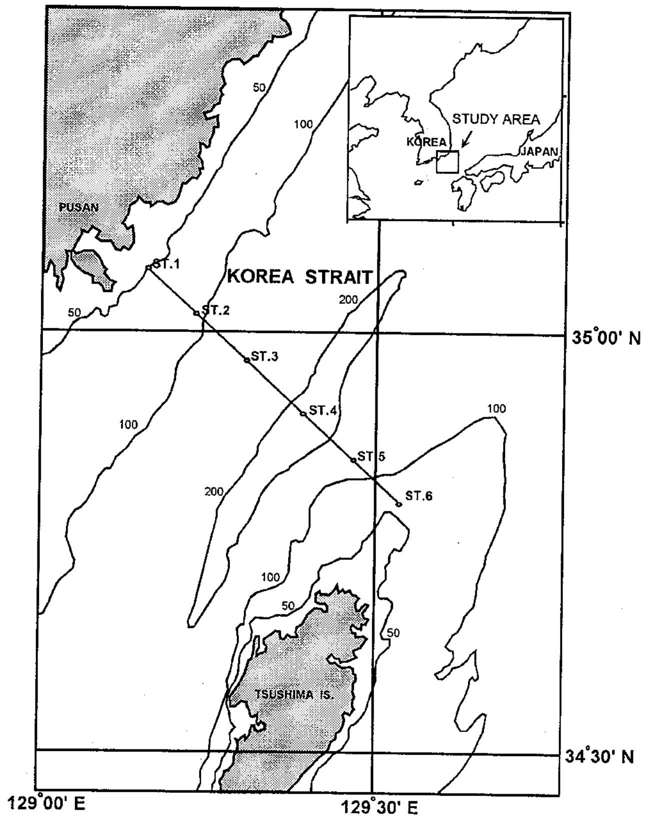

Fig. 1. Study area showing the stations across the western channel of the Korea Strait where simultaneous and long-time observations of currents are made.

Table 1. Locations and depths of the observation stations across the western channel of the Korea Strait

Station	Location		Depth (m)	Distance from Station 1 (km)
	Latitude	Longitude		
1	35°04'30"N	129°09'00"E	50	0
2	35°01'12"N	129°13'36"E	90	9.24
3	34°58'00"N	129°18'12"E	111	18.47
4	34°54'14"N	129°23'22"E	225	28.88
5	34°51'00"N	129°28'00"E	117	38.08
6	34°48'00"N	129°32'12"E	69	46.50

The observed currents at any depth can be considered to be composed of tidal and nontidal components as Eq. (1) and were subjected to a detailed harmonic analysis (Foreman, 1978).

$$V(t)=V_T(t)+V_{NT}(t) \qquad (1)$$

where $V(t)$, $V_T(t)$, $V_{NT}(t)$ are observed, tidal and nontidal currents, respectively. The nontidal current can be further separated as follows;

$$V_{NT}(t)=\mathbf{Z0}+Z(t) \qquad (2)$$

The first term on the right hand side of Eq. (2), **Z0**, is the mean current from averaging the nontidal current and the second term, $Z(t)$, is the fluctuating nontidal current component.

The tidal current, $V_T(t)$, is induced by the astronomical forcing and the nontidal current, $V_{NT}(t)$, has the forcings other than the tidal forcing. Various tidal components may be present in the observed currents with their own frequencies, amplitudes and phases. The nontidal currents may include the Tsushima Current, wind-induced currents, etc. For stations where

Table 2. Summary of observations of currents in the western channel of the Korea Strait

Date	Lunar Date	Observed Item				Duration
		St. 2	St. 3	St. 4	St. 5	
May 12-13, 1994	April 2-3		ADCP			25 hours
May 19-20, 1994	April 9-10		ADCP			25 hours
Dec. 9, 1995-Jan. 17, 1996	Oct. 17- Nov. 27			ADCP		39 days
March 19-20, 1996	Feb. 1-2	ADCP	ADCP			25 hours
June 3-5, 1996	April 18-20		ADCP		ADCP	50 hours
Sept. 17-18, 1996	Aug. 5-6				ADCP	25 hours

25 or 50 hours of observations were made, semidiurnal and diurnal tidal components, and nontidal components of currents were separated. We describe first the characteristics of observed currents at each station, and then reviewing the results of tidal and nontidal components of currents from each station, we attempt to understand the vertical and horizontal structures of tidal and nontidal currents in the western channel of the Korea Strait.

RESULTS

Current structure at the deepest point (St. 4) of the Korea Strait

The stick plots of currents observed in winter of 1995-1996 at the deepest point of the Korea Strait are shown with the tidal and nontidal components for selected depths in Fig. 2. The currents at 10 m

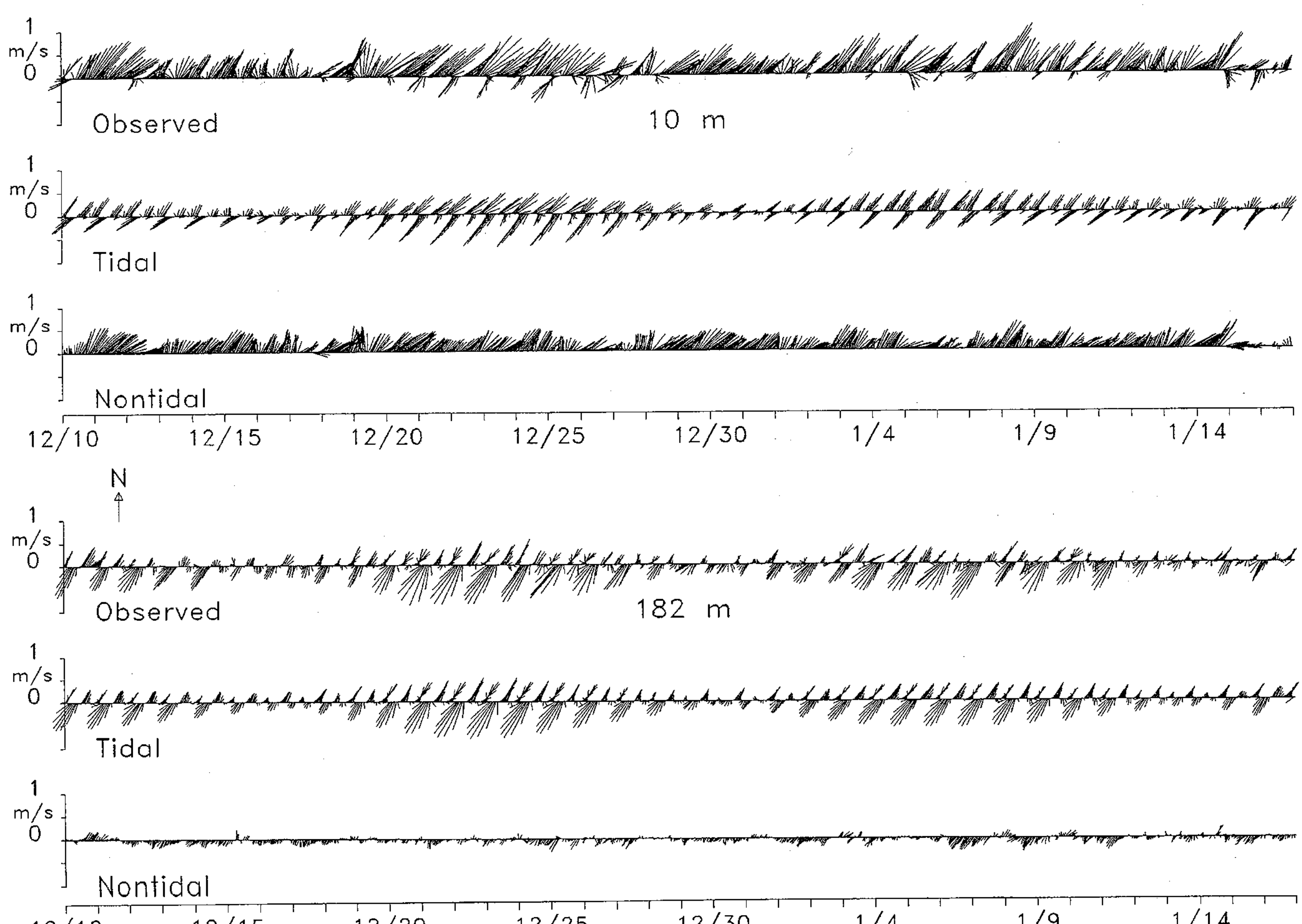

Fig. 2. Stick plots of observed, tidal and nontidal currents at the depths of 10 m (a) and 182 m (b) at the center of the western channel in the Korea Strait from Dec. 10, 1995 to Jan. 16, 1996.

depth flow generally northeastward, and the maximum current speed reaches up to 1.2 m/s during ebb at spring tide. However, southwestward currents over 0.5 m/s were also observed during flood at spring tide. The tidal currents show the reversal of northeastward (flood) and southwestward (ebb) currents twice a day and they are rectilinear in general with slight clockwise rotational tendency. However, the magnitudes of two southwestward currents show a great fluctuation and sometimes the southwest current appears only once a day suggesting the strong diurnal inequality of tidal currents in the Strait. The nontidal current persistently flows northeastward and is considered to be contributed mostly by the TC. As the water depth increases, the northeastward current speed gradually decreases and the relative importance of tidal current compared to the nontidal current increases. At the 150 m depth, the observed currents regularly reversed directions to northeast and southwest following the tidal currents, and it appears that the TC does not reaches to this depth (not shown). Below the 150 m depth, the southwestward flowing current becomes stronger than the northeastward current suggesting the existence of the southwestward flowing nontidal current, but the current reversal persists due to the strong tidal currents. The tidal current show significant counterclockwise rotational characteristics and the southwestward flowing nontidal current is evident at 182 m depth (Fig. 2b). The southwestward current is known to exist during summer as a compensating flow when the TC becomes strong. However, it appears that this current has not been detected so far during winter.

The vertical structures of amplitudes and phases of major tidal current constituents, and the nontidal current observed at St.4 are shown in Fig. 3 (See Appendix for the tidal ellipse characteristics). The mean current (Z0) flows northeastward and is considered to be the TC. The current speed is 35 cm/s at 10 m depth, but it decreases with the counterclockwise rotation of the current direction as the depth increases. The current direction changes rapidly between 130 m and 170 m depth and the minimum current velocity of 1.9 cm/s is found at 150 m depth where the current flows northwest. Below this depth, the current generally flows southwestward and the maximum current velocity of 6.3 cm/s is found at 180 m. Accordingly, the northeastward TC appears to

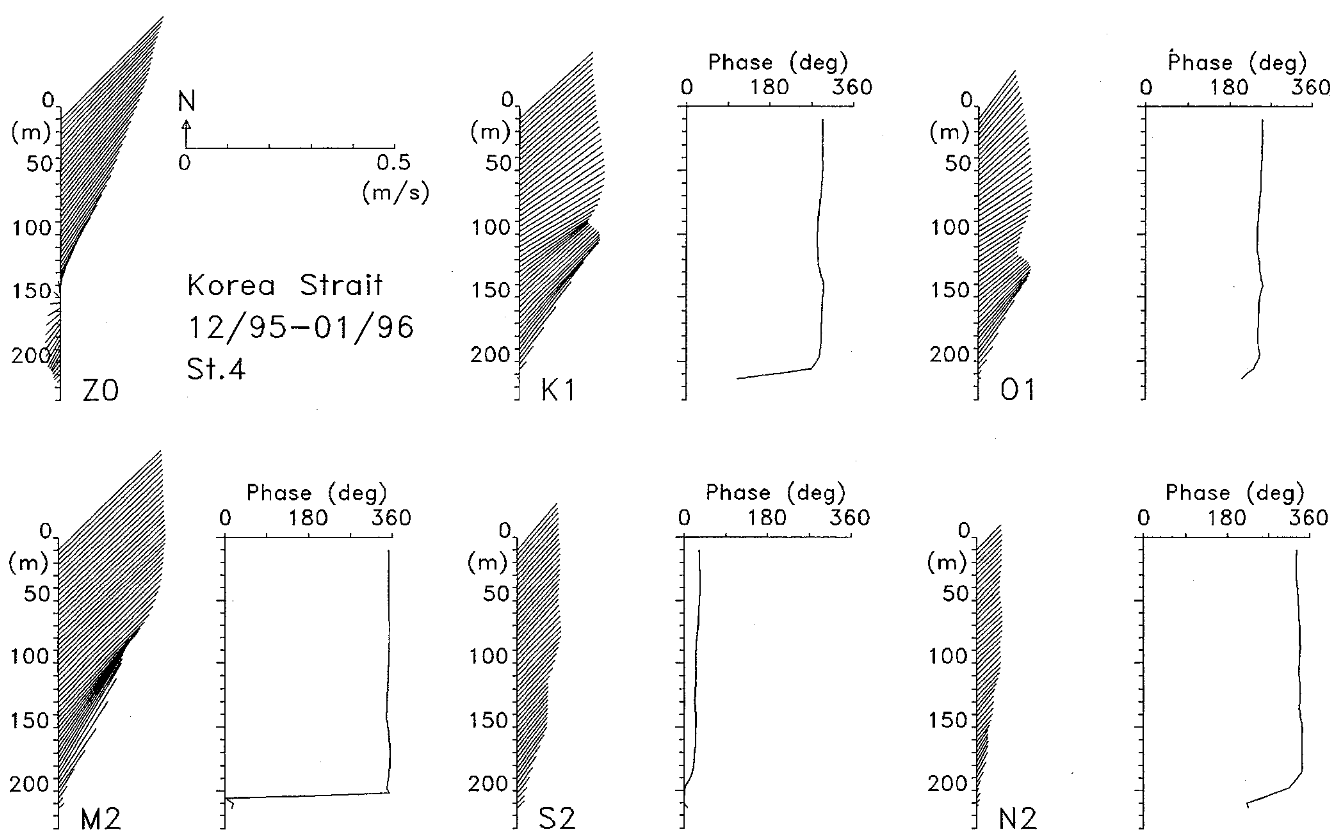

Fig. 3. Vertical profiles of the amplitudes and phases of the mean, diurnal and semidiurnal currents at the center of the western channel in the Korea Strait in winter 1995-1996. The phase lag in degrees is referred to 135°E.

influence up to 150 m, about two-thirds of the water depth and below this depth, the southwestward undercurrent, which we may call the Korea Strait Undercurrent (KSU), persists even in winter.

The K_1 current, a diurnal tidal current component, is largely rectilinear (ellipticity, $\varepsilon<0.1$) and the amplitude of current ranges from 20 to 28 cm/s except near the bottom with the northeast orientation of the major axis (Fig. 3). The minimum K_1 current velocity is found near the depth of 130 m and the maximum near 180 m. Considering the barotropic nature of the tidal current, this current profile with the minimum and the maximum speeds in the middle and the lower layer of the water column, respectively may be due to nontidal effects. The phase of K_1 current varies from 282° to 297°. Another diurnal current component, O_1 shows the vertical profile similar to that of K_1 with the amplitude of 12 to 18 cm/s and it is also rectilinear. The phase of O_1 current varies from 240° to 252°.

The semidiurnal M_2 current which flows NE–SW direction shows more or less uniform speed (32–36 cm/s) and direction (44°–45° from the east) down to 130 m, but below this depth the major axis rotates slightly counterclockwise toward the Korean coast and the current speed is reduced (Fig. 3). In addition, although the ellipticity is small, the rotation of tidal ellipse is clockwise above 130 m while it is counterclockwise below 130 m. Interestingly, this depth coincides with the depth where the minimum current amplitudes of K_1 and O_1 are found. The phase of the M_2 current is 349°–355°. The S_2 and N_2 currents shows the vertical structures similar to that of M_2, but their amplitudes are about half (12–15 cm/s) and a quarter (6–9 cm/s) of that of the M_2 current with the phases of 21°–34° and 331°–344° except near the bottom, respectively (Fig. 3).

Comparing the results at St. 4 with the data of Odamaki (1989, St. (b)) for the depth of 10 m, two data sets show similar patterns of amplitudes and phases (Fig. 4). The phase differences between two stations are about 10° for M_2, S_2, and K_1 and 20° for O_1. However, the amplitude of M_2 in Odamaki (1989) is about two times of the observed one, which may be caused by the shallower water depth of the St. (b) located on the shelf where the tidal currents

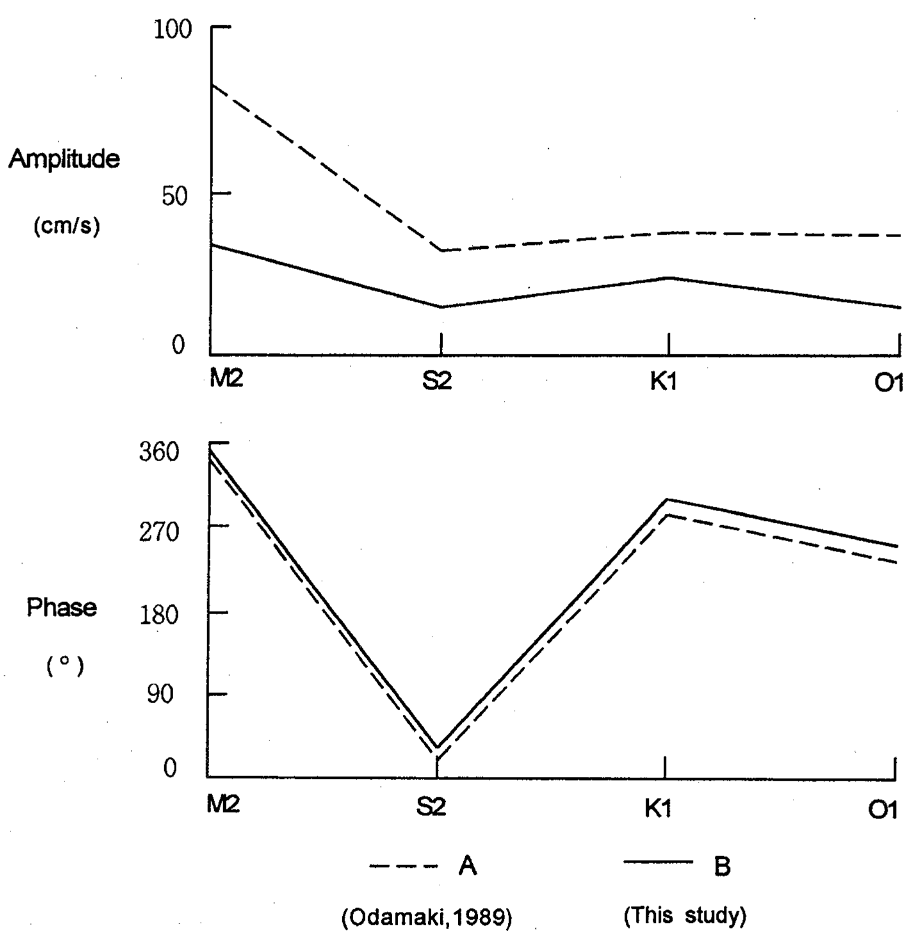

Fig. 4. Comparison of observed amplitudes and phases of major tidal constituents at the center of the western channel in the Korea Strait in winter 1995-1996 with those of Odamaki (1989, St. (b)). The phase lag in degrees is referred to 135°E.

appear to become stronger. Also, it may be caused by the short period (25 hours) of data used in Odamaki (1989). The results also suggest that the diurnal inequality of the tidal currents becomes large near the deep channel whereas it is relatively small on the shelf.

Current structure from 25 and 50 hours of observation

Observations at St. 2 and St. 3 in March, 1996: The currents observed at St. 2 in March, 1996 are dominated by the semidiurnal currents, and the mean and diurnal currents are small (Fig. 5a). The amplitude of the semidiurnal current is 40 to 60 cm/s with the major orientation of ENE-WSW, and the phase is 355o–359o except near the bottom. The amplitude, orientation and phase of diurnal component are, however, quite variable suggesting the influence of non-tidal effects of diurnal period. The observed currents at St. 3 are also dominated by the semidiurnal current with the current speed of about 55 cm/s (Fig. 5b). However, unlike the mean current at St. 2, the mean current at St. 3 flows generally to ENE with about 10 cm/s except near the bottom, suggesting influence of the TC at this location. The diurnal current shows similar variability as observed at St. 2. The results suggest that the mean current becomes stronger off-shoreward. The maximum semidiurnal current at St. 3 appears to occur within 10 minutes after the maximum current at St. 2.

Observations at St. 3 and St. 5 in June and at St. 5 in September, 1996: The mean current observed at St. 3 in June, 1996 flows northeastward with the current speed of about 40 cm/s, which is comparable to those of diurnal and semidiurnal currents (Fig. 6a). The strength of the mean current is greatly enhanced from that observed in March, which suggests the increased strength of the TC in June. The major axis orientations of both diurnal and semidiurnal currents are NE except the surface layer where the orientation is NNE. The mean current observed at St. 5 has the magnitude of 32 cm/s at surface and the direction changes counterclockwise from ENE to NNE as the depth increases (Fig. 6b). The diurnal and semidiurnal currents are slightly stronger than the mean current and their major axis are oriented generally ENE. Thus, the mean current, diurnal and semidiurnal currents obser-ved at St. 3 are comparable to those at St. 5. The maximum semidiurnal and diurnal currents at St. 3 occur about 10 minutes and 2 hours earlier than those at St. 5, respectively.

The mean and semidiurnal currents observed at St. 5 in September, 1996 (Fig. 6c) show similar patterns as those observed in June, 1996. However, their

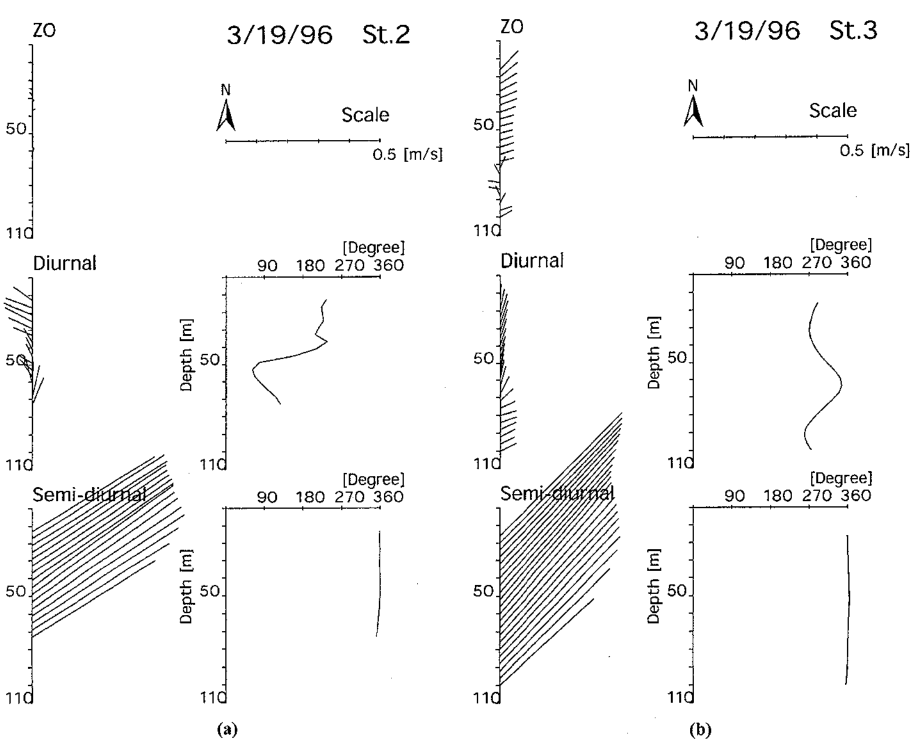

Fig. 5. (**a**) Mean, diurnal and semidiurnal currents observed at St. 2 in the western channel of the Korea Strait on March 19–20, 1996. The phase lag is referred to 135°E. (**b**) Mean, diurnal and semidiurnal currents observed at St. 3 in the western channel of the Korea Strait on March 19–20, 1996. The phase lag is referred to 135°E.

strengths are slightly reduced from those in June. On the other hand, the diurnal currents observed in September show very irregular distribution of velocity profile unlike those observed in June suggesting strong nontidal effects.

Relationship between the tide and the tidal currents

It would be useful to understand the characteristics of tidal currents at the center of the western channel in relation to the tide at Pusan. To this end, the major components of the tidal currents observed at 10 m depth at St. 4 are compared with the corresponding component observed at Pusan as shown in Table 3. Also shown are tides at St. 4 estimated from Odamaki (1989).

The tides at Pusan and at St. 4 are predominantly semidiurnal $((K_1+O_1)/(M_2+S_2) < 0.2)$ while the tidal currents at St. 4 are mixed type where the semidiurnal and diurnal currents are comparable each other $((K_1+O_1)/(M_2+S_2)\sim 0.8)$. The maximum flood and ebb currents of the semidiurnal tidal current components at the center of the western channel of the Korea Strait occur about 4 hours after low and high waters at Pusan, respectively. Comparing the tide with the tidal current at St. 4, we find that the phase differences are 77° for M_2 and 70° for S_2. This means that the high tides of M_2 and S_2 at St. 4 are reached 2.6 and 2.3 hours after their maximum flood currents, respectively. In other words, the semidiurnal tides in the Korea Strait are standing wave type. The maximum northeastward (ebb) current of K_1 occurs 4.5 hours after the high tide whereas that of O_1 occurs 0.7 hour before the high tide. This suggests that the diurnal tides are progressive wave type, but the K_1 tide shows some modification. This may be due to the fact that the K_1 tide in the Korea Strait is composed of both incident and reflected Kelvin waves (Odamaki, 1989). From the results of the 39 days and 25 to 50 hour observations discussed above with the previous result on observation in May, 1994 (Ro *et al.*, 1995), we present the current structure in the western channel of the Korea Strait.

Current structure in the western channel of the Korea Strait

Mean Current: The mean current flows generally

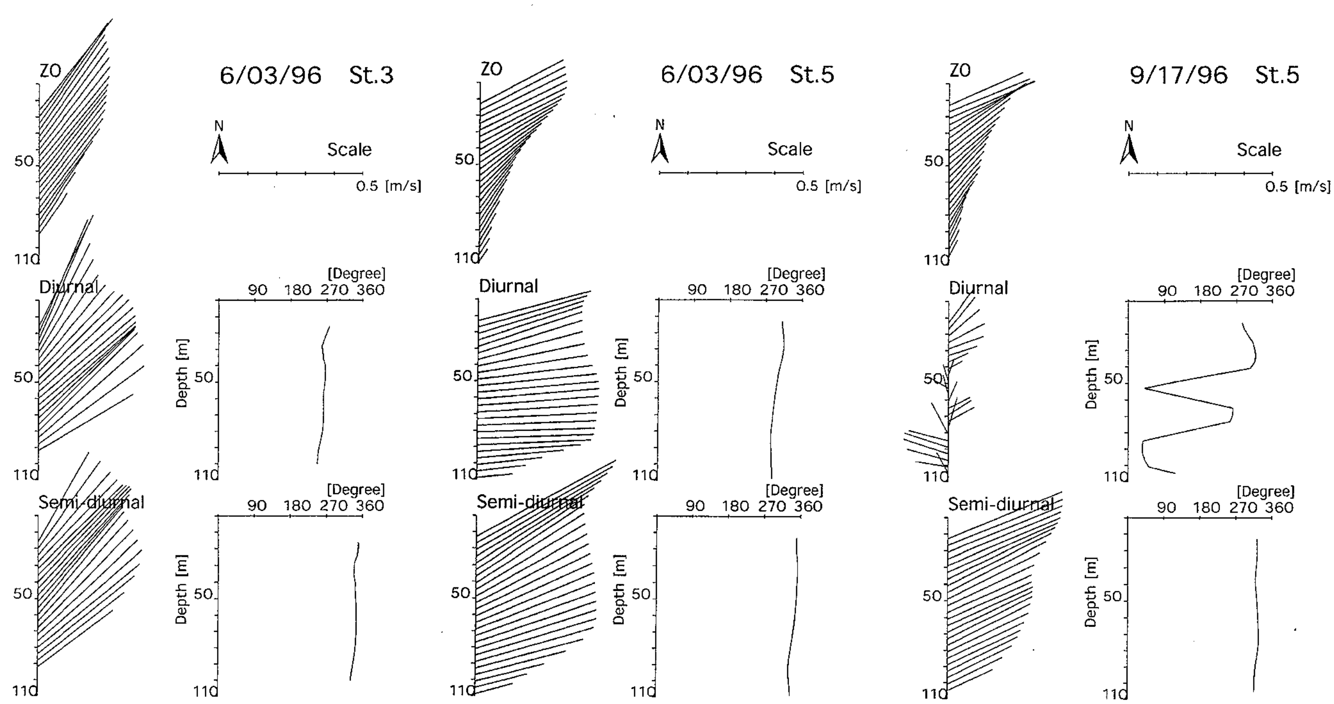

Fig. 6. (**a**) Mean, diurnal and semidiurnal currents observed at St. 3 in the western channel of the Korea Strait on June 3–5, 1996. The phase lag is referred to 135°E. (**b**) Mean, diurnal and semidiurnal currents observed at St. 5 in the western channel of the Korea Strait on June 3–5, 1996. The phase lag is referred to 135°E. (**c**) Mean, diurnal and semidiurnal currents observed at St. 5 in the western channel of the Korea Strait on Sept. 17–18, 1996. The phase lag is referred to 135°E.

Table 3. Comparison of observed currents at St. 4 for the depth of 10 m with observed tides at Pusan and at St. 4

Major Tidal Constituent	Tide at Pusan		Tide at St. 4		Current at St. 4	
	Amp. (cm)	Phase (°)	Amp. (cm)	Phase (°)	Amp. (cm/s)	Phase (°)
M_2	39.8	236	32.5	250	34.4	353
S_2	18.7	274	15.5	283	14.7	33
N_2	7.6	225	N/A	N/A	8.5	331
K_1	4.5	144	4.2	225	23.8	293
O_1	1.7	106	3.9	262	14.7	252

The tide data at Pusan were obtained from a harmonic analysis of the observed sea level from Jan. 1, 1960 to Dec. 31, 1993. The tides at St.4 were estimated from Odamaki (1989). The phase lags are referred to 135°E.
*N/A: Data are not available.

northeastward with the speed of 30–40 cm/s at surface, but the current speed decreases with the counterclockwise rotation of the direction to the north down to 150 m depth. The mean current flows southwestward in general below 150 m depth with the maximum velocity of 6.3 cm/s at 180 m. Thus, the TC and the KSU occupy upper two-thirds and lower one-third of the water column at the center of the channel, respectively. The strength of the mean current increases rapidly from the Korean coast offshoreward and the maximum current appears to exist near the center of the channel (Fig. 7). The veering of the current direction to ENE at the surface near the Tsushima Island (St. 5) is probably due to the fact that the station is located downstream behind the island. The mean current tends to be intensified from March to June and the current strength in September is comparable to that in June. Thus, it appears that the mean current reaches the maximum velocity sometime in summer.

Diurnal current: The K_1 and O_1 currents flow generally NE (ebb)– SW (flood) directions with the amplitudes of 24 and 15 cm/s and phases of 287° and 246° on the average except near the bottom, respectively and they are nearly rectilinear at the center of the channel. However, the rotational tendency is relatively strong at St. 3 and the current direction tends to be E-W near the Tsushima Island (Fig. 8). The amplitude of diurnal current across the central part of the channel (Stations 3, 4, and 5) appears to be more or less uniform. The phase difference of the diurnal current is about 70° or five hours across the channel.

Semidiurnal current: The M_2, S_2 and N_2 currents flow NE (ebb)–SW (flood) directions with the amplitudes of 34, 14 and 8 cm/s and phases of 352°, 27° and 336° on the average, respectively at the center

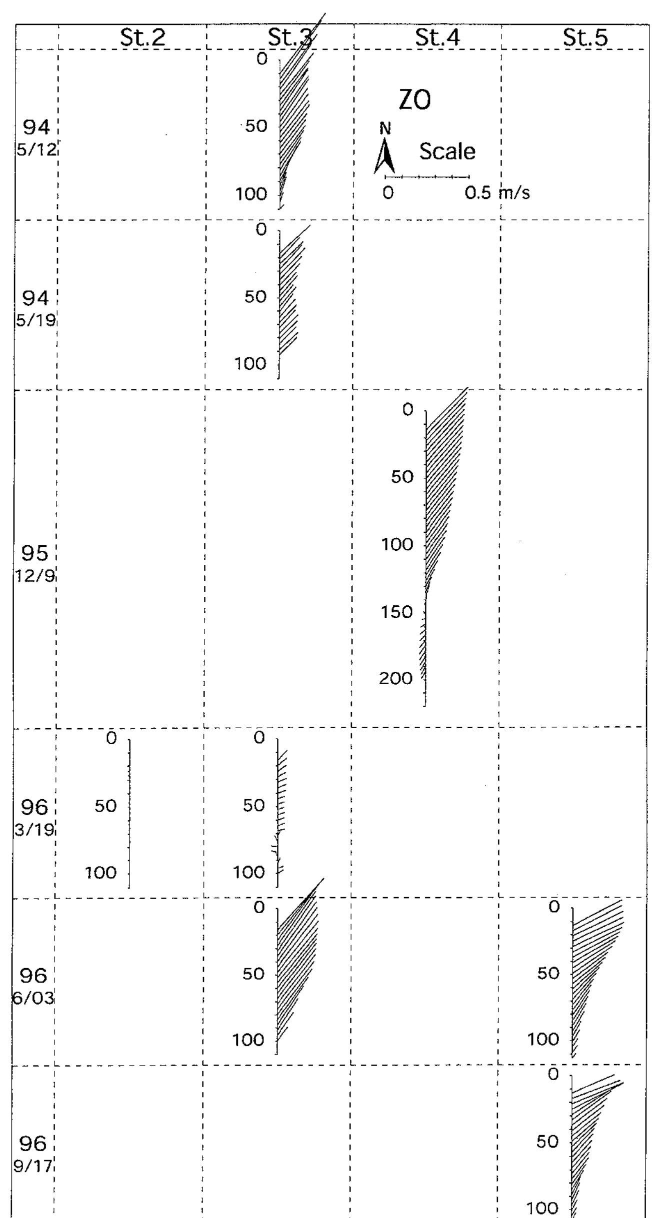

Fig. 7. Mean currents observed across the western channel of the Korea Strait from May, 1994 to September, 1996.

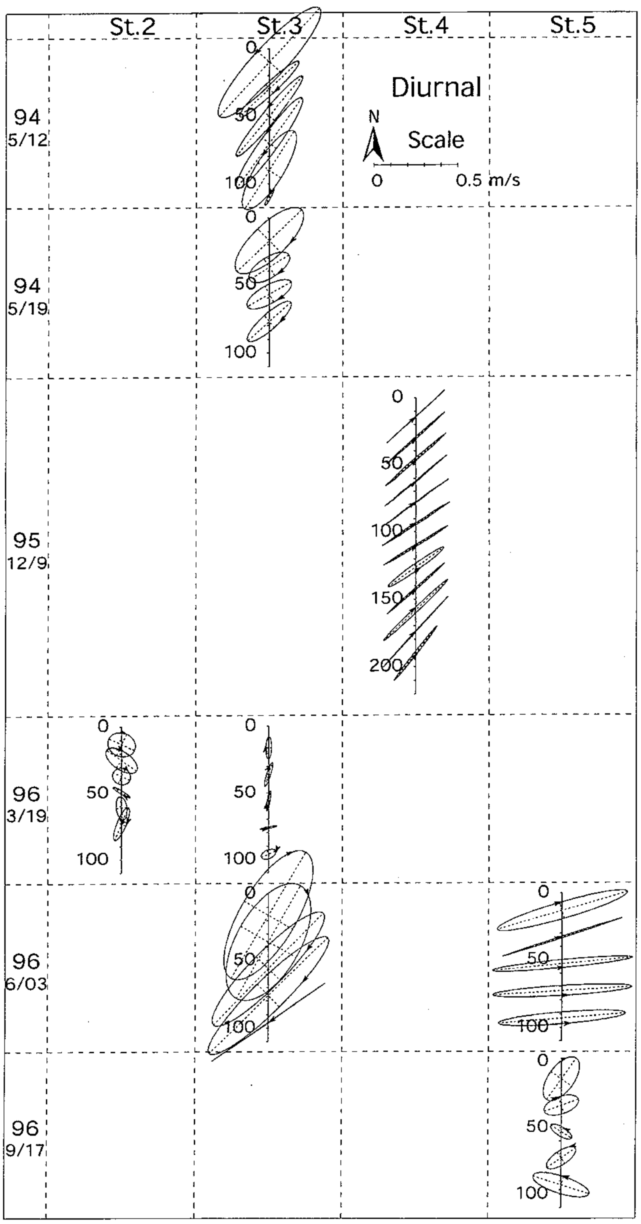

Fig. 8. Diurnal current ellipses observed across the western channel of the Korea Strait from May, 1994 to September, 1996.

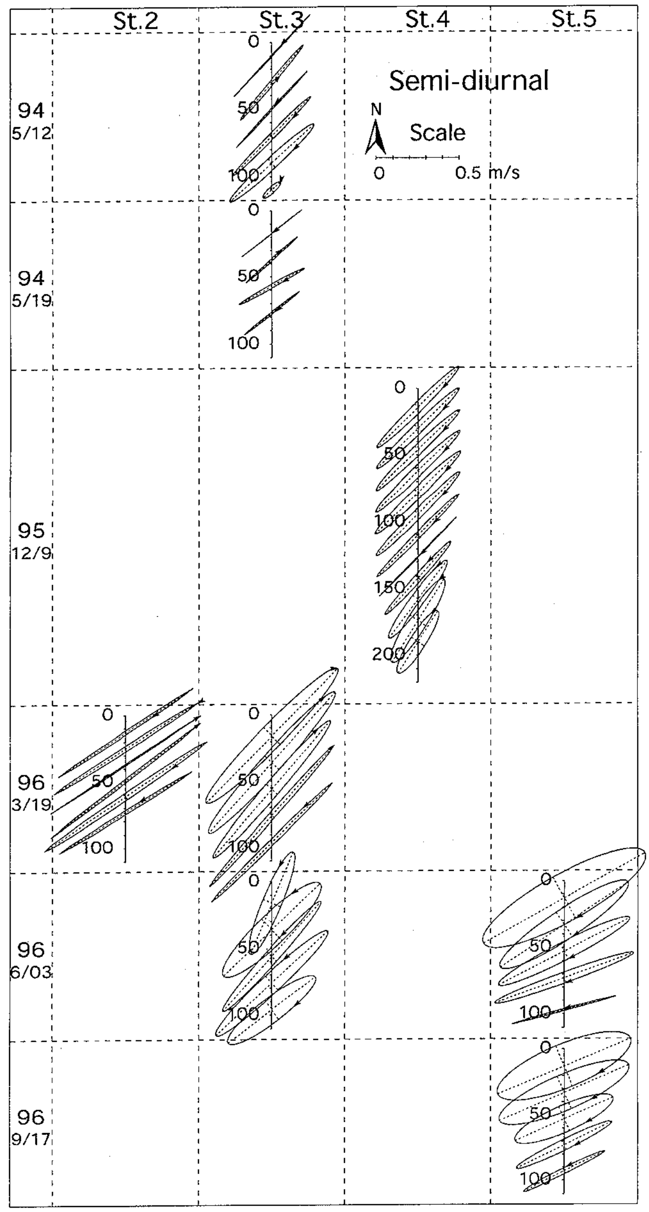

Fig. 9. Semidiurnal current ellipses observed across the western channel of the Korea Strait from May, 1994 to September, 1996.

of the channel. The M_2 and S_2 currents are largely rectilinear except the lower layer of the water column where the ellipticity becomes about 0.2 with the counter-clockwise rotation (Fig. 9). The N_2 current has the rotary current character throughout the water column with the ellipticity of about 0.2 and it rotates clockwise above 130 m and counter-clockwise below 130 m. Near the Tsushima Island the rotational tendency is also strong and the current direction tends to be ENE–WSW. The amplitude of the semidiurnal current appears to be uniform across the channel and the phase difference is about 10° or 0.3 hour.

DISCUSSION

We presented the current structures of the Tsushima Current, the Korea Strait Undercurrent and major tidal currents across the western channel of the Korea Strait from the results of 39 days and 25 and 50 hour observations of currents during the period from 1994 to 1996. However, we could not separate out detailed tidal constituents due to insufficient data except at the center of the channel. The time series of tidal and nontidal currents for 39 days indicated large variability of both components over the observed period and is analyzed further by Lee *et al.* (1998). They found that the semidiurnal and diurnal tidal currents are coherent with the sea level difference across the Strait. We notice that the tidal currents between two successive spring tide conditions vary significantly (Fig. 2), which suggests that the N_2 tidal current should be included for the proper representation of the tidal currents in the Strait (See Appendix for the details on the N_2 tidal current). Thus, repeated measurements of 25 to 50 hour observations of currents at the same location may not be enough for an accurate information on the tidal currents. In order to estimate the tidal volume transport in the western channel of the Korea Strait, we need to know the horizontal and vertical distributions of amplitudes, directions and phases of major tidal constituents at three (minimum) stations including one at the center of the channel. Also, long-time observations for at least a year are needed to understand the seasonal variation of the mean currents such as the Tsushima Current and the Korea Strait Undercurrent, which is essential to understand the volume transport in the western channel of the Korea Strait.

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APPENDIX. The tidal ellipse characteristics of the major tidal constituents at the center (St. 4) of the western channel of the Korea Strait. Inclination is the angle of the northern major semi-axis from the east and phase lag is referred to 135°E. C-W; clockwise, CCW; counter-clockwise

	Depth m	Major cm/s	Minor cm/s	Inclination °	Phase °	Rotation
M_2						
	10	34.4	−2.8	44	353	C-W
	30	34.7	−2.9	44	352	C-W
	50	34.7	−2.8	44	353	C-W
	70	35.3	−3.0	44	353	C-W
	102	35.4	−2.4	45	352	C-W
	150	29.0	3.0	50	351	CCW
	198	11.2	2.3	55	349	CCW
S_2						
	10	14.7	−0.5	49	33	C-W
	30	15.0	−0.5	48	34	C-W
	50	15.3	−0.9	47	33	C-W
	70	15.2	−1.7	48	30	C-W
	102	15.0	−0.8	46	25	C-W
	150	11.5	0.6	49	25	CCW
	198	6.3	1.1	53	2	CCW
N_2						
	10	8.5	−1.7	46	331	C-W
	30	8.6	−1.7	45	331	C-W
	50	8.2	−1.6	46	335	C-W
	70	8.3	−1.6	43	338	C-W
	102	8.3	−1.2	45	337	C-W
	150	6.2	2.2	48	343	CCW
	198	2.1	−0.1	61	313	C-W
K_1						
	10	23.8	0.3	42	293	CCW
	30	23.6	0.7	41	293	CCW
	50	24.0	0.8	40	294	CCW
	70	24.4	0.0	38	290	CCW
	102	23.7	−0.2	31	283	C-W
	150	24.5	−0.3	43	294	C-W
	198	9.6	0.5	51	285	CCW
O_1						
	10	14.7	0.8	53	252	CCW
	30	15.3	0.4	48	251	CCW
	50	15.7	0.5	42	249	CCW
	70	15.8	0.4	38	247	CCW
	102	14.8	1.1	31	240	CCW
	150	14.5	0.1	40	246	CCW
	198	7.8	1.1	52	244	CCW