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The Seasonal and Interannual Variability of the Volume Transport through the Western Channel of the Korea Strait

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The variation of volume transport during the period from 1965 to 2000 through the western channel of the Korea Strait was estimated by obtaining an relation function between the ADCP volume transport and the geostrophic volume transport estimated by the sea level difference between Pusan and Izuhara. The estimated climatological mean volume transport during past 36 years has seasonal variation with a minimum of 1.15 Sv in February and a maximum of 1.88 Sv in October. The mean volume transport for 36 years is 1.51 Sv. The annual mean volume transport has an interannual variation with a minimum of 1.26 Sv in 1968 and maximum of 1.90 Sv in 1973, with three dominant periods of variations of 14.96 years, 4.96 years and 2.99 years.

Key words: ADCP Volume Transport, Geostrophic Volume Transport, Sea Level Difference, Relation Function, Seasonal and Interannual Variation

INTRODUCTION

The East Sea is connected to the East China Sea through the narrow Korea Strait (about 200 km wide) between the south coast of the Korea and the northern coast of Kyushu, Japan. The Tsushima Islands devide the Korea Strait into two channels; the western channel between the south coast of Korea and the Tsushima Islands, the eastern channel between the Tsushima Islands and the northern coast of Kyushu. The Tsushima Warm Current flows through this straits into the East Sea and influences greatly the circulation in the East Sea.

So far, many observations have been conducted to estimate surface currents and volume transport through the Korea Strait. Hidaka and Suzuki (1950) and Yi (1966) estimated the surface current velocity or the total volume transport through the Korea Strait through dynamic calculations with a level of "no motion" at the bottom showing a maximum transport in summer to autumn and a minimum in winter to spring. However, the validity of the dynamical calculation with the level of no motion at the bottom layer of the Korea Strait seems to be doubtful due to the shallowness of the Korea Strait.

The volume transport and the surface current velocity have also monitored by the sea level difference across the Strait. Kawabe (1982) and Toba *et al.* (1982) reported that the volume transport through the Korea Strait has a maximum in summer to autumn and a minimum in winter to spring as shown by Hidaka and Suzuki (1950) and Yi (1960), assuming the volume transport to be proportional to the sea level difference between Pusan and Hakada. Kawabe (1982) also reported that the sea level difference between Pusan and Izuhara shows the remarkable seasonal variation in the western channel of the Korea Strait, but not in the eastern channel.

Recently, Teague *et al.* (2001) and Jacobs *et al.* (2001) carried out the current measurements at eleven stations along two lines across the Korea Strait, northeast and southwest of the Tsushima Islands, for about five months using ADCP and estimated the volume transport through each section. However it is

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not sufficient due to the short period.

In spite of many past studies such as shown above, due to the scarcity of long-term direct current measurements, the seasonal and especially, interannual variation of the volume transport through the Korea Strait are still not well understood.

In this study, an empirical relation function between sea level difference and volume transport in the western channel of the Korea Strait is proposed through the analysis of sea level data at Pusan and Izuhara and velocity data measured by ADCP mounted to a ferry boat *Camellia* from 1997 to 2000. Then the variation of the volume transport in the western channel of the Korea Strait from 1965 to 2000 will be studied by applying this relation function, focusing on the seasonal and interannual variation.

DATA AND METHOD

The velocity data used in this study were obtained from February, 1997 to December, 2000 by a multilevel type ADCP (VM-BBADCP, 300 kHz, RD Instruments) mounted to a ferry boat *Camellia* between Hakata and Pusan. The *Camellia* makes a round trip between Hakata and Pusan three times a week at a cruising speed of about 17 knots (Fig. 1). The data are sampled every 24 seconds and 8 meters, from 18 meters to 258 meters depth. More details are shown in Takikawa *et al.* (2003). The observed current velocity contains both various tidal components and residual current. In order to obtain residual currents, major 10 tidal components (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2, M_{sf}, M_f) were removed from the current velocity data following Takikawa *et al.* (2003).

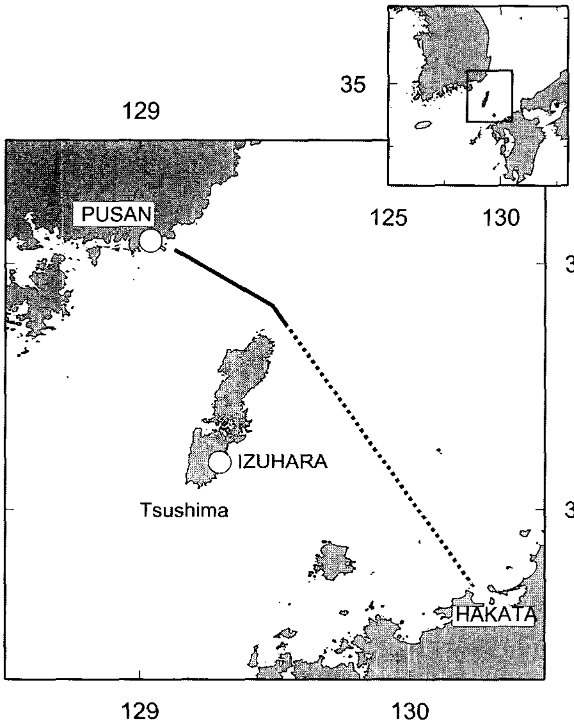

Fig. 1. *Camellia* cruise line where current velocity were observed by ADCP (black line) and tidal stations at Pusan and Izuhara (white circle) in the Korea Strait. The black solid line shows the range of ADCP data used for western channel in this study.

The hourly sea level data at Pusan in Korea and at Izuhara in Japan have been accumulated for long years. These were provided from NORI (National Oceanographic Research Institute) in Korea and JCG (Japan Coast Guard) in Japan, respectively. Since the width of the Korea Strait is much shorter than the synoptic length scale of the atmospheric pressure variation, the inverse barometric adjustment may not be necessary for the sea level difference between Pusan and Izuhara. The tidal effects on the sea level were removed using a 25-hours running mean. These data from 1997 to 2000 are used to obtain the relation function between the geostrophic volume transport and the ADCP volume transport. The data from 1965 to 2000 is used to estimate the long-term volume transport for the past few decades.

RELATION BETWEEN SEA LEVEL DIFFERENCE AND VOLUME TRANSPORT

Assuming a steady frictionless flow without any external forces except gravitational force, the surface current velocity (v_g) through the western channel of the Korea Strait is approximated as a geostrophic flow by a geostrophic equation

$$v_g = \frac{g}{f} \cdot \frac{\delta h}{\delta x} \tag{1}$$

where f is the coriolis parameter at the middle point between Izuhara and Pusan, δh the sea level difference between Pusan and Izuhara, δx the distance between Pusan and Izuhara. The tidal station at Izuhara, which locates in the south-eastern part of the Tsushima islands, may not be proper as a representative station of the Tsushima islands for calculating the geostrophic current through the western channel of the Korea Strait. Such an adopting the tidal data at Izuhara for calculating the geostrophic current through the western channel of the Korea Strait can be one error source, for example, which may include the sea level disturbance caused in east-

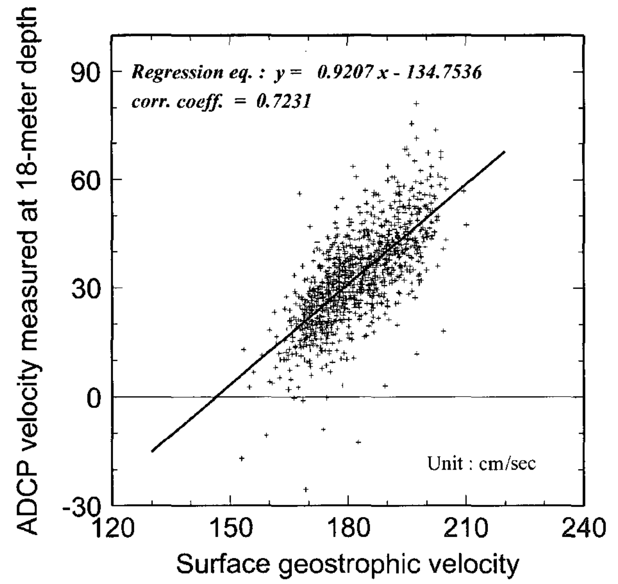

Fig. 2. The scatter plots for the surface geostrophic velocity and the ADCP velocity measured at 18 meter depth for the period from February, 1997 to December, 2000 in the western channel of the Korea Strait. Correlation coefficient is 0.7231. Solid line shows the regression line between two velocities, whose regression coefficient is 0.9207.

ern channel or by island effect. However, the tidal data at Izuhara is adopted owing to no other tidal stations in the Tsushima islands.

The ADCP surface velocity through the western channel of the Korea Strait is obtained by averaging the velocities measured at 18 meter depth along the *Camellia* cruise line within the western channel, it covers north of the 34.75°N shown as black solid line in Fig. 1. In this paper, the velocities measured at 18 meter depth are approximated to the surface velocities, although such an approximation may be cause of error, because the ADCP mounted to a ferry boat *Camellia* cannot measure the current velocities shallower than 18 meter depth.

Fig. 2 shows scatter plots for the surface geostrophic velocity *vs.* the ADCP surface velocity in the western channel of the Korea Strait, where a linear regression line intersects the abscissas at 146.4 cm/s for the surface geostrophic velocity. If the geostrophic balance is assumed, the regression line is expected to intersect the abscissas at the origin. As it were, the intersection of the abscissas at 146.4 cm/s implies the difference of the standard sea level between Pusan and Izuhara. Therefore, the surface geostrophic velocity is adjusted by increasing the standard sea level of Izuhara by δh_s=85.5 cm using Eq. (1) with $f = 8.268\times10^{-5}$ s^{-1}, g=9.8 m/s^2, and δx=69.239 km.

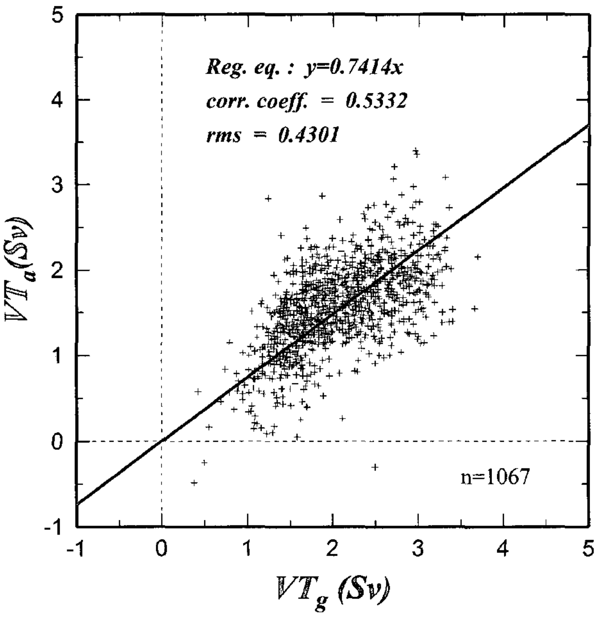

Fig. 3. Scatter plots for geostrophic volume transport (VT_g) and the ADCP volume transport (VT_a) in the western channel of the Korea Strait. "n (number of data)" is 1067. Correlation coefficient is 0.5332 and rms (root mean square) is 0.4301. Solid line shows the regression line between two volume transports, whose regression coefficient is 0.7414.

Assuming the adjusted surface geostrophic velocity is uniform from the surface to the bottom, geostrophic volume transport (VT_g) through the western channel is calculated by multiplying the adjusted geostrophic velocity by the vertical cross section area along the *Camellia* ferry line as follows:

$$VT_g = \frac{g}{f}\cdot\frac{(\delta h-\delta h_s)}{\delta x}\times S \qquad (2)$$

where δh_s=85.5 cm is the adjusted standard level difference and S (=5.801 km^2) is the vertical cross section area. But this geostrophic volume transport does not correspond with the true volume transport in that the variable current structure with the depth is overlooked or the true volume transport may contain the other volume transport which is not transported by geostrophic balance. Hence, the volume transport resulted from these effect above must be incorporated into the geostrophic volume transport to improve the estimation of the volume transport.

The amount of volume transport resulted from these effect above is examined by comparing the geostrophic volume transport with the ADCP volume transport obtained by summing up the volume transport through small bins, into which the vertical cross section along the ferry line is divided with the vertical width of 8 meters and the horizontal length of 1311.5 meters (for west of 129.5°E) or 1961.2 meters (for east 129.5°E).

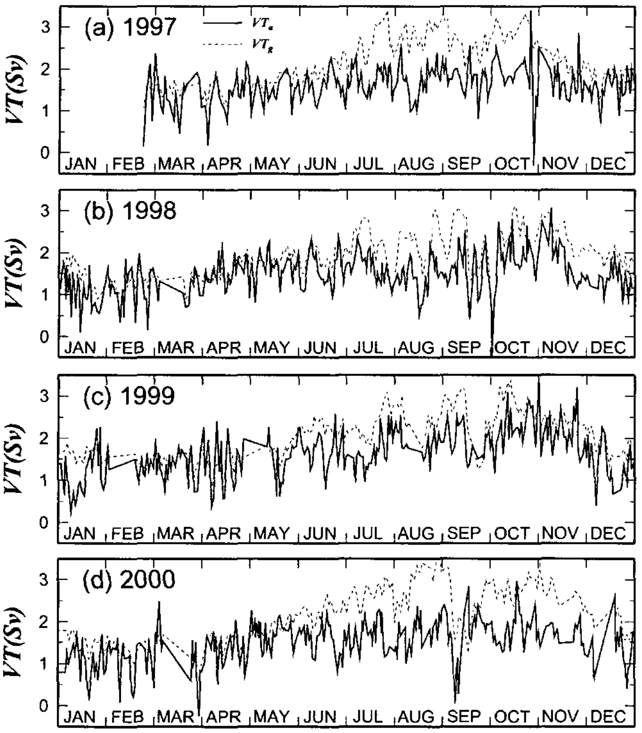

Fig. 4. Time series of the geostrophic volume transport (VT_g, dashed line) calculated from Eq. (2) and the ADCP volume transport (VT_a, solid line) for the period from Feb., 1997 to Dec., 2000 in the western channel of the Korea Strait.

Fig. 3 shows a scatter diagram for VT_g *vs.* VT_a and the regression line between VT_g and VT_a. The correlation coefficient (0.5332) between VT_g and VT_a, which is not high, shows that VT_g does not agree with VT_a enough. As mentioned above, this disagreement seems to result from the vertically variable current structure or the volume transport transported by the other factors except by geostrophic balance. The regression coefficient (0.7414) of the regression line can make a conjecture on the average ratio of VT_a to VT_g, as it were, the VT_a to VT_g can be explained as 0.7414 to 1.0 on the average. Moreover, the time series comparing VT_g to VT_a (Fig. 4) shows that the extent of the agreement of VT_g with VT_a varies seasonally. The VT_g and VT_a are relatively in a good agreement in winter and spring, but VT_g exceeds VT_a considerably in summer and autumn.

To incorporate these effect above into the geostrophic volume transport, we define a new geostrophic volume transport, "adjusted geostrophic volume transport", $VT_{gc} = \alpha(t) \cdot VT_g$. The coefficient $\alpha(t)$ is determined by the regression coefficients of the linear regression line of scatter plots for VT_g and VT_a for each month as shown in Fig. 5, where the linear regression lines are assumed to pass through the origin based on the definition of VT_{gc}. The regression coefficient increases toward early next spring from summer except in January. The regression coefficients are 0.9305, 0.9629, 0.8993 in March, April and May, respectively, which are nearly equal to unity, implying that the currents are almost vertically uniform and the great part of volume transport is transported by geostrophic balance. However, those in summer and autumn are much lower than 1.0, implying the increase of vertical baroclinicity of current or the increase of the other volume transport not transported by geostrophic balance. The relatively higher dispersion in summer than other seasons suggests that the short period variations are more dominant in summer than in other seasons, which will be referred as one possible error source later. Taking those above into consideration, the regression coefficient in the scatter plots for each month can be defined as a "relation coefficient" between the geostrophic volume transport (VT_g) and the ADCP volume transport (VT_a). Annually and semi-annually varying sine functions are fitted to these 12 coefficients using least square method, giving a following relation coefficient function:

$$\alpha(t) = 0.7819 + 0.1207 \sin\left(\frac{\pi}{6}t\right) - 0.0164 \cos\left(\frac{\pi}{6}t\right) - 0.0700 \sin\left(\frac{\pi}{3}t\right) - 0.0274 \cos\left(\frac{\pi}{3}t\right) \qquad (3)$$

where t is time (Fig. 6).

Using this relation coefficient function, the adjusted geostrophic volume transport (VT_{gc}) can be calculated by the equation.

$$VT_{gc} = \alpha(t) \times \frac{g}{f} \cdot \frac{(\delta h - \delta h_s)}{\delta x} \times S \qquad (4)$$

Fig. 7 shows the adjusted geostrophic volume transport (VT_{gc}) and the ADCP volume transport (VT_a). Time changes of these two volume transports are in a good agreement except those with time scale less than several days. The scatter plots for VT_{gc} *vs.* VT_a with a regression line between VT_{gc} *vs.* VT_a are shown in Fig. 8. The regression coefficient of the regression line becomes nearly equal and the correlation coefficient (0.6559) between VT_{gc} and VT_a becomes higher than that (0.5332) between VT_g and VT_a.

The higher correlation coefficient and lower rms (root mean square) between VT_{gc} and VT_a compared with those between VT_g and VT_a imply that VT_{gc} defined by Eq. (4) provides more improved estimation of the volume transport through the western channel. However, it should be noted that these esti-

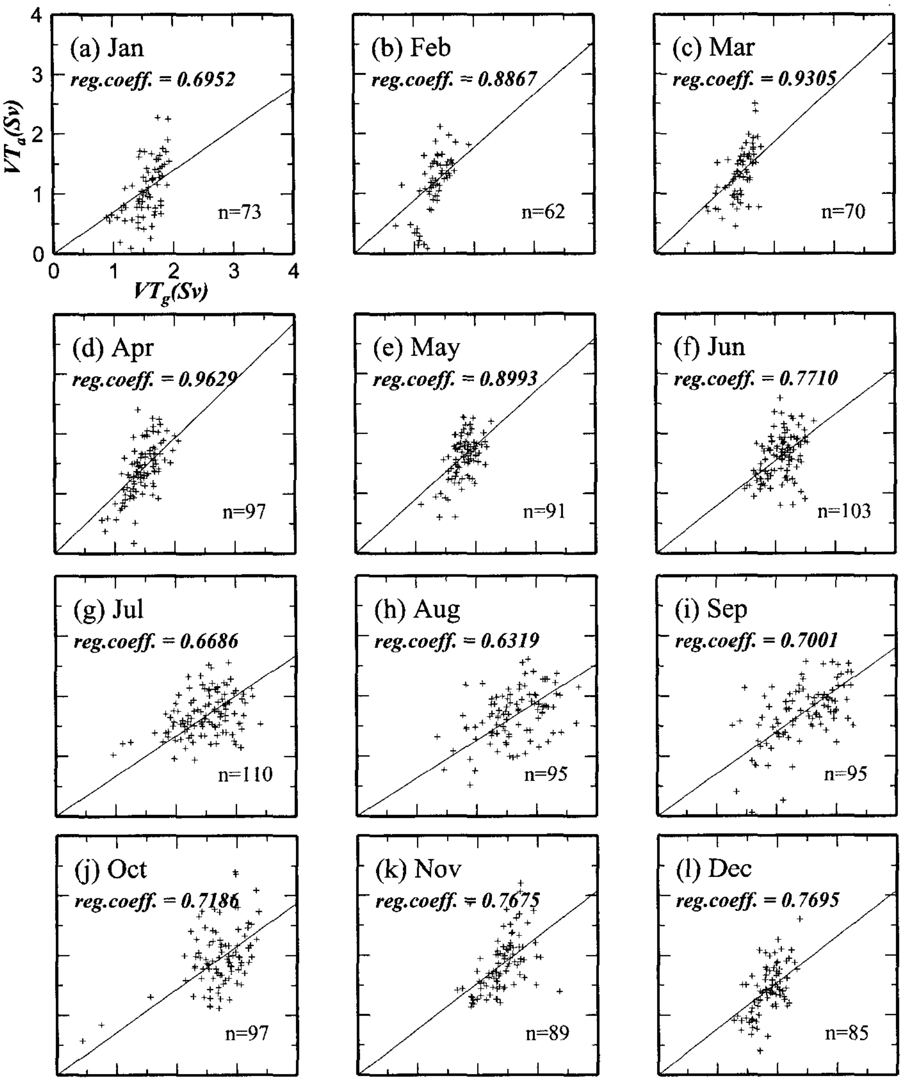

Fig. 5. Scatter plots and linear regression lines (solid line) for the geostrophic volume transport and the ADCP volume transport for Jan. (a) to Dec. (l).

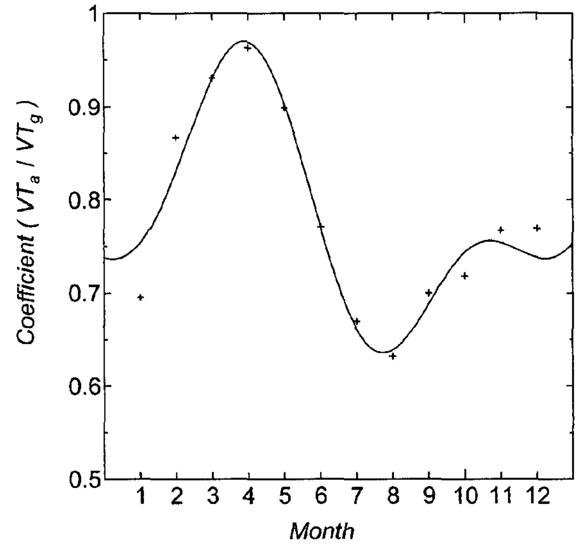

Fig. 6. Relation coefficients between the geostrophic volume transport (VT_g) and the ADCP volume transport (VT_a) for each month and the curve of the relation coefficients function.

mations may still include errors which are estimated to be 0.3838 Sv from the correlation analysis between VT_{gc} and VT_a. The main reason for this error seems to result from the shorter period variations less than several days, which are more dominant in summer than in other seasons, those variation can not be adjusted by $\alpha(t)$ reflecting the variations of seasonal time scale. The bottom friction, the inappropriate tidal position of Izuhara, the approximation of ADCP surface velocity to 18 meter depth and so on can also be other possible reasons for errors.

THE VARIATION OF THE VOLUME TRANSPORT DEDUCED FROM THE SEA LEVEL DIFFERENCE BETWEEN PUSAN AND IZUHARA

The hourly volume transport through the western channel of the Korea Strait during the period from

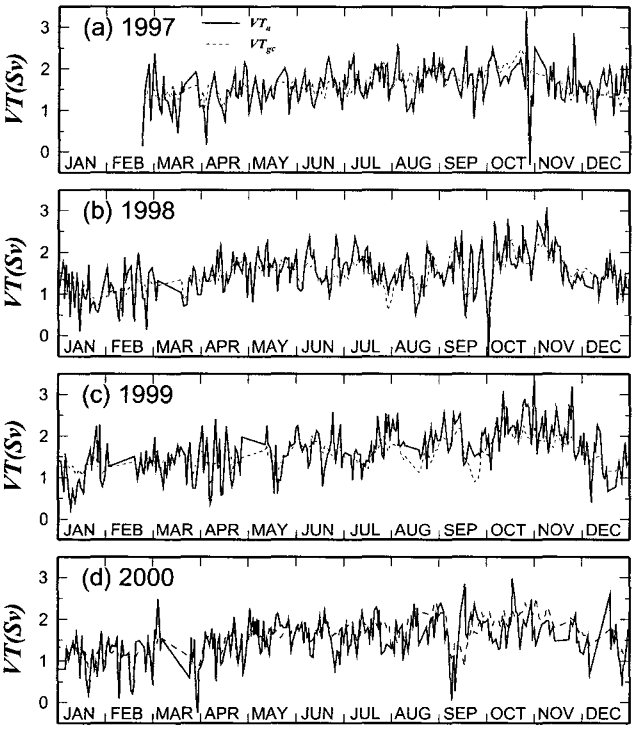

Fig. 7. Time series of the adjusted geostrophic volume transport (VT_{gc}, dashed line) and the ADCP volume transport (VT_a, solid line) for the period from Feb., 1997 to Dec., 2000 in the western channel of the Korea Strait.

1965 to 2000 is estimated by Eq. (4) using hourly sea level differences between Pusan and Izuhara from 1965 to 2000. The monthly mean volume transport during the period from 1965 to 2000 is shown in Fig. 9. It shows a general pattern with a high peak in late autumn and a low peak in late spring. However, exceptionally, in 1973, the volume transport attains a high peak in spring and then decreases monotonously until winter. As mentioned above, these analysis may include errors which may be estimated to be 0.3838 Sv from the correlation analysis between VT_{gc} and VT_a.

Seasonal variation of the volume transport

The monthly mean volume transports averaged climatologically during the period from 1965 to 2000 and the error bars indicating the root mean square error between VT_{gc} and VT_a for each month are shown in Fig. 10. It increases gradually from February toward October and decreases rapidly from October to next February, with a minimum of 1.15 Sv in February and a maximum of 1.88 Sv in October. However, this result may be fair to interpret as the general pattern of seasonal variation with a peak in late autumn and a trough in late spring in that the ranges of error bars cover the width of seasonal variation, especially in late summer and early autumn.

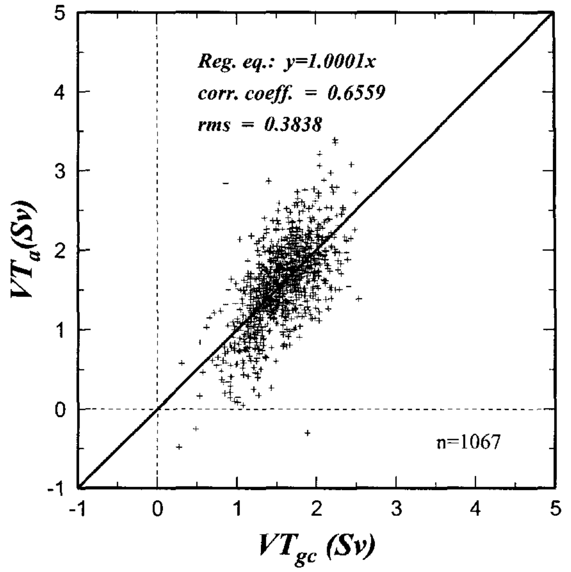

Fig. 8. Scatter plots for the adjusted geostrophic volume transport (VT_{gc}) and the ADCP volume transport (VT_a). "n (number of data)" is 1067. Correlation coefficient is 0.6559 and rms (root mean square) is 0.3838. Solid line shows the regression line between two volume transports, whose regression coefficient is 1.0001.

It agrees with the previous studies by Hidaka and Suzuki (1950), Yi (1966), Kawabe (1982) and Toba *et al.* (1982) who reported that the volume transport through the Korea Strait has a maximum in summer to autumn and a minimum in winter to spring.

Interannual variation of the volume transport

A two-year low-pass filtering is applied to the hourly volume transport to exclude components with the period less than one year (Fig. 11). The maximum and minimum of the volume transport during the period from 1965 to 2000 are 1.26 Sv in 1968 and 1.90 Sv in 1973, respectively and the mean volume transport during the period is 1.51 Sv. A large amplitude vari-

Table 1. Monthly volume transport averaged climatologically during the period from 1965 to 2000.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Volume transport	1.16	1.15	1.31	1.45	1.49	1.51	1.55	1.71	1.73	1.88	1.80	1.38

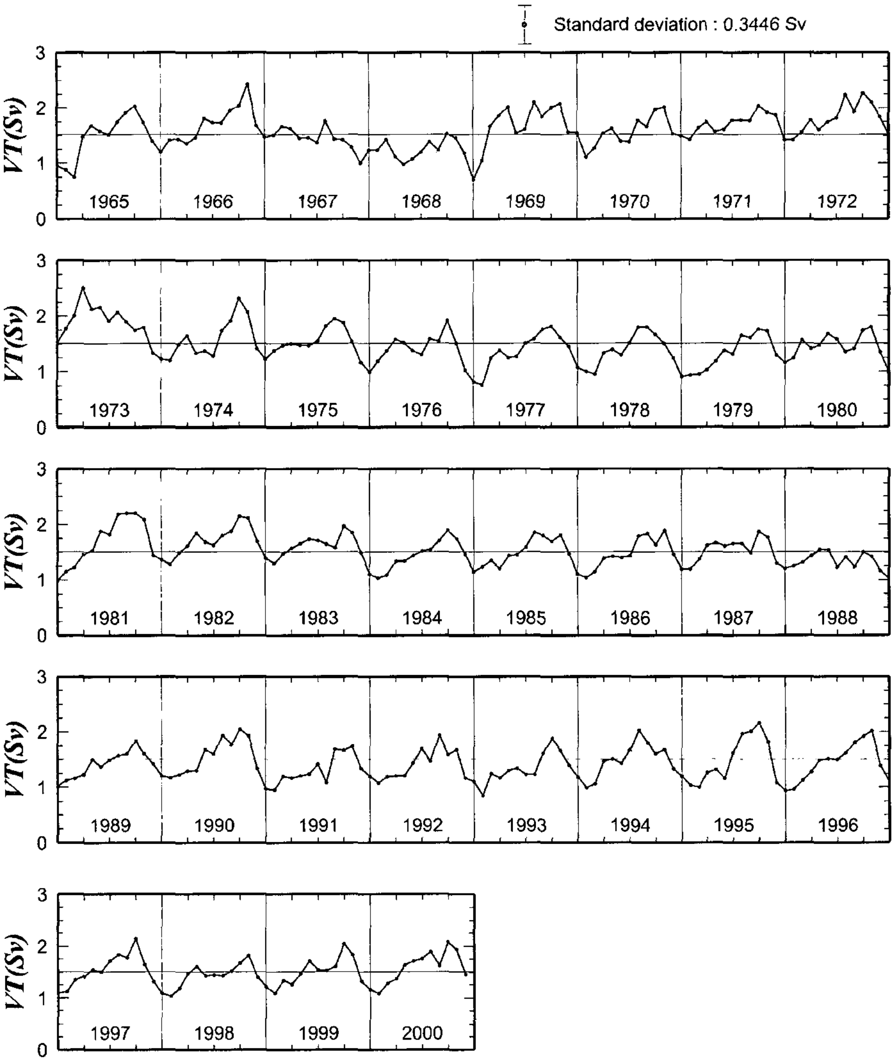

Fig. 9. Time series of monthly mean volume transports estimated by applying the relation coefficients function to the sea level data at Pusan and Hakata (Eq. (4)) during the period from 1965 to 2000. Error bar means the standard deviation for the adjusted geostrophic volume transport (VT_{gc}).

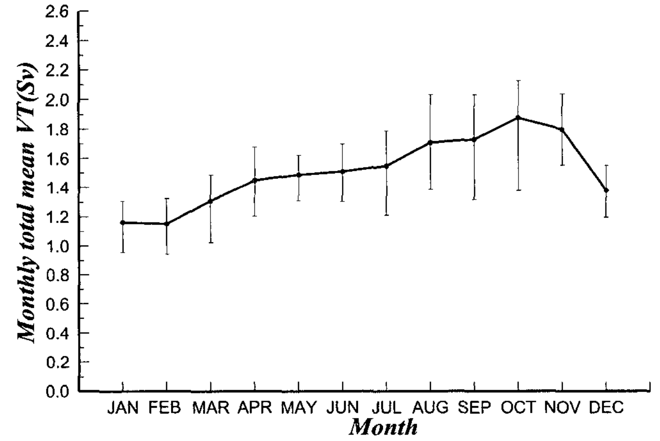

Fig. 10. Monthly volume transport averaged climatologically during the period from 1965 to 2000. Error bars mean the standard deviation for the adjusted geostrophic volume transport (VT_{gc}) for each month.

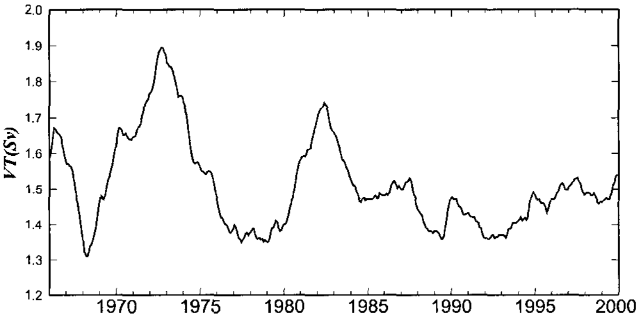

Fig. 11. 2-year low-passed volume transport from 1965 to 2000.

ation with about 10 year time scale is dominant before 1984, whereas, after 1984, the smaller amplitude variations with the time scale of a couple of years are dominant. The volume transport tends to decrease from the early 70's to early 90's, then increases from early 90's. And the volume transport during about fifteen years from the middle of 80's is being kept below the mean.

To know the dominant period, a power spectrum

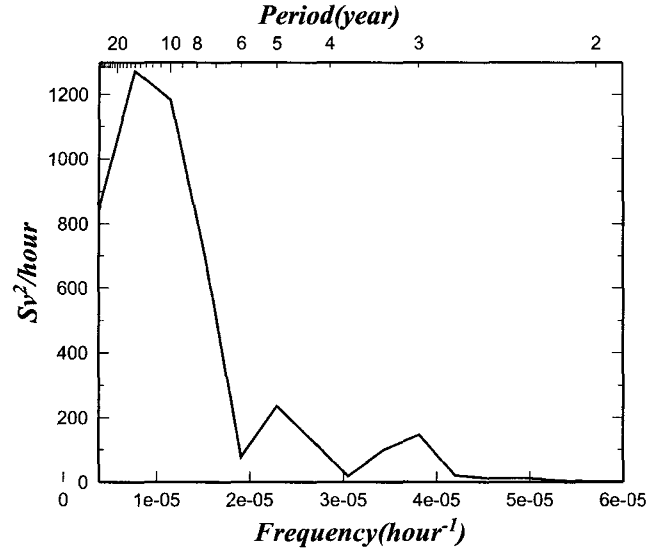

Fig. 12. Power spectrum of 2-year low-passed volume transport from 1965 to 2000.

of the time series of the volume transport using the Fast Fourier Transform is obtained (Fig. 12). Three dominant periods of 14.96 years, 4.96 years, and 2.99 years are seen.

SUMMARY

The geostrophic volume transport (VT_g) estimated from the sea level difference between Pusan and Izuhara based on the assumption of vertically uniform current does not agree enough with ADCP volume transport (VT_a) through the western channel of the Korea Strait. These disagreement seems to come from the vertical baroclinicity of the current, the volume transport except geostrophic volume transport, the internal friction, the bottom friction, inappropriate tidal position of Izuhara and so on. Therefore, the adjusted geostrophic volume transport (VT_{gc}) is introduced and provides a better agreement with ADCP volume transport (VT_a), with higher correlation coefficient between VT_{gc} and VT_a than that between VT_g and VT_a. However, the adjusted geostrophic volume transport (VT_{gc}) still include some errors estimated to be 0.3838 Sv from the correlation analysis between VT_{gc} and VT_a.

The past volume transport estimated by the adjusted geostrophic volume transport using sea level difference between Pusan and Izuhara during the period from 1965 to 2000 shows the general pattern of seasonal variation with a peak in late autumn and a trough in late spring. It also shows dominant variations of a large amplitude with about 10 year time scale before 1984 and a small amplitude with the time scale of a couple of years after 1984. The volume transport tends to decrease from the early 70's to early 90's, then increases from early 90's. The Power Spectrum analysis of the two-year low-passed volume transport during the period from 1965 to 2000 shows three dominant periods of 14.96 years, 4.96 years, 2.99 years. These interannual variations are considered to be related with that of the North Pacific Ocean. The relation between those will be investigated in future study.

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