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Volume Transport through the Tsushima Straits Estimated from Sea Level Difference

TETSUTARO TAKIKAWA[1]* and JONG-HWAN YOON[2]

[1]*Department of Earth System Science and Technology, Interdisciplinary Graduate School of Engineering Science, Kyushu University, Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan*
[2]*Research Institute for Applied Mechanics, Kyushu University, Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan*

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The relations between the volume transport and the sea level difference across the Tsushima Straits have been investigated using current data provided by ADCP mounted on the ferry *Camellia*, plying between Hakata and Pusan. Empirical formulas to deduce the volume transports using the sea level differences across the eastern and western channels are proposed, considering the seasonal variation of the vertical current structure. The interannual variation of volume transport through the Tsushima Straits for 37 years from 1965 to 2001 is estimated using the empirical formulas. The total volume transport through the Tsushima Straits, averaged for 37 years, is 2.60 Sv and those of the eastern and western channels are 1.13 Sv and 1.47 Sv, respectively. The total volume transport through the Tsushima Straits tends to decrease with a roughly 15 year variation until 1992, then begins to increase.

Keywords:
· Tsushima Warm Current,
· Tsushima Straits,
· volume transport,
· sea level difference,
· ADCP.

1. Introduction

The Tsushima Straits are channels connecting the Japan Sea and the East China Sea, with width, length and mean water depth of about 180 km, 330 km and 100 m, respectively, and are divided by the Tsushima Islands into the eastern and western channels. The Tsushima Warm Current flows through this strait into the Japan Sea and greatly influences the circulation due to the transport of heat, salt and momentum (e.g. Katoh, 1994; Hirose *et al*., 1996; Hase *et al*., 1999). In order to model the circulation in the Japan Sea as realistically as possible, accurate inflow data such as current, temperature and salinity are required at the Tsushima Straits.

The Research Institute for Applied Mechanics (RIAM) of Kyushu University has been carrying out long-term acoustic Doppler current profiler (ADCP) observations six times a week since 21 February 1997 using the ferry *Camellia* along the cruise line between Hakata and Pusan (Fig. 1) to measure the current structure and its time variations at the Tsushima Straits. Takikawa *et al*. (2005) studied the spatial current structure of the Tsushima Warm Current in the Tsushima Straits using above ADCP data, showing that the total volume transport averaged over five and half years was 2.64 Sv, and the averaged volume transports through the eastern and western channels were 1.10 Sv and 1.54 Sv, respectively. The results of Takikawa *et al*. (2005) revealed the seasonal variation of the volume transport through the Tsushima Straits, but its year-to-year variation could not be elucidated because the data series is not long enough to discuss the year-to-year variation. The aim of this study is to estimate the volume transport through the Tsushima Straits and its seasonal and year-to-year variations from the sea level difference across the Tsushima Straits using the correlation relation between the volume transport (Takikawa *et al*., 2005) and sea level difference across the Tsushima Straits.

The relation between the surface current velocity or the volume transport and the sea level difference across the Tsushima Straits has been studied by Yi (1970), Kawabe (1982), Toba *et al*. (1982) and Mizuno *et al*. (1989). Yi (1970) and Mizuno *et al*. (1989) proposed empirical formulas relating the surface current velocities to the sea level differences at the western and eastern channels, respectively. Kawabe (1982) revealed the pronounced seasonal variation of the sea level difference in the western channel, while the seasonal variations of the

* Corresponding author. E-mail: tetu@fish-u.ac.jp
Present address: National Fisheries University, 2-7-1 Nagata-Honmachi, Shimonoseki 759-6595, Japan.

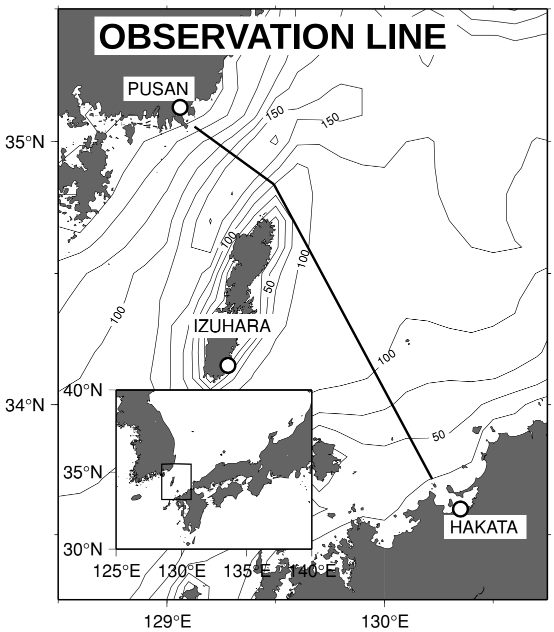

Fig. 1. The cruise line (thick solid line) of the ferry *Camellia* along which ADCP current measurements were carried out, and tidal stations (○) at Hakata, Izuhara and Pusan. Contour lines show the water depth in meters.

sea level difference (Kawabe, 1982) and the surface velocity (Mizuno *et al.*, 1989) were indistinct in the eastern channel. Recently, Lyu and Kim (2003) showed that a strong linear relationship exists between the transport through the Tsushima Straits and the sea level difference, using cross-strait hydrographic sections to remove baroclinic effects.

In this paper, we first show the relation between the surface current velocity and the sea level difference across each channel. Secondly, we propose empirical formulas for the relation between the volume transport and the sea level difference considering the seasonal variation of the vertical current structure. Finally, we calculate the volume transports through the Tsushima Straits using these empirical formulas, and then discuss seasonal and year-to-year variations.

2. Data and Method

Current data used in this study were obtained for about five years from February 1997 to December 2001 by a multi-level type ADCP system (VM-BBADCP, 300 kHz, RD Instruments) mounted on the ferry *Camellia*. The *Camellia* makes round trips between Hakata and Pusan (Fig. 1) three times a week measuring currents at every 8 m depth from 18 m to 258 m. In order to investigate phenomena with time scales longer than a few days, tidal currents must be removed from the ADCP data since tidal currents are very strong, comparable to the mean current due to the shallow depth and narrow width of the straits. Ten tidal constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2, MSf and Mf) are removed by harmonic analysis from the ADCP data (Takikawa *et al.*, 2003), and the volume transports through the Tsushima Straits are then estimated (Takikawa *et al.*, 2005).

To find the correlation between the sea level difference (Hakata–Pusan) and the volume transport through the Tsushima Straits, we analyzed the sea level data at Hakata, Izuhara and Pusan (Fig. 1) with sampling interval of one or three hours accumulated from 1965 to 2001. The barometric adjustment for the sea levels is represented as follows:

$$\eta = \eta' + c(P - P_0), \qquad (1)$$

where η (cm) is adjusted sea level, η' (cm) is the sea level before adjustment, c (=1.0 cm/hPa) is a correction factor for atmospheric pressure, P (hPa) is the sea surface pressure and P_0 (=1013 hPa) is a reference pressure. The sea surface pressure has been also observed near three tidal stations (Hakata, Izuhara and Pusan) every one, or three or six hours. The sea level and sea surface pressure data are linearly interpolated every hour. The tidal variations of the adjusted sea level are removed using a 25-hour running mean. We then used the tide free adjusted sea level from 1997 to 2001 to obtain an empirical formula to correlate the volume transport and sea level difference between Hakata and Pusan. The variation of the volume transport in the past few decades is estimated by this empirical formula using the sea level data from 1965 to 2001.

3. Relation between the Surface Current Velocities and Sea Level Differences

The ADCP mounted on the ferry *Camellia* cannot measure the current velocities at depth shallower than 18 m. In this paper, the surface current velocity is considered approximately as the current velocity at 18 m depth. Comparison of the surface current velocity normal to the section averaged every cruise in the eastern channel (south of 34.75°N) with the sea level difference between Hakata and Izuhara at the centered time of the cruise in the channel is shown by a scatter diagram in Fig. 2(a). The solid line indicates a regression line, showing a good correlation when the correlation coefficient and the root mean square (RMS) of current velocity are 0.67 and 4.09 cm/s, respectively. If the relation between the surface current velocity and the sea level difference is in geostrophic balance, the regression line should pass the origin of the coordinates. However, since the regression line does not pass through the origin, it should be considered that the reference sea levels at the tidal stations of Hakata and

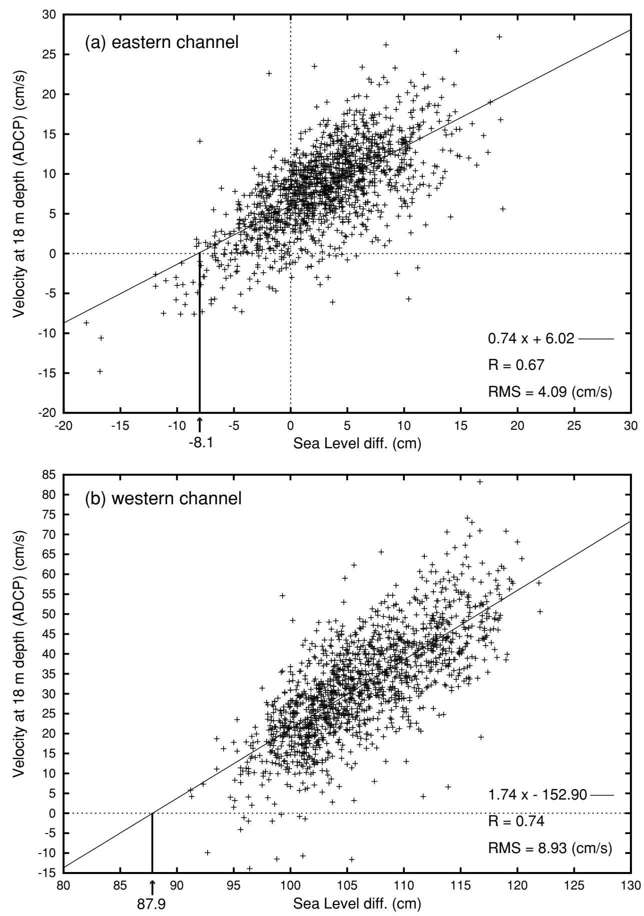

Fig. 2. (a) Comparison between the ADCP-measured velocity normal to the section toward the Japan Sea averaged in the eastern channel at 18 m depth and the sea level difference (Hakata–Izuhara) by scatter diagram. (b) As (a) in the western channel (Izuhara–Pusan). The solid line is a regression line. R: correlation coefficient, RMS: root mean square of current velocity.

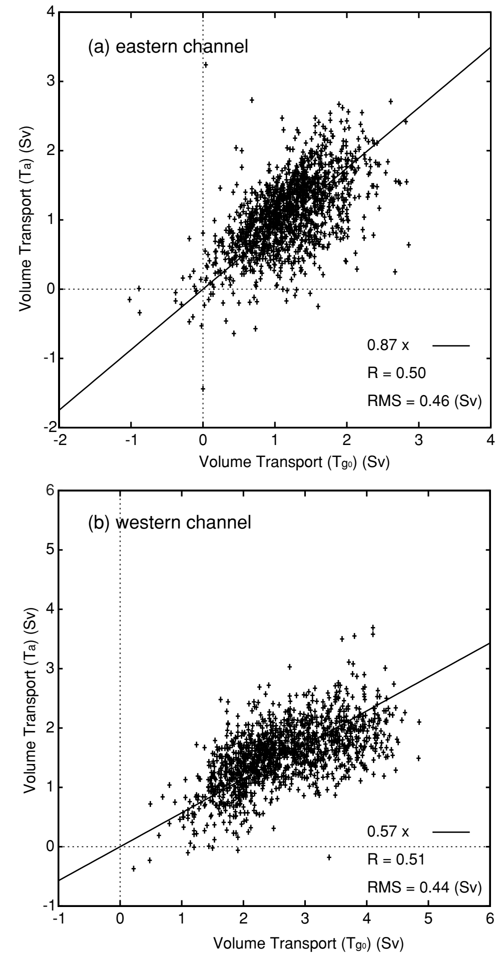

Fig. 3. (a) Comparison between the volume transport (T_a) measured by ADCP survey at the eastern channel and the transport (T_{g0}) calculated from Eq. (3) using the sea level difference (Hakata–Izuhara) by scatter diagram. (b) As (a) in the western channel (Izuhara–Pusan). The solid line is a regression line. R: correlation coefficient, RMS: root mean square of volume transport.

Izuhara are different. The regression line in Fig. 2(a) intersects at $x = -8.1$ cm on the abscissa, implying that the reference sea level at Hakata is higher than that of Izuhara by 8.1 cm. Taking the reference sea level difference η_0 to be –8.1 cm, an empirical formula for the relation between the surface current velocity (v) and the sea level difference ($\Delta\eta$) across the eastern channel is:

$$v(\Delta\eta) = \frac{g}{f} \cdot \frac{\Delta\eta - \eta_0}{\Delta x}, \qquad (2)$$

where g (=9.8 m/s) is gravitational acceleration, f (=8.22 × 10^{-5} s^{-1}) is the Coriolis parameter and Δx (=124.46 km) is the width of the eastern channel.

Figure 2(b) shows a comparison of the surface current velocity normal to the *Camellia* cruise line averaged every cruise in the western channel (north of 34.75°N) with the sea level difference between Izuhara and Pusan at the centered time of the cruise in the channel. The correlation coefficient and the RMS of current velocity are 0.74 and 8.93 cm/s, respectively. An empirical formula for the western channel is also given by Eq. (2), where η_0 = 87.9 cm, f = 8.34 × 10^{-5} s^{-1} and Δx = 51.17 km. According to Kim *et al.* (2004) who analyzed the same data for the western channel from 1997 to 2000, the correlation coefficient and η_0 were 0.72 and 85.5 cm, respectively. The small differences between this study and that of Kim *et al.* (2004) might originate from the different observation periods.

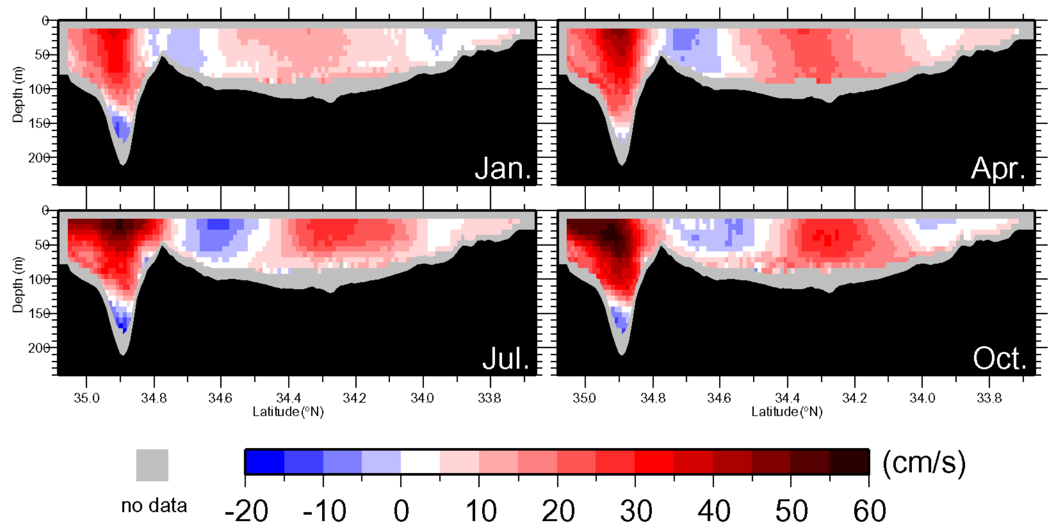

Fig. 4. Monthly averaged current velocities on the vertical section along the ferry track from February 1997 to August 2002 (Takikawa *et al.*, 2005). The velocities are normal to the section, and the positive velocities are toward the Japan Sea.

4. Relation between the Volume Transports and Sea Level Differences

Assuming that the current velocity from Eq. (2) is vertically uniform, the volume transport (T_{g0}) through each channel is calculated using Eq. (2) as

$$T_{g0}(\Delta\eta) = v(\Delta\eta)\cdot S, \tag{3}$$

where S is the cross-sectional area of each channel: 11.61 km^2 for the eastern channel and 6.66 km^2 for the western channel. The volume transports in the eastern and western channels, calculated from the ADCP data, are compared in Fig. 3 with the transports estimated from the sea level differences using the empirical formula, Eq. (3). The solid lines represent regression lines passing through the origin, where the correlation coefficients at the eastern and western channels are 0.50 and 0.51, respectively. These lines show relatively poor correlations compared with the relations between the surface current velocities and the sea level differences. This poor correlation compared with the correlation between surface current and sea level difference originates from the variation of the current baroclinicity. The RMS of volume transport in the eastern and western channels are 0.46 and 0.44 Sv, respectively. According to Kim *et al.* (2004), who analyzed the same data for the western channel from 1997 to 2000, the correlation coefficient and the RMS of volume transport for the western channel were 0.53 and 0.43 Sv, respectively. The gradients of the regression lines at the eastern and western channels are 0.87 and 0.57, respectively, implying that the current structure in the western channel is more baroclinic than that of the eastern one, as shown in Fig. 4. It is considered that one reason for the current baroclinicity in the western channel is associated with the intrusion of bottom cold water into the western channel from the Japan Sea (Lim and Chang, 1969; Cho and Kim, 1998; Johnson and Teague, 2002).

The solid and dotted lines in Fig. 5 show the volume transports across the eastern channel calculated from the ADCP data and from Eq. (3) using the sea level difference, respectively. These show good agreement with a variation of a few weeks between the two volume transports. Although the difference of the seasonal variation between those two volume transports across the eastern channel is small, the volume transports across the western channel (Fig. 6) display a large discrepancy between the two volume transports, except from February to April when the current baroclinicity becomes weak.

In order to incorporate the effect of current baroclinicity in the estimation of the volume transport, the monthly regression lines between the volume transport calculated from the ADCP data and the empirical formula of Eq. (3) passing through the origin for about five years are obtained for each channel, and the monthly gradients of the regression lines are then plotted, shown by open circles in Fig. 7. The gradients correlate mainly with the strength of the baroclinic structure of the current; a large value corresponds to less baroclinicity of the current structure and a small value indicates stronger baroclinicity. For reference, the open triangles in Fig. 7 show the monthly gradients of the regression lines for each year. Although the monthly gradients have a little variation through about five years, the year-to-year variation of the current baroclinicity is not considered in this

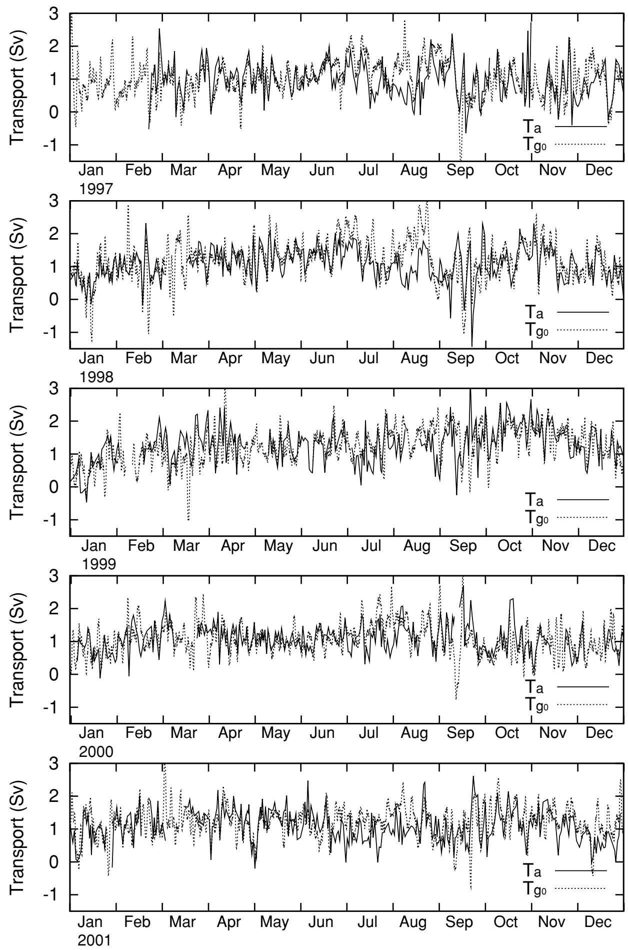

Fig. 5. Time changes of the volume transport measured by ADCP survey (T_a) at the eastern channel every cruise and calculated from Eq. (3) using the sea level difference between Hakata and Izuhara (T_{g0}) every hour. Missing data of T_a more than two days is represented by a blank.

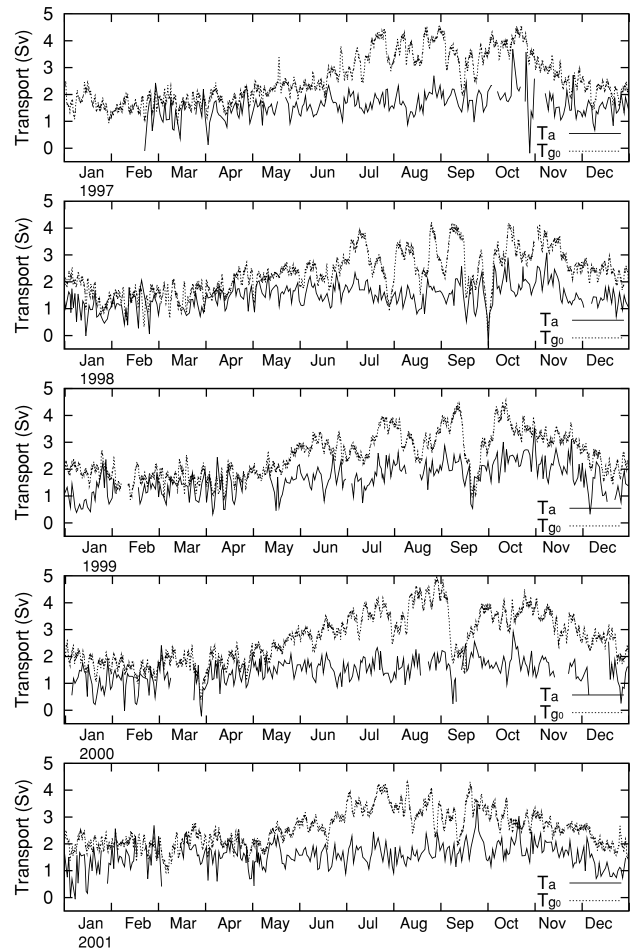

Fig. 6. As Fig. 4 at the western channel (Izuhara–Pusan).

study. Considering not only the seasonal variation of the current baroclinicity but the seasonal variation with double peaks of the volume transport (Takikawa *et al*., 2005), the monthly gradients for about five years (open circle in Fig. 7) are fitted by functions with annual and semi-annual periods using the least squares method, as shown by the solid lines in Fig. 7:

$$\alpha(t) = \alpha_0 + a_1 \cos\frac{\pi}{6}t + b_1 \sin\frac{\pi}{6}t + a_2 \cos\frac{\pi}{3}t + b_2 \sin\frac{\pi}{3}t, \quad (4)$$

where the unit of time t is one month and coefficients (a_1, a_2, b_1 and b_2) are listed in Table 1. The gradients tend to be large from winter to spring and small in summer, roughly corresponding to the seasonal variation of the vertical profile of water temperature discribed by Isobe (1994a). The large values in autumn at the eastern and western channels seem to be associated not only with intensification of the current baroclinicity but also with other seasonal changes, such as the strength of the countercurrent east of the Tsushima Islands and the depth of the current core at the western channel. According to Takikawa *et al*. (2005), the countercurrent east of the Tsushima Islands becomes stronger from summer to autumn (Fig. 4). Because the structures of the northeastward current at the central part of the eastern channel and southwestward countercurrent east of the Tsushima Islands have strong baroclinicity in autumn, the current baroclinicity become weak due to integration of the currents along the channel. The core of the current at the western channel shifts from the surface to the subsurface (about 40 m depth) in autumn, as shown in Fig. 4. In such a case, if the relation between the surface current velocity and the

Table 1. Coefficients of Eq. (4).

	α_0	a_1	b_1	a_2	b_2
Eastern channel	0.910	0.037	0.089	–0.061	–0.114
Western channel	0.607	0.008	0.100	–0.037	–0.043

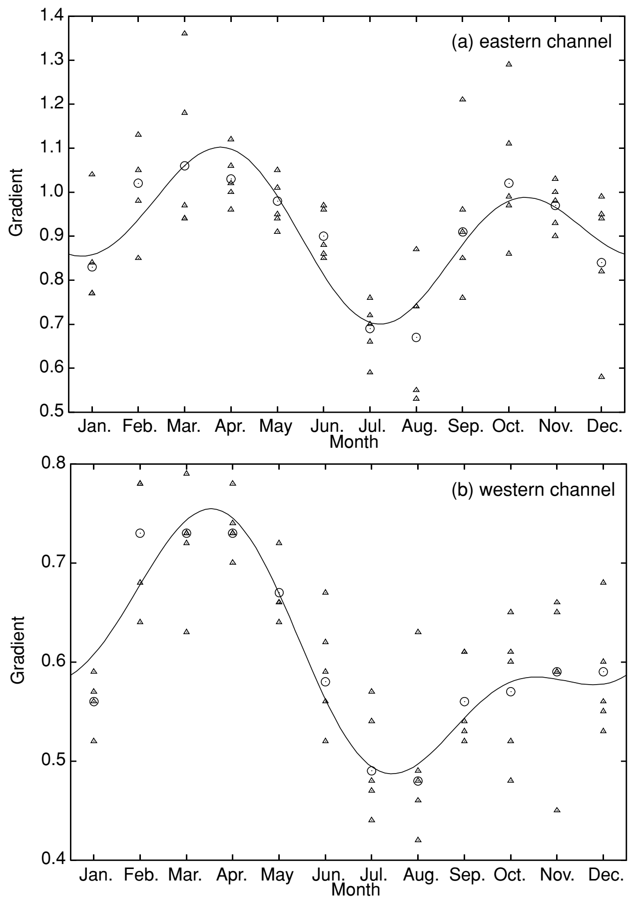

Fig. 7. Seasonal variations of the gradient of the monthly regression lines given by Eq. (4) in the eastern (a) and western (b) channels. Open circles and open triangles indicate the monthly gradient for about five years and each year, respectively. The solid lines are fitted to the open circles by functions with annual and semi-annual periods using the least squares method.

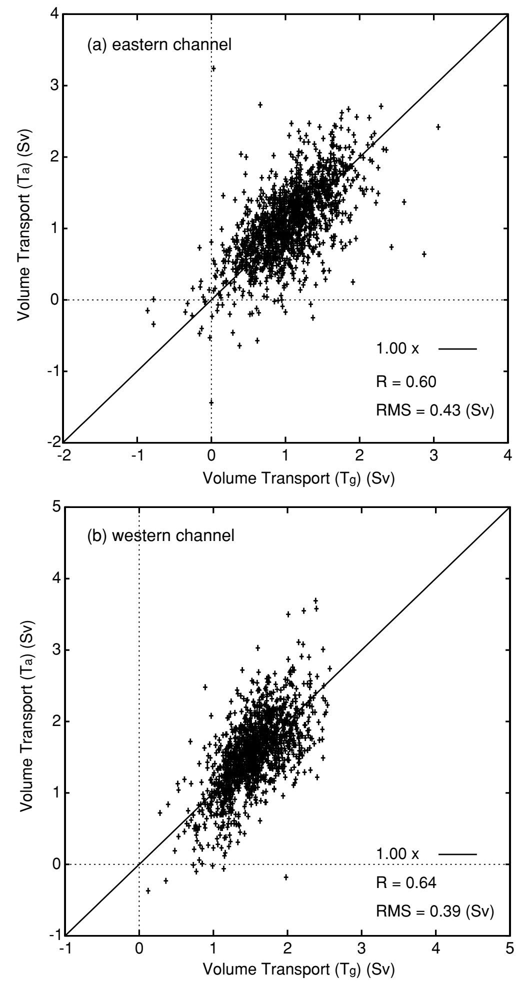

Fig. 8. As Fig. 3 calculated from Eq. (5).

sea level difference is in geostrophic balance, the gradients of the regression lines become large because the subsurface current core does not affect the sea level difference and the volume transport estimated from sea level difference alone is underestimated.

Taking the above seasonal variation described by Eq. (4) into account, an empirical formula of the volume transport (T_g) is given by:

$$T_g(\Delta\eta, t) = \alpha(t)\cdot T_{g0}(\Delta\eta). \quad (5)$$

Figure 8 shows scatter diagrams of volume transports for the geostrophic transport using Eq. (5) at the eastern and western channels. The solid line indicates a regression line passing the origin and the correlation coefficients at the eastern and western channels are 0.60 and 0.64, respectively, showing relatively good correlations compared with those of Fig. 3. The RMS of volume transport at the eastern and western channels are 0.43 and 0.39 Sv, respectively. According to Kim *et al*. (2004), who analyzed

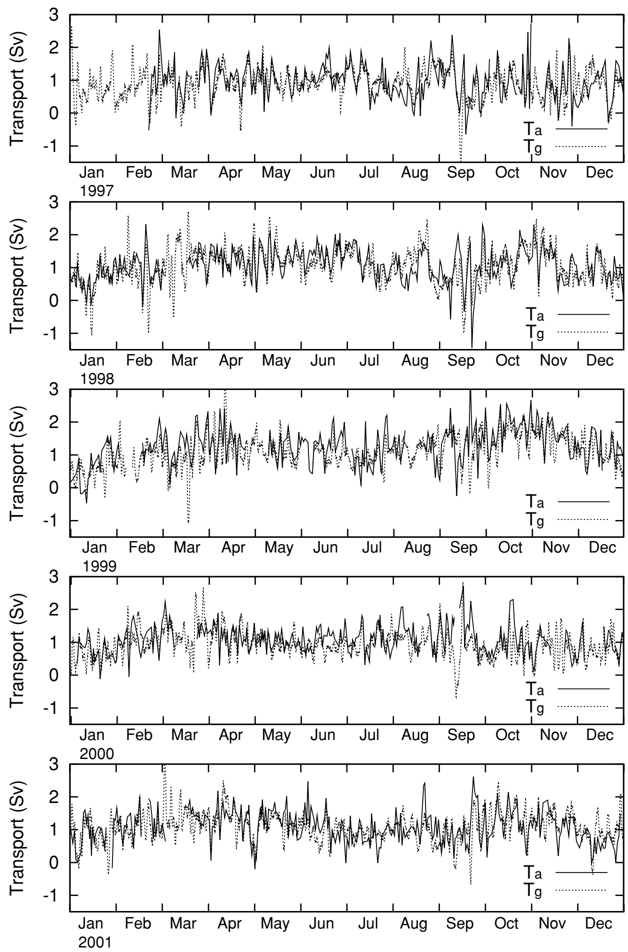

Fig. 9. As Fig. 5 calculated from Eq. (5).

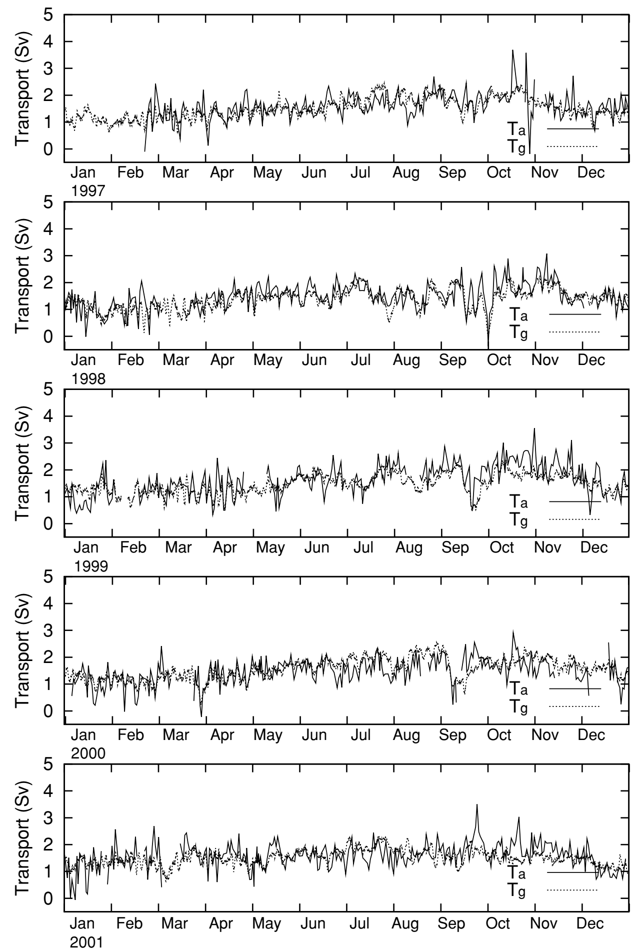

Fig. 10. As Fig. 9 at the western channel.

the same data at the western channel from 1997 to 2000, the correlation coefficient and the RMS of volume transport at the western channel were 0.66 and 0.38 Sv, respectively.

The solid and dotted lines in Fig. 9 show the volume transports across the eastern channel calculated from the ADCP data and from Eq. (5) using the sea level difference, respectively. The volume transports across the western channel are shown in Fig. 10. The discrepancy between transport calculated from ADCP and geostrophic transport in Figs. 5 and 6 are markedly reduced, showing good agreements between the two transports, except for variations of a few days.

5. Seasonal and Year-to-Year Variations of the Volume Transports through the Tsushima Straits

The monthly mean geostrophic volume transport through the Tsushima Straits can be estimated from the hourly data of the sea level differences using the empirical formula of Eq. (5). Figure 11 shows the comparison between the monthly mean volume transport ($\overline{T_a}$) measured by ADCP survey and the monthly mean geostrophic transport ($\overline{T_g}$) at the eastern and western channels. The correlation coefficients at the eastern and western channels are 0.67 and 0.73, respectively.

The monthly mean volume transports through the Tsushima Straits estimated from the sea level differences using the empirical formula of Eq. (5) are shown in Fig. 12 using the sea level data in Hakata, Izuhara and Pusan from 1965 to 2001. The data in Hakata from January 1965 to March 1966 are considered to be missing data due to their abnormal values. The total volume transport averaged over 37 years is 2.60 Sv. The average volume transports through the eastern and western channels are 1.13 Sv and 1.47 Sv, respectively. It should be noted that the volume transports tend to have a minimum in winter and two or three maxima from spring to autumn. The thick gray lines in Fig. 12 show the monthly mean volume transports calculated from the ADCP data, showing good agreement with the seasonal variations between those volume

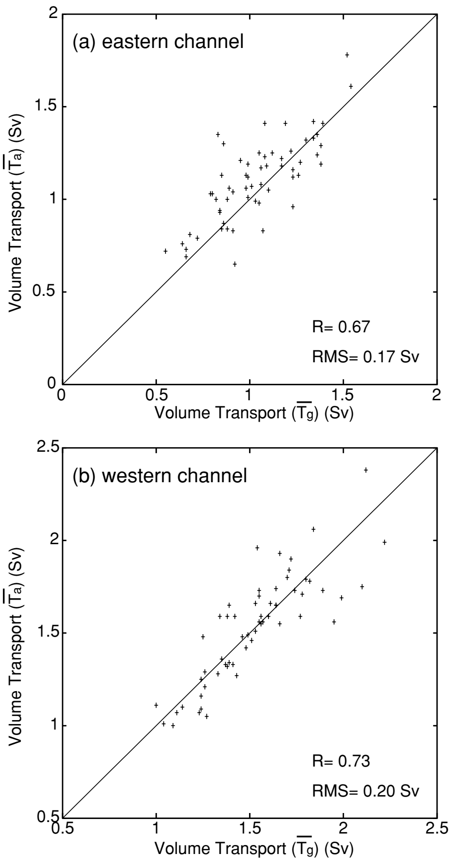

Fig. 11. Comparison between the monthly mean volume transport ($\overline{T_a}$) measured by ADCP survey and the monthly mean geostrophic transport ($\overline{T_g}$).

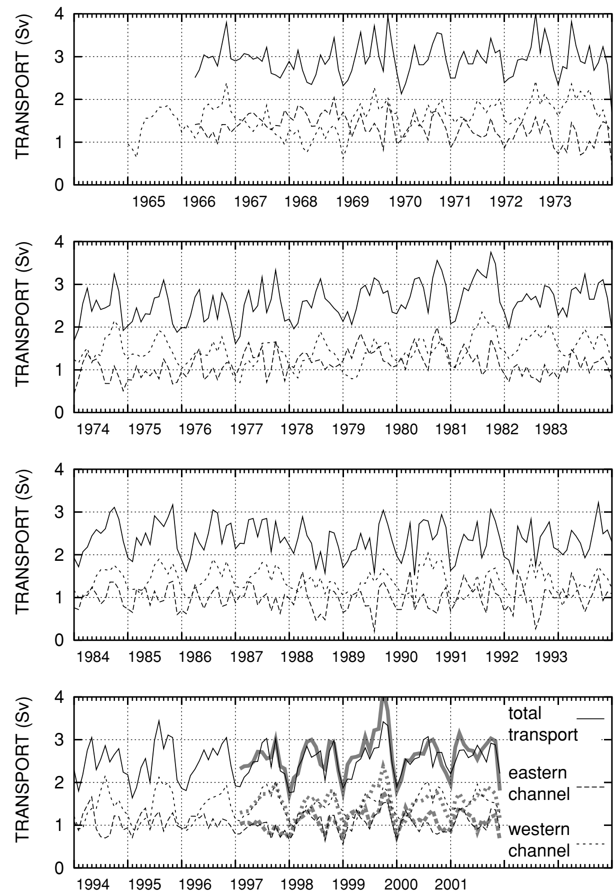

Fig. 12. Monthly mean volume transports through the Tsushima Straits from 1965 to 2001 estimated from sea level differences using empirical formula of Eq. (5). Thick gray lines show the monthly mean volume transports from 1997 to 2001 calculated from the ADCP data (solid line: total transport, broken line: eastern channel, dotted line: western channel).

transports.

Figure 13 shows the mean annual variation of the volume transports through the Tsushima Straits averaged over 37 years. The transport through the western channel has a seasonal variation with a minimum in February and two maxima in August and November. The transport through the eastern channel shows more pronounced seasonal, variation with double peaks, than that of the western channel, where the maximum values are found in April and October, and minima in January and September. The variation of the transport from June to September between the double peaks is small. The total transport has a seasonal variation with a minimum in winter and three maxima between spring to autumn. The annual ranges of volume transport through the eastern and western channels are estimated to be about 0.5 Sv and 0.7 Sv, respectively, and that of total transport is estimated to be about 0.9 Sv, showing the narrow range compared with past study (e.g. Yi, 1970; Toba *et al.*, 1982). The RMS of volume transport at the eastern and western channels are 0.17 and 0.20 Sv, respectively, as shown in Fig. 11.

Figure 14 shows the interannual variation of annual mean volume transport through the Tsushima Straits from 1965 to 2001. The transport through the eastern channel has large maxima in 1968 and 1980 and a minimum in 1975, before 1982 when the interannual variation is bigger than those after 1982. Before 1982, the variation of the transport through the eastern channel leads that of the western channel by a few years, where the western channel has maxima in 1973 and 1982 and a minimum in 1979. The total volume transport tends to decrease with roughly 15 year variation from the early 1980s until 1992 and then begins to increase after 1992. Summarizing past ADCP observations (Kaneko *et al.*, 1991; Kawano, 1993; Isobe *et al.*, 1994), Isobe (1994b) showed that the average volume transport through the Tsushima Straits from 1987 to 1991 is 2.2 Sv. According to Takikawa *et al.* (2005), the

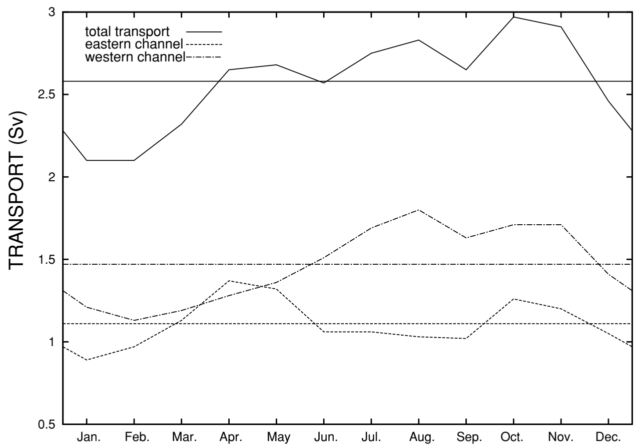

Fig. 13. Annual variations of the volume transports through the Tsushima Straits averaged for 37 years estimated from sea level differences using empirical formula of Eq. (5).

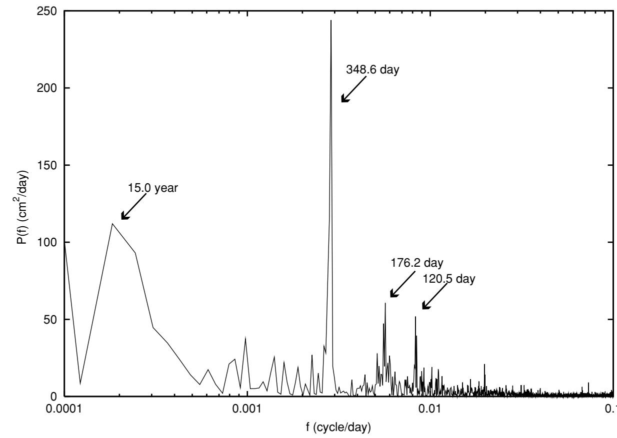

Fig. 15. Spectra of the total volume transport through the Tsushima Straits estimated from sea level differences.

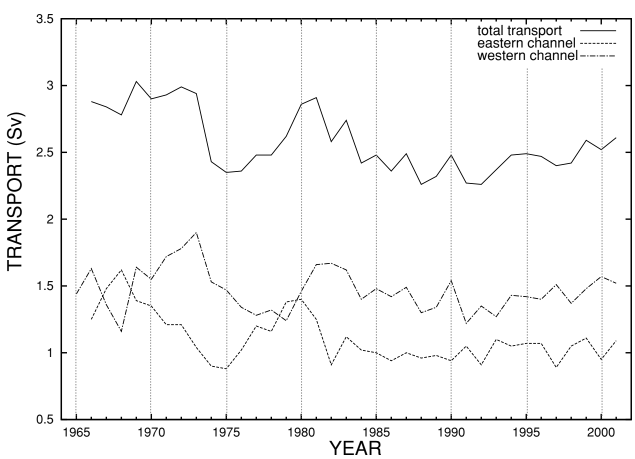

Fig. 14. Yearly mean volume transports through the Tsushima Straits from 1965 to 2001 estimated from sea level differences using empirical formula of Eq. (5).

average volume transport through the Tsushima Straits from 1997 to 2002 is 2.64 Sv. The incrementation of the transport from 1990s to 2000s from these results above is in good agreement with the interannual variation estimated in this study.

Figure 15 shows the power spectrum of the total volume transport, where spectrum peaks are observed at about one, half and one-third year periods. Although the data series is not long enough to detect any decadal variation precisely, it should be noted that a roughly 15 year oscillation is observed in Fig. 15.

6. Summary and Discussion

The relations between the surface current velocities and the sea level differences across the eastern and western channels are approximately in geostrophic balance. The reference sea level at Hakata, estimated from the regression formula, is higher than that of Izuhara by 8.1 cm, and that of Izuhara is lower than that of Pusan by 87.9 cm.

An empirical formula relating the volume transports and the sea level differences across each channel has been proposed, incorporating the seasonal variation of the current baroclinicity through the gradient of regression lines. It is suggested that the large value of the gradient reflects not only weaker baroclinicity but the countercurrent east of the Tsushima Islands and the subsurface current core at the western channel.

The volume transport through the Tsushima Straits for 37 years has been estimated using an empirical formula. The transport through the western channel has a seasonal variation with a minimum in winter and two maxima in summer and autumn. Another minimum transport between double peaks is not pronounced. The transport through the eastern channel has pronounced seasonal variation with double peeks compared with that of the western channel, with minima in spring and autumn and maxima in winter and summer.

The volume transports through the eastern and western channels increase rapidly after the mid-1970s and the late 1970s, respectively. According to Yasuda and Hanawa (1997), the Kuroshio transport also increased rapidly after the middle 1970s associated with wind-driven ocean circulation due to intensification of the Aleutian Low in winter. It is suggested that the variation of the Tsushima Warm Current as a part of the western boundary current in the subtropical gyre is influenced by atmospheric and oceanic variabilities over the North Pacific. Lyu and Kim (2003) suggested that long-term variations of the transport through the Tsushima Straits is related to changes in the Pacific Ocean, such as El Niño and decadal climate variations. After the early 1980s, the total volume transport through the Tsushima Straits decrease with about a 15 year variation until 1992, then begin to increase. Although the sea level differences include the interannual variation of the Tsushima Warm Current, this needs interpreting with case, since the year-to-year variation of the current structure, such as a current baroclinicity, as reported in this study, is not considerd.

The volume transport through the Tsushima Straits can be estimated from sea level difference at the coastal stations. The results obtained in this study will provide the boundary condition for numerical models of the Japan Sea circulation.

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