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Volume Transport of the Tsushima Warm Current, West of Tsugaru Strait Bifurcation Area

MITSUYO ONISHI and KIYOTAKA OHTANI

Department of Physical Oceanography, Faculty of Fisheries, Hokkaido University,
Minato-cho 3-3-1, Hakodate-shi, Hokkaido 041, Japan

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Northern and southern latitudinal transects were conducted west of Tsugaru Strait to estimate the volume transport in this area. It was found that the Tsushima Warm Current is the northward volume transport across the southern transect and the Northward Current is the northward volume transport across the northern transect. The current in Tsugaru Strait, *viz.* the Tsugaru Warm Current, is the flow remaining when the Northward Current is subtracted from the Tsushima Warm Current. Both CTD transects covered from near-shore to west of the subarctic front, and observed depths were from the surface to the bottom or to 1000–1500 m depth. Our estimations indicate that large interannual variations of volume transport occur, relative to the seasonal ones, with interannual variations sometimes exceeding seasonal variations in the Tsushima Warm Current and the Northward Current. The Tsugaru Warm Current has near-steady transport. Fluctuations in the Tsushima Warm Current are thus transmitted to the Northward Current. Further, our results revealed seasonal variations in the flow: the baloclinic structure became deeper in April and the current axis tended to shift in a near-shore direction in October. Therefore, previous studies, which had shallow reference levels and lacked near-shore stations, may have underestimated the transport and excessive seasonal variations.

Keywords:
- Tsushima Warm Current,
- Sea of Japan,
- observation.

1. Introduction

The Sea of Japan is a marginal sea, lying between the Asian continent and Japan. It is connected to the North Pacific Ocean and adjoining marginal seas by narrow and shallow straits, i.e. the Tsushima, Tsugaru, Soya and Mamiya straits. More than 80% of Sea of Japan is composed of a nearly homogeneous cold water mass called the Japan Sea Proper Water (Yasui *et al.*, 1967). The Tsushima Warm Current is the only major warm current in the Sea of Japan, and this flows into the Sea from the southernmost strait, i.e. the Tsushima Strait. A reviewing of the results of many investigations revealed two general concepts about the flow patterns of the Tsushima Warm Current. One is that the current has a two- or three-branch flow pattern (e.g. Suda and Hidaka, 1932; Uda, 1934; Kawabe, 1982; Naganuma, 1985), and the other is that the current has a meandering flow pattern (e.g. Moriyasu, 1972). In both concepts of flow, the Tsushima Warm Current flows over the Japan Sea Proper Water in the southern part of the Sea of Japan. Ultimately, the Tsushima Warm Current flows out of the Sea through the Tsugaru and the Soya Straits.

From an oceanographic point of view, the area west of Tsugaru Strait is a very interesting place, because the Tsushima Warm Current always converges southwest of the Strait and then diverges into two currents at the Strait. One branch is the Tsugaru Warm Current, which flows into the North Pacific Ocean through the Tsugaru Strait. The other is the remaining flow of the Tsushima Warm Current, which flows northward along the west coast of Hokkaido Island, which we call the Northward Current. The mechanism responsible for the separation of the Tsushima Warm Current has been considered an important oceanographic problem, but it remains unsolved. To understand the separation mechanism, one first needs an accurate estimate of the volume transports.

According to Hata (1962), the volume transport of the Tsugaru Warm Current varied from 50% to 100% of that of the Tsushima Warm Current, with an average value of 78%. Shuto's (1982) review stated that the volume transport which flows out through the Tsugaru Strait ranged from 1.0 to 4.1 sv, and the average value of the transport corresponded to 80% of that of the Tsushima Warm Current. At present these values are accepted as the standard values and are cited in many reports about the Sea of Japan.

Ohtani *et al.* (1989), however, indicated that in October 1988, 26% of total volume transport consisted of the transport occurring within 10 nautical miles of the coast. Ohtani and Nishida (1990) examined this phenomenon in detail and showed that the percentage of the total transport that occurred near-shore was significant and extremely variable (1–31%). Also, their results indicated that reference levels need to be deeper than 500 m near Tsugaru Strait. In addition, it is evident from Table 1 in Toba *et al.* (1982) that measurements of transport made several decades ago had reference levels that were too shallow. Furthermore, in past studies there were no near-shore stations. We consider that the volume transport of near-shore flow can not be ignored. There have been few valid continuous hydrographic cruises to estimate the volume transports, besides the cruises conducted for the present study. Therefore, we consider that the volume transport and the separation ratio have not yet been correctly estimated. In this paper we present the values of transports to the west of Tsugaru Strait and discuss their interannual variations from data we have collected from cruises during the last eight years.

2. Cruise Data and Method

Our observational cruises have been carried out since April 1986 and are still continuing; this report includes results obtained from 1986 to 1993 (Hokkaido University, 1987–1994). Several hydrographic transects off Tsugaru Strait, from the coast to the Tsushima Warm Current offshore front, have been sampled twice a year, i.e. early April and mid-October (Fig. 1). Toba *et al.* (1982) concluded that the average seasonal variation of the volume transport of the Tsushima-Tsugaru Warm Current system was characterized by a minimum in February through May, and a maximum in August through September. Shuto's (1982) review stated that the geostrophic transport referred to 400 db reached a peak in October in this area. The peak was delayed due to northward advection. Following these reports, we planned our cruise to coincide with the times of the minimum and the maximum transport in the year. The spring cruises were conducted aboard the *T/S OSHORO MARU*, and the autumn cruises aboard the *T/S HOKUSEI MARU, Faculty of Fisheries, Hokkaido University*. The details of the observations are shown in Table 1. Most hydrographic measurements

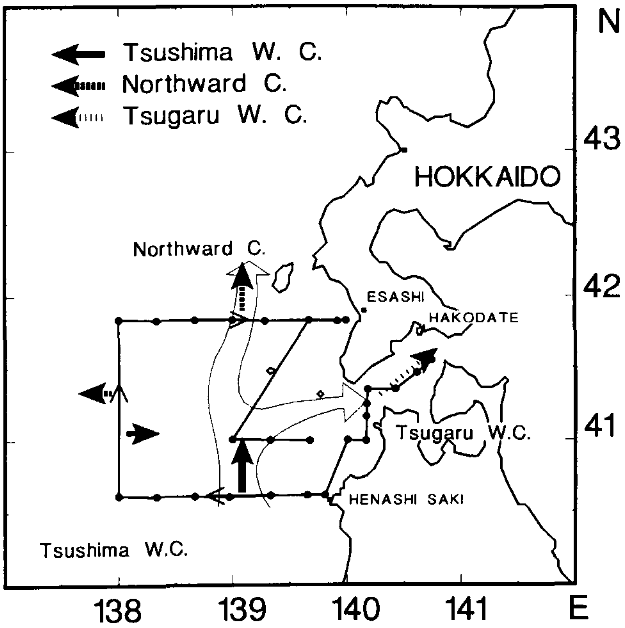

Fig. 1. Cruise track for two latitudinal transects carried out aboard the *T/S OSHORO MARU* during April 1992 and diagrams of the three identified currents.

Table 1. Observation periods, transects sampled, depths sampled and sampling methods. ○: sampled. —: not sampled.

Sampling period		Transect			
Month/Year	Day	South	North	Depth (m)	Method
April, 1986	1–10	—	○	500	CTD
April, 1987	1–10	—	○	1500	CTD
Oct., 1987	18–28	—	○	800	NANSEN
April, 1988	1–10	○	○	1500	CTD
Oct., 1988	11–25	○	○	1000	CTD
April, 1989	1–10	○	○	1500	CTD
Oct., 1989	12–26	○	○	1000	CTD
April, 1990	1–10	○	○	1500	CTD
Oct., 1990	12–26	○	○	1000	CTD
April, 1991	1–10	○	○	1500	CTD
Oct., 1991	12–26	○	—	1000	CTD
April, 1992	1–10	○	○	1500	CTD
Oct., 1992	12–26	○	○	1000	CTD
April, 1993	1–10	○	○	1500	CTD
Oct., 1993	12–26	○	○	1000	CTD

were performed with a CTD (Neil Brown Mark 3B) from the surface to near the bottom at the near-shore stations, and to 1000 or 1500 m depth at the offshore stations. The casts covered a depth range of 0–500 m in April 1986. A Nansen bottle sampler with reversing thermometers was used and covered depths of 0–800 m in October 1987. When planning the hydrographic transects for calculating geostrophic flows, we made sure that reference levels were set sufficiently deep (i.e., >500 m), and the transects were set wider than the width of the current. As stated in the Introduction, we were concerned about leakage of the current between the near-shore end of the transects and the shoreline. We set both westernmost stations at longitude 138°E. The eastern end of the transect was set about 1 nautical mile off Cape Henashi, and the eastern end of the northern transect was set about 5 nautical miles off the coast of Hokkaido, respectively. Intervals between offshore stations were approximately 20–30 nautical miles. The southern transect, near-shore stations, where the bottom bathymetric features are abrupt, had intervals of 1–10 nautical miles. Using these sections we calculated the volume transports of the Tsushima Warm Current, the Tsugaru Warm Current and the Northward Current as the geostrophic flows referred to 800 m depth. It can be assumed that little baroclinic structure exists at this depth.

We defined the northward volume transport across the southern transect and the inflow transport from the west side of the sections as transports of the Tsushima Warm Current, although the latter transport is almost always negligible. Similarly, volume transport across the northern transect and the outflow transport from the west side was defined as transport of the Northward Current (Fig. 1). It is considered that the current in the Tsugaru Strait does not have a complete baroclinic structure. The transport of the Tsugaru Warm Current can therefore be defined as the flow that remains when the Northward Current is subtracted from the Tsushima Warm Current.

3. Results

3.1 Difference of the physical properties between April and October transects

In most observations, the Tsushima Warm Current flow converged near the southwest of the Tsugaru Strait. The steep horizontal gradients in temperature and density were always narrow and localized along the southern vertical transect. The location of the steep horizontal gradients changed greatly each year; however, they occurred during the same season. Therefore, if we make average maps of the physical properties, the mobile steep structures will be smoothed, i.e. the isolines are generally depressed toward the coast in the vertical transects, or isolines are drawn with almost constant intervals in the horizontal transects; hence these will not express typical features.

We give two examples in October 1990 and April 1991 to help explain the features. Figures 2(a) and (b) show the dynamic topography (0/0–800) in the study area. In October 1990, the contours of dynamic height anomalies show one of the extreme features in this area. There was no meandering southwest of Tsugaru Strait, and the contours were converging shoreward. On the other hand, in April 1991, the contours were set going 50–100 km in an offshore direction

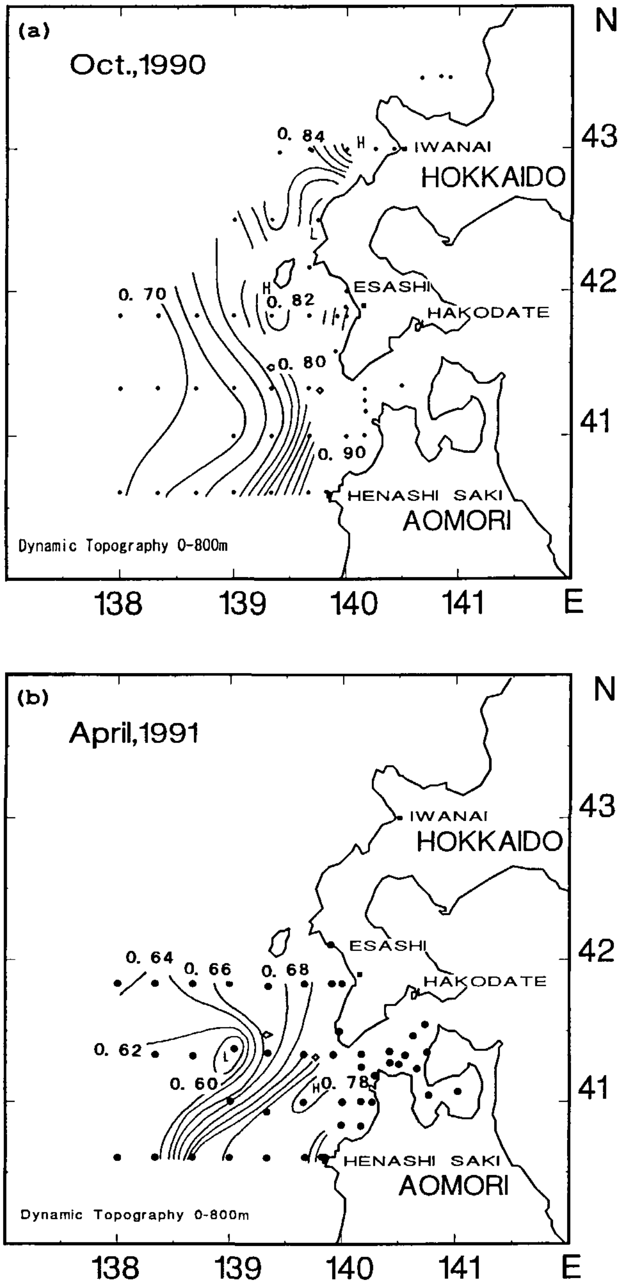

Fig. 2. Typical distributions of dynamic topography ((a): October 1990, (b): April 1991). The contours are in dynamic meters (1 dyn m = 10 J kg^{-1}).

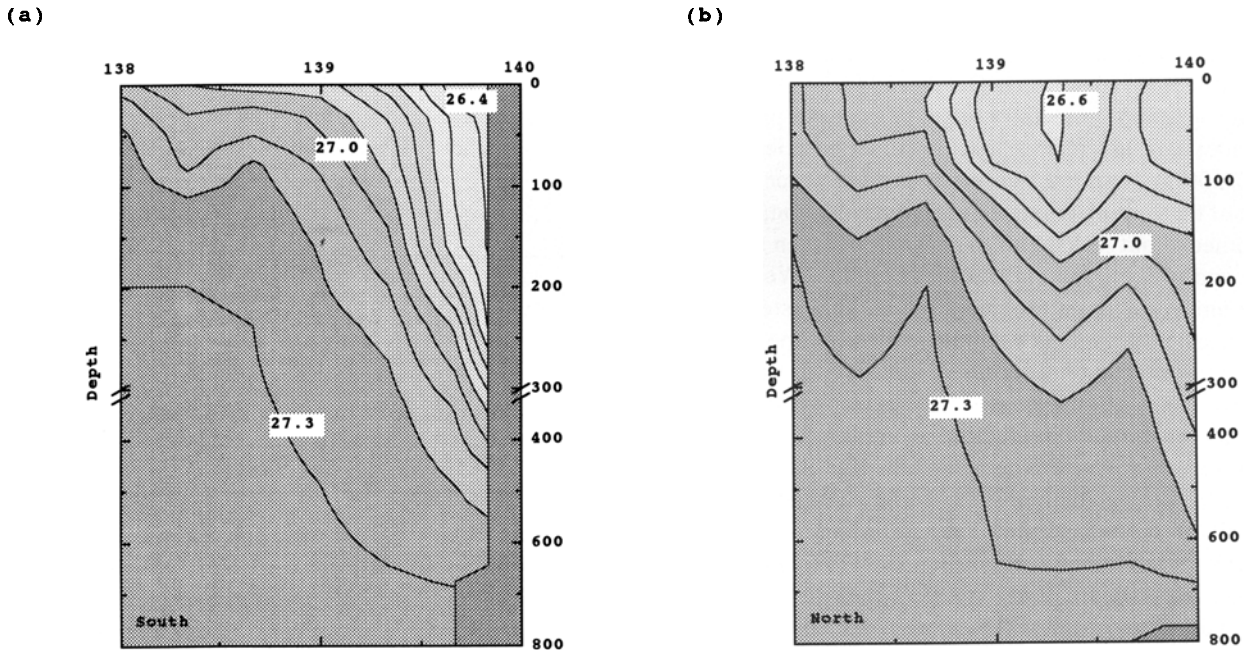

Fig. 3. Vertical distributions of σt in April 1989 ((a): southern transect, (b): northern transect).

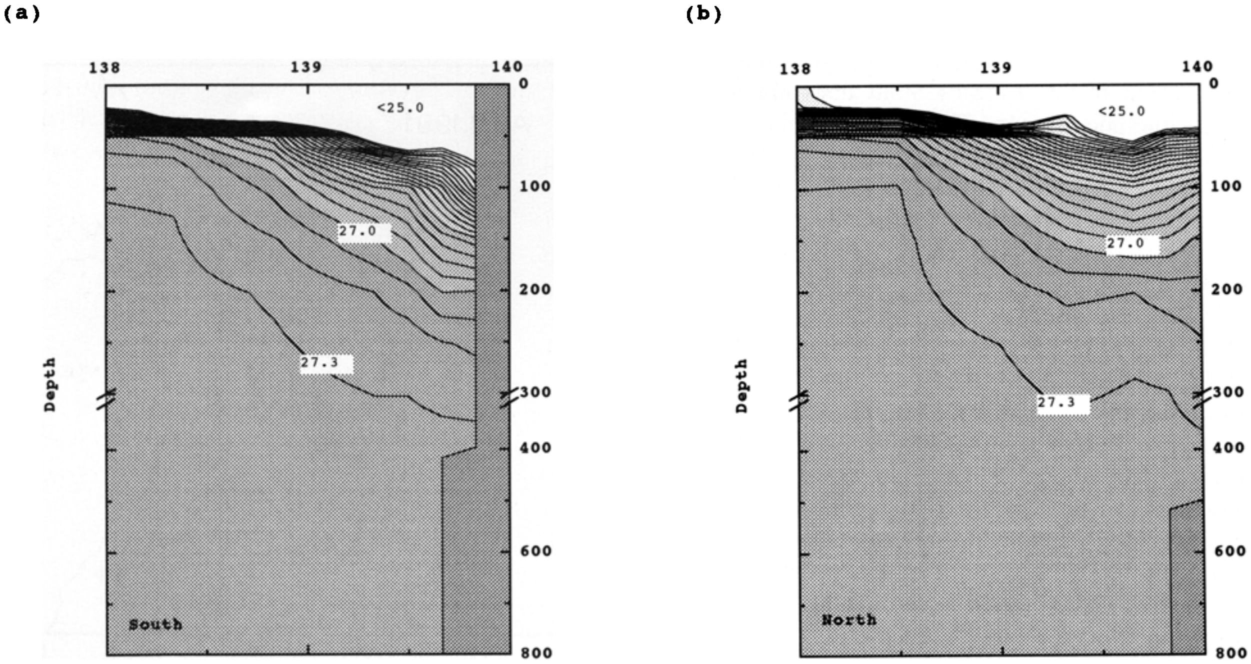

Fig. 4. Vertical distributions of σt in October 1989 ((a): southern transect, (b): northern transect).

to the southwest of Tsugaru Strait. The former case occurred during three of the six cruises in April and five of the six cruises in October, with the later case occurring in the remaining cruises. In brief, the current axis in autumn tends to shift in a near-shore direction rather than in spring. In both cases, contours to the northwest of Tsugaru Strait showed a loss of convergence and extended widely offshore. They showed meandering and eddy-like features.

Figures 3(a) and (b) show the vertical distributions of density in April 1989 along the southern and northern transects, respectively. This case is a typical one, with similar structure seen all observations. Along the southern transect (Fig. 3 (a)), warm water with low density approached the coast and formed a steep gradient with the Proper Water mass. This steep gradient corresponds to the location of the group of contours seen in the dynamic topography. By contrast, along the northern transect (Fig. 3 (b)), light water less than 26.5σt was not found, and the center of the low density water moved in an off-shore direction. Further, the isopycnals became undulatory and their intervals lengthened, indicating the stratification and current speed became weaker.

Figures 4(a) and (b) show the vertical distributions of density in October 1989. The density of the water in the upper 50 m layer was significantly decreased. The lower density water, of higher temperature and lower salinity (less than 25σt), spread across the upper 50 m depth and formed a strong seasonal pycnocline in the subsurface layer. In addition, the horizontal density gradient was large around the strong pycnocline. However, the denser water (greater than 27σt) extends upward, and the horizontal density gradient was rather smaller at the mid and lower depth than that in April. But the principal differences of the structures between the northern and southern transects were similar to those in April.

3.2 Geostrophic transport

As mentioned above, we were concerned with the leakage of the transport. Table 2 shows the contributions of near-shore transport (less than 10 nautical miles from shore) to the total transport across the southern transect. As is evident from Table 2, the ratio of contributions from near-shore transport has large fluctuations and cannot be ignored (the maximum is 24%). It appears that the total transport in October depends more on near-shore transport than the total transport in April. This feature coincides with the shift of the group of contours in the dynamic topographies, which was discussed in Subsection 3.1.

Table 3 shows comparisons of the transport referred to 800 m and that referred to 300 m. The rate of increase related to the setting of a deeper reference level varied from 2 to 57%, and the rate of increase of transport in April was relatively high, compared to October.

Further, to clarify the difference in the current structure between April and October, we calculated the percentage of total volume transport occurring within each 50 m depth layer along the southern transect (Fig. 5). The seasonal differences in the contribution to the volume transport of each depth interval indicates that the baroclinic structure is deeper in April than in October. During both months, the features of the contribution divide at about 50–100 m depth, and are counteracted in both the upper and lower layers. This depth corresponds to the bottom of the well-mixed surface layer in April and the center of the seasonal pycnocline in October.

Table 2. Contributions of near-shore transport (less than 10 nautical miles off the coast) in southern transect. %: percentage of total flow that occurred near-shore.

Period	Total flow (sv)	Near-shore flow (sv)	%
April, 1988	1.86	0.14	7
Oct., 1988	2.96	0.59	20
April, 1989	2.82	0.67	24
Oct., 1989	3.13	0.56	18
April, 1990	2.62	–0.05	–2
Oct., 1990	2.16	0.13	6
April, 1991	2.50	–0.18	–7
Oct., 1991	1.93	–0.08	–4
April, 1992	1.83	0.12	6
Oct., 1992	3.16	0.72	23
April, 1993	3.60	–0.09	–2
Oct., 1993	4.13	0.48	12
April mean	2.54	0.10	4
Oct. mean	2.91	0.40	14

The volume transport in April 1990 was greater than in October 1990 (Table 3), and thus the interannual variation exceeded the seasonal variation. The difference between the transports was 0.46 sv. If the transports are calculated with a shallower reference level (set at 300 m depth), the difference decreases to 0.25 sv. Furthermore, the transport in the 300–800 m depth interval contributed 17% to the total transport in April, and 11% in October. Major volume transport in October occurred in the shallow layer, while in April the deeper layers bore a larger part of the transport. If we set the reference level at 300 m, as was done in many previous studies, the volume transport in spring is underestimated.

Figure 6 shows a time series of the volume transports of the Tsushima Warm Current system in the bifurcation area. Minimum values of the Tsushima Warm Current, Northward Current and Tsugaru Warm Current were 1.83 sv (April, 1992), 0.24 sv (April, 1992) and 0.93 sv (April, 1989), respectively. The maxima were 4.13 sv (October, 1993), 2.44 sv (October, 1993) and 2.67 sv (April, 1993). The average volume transports during the eight years studied were 2.73 sv, 1.39 sv and 1.47 sv, respectively, and the standard deviations were 0.72 sv, 0.73 sv and 0.46 sv,

Table 3. Comparisons of the transport referred to 800 m depth and 300 m depth, and rate of increase (%) due to the deepening of the reference depth from 300 m to 800 m.

Period	T.W. Current (sv)			N. Current (sv)		
	0–800 m	0–300 m	%	0–800 m	0–300 m	%
April, 1986				0.61	0.56	8
April, 1987				1.91	0.83	57
Oct., 1987				2.43	2.12	13
April, 1988	1.86	1.59	15	0.50	0.29	42
Oct., 1988	2.96	2.90	2	1.41	1.01	28
April, 1989	2.82	2.15	24	1.89	1.23	35
Oct., 1989	3.13	3.03	3	1.81	1.41	22
April, 1990	2.62	2.17	17	1.49	1.19	20
Oct., 1990	2.16	1.92	11	0.83	0.57	31
April, 1991	2.50	2.00	20	0.92	0.84	9
Oct., 1991	1.93	1.74	10	—	—	
April, 1992	1.83	1.74	5	0.24	0.18	25
Oct., 1992	3.16	2.96	6	2.11	1.56	26
April, 1993	3.60	3.08	14	0.93	0.80	14
Oct., 1993	4.13	3.74	9	2.44	2.07	15
April mean	2.54	2.12	16	1.06	0.74	26
Oct. mean	2.91	2.72	7	1.84	1.46	23

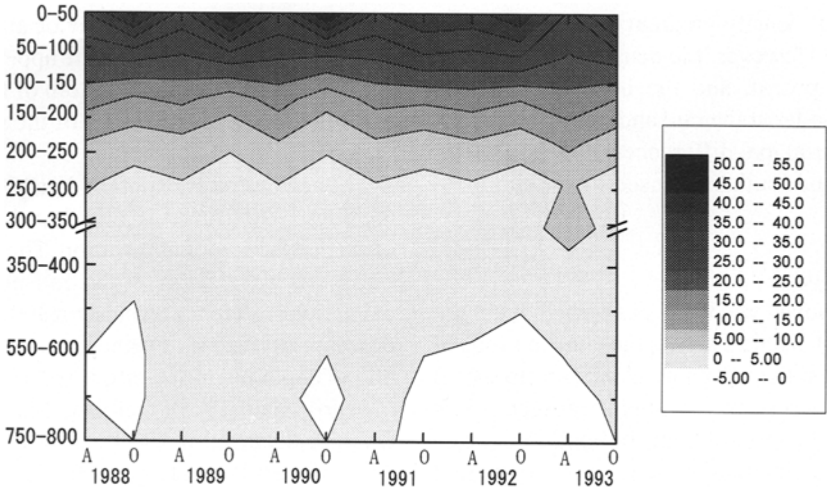

Fig. 5. Time series of the percentages of volume transports at each 50 m depth layer in southern transect.

respectively. Based on these transport values, the average value of the volume transport of the Tsugaru Warm Current corresponds to 55% of the Tsushima Warm Current.

The results of our estimations show large interannual variations of transport in the Tsushima Warm Current system, which are clearly evident, compared to the seasonal variations. The interannual fluctuations of transport in the Tsushima Warm Current and the Northward Current were found to be very similar, except during April 1993. In this month, the transport of the Northward Current was fairly small. The time scale of these fluctuations was roughly 4–6 years. Meanwhile, the Tsugaru Warm Current was not influenced by the fluctuations of those currents and was roughly constant. Shikama (1994) directly measured the volume transport of the Tsugaru Warm Current using ADCP meters, and obtaining an average value of about 1.4 sv, with

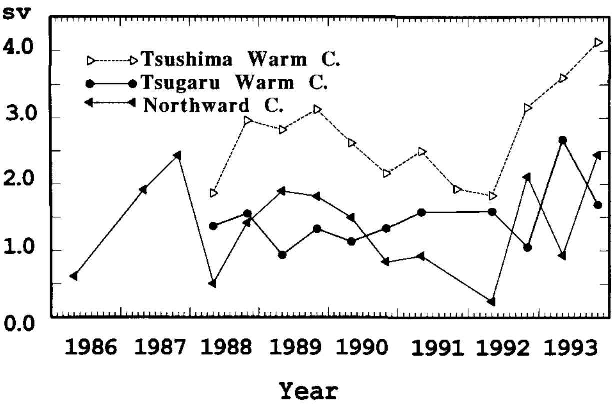

Fig. 6. Interannual variations in the transport of the Tsushima Warm Current System.

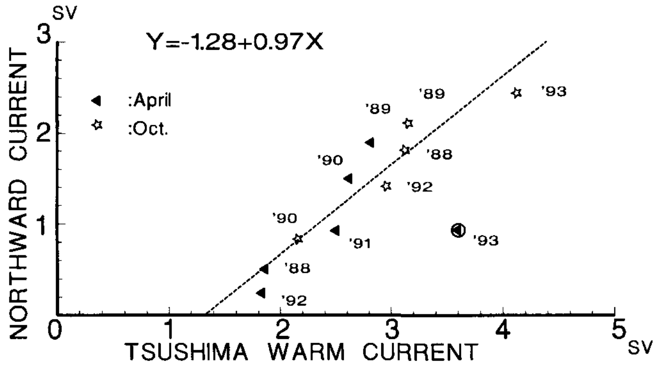

Fig. 7. Comparison of the Tsushima Warm Current and the Northward Current (regression line was calculated by excluding the April 1993 value). The coefficient is statistically fairly significant.

a fluctuation within 0.5–1 sv. Our estimated transport supports this value, although his data were collected over only a 6 month period (May–November). To compare the transports between the Tsushima Warm Current and the Northward Current, we calculated the regression line between the two currents (Fig. 7). The estimated value of the slope is 0.97, and the correlation coefficient is 0.94 ($n = 10$). It can be concluded statistically that the transport of two currents experienced very similar fluctuations. The x-axis border value of 1.32 is satisfactory compared to the transport of outflow through Tsugaru Strait, i.e. the Tsugaru Warm Current.

4. Discussion and Conclusions

To summarize our interpretation of the results from the geostrophic calculations: the volume transports of the Tsushima Warm Current system have large interannual variations which sometimes exceed the seasonal variations.

The problems of leakage can be summarized as follows: along the southern transect, the contribution of the near-shore transport has large fluctuations, hence the near-shore transport cannot be ignored. The Tsushima Warm Current system in April has a deep baroclinic structure, unlike the structure in October. Hence the transports in previous studies, which had shallow reference levels and lack of near-shore stations, may be under estimation's.

The pattern of the bifurcation is roughly constant between the transport of the Tsugaru Warm Current to the North Pacific, and the remaining flow northward of the Northward Current (including most of the variations). The trends of the interannual variations of volume transports of the Tsushima Warm Current and that of the Northward Current were similar, except during April 1993. Our data indicate that the average bifurcation ratio of the Tsugaru Warm Current to the Northward Current is almost 1:1. However, it has large variations (7:1 to 1:2). Especially in April, the volume transport of the Tsushima Warm Current is sometimes small; hence the remainder, after subtracting the roughly constant outflow (the Tsugaru Warm Current) from the Northward Current is very small. Hence, the seasonal and year-to-year variation of the bifurcation ratio has a close relationship to the volume transport of the Tsushima Warm Current.

Finally, we think we know the reason why there was an extraordinary flow condition in April 1993. Hata (1962) suggested that the approach of a depression in this area caused a rise in sea levels and intensified the Tsugaru Warm Current. However, there was calm weather during our cruise

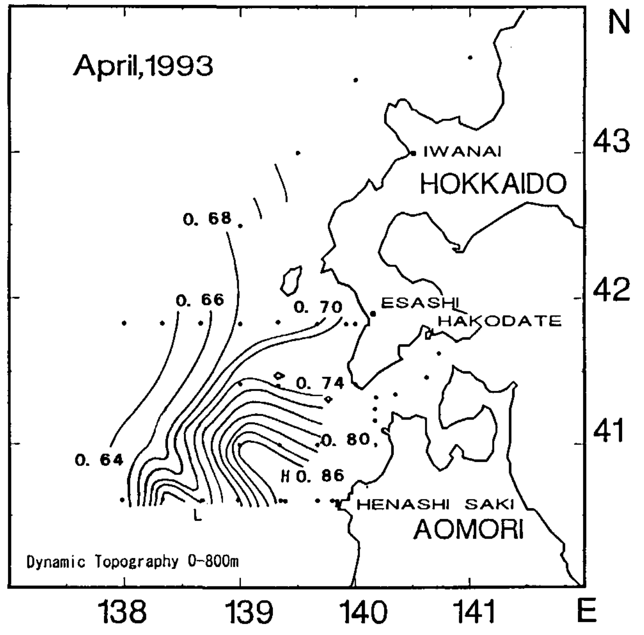

Fig. 8. Dynamic topography in April 1993. The contours are the same as in Fig. 2.

in April 1993. Ohtani and Nishida (1990) suggested that a relationship exists between the distance of the major flow from the coast and the bifurcation ratio of the Tsugaru Warm Current. They expected a strong negative correlation between them. However, such a relationship was not seen in April 1993, and probably did not occur during the other cruises (see Tables 2 and 3). Figure 8 shows the dynamic topography in April 1993. This reveals that a large eddy-like structure was formed west of Tsugaru strait, and no significant Northward Current could be seen. Such a structure was not observed during other cruises. It is suggested that this clockwise eddy affected the current structure at the west of Tsugaru Strait, intensifying the Tsugaru Warm Current, and interrupting the Northward transport.

There are problems that still remain to be solved. These include determining why the volume transport of the Tsugaru Warm Current is roughly constant and why the current fluctuations of the Tsushima Warm Current are propagated only to the Northward Current. We want to address these questions in the near future.

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