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Author(s)	Ohtani, Kiyotaka; Onishi, Hiroji; Kobayashi, Naoto; Anma, Gen
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Baroclinic Flow Referred to the 3000 m Reference Level across the 180° Transect in the Subarctic North Pacific

Kiyotaka OHTANI[1], Hiroji ONISHI[1], Naoto KOBAYASHI[2]
and Gen ANMA[3]

Abstract

Zonal flow structures and volume transports relative to the 3,000 m were estimated along the 180° meridian between 36° and 51°N based on the CTD observations during summer cruises of the T.S. OSHORO MARU in June 1990-1996. Increase in velocities at 1,000 m depth using the 3,000 m reference level were 10-15 cm•s^{-1} in the Alaskan Stream, 6-8 cm•s^{-1} in the Subarctic Current and a few cm•s^{-1} in other areas. Eastward subsurface flow in excess of 10-15 cm•s^{-1} in the Subarctic Current had been observed at south of 50°N until 1992, however, its positions shifted near the subarctic front since 1993.

The 22-33 sv of westward transport in the Alaskan Stream and the 21-37 sv of eastward one in the Subarctic Current and the Transition Domain were consistently obtained, and these values are almost twice those of transports referred to the 1500 m reference level and comparable to the baroclinic transport in the Kuroshio Extension far to the west.

Key words : Baroclinic transport, Alaskan Stream, Subarctic Current, Northern North Pacific.

Introduction

Magnitudes of volume transports in the subarctic circulation in the North Pacific were estimated by means of geostrophic calculations relative to a 1,000 or 1,500 m reference level (Favorite et al., 1976). The Alaskan Stream is the strongest westward flow in the subarctic circulation and its volume transports have been estimated as within 10 to 15 sv in many previous studies (Favorite, 1967, 1974; Ohtani, 1970; Reed, 1984; Royer and Emery, 1987; etc.).

However, Favorite (1974) indicated the large difference between a velocity profile calculated from a pair of hydrographic stations and mean parachute drogue velocities, and pointed out that the discrepancy was a result of neglecting the actual velocity of 28 cm•s^{-1} measured at the 1,000 m reference level in the geostrophic calculations. Reed (1984) and Warren and Owens (1988) moreover indicated from a number of deep hydrocasts that the values of geostrophic velocity and transport increased as the reference level deepens. Favorite (1974) suggested that geostrophic velocities referred to levels near 3,000-4,000 m were more representative of actual flow than those computed from shallower reference levels. Warren and Owens

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[1] *Laboratory of Physical Oceanography, Faculty of Fisheries, Hokkaido University.*
(北海道大学水産学部物理海洋学講座)

[2] *Training Ship of Hokusei maru, Faculty of Fisheries, Hokkaido University.*
(北海道大学水産学部練習船北星丸)

[3] *Training Ship of Oshoro maru, Faculty of Fisheries, Hokkaido University.*
(北海道大学水産学部練習船おしょろ丸)

(1988) presented that the above result was a consequence of the isopycnals sloping downward toward the Aleutian Islands arc at all depths in the Alaskan Stream. These reports also imply that the reference levels in the geostrophic calculation for the subarctic region need to be deeper than those in the subtropical region.

The purpose of this article is to describe the magnitude of volume transports referred to the 3,000 m reference level across a transect along the date line in the subarctic circulation.

Data and observations

Hydrographic observations shallower than 1,500 m along the 180° meridian between 37°N and 49°N were carried out every June from 1979 to 1989 by the T.S. OSHORO MARU of the Faculty of Fisheries, Hokkaido University (Anma et al. 1990). Since 1990, the CTD (Neil Brown Mark 3b) observations were made at closer station intervals and to greater depths in order to obtain a better estimate of volume transport in the central part of the subarctic circulation from south of the Subarctic Boundary to the Aleutian Islands. The hydrographic data were obtained with CTD casts deeper than 3,000 m (nearly maximum capacity of equipment on board the OSHORO MARU) at every degree of latitude from 37° (36°since 1993) N to 49°N and at stations of 20-25 nautical mile intervals from 49° 45′N to 51° 10′N, as well as data to 1500 m at each half degree between the deeper observations between 49°30′N and the southernmost station. Locations of CTD casts are typically shown in Fig. 1. Similar observations are repeated by the OSHORO MARU during every summer cruise. Data obtained during 1990-1996 summer cruises (Hokkaido Univ., 1991-1997) are used in this report.

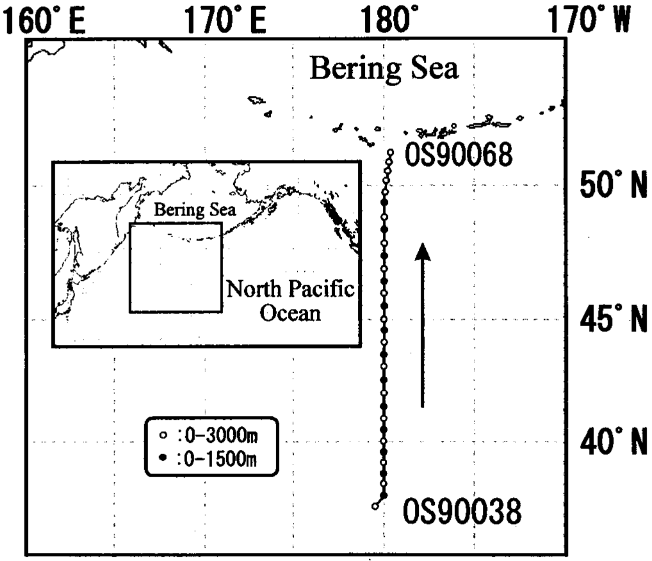

Fig. 1. Locations of the CTD stations along the date line in 1990. Similar observations are annualy repeated by OSHORO MARU up to the present (1997).

Results along the 180°meridian

1. Vertical structures

Vertical structures of potential temperature (a), salinity (b) and potential density (c) in 1990 are typically shown in Fig. 2, respectively. A characteristic structure of isopleths is found at 50°N, where a convex peak of isolines exists below the permanent halocline in each figure. This is known as the dome-like structure (Uda, 1963) or a crest of the Ridge Domain (Favorite et al., 1976). Isolines below the subsurface deepen sharply northward from the convex peak toward the Aleutian Islands and gradually undulate southward. The narrow area on the northward slope of the dome is the Alaskan Stream of westward flow.

The Subarctic Current flows eastward in the area between the top of the dome (50°N) and north of 46°N, where the minimum temperatures (dichothermal water : Dodimead et al., 1963) appear inside or under the permanent halocline layer which are affected by the Okhotsk subsurface water (Ohtani, 1965, 1970) (Fig.2a). The

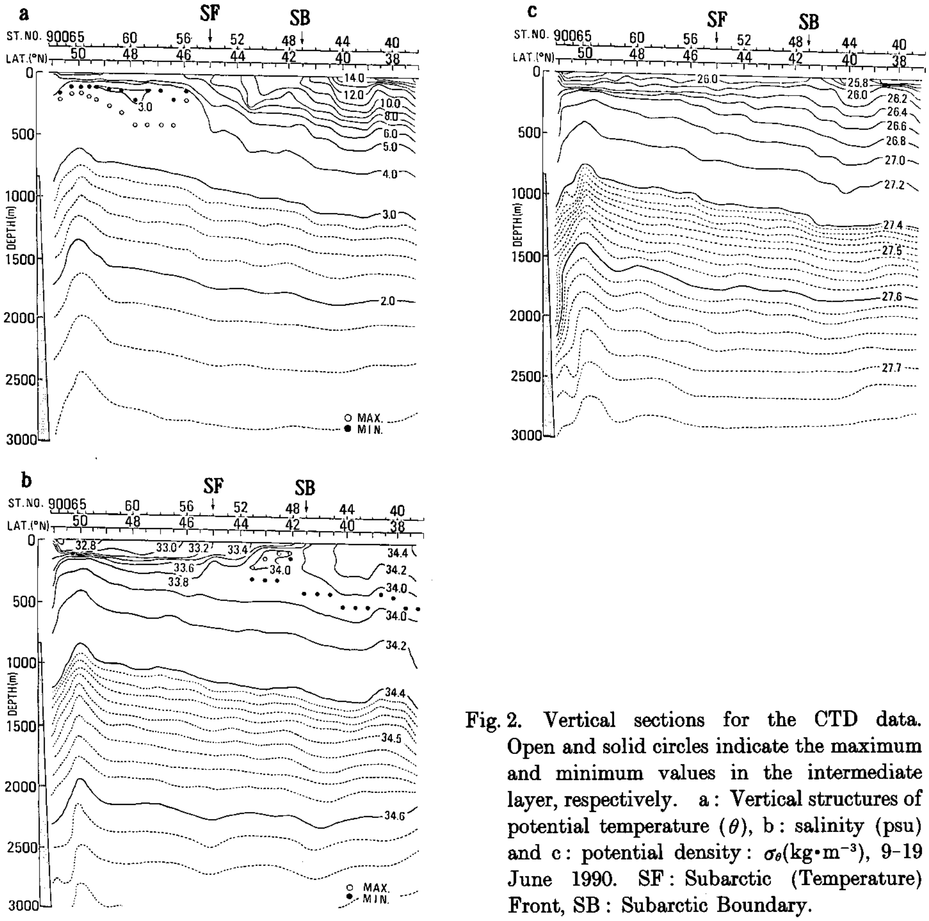

Fig. 2. Vertical sections for the CTD data. Open and solid circles indicate the maximum and minimum values in the intermediate layer, respectively. a : Vertical structures of potential temperature (θ), b : salinity (psu) and c : potential density : σ_θ(kg·m^{-3}), 9-19 June 1990. SF : Subarctic (Temperature) Front, SB : Subarctic Boundary.

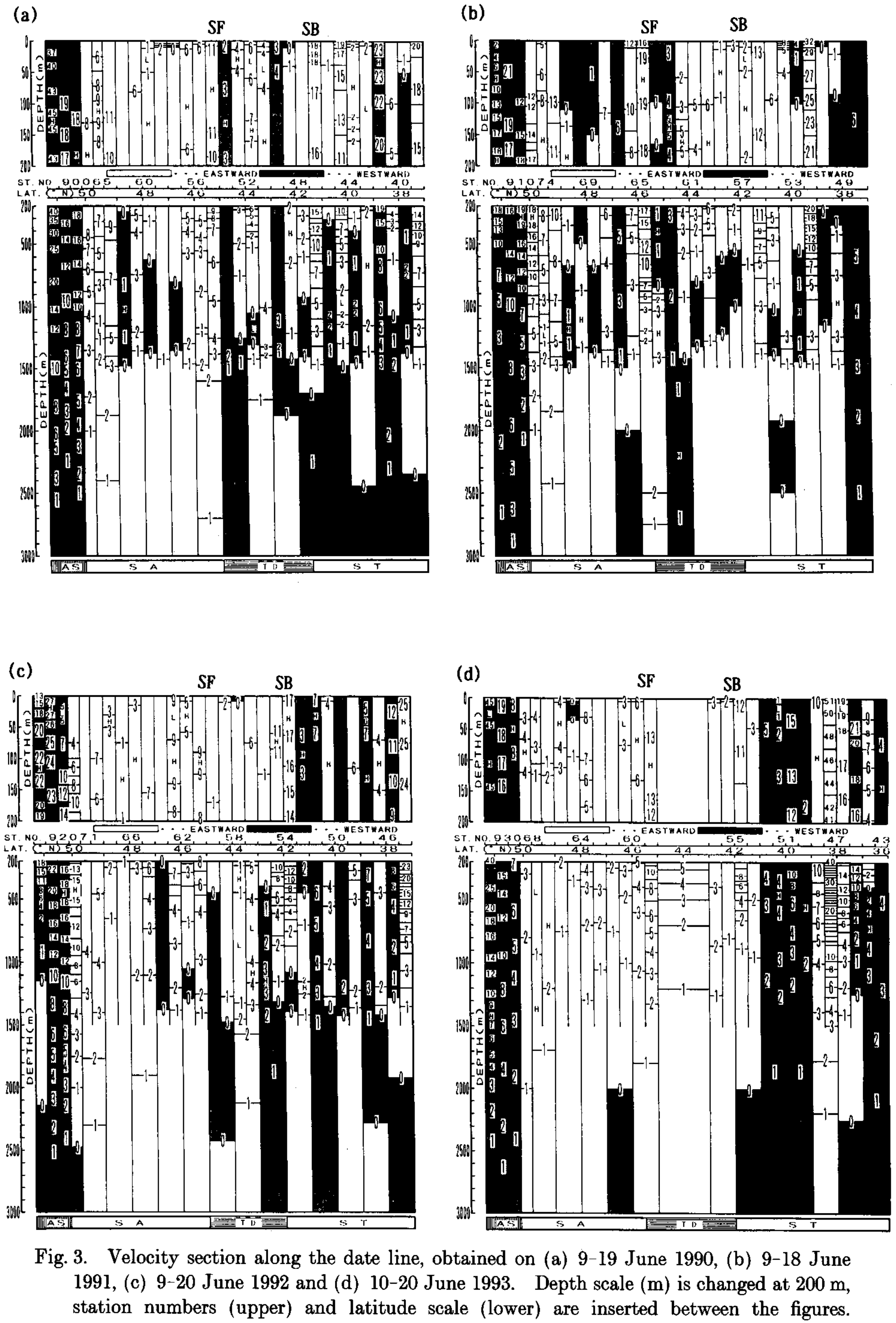

Fig. 3. Velocity section along the date line, obtained on (a) 9-19 June 1990, (b) 9-18 June 1991, (c) 9-20 June 1992 and (d) 10-20 June 1993. Depth scale (m) is changed at 200 m, station numbers (upper) and latitude scale (lower) are inserted between the figures. Numerals in the columns indicate a velocity at depth in cm•s^{-1}. Shadowed areas indicate westward flows. AS: Alaskan Stream, SA: Subarctic Current, TD: Transition Domain (Favorite et al, 1976) and ST: Subtropical waters in Transition Zone (Roden, 1991).

temperature maxma under the dichothermal layer (mesothermal water : Dodimead et al.,1963) of the Subarctic Current are perceptibly colder and denser than those of the Alaskan Stream. The subsurface temperature front which outcrops to the sea surface in winter (the subarctic temperature front in Roden, 1991 ; polar front in Roden et al., 1982) is indicated by vertical 4°C isotherm and denotes the southern boundary of the purely subarctic water masses (Dodimead et al., 1963).

The area between the subarctic temperature front and the Subarctic Boundary, which is indicated by the vertical 34.0 psu isohaline shallower than the intermediate salinity minimum layer in the subtropical waters, is the Transition Domain (Favorite et al., 1976) and salinity frontal zone (Roden, 1991). There are weak temperature and salinity fronts without a density front at middle portion of the Transition Domain, from where the salinity minima have continuity with the intermediate salinity minimum layer under the Transition Zone (Roden, 1991 : southern area of the Subarctic Boundary). Vertical structures in this area are annually changed and confused as shown in Figs. 2a, 2b and Anma et al. (1990).

2. *Velocity structure*

Spatial distributions of the zonal component of geostrophic velocities referred to the 3,000 m level are shown in Fig. 3. Relatively strong westward flow of the Alaskan Stream appears north of 50°N even at the depths which were used as reference levels in previous studies. Subsurface velocity maxima between some pairs of stations are seen at depths, usually corresponding to the halocline. These subsurface velocity maxima are common structures along the Aleutian Islands as Favorite (1974) pointed out. The vertical mixing induced by reciprocating tidal currents in the shallow straits of the Aleutian islands breaks the stratified structure, such as the halocline near the Aleutian Islands while the diluted upper layer over the sharp subsurface halocline remains in the central portion of the Alaskan Stream (Ohtani et al., 1972). Therefore the specific volume anomalies of a pair of stations in both

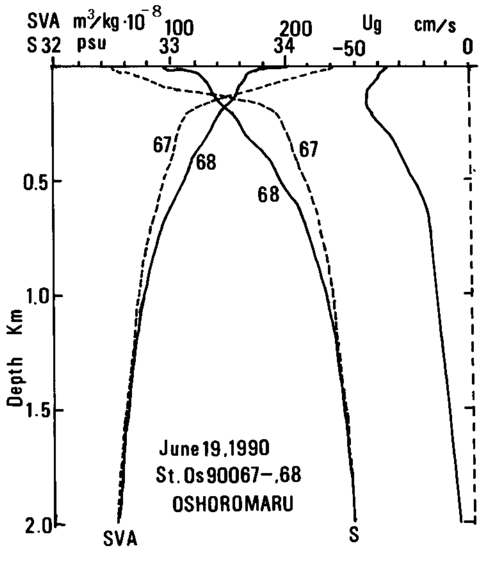

Fig. 4. Typical vertical profiles of salinity (psu) and specific volume anomaly ($m^3 \cdot kg^{-1} \times 10^{-8}$) at the station near the Aleutian Islands and its neighboring one in the Alaskan Stream (left), and the velocity profile calculated by the station pair (right).

waters interleaf at a subsurface layer as shown in Fig. 4. So difference of the steric height between them has a maximum at subsurface layer and leads to a subsurface maximum in baroclinic velocity structure as measured by parachute drogue (Ingraham and Favorite, 1968; Favorite, 1974).

Relatively strong eastward flows of 10-18 cm • s^{-1} in the subsurface layer appear at south of the dome above the deep eastward jet as forced by the bottom configuration and beta effect (Warren and Owens, 1985). Other eastward flows of 10-19 cm•s^{-1} are also found near the subarctic temperature front and the Subarctic Boundary. Eastward components of these strong flows have also 3-7 cm•s^{-1} of geostrophic velocity at 1,000-1,500 m depths. Roden (1991) indicated there were no appreciable density fronts in the upper waters at the temperature and the salinity fronts, however, horizontal velocity shear zones sustained by a relatively deep velocity structure reaching the mid depths occur. In other portions of the subarctic waters and in the Transition Zone, except for westward flows south of 39°N in 1990 and 38°N in 1991, flows of ±1 cm•s^{-1} occur everywhere below 1,500 m.

Annual maximum eastward velocity in the Subarctic Current was found at the south of 50°N until 1992, however this strong flow decresed and shifted near the Subarctic Front since 1993 then these decreased in 1996 (Table 1).

A typical difference in velocity structure between the strongest westward flow in the Alaskan Stream and the eastward one in the Transition Zone is shown in Fig. 5. Velocities in the Alaskan Stream increase by about 10 cm•s^{-1} with the increased reference level (3,000 m). However, at least by 3,000 m, the velocity structure in the Transition Zone is almost the same for various reference levels below 1,500 m.

The maxima of baroclinic velocity at the surface and in the subsurface layer are summarized in Table 1.

Table 1. The maximum geostrophic velocities in cm • s^{-1} at the surface or in subsurface (in parenthesis) for each current system (1990-1996). Positive values indicate eastward flows.

Waters \ Year	Alaskan Stream	South of the Dome	Subarctic Front	Transition Domain	Subarctic Boundary	South Area of Subarctic Boundary
1990	−36 (−45)	11	11	6 (7)	19	−23
1991	−21	13 (18)	16	6	13	32
1992	−27	3 (15)	9	6	17	25
1993	−45 (−46)	3 (4)	12 (13)	5	12	51
1994	−49 (−56)	6	24	−6	17	23
1995	−49	10 (11)	25 (26)	3	12	24
1996	−39 (−45)	6 (10)	9 (12)	5	10	24

3. *Volume transports*

Volume transports referred to the 3,000 m level between two neighboring stations and latitudinal integrated transports with the 3,000 m and 1,500 m reference levels from the top of the dome to the Aleutian Islands and to the south of the Subarctic Boundary are shown in Fig. 6. The horizontal distributions of total transports of each current for 1990-1992 are summarized in Fig. 7.

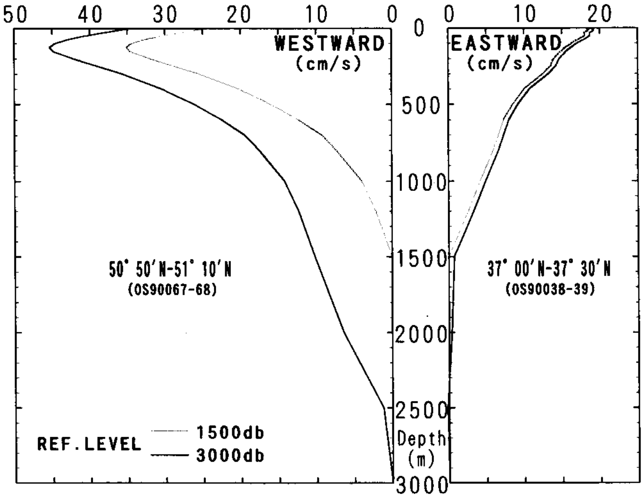

Fig. 5. Typical differences between the geostrophic velocity profiles calculated by using the 1,500 m and the 3,000 m reference levels in the Alaskan Stream (left) and in the Transition Zone (right) (June, 1990).

For the Alaskan Stream, 22-33 sv of westward transports were obtained during 1990-1996 (Table 2) across the narrow interval between 50°N, 180° and 51° 10′N, 179° 43′W (Fig. 7). Total transports referred to the 3,000 m depth are about twice those referred to 1,500 m, and more than twice of many past results with shallower reference levels. These transports are comparable to 28 sv at 175°W in 1982 referred to a mooring measurement at the 2,000 m depth (Warren and Owens, 1988), 23 sv at 180° in 1981 (Reed, 1984) and 38 sv at 180° in 1993 referred to the 4,000 m level (Roden, 1995).

On the other hand, 13 sv of westward transport across 172°W in 1991 was relatively small. However, the westward transport at the date line was increased to 24.2 sv by almost all of the northward transport of 12.5 sv mainly in subsurface layer across the latitudinal section of 50°N between the date line and 172°W (Fig. 7).

The Subarctic Current between the top of the dome and the subarctic temperature front had similar eastward transports of 29-33 sv during the former 3 years. A major portion of the eastward transport occurred on the southerly slope of the dome (13-16 sv) and near the subarctic temperature front (5-12 sv), then transports decrease to almost half of them during the later 3 years. A half of the eastward transport in the Subarctic Current shifted to the Transition Domain and near the subarctic temperature front as shown in velocity structure (Fig. 3). However, sum of the transports in the Subarctic Current and the Transition Domain had 28-37 sv consistently until 1995 except for sudden decrease in 1996 (Table 2). Integrated transports of the Subarctic Current referred to the 3,000 m level were also twice those referred to 1,500 m (Fig. 6)

In the Transition Domain, the net eastward transports were relatively small because of contrary and weak flows, except for near the Subarctic Boundary, south of which relatively strong (20-30 cm•s^{-1} at the surface) flows exist. However, a part of this eastward transport was canceled by the same order of westward transports in

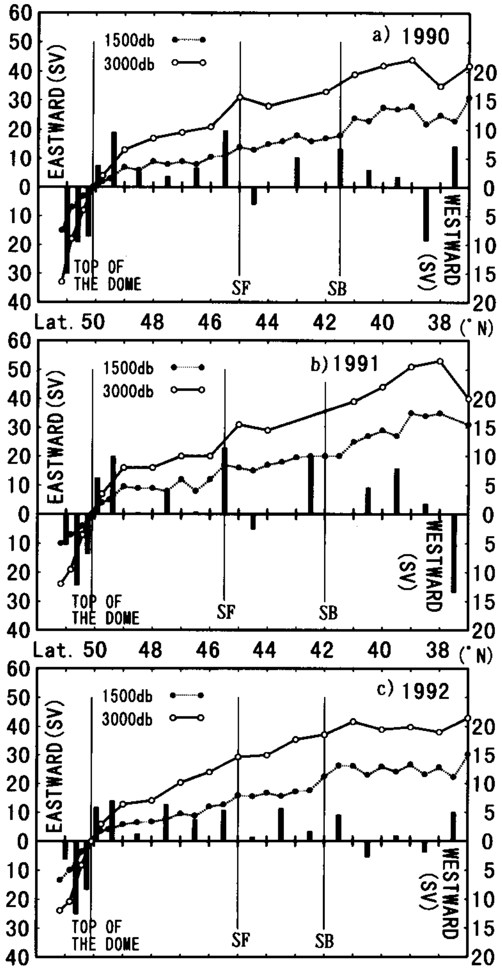

Fig. 6. Volume transports (sv) at the deep stations referred to 3,000 m level (vertical bars and right ordinate) and the east-west integrated transports (left ordinate) referred to the 1,500 m (solid circle) and the 3,000 m(open circle) levels from the top of the dome to the north and to the south in a) 1990, b) 1991 and c) 1992.

the Transition Domain, thus reduced eastward transports were obtained in the Transition Domain. Relatively strong eastward flows appeared in the Transition Zone as shown in Fig. 3, however, net eastward transports were subtracted by neiboring westward flows.

Almost all of the differences in transports referred to the 3,000 m and the 1,500 m levels occurred in north of the Subarctic Boundary.

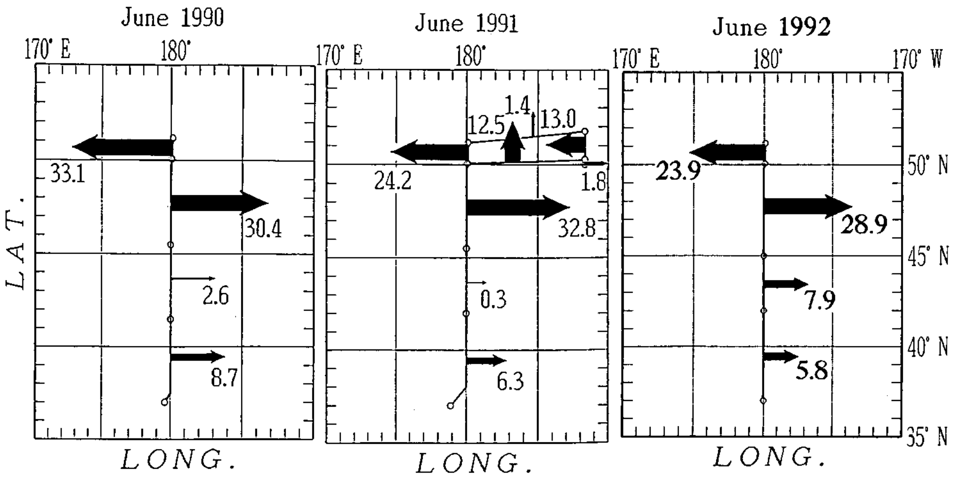

Fig. 7. Direction and total transport (sv) for each current system (1990-1992).

Table 2. Geostrophic transports in sv referred to the 3,000 m level for each current system (1990-1996). Positive values indicate eastward flows.

Waters \ Year	Alaskan Stream (A.S.)	Subarctic Current (S.A.)	Transition Domain (T.D.)	S.A.+T.D.	South Area of Subarctic Boundary (S.SAB)
1990	−33.1	30.4	2.6	33.0	8.7
1991	−24.2	32.8	0.4	33.2	6.4
1992	−23.9	29.2	7.9	37.1	5.8
1993	−26.5	15.1	18.3	33.4	10.1
1994	−26.8	19.2	11.2	30.4	−1.5
1995	−21.7	17.5	10.1	27.6	17.0
1996	−22.4	22.0	−1.3	20.7	10.9

Discussion and Summary

As indicated in the velocity structure, increases in velocities of the surface layer with a increase of reference level are relatively small even in the Alaskan Stream (10-15 cm•s^{-1} westward : compare with a velocity at the 1,000 m level). Maximum surface velocities were 21-49 cm•s^{-1} for the Alaskan Stream and 3-25 cm•s^{-1} for the Subarctic Current although both had subsurface velocity maxima, 10-19 cm•s^{-1} near the Subarctic Boundary and 23-51 cm•s^{-1} in the Transition Zone.

Satellite-tracked drift buoys measurements in the Alaskan Stream in 1986-1987 indicated maximum daily mean velocities of 65-93 cm•s^{-1} and mean velocities of 8-55 cm•s^{-1} during the resident time in quadrangle between 155°W and 175°W (Stabeno and Reed, 1991). Calculated velocities in the Alaskan Stream based on the 3,000 m reference level are less than the maximum daily mean velocities by drift buoys and comparable to the mean current velocities of 30-40 cm•s^{-1} interpolated to 1° longitude ×0.5° latitude near the date line (Stabeno and Reed, 1994).

Increases in velocity based on the deeper reference level are not so large, however, the total volume transports increase as the reference depth increases. The 7-10 sv of transports between the 1,000 and 3,000 m depth range and 3-5 sv between the 1,500 and 3,000 m depth range referred to the 3,000 m level contributed to the total transport of 24-33 sv in the Alaskan Stream across the date line as shown in Fig. 8. Those deep transports correspond to 29-33% and 13-20% of total transports in 1990-1992, respectively but percentages of deep transports were smaller than 34-39% of total transport for the 1,500-3,000 m depth range in 1981 (Reed, 1984). This suggests that major variations in transport in the Alaskan Stream occur in shallower layer ($<$1000 m) and the westward deeper flow measured by mooring system consistently continues along the south slope of the Aleutian Islands (Onishi et al., personal information).

The eastward transports increase at the southward slope of the dome and near the subarctic temperature front. The 7-8 sv of transports of 1,500-3,000 m range in total transport of 13-16 sv on the southward slope are comparable to those of along 175°W in 1982 (Warren and Owens, 1988).

In many previous studies, the geostrophic calculations with the shallow reference levels led to the conclusion that the subarctic circulation was composed of weak flows and consequently of small transports since a weak baroclinisity as small lateral temperature gradient in the upper layer. As mentioned above, however, it has the eastward transports of about 30 sv in the Subarctic Current and the Transition

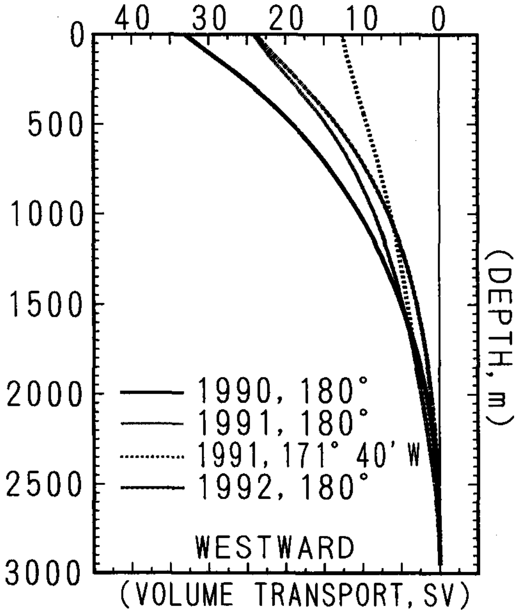

Fig. 8. Vertical profiles of the accumulated transports (sv) of the Alaskan Stream obtained by integrating from the 3,000 m reference level to the surface across the date line and 172°W (1990-1992).

Domain, and the westward transport of about 25 sv in the Alaskan Stream, based on the 3,000 m reference level. Though a part of these values might include recirculated one, and a deeper transport such as along the Aleutian Trench and shallower transports along the the Aleutian Islands shelf slope were excluded in this calculation, so those large transports should be considered with the eastward transports of 54±2 sv at 165°E and 23±4 sv at 175°W (Joyce, 1987) or 49 sv of baroclinic eastward transport referred to the 4,000 m level between 34° and 37°N along 165°E in the Kuroshio Extension (Joyce and Schumitz, 1988).

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