Journal of Oceanography, Vol. 59, pp. 855 to 869, 2003

Transport of Oyashio Water across the Subarctic Front into the Mixed Water Region and Formation of NPIW

MASACHIKA MASUJIMA[1]*, ICHIRO YASUDA[1], YUTAKA HIROE[2] and TOMOWO WATANABE[2]

[1]*Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*National Research Institute of Fisheries Science, Fisheries Research Agency, Fukuura, Kanazawa-ku, Yokohama, Kanagawa 236-8648, Japan*

(Received 19 February 2003; in revised form 22 July 2003; accepted 8 August 2003)

Oyashio water flowing into the Mixed Water Region (MWR) and the Kuroshio Extension region that forms North Pacific Intermediate Water (NPIW) has been examined, based on four Conductivity-Temperature-Depth profiler (CTD)/Lowered Acoustic Doppler Current Profiler (L-ADCP) surveys of water masses and ocean currents. There are two processes by which the Oyashio water intrudes across the Subarctic Front (SAF): one is a direct cross-nearshore-SAF transport near Hokkaido along the western boundary, and the other is a cross-offshore-SAF process. Seasonal variations were observed in the former process, and the transport of the Oyashio water across SAF near Hokkaido in the density range of 26.6–27.4σ_θ was 5–10 Sv in spring 1998 and 2001, and 0–4 Sv in autumn 2000, mainly corresponding to the change of the southwestward Oyashio transport. Through the latter process, 5–6 Sv of the Oyashio water was entrained across the offshore SAF from south of Hokkaido to 150°E in both spring 2001 and autumn 2000. The total cross-SAF Oyashio water transport contributing to NPIW formation is more than 10 Sv, which is larger than previously reported values. Most of the Oyashio water formed through the former process was transported southeastward through the Kuroshio Extension. It is suggested that the Oyashio intrusion via the latter process feeds NPIW in the northern part of the MWR, mainly along the Subarctic Boundary and SAF.

Keywords:
· Oyashio,
· Mixed Water Region,
· Subarctic Front,
· L-ADCP,
· CTD,
· NPIW.

1. Introduction

Low-salinity Oyashio water flows into the Mixed Water Region (MWR) and the Kuroshio Extension region, and forms North Pacific Intermediate Water (NPIW), which is characterized by a salinity minimum that is widely distributed in the North Pacific subtropical region (e.g. Sverdrup *et al*., 1942; Reid, 1965; Talley, 1993). The Oyashio is the western boundary current of the western subarctic gyre in the North Pacific and Oyashio water is strongly influenced by Okhotsk Sea water and Bering Sea water (e.g. Ohtani, 1989). The MWR (Kawai, 1972) is here defined as the area between the northern edge of the Kuroshio Extension and the Subarctic Front (SAF), defined here as the 4°C isotherm at 100 m depth, following to Favorite *et al*. (1976). The MWR is thought to be part of the subtropical region because the wind-driven gyre boundary between the subtropical and subarctic gyres, as determined from wind-stress fields, roughly corresponds to the SAF (Yuan and Talley, 1992). This paper focuses on where and how much Oyashio water flows into the MWR and the Kuroshio Extension region, and where it flows eastward through the MWR and the Kuroshio Extension region, based on observations.

There are previous studies of Oyashio water flowing into the MWR and the Kuroshio Extension region, which is related to NPIW formation. Reid (1965) suggested that low-salinity Oyashio water diffuses laterally along the gyre boundary and influences the properties of the subtropical water. Talley (1993) reported that NPIW is formed especially in the MWR in the western North Pacific. Yasuda *et al*. (1996) demonstrated that Oyashio water reached the Kuroshio Extension in the area east of Japan and then flowed eastward along the Kuroshio Extension, suggesting that there are direct intrusions of Oyashio water into the subtropical region along the west-

* Corresponding author. E-mail: masujima@eps.s.u-tokyo.ac.jp

ern boundary, and that NPIW is formed mainly near the Kuroshio Extension by isopycnal mixing between Oyashio water and the high-salinity intermediate water transported along the Kuroshio. Talley *et al*. (1995) estimated that the eastward transport of Oyashio water through the MWR is 3 Sv, and Talley (1997) reported it to be 3–5 Sv through the MWR and the Kuroshio Extension. Yasuda (1997) suggested that the main origin of NPIW is a low-salinity, low-potential-vorticity (PV) water mass in the Okhotsk Sea Kuril Basin (Okhotsk Sea Mode Water: OSMW) that has a PV-minimum centered at $26.8\sigma_\theta$.

These previous studies argued that NPIW formation is based on such water properties as temperature and salinity, and with the geostrophic flow field assuming a level of no motion. This assumption, however, is not necessarily valid for the real ocean. Recently it has become possible to measure the absolute horizontal velocity field using lowered acoustic Doppler current profilers, L-ADCP.

Recent Conductivity-Temperature-Depth profiler (CTD)/L-ADCP observations are demonstrating the importance of the cross-nearshore-SAF Oyashio transports along the western boundary near Hokkaido (Yasuda *et al*., 2001) as well as cross-offshore-SAF transport, probably due to isopycnal mixing across the offshore SAF, as suggested by Reid (1965). Yasuda *et al*. (2001) defined the cross-nearshore-SAF Oyashio transport as the transport integrated from the Hokkaido coast to SAF, where the southwestward Oyashio transport usually exceeds the northeastward one, so that the excess southwestward Oyashio transport must cross the SAF and could contribute to the formation of NPIW in the downstream area. They reported that 5 Sv of Oyashio water, of which 2.5 Sv was OSMW, crossed the SAF near the Hokkaido coast and flowed directly into the MWR, based on a spring 1998 survey. Hiroe *et al*. (2002) reported that most of this Oyashio water was entrained into the Kuroshio Extension and another 2 Sv of Oyashio water flowed southward across 39°N (see also Shimizu *et al*., 2003). Yoshinari *et al*. (2001) reported that part of NPIW formed near the Kuroshio Extension was transported northward to form a main part of NPIW in the MWR, while NPIW in the MWR needs additional Oyashio water to explain the salinity distribution in the MWR. Yasuda *et al*. (2002) defined the cross-offshore-SAF Oyashio transport as the transport difference between two sections that extend from the coast to SAF, where one section is located south of Hokkaido and the other south of the Kuril Islands. They indicated that the cross-offshore-SAF Oyashio transport could be 5–7 Sv between 147–152°E, based on a survey conducted in summer 1999, although the authors stated that the resolution of the observations was not adequate to allow definite conclusions.

These previous studies suggest that both cross-SAF processes—direct cross-SAF transport along the western boundary current and diffusive transport across offshore SAF—could be important for NPIW formation. However, the observational underpinnings of this hypothesis are not adequate since the temporal variations of the Oyashio transports have been completely ignored, and there have been few studies of the cross-offshore SAF process.

The Oyashio water transport into NPIW is thought to be important for isolating anthropogenic CO_2 (ex-CO_2) into the intermediate depth of the subtropical gyre (Tsunogai *et al*., 1993). The estimate of the ex-CO_2 transport through NPIW depends on the cross-SAF Oyashio transports into NPIW. Ono *et al*. (2000) and Andreev *et al*. (2001) estimated the ex-CO_2 transport, and most recently Yasuda *et al*. (2002) estimated it to be about 0.022 GtC/yr. However, these values are based on the cross-nearshore-SAF Oyashio transport near the western boundary, and do not include the cross-offshore-SAF Oyashio transport.

In this study we examine the cross-SAF Oyashio transport, cross-SAF processes of Oyashio water near the western boundary and across the offshore SAF, and the variations of the transport into the MWR and the Kuroshio Extension region, using observational data of the vertical and horizontal distribution of density and current field.

A comparison between the data from two seasons, namely spring (May to June) and autumn (October to November), shows that the inflowing form of Oyashio water into the MWR is different in the two seasons. The cross-nearshore-SAF Oyashio transport near Hokkaido in spring was larger than in autumn. Furthermore it is suggested that Oyashio was water flowing into the MWR across the offshore SAF from near Hokkaido to 150°E.

The next section explains the observational data and

Table 1. Cruise IDs, period, research vessels, chief scientists in the four observation cruises for the data used in the present analysis.

ID	Period	R/V	Chief scientist	Data type
SO9805	12th May–17th Jul, 1998	*Soyo-Maru*	Y. Hiroe	CTD, L-ADCP
SO0010	20th Oct–1st Nov, 2000	*Soyo-Maru*	K. Kawasaki	CTD, L-ADCP
HK0105	25th May–12th Jun, 2001	*Hokko-Maru*	T. Watanabe	CTD, L-ADCP
HK0207	6th–20th Jul, 2002	*Hokko-Maru*	T. Watanabe	CTD, L-ADCP

analysis method. In Section 3 we examine the cross-nearshore-SAF Oyashio transport near the western boundary and its variation, including hydrographic and current structures of the Oyashio. Section 4 discusses the cross-offshore-SAF Oyashio transport and process. We then examine the pathway of these cross-SAF Oyashio waters in the MWR and the Kuroshio Extension region west of 150°E (Section 5) and at 162°E (Section 6). In the last section the results are summarized and discussed.

2. Data and Analysis Method

2.1 Data

L-ADCP and CTD data were obtained during four cruises, the details of which are shown in Table 1; the observation stations are plotted in Fig. 1. In the first three surveys the observational line enclosed the MWR and the Kuroshio Extension region from coast to coast. At each station, measurements with L-ADCP and CTD were carried out mostly down to 1500 dbar or to near-bottom if the bottom was shallower than 1500 dbar.

2.2 Analysis method

2.2.1 Oyashio mixing ratio

We calculated the mixing ratio between Kuroshio and Oyashio waters from isopycnal potential temperature and salinity data. Waters in the MWR and the Kuroshio Extension region always have properties intermediate between warmer, saltier Kuroshio water and colder, less saline Oyashio water in the density range of 26.6–27.5σ_θ which scarcely outcrops in the surface in the open North Pacific. Assuming that the measured water is isopycnally mixed between pure Kuroshio water and pure Oyashio water, the Oyashio mixing ratio, R_o (=1 – [Kuroshio mixing ratio, R_k]) is calculated in each 0.1σ_θ density layer as $R_o = (R_o^\theta + R_o^S)/2$, $R_o^\theta = (\theta_k - \theta)/(\theta_k - \theta_o)$, $R_o^S = (S_k - S)/(S_k - S_o)$, where R_o^θ and R_o^S are the Oyashio mixing ratio based on isopycnal potential temperature and salinity re-

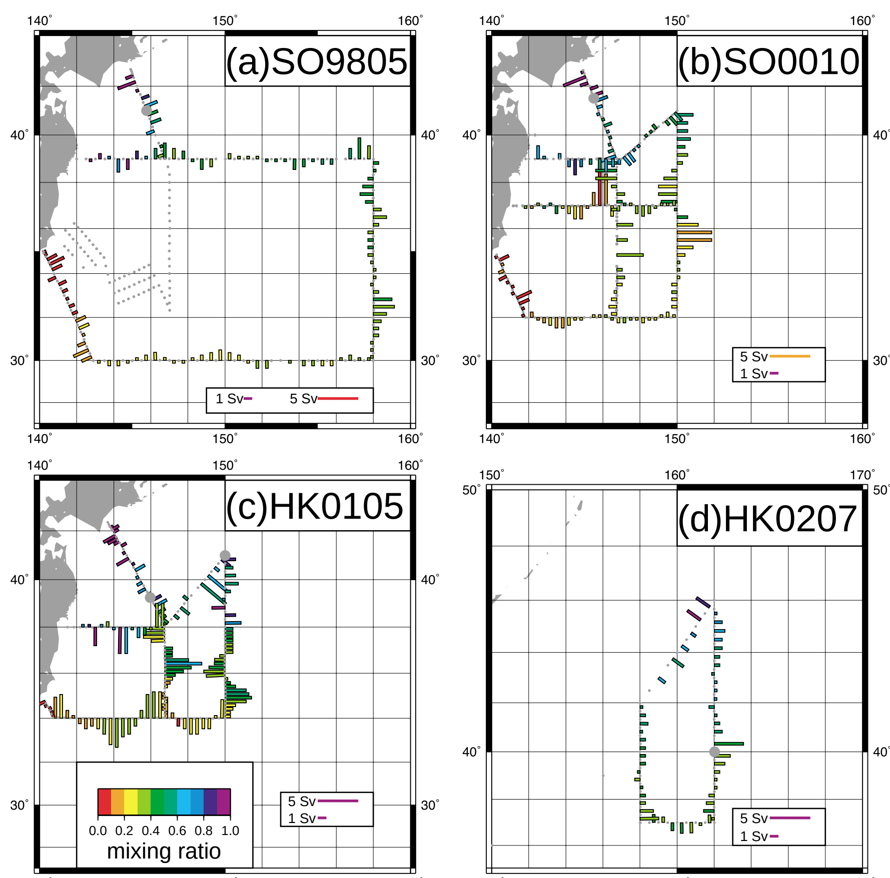

Fig. 1. Transport distribution, Oyashio mixing ratio and station locations in the four cruises, (a) SO9805, (b) SO0010, (c) HK0105, and (d) HK0207. Bar length denotes the volume transport (Sv = 10^6 m^3/s) between each station pair estimated in the density of 26.6–27.0σ_θ from the adjusted geostrophic velocity field. Color means the Oyashio-mixing ratio. Small dots represent observational stations and large dots represents locations of subarctic front (SAF) in (a), (b), and (c), and of subarctic boundary (SAB) in (d).

spectively, and (θ, S), (θ_k, S_k) and (θ_o, S_o) are the isopycnal potential temperature and salinity of sample, the pure Kuroshio and the pure Oyashio waters, respectively. The isopycnal temperature and salinity profile of the pure Oyashio water is the average of the measured profiles at several stations near Hokkaido in May 1998, and the pure Kuroshio water is taken to be near Boso Peninsula (see Yasuda *et al*., 2001 for details). The transport of the Oyashio (Kuroshio) component is obtained by multiplying the Oyashio (Kuroshio) mixing ratio by the transport between stations.

This Oyashio mixing ratio quantifies the water mixing between subtropical water and the Oyashio (subarctic) water, and is useful for the description of the transport and mixing processes of Kuroshio and Oyashio waters. Similar procedures have been used in previous studies (Talley *et al*., 1995; Yasuda *et al*., 1996, 2001; Talley, 1997; Yasuda, 1997; Shimizu *et al*., 2001; Yoshinari *et al*., 2001).

2.2.2 Vertical profiles of geostrophic velocities

Here we use the following three sets of velocity fields.

2.2.2.1 Geostrophic velocity relative to 1500 dbar

Assuming that there is no flow at 1500 dbar, the geostrophic velocity profiles at each pressure level are calculated from temperature, salinity and pressure field measured by CTD. If the bottom of the ocean is shallower than 1500 dbar, a reference pressure level is set at the bottom at shallower stations.

2.2.2.2 Adjusted geostrophic velocity

Vertical profiles of horizontal velocities were obtained at 20 dbar intervals by L-ADCP. L-ADCP data are processed by the methods by Fischer and Visbeck (1993) with GPS positioning data and CTD data using the routine provided by Prof. Eric Firing, University of Hawaii, modified for direct incorporation with CTD data (Katsumata *et al*., 2001). These L-ADCP velocity profiles contain ageostrophic components with a vertical length scale of several tens of meters and relatively short periods. In this study, however, we want to extract geostrophic components, which have a time scale of more than a day and larger vertical scale.

For each station pair, velocities at the reference levels were estimated so as to minimize the differences between the geostrophic velocity profile and the velocity profile obtained by subtracting the barotropic tide (Egbert *et al*., 1994) from the directly measured L-ADCP profile (Yasuda *et al*., 2001). Hereafter, we call this velocity profile the "adjusted geostrophic velocity".

2.2.2.3 Velocity field conserving the fluxes of volume, salinity and temperature

Since the adjusted geostrophic velocity data contain errors, the volume flux is not exactly conserved in the box surrounding the MWR and the Kuroshio Extension region from coast to coast. Velocity fields at reference levels are estimated by the inverse method using singular value decomposition (SVD) so as to minimize the sum-of-squares of the difference between the velocities estimated by the adjusting procedure in 2.2.2.2 and the newly estimated velocities under the constraints of conserving the fluxes of volume, salinity and temperature (see Appendix A). Defining the surface layer as the density range 0–26.6σ_θ, and two intermediate layers as 26.6–27.0σ_θ and 27.0–27.4σ_θ, the volume balance is applied to surface and two intermediate layers, and the balances of salinity and temperature fluxes are also applied to the two intermediate layers. In the surface layer the volume flux conserves but the salinity and temperature fluxes do not, because the surface layer is influenced by air-sea interactions and the density less than 26.6σ_θ outcrops in winter and the surface fluxes could directly modify the temperature and salinity fields in the surface layer.

The Tsugaru Warm Current flows into the MWR from Japan Sea through the Tsugaru Strait. Toba *et al*. (1982) reported the annual average transport to be 2.0 Sv. Inflow of the Tsugaru Warm Current to the surface layer (<26.6σ_θ) of 2 Sv is thus assumed in the inverse model.

3. Cross-SAF Oyashio Transport near Hokkaido

This section examines the inflow of Oyashio water into the MWR near the east coast of Japan in terms of the transport distribution of the Oyashio component. The subarctic front (SAF) near Hokkaido, defined here as 4°C at 100 m (Favorite *et al*., 1976), was observed at 41°N, 145.75°E in May 1998 (see also Yasuda *et al*., 2001), at 41.5°N, 145.5°E in October 2000 (large dot in Fig. 1(b); downward arrow in Fig. 2(a)), and at 40.5°N, 145°E in May 2001 (southeastern dot in Fig. 1(c); downward arrow in Fig. 2(c)). In May 2001, the SAF was once again observed at 41°N, 150°E (northeastern dot in Fig. 1(c)).

The Oyashio-component transports in the density range 26.6–27.4σ_θ were calculated along the observation lines south of Hokkaido in order to estimate the volume of Oyashio water flowing into the MWR. Generally, near the east coast of Hokkaido the Oyashio flows southwestward, and on its offshore side the Oyashio counter-current flows northeastward (Figs. 1(a) and (b)). The volume transports do not compensate in the area from the Hokkaido coast to the SAF, and generally the southwestward Oyashio volume transport is greater than that of the northeastward Oyashio counter-current (Kono, 1997; Yasuda, 1997; Yasuda *et al*., 2001). This residual part of the Oyashio water transport that is integrated from the coast of Hokkaido to the SAF thus flows into the area south of the SAF. This part could participate in the formation of NPIW in the subtropical region, as suggested by Yasuda *et al*. (1996). This Oyashio transport hence represents the cross-gyre transport from the subarctic gyre

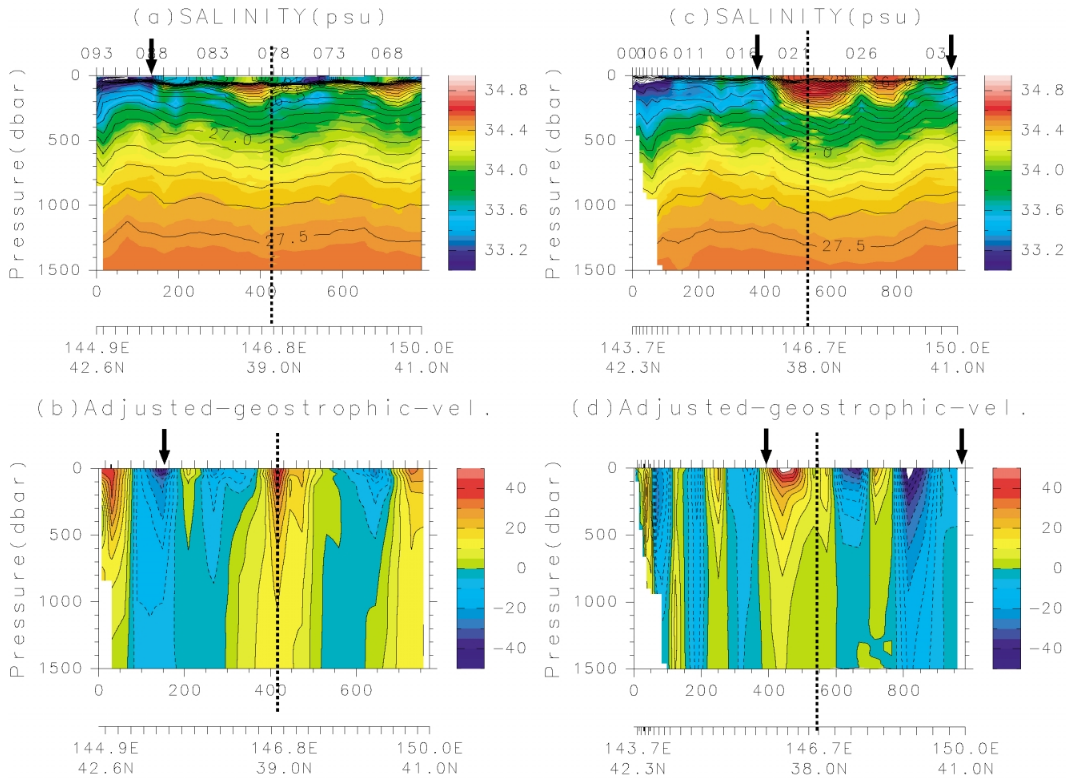

Fig. 2. Vertical cross-sections along the V-shaped lines from the coast of Hokkaido to the northern-most station of 150°E from the SO0010 and HK0105 cruises. (a) Salinity (psu), (b) adjusted geostrophic velocity (cm/s) in SO0010, with potential density (σ_θ) contours (CI = 0.1). (c) Salinity, (d) adjusted geostrophic velocity in HK0105. The downward arrows denote the subarctic front. The dashed lines denote the turning points of V-shaped observational lines.

to the subtropical gyre along the western boundary current region because the SAF roughly corresponds to the wind-driven gyre boundary, as noted in Section 1. We call this net southwestward Oyashio-component volume transport "cross-nearshore-SAF Oyashio transport near Hokkaido". The southwestward, northeastward and cross-nearshore-SAF Oyashio transports near Hokkaido in the density range between 26.6–27.4σ_θ, is summarized in Table 2 for the three kinds of velocity fields mentioned in Subsection 2.2.2.

Comparison among the cross-nearshore-SAF Oyashio transports near Hokkaido in each survey reveals the existence of seasonal variations. The cross-nearshore-SAF Oyashio transport near Hokkaido is greater in spring than in autumn. The volume transports both from the geostrophic velocity field relative to 1500 dbar (3.7 Sv) and from the adjusted geostrophic flow (0.7 Sv) in October 2000 are less than those in springtime observations where relative geostrophic transport is 6.5 Sv and the adjusted geostrophic one is 4.9 Sv in May 1998, 4.4 Sv and 7.0 Sv in May 2001 (Table 2). Similarly, the cross-nearshore-SAF Oyashio transport near Hokkaido in autumn, calculated from the inverse method, are less than in spring. In the HK9908 cruise in August 1999 (Yasuda *et al.*, 2002), the adjusted geostrophic southwestward transport was found to be 9.5 Sv, northeastward 2.8–7.0 Sv (mean 5.4 Sv) and cross-nearshore-SAF transport 1.4–6.7 Sv (mean 4.0 Sv), i.e., between autumn and spring observations. In the HK9908 observation, however, there was great uncertainty about the northeastward transport because of the inadequate horizontal resolution near the SAF (Yasuda *et al.*, 2002).

The southwestward transport (4.9 Sv) in October 2000, found from the adjusted geostrophic velocity field, is less than 7–10 Sv in springtime (Table 2). On the other hand, the northeastward Oyashio-component transport of 4 Sv in October 2000 was almost the same as or a little larger than about 3 Sv in spring. Based on these results, it is suggested that the main cause of the seasonal variation of the Oyashio transport across the SAF near Hokkaido is the change of southwestward transport between spring and autumn. It is necessary to study further how significant the change of the northeastward Oyashio transport is.

Table 2. Oyashio-component transports (in Sv) near Hokkaido based on three velocity fields in the density of 26.6–27.4σ_θ showing the cross-nearshore-SAF Oyashio transport near Hokkaido, with southwestward and northeastward component. (a) Geostrophic flow field relative to 1500 dbar, (b) adjusted geostrophic flow field, (c) geostrophic velocity field from inverse method. HK9908 data are adapted from Yasuda *et al*. (2002). The annual mean values from the adjusted geostrophic field are the average of the Oyashio transports in the four cruises. The uncertainties (±1σ) for the transports are considered by taking account of the uncertainties (±1σ) of the velocities estimated from the inverse method.

	Cross-nearshore-SAF transport			Southwestward transport			Northeastward transport		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
SO9805	6.5	4.9	4.9 ± 1.8	9.0	7.6	8.0 ± 1.2	2.4	2.7	3.2 ± 1.3
SO0010	3.7	0.7	1.5 ± 1.9	5.2	4.9	6.3 ± 1.4	1.5	4.2	4.8 ± 1.3
HK0105	4.4	7.0	11.5 ± 4.5	5.8	9.7	12.7 ± 3.0	1.5	2.6	0.7 ± 0.8
MEAN		4.2			7.4			3.2	
HK9908		1.4–6.7 (4.0)			9.5			2.8–7.0 (5.4)	

The annual mean cross-nearshore-SAF Oyashio transport near east coast of Hokkaido is estimated to be 4.2 Sv in the density range of 26.6–27.4σ_θ as an average of the four data series of 2 spring, 1 summer and 1 autumn surveys. Four data series are of course not enough for annual mean estimates; as a first step, the estimate is believed to be valuable. From seasonal repeat hydrographic observations off Hokkaido along 144°E, the annual-mean cross-nearshore-SAF Oyashio transport relative to 2000 dbar was estimated to be 3.2 Sv (Miyao and Ishikawa, 2003); this value is somewhat lower than the estimate given in the present study, probably because of the deep Oyashio structure where absolute velocity measurements are necessary. This estimate is used for the anthropogenic CO_2 estimate into NPIW near Hokkaido in Ono *et al*. (2003).

The transport distribution of the Oyashio component and the current structure in the area between Hokkaido and the SAF were different in the three cruises SO9805, SO0010, and HK0105. In May 1998 and October 2000 a typical structure was observed: the Oyashio flowed southwestward near Hokkaido (warm-colored area on the left side of arrow representing SAF in Fig. 2(b)), and the Oyashio counter current flowed northeastward on the offshore side of the southwestward Oyashio (cold-colored area on the left side of the arrow in Fig. 2(b)). The typical current structure can be seen in the transport diagrams (southwestward cold-colored bars near Hokkaido are distributed north of the northeastward bars in Figs. 1(a) and (b)). On the other hand, in May 2001, an anticyclonic Oyashio eddy (cf. Shimizu *et al*., 2001) with a horizontal scale of about 60 km was adjacent to the coast of Hokkaido (blue and red color in the distance of 0–100 km distant from the coast in Fig. 2(d)), whose northeastward transport on the northwestern side of the eddy center (purple bars around 42°N, 144°E in Fig. 1(c)) was 2.6 Sv, found from the adjusted geostrophic velocity field (Table 2; see Shimizu *et al*., 2003 for the analysis of subsurface floats). As this is different from the typical current structure, the southwestward and northeastward flows appeared alternately from the center of the Oyashio eddy to the SAF in May 2001 (Fig. 2(d)).

Although the cross-nearshore-SAF Oyashio has been studied transport near Hokkaido, the new point of this study is that the seasonal change of the cross-nearshore-SAF Oyashio transport is suggested for the first time, based on the data from the direct current measurement with L-ADCP.

4. Cross-Offshore-SAF Oyashio Transport

It has been argued that it is possible for the Oyashio water to flow across the SAF near the Hokkaido coast into the MWR to contribute to the formation of North Pacific Intermediate Water. Despite the possibilities that Oyashio water may cross the SAF other than near the Japan coast, there is only one estimate of the cross-offshore-SAF transport: Yasuda *et al*. (2002) suggested that 5–7 Sv of the Oyashio water crossed the offshore SAF between 147–152°E, based on summertime observation in the density range of 26.7–27.4σ_θ. The authors pointed out the inadequate spatial resolution of the observation, however. They defined the cross-offshore-SAF Oyashio transport as the integrated transport difference between two sections that extend from coast to SAF, where one section is located south of Hokkaido and the other south of Kuril Islands.

In this section, Oyashio transports across the offshore SAF are estimated, and the inflowing process is discussed, using the observation data obtained in October 2000 and May 2001. The Oyashio-component volume transports are integrated along the observation lines from the station where the SAF was observed south of Hokkaido to the station at 41°N, 150°E where the offshore SAF was observed in May 2001, and very close to the SAF in Octo-

Table 3. Cross-offshore-subarctic-front Oyashio transports (in Sv) in the SO0010 and HK0105 cruises in the density of 26.6–27.4σ_θ. (a) Geostrophic flow field relative to 1500 dbar, (b) adjusted geostrophic flow field, (c) geostrophic velocity field from inverse method. The uncertainties ($\pm 1\sigma$) for the transports are considered.

	(a)	(b)	(c)
SO0010	−1.3	6.2	5.1 ± 3.4
HK0105	1.3	5.4	4.0 ± 2.0

ber 2000. We here call this volume transport "the cross-offshore-SAF Oyashio transport".

The cross-offshore-SAF Oyashio transports in October 2000 and in May 2001 are 6.2 Sv and 5.4 Sv, respectively, as found from the adjusted geostrophic velocity field as shown in Table 3. The cross-offshore-SAF Oyashio transports could be reduced to 4.0 Sv and 3.7 Sv, respectively, yielding possible minimum cross-offshore-SAF Oyashio transports, where the reduced transports were estimated by moving the SAF stations to the nearest stations. Since these cross-offshore-SAF transports are comparable with the cross-nearshore-SAF transport estimated near Hokkaido, the Oyashio water across the offshore SAF could make an important contribution to the formation of NPIW.

The cross-offshore-SAF Oyashio transport estimated from the geostrophic velocity field relative to 1500 dbar was less than the values found from the adjusted velocity field, because the current around the offshore SAF had a structure deeper than 1500 dbar (Figs. 2(b) and (d) show that blue or red colored areas extend from the surface to 1500 dbar on the right-hand side of the dashed line representing the southernmost station of the V-shaped line). In contrast to the transports near Hokkaido, the transports across the offshore SAF show that a similar amount of Oyashio water flowed into the MWR in both spring and autumn.

In October 2000, two anticyclonic eddies were observed near the offshore SAF (Figs. 2(a) and (b)): one was centered around Sta. 80 and the other around Sta. 67. Near the surface of these anticyclonic eddies, waters with relatively high salinity and high temperature override low salinity and low temperature water near the density of 26.6σ_θ. In May 2001, two anticyclonic eddies were also observed around the offshore SAF (right side of the dashed line in Figs. 2(c) and (d)); one is centered around Sta. 23 and the other around Sta. 28. From the cross-sections of the salinity and the currents (Figs. 2(a) and (b), or 2(c) and (d)), the water transported through these anticyclonic eddies already had a salinity minimum that was not that of the pure Oyashio water. The salinity minimum was 33.4–33.8 psu at around 26.6σ_θ in both the HK0105 and

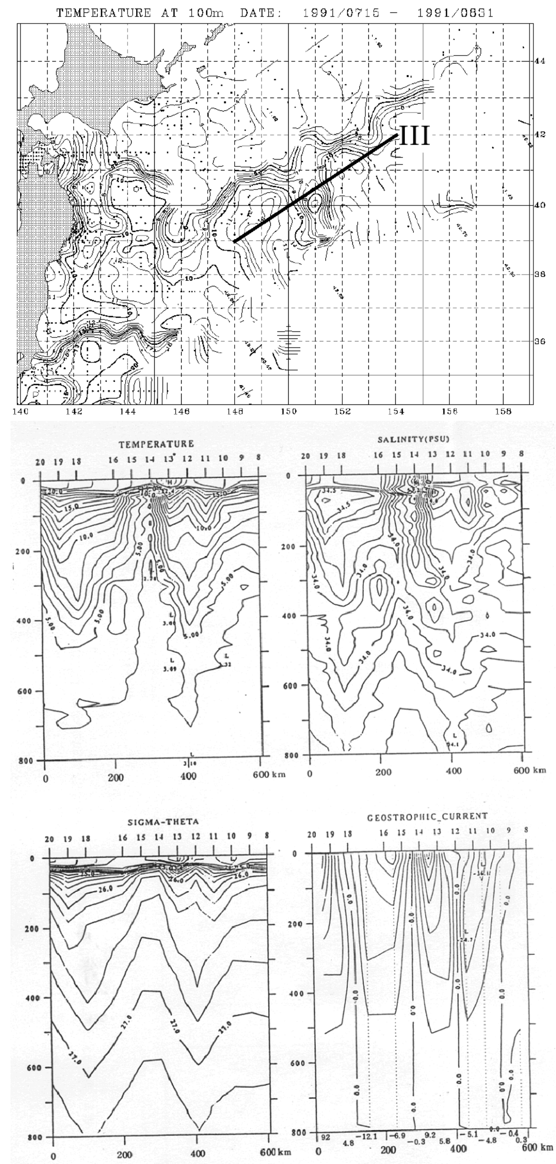

Fig. 3. Temperature distribution at 100 m (upper panel) and the vertical cross-sections of temperature (°C), salinity (psu), sigma-theta, and geostrophic current relative to 800 dbar (cm/s) along line III (lower four panels) in 15th July–31t August 1991 (reproduced from Annual Report of the Research Meeting on Saury Resources, October 1992, Tohoku National Fisheries Research Institute).

SO0010 cruises. From the transport diagrams (see northeastward line that reaches 150°E, 41°N in Figs. 1(b) and (c)), waters with the Oyashio mixing ratio of 0.5–0.8 (green to blue in Fig. 1) were transported through the eddies across the V-shaped lines around 39°N. By contrast, more pure Oyashio water was transported near the coast of Hokkaido. These results suggest that the water transported across the offshore SAF had already experienced mixing around the offshore SAF, and the salinity

Table 4. The Oyashio-component transports (in Sv) flowing eastward or southward out of the box through the MWR or the KE region in the density of 26.6–27.4σ_θ (1) in the area south of the Kuroshio Extension including KE axis, (2) in the area north of KE (thus MWR) and (3) near the KE axis. Positive value means the transports out of the box. (a) Geostrophic flow field relative to 1500 dbar, (b) adjusted geostrophic flow field, (c) geostrophic velocity field from inverse method. The uncertainties (±1σ) for the transports are considered.

	(1) south of the KE axis			(2) north of KE (MWR)			(3) around the KE axis		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
SO9805	3.4	7.1	5.5 ± 2.6	2.6	1.3	0.8 ± 3.2	4.2	7.1	6.9 ± 1.1
SO0010	2.8	13.8	6.7 ± 2.3	–0.4	4.2	–0.4 ± 2.5	4.4	10.4	5.9 ± 1.9
HK0105	4.3	22.9	11.5 ± 4.5	3.1	6.0	4.2 ± 2.2	5.2	15.6	14.0 ± 2.5

minimum structure had been formed before the water reached the observation lines.

The mixing process around the offshore SAF is thought to be isopycnal mixing around the mesoscale eddy. The isopycnal mixing process around mesoscale eddies where warm, saline water flows northward and cold, low-salinity water flows southward is supported from previous data of horizontal temperature distribution during 15 July–31 August 1991 (Fig. 3). Around the offshore SAF, the southward intrusion of a cold water mass (<7°C at 100 m depth) is seen around 151°E, 39–41°N, while warm water with temperature greater than 12°C extends northward around 149°E, 38–41°N. The vertical cross-sections of temperature, salinity, potential density and geostrophic currents relative to 800 dbar (Yasuda *et al.*, 1992) show that the cold, low-salinity intrusion is caused by the southward flow on the eastern side of the anticyclonic eddy centered around 149°E, 39°N (along the line III in upper panel of Fig. 3, or at around Sta. 18 in the lower panel of Fig. 3) and the northward, warm, saline water extension corresponds to the northward flow on the western side of the anticyclonic eddy.

5. Pathway of Oyashio Water in the MWR West of 150°E

In this section we discuss the transports of the Oyashio component out of the boxes (see Figs. 7(a), (b) and (c)) across the meridional section at 150°E or 158°E and the southern sections in the Mixed Water Region (MWR) and the Kuroshio Extension region (KE). In order to simplify the arguments, we have divided this area into two regions, namely, the southern area of the Kuroshio Extension which includes the Kuroshio Extension axis, and the MWR from the northern edge of the Kuroshio Extension to the northern-most station at 150°E, 41°N around SAF (Table 4). The MWR defined here thus does not include the Kuroshio Extension itself. The axis of the Kuroshio Extension is defined as the temperature of 14°C at 200 m depth (Kawai, 1972). The axis of the Kuroshio Extension can be seen as a steep slope of isopycnal contours and a strong eastward current (around Sta. 57 in Fig. 4, Sta. 050 in Fig. 5 and Sta. 58 in Fig. 6). In Table 4, the Kuroshio Extension is defined as the area where eastward volume transports are continuously distributed around the axis of the Kuroshio Extension as shown in Fig. 1 (in SO9805 cruise, the eastward bars of Fig. 1(a) from 31°N to 33°20′ N; in SO0010, from 33°40′ N to 36°40′ N in Fig. 1(b); in HK0105 cruise, from 34°N to 36°N in Fig. 1(c)). The SAF was observed at the northernmost station of 150°E line in the HK0105 cruise (Sta. 032 in Fig. 6). In the SO0010 cruise, the SAF was also observed very near the northern-most station of 150°E (Sta. 065 in Fig. 5). At 150°E, the SAF and the Subarctic Boundary (SAB) defined as the salinity of 34 psu (Favorite *et al.*, 1976) were not separated.

The eastward or southward transports of the Oyashio component flowing through (1) south of the KE axis including KE axis, (2) the MWR, and (3) around the KE axis in the density of 26.6–27.4σ_θ are listed in Table 4, where a positive value means outflow from the box enclosing the MWR and the Kuroshio Extension region. In May 1998, since the 158°E observational line did not reach the offshore SAF, the transport north of the Kuroshio Extension through the MWR in Table 4 denotes the integrated volume transports of the Oyashio component along the line from the northern edge of the Kuroshio Extension to the SAF near the coast of Hokkaido (dot in Fig. 1(a)).

The incoming and outgoing volume transports did not balance in the adjusted geostrophic velocity field for each cruise, probably because of the overestimate of transport around the Kuroshio Extension. The overestimate could be evaluated by the uncertainty of the L-ADCP velocity around the Kuroshio Extension. Hence, we look at the transports using the inverse method, conserving the mass balance and the temperature and salinity flux for examining the pathway of Oyashio waters. Transport distributions of the Oyashio water component based on the velocity fields estimated from the inverse method are depicted in Fig. 7, which shows the pathways of Oyashio

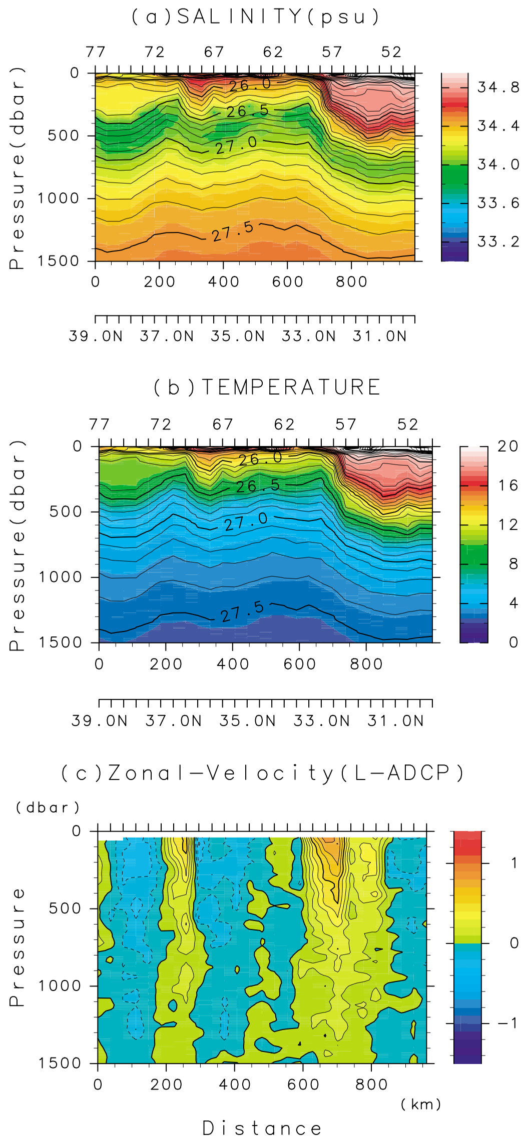

Fig. 4. Cross-sections along 150°E of (a) salinity, (b) temperature, and (c) zonal velocity measured by L-ADCP for the SO9805 cruise. The horizontal axis denotes the station number, and the distance (km) from the northernmost station.

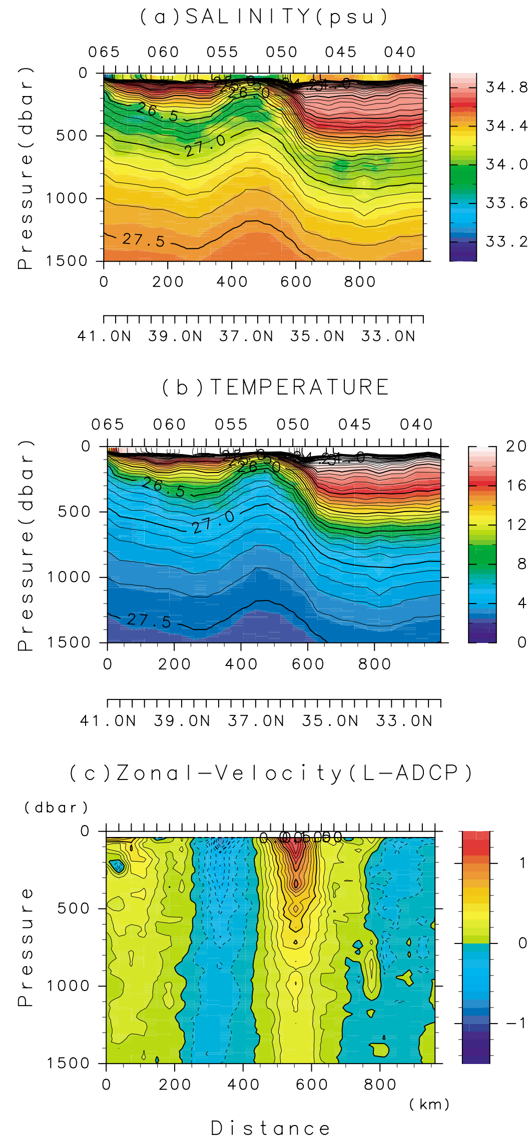

Fig. 5. As Fig. 4 but for the SO0010 cruise.

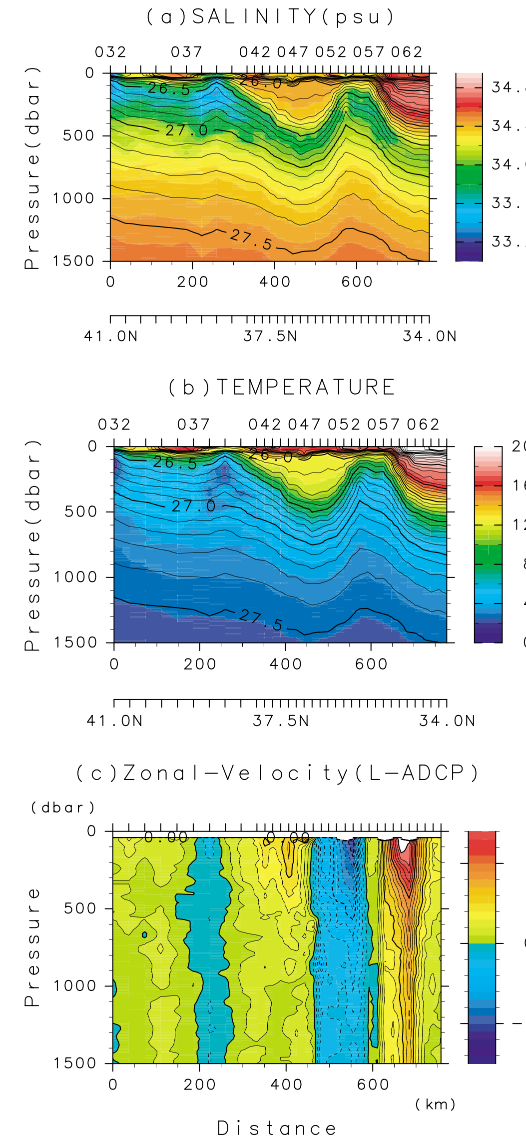

Fig. 6. As Fig. 4 but along 158°E for the HK0105 cruise.

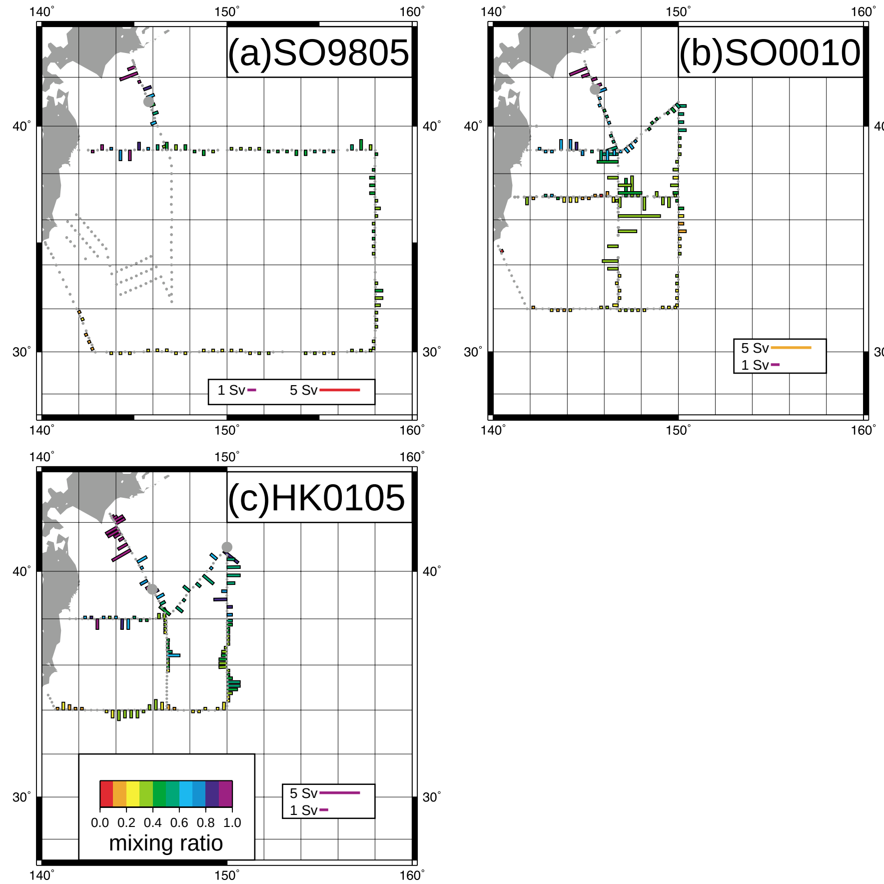

Fig. 7. Transport distributions of the Oyashio water component in the density of 26.6–27.4σ_θ, based on the velocity fields estimated from inverse methods, with Oyashio mixing ratio (color) and station locations in the three cruises, (a) SO9805, (b) SO0010, (c) HK0105. Color and marks are the same as Fig. 1.

waters. Relatively large Oyashio transports are seen near the Hokkaido coasts, corresponding to the southwestward nearshore Oyashio, in the MWR around the SAF and the SAB, and around the Kuroshio Extension axis in the meridional sections at 147–158°E.

The Oyashio-component transport in the area south of the KE axis found using the inverse method was 6–12 Sv, and the Oyashio transport around the KE axis was 6–14 Sv (Table 4(c)). These transports are larger than the cross-nearshore-SAF Oyashio transports near Hokkaido (2–12 Sv from the geostrophic field from the inverse method in Table 2(c)). The water with high Oyashio mixing ratio (>0.7) near Hokkaido (blue or purple bars in Fig. 1) flowing southward reached the Kuroshio Extension east of Japan (blue or purple bars flowing southward across 39°N in SO9805 and SO0010, and 38°N in HK0105). When the water came out of the box across the 147°E section, the water changes its Oyashio mixing ratio to 0.5–0.6 (green bars along 147°E in Figs. 1(b) and (c)). The water flowing along the KE axis has properties intermediate between Oyashio and Kuroshio waters, probably because of mixing along the Kuroshio Extension. These results indicate that cross-nearshore SAF Oyashio water flows southward, encounters the Kuroshio waters, and then strong mixing occurs between Oyashio and Kuroshio water in the area east of Japan; and that Oyashio water crossing SAF near Hokkaido flows into the area south of the KE mainly along the KE axis.

Table 4 shows that the Oyashio transports through the MWR (–0.4 and 4.2 Sv in the SO0010 and HK0105 cruises, respectively, from the geostrophic velocity field found using the inverse method) are smaller than or comparable with the cross-offshore-SAF Oyashio transports of 5.1 and 4.0 Sv in SO0010 and HK0105 cruises, respectively, found from the inverse method in Table 3. The transport diagrams along the 150°E of HK0105 and SO0010 (Fig. 7) show that an outflow of Oyashio water from the box through the MWR mainly occurs around the offshore SAF or SAB with continuous eastward bars around 40°N along 150°E. Thus, the cross-offshore-SAF Oyashio water flows eastward through the MWR, mainly around the offshore SAF, and some part of the Oyashio

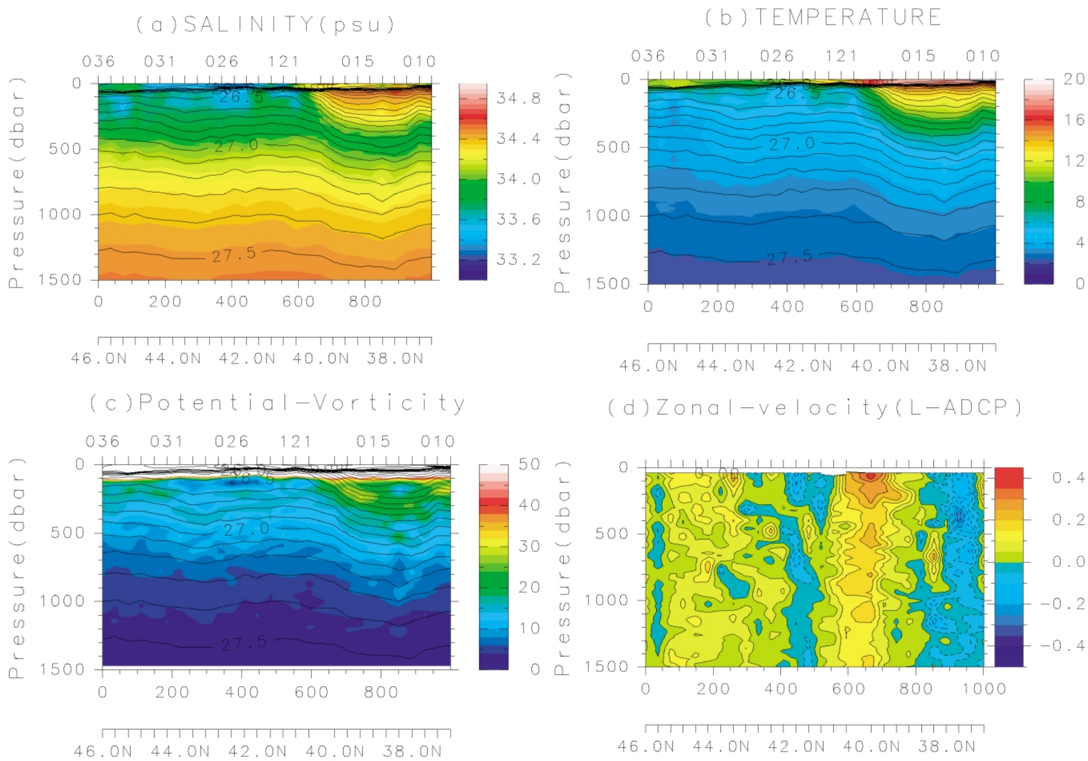

Fig. 8. Vertical cross-sections along 162°E from the HK0207 cruise. (a) Salinity (psu), (b) temperature (°), (c) potential vorticity (1/ms), (d) adjusted geostrophic velocity (cm/s), with potential density (σ_θ) contours (CI = 0.1).

water across the offshore SAF reaches the Kuroshio Extension, because the cross-offshore-SAF Oyashio transports (3) are greater than the outflow Oyashio transport in the MWR across 150°E (4).

6. NPIW and Oyashio Transport at 162°E

Here we examine the water properties and transport of NPIW in the further offshore area in the MWR at 162°E between 37–46°N using CTD/L-ADCP data obtained in the HK0207 cruise (Table 1). Figure 8 shows the vertical cross-sections at 162°E of temperature, salinity and potential vorticity with potential density contours and also the section of zonal velocity from L-ADCP. SAB was located around 40.5°N (Stas. 18–20), to the south of which relatively high-salinity subtropical water superposed over salinity minimum with a salinity of 33.9–34 psu at around 26.7σ_θ. This salinity minimum water is typical of that observed in the MWR (“Type-III” in Yasuda *et al.*, 1996; “Subtropical Transitional Water” in Talley *et al.*, 1995). In the area north of SAB, a hydrographic structure was observed peculiar to the so-called “Transition Domain” (Favorite *et al.*, 1976; Ueno and Yasuda, 2000, 2001). In the Transition Domain, the salinity roughly increases with depth as in the subarctic regions; however, isopycnal temperature and salinity are greater than the values in the subarctic region and less than those south of SAB. The changes in water properties are remarkable in the density range less than 26.6σ_θ across SAB. Isopycnal salinities in the density range of 26.6–27.4σ_θ (NPIW density range) also change across SAB; the Oyashio mixing ratios change from 0.42 (average south of SAB) to 0.64 (average north of SAB). The Oyashio mixing ratio is quite uniform between 37°N and SAB and it tends to increase with latitude north of SAB from 0.57 at SAB to 0.75 at 46°N where the observation line did not cross the SAF, because pure Oyashio water was not observed. When we look more closely at the Transition Domain north of SAB, we can see a weak salinity minimum at 26.5–26.6σ_θ with a temperature minimum and potential vorticity (PV) minimum as shown in Figs. 8(a), (b), and (c). This PV, salinity and temperature minimum water might correspond to the dense part of Central Mode Water that was observed in the Transition Domain (Yasuda *et al.*, 1994; Yasuda, 2003).

The net eastward Oyashio (Kuroshio) transport across 162°E in the density between 26.7–27.4σ_θ was 11.3 Sv (4.9 Sv) between SAB and 46°N and 5.4 Sv (5.6 Sv) between SAB and 37°N from the adjusted geostrophic velocity field. The Oyashio transport of 11.3 Sv north of the SAB is greater than the cross-offshore-SAF Oyashio transport west of 150°E (5–6 Sv). That is, the Oyashio water transport between SAF and SAB increases by about 5 Sv from 150°E to 162°E. This suggests that isopycnal mixing along the SAF further proceeds in the downstream direction from 150°E to 162°E.

As shown in the zonal velocity section (Fig. 8(d)), a relatively large eastward velocity was observed around SAB at 40.5°N and near SAF at around 46°N. This is consistent with the intermediate water flow field obtained from subsurface profiling floats by Iwao *et al*. (2003).

7. Summary and Discussion

Hydrographic and direct current data with CTD/L-ADCP in the MWR and the Kuroshio Extension region in the North Pacific obtained in May 1998, October 2000, May 2001 and July 2002 have been used as a basis for discussing the transports of Oyashio water through the MWR and the Kuroshio Extension region. Two kinds of velocity fields were used in this study other than the geostrophic velocity relative to 1500 dbar; one is the geostrophic velocity adjusted to L-ADCP profile and the other conserves the volume and temperature/salinity fluxes obtained by an inverse method. The Oyashio mixing ratios of sampled waters were calculated from temperature and salinity data assuming isopycnal mixing between pure Oyashio and pure Kuroshio waters, and the volume transports of the Oyashio component were estimated as the volume transport multiplied by the Oyashio mixing ratio.

There are two pathways of the Oyashio flowing into the area south of Subarctic Front (SAF). One is a direct Oyashio intrusion along the western boundary near the coast of Hokkaido, and the other occurs around the offshore SAF probably due to isopycnal mixing (eddy diffusion) around SAF. From the transport estimate of the Oyashio component through the former process (OY1 in Fig. 9), a seasonal variation was detected; the cross-nearshore-SAF Oyashio transport flowing southward along the south coast of Hokkaido is larger in the spring of 1998 and 2001 (5–10 Sv) than in the autumn of 2000 (0–4 Sv) in the density range 26.6–27.4σ_θ; the annual mean transport was estimated to be 4.2 Sv. This change was related to the variation in the southwestward Oyashio transport flowing near the Hokkaido coast, corresponding to the seasonal variation of the western subarctic gyre (e.g. Kono and Kawasaki, 1997; Isoguchi *et al*., 1997; Yasuda *et al*., 2000). Kono and Kawasaki (1997) reported a large seasonal variation (strong in winter-spring and weak in summer-fall) in the southwestward Oyashio transport using repeated hydrographic observations and moored current meters. Most of this cross-nearshore-SAF Oyashio water flowed southward along the east coast of Japan and reached the Kuroshio Extension, mixed with the subtropical water transported along the Kuroshio, and

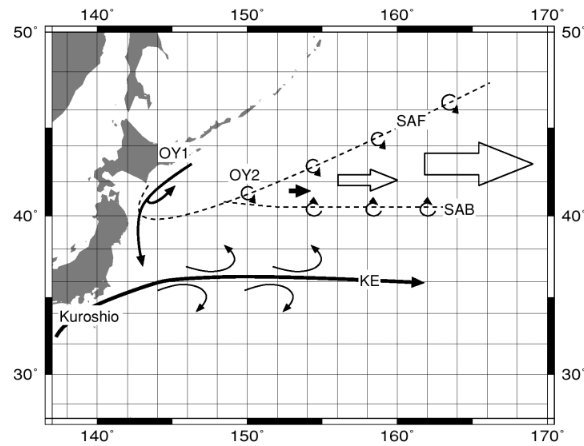

Fig. 9. Schematic illustration oft the pathways of the Oyashio water intrusions across the SAF into the MWR, Transition Domain and the Kuroshio Extension region in the northwestern Pacific. The cross-nearshore-SAF Oyashio water near the western boundary (OY1) reaches the Kuroshio Extension in the area east of Japan and flows eastward along the Kuroshio Extension, being mixed isopycnally with the Kuroshio water. The cross-offshore-SAF Oyashio water across the offshore subarctic front (OY2) is mixed around the subarctic front, and the eastward Oyashio transport in the Transition Domain increase in its downstream.

then together flowed eastward along the Kuroshio Extension or southward across the Kuroshio Extension (Fig. 9). Hence this cross-nearshore-SAF Oyashio transport can be said to be direct cross-gyre transport from the subarctic to subtropical gyres through the western boundary current of the Oyashio, because the Kuroshio Extension is the western boundary current of the subtropical gyre.

The cross-offshore-SAF Oyashio transport (OY2 in Fig. 9) was examined in October 2000 and May 2001. In both the observations, about 6 Sv of Oyashio water, which had already experienced mixing with subtropical water and had a salinity minimum structure, flowed into the MWR across the offshore SAF. These estimates of 6 Sv from the adjusted geostrophic velocity or velocity field obtained by the inverse method are different from the value estimated from the relative geostrophic velocity, indicating that the velocity around the offshore-SAF region had a structure extending deeper than 1500 dbar.

Considering this cross-offshore SAF transport of Oyashio water as well as the cross-nearshore-SAF Oyashio transport, the total cross-SAF Oyashio transport across the SAF west of 150°E amounts to over 10 Sv, which is much larger than the previous estimates of 3–7 Sv (e.g. Talley *et al*., 1995; Yasuda *et al*., 1996, 2001, 2002; Yasuda, 1997; Talley, 1997; Hiroe *et al*., 2002; Shimizu *et al*., 2003). Anthropogenic carbon (ex-CO_2)

transports though NPIW could be greater than previous estimates; Ono *et al*. (2003) estimated ex-CO_2 into NPIW to be 0.045 ± 0.020 GtC/yr on the basis of the present study, which contributes about 35% of the annual ex-CO_2 accumulation of the whole temperate North Pacific.

Downstream of the confluence of Oyashio and Kuroshio waters, the meridional width between the SAF and the SAB (that is, the Transition Domain) becomes progressively wider with longitude, and the Oyashio eastward transport in the MWR and the Transition Domain becomes large (about 6 Sv at 150°E and 11.3 Sv at 162°E). This result is consistent with those of Miyao and Ishikawa (2003) and Iwao *et al*. (2003) who reported that the eastward Oyashio (Kuroshio) component transport in the area from the SAB to SAF at 152°E and 165°E were 5.0 and 13.8 Sv (1.4 and 4.7 Sv) respectively, based on the geostrophic velocity fields relative to 2000 dbar. This increase of the eastward transport with longitude in the Transition Domain and MWR suggests that isopycnal diffusion around the SAF and SAB proceeds in the downstream direction and the diffused Oyashio water is fed into the Transition Domain (Fig. 9).

Appendix. Inverse Method

The adjoint inverse method (Wunsch, 1996) was used in this paper. What we want to estimate are the velocities between stations conserving the volume transport in the surface and two intermediate density layers, and the temperature/salinity fluxes in the two intermediate density layers. So the number of the unknown variables is the number of the station-pairs in each observation, M.

Since the balances of volume transport for the three density layers and the balance of temperature/salinity fluxes for the two intermediate density layers (see 2.2.2.3) in the box enclosed by the observational lines are constraints in this inverse model, the five model equations can be written in matrix form as

$$\mathbf{Ax} = \mathbf{q}, \tag{A1}$$

where $\mathbf{A}$ is an $N \times M$ matrix ($N = 5$) corresponding to the area of the density layer between each station, and $\mathbf{q}$ is an $N \times 1$ vector whose elements are the excess of volumes and temperature/salinity fluxes in the box from the geostrophic velocity fields relative to 1500 dbar.

Furthermore, since the estimated velocities at the reference level of 1500 dbar should be close to the velocities calculated in the procedure using the adjusted geostrophic velocity, we added the data equations to this equation system. The data equations, the number of which is equal to the number of unknowns, M, can be written as follows:

$$\mathbf{Ex} + \mathbf{n} = \mathbf{y}, \tag{A2}$$

where $\mathbf{E}$ is a unit matrix ($M \times M$), $\mathbf{n}$ is a ($1 \times M$) vector whose elements are the uncertainties of the observed velocities, and $\mathbf{y}$ is a ($1 \times M$) vector of the velocities calculated in the procedure of the adjusted geostrophic velocity field.

Considering the Lagrange multiplier, an objective function, J, can be set as

$$J = (\mathbf{Ex} - \mathbf{y})^{\mathbf{T}}(\mathbf{Ex} - \mathbf{y}) - 2\boldsymbol{\mu}^{\mathbf{T}}(\mathbf{Ax} - \mathbf{q}), \tag{A3}$$

treating both $\boldsymbol{\mu}$ and $\mathbf{x}$ as independently varying unknowns. After setting the derivatives of J with respect to $\boldsymbol{\mu}$ and $\mathbf{x}$ to zero, the solution $\tilde{\mathbf{x}}$ and the covariance matrix $\mathbf{P}$ are produced as

$$\tilde{\mathbf{x}} = \tilde{\mathbf{x}}_{\mathbf{u}} + \left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1}\mathbf{A}^{\mathbf{T}}\left[\mathbf{A}\left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1}\mathbf{A}^{\mathbf{T}}\right]^{-1}\left(\mathbf{q} - \mathbf{A}\tilde{\mathbf{x}}_{\mathbf{u}}\right), \tag{A4}$$

$$\mathbf{P} = \sigma^2\left\{\left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1} - \left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1}\mathbf{A}^{\mathbf{T}}\left[\mathbf{A}\left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1}\mathbf{A}^{\mathbf{T}}\right]^{-1}\mathbf{A}\left(\mathbf{E}^{\mathbf{T}}\mathbf{E}\right)^{-1}\right\}, \tag{A5}$$

where $\tilde{\mathbf{x}}_{\mathbf{u}} \equiv (\mathbf{E}^{\mathbf{T}}\mathbf{E})^{-1}\mathbf{E}^{\mathbf{T}}\mathbf{y}$, and σ is the value to which a row scaling of the data equations is applied so as to set all elements of vector $\mathbf{n}$. This solution $\tilde{\mathbf{x}}$ perfectly satisfies the constraint (A1) and is as close as possible to the adjusted geostrophic velocity field in the least square sense, considering their uncertainties.

The measurement error of L-ADCP and the error proportional to the velocity are here considered as uncertainties. The former is at most 3 cm/s, considering that the depth interval where the shear of the horizontal velocities are averaged is 5 m, the number of the data in each 5 m depth interval is about 100, the standard deviation of the shear is about 3.3×10^{-3} s^{-1}, the standard deviation of the velocity measured by the instrument is reported to be 2 cm/s, and the accuracy of the position measured by the Differential-GPS is about 20 m. The latter is assumed to be the same as the velocity at 1500 dbar or at the bottom, because the unsteady state of the currents could cause a large velocity error in the area where current structures change temporally and spatially around the Kuroshio Extension, and unsteadiness of the currents could occur when the velocity is large.

References

Andreev, A., M. Honda, Y. Kuramoto, M. Kusakabe and A. Murata (2001): Excess CO_2 and pH_{excess} in the intermediate water layer of the northwestern Pacific. *J. Oceanogr.*, **57**, 177–188.

Egbert, G. D., A. F. Bennet and M. G. G. Foreman (1994): TOPEX/POSEIDON tides estimated using a global inverse model. *J. Geophys. Res.*, **99**, 24821–24852.

Favorite, F., A. J. Dodimead and K. Nasu (1976): Oceanography of the Subarctic Pacific region, 1960–71. *Bull. Int. North Pacific Comm.*, **33**, 1–187.

Fischer, J. and M. Visbeck (1993): Deep velocity profiling with self-contained ADCPs. *J. Atmos. Oceanic Tech.*, **10**, 764–773.

Hiroe, Y., I. Yasuda, K. Komatsu, K. Kawasaki, T. M. Joyce and F. Bahr (2002): Transport of the North Pacific Intermediate Water in the Kuroshio-Oyashio Interfrontal zone. *Deep-Sea Res. II*, **49**, 5353–5364.

Isoguchi, O., H. Kawamura and T. Kono (1997): A study on wind-driven circulation in the subarctic North Pacific using the TOPEX/POSEIDON altimeter data. *J. Geophys. Res.*, **102**, 12457–12468.

Iwao, T., M. Endoh, N. Shikama and T. Nakano (2003): Intermediate circulation in the northwestern North Pacific derived from subsurface floats. *J. Oceanogr.*, **59**, this issue, 893–904.

Katsumata, K., I. Yasuda and Y. Kawasaki (2001): Direct current measurements in Krusensterna Strait in summer. *Geophys. Res. Lett.*, **28**, 319–322.

Kawai, H. (1972): Hydrography of the Kuroshio Extension. p. 235–352. In *Kuroshio, Its Physical Aspects*, ed. by H. Stommel and K. Yoshida, University of Tokyo Press, Tokyo.

Kono, T. (1997): Modification of the Oyashio Water in the Hokkaido and Tohoku Area. *Deep-Sea Res. I*, **44**, 669–688.

Kono, T. and Y. Kawasaki (1997): Results of CTD and mooring observations southeast of Hokkaido 1. Annual velocity and transport variations in the Oyashio. *Bull. Hokkaido Natl. Fish. Res. Inst.*, **61**, 65–81.

Miyao, T. and K. Ishikawa (2003): Formation, distribution and volume transport of the North Pacific Intermediate Water studied by repeat hydrographic observations. *J. Oceanogr.*, **59**, this issue, 905–919.

Ohtani, K. (1989): The role of the Sea of Okhotsk on the Oyashio Water. *Umi to Sora*, **65**, 63–83 (in Japanese).

Ono, T., Y. W. Watanabe and K. Sasaki (2000): Annual anthropogenic carbon transport into the North Pacific Intermediate Water through the Kuroshio/Oyashio interfrontal zone: an estimation from CFCs distribution. *J. Oceanogr.*, **56**, 675–689.

Ono, T., K. Sasaki and I. Yasuda (2003): Re-estimation of annual anthropogenic carbon input from Oyashio into North Pacific Intermediate Water. *J. Oceanogr.*, **59**, this issue, 883–891.

Reid, J. L., Jr. (1965): Intermediate waters of the Pacific Ocean. *The Johns Hopkins Oceanographic Studies*, **5**, 96 pp.

Shimizu, Y., I. Yasuda and S. Ito (2001): Distribution and circulation of the coastal Oyashio intrusion. *J. Phys. Oceanogr.*, **31**(6), 1561–1578.

Shimizu, Y., I. Yasuda, S. Ito and K. Hanawa (2003): ADCP-referenced Kuroshio and Oyashio water transports for the North Pacific Intermediate Water formation. *J. Phys. Oceanogr.*, **33**, 220–233.

Sverdrup, H., M. W. Johnson and R. H. Fleming (1942): *The Oceans, Their Physics, Chemistry, and Biology*. Prentice-Hall, 1087 pp.

Talley, L. D. (1993): Distribution and formation of North Pacific intermediate water. *J. Phys. Oceanogr.*, **23**, 517–537.

Talley, L. D. (1997): North Pacific intermediate water transports in the Mixed Water Region. *J. Phys. Oceanogr.*, **27**, 1795–1803.

Talley, L. D., Y. Nagata, M. Fujimura, T. Kono, D. Inagake, M. Hirai and K. Okuda (1995): North Pacific intermediate water in the Kuroshio/Oyashio mixed water region. *J. Phys. Oceanogr.*, **25**, 475–501.

Toba, Y., K. Tomizawa, Y. Kurasawa and K. Hanawa (1982): Seasonal and year-to-year variability of the Tsushima-Tsugaru Warm Current system with its possible cause. *La mer*, **20**, 41–51.

Tsunogai, S., T. Ono and S. Watanabe (1993): Increase in total carbonate in the western North Pacific water and a hypothesis on the missing sink of anthropogenic carbon. *J. Oceanogr.*, **49**, 305–315.

Ueno, H. and I. Yasuda (2000): Distribution and formation of the mesothermal structure (temperature inversions) in the North Pacific subarctic region. *J. Geophys. Res.*, **105**(C7), 16,885–16,897.

Ueno, H. and I. Yasuda (2001): Warm and saline water transport to the North Pacific Subarctic region: WOCE and SAGE data analysis. *J. Geophys. Res.*, **106**(C10), 22131–22141.

Wunsch, C. (1996): *The Ocean Circulation Inverse Problem*. Cambridge University Press, Cambridge, 442 pp.

Yasuda, I. (1997): The origin of the North Pacific Intermediate Water. *J. Geophys. Res.*, **102**(C1), 893–909.

Yasuda, I. (2003): Hydrographic structure and variability of the Kuroshio-Oyashio Transition Area. *J. Oceanogr.*, **59**, 389–402.

Yasuda, I., H. Kubo, Y. Katsumata, Y. Abe, S. Takasugi, T. Sato, M. Ishi, D. Inagake and A. Tomosado (1992): Hydrophic structure in summer 1991. *Annual Report of the Research Meeting on Saury Resources* (published by Tohoku National Fisheries Research Institute), **41**, p. 275–288.

Yasuda, I., T. Honma, S. Takasugi, Y. Izumi, T. Sato, R. Ando, K. Hiramoto and Y. Katsumata (1994): Hydrographic structures in the western Subarctic Gyre and mixed water region in summer 1993 and fishing ground formation of Pacific saury. *Annual Report of the Research Meeting on Saury Resources* (published by Tohoku National Fisheries Research Institute), **43**, p. 216–237.

Yasuda, I., K. Okuda and Y. Shimizu (1996): Distribution and modification of the North Pacific Intermediate Water in the Kuroshio-Oyashio Interfrontal zone. *J. Phys. Oceanogr.*, **26**, 448–465.

Yasuda, I., S. Ito, Y. Shimizu, K. Ichikawa, K. Ueda, T. Honma, M. Uchiyama, K. Watanabe, T. Suno, K. Tanaka and K. Koizumi (2000): Cold-core anti-cyclonic eddies south of the Bussol' Strait in the north-western Subarctic Pacific. *J. Phys. Oceanogr.*, **30**, 1137–1157.

Yasuda, I., Y. Hiroe, K. Komatsu, K. Kawasaki, T. M. Joyce, F. Bahr and Y. Kawasaki (2001): Hydrographic structure and transport of the Oyashio south of Hokkaido and the forma-

tion of the North Pacific Intermediate Water. *J. Geophys. Res.*, **106**(C4), 6931–6942.
Yasuda, I., S. Kouketsu, K. Katsumata, M. Ohiwa, Y. Kawasaki and A. Kusaka (2002): Influence of intermediate Okhotsk Sea water on the Oyashio and North Pacific Intermediate Water. *J. Geophys. Res.*, **107**(C12), 3237, doi:10.1029/2001JC001037.
Yoshinari, H., I. Yasuda, S. Ito, E. Firing, Y. Matsuo, O. Kato and Y. Shimizu (2001): Meridional transport of the North Pacific Intermediate Water in the Kuroshio-Oyashio interfrontal zone. *Geophys. Res. Lett.*, **28**, 3445–3448.
Yuan, X. and L. D. Talley (1992): On shallow salinity minima in the north Pacific. *J. Phys. Oceanogr.*, **50**, 1302–1316.