Distribution and Modification of North Pacific Intermediate Water in the Kuroshio–Oyashio Interfrontal Zone

ICHIRO YASUDA*

Tokuhu National Fisheries Research Institute, Shiogama-shi, Miyagi, Japan

KUNIAKI OKUDA

National Research Institute of Fisheries Science, Yokohama, Kanagawa, Japan

YUGO SHIMIZU

Tokuhu National Fisheries Research Institute, Shiogama-shi, Miyagi, Japan

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ABSTRACT

A multiship CTD survey was conducted in the Kuroshio–Oyashio interfrontal zone in the area of 30°–41°N, 140°E–180° from May to June 1992 to examine the distribution, modification process, and formation site of North Pacific Intermediate Water (NPIW). Low salinity Oyashio water and high salinity Kuroshio water merge along the Kuroshio Extension just off the east coast of Japan and together flow eastward. Eastward geostrophic transport and salinity across the Kuroshio strong current indicate that the mixture of the Kuroshio and Oyashio waters along the Kuroshio Extension can produce new NPIW. Transport estimate suggests that the new NPIW bifurcates into the interfrontal zone and into the recirculation of the subtropical gyre. A salinity minimum structure can be also created due to the isopycnal mixing along the Kuroshio Extension between the Oyashio and Kuroshio waters, which have different salinity and vertical velocity structures. The low-salinity Oyashio water seen along the Oyashio branches and the Kuroshio Extension has low potential vorticity ($Q = \rho^{-1} f \partial \rho / \partial z$), suggesting that NPIW formation is primarily density driven due to sinking in the Okhotsk Sea.

1. Introduction

A remarkable feature of the entire North Pacific subtropical gyre is the existence of a well-defined salinity minimum at depths of 300–800 m with a density range centered at 26.7–26.9 σ_θ (Sverdrup et al. 1942; Reid 1965; Talley 1993; Talley et al. 1995). North Pacific Intermediate Water (NPIW) is defined as this salinity minimum (Sverdrup et al. 1942) or as the waters characterized by the salinity minimum (Reid 1965). Relating to the problems of global climate change and the missing sink of CO_2, NPIW and intermediate depth circulation in the North Pacific has increasingly attracted attention as a media for transporting CO_2-rich surface waters in the subpolar gyre to deeper depths (Tsunogai et al. 1992). Many scientists have attempted to explain the mechanism by which the salinity minimum is developed, such as how and where the low-salinity water enters into the intermediate depth of subtropical high salinity waters. However, there still remains many questions on NPIW and previous explanations are far from clear.

Questions on NPIW are summarized as follows: 1) What are the driving forces that produce the NPIW (density-driven, wind-driven or mixing), 2) how and where is the salinity minimum formed (actual formation process and site), and 3) what sets the NPIW density range? Furthermore, these three questions are probably linked to each other.

One of the reasons why the NPIW formation has long been controversial is that NPIW in the subtropical gyre has neither an apparent pycnostad nor a surface outcropping area in the open ocean. These characteristic features of NPIW are different from other intermediate water such as Labrador Sea Water (LSW) and North Atlantic and Antarctic Intermediate Water (AAIW) (Talley 1993). LSW and AAIW have a very apparent pycnostad and vertical potential vorticity minima, whereby heavy waters produced by convection are

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[*] Current affiliation: Graduate School of Environmental Earth Science, Hokkaido University, Sapporo, Hokkaido, Japan.

Corresponding author address: Dr. Ichiro Yasuda, Graduate School of Environmental Earth Science, Hokkaido University, Kita-10, Nishi-5, Kita-ku, Sapporo, Hokkaido 060 Japan.
E-mail: ichiro@eoas.hokudai.ac.jp

transported into an intermediate depth by density and/or wind-driven circulation (e.g., Talley and McCartney 1982). Because of the absence of a distinctive pycnostad in NPIW, Hasunuma (1978) suggested that NPIW is not a water mass but just the vertical boundary between subtropical and subpolar waters in the subtropical gyre, and Talley (1993) also suggested that a convective source is unlikely. However, the absence of an apparent pycnostad does not necessarily mean a nonconvective source. A pycnostad that is distinctive near a source region might disappear due to the strong modification in the process of contact with subtropical waters and NPIW formation. Such an intergyre-scale density-driven mechanism, as Wüst (1930) ascribed NPIW to sinking in the Okhotsk Sea, has not been validated either.

The shallow salinity minima (SSM) are other salinity minima in the North Pacific subtropical gyre and do not have apparent pycnostads (Reid 1973; Tsuchiya 1982; Yuan and Talley 1992). Thus, SSM appears to be similar to NPIW. However, the SSM is formed by a mechanism whereby near-surface low salinity water is pushed into the intermediate depth by downward Ekman pumping (Talley 1985; Yuan and Talley 1992), a mechanism which is essentially the same as in the theory given by Luyten et al. (1983). However, in the case of NPIW, the outcropping of the NPIW density surface ($\sigma_\theta \geqslant 26.7$) cannot be found in the open ocean where downward Ekman pumping prevails (Reid 1965; Talley 1993). Hence, ventilation by an SSM-type mechanism is impossible.

Reid (1965) hypothesized that the salinity minimum is caused by two combined processes: vertical mixing along the cyclonic path around the subpolar gyre and advection and lateral mixing for the spread of subpolar low-salinity properties into the subtropical gyre. The former leads to the addition of freshwater to the subpolar water giving densities similar to the NPIW density range and the latter for the formation mechanism of the salinity minimum in the subtropical gyre. Reid's hypothesis need not consider a convective source. Talley (1991) suggested that most of the freshening occurs in the Okhotsk Sea through sea ice formation and vertical mixing. Van Scoy et al. (1991) suggested that freshening can take place to the NPIW density range in the Alaskan Gyre in wintertime.

There is no question that advection and isopycnal mixing are important processes for the formation and spread of NPIW, as Reid (1965), Talley (1993), Qiu (1995), and Yamanaka et al. (1995) have pointed out. For a primary driving mechanism, there is a difference between the density-driven formation (Wüst 1930) and the combination of vertical mixing for freshening to the NPIW density and lateral mixing for the spread into the subtropical gyre (Reid 1965). The former permits the net cross-gyre transport from the subpolar to the subtropical gyre with intergyre-scale meridional diapycnal thermohaline circulations. While in the latter, only exchange of water properties between gyres is allowed. It might be difficult to clearly distinguish the above two driving mechanisms only from a pycnostad, as other signatures are needed to clarify the difference.

Hasunuma (1978) suggested that the salinity minimum is formed by an overrun of subpolar waters from the Oyashio by subtropical waters from the Kuroshio in the Kuroshio–Oyashio mixed water region near the northwestern edge of the subtropical gyre. Talley concluded that NPIW is formed only in the northwestern subtropical gyre. Talley (1993) and Talley et al. (1995) suggested that the overrun (primarily along the Oyashio front) is a dominant formation process, and proposed possible formation sites and processes around the intense current and frontal systems. However, in order to detect the actual formation processes and sites and to evaluate the relative importance of various potential sites and processes, many more studies are still required, in particular with synoptic observations of high spatial resolution and wide coverage.

For the narrowly defined NPIW density range, Talley (1993) and Talley et al. (1995) hypothesized that the surface density of the subpolar winter mixed layer ($\sigma_\theta \sim 26.5$) determines the NPIW density and subsequent preferential erosion of the minima from the top increases the NPIW density. Qiu (1995) indicated that seasonal outcropping near the northwestern edge of the subtropical gyre blocks the subarctic water from advecting and diffusing into the subtropical gyre and enhances the vertical mixing to determine the lower boundary of the NPIW density ($\sigma_\theta \sim 26.2$). Although the above studies gave important information and limit density range, more studies are needed for clear understanding of NPIW density, especially in the NPIW formation area.

Uncertainties remain because observations that can trace the processes of the NPIW formation have not been sufficient. In the present study, we show the NPIW formation along the Kuroshio Extension as it is being formed on the basis of a new synoptic CTD dataset densely sampled in the NPIW formation area. It is suggested that a significant input of low-salinity water into the subtropical gyre along the Kuroshio Extension can produce new NPIW, which is distributed widely in the Kuroshio–Oyashio interfrontal zone. The low-salinity waters probably originate from ventilated waters in the Okhotsk Sea. These results support the hypothesis that NPIW is primarily density-driven and its origin is sinking water in the Okhotsk Sea. CTD data obtained in the Okhotsk Sea and the region around the Kuril Islands is currently being used to substantiate the present results.

In the next section, previous data on the circulation and water characteristics near the northwestern edge of the subtropical gyre are described in relation to NPIW formation. In section 3, the data used is described. In section 4, the horizontal salinity and geostrophic flow distribution along the NPIW density surface is depicted. In section 5, we examine the eastward spreading of low-salinity waters originating from the Oyashio along the northern edge of the Kuroshio Extension. It is suggested that this low-salinity input into the subtropical gyre and isopycnal mixing with old saline NPIW originating from the Kuroshio is significant in the formation of the NPIW. Low potential vorticity found along the path of low-salinity water suggests that the low salinity water originates from ventilated water in the Okhotsk Sea (section 6). In section 7, we discuss the spatial variations of density and salinity at the lowest salinity minimum. In section 8, results are summarized and possible flow patterns and water modification inferred from the current and previous results are proposed.

2. Background

The primary source of low-salinity water for NPIW is unquestionably in the North Pacific subpolar gyre, especially in the Okhotsk Sea, where vertical mixing and/or convection by sea ice formation freshen waters to the NPIW density range (Reid 1965; Kitani 1973; Talley 1991) (see Fig. 1). Some recent results of a numerical simulation (Yamanaka et al. 1995) and an inverse model with the Levitus dataset (Fukasawa 1992) suggest that marginal seas such as the Okhotsk Sea and the Bering Sea are important freshwater sources.

Low-salinity waters outflow through the straits between the Kuril Islands from the Okhotsk Sea and flow southwestward along the Kuril Islands and the east coast of Hokkaido as the Oyashio, mixing with the East Kamtchatka Current waters (Fig 1; Ohtani 1989; Kawasaki and Kono 1992; Kono 1995). A part of the Oyashio flows farther southward along the east coast of Honshu Island as the first and second Oyashio branches (Kawai 1972), and another part returns northeastward as the Oyashio Extension, forming water mass fronts [Oyashio Front: Kawai (1972); subarctic front: Zhang and Hanawa (1993)] with the high salinity waters originating mostly from the subtropical gyre. The low-salinity waters in the first and second Oyashio branches meet with the Tsugaru warm current waters (Yasuda et al. 1988) and Kuroshio warm core rings (Yasuda et al. 1992) and are strongly modified. The modified, but still low-salinity, waters meet with the Kuroshio Extension and form the Kuroshio Front (Fig 1; Kawai 1972).

Part of the relatively fresh and cold waters return to the subpolar gyre, while another part flows eastward along the northern edge of the Kuroshio Front. The latter is referred to as an "inner cold belt" near the surface and a "cold and low-salinity core" around NPIW density range (Masuzawa 1955a,b, 1956; Ichiye 1956; Kawai 1972). These features are commonly observed near the east coast of Japan around 145°E. However, east of 145°E, the feature has not been well demonstrated.

From a salinity point of view, the most saline NPIW in the subtropical North Pacific is distributed near the western edge of the North Pacific from Taiwan to Kyushu with a salinity of over 34.3 psu (Reid 1965; Talley 1993) along the Kuroshio, the western boundary current of the North Pacific subtropical gyre. For NPIW in the Kuroshio along the south coast of Japan, salinity is slightly lower at 34.2–34.3 psu (Reid 1965; Yang et al. 1993; Talley 1993). The high salinity NPIW flows northeastward and meets with the low salinity Oyashio water, following the separation of the Kuroshio Extension from the Japan coast (Fujimura and Nagata 1992).

From some global maps of NPIW isopycnal surface ($\sigma_\theta \sim 26.8$), NPIW salinity of 33.9–34.1 psu occupies a dominant part of the subtropical gyre (Reid 1965; Talley 1993). Waters with a salinity of 33.9–34.0 psu are distributed almost zonally at 35°–42°N from 150°E to 170°W. The waters extend southward to about 30°N in the eastern North Pacific from 170° to 140°W (Talley 1993). This southward extension is ascribed to the southward recirculation of the subtropical gyre (Reid 1965; Talley 1993; Qiu 1995). Waters with a salinity of 34.0–34.1 psu are distributed from 25° to 37°N east of 150°E. If we assume that diapycnal mixing is small enough to conserve the salinity along the eastward flow of the subtropical gyre, waters with salinity of 33.9–34.1 psu are created off the east coast of Japan where the low-salinity and the high-salinity NPIW meet (Talley 1993; Talley et al. 1995). Thus, a detailed study of this region is important.

The formation site for the salinity minimum is the area off the east coast of Japan (Hasunuma 1978; Talley 1993), which is often referred to as the mixed water region between the Oyashio and Kuroshio waters (Kawai 1972). We here call this region the Kuroshio–Oyashio interfrontal zone between the Oyashio and Kuroshio Fronts. The interfrontal zone is peculiar in that the two fronts, each of which accompanies a boundary current, locate separately in the northwestern Pacific; the Oyashio Front is roughly 5° north of the Kuroshio Front. The interfrontal zone is recognized as a part of the subtropical gyre from a wind-driven circulation theory since the zero of the annual-mean Sverdrup transport roughly coincides with the Oyashio (subarctic) Front (Talley 1993). Talley et al. (1995) showed that newly formed and well-mixed NPIW in the interfrontal zone consists of 45% Oyashio and 55% Kuroshio water in origin. New NPIW formation in the interfrontal zone, which is in the subtropical gyre, might imply the existence of cross-gyre transport caused by density-driven circulation.

As a more specific site and process for NPIW formation in the interfrontal zone, Talley (1993) suggested four mechanisms: subduction of subpolar water beneath subtropical water at the Oyashio Front, entrainment and intrusion of subpolar water into warm (saline) warm core rings, overrun of subpolar water by Tsugaru warm (saline) water, and intrusions into the Kuroshio Extension itself. Talley et al. (1995) indicated that a Kuroshio warm core ring was the dominant site for salinity minimum formation when synoptic observations were carried out. However, it is still not clear which process and site is predominant.

From annual-mean wind stress fields, it is expected that the barotropic flow field has dominant eastward flow with small northward flow in the Kuroshio–Oyashio interfrontal zone because of upward Ekman pumping in the area of 35°–40°N, 150°E–180° (Kutsuwada and Teramoto 1987; Yuan and Talley 1992). A numerical model result with real wind stresses also indicates the existence of a northward flow component (e.g., Yamanaka et al. 1995). Fukasawa (1992) showed that northward transport is dominant from 150°E to 180° across 35°N latitude in the NPIW density range, using an inverse method and a heavily smoothed Levitus (1982) dataset. This northward flow field is consistent with an acceleration potential map given by Reid (1965) and Qiu (1995) and the temperature field at 300-m depth by Mizuno and White (1983), where the temperature contours are directed northeastward in that area. From climatological-mean dynamic height data at the surface (Teague et al. 1990) the flow field has a northward component in the area of 35°–40°N, 150°E–180°.

The question why new NPIW is formed in the Kuroshio–Oyashio interfrontal zone where saline subtropical water should be carried northward by the northward mean flow is raised. One possible reason is to consider the strong isopycnal mixing and entrainment of subpolar water due to mesoscale eddies (Talley et al. 1995). Another reason is low-salinity water intrusion along the Kuroshio Front. In the latter case, the northward mean flow transports already freshened NPIW into the interfrontal zone. We show here the latter process actually occurs and significantly contributes to the formation of new NPIW.

3. Data

In order to elucidate the actual formation processes of the salinity minimum, synoptic observations with sufficient resolution over a wide area are required. Tohoku National Fisheries Research Institute (TNFRI), National Research Institute of Fisheries Science (NRIFS), Ibaragi Prefectural Fisheries Experimental Station (IPFES), and Miyagi Prefectural Fisheries Exploitation and Research Center (MPFERC) conducted joint CTD observations in the Kuroshio–Oyashio interfrontal zone of 30°–40°N, 140°E–180°. Figure 2 shows the CTD stations of these joint observations. CTD data were taken down to almost 1000 dbar. In Table 1, the vessels, sampling period, investigators, and data sources for the observation program are described. In the area from 32° to 38°N, 140° to 150°E, where the Kuroshio Extension leaves the coast and meets with Oyashio low-salinity water, a detailed CTD survey of 11 meridional sections and one other section that crossed the Kuroshio Extension was conducted onboard the *Wakataka Maru* and *Soyo Maru.*

Raw CTD data were averaged to 1-dbar interval data. The 1-dbar data were smoothed by the ten times operation of $[A_{i-1} + 2A_i + A_{i+1}]/4$ (A_i represents a water property at ith pressure). The data were used for the following analysis. For the estimation of potential vorticity, the density gradient was calculated as a least mean square of 50-dbar data for each 1-dbar interval. For the isopycnal potential vorticity in section 6, the density gradients were averaged for the range of 26.7–26.8 σ_θ.

4. Horizontal distributions of salinity and geostrophic current along the 26.7–26.8 σ_θ isopycnal layer

Figure 3a shows the salinity distribution along the 26.7–26.8 σ_θ isopycnal layer. The salinity values are vertically averaged within the density range. This density range is chosen since the representative density of NPIW is within this range in the Kuroshio–Oyashio interfrontal zone (Talley 1993; Talley et al. 1995).

The salinity distribution can be classified into four types of waters: The first one is the highest salinity tongue with a salinity of over 34.1 psu found west along the Kuroshio Extension in the area of 34°–37°N, 140°–144°E and near 34°N, 146°E. We refer to this high-salinity tongue as Type I water. Type I water with a salinity of over 34.2 disappears east of 150°E. The next type of water is low-salinity water with a salinity of less than 33.8 psu originating from the Oyashio. This low-salinity water is distributed meridionally along the coastal and offshore Oyashio branches and meets with the Kuroshio Extension. Thereafter, the low-salinity water is distributed along the Kuroshio Extension within a narrow meridional width of about 50 km. We refer to this water as Type IV water. The third type is the most common water in the Kuroshio–Oyashio interfrontal zone with a salinity between 33.9 and 34 psu. This water is fairly uniformly distributed east of 148°E. We refer to this water as Type III. The fourth type is associated with water south of the Kuroshio Extension and has a salinity ranging from 34 to 34.1 psu. We refer to this water as Type II water. The uniform distribution of Type III water in the Kuroshio–Oyashio interfrontal zone agrees well with the one by Talley (1993) in spite of the difference of the datasets: data from Talley (1993) and present synoptic data.

Figure 4 is the salinity profiles for σ_θ showing the features of the classified water columns. The density of

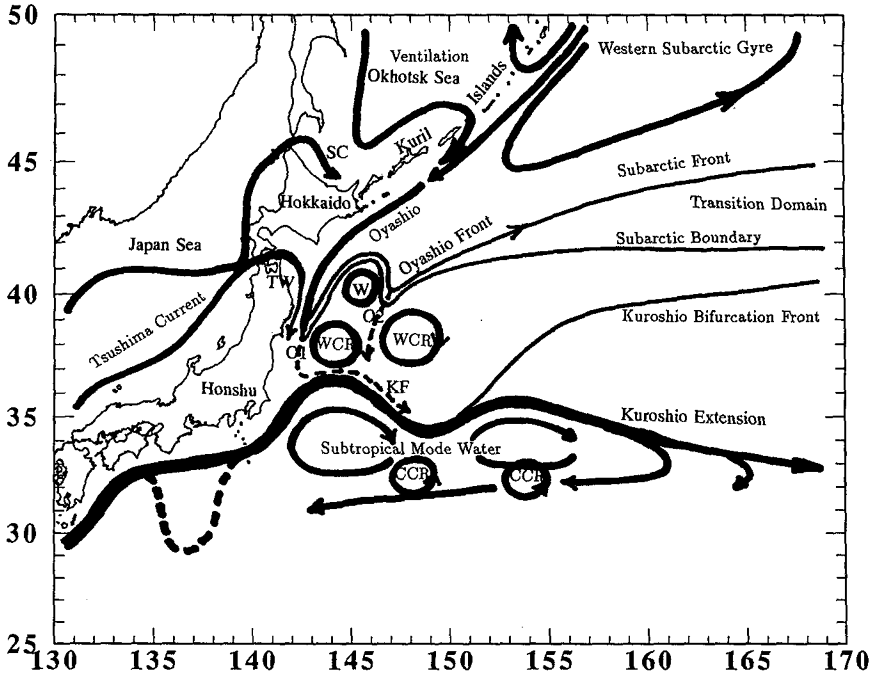

FIG. 1. Schematic representation of the current and frontal systems in the study area. SC: Soya Current, TW: Tsugaru warm current, O1: Oyashio first branch (Coastal Oyashio Intrusion), O2: Oyashio second branch (Offshore Oyashio Intrusion), WCR: warm core ring, CCR: cold core ring, KF: Kuroshio Front.

the salinity minimum decreases from Types I to IV waters. The profile is relatively smooth in Type I, II, and III waters, although these profiles are disturbed when the stations are adjacent to Type IV water. Talley et al. (1995) classified vertical profiles in the mixed water region into five regimes: 1) subtropical, 2) sub-

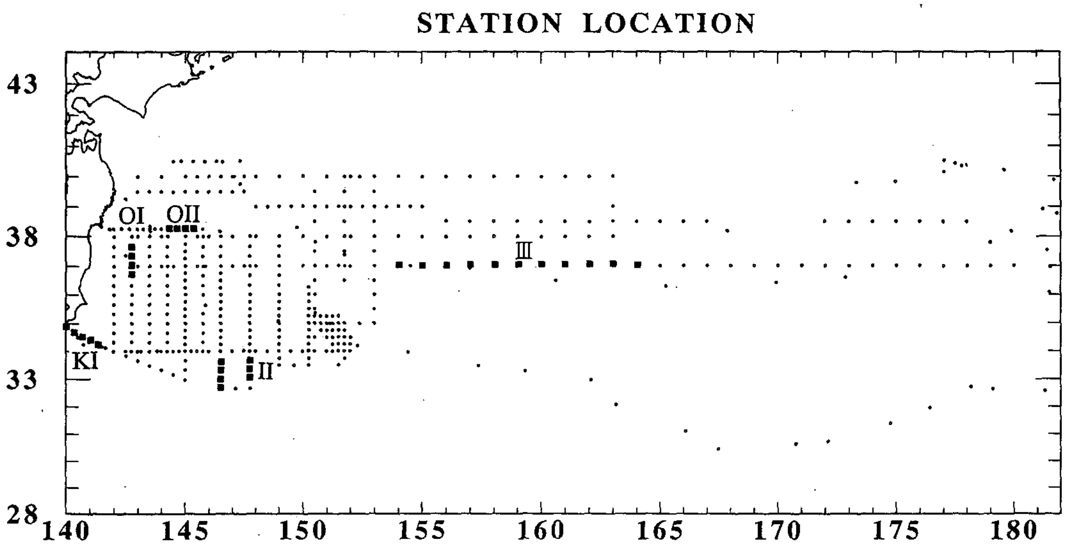

FIG. 2. Location of stations for *Wakataka Maru* leg 1 and leg 2, and *Soyo Maru, Shin-hoyo Maru, Shin-miyagi Maru, Mito Maru,* and *Wakatori Maru* cruises during May–June 1992. Squares denote the stations used in the following analyses.

TABLE 1. Vessels, data source, period, principal investigators for CTD data used in the present analysis from May to June 1992.

R/V	Data source	Period	Investigator
Wakataka Maru	TNFRI[a]		
leg 1		20 May–10 Jun	I. Yasuda
leg 2		15–23 Jun	S. Kubota
Soyo Maru	NRIFS[b]	10 May–2 Jun	K. Okuda
Shin-hoyo Maru	TNFRI	14 May–17 Jun	Y. Takahashi
Mito Maru	IPFES[c]	16–23 Jun	R. Andoh
Shin-miyagi Maru	MFREC[d]	21 May–13 Jun	Y. Izumi
Wakatori Maru	TNFRI	1–4 May	Y. Matsuo

[a] Tohoku National Fisheries Research Institute.
[b] National Research Institute of Fisheries Science.
[c] Ibaragi Prefectural Fisheries Experimental Station.
[d] Miyagi Fisheries Research and Exploitation Center.

polar, 3) Tsugaru, 4) subtropical transitional, and 5) subpolar transitional. Type IV water roughly corresponds to the subpolar and subpolar transitional regimes. Type III roughly corresponds to the subtropical transitional regime although Type III water is slightly less saline than the subtropical transitional regime water. In the present study, the subtropical regime is further classified into Types I and II.

Figure 3b is an acceleration potential (Montgomery 1937) map along 26.7–26.8 σ_θ, referring to 1000 dbar with the distribution of I, III, and IV waters. The contours indicate geostrophic flow streamlines assuming that 1000 dbar is the level of no motion. The strongest current is the Kuroshio Extension, which flows southeastward with large meanders. Two intense warm core rings were located centered at 39°N, 149°E and 36°30′N, 152°E. In the area of 37°–40°N, 155°–180°E complicated eddy fields were observed with their wavelengths larger than that west of 150°E (not shown).

When we look at both the geostrophic streamlines and salinity distribution (Fig. 3b), Type I high salinity water comes into this area along the Kuroshio Extension. Low-salinity Type IV water extends along the southward flow of the Oyashio coastal branch and meets the Type I high salinity water to the east of Japan, and then flows eastward along the Kuroshio Extension. In the interfrontal zone between the Kuroshio and Oyashio Fronts, many eddies are seen in contrast to the uniform salinity distribution of Type III water. From the northern Oyashio Front, low-salinity water enters into this area along the southward streamlines. South of the Kuroshio Extension, relatively uniform Type II waters are distributed, and two recirculation gyres are apparent, centered at 35°N and 144°E and at 34°N and 150°E. The geostrophic flow and salinity distribution suggest that high salinity water and low salinity water merge along the Kuroshio Extension, and Type II and Type III waters are produced.

When we look at the salinity distribution for the entire North Pacific from Reid (1965) and Talley (1993), Type II and Type III waters occupy a dominant part of the subtropical gyre. Thus, it is valuable to study the merging of intermediate Kuroshio and Oyashio waters and the formation of Type II and III waters in further detail.

5. Water formation along the Kuroshio Extension

a. *Detailed features along the Kuroshio Extension*

In the upstream part of the Kuroshio Extension, Type I water occupies the strong current region (Fig. 3b). To the east along the strong current, low salinity Type IV water replaces Type I in the area of 145°–151°E. That is, low salinity water has a strong eastward velocity. Low salinity patches are also found in the strong current and south of the Kuroshio Extension, centered at 36°N, 143°E and 34°N, 151°30′E. These patchy features probably arise from instability phenomena along the strong jet.

The other important feature is the modification of low-salinity Type IV water along the Kuroshio Extension. If Type IV water returns to the subarctic gyre without any modification, no low salinity water input into the NPIW would occur. When we trace the streamline originating from the Oyashio water along the Kuroshio Extension, the low salinity feature is conserved along the eastward flow. On the return path to the subarctic gyre, Type IV water was not found, instead the water is already modified to Type III water. This result suggests that eastward flowing low-salinity water contributes to the freshening of NPIW.

Salinity profiles can be traced along the Type IV waters near the Kuroshio Extension. In Fig. 4, three kinds of salinity profiles of Type IV water are demonstrated. Type IV-OA represents a mean salinity profile for the CTD stations east of 144°E with the salinity $S < 33.5$ psu for 26.7–26.8 σ_θ. Hence, the salinity profile represents the one in the coastal Oyashio branch in which salinity fundamentally increases with density. Type IV-OB represents stations north of the Kuroshio Extension with $S < 33.7$ in the area 35°–39°N, 145°–146°E where Type IV water flows southeastward north of the Kuroshio Extension (Fig. 3). The salinity is greater for the whole density range compared to the IV-OA profile. A salinity minimum is formed at around 26.6 σ_θ. Type IV-OC represents farther downstream Type IV water with $S < 33.7$ psu in the area of 35°–37°N, 146°–151°E along the Kuroshio Extension (Fig. 3). The salinity further increases and is the same as the Type III water profile except in the density range 26.5–26.9 σ_θ. This suggests that the salinity minimum structure in Type III water, defined as new NPIW by Talley (1993), is created in this area except for 26.5–26.9 σ_θ. The salinity minimum density is near 26.7 σ_θ; thus it increased compared to the IV-OB profile.

Based on the idea that a mixture of eastward low-salinity Type IV and high salinity Type I waters can

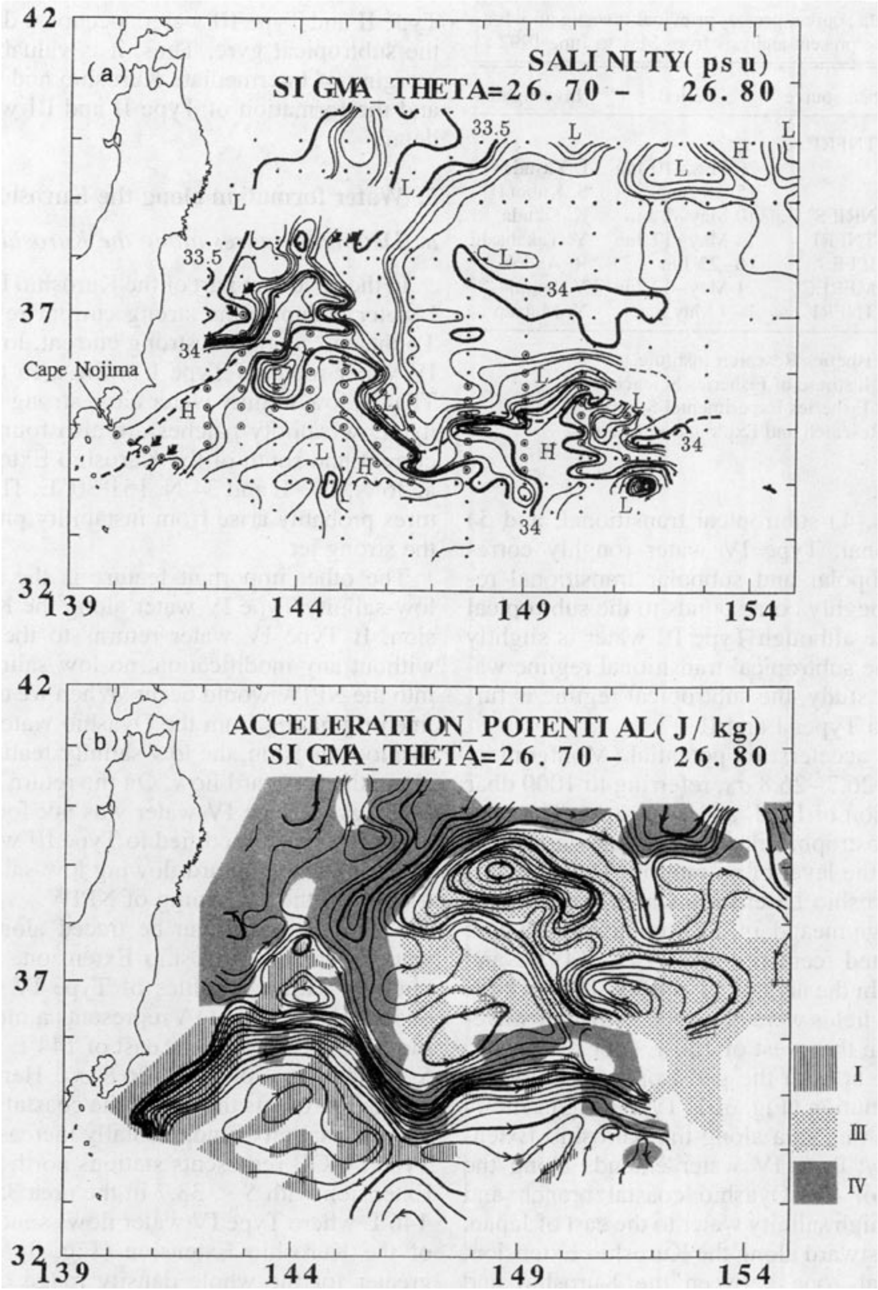

FIG. 3. Salinity (a) and acceleration potential referred to 1000 dbar with the distribution of Type I ($S > 34.1$), III ($33.9 < S < 34$), and IV ($S < 33.8$) waters (b) along $\sigma_\theta = 26.7$–26.8 isopycnal layer. In (a), circles denote the CTD stations used in the estimate of salinity and transport across meridional sections. Arrows indicate the CTD station used for showing vertical profiles of the Kuroshio and Oyashio branches. The broken curve denotes the 200-m 14°C isotherm, which is indicative of the axis of the Kuroshio Extension (Kawai 1972). Contour intervals are 0.1 psu (a) and 0.1 J kg^{-1} (b).

contribute to the freshening of NPIW, we will check this by using CTD data in two ways. One method is to estimate the salinity if the water that crosses a CTD section isopycnally mixes. The estimate is applied to the eastward flow along the Kuroshio Extension. Secondary, we examine the water properties of upstream sources, which eventually mix along the Kuroshio Extension.

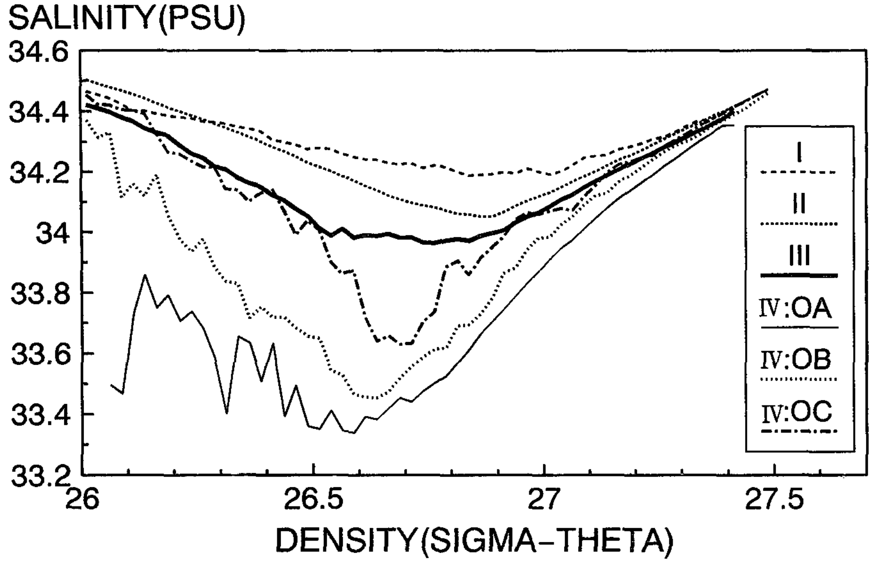

FIG. 4. Salinity profiles for σ_θ for the four water types. Average among several CTD stations was operated for each profile. Profile I: salinity ($S > 34.2$) in 26.7–26.8 σ_θ for the stations east of 144°E. Profile II: $34 < S < 34.1$ for the stations denoted by squares and II in Fig. 2. Profile III: $33.9 < S < 34$ for the stations in Fig. 2. Profile IV-OA: $S < 33.5$ east of 144°E. Profile IV-OB: $S < 33.7$ in the area 35°–39°N and 145°–146°E. Profile IV-OC: $S < 33.7$ in the area 35°–37°N and 146°–151°E.

b. Water modification along the Kuroshio Extension for 26.7–26.8 σ_θ

We use the 11 meridional CTD sections and another one off Cape Nojima that crosses the Kuroshio Extension. For each station pair, we calculate the salinity S_i and volume transport Tr_i, referring to 1000 dbar at the center of the station pair, S_i and Tr_i, which averaged between 26.7 and 26.8 σ_θ. The salinity, $\overline{S}$, is calculated by the following formula:

$$\overline{S} = \sum_{i=1}^{N} S_i \,\mathrm{Tr}_i \Big/ \sum_{i=1}^{N} \mathrm{Tr}_i ,$$

where we choose N station pairs in which the velocity across the station pair is over 5 cm s^{-1} along the Kuroshio Extension for each section (Fig. 3a) because velocity is the most dominant factor contributing to $\overline{S}$ and the contribution of other station pairs is negligible. This salinity value $\overline{S}$ corresponds to the salinity that results if the water that passed through the section completely mixed along the isopycnal layer downstream. Because this calculation considers transport, the salinity of the largest transport contributes most to the resulting salinity.

Figure 5 shows the salinity values $\overline{S}$ for 26.7–26.8 σ_θ from the section off Cape Nojima to 151°E. Toward the east $\overline{S}$ was reduced because of merging between Type I and Type IV waters. From section to section $\overline{S}$ greatly varied, which reflects active eddies and unstable features around the strong jet of the Kuroshio Extension.

In the western two sections, the salinity is higher than 34.2 psu, indicating Type I water. This is because the Kuroshio Extension has not yet converged with Oyashio water. After meeting the low salinity Type IV water near the Oyashio coastal branch, the salinity decreased in the 142°45′E section. In the 143°30′E section, a low salinity patch ($S \sim 33.6$ psu) existed in and south of the Kuroshio Extension (Fig. 3b); thereby $\overline{S}$

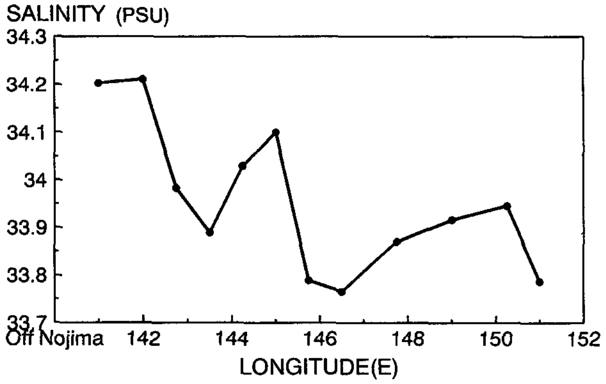

FIG. 5. Salinity values in the $\sigma_\theta = 26.7$–26.8 layer for each section across the Kuroshio Extension, assuming isopycnal mixing between the Oyashio and Kuroshio waters near the Kuroshio Extension when volume transports of each water are considered. CTD stations are denoted by circles in Fig. 3a.

was further reduced. The $\bar{S}$ increased in the 144°15′E and 145°E sections where low salinity patches were not found. In the 145°45′E section, the penetration of low salinity water, which had flowed southward along the Oyashio branch, was seen (Fig. 3a); thus $\bar{S}$ was significantly reduced. In the section east of 145°45′E, the Type IV water flows eastward along the Kuroshio Extension (Fig. 3b). Type IV waters were seen south of the Kuroshio Extension in the area of 35°–37°N and 150°–152°E (Fig. 3a), which causes low salinity value $\bar{S}$ in the 151°E section.

Further penetrations of low salinity Type IV water as seen along the offshore Oyashio branch in the 145°45′E section were not observed east of 146°E. Without new low salinity water penetration, $\bar{S}$ would approach a constant value that is the salinity of water produced due to isopycnal mixing along the Kuroshio Extension. However, $\bar{S}$ is not constant in the section 146°–151°E, probably because the eastward low salinity intrusion along the Kuroshio Extension is not laminar but patchy. In order to get a reliable estimate of salinity produced due to the isopycnal mixing along the Kuroshio Extension, we took the mean of six meridional sections from 145°45′E to 151°E where low salinity water through the Oyashio branch intruded along the Kuroshio Extension. The mean salinity was 33.85 psu, being less than Type II and III waters. Thus, this salinity is consistent with the idea that the merger of Type I and IV waters along the Kuroshio Extension produces Type II and III waters, which are distributed throughout most of the subtropical gyre, even when vertical diffusion somewhat increases the NPIW salinity.

c. *Salinity minimum formation along the Kuroshio Extension*

We applied the same calculation procedure to the other isopycnal layers (Fig. 6) in which the density interval in each layer is 0.1 σ_θ for 12 sections from off Cape Nojima to 151°E to get salinity profiles (broken lines) for each section. Volume transports across the sections for 0.1 σ_θ intervals are also shown in Fig. 6 (solid lines).

The salinity profile across the section off Cape Nojima (Fig. 6a) is similar to the Type I water profile (Fig. 4), defined as old NPIW by Talley et al. (1995). The transport (Sv $\equiv 10^6$ m^3 s^{-1}) for 26–26.4 σ_θ [~1.5 Sv for each 0.1 σ_θ interval] is larger than that for 26.5–27.2 σ_θ (0.5–0.8 Sv). The transport for 26–26.4 σ_θ is similar to that in other sections except for the 150°25′E and 151°E sections in which the station coverage was not enough. At 142°E section (Fig. 6b), the salinity is slightly reduced and the transport increased to 0.8–1.5 Sv for 26.4–27.2 σ_θ, compared with the section off Nojima. This might be due to the addition of low salinity Oyashio water.

In the three sections from 142°45′E to 144°15′E, low salinity water input is apparent and the salinity is considerably reduced for 26.4–27.2 σ_θ (Figs. 6c–e). The salinity profiles are variable between these three sections; while the transport profiles are similar with respect to the maximum transport (about 2 Sv) near 26.5–26.7 σ_θ. Note that double salinity minima are seen at 26.55 σ_θ and 26.85 σ_θ for the 142°45′E and 144°15′E sections, respectively, and that a salinity minimum occurs at 26.75 σ_θ for the 143°30′E section. At 145°E section (Fig. 6f), the transport is significantly reduced for 26.5–27.2 σ_θ and the salinity increases.

In the two sections, 145°45′ and 146°30′E, where low salinity Type IV water penetration is seen (Fig. 3), a transport maximum (~2.5 Sv) and a salinity minimum (~33.65 psu) emerge at 26.6–26.7 σ_θ. The salinity reduction and transport increase is due to the addition of Oyashio Type IV water. In the 147°45′E and 149°E sections, both salinity and transport profiles are more smooth compared with the previous sections. The center of the salinity minimum and transport maximum is shifted to 26.75 σ_θ.

The salinity profile average taken for the six profiles from 145°45′E to 151°E is given in Fig. 7. For comparison a Type III water profile, defined as new NPIW by Talley (1993), is also shown. These sections are averaged because each salinity profile is variable and no further low-salinity water penetration was seen after 145°45′E. Salinity minimum structure is reasonably reproduced although the salinity is lower than that of Type III water for 26.5–27 σ_θ and the salinity minimum density (26.65 σ_θ) is slightly less than in Type III water. This suggests that the salinity minimum structure can be created in the process of water modification along the Kuroshio Extension. In order to further clarify the method of NPIW formation along the Kuroshio Extension, we next trace the source water column structures in the Kuroshio off Cape Nojima and the Oyashio branches.

d. *Vertical structures in the source water before NPIW formation*

Here we examine the vertical structures of water columns of the Kuroshio and the Oyashio branches that have not yet merged along the Kuroshio Extension. Stations with arrows in Fig. 3a are used to show the vertical structures. Through these stations, the Oyashio and Kuroshio waters enter into the Kuroshio–Oyashio interfrontal zone. Figures 8a and 8b show the vertical profiles of the salinity and geostrophic velocity (referring to 1000 dbar) in the Oyashio coastal branch (O1), the Oyashio near 38°15′N, 144°–145°E (O2), and the Kuroshio off Cape Nojima (K). The salinity in the Oyashio coastal branch (O1) is lowest near the surface and increases with depth; the salinity in the Kuroshio is highest for 0–200 dbar, decreases to 600 dbar, and

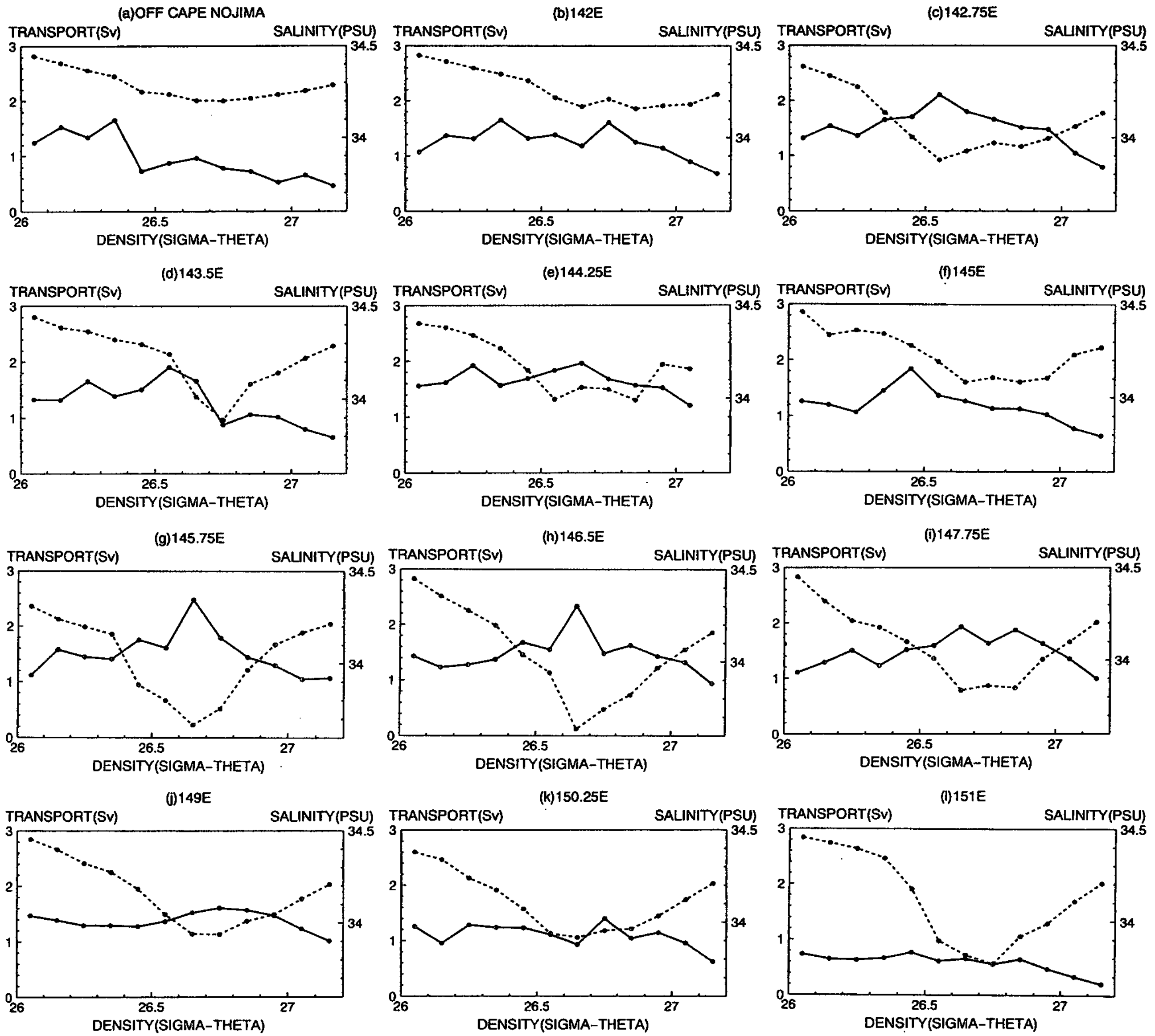

FIG. 6. Volume transport and salinity across the sections from Cape Nojima to 151°E (denoted by circles in Fig. 3a) along the Kuroshio Extension. The transports are in the interval of 0.1 σ_θ and are referred to 1000 dbar. The salinity profiles were calculated by the same procedure as in Fig. 5.

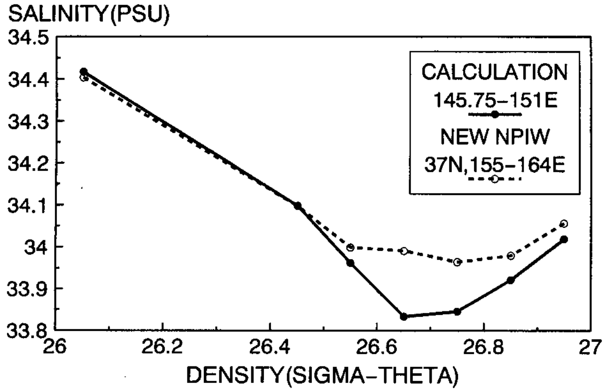

FIG. 7. Mean salinity profile along the Kuroshio Extension (solid line) calculated with the same procedure as in Fig. 5 and Type III water profile (broken line) for the various density layers. The mean was taken for the six sections of 145°45′–151°E. The density range of 26.6–26.8 σ_θ can be a consistent salinity minimum by assuming the isopycnal mixing near the Kuroshio Extension.

increases with depth for more than 600 dbar. The geostrophic velocity profiles are different between the Kuroshio and Oyashio branches: in the Oyashio branches, the velocities are significantly smaller compared with the Kuroshio for 0–400 dbar. The speed in the Oyashio branch slowly decreases with depth; the Kuroshio speed rapidly decreases with depth below 200 dbar.

Figures 8c, 8d, and 8e show the salinity, layer thickness, and volume transport for density profiles for the sections through which the Kuroshio (KI) and the Oyashio (OI and OII) waters enter the area near the Kuroshio Extension (sections KI, OI, and OII are shown in Fig. 2). The salinity and layer thickness are averaged in 0.1 σ_θ intervals. In the salinity profiles (Fig. 8c), the salinity increases as density in the 26–27.2 σ_θ in the Oyashio coastal branch (OI); while the salinity in the Kuroshio shows a salinity minimum near 26.85 σ_θ. The salinity through the OII section is slightly higher in 26–26.5 σ_θ than in the Oyashio coastal branch.

The layer thickness profiles (Fig. 8d) indicate the important differences between the Kuroshio and the Oyashio. For 26.5–27.1 σ_θ, the thickness in the Oyashio branches (OI and OII) is larger than in the Kuroshio. In contrast, the layer in the Kuroshio is thicker than in the Oyashio branches for 26–26.4 σ_θ. These are probably because the Okhotsk Sea outflow increases the layer thickness in the Oyashio branches and the subduction in the outcrop regions in the northern edge of the subtropical gyre (Nakamura 1996) contributes to the layer thickness of the Kuroshio.

For the volume transport profiles (Fig. 8e), the Kuroshio transport is largest, especially in the 26–26.4 σ_θ. For 26.5–27.2 σ_θ, Kuroshio transport is not dominant but is comparable to the Oyashio transport. The percentage of the Kuroshio transport (KI) over the transport (KI + OII) is 65% and the Oyashio transport (OII) is 35% for 26.7–26.8 σ_θ. Although transport calculations are sensitive to the selection of stations and reference levels, this ratio roughly coincides with the mixing rate of new NPIW in the 152°E estimated by Talley et al. (1995).

We estimated the salinity profile using the assumption that waters through the two sections of KI and OII are isopycnally mixed as shown in Fig. 8f. The estimate is carried out using the same procedure as in the previous subsection. Salinity minimum structure is again reproduced. This salinity profile is consistent with the salinity profile of Type III water, defined as new NPIW by Talley (1993) and Talley et al. (1995), although the salinity minimum density and salinity are not exactly coincident.

Thus the isopycnal mixing between the Kuroshio and the Oyashio source waters can produce a salinity minimum structure similar to the one seen in the Kuroshio–Oyashio interfrontal zone, where the mixing rate is restricted by the transport of each source of water in which the Kuroshio and Oyashio waters have different vertical velocity and salinity structures. In the density range less than the NPIW density, the Kuroshio high-salinity water is dominant. While in the range larger than NPIW density, the Oyashio and Kuroshio waters are comparable and the salinity of both of the two waters increases with density. As a result, a salinity minimum is created in an intermediate layer.

e. *Eastward volume transport of new NPIW formed along the Kuroshio Extension*

To discuss the relative importance of NPIW formation sites and processes, we need to trace back the complete paths of the new NPIW (Type II and III waters) to their formation sites. Unfortunately, we cannot do that because of the lack of data in the area of 30°–36°N, 155°E–180° where new NPIW (Type II and III) bifurcate into the interfrontal zone (Type III) and the recirculation zone of the subtropical gyre (Type II) from the Kuroshio Extension region. One way to estimate the relative importance is to compare volume transports of new NPIW formed at various formation sites and processes. Here we estimate the transport of new NPIW formed along the Kuroshio Extension.

Figure 9 shows the volume transports across the meridional sections from 142° to 150°15′E and the one off Cape Nojima (see Fig. 3a) for the density range of 26.6–27.2 σ_θ referred to (1000, 1500) dbar and for 26.6–27.5 σ_θ referred to 1500 dbar.

From the transport for 26.6–27.2 σ_θ referred to 1000 dbar, the transport of old NPIW across the section off Cape Nojima is 4.1 Sv. With the addition of Oyashio water, the transport increases to 6–8 Sv for 142°–145°E. Further penetration of the Oyashio water near 145°45′E enhances the transport up to 8–11 Sv for 145°45′–149°E.

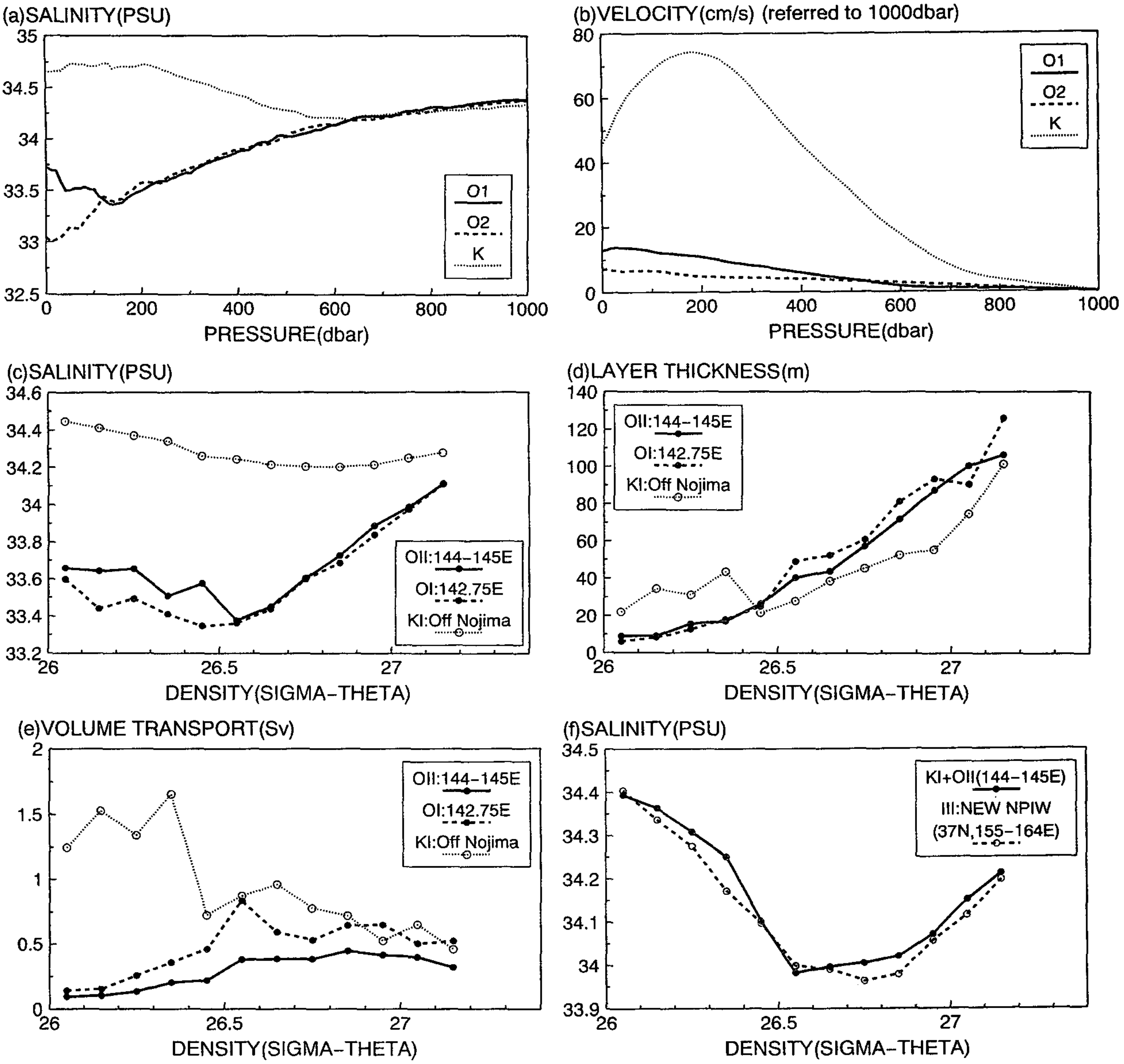

FIG. 8. Vertical profiles of the source water columns in the Kuroshio, the Oyashio coastal branch, and the Oyashio in the offshore area. (a) Salinity vs pressure. The profile was averaged between the station pairs denoted by the arrows in Fig. 3a. K: in the Kuroshio Extension off Cape Nojima. O1: in the Oyashio coastal branch in the 142°45′E section. O2: in the Oyashio branch in 38°15′N and 144°–145°E. (b) *Geostrophic velocity referred to 1000 dbar vs pressure. (c) Salinity vs* σ_θ. *The profiles were averaged for 0.1* σ_θ *interval and for the stations* denoted by squares and letters (OI, OII, and KI) in Fig. 2. (d) Layer thickness vs σ_θ. (e) Volume transport vs σ_θ. (f) The salinity vs σ_θ when the waters from the Kuroshio (KI) and the Oyashio in 144°–145°E (OII) are isopycnally mixed. The broken line denotes the Type III water salinity profile for comparison.

The rapid decrease across 150°25′E section might be caused by the insufficient coverage of the section. The transport of new NPIW formed along the Kuroshio Extension can be estimated as an average value between three sections from 146°30′ to 149°E to be (9.5, 13.2) Sv for 26.6–27.2 σ_θ referred to (1000, 1500) dbar and 17.8 Sv for 26.6–27.5 σ_θ referred to 1500 dbar.

Compared with the estimate by Talley et al. (1995) for the eastward transport of Type III water out of the mixed water region across 152°E (6.1 Sv for 26.65–27.4 σ_θ referred to 2000 dbar), the transport of new NPIW formed along the Kuroshio Extension (17.8 Sv for 26.6–27.5 σ_θ referred to 1500 dbar) is much larger, suggesting that new NPIW formation

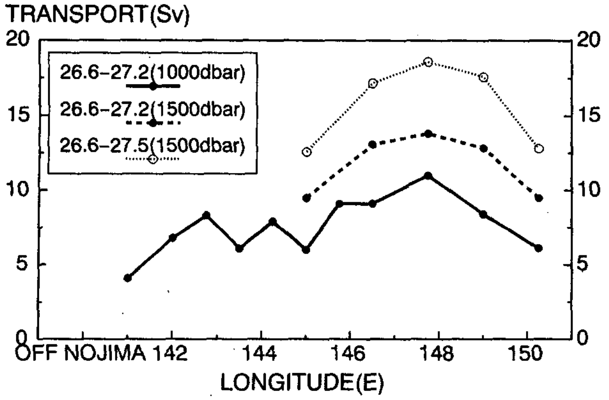

FIG. 9. Volume transport across the sections from Cape Nojima to 151°E in intermediate layers. The sections and CTD stations are indicated by circles in Fig. 3a.

along the Kuroshio Extension is enough to maintain Type III water widely distributed in the Kuroshio–Oyashio interfrontal zone. The rest of the transport (11.7 Sv) might feed Type II water south of the Kuroshio Extension where the southwestward subtropical recirculation gyre exists.

6. Isopycnal potential vorticity distribution

A conservative property independent of salinity and temperature that also shows water characteristics is potential vorticity, which is defined here as $Q = \rho^{-1} f \partial\rho / \partial z$. Isopycnal Q distributions along 26.7–26.8 σ_θ are shown in Fig. 10. Compared with the isopycnal salinity distribution (Fig. 5a), Type I and II waters have a relatively high Q value [$15\text{–}30(\times 10^{-11}\ \mathrm{m^{-1}\ s^{-1}})$]. The highest Q value is found in the crests of the meandering Kuroshio Extension, where the anticyclonic curvature of the Kuroshio jet (with a negative relative vorticity) might contribute to the Q value from a conservation of absolute potential vorticity (Yoshimori 1994).

Type IV water distributed in the coastal and offshore Oyashio branches and along the edge of the Kuroshio Extension has low Q value [$8\text{–}15\ (\times 10^{-11}\ \mathrm{m^{-1}\ s^{-1}})$]. That is, Type IV water is vertically thicker than the other waters as also shown in section 5d. We found the lowest Q area along the east coast of Japan in the Oyashio coastal branch. Talley (1993) discussed the isopycnal potential vorticity and indicated the existence of low Q water in the Okhotsk Sea and along the Kuril Islands and Hokkaido. Talley attributes the low Q water to the relative vorticity. However, the relative vorticity cannot greatly change the potential vorticity. For instance, even if the horizontal velocity

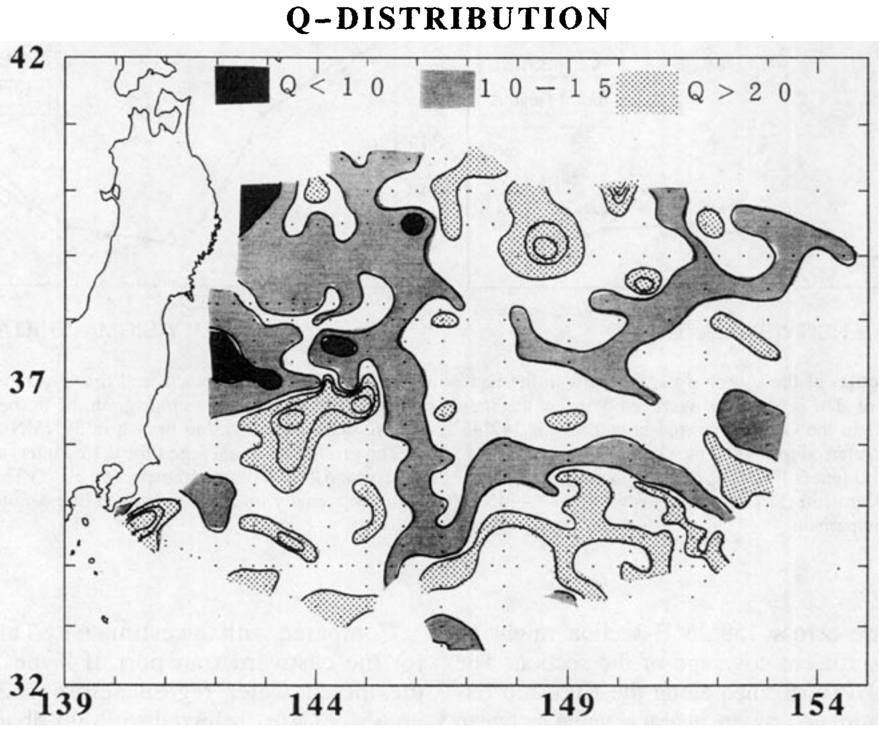

FIG. 10. Potential vorticity distribution, defined as $Q = \rho^{-1} f \partial\rho/\partial z$ ($10^{-11}\ \mathrm{m^{-1}\ s^{-1}}$), along the isopycnal surface of 26.7–26.8 σ_θ. Contour interval is $5 \cdot 10^{-11}\ \mathrm{m^{-1}\ s^{-1}}$.

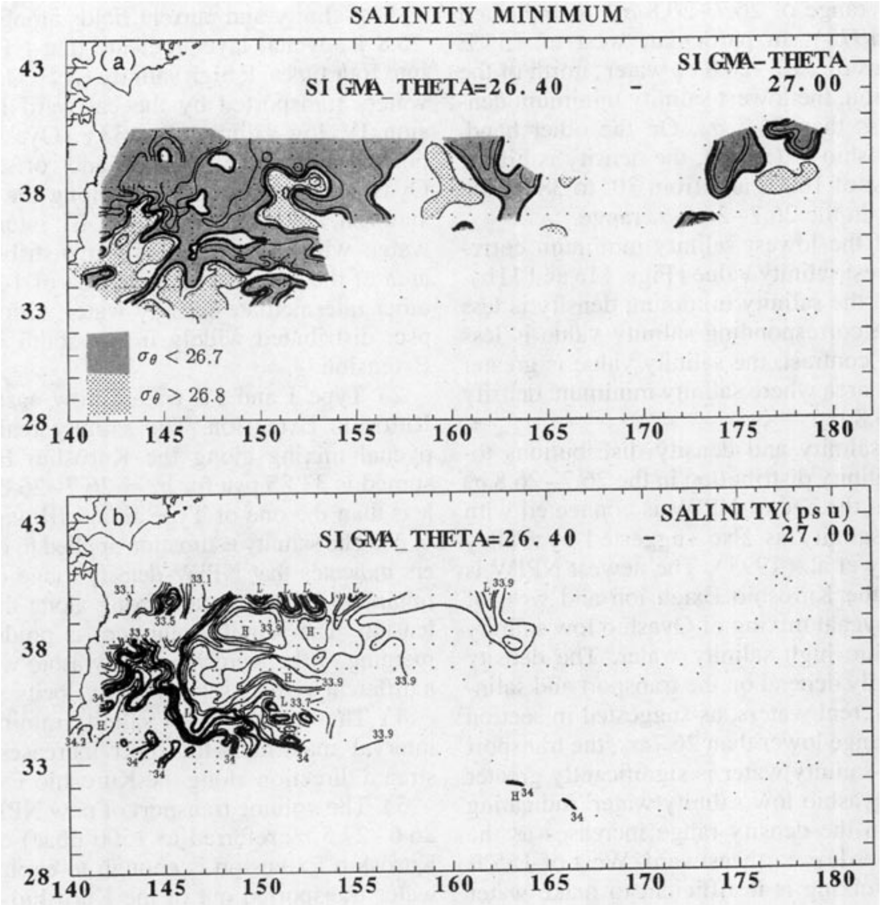

FIG. 11. Density (a) and salinity (b) distribution at the lowest salinity within the density range of 26.4–27 σ_θ. Contour intervals are 0.1 σ_θ (a) and 0.1 psu (b).

shear is 1 m s^{-1}/50 km, typical in the Kuroshio strong current regions, the relative vorticity is only 20% of the Coliolis parameter. Hence, relative vorticity can alter at most 20% of the present Q value. This change does not alter the fundamental distribution of the low-Q water distribution.

The low Q water in the Okhotsk Sea (Talley 1993) suggests the ventilation in the Okhotsk Sea. The low Q, Type IV water distribution in the Kuroshio–Oyashio interfrontal zone suggests that the ventilated water outflowing from the Okhotsk Sea flows southwestward along the Kuril Islands, the southeast coast of Hokkaido, and along the east coast of Honshu. The originally low Q waters are probably modified by horizontal and/or vertical mixing with high Q (Type I) waters and the Q value is increased as it flows eastward along the Kuroshio Extension. This low Q water injection into the subtropical gyre and NPIW formation imply that the primary cause of the salinity minimum is the sinking in the Okhotsk Sea as Wüst (1930) suggested.

In the area where Type III water is distributed, Q is relatively uniform at a value of 15–20 ($\times 10^{-11}$ m^{-1} s^{-1}). Type III water has intermediate characteristics between Type (I, II) and Type IV waters, supporting the results in section 4. Some low Q tongues of water with a Q of 8–15 ($\times 10^{-11}$ m^{-1} s^{-1}) are found in the Type III water region. The one in the area of 37°–40°N, 147°–155°E closely corresponds to low salinity water with a salinity of less than 33.9 psu that intruded from the Oyashio Front and suggests a mechanism for the freshwater supply across the Oyashio Front.

7. Density and salinity distribution at the lowest salinity for 26.4–27 σ_θ

A density contour map of the lowest salinity within the range of 26.4–27 σ_θ is shown in Fig. 11a, in which there might not be a salinity minimum in the region where the density is very close to 26.4 σ_θ. The density showing the lowest salinity minimum varied greatly beyond the density range of 26.7–26.8 σ_θ, as indicated by Hasunuma (1978). In particular, west of 155°E there are few areas of 26.7–26.8 σ_θ water; north of the Kuroshio Extension, the lowest salinity minimum density is mostly less than 26.7 σ_θ. On the other hand, south of the Kuroshio Extension, the density is higher than 26.8 σ_θ. East of 160°E and from 30° to 38°N, the density is mostly in the 26.7–26.8 σ_θ range.

The density of the lowest salinity minimum correlates with the lowest salinity value (Figs. 11a and 11b). In the area where the salinity minimum density is less than 26.7 σ_θ, the corresponding salinity value is less than 33.9 psu; in contrast, the salinity value is greater than 34 psu in the area where salinity minimum density is greater than 26.8 σ_θ.

These lowest salinity and density distributions together with the salinity distribution in the 26.7–26.8 σ_θ range suggest that the age of NPIW is connected with the density and salinity as also suggested by Talley (1993) and Talley et al. (1995). The newest NPIW is formed north of the Kuroshio Extension and west of 155°E by the isopycnal mixing of Oyashio low salinity water and Kuroshio high salinity water. The density and salinity strongly depend on the transport and salinity of the two different waters, as suggested in section 5. In the density range lower than 26.7 σ_θ, the transport of Kuroshio high-salinity water is significantly greater than that of the Oyashio low salinity water, indicating that the salinity in the density range increases as the water flows eastward or northeastward. West of 155°E where isopycnal mixing is insufficient to make water of uniform salinity and the water property is mostly conserved, the salinity and density showing the lowest salinity varies from place to place. Before the water reaches 160°E, horizontal mixing makes the field uniform.

Vertical salinity diffusion modifies a salinity minimum density. The vertical salinity gradient is stronger in the lower density range of NPIW than in the higher range in the Kuroshio–Oyashio interfrontal zone. Thus, salinity is increased from the upper part of the salinity minimum. This suggests that the density and salinity gradually increase as the fluid circulates. This salinity and density increase will depend on the salinity values of high salinity waters superimposed on NPIW and on the vertical velocity shear. In the area south of the Kuroshio Extension and in the western boundary current region where both vertical velocity shear and salinity gradients are high, NPIW salinity and density significantly increase. This can be seen in Talley (1993).

8. Summary and discussion

North Pacific Intermediate Water (NPIW) in the Kuroshio–Oyashio interfrontal zone has been examined with multiship CTD data from May to June of 1992. The main results can be summarized as follows.

1) Salinity and current fields along the σ_θ = 26.7–26.8 isopycnal layer indicate that NPIW is classified into four types, I: high salinity ($S > 34.1$ psu) Kuroshio waters transported by the eastward Kuroshio Extension, IV: low salinity ($S < 33.8$) Oyashio waters transported along the coastal and offshore southward Oyashio branches and then along the eastward Kuroshio Extension west of 150°E, III: intermediate salinity waters with $33.9 < S < 34$ psu, distributed over a wide area of the interfrontal zone east of 148°E, and II: another intermediate salinity water with $34 < S < 34.1$ psu, distributed widely in the south of the Kuroshio Extension.

2) Type I and IV waters flow eastward along the Kuroshio Extension. The salinity realized if the isopycnal mixing along the Kuroshio Extension is assumed is 33.85 psu for σ_θ = 26.7–26.8. The salinity is less than the one of Type II and III waters.

3) The salinity estimation applied to other density layers indicates that NPIW density range can be a salinity minimum by isopycnal mixing along the Kuroshio Extension. The salinity minimum is produced due to the merging of the Kuroshio and Oyashio waters, which has a different vertical salinity and velocity structure.

4) The density of the salinity minimum and 0.1 σ_θ interval maximum transport increases in the downstream direction along the Kuroshio Extension.

5) The volume transport of new NPIW (17.8 Sv for 26.6–27.5 σ_θ referred to 1500 dbar) created near the Kuroshio Extension is enough to explain the Type III water transported out of the Kuroshio–Oyashio interfrontal zone [6 Sv by Talley et al. (1995)]. It is speculated that the rest (~12 Sv) feeds Type II water of the recirculation of the subtropical gyre. This suggests that the merger of I and IV waters along the Kuroshio Extension produces Type II and III waters, which are the dominant part of the subtropical gyre.

6) Isopycnal potential vorticity, Q, defined as $Q = \rho^{-1} f \partial \rho / \partial z$ along the NPIW density range, showed that Type IV water has a low Q value, I and II waters have high Q, and III water has intermediate Q values. The lowest Q distribution is seen along the east coast of Japan. This suggests that the origin of NPIW is ventilated waters from the Okhotsk Sea and that NPIW formation is a primarily density driven due to a sinking in the Okhotsk Sea.

7) The density at the salinity minimum varied greatly west of 155°E. In the area north of the Kuroshio Extension, the salinity minimum density is lower than 26.7 σ_θ; south of the Kuroshio Extension, the density is greater than 26.8 σ_θ. The density east of 155°E is in the range of 26.7–26.8 σ_θ.

Similar results to the present results of 1) and 7) were also found by Talley (1993) and Talley et al. (1995) based on historical data (Talley 1993) and synoptic data west of 145°E (Talley et al. 1995). In the present study, we have shown them very clearly with densely sampled synoptic data.

Figure 12 schematically shows the NPIW circulation and water modification pattern in the western North Pacific inferred from the present and previous studies. In the Okhotsk Sea wintertime ventilation through sea ice formation and vertical mixing makes the water fresh and lowers the potential vorticity (Q) in the NPIW density range. The freshwater originally comes from the excess precipitation over evaporation in the subpolar North Pacific region. The vertical mixing and convection brings the freshwater to a higher density range. The low Q water (Type IV water in the present study) outflows from the Okhotsk Sea and flows southwestward along the west coast of the Kuril Islands, Hokkaido, and Honshu. Since this current might have a component of a density-driven current due to the sinking in the Okhotsk Sea, this low Q and fresh water enters into the subtropical gyre from the subpolar gyre across the gyre boundary that separates the wind-driven subtropical and subpolar gyres.

When Type IV water meets the Kuroshio Extension (high salinity Type I water), which is primarily wind driven, just off the east coast of Japan, I and IV waters together flow eastward because the wind-driven circulation is more active than the density-driven southward current. The two waters mix rapidly along the isopycnal surface probably due to the instability of strongly nonlinear jets and eddies where ''Lagrangian (chaotic) mixing'' (e.g., Polvani and Wisdom 1990) very efficiently mixes waters around time-dependent jets and/or eddies.

Waters above and below the NPIW density range also mix near the Kuroshio Extension due to the similar process as that in the NPIW density range. The Oyashio water of lower density than in the NPIW range has a much lower salinity ($32.5 < S < 33.5$ psu), but it has nearly the same velocity as in the NPIW range. On the other hand, the Kuroshio water has a higher salinity ($34.2 < S < 34.9$ psu) and much larger velocity than in the NPIW range; mixed water therefore has a higher salinity than that in the NPIW density range. In the range of density lower than the NPIW, the salinities on both sides of the Oyashio and the Kuroshio increase with density and are higher than those in the NPIW range. Thus, mixed water has a salinity higher than in

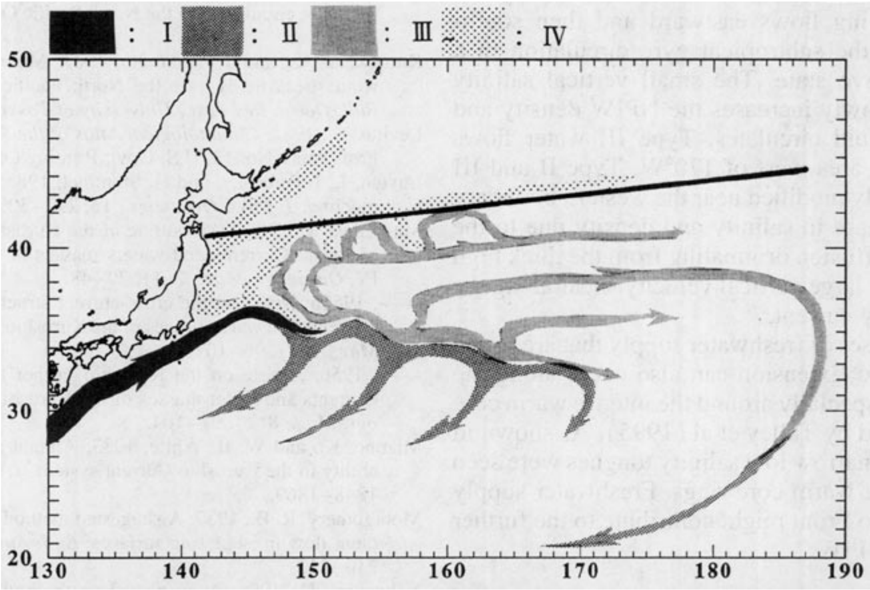

FIG. 12. Schematic representation for the NPIW circulation pattern and water modification, inferred from the present and previous studies. The thick line indicates the boundary separating wind-driven gyres estimated from the wind-stress field. The origin of fresh and low potential vorticity water in the NPIW is the ventilated water in the Okhotsk Sea. The low-salinity Type IV water outflows from the Okhotsk Sea and flows southwestward. The Type IV water meets Type I Kuroshio high-salinity water (the old NPIW) east of Japan. The two waters flow eastward along the Kuroshio Extension, producing Type II and III waters. Part of the modified water flows southwestward and becomes Type II water. The rest of the modified water flows northeastward and enters into the Kuroshio–Oyashio interfrontal zone and becomes Type III water. Near the Oyashio Front, phenomena similar to the one near the Kuroshio Extension might occur because of the high eddy activity. This might contribute to the further refreshment of NPIW. Type III water flows eastward and deflects southwestward as the recirculation of the subtropical gyre, increasing its salinity and density due to vertical diffusion.

the NPIW range. As a result, a salinity minimum develops due to the isopycnal mixing between the two waters with a vertically different salinity and velocity structure.

Part of this water is strongly modified near the Kuroshio Extension as it flows northeastward as a subtropical gyre circulation and enters the Kuroshio–Oyashio interfrontal zone (Type III water). A salinity minimum in the area west of 155°E north of the Kuroshio Extension is formed along with a density range lower than the typical NPIW range because isopycnal mixing processes do not yet make these waters horizontally uniform and also because Oyashio waters in the density range lower than the typical NPIW density are originally much less saline. Vertical salinity profiles in this area are complicated, and thus vertical diffusion must be actively occurring. The vertical salinity gradient is larger in the upper part of the NPIW than in the lower part; therefore, vertical diffusion is more active in the upper part of NPIW, whereby the density and salinity at the salinity minimum increases as the fluid circulates. Another part of this water is modified near the Kuroshio Extension and flows southeastward and then southwestward along the Kuroshio Extension and subtropical gyre recirculation (Type II water).

NPIW in the area east of 160°E after active isopycnal and vertical mixing flows eastward and then southwestward along the subtropical gyre circulation in a nearly nondiffusive state. The small vertical salinity diffusion very slowly increases the NPIW density and salinity as the fluid circulates. Type III water flows southward in the area west of 170°W. Type II and III waters are strongly modified near the western boundary and rapidly increase in salinity and density due to the strong vertical diffusion originating from the thick high salinity layer and large vertical velocity shear along the western boundary current.

Similar processes of freshwater supply that are found near the Kuroshio Extension can also occur along the Oyashio Front, especially around the intense warm core rings as suggested by Talley et al (1995). As shown in sections 4 and 7, narrow low salinity tongues were seen along the edge of warm core rings. Freshwater supply along the Oyashio Front might contribute to the further refreshment of NPIW.

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