NOTES AND CORRESPONDENCE

North Pacific Intermediate Water Transports in the Mixed Water Region

LYNNE D. TALLEY

Physical Oceanography Research Division, Scripps Institution of Oceanography, La Jolla, California

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ABSTRACT

Initial mixing between the subtropical and subpolar waters of Kuroshio and Oyashio origin occurs in the mixed water region (interfrontal zone) between the Kuroshio and Oyashio. The relatively fresh water that enters the Kuroshio Extension from the Mixed Water Region is this already mixed subtropical transition water. Subtropical transition water in the density range 26.64–27.4 σ_θ can be considered to be the newest North Pacific Intermediate Water (NPIW) in the subtropical gyre; this density range is approximately that which is ventilated in the subpolar gyre with significant influence from the Okhotsk Sea. Freshening of the Kuroshio Extension core occurs between 140° and 165°E in the upper part of the NPIW (26.64–27.0 σ_θ), with the greatest freshening associated with the eastern side of the first and second Kuroshio meanders. Kuroshio Extension freshening in the lower part of the NPIW (27.0–27.4 σ_θ) occurs more gradually and farther to the east. There is nearly no distinction in water properties north and south of the Kuroshio Extension by 175°W. The upper part of the NPIW in the Mixed Water Region progresses from very intrusive and including much freshwater in the west, to much smoother and more saline water in the east. The lower part of the NPIW in the mixed water region progresses from very intrusive and fresh in the far west, to noisy and more saline at 152°E, to smooth and fresher in the east. These suggest a difference between the two layers in both advection direction and possibly transport across the Subarctic Front. Assuming that all waters in the region are an isopycnal mixture of subtropical and subpolar water, the zonal transport of subpolar water in the subtropical gyre at 152°E is estimated at about 3 Sv (Sv $\equiv 10^6$ m^3 s^{-1}). This could be approximately one-quarter of the Oyashio transport in this density range.

1. Introduction

The primary formation site for the North Pacific's main salinity minimum, known as North Pacific Intermediate Water (NPIW), is in the mixed water region (MWR) in the far western Pacific (Hasunuma 1978; Talley 1993). At least three definitions of NPIW are current: the narrowly defined salinity minimum of the subtropical gyre; the entire isopycnal layer in the subtropical gyre, which is affected by input of water ventilated in the northwestern subpolar gyre and Okhotsk Sea; or this entire ventilated layer throughout the North Pacific including the subtropical and subpolar gyres. The last is the most inclusive and is appropriate for a full discussion of North Pacific ventilation. In this paper, the second definition is used—the subtropical layer that is ventilated from the north. ''New'' NPIW is considered to be the initial mixture of the ventilated subpolar water and the older subtropical water of the same density range.

Although the MWR lies between the separated Kuroshio and Oyashio Fronts, dynamically it is a part of the subtropical gyre since it lies south of the climatological zero Sverdrup transport (albeit north of the zero wind stress curl). The new NPIW ''formed'' in the MWR is a mixture of relatively fresh, recently ventilated Oyashio water coming from the subpolar gyre, and more saline, older Kuroshio water. The mixing process results in a salinity minimum and also in rejuvenation of the NPIW layer in the subtropical gyre due to the Oyashio input. Ventilation of the NPIW layer, defined broadly as the potential density range 26.65–27.4 or 27.6 σ_θ, takes place most directly in the Okhotsk Sea and Kuril Straits (Kitani 1973; Talley 1991; Wong et al. 1996, submitted to *J. Geophys. Res.*). Further ventilation of just the uppermost part of the NPIW (potential density around 26.7 σ_θ) might take place throughout the Oyashio region where the winter surface densities reach 26.65 σ_θ; mixing of this surface water with more saline Kuroshio waters results in up to a 0.1 σ_θ density increase due to cabbeling (Talley and Yun 1997, unpublished manuscript); density may also increase through double diffusive interleaving. Thus, the surface water from a region in the western North Pacific, which is larger in extent than the sinking region in the Okhotsk Sea, may also contribute to ventilation of the upper part of the NPIW.

Corresponding author address: Dr. Lynne D. Talley, Physical Oceanography Research Division, Scripps Institution of Oceanography, La Jolla, CA 92093-0230.
E-mail: ltalley@ucsd.edu

Talley et al. (1995) analyzed CTD data from spring 1989 in the mixed water region and suggested that the primary renewal site for the salinity minimum during that particular spring was entrainment of fresh, cold water of Oyashio origin by a warm core ring (WCR) composed primarily of Kuroshio water. The WCR was found just east of Japan near 37°N, 143°E, at a site where WCRs form from the first meander of the Kuroshio Extension after it separates from the western boundary. Many other observations in this region in other years show similar intrusions of fresh Oyashio water into a WCR (e.g., Mutoh 1982). Fresh intrusions are also observed regularly in the Kuroshio Extension itself; examples are presented in Talley et al. (1995) and Yasuda et al. (1996). However, because the NPIW observed north of the Kuroshio Extension in 1989 was considerably fresher than that in the Kuroshio Extension, because salinity minima at the NPIW density were found throughout the MWR, and because it appeared from the analyzed stations that pure Oyashio water (identified by a monotonic increase in salinity with depth from a surface minimum) is only occasionally found directly adjacent to the Kuroshio, Talley et al. (1995) suggested that initial formation of the salinity minimum water type occurs primarily in the MWR rather than in the Kuroshio Extension.

Eastward transport of new NPIW out of the MWR, using data only from north of the Kuroshio Extension, was estimated at 6.1 Sv for 26.65–27.4 σ_θ referenced to 2000 dbar (Talley et al. 1995). Because there are only two source waters in this density range in the MWR (i.e., subpolar water from the Oyashio and subtropical water from the Kuroshio), it was possible to estimate a contribution of 3 Sv of subpolar water to the new NPIW being advected eastward. It was then assumed that this was the net transport of subpolar water into the subtropical gyre's MWR. This was erroneous and potentially an underestimate because it ignored the Oyashio origin water in the Kuroshio and recirculation. An error in the assignment of transport to isopycnal layers resulted in a slight overestimate in the previous calculation. The new calculation presented below corrects the programming error and includes the Kuroshio and recirculation; the result is essentially unchanged from that in Talley et al. (1995) but is now based on correct assumptions and calculations.

Yasuda et al. (1996) suggested that the primary formation site for new NPIW is intrusion of freshwater into the Kuroshio Extension based on their May–June 1992 survey of the mixed water region and Kuroshio Extension. They showed that the Kuroshio Extension freshens downstream due to entrainment of fresher water from the north. They noted that the new NPIW transport is larger in the Kuroshio Extension than in the mixed water region, obtaining a total transport of 17.8 Sv for 26.6–27.5 σ_θ referenced to 1500 dbar. They attributed the existence of a renewed salinity minimum in the MWR to detrainment toward the north from the Kuroshio Extension and net westward transport in the MWR.

The datasets used below were the basis of our previous conclusion that the newest NPIW between the Kuroshio Extension and subarctic front originates in the MWR rather than within the Kuroshio Extension. This region, including the Kuroshio Extension, is extremely active, and mixing between the subpolar and subtropical waters can occur in a number of places and is likely to be very time dependent; thus, particular conclusions regarding the formation ''site'' may be dataset dependent. However, this dataset suggests that most direct mixing between pure subpolar and subtropical waters occurs within the MWR and that most of the freshening of the Kuroshio Extension core is from this already-formed ''new'' NPIW. The Kuroshio Extension mixtures themselves then enter the MWR through additional warm core ring-shedding; westward movement of the rings brings the mixtures to the west. However, the net transport in the MWR is eastward, at least in the upper layers, and MWR salinity progresses generally from lowest in the west to highest in the east, suggesting that the origin of the new NPIW is near the western boundary rather than along the Kuroshio Extension.

The next section describes the evolution of salinity from west to east north of, in, and south of the Kuroshio Extension; it appears that the upper and lower parts of the NPIW layer, divided at about 27.0 σ_θ, exchange and mix differently. In the final section, the transport of Oyashio water into the subtropical gyre is estimated using zonal transports across 152°E, and including the Kuroshio and its recirculation as well as the eastward flow between the Kuroshio and subarctic front. Meridional transports from a section at 24°N show negligible meridional transport of Oyashio water in this box balance.

2. Salinity in the NPIW layer in the mixed water region and Kuroshio Extension

The principal water masses of the mixed water region were defined similarly by Talley et al. (1995) and Yasuda et al. (1996). Figure 1, after Talley et al., shows the average potential temperature–salinity profiles for waters of subpolar and subtropical origin. The former is relatively fresh at low density, with salinity increasing monotonically with depth and increasing density. (Stations from the Oyashio east of Hokkaido from spring 1989 were used for the average.) The subtropical water is saltier and warmer at all densities and has a characteristically smooth salinity minimum around 26.8 σ_θ, called the NPIW salinity minimum. In the MWR, where these two waters mix together, the average potential density–salinity profile falls about halfway between. This mixed water mass was called ''subtropical transition water'' in Talley et al. (1995), who also identified it as the ''new'' NPIW for the subtropical gyre. We showed that the fraction of subpolar water in the sub-

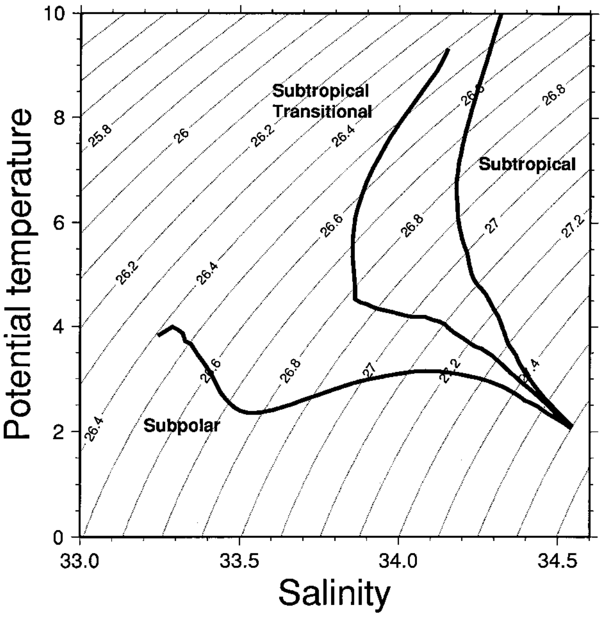

FIG. 1. Average profiles of potential temperature vs salinity for three dominant water masses in the mixed water region: subtropical (most saline Kuroshio stations just near the coast of Japan), subpolar (fresher water in the Oyashio), and subtropical transition water (mixed water in the mixed water region). Two other water masses in Talley et al. (1995) are not included here: subpolar transition water, which occupies a much smaller part of the mixed water region than subtropical transition water, and Tsugaru Water, which occurs in a lower density range than that of interest in this note. The profiles were obtained from averaging CTD profiles collected in April 1989 (Talley et al. 1995).

tropical transition water of the MWR is about 0.45 through the density range 26.65 to 27.4 σ_θ, falling markedly at lower and higher densities.

Stations in the Kuroshio at 144°E, just downstream of its separation point, were used to define the ‘‘Kuroshio water.’’ The Kuroshio core at the separation point is more saline than this (Fig. 4). This results in a slight underestimate of the amount of Oyashio water in the various mixtures through the rest of this paper. These 144°E stations are especially too far east to be used as an end-member for waters denser than 27.4 σ_θ.

Subtropical transition water is characterized by a broad salinity minimum at about 4.5°–6.0°C, 33.8 psu, and 26.6–26.8 σ_θ (Fig. 1). Most individual station profiles in the far western MWR are more complicated than this smooth profile, with large vertical contrasts between interleaving layers of subtropical and subpolar water. In the eastern part of the MWR (east of about 150°E), many stations resemble the subtropical transition water.

The average subtropical and subpolar profiles of Fig. 1 can be used to calculate the fraction of subtropical or subpolar water at every location in the northwestern subtropical gyre since there is no other surface source of water at densities greater than 26.6 σ_θ. CTD stations from a set of meridional sections at 144°E, 152°E, 165°E, and 175°W are used, as in Talley (1993) and Talley et al. (1995).

Four zones are considered in the meridional direction: 1) south of the Kuroshio, 2) the Kuroshio Extension core, 3) the mixed water region between the Kuroshio Extension and the Oyashio, or Subarctic Front, and 4) north of the Subarctic Front. The Kuroshio Extension core was defined by the strong eastward flow, which was easily distinguished from the westward recirculation to the south and weak circulation to the north. The Subarctic Front was defined by the large jump in temperature–salinity properties across it.

Within the Kuroshio Extension core at 144°E are found the saltiest waters. These come from lower latitudes where the effect of surface evaporation raises salinities on nonoutcropping isopycnals through vertical diffusion. This effect is apparent from maps of salinity on isopycnals (e.g., Reid 1965); the salinification extends very deep (Talley and Johnson 1994) although it is unclear whether the increases in the very deepest waters are due to vertical diffusion from above, advection from the southern ocean, or hydrothermal activity from below (J. Reid 1995, personal communication). For the NPIW density range, the low latitude high salinity is due to diffusion from above. The Kuroshio Extension waters were used to define ‘‘subtropical’’ water in this analysis (Fig. 2, third row).

For 26.64–27.0 σ_θ in the Kuroshio, relatively fresh intrusions are found at 152°E. Since the intrusions fall right on the dashed curve, they are not pure subpolar water but rather intrusions of new NPIW, matching the new NPIW in the MWR to the north. The overall envelope continues to freshen slightly toward 165°E and then becomes more saline at 175°W. Most freshening of the core occurs between the 144°E and 152°E sections. Yasuda et al.'s (1996) analysis at 26.7 σ_θ showed a source of freshening in 1992 to be a streamer of relatively fresh water from the MWR entering the Kuroshio core on the offshore side of the first meander or WCR at about 143°E; based on its salinity of 33.7, the streamer was similar to the intrusions shown here at 152°E, that is, of newly formed NPIW rather than pure subpolar water. Salinity and acceleration potential at 26.8 σ_θ from historical data (Fig. 4a) show rapid freshening along the Kuroshio core from separation at 140°E to about 146°E, hence associated with the first Kuroshio meander. A secondary injection of freshwater occurs on the eastern side of the second meander, at around 152°E. Thus, the Kuroshio meanders appear to be preferred sites of southward flux of new NPIW from the mixed water region.

In the denser layer, 27.0–27.4 σ_θ, the Kuroshio core salinity smoothly decreases from 144°E to 175°W (Fig. 2, third row). The pivot point between continuous eastward decrease and slight eastward salinification is somewhere between 26.9 and 27.0 σ_θ. A fresh intrusion of new NPIW is apparent on the 144°E section. On the isopycnal map (Fig. 4c) the high salinity west of 140°E does not reach the separated Kuroshio, but rather is

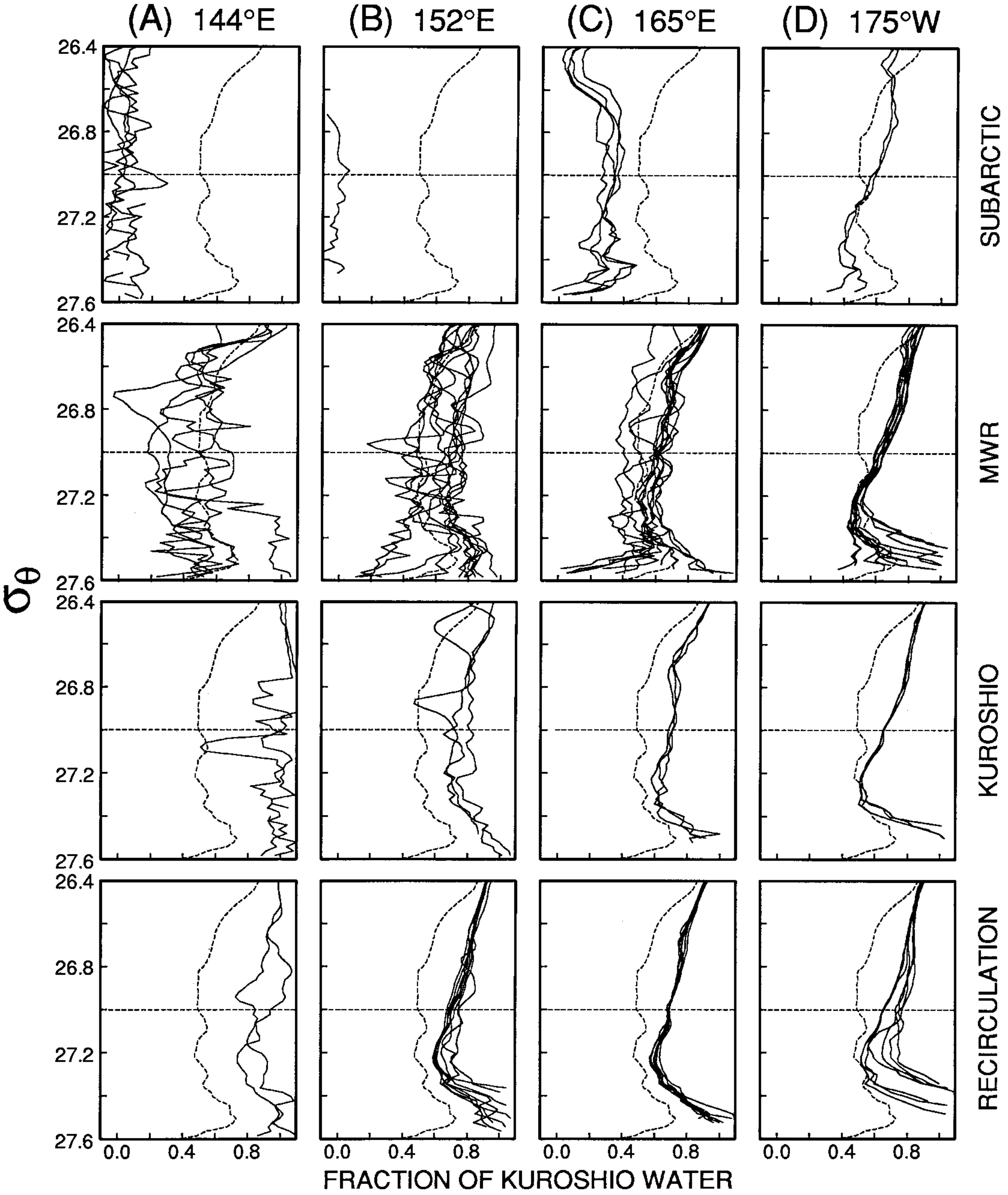

FIG. 2. Percentage of subtropical water for all CTD stations along four longitudes. The percentage was calculated assuming that all water is an isopycnal mixture of subtropical and subpolar water (Fig. 1) and is displayed rather than salinity because the salinity contrast between the source waters varies with density. The higher the percentage, the more saline the water at that density. Percentages are based on the temperature of the waters. Because of the nonlinear equation of state, the percentage of subtropical water is lower if calculated using salinity. The dashed curve in each panel is the percentage of subtropical water in the "subtropical transitional water," or new North Pacific Intermediate Water (Talley et al. 1995). Top to bottom rows are 1) in and north of the Subarctic Front, 2) between the Kuroshio Extension and the Subarctic Front, 3) in the Kuroshio Extension core, and 4) south of the Kuroshio Extension. (a) Stations at 144°E (Apr 1989) (Talley et al. 1995). (b) Stations at 152°E (Jun 1982) (Niiler et al. 1983). (c) Stations at 165°E (Sep 1984) (Joyce 1987). (d) Stations at 175°W (Nov 1983) (Joyce 1987).

associated with a closed anticyclonic circulation west of the Izu Ridge at 140°E (Fig. 4d).

In the recirculation region south of the Kuroshio, the most saline water occurs at the western end of the region at 144°E (Fig. 2, fourth row). This saline water is fresher than in the Kuroshio Extension, suggesting detrainment of freshened Kuroshio waters farther east with recirculation westward south of the Kuroshio Extension. In the upper 26.6–27.0 σ_θ layer, there is little contrast between 152°E, 165°E, and 175°W. Slightly fresher water is found at 165°E compared with 152°E and 175°W. Thus, freshening occurs mainly between 144°E and 152°E, as in the Kuroshio core freshening. At densities greater than 27.0 σ_θ on the other hand, the freshest stations are at 175°W, indicating continual freshening from 144°E to 175°W.

In the upper layer in both the recirculation and Kuroshio Extension, the freshest waters occurred at 165°E, especially in a small bulge between 26.6 and 26.8 σ_θ. It is possible that these 1984 data were influenced by a time-dependent injection of freshwater; on the isopycnal map (Fig. 4a) it looks like a meandering intrusion from the Subarctic Front. However, the same salinity structure was evident in the independent section at 165°E made in 1983 suggesting that the meandering is not uncommon. It might be associated with the eastern side of Shatsky Rise.

In the mixed water region (Fig. 2, second row), the upper layer becomes more saline on the whole toward the east. The fresh bulge in the upper layer at 165°E, evident in the Kuroshio profiles, is also present in these MWR profiles. In contrast, the lower layer is most saline at 152°E and then freshens by 165°E and more so by 175°W. This same structure is observed if alternate sections at 152°E (in 1981) and at 165°E (in 1983) are used. The amount of interleaving (vertical structure in the CTD profiles) decreases considerably in both layers toward the east.

North of the Oyashio (Subarctic) Front, waters at 144°E are the freshest and were the basis for the definition of subpolar water in this analysis. Toward the east, the waters north of the Subarctic Front become more saline. Thus, there is mixing across the Subarctic Front as well as across the Kuroshio Extension; thus some of the new NPIW, which is saltier than the subpolar water of the same density, escapes northward into the subpolar gyre immediately after being formed and probably continuously across the North Pacific. It is likely that there is an input of freshwater into the mixed water region all along the Subarctic Front; the amount is difficult to calculate because of the input of saline waters from across the Kuroshio Extension.

Finally, at 175°W, profiles at all stations south of the Subarctic Front—that is, south of the Kuroshio, in the Kuroshio and in the mixed water region—are similar, suggesting that mixing has occurred across the Kuroshio Extension and nearly eliminated the property differences between the three zones. Even profiles north of the Subarctic Front are much more similar to this mixed water than to subarctic water at the more western sections.

Thus, in the upper part of the intermediate water (26.6–27.0 σ_θ), subtropical transition water from the mixed water region freshens the Kuroshio between 144° and 152°E. Exchange between the Kuroshio core and its recirculation decreases the salinity south of the Kuroshio core toward the east. The recirculation water is advected westward and hence appears fresher than the Kuroshio at the westernmost locations. By 175°W the waters are nearly indistinguishable across the Kuroshio. Mixing across and detrainment from the Kuroshio also increases the salinity of waters north of the Kuroshio toward the east. There is also exchange with waters across the Subarctic Front since waters north of the Subarctic Front become more saline to the east.

In the lower part of the Kuroshio core and recirculation (27.0–27.4 σ_θ), the input of fresher water from the mixed water region occurs more gradually toward the east than in the upper layer. In the MWR, the freshest water is found at 144°E; the most saline water plus some fresher water is found at 152°E followed by overall freshening of the envelope toward the most mixed water in the east. This pattern could be consistent with eastward advection of increasingly mixed water, or with some input of fresher water from the subarctic toward the east. Some westward advection could be possible in the latter scenario and is suggested by the transport calculation of the section below, but the overall reduction in vertical structure toward the east suggests that most freshwater input and mixing occurs in the west. The temperature–salinity properties do not lead to an unambiguous description of the advection and mixing in this lower layer in the MWR.

Additional sections made in other years at 152°E and 165°E substantiate the spatial tendencies for salinity shown in Fig. 2. The nonsynoptic historical data used in Fig. 4 also fit these various meridional CTD sections. The strong time-dependence in this region appears to be mainly dynamical, moving waters around whose properties do not vary much. Mixing due to the time-dependent meandering and rings is an essential part of producing the observed water properties, but its net effect seems to vary little over the years.

The relatively fresh water entering the Kuroshio Extension and its recirculation is the new subtropical NPIW that is formed in the MWR. Thus, the Kuroshio and its recirculation must be considered when estimating the net amount of subpolar water entering the subtropical gyre.

3. Amount of subpolar water entering the subtropical gyre

Talley et al. (1995) may have underestimated the production rate of new NPIW and the transport of subpolar-origin water in the subtropical gyre because the Kuroshio and recirculation were not included in the transport calculation (Yasuda et al. 1996). Because the definition of ''new'' NPIW is arbitrary and differs from treatment to treatment, I focus here on the eastward transport of subpolar (Oyashio) water in the northern subtropical gyre in a density range that is not affected by local air–sea interaction, using the meridional sections employed in the previous section.

TABLE 1. Zonal transports ($\times 10^6$ m^3 s^{-1}) relative to 2000 dbar at 152°E (May 1981) for each layer and its subpolar component (Fig. 1).

Layer		South of Kuroshio stations 3–14	Kuroshio stations 14–18	North of Kuroshio stations 18–23	Total/2000 stations 3–23
26.64–27.0 σ_θ	All	−2.30	6.88	2.48	7.06
	subpolar	−0.68	2.12	1.01	2.46
27.0–27.4 σ_θ	All	−5.09	9.10	1.61	5.62
	subpolar	−1.99	2.37	0.41	0.79
26.64–27.4 σ_θ	All	−7.39	15.98	4.09	12.68
	subpolar	−2.67	4.50	1.43	3.25
27.4–27.6 σ_θ	All	−1.85	3.86	0.39	2.40
	subpolar	−0.10	0.41	−0.03	0.28

TABLE 2. Zonal transports ($\times 10^6$ m^3 s^{-1}) relative to 2000 dbar at 152°E (June 1982) for each layer and its subpolar component (Fig. 1).

Layer		South of Kuroshio stations 3–11	Kuroshio stations 11–14	North of Kuroshio stations 14–25	Total/2000 stations 3–25
26.64–27.0 σ_θ	All	−2.42	6.46	0.10	4.14
	subpolar	−0.62	1.88	−0.14	1.12
27.0–27.4 σ_θ	All	−3.00	6.47	−0.47	3.01
	subpolar	−0.96	1.83	−0.09	0.78
26.64–27.4 σ_θ	All	−5.42	12.94	−0.37	7.14
	subpolar	−1.58	3.71	−0.23	1.89
27.4–27.6 σ_θ	All	−1.53	2.24	−0.54	0.17
	subpolar	−0.06	0.23	−0.35	−0.18

The goal is to estimate how much subpolar water enters the MWR by using estimates of the transport of subpolar water out of a closed region bounded to the north by the Subarctic Front, to the east by an arbitrary meridional section, and to the south by a zonal section or simply an assumption that net southward transport of subpolar water across, say, 24°N is negligible. This method is chosen rather than a direct estimate of exchange since the input of Oyashio water into the MWR is sporadic and accomplished by streamers and rings spun off the meandering Oyashio Front. The central calculation is the sum of zonal transports of the subpolar fraction in the MWR (weak eastward flow), in the Kuroshio (strong eastward flow), and in the recirculation (westward flow). The eastern side of the box is chosen to be 152°E since there are several sections there, since it is close enough to the western boundary that loss of MWR subpolar component northward back across the subarctic front can be assumed small, and since it is far enough from the western boundary that most of the initial mixing between Kuroshio and Oyashio water has been accomplished. It is also close enough to the western boundary that additional, extensive vertical mixing might not be a factor compared with near-isopycnal mixing. The 1985 zonal section at 24°N is used to show that there is negligible transport southward out of the box. Because of the missing northern boundary, this is not a completely closed calculation, but it captures the important flows and relies on an assumption of minimal meridional flow.

The 152°E sections from May 1981 and June 1982 are used (Joyce 1987). The 1981 section extended from 27°45′ to 41°35′N with the Kuroshio between 33°50′ and 36°12′N. In 1982 the section extended from 27°45′ to 42°49′N with the Kuroshio between 32°28′ and 33°27′N. In 1982 there was a large warm core ring north of the Kuroshio. The 1981 section did not cross the Subarctic Front, but the northernmost station was presumably close to the front. The 1982 section crossed the Subarctic Front. The 24°N section from March–May 1985 (Roemmich and McCallister 1989) was used for meridional transport.

Transports were calculated relative to 2000 dbar for the layers 26.64–27.0 σ_θ and 27.0–27.4 σ_θ and for the total of the two layers (Tables 1 and 2 and Fig. 3). In this total layer, the percentage of subtropical water in subtropical transitional water is approximately 55% (Talley et al. 1995 and Fig. 2); the percentage rises above and below the layer. The upper density limit corresponds roughly to the maximum winter surface density in the western mixed water region (Talley et al. 1995). The

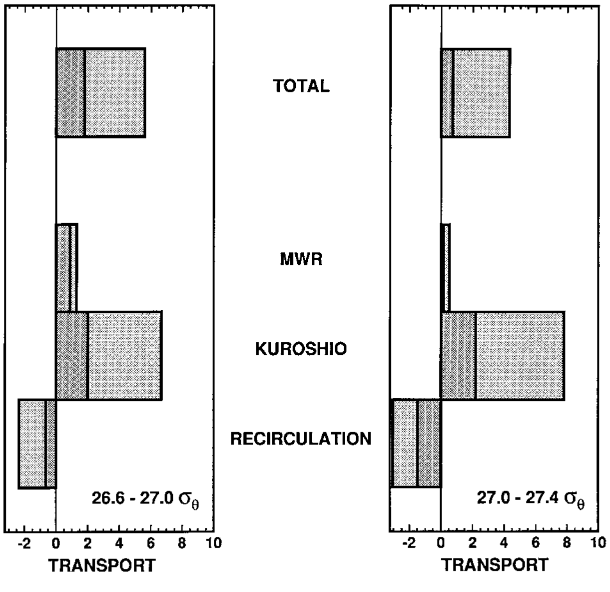

FIG. 3. (a) Transports relative to 2000 dbar in the upper isopycnal layer (26.64–27.0 σ_θ) at 152°E; dark shading indicates the Oyashio component of the total. The average of the 1981 and 1982 values given in Tables 1 and 2 is shown. (b) Transports as in (a) but for the lower isopycnal layer (27.0–27.4 σ_θ). MWR is the mixed water region. Stations used for the transports are listed in the tables. CTD profiles for the 1982 stations were shown in Fig. 2b; the MWR stations are in row 2, the Kuroshio stations in row 3, and the recirculation stations in row 4.

division at 27.0 σ_θ is based on the different salinity tendencies from west to east described in the previous section. The 2000-dbar level was chosen because many of the 1982 stations did not extend deeper than this. Sensitivity to reference level choice is discussed below.

The transport of subpolar (Oyashio) water at each station pair was estimated as a fraction of the total transport using the average potential temperature and salinity on isopycnals for the station pair and the average subtropical and subpolar profiles shown in Fig. 1. Serious errors are made if the station pair temperature and salinity are averaged at the same depth because of the steep rise in isopycnals across the Kuroshio. (These estimates are not valid for the densest layer 27.4–27.6 σ_θ since the reference profiles were actually fresher than the water south of the Kuroshio Extension in this density range, as can be seen in Fig. 2.)

Transports for 27.4–27.6 σ_θ were also calculated since this layer is freshened through vertical diffusion in the subpolar region. However, the direction of transport in this layer is more suspect than in the shallower two layers that lie mainly above 1000 dbar; Niiler et al. (1985) show zero net zonal transport at about 1000 dbar and Roemmich and McCallister (1989) at about 1500 dbar.

South of the Kuroshio, net layer transports were westward with strong westward recirculation just south of the Kuroshio decaying to much weaker westward flow at the southernmost stations pair. A fresh intrusion at the southernmost station of the Kuroshio in 1981 (Fig. 2b, bottom row) resulted in a 1 Sv (Sv $\equiv 10^6$ m^3 s^{-1}) difference in Oyashio water transport in the recirculation, with a higher value in 1981. It is not clear however that this subpolar water was really recirculating westward just south of the Kuroshio; one more station just to the south might have shown it to be within the Kuroshio and not extending into the recirculation.

The Kuroshio transport was large and eastward in both years and both layers. Transport in the upper layer in the mixed water region between the Kuroshio and Subarctic Front was eastward on both occupations. In the denser layer (27.0–27.4 σ_θ), MWR transport was eastward in 1981 but westward in 1982, probably as a result of the large warm core ring in 1982. This direction contrast might be responsible for the difference in property evolution from west to east described in the previous section.

Overall, there appears to be about 3 Sv of subpolar water being advected eastward relative to 2000 dbar in the northern subtropical gyre, which includes the mixed water region, the Kuroshio, and the westward recirculation region south of the Kuroshio. Twice as much subpolar water is advected eastward in the Kuroshio as in the MWR, but about half of this is recirculated westward south of the Kuroshio. The net eastward transport of subpolar water to regions farther east is about half in the Kuroshio and half in the MWR.

The ‘‘box’’ used to calculate the net exchange of subpolar water into the subtropical gyre in these layers consists of just the one meridional section. A zonal hydrographic section at 24°N closes the box on the south side. West of 152°E, the 24°N section is heavily dominated by eddies (Fig. 5) with zonal length scales of about 500 km and transport amplitudes of about 1–2 Sv (Hautala et al. 1994). The net meridional transport is probably close to zero but depends heavily on where the box edges are taken because of the eddy variability. There remains a 400-km meridional gap between the southern end of the 152°E sections at 27°45′N and 24°N through which there might be eastward flow. This is probably the biggest source of uncertainty in the exchange estimate. In their inverse calculation, Roemmich and McCallister (1989) show a net northward flow of 1.3 Sv west of 152°E in the layer 26.8–27.3 σ_θ. Of this, 4.8 Sv were flowing southward between 152° and 137°E; based on salinity (Fig. 4) this might be one-quarter Oyashio water, while the northward flow west of 137°E is nearly pure Kuroshio water. This might translate to 1–2 Sv of Oyashio water flowing southward from this western box, but it might be offset by missing westward flow in the gap between the 152°E and the 24°N sections.

It is emphasized that these subpolar water transports are all rather small numbers and subject to uncertainties in the reference velocity choices.

Niiler et al. (1985) meridionally and temporally averaged 2-yr current meter records at 1200 m and 4000 m along 152°E between 29° and 41°N. Combining their means with the hydrographic sections, they found meridionally averaged zonal transport of 0 at about 1000 m, with net westward flow from there to the bottom. When Roemmich and McCallister (1989) incorporated an approximation to Niiler et al.'s mean velocities in their inverse calculation for the North Pacific, their smoothed velocity section at 152°E showed a zero velocity level at around 1200–1500 m. So one error bound on the 2000-dbar calculation can be made by using a 1500-dbar reference level. This results in both a weaker Kuroshio and weaker recirculation and almost no change in the net subpolar water transport (Table 3).

Another bound uses rough values of velocity at 4000 m from Roemmich and McCallister's (1989) velocity section: about 1.5 cm s^{-1} westward at 35°N, decreasing to 0 at 42° and 28°N. This choice creates a stronger eastward Kuroshio and stronger westward recirculation; it also weakens the eastward MWR flow. The net result is a net eastward transport of subpolar water close to zero.

Using zero velocity at 4000 m, the recirculation and Kuroshio are strengthened as in the Roemmich and McCallister reference choice, but the MWR transport remains robustly eastward, and so the net transport of subpolar water is around 3 Sv.

In Talley et al. (1995), only the transport of subpolar water and subtropical transition water north of the Kuroshio were calculated. The new estimate of 3 Sv is similar to the old one, which was more roughly cal-

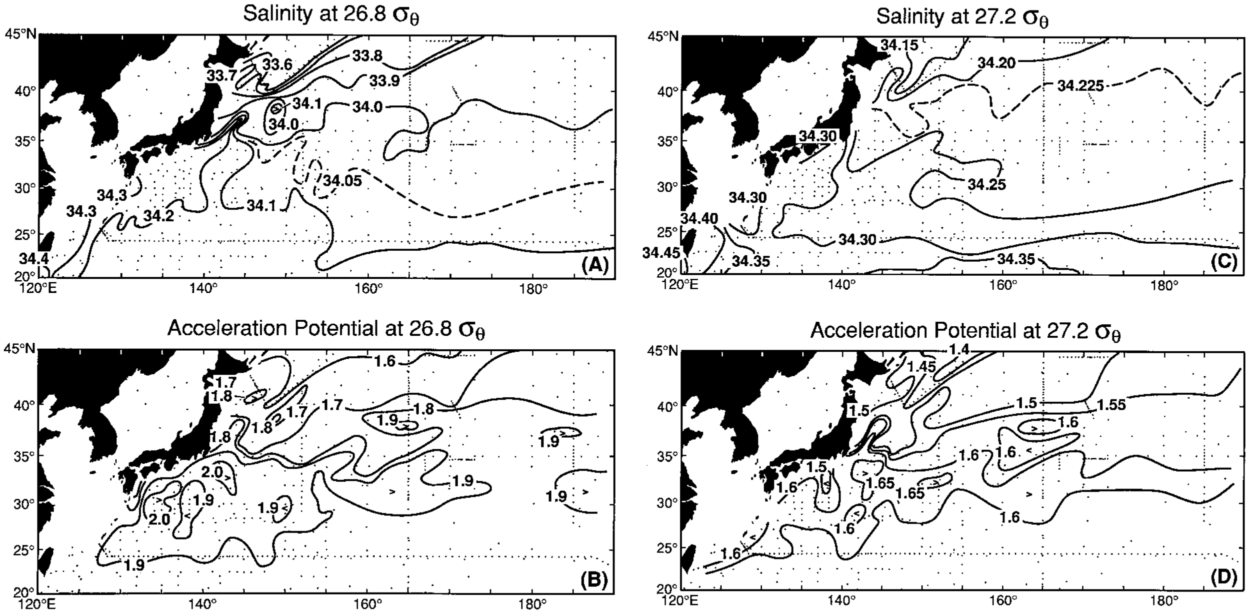

FIG. 4. Salinity (a) and acceleration potential (b) relative to 2000 dbar at 26.8 σ_θ. Salinity (c) and acceleration potential (d) relative to 2000 dbar at 27.2 σ_θ. Most stations are from the historical dataset compiled by Mantyla and Reid (1995, personal communication). Stations used for Figs. 1, 2, 3, and 5 are included.

culated. Less than one-third of the Oyashio's baroclinic transport in this density range enters the subtropical gyre at the western boundary. This southward transport of subpolar water is about half of the size of the southward Ekman transport from the subpolar to the subtropical gyre, but affects a higher density range than the Ekman layer.

Where does the subpolar water go after it enters the subtropical gyre? Since there is no surface source for high salinity at these densities, the low salinity must be eroded away, most likely by vertical diffusion downward from the high surface salinities in the evaporative trade wind zone. Highest salinities at these intermediate densities occur in the Tropics, as is clear from Reid's (1965) isopycnal maps, and are not coincident in space with the cells of highest surface salinity. The relative freshness of the subtropical region compared with the Tropics, despite the presence of highest surface salinity in the subtropics, must be due to the input of subpolar water.

Where does the mass associated with the input of subpolar water return to the subpolar region? It and the net southward Ekman transport of about 6–8 Sv at 40°N across the Pacific must return northward in the central and eastern Pacific. Evidence for a northward incursion of subtropical water into the subpolar gyre, particularly

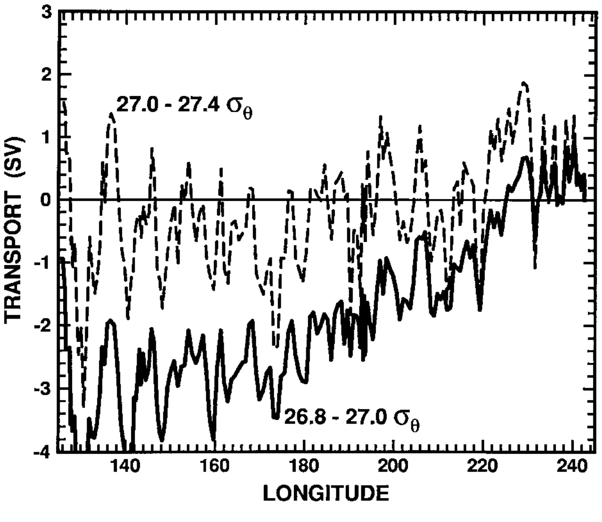

FIG. 5. Transport relative to 2000 dbar along approximately 24°N in the layers 26.64–27.0 σ_θ (heavy) and 27.0–27.4 σ_θ (light), integrated from the eastern boundary of the Pacific.

TABLE 3. Sensitivity of total zonal transports ($\times 10^6$ m^3 s^{-1}) at 152°E (May 1981) to reference velocity choices. Transports relative to zero velocity at 2000 dbar are reproduced from Table 1, along with transports relative to zero veocity at 1500 and 4000 dbar, and relative to 4000 dbar velocities after Roemmich and McCallister (1985).

Layer		Total/ 1500 stations 3–23	Total/ 2000 stations 3–23	Total/ 4000 stations 3–23	Total/ RM stations 3–23
26.64–27.0 σ_θ	All	6.75	7.06	7.51	5.06
	subpolar	2.36	2.46	2.62	1.74
27.0–27.4 σ_θ	All	5.08	5.62	5.99	0.56
	subpolar	0.97	0.79	0.43	−1.37
26.64–27.4 σ_θ	All	11.83	12.68	13.50	5.62
	subpolar	3.33	3.25	3.04	0.37
27.4–27.6 σ_θ	All	0.68	1.33	2.09	−3.42
	subpolar	−0.03	0.07	0.13	−0.32

in the Gulf of Alaska, is clear (Talley et al. 1991; Musgrave et al. 1992; Zhang and Hanawa 1993; Yuan and Talley 1996). The Ekman transport probably returns as denser water. Some of the returning intermediate water and Ekman-compensation flow must upwell in the subpolar gyre to feed the intermediate water formation in the Okhotsk Sea and the Ekman flux. Upwelling is most intense in the central Gulf of Alaska and also in the western subarctic gyre center where the intermediate density isopycnals are found domed up to just below the intense pycnocline. A complete transport analysis is beyond the scope of this note; work is being undertaken currently by a number of investigators.

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