The Role of Cabbeling and Double Diffusion in Setting the Density of the North Pacific Intermediate Water Salinity Minimum

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ABSTRACT

The top of the North Pacific Intermediate Water (NPIW) in the subtropical North Pacific is identified with the main salinity minimum in the density range $\sigma_\theta = 26.7$–26.8. The most likely source of low salinity for the NPIW salinity minimum is the Oyashio winter mixed layer, of density $\sigma_\theta = 26.5$–26.65. The Oyashio waters mix with Kuroshio waters in the broad region known as the Mixed Water Region (MWR), between the separated Kuroshio and Oyashio Fronts just east of Japan. It is shown that cabbeling during mixing of the cold, fresh Oyashio winter mixed layer water with the warm, saline Kuroshio water increases the density of the mixture by up to $\sigma_\theta = 0.07$ at densities around $\sigma_\theta = 26.6$–26.65, regardless of the mixing mechanism. Thus cabbeling accounts for about half of the observed density difference between the Oyashio winter mixed layer water and the top of the NPIW.

Double diffusion during mixing of the interleaving layers of Oyashio and Kuroshio waters in the MWR can also change the density of the mixing intrusions. Density ratios favorable to double diffusion are shown to be especially prominent in Oyashio intrusions into a Kuroshio warm core ring in the 1989 data examined here. The average potential temperature–salinity profile of the new subtropical NPIW just east of the MWR, with its nearly uniform salinity, suggests the dominance of salt fingering over diffusive layering. Using the observed salinity and density differences between Oyashio surface water and the NPIW salinity minimum, after subtracting the density difference ascribed to cabbeling, an effective flux ratio of about 0.8 is estimated for possible double diffusive processes in the MWR.

1. Introduction

North Pacific Intermediate Water (NPIW) is broadly defined as the North Pacific layer that is ventilated in the northwestern Pacific, including the Okhotsk Sea. The full density range that is ventilated in winter is approximately $\sigma_\theta = 26.6$ to 26.8 by open ocean processes in the Oyashio and southern Okhotsk Sea, to approximately $\sigma_\theta = 27.2$ through brine rejection under ice formation in the Okhotsk Sea, to approximately $\sigma_\theta = 27.6$ through tidal mixing in the Kuril Straits (Talley 1991). A portion of the newly ventilated NPIW enters the subtropical gyre near the western boundary where the Oyashio and Kuroshio waters meet, interleave, and mix in the broad Mixed Water Region (MWR) between the separated Oyashio and Kuroshio Fronts (Hasunuma 1978; Talley 1993; Talley et al. 1995; Yasuda et al. 1996). Within the North Pacific's subtropical gyre, NPIW is often identified by a salinity minimum at a potential density of $\sigma_\theta = 26.7$–26.8. This salinity minimum is referred to herein as the NPIW salinity minimum; it marks the top of the complete NPIW layer. (In the subpolar gyre, salinity is lowest at the sea surface—NPIW is revealed through high oxygen content rather than a subsurface salinity minimum.)

Talley (1993) and Talley et al. (1995) hypothesized that the Oyashio winter surface layer is the source of the subtropical NPIW salinity minimum since it contributes volumetrically the most to the mixing process compared with less dense seasonal Oyashio layers or the more stratified and saline underlying waters. The winter surface density over a wide region of the Oyashio is about $\sigma_\theta = 26.65$. Widespread outcropping of waters at the lowest NPIW salinity minimum density of $\sigma_\theta = 26.7$ does not occur except in small patches along the coasts of Hokkaido and northern Honshu (e.g., Talley and Nagata 1991). Therefore there must be a density increase upon mixing with Kuroshio water as the new subtropical NPIW salinity minimum is formed. Note that this density increase in itself does not constitute

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renewal of the NPIW, which is accomplished through ventilation in the subpolar region upstream. Based on horizontal advection using the same CTD datasets as used here, Talley (1997) calculated a net transport of 3.4 Sv (Sv $\equiv 10^6$ m^3 s^{-1}) of pure subpolar water into the subtropical gyre in the density range $\sigma_\theta = 26.64$ to 27.6, contributing to the subtropical NPIW.

Two candidate mixing mechanisms that can create the observed density increase are cabbeling and double diffusion. Cabbeling is the increase in density that occurs when waters of differing temperature and salinity mix. It is due to the nonlinearity of the equation of state (Witte 1902). It is most easily described when considering mixing between waters of the same initial density and at the same pressure. Since salinity and enthalpy mix proportionally, hence along straight lines in a potential temperature–salinity diagram (Fig. 2a), and since isopycnals in this space are concave downward, mixing creates higher density (net contraction of a volume of fixed mass). Cabbeling and other mixing processes that depend on temperature, salinity, and pressure have been discussed in detail by McDougall (1984). Because of the volume contraction, cabbeling affects potential energy and so could affect dynamics and enhance mixing [see a recent contribution by Fofonoff (1995, 1998) for the Gulf Stream]. The overall dynamical effects are likely too small to discern in this region of vigorous separated boundary currents, meanders, and rings. The density change upon mixing due to cabbeling however is a large-scale robust feature that is independent of the vigorous currents except inasmuch as they provide stirring between the different water masses.

It is assumed here that the waters that mix are in close proximity vertically and hence very close to each other in density. Frontal processes occurring throughout the MWR at meanders, large-scale intrusions, and rings cause the observed interleaving between the water masses on either side of the front. Density contrasts across the interfaces above and below the intrusions are small. The juxtaposed waters of nearly the same density then mix, as described and parameterized by Joyce (1977). Because cabbeling occurs during any mixing process, it must occur during the mixing that forms the subtropical NPIW, so there must be a density increase.

Cabbeling is often considered just an academic curiosity because the property contrast between mixing waters is usually small. However, Fofonoff (1956) and Foster (1972) explored the role of cabbeling in Antarctic Bottom Water formation in the Weddell Sea. Martineau (1953) considered cabbeling effects on Antarctic Intermediate Water at the Brazil–Falkland Current confluence, but emphasized sinking in physical rather than density space. Similarly, Smith et al. (1937) invoked cabbeling to explain physical sinking of saline water entering the Labrador Sea in the West Greenland Current, but it is not clear from their figures whether other mechanisms such as buoyancy flux might also be at work. In the Kuroshio–Oyashio confluence considered here, the temperature–salinity contrast between the source waters, over a depth range of more than 1000 m and a density range from the surface to $\sigma_\theta = 27.6$, is arguably the largest found between adjacent, mixing water masses in the open ocean. It is shown herein that the density increase due to cabbeling is sufficient to account for at least half of the difference between the Oyashio winter mixed layer density and the NPIW salinity minimum density.

Salt fingering between warm, salty overlying and cool, fresh underlying water also results in net densification of the fresher water. Diffusive layering at the bottom of the cold, fresh intrusion decreases the intrusion's density. Double diffusion's effect on the salinity minimum density is thus more difficult to quantify absent knowledge of the exact proportions of salt fingering and diffusive layering. Effective flux ratios, measured empirically in laboratories or through intensive ocean experiments, are required to estimate the density change. Effective flux ratios that apply to the temperature/salinity/density structure of the Oyashio and Kuroshio water are not available. Flux ratio and density ratio arguments from Schmitt (1979a) and Turner (1965) and laboratory and in situ Atlantic results for double diffusive intrusions from Ruddick and Hebert (1988), Ruddick (1992), and Walsh and Ruddick (1995, 1998) are used herein to give bounds on the density change due to double diffusion. Finally, assuming that double diffusion is responsible for all of the remaining density change above that due to cabbeling, an effective flux ratio for double diffusive mixing between Oyashio and Kuroshio intrusions is calculated.

Another mechanism for changing density during mixing is thermobaricity (McDougall 1984). However the change in pressure between the source and outflow waters in the Mixed Water Region (MWR), while not negligible, [O(300–400 m), is not likely to be a factor in the observed density increase.

The data are described in section 2 and are the same as were used by Talley et al. (1995) and Talley (1997). Cabbeling effects are presented in section 3. Double diffusive effects are presented in section 4.

2. Dataset and source water properties for the Mixed Water Region

CTD profiles of temperature, salinity, and pressure were collected in April–June 1989, May 1981, and May–June 1982 in the area of the western North Pacific known as the Mixed Water Region (Fig. 1 and Table 1). The westernmost data (1989) were collected by several Japanese government agencies, most of which sample this region at least seasonally. Data at 152°E were collected by Niiler et al. (1985) and Joyce (1987). The 1989 Japanese datasets had a vertical resolution of 1 dbar and the 1981–82 U.S. datasets a resolution of 2 dbar. The profiles from these datasets are typical of CTD data collected in many other surveys in this area. Ver-

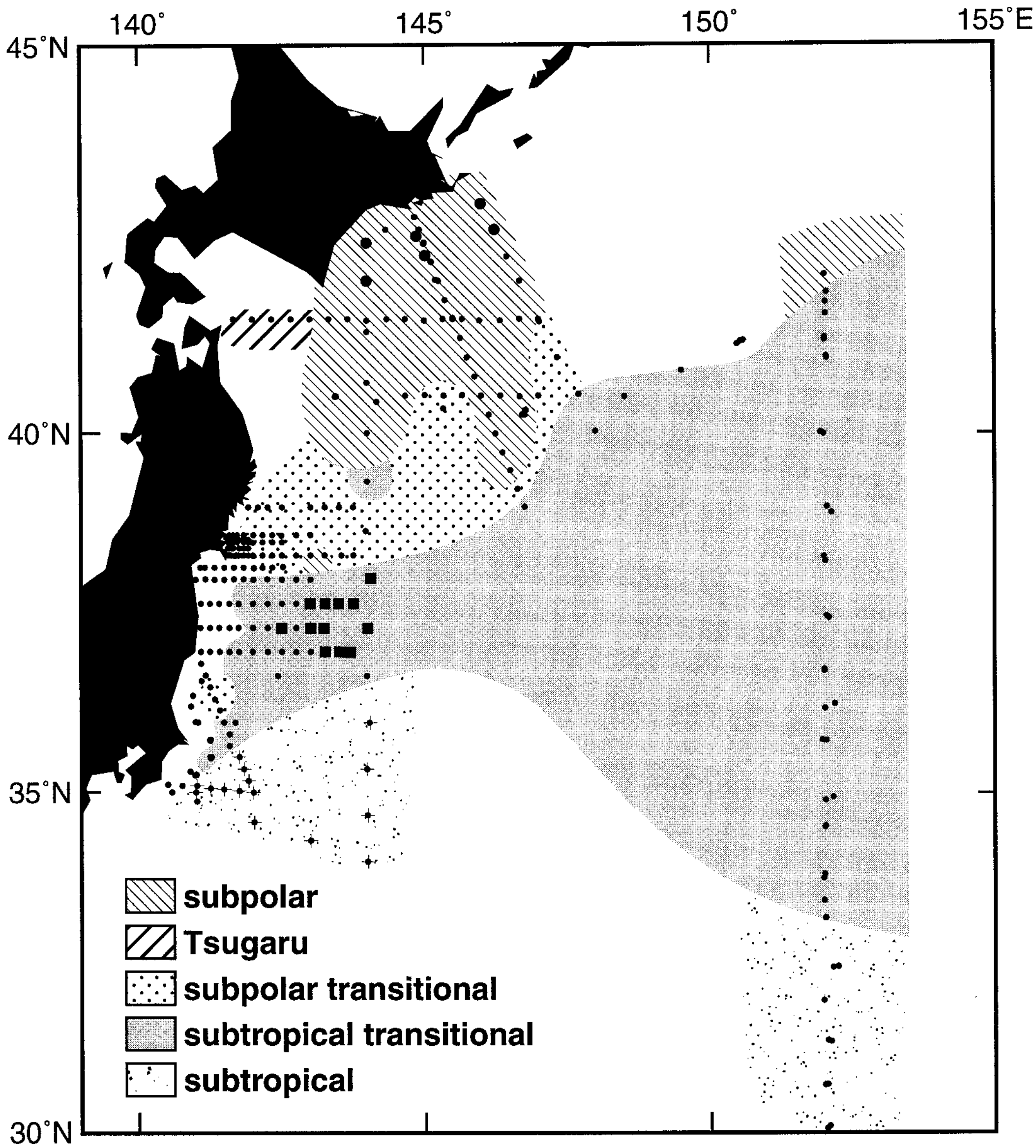

FIG. 1. CTD stations used herein. Stations west of 150°E were collected by various Fisheries Research Institutes in Japan in Apr 1989. Stations along 152°E are from May 1981. Regime classifications are based on averaged CTD profiles and include subtropical water (Kuroshio origin), subpolar water (Oyashio origin), subtropical transition water (saltier average mixture of subtropical and subpolar waters), and subpolar transitional water (fresher average mixture of subtropical and subpolar water). The figure is taken from Talley et al. (1995), in which the dataset and the water mass classifications are described. Stations denoted by large circles were used for the subpolar average temperature–salinity profile of Fig. 2. Stations denoted by square boxes are the warm core ring stations described in section 4.

tical gradients for the density ratio, $R_\rho = \alpha\delta T/\beta\delta S$, where α is the thermal expansion coefficient and β is the haline contraction coefficient, were calculated from a least squares linear fit to the profiles at each pressure, with a Gaussian weighting of variously 5–25 dbar half-width centered at the desired pressure.

The CTD data used here were examined and described by Talley et al. (1995) and are typical of profiles collected in other years. Profiles were classified therein according to whether they were charcteristic of the inflowing warm, saline Kuroshio water (subtropical water); cool/fresh Oyashio water (subpolar water); or mixtures, divided into (a) more saline subtropical transitional and (b) fresher subpolar transitional water. Interleaving between the strongly contrasting Oyashio and Kuroshio waters is apparent in this dataset (Fig. 2a) and is typical of the MWR, in contrast with the rest of the expanse of the subtropical gyre (e.g., Talley 1993).

CTD profiles characterized as subtropical and subpolar (Fig. 1) were averaged in Talley et al. (1995) as

TABLE 1. CTD datasets.

Region	Ship	Dates	Reference
Mixed water region and 144°E	*Kofu-maru*	10 Apr–8 May 1989	Talley et al. (1995)
Mixed water region	*Tankai-maru*	13 Apr–3 Jun 1989	Talley et al. (1995)
Mixed water region	*Wakataka-maru*	2 May–31 May 1989	Talley et al. (1995)
Mixed water region	*Soyo-maru*	15 May–23 May 1989	Talley et al. (1995)
152°E	R/V *Thomas Washington*	13 May–28 May 1981	Niiler et al. (1985)
152°E	R/V *Thomas Thompson*	25 May–5 Jun 1982	Joyce (1987)

a function of potential density σ_θ to produce the end members for the mixing analysis in the MWR (Fig. 2b). The end members should represent the most extreme incoming source water properties. Profiles characterized as mixed water were averaged to produce the ''subtropical transitional'' profile; this profile is similar to the more mixed waters found to the east of the study region. Gaussian smoothing in the vertical of 10 dbar (subpolar) or 50 dbar (subtropical and subtropical transitional) half-width was applied to the temperature and salinity profiles, which were then interpolated to potential density at intervals of $\sigma_\theta = 0.005$, and then analyzed isopycnally to yield the source water profiles. The subtropical end member was composited from the most saline waters on isopycnals and is thus more saline than the average used in Talley et al. (1995). The subpolar end member was averaged from six CTD profiles characterizing the purest Oyashio water and is fresher than the average used in Talley et al. (1995).

Subtropical source water is characterized by high salinity and a broad salinity minimum at a potential density of $\sigma_\theta = 26.8$. Subpolar source water is characterized by freshest water at the sea surface and a subsurface temperature minimum at a density of about $\sigma_\theta = 26.65$, which is the approximate density of the Oyashio winter surface layer (Talley et al. 1995). The subtropical and subpolar profiles differ from each other over the full potential density range shown, that is, down to $\sigma_\theta = 27.6$. This is due to the input of low salinity water in the subpolar gyre. The higher salinity of the subtropical water at depth is due to mixing downward in the Tropics from the high salinity surface waters (e.g., Reid 1965; Talley and Johnson 1994).

The new subtropical type of NPIW emerging from the MWR and entering the subtropical gyre is represented by the average subtropical transitional water profile in Fig. 2b. The salinity minimum is broad, with an absolute minimum at $\sigma_\theta = 26.71$ and a range of about $\sigma_\theta = 26.65$–26.85. If this salinity minimum in the mixed water arises from Oyashio winter surface water, then the density increase that accompanies its formation is roughly $\sigma_\theta = 0.05$–0.15. The ambiguity in the actual increase that requires explanation means that it is not possible to be precise about whether cabbeling can result in the entire required density increase, even though the density increase due to cabbeling can be accurately calculated. Since double diffusive processes can also yield a density increase, it is important to evaluate their effectiveness as well.

3. Cabbeling in the Mixed Water Region

Cabbeling is most effective in increasing density when there is a large difference in temperature and salinity along isopycnals between the mixing source waters and when the two source waters mix in roughly equal proportions. Mixing occurs along straight lines in potential temperature–salinity space; if mixing is between parcels of the same density initially, the final temperature, salinity, and density of the mixed parcel falls along this line proportional to the amount of water of each end member (Figs. 2b, c). Differences in temperature and salinity between the subpolar and subtropical source waters in the MWR are greatest at $\sigma_\theta = 26.4$ and $\sigma_\theta = 26.6$–26.65 (Fig. 2b). The latter is the density range of the Oyashio winter mixed layer water (Talley et al. 1995). Under the assumption that mixing is basically isopycnal, it was shown in Talley et al. (1995) that the average subtropical transitional profile is composed of approximately 55% Kuroshio and 45% Oyashio water in the density range $\sigma_\theta = 26.65$–27.4, as can be seen in Fig. 2c. This implies nearly maximum effectiveness of cabbeling in increasing the density of the mixture of Oyashio winter surface water with Kuroshio water. From Figs. 2b and 2d, the density increase should be somewhat greater than $\sigma_\theta = 0.06$.

The effect of cabbeling at stations between the separated Kuroshio and Oyashio is illustrated with the meridional section made in 1981 at 152°E, which lies east of the most vigorous mixing but close enough to the MWR to represent the newest mixed water. The NPIW salinity minimum is well defined at 200–400 dbar and about $\sigma_\theta = 26.7$ north of the Kuroshio and 700 dbar and $\sigma_\theta = 26.8$ south of the Kuroshio (Figs. 3a, b). The proportion of subtropical (Kuroshio) and subpolar (Oyashio) water was calculated at each station along the section at intervals of $\sigma_\theta = 0.005$ (Fig. 3b), assuming mixing along straight lines in the potential temperature–salinity plane between end members of the same density (thus using the information shown in Fig. 2c). Also shown in Fig. 3b (black contours) is the change in density of each water parcel during mixing if cabbeling were the only process changing the density of the mixture.

Fractions greater than 0.9 in Fig. 3b are nearly pure subtropical water. The lowest density water is in this category. The Kuroshio Extension (34°30′N to 37°N) contains a lens of pure subtropical water centered at $\sigma_\theta = 26.8$. Because this section did not cross the subarctic front (Oyashio extension) in the north, pure subpolar

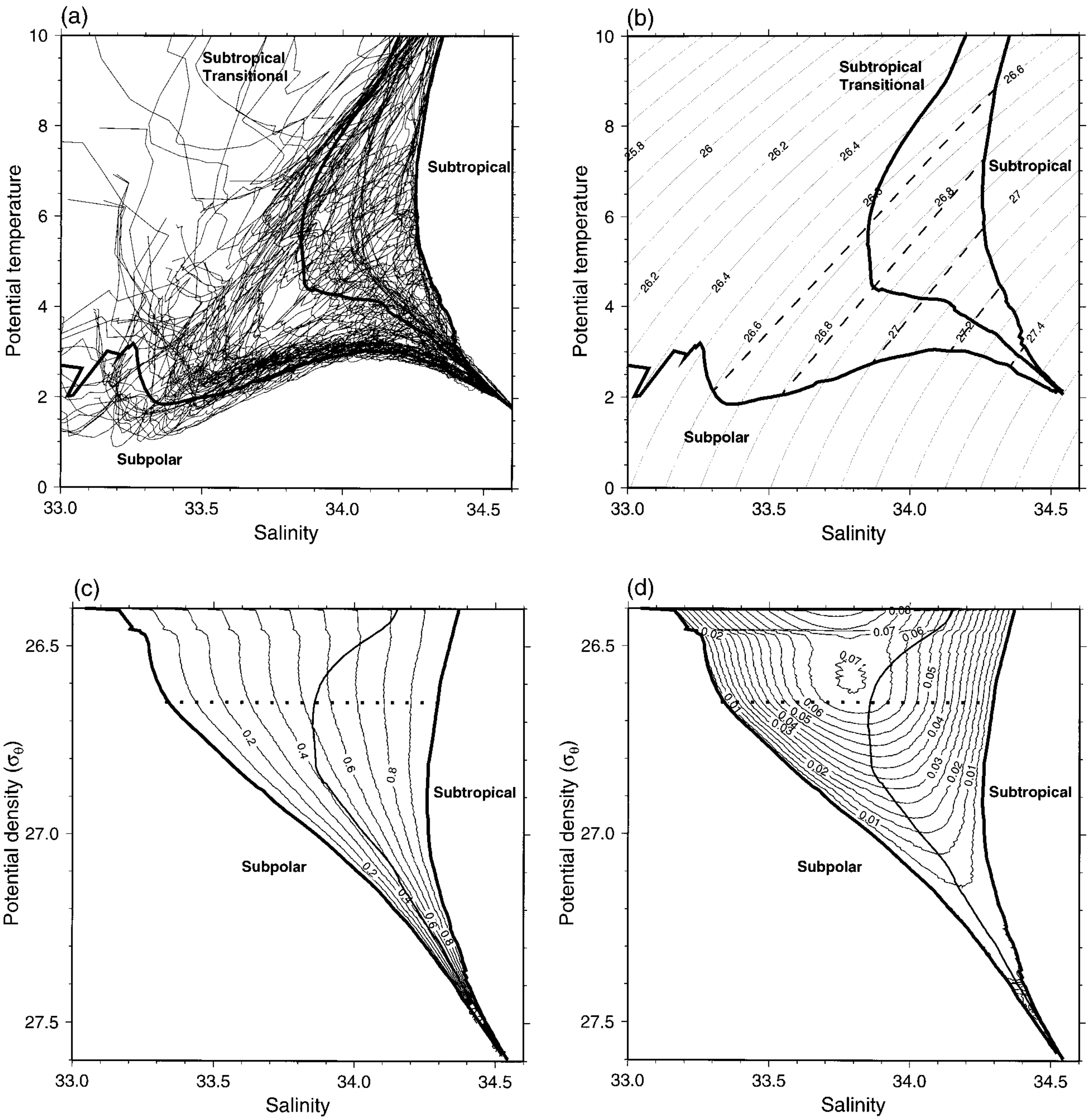

FIG. 2. (a) CTD profiles from all stations shown in Fig. 1, with Gaussian smoothing of 10-dbar half-width. (b) Potential temperature vs salinity for the subtropical and subpolar source water masses and the subtropical transitional water, which is the newly mixed water in the Mixed Water Region. The subtropical source water is a composite of the most saline water at each $\sigma_\theta = 0.005$ from stations identified as subtropical. The subpolar source water is averaged along isopycnals from the six most extreme Oyashio profiles. (Stations for each are shown in Fig. 1.) Also shown are contours of potential density referenced to the surface, σ_θ, and the straight lines along which mixing occurs between parcels of the same initial density. Because of the nonlinear equation of state, an increase in density (cabbeling) results from such mixing. (c) Fraction of subtropical water at each salinity and potential density if mixing is assumed to be along straight lines connecting points of the same potential density σ_θ. (d) Density increase after cabbeling as a function of the initial density of the source waters, assuming cabbeling is the only mechanism affecting density during mixing. The dotted line at $\sigma_\theta = 26.65$ in (c) and (d) represents the winter Oyashio mixed layer water.

water is not observed, although water at the northernmost station is close to pure. South of the Kuroshio Extension is found a mixture of subtropical and subpolar waters because of the westward recirculation of mixed water from farther downstream in the Kuroshio (e.g., Talley 1997). The change in relative fraction of subpolar water above and below $\sigma_\theta = 26.7$ was previously noted in Talley (1997). Between the Kuroshio Extension and the northern end of the section (37° and 41°N), the water column is characterized by fractions of 30%–50%, which is the subtropical transitional water (Fig. 2).

The maximum density increase ascribed to cabbeling (Figs. 3b and 3c) is $\sigma_\theta = 0.07$ within and just above the main NPIW salinity minimum north of the Kuroshio and about $\sigma_\theta = 0.06$ south of the Kuroshio. The maximum density increase at 152°E occurs at a potential density of $\sigma_\theta = 26.67$, hence implying an original density of $\sigma_\theta = 26.61$ if the only mixing process affecting density is cabbeling. This maximum density increase is not quite collocated with the NPIW salinity minimum, which is denser than $\sigma_\theta = 26.7$. Even so, at the NPIW salinity minimum, the density increase is nearly $\sigma_\theta =$ 0.06, which relates it back almost to the average Oyashio winter layer density of $\sigma_\theta = 26.65$. As seen above, the broad salinity minimum layer extends to higher density than the salinity minimum core north of the Kuroshio, and also the exact salinity minimum is at a higher density south of the Kuroshio. Therefore it is useful to evaluate other mechanisms that can increase density, as described in the next section.

The dynamical effect of cabbeling is likely too small to discern in this region. As McDougall (1984) notes, the diapycnal velocities resulting from processes like cabbeling are orders of magnitude smaller than actual vertical velocities, which, in this region with subpolar intrusions wrapping into warm core rings, can be as high as 500 m in a few months (about 0.001 m s^{-1}).

4. Double diffusion and the density of NPIW

Double diffusion can change potential density during mixing in the MWR, where the strongly contrasting sources waters are juxtaposed as layered intrusions (Fig. 2a). Double diffusive intrusions have been described in a number of regions (e.g., Toole 1981; Ruddick and Hebert 1988, Ruddick 1992); see Schmitt (1994) for a comprehensive review. Intrusions of nearly pure cold/fresh Oyashio water into the nearly pure warm/salty Kuroshio water are commonly found in the westernmost MWR, particularly around warm core rings formed from Kuroshio water, and at the Kuroshio and Oyashio fronts (e.g., Talley et al. 1995). Salt fingering interfaces occur at the top and diffusive interfaces at the bottom of the intruded fresh, cold Oyashio layers. Salt fingering increases the density of the fresh intrusion while diffusive layering does the opposite. The balance between the two is represented by an effective flux ratio, which is determined experimentally or by direct observation of the effects of mixing.

Salt fingering is most active when the density ratio $R_\rho = \alpha\delta T/\beta\delta S$, based on vertical differences in temperature and salinity across the intrusion interface, is less than 2 (Schmitt 1979a, b). Diffusive layering is most active when R_ρ is between 0.5 and 1.0.

The buoyancy flux in terms of the temperature and salinity fluxes, F_T and F_S, assuming a linear equation of state, is

$$F_\rho = -\alpha F_T + \beta F_S = \beta F_S(1 - \gamma)$$
$$= -\alpha F_T(1 - 1/\gamma), \quad (1)$$

where the flux ratio is

$$\gamma = \alpha F_T/\beta F_S. \quad (2)$$

For salt fingering, the empirically determined flux ratio γ is about 0.6 (Turner 1967; Schmitt 1979b). Thus

$$F_{\rho\mathrm{SF}} \approx 0.4\beta F_S. \quad (3)$$

The empirically determined flux ratio γ for a diffusive interface is about 6.7 (Turner 1965) and hence

$$F_{\rho\mathrm{DI}} \approx -5.7\beta F_S. \quad (4)$$

The differences in salinity, temperature, and density between the source water and output NPIW are used in the following in evaluating the above quantities instead of fluxes.

What is the balance between buoyancy gain and loss in a double diffusive intrusion with potential for both salt fingering and diffusive layering, and what is the end density after mixing? Direct measurements for every particular situation are required. For a salt/sugar laboratory system Ruddick (1992) showed that the relative importance of salt fingering and diffusion depends on the density ratio of the layers sandwiching the intrusion, with salt fingering dominating the evolution of the intrusion if the outer two layers are themselves favorable to salt fingering, and vice versa. Thus the larger (vertical) scale tendency for salt fingering or diffusion determines the evolution. Observations of changes of a warm, saline lens of Mediterranean Water (meddy) with cold, fresh Atlantic water intrusions substantiated the laboratory results—the large-scale background tendency determined the relative importance of the two processes (Ruddick 1992). In the upper part of the meddy, the overall mixing of the cold/fresh intrusions was dominated by diffusive mixing, and the cold/fresh intrusions gained buoyancy with an effective flux ratio γ_{eff} of 1.1, considerably reduced from the 6.7 of a purely diffusive interface. In the lower portion of the meddy, where the background profile was favorable to salt fingering, the fresh intrusion lost buoyancy with γ_{eff} of about 0.9, which is larger than the laboratory value of 0.6 for a salt fingering interface. Therefore diffusive and salt fingering effects moderated each other in both regions.

Observations tracking the history of actual intrusions in the MWR like those made in the meddy are not available. An intrusion model specific to this Kuroshio–Oyashio confluence region, like that of Walsh and Ruddick (1998) for a much more idealized initial temperature/salinity structure, has not been developed. It seems appropriate however to expect some similarity between the meddy and laboratory intrusions and those in the MWR, since all have both fingering and diffusive in-

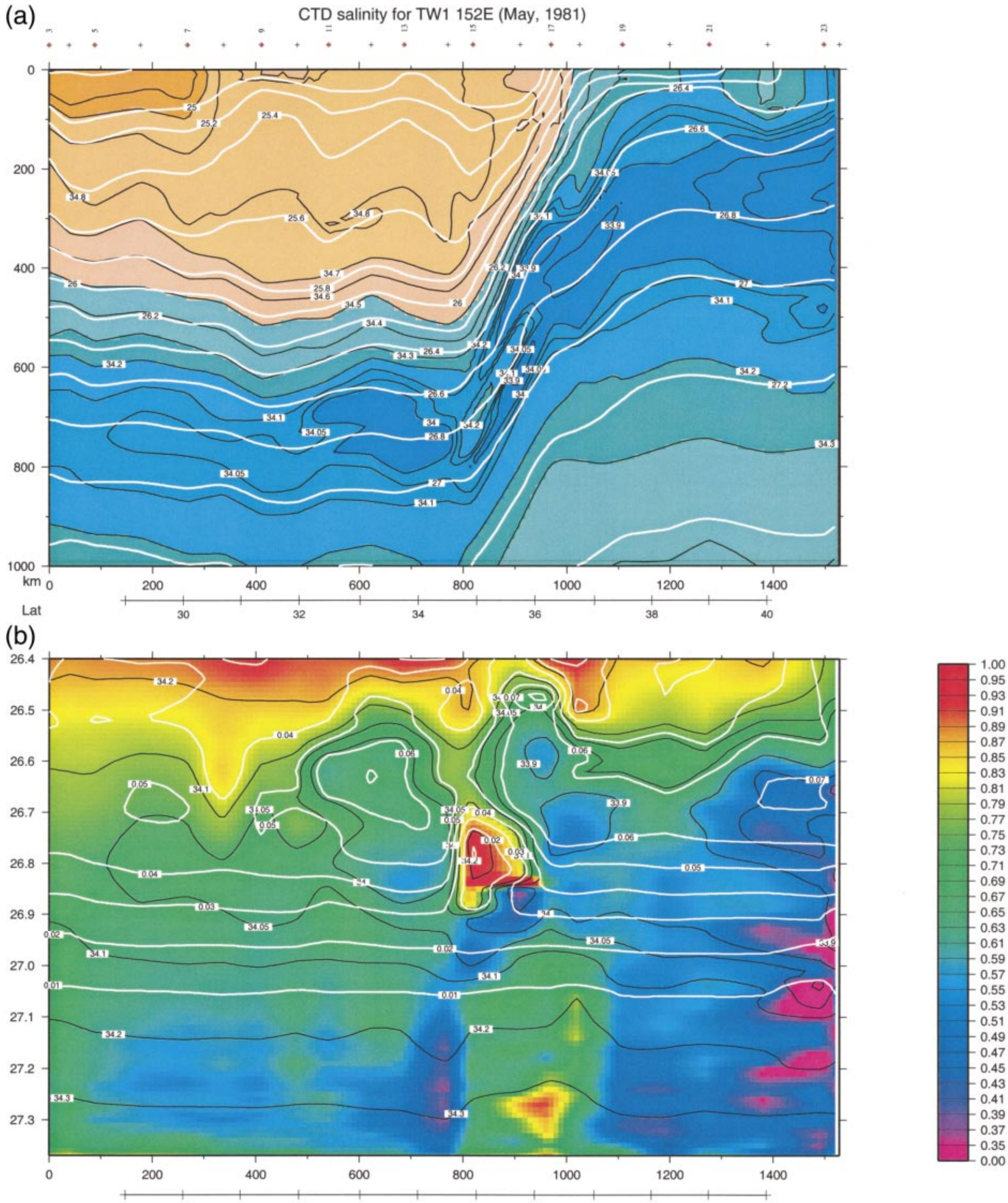

FIG. 3. (a) Salinity (color) and potential density σ_θ (white contours) at 152°E (Niiler et al. 1985). (b) Fraction of Kuroshio water (color shading) using values from Fig. 2c, as a function of σ_θ. Salinity (black contours). Increase in density from initial mixing end members (white contours), using Fig. 2d. (c) Increase in density, assuming cabbeling only, for parcels in $\sigma_\theta = 0.005$ density intervals averaged from stations along 152°E between the Kuroshio and Oyashio (data from the 1981 section listed in Table 1), assuming cabbeling is the only mechanism affecting density. The vertical axis is observed density. The maximum density increase of $\sigma_\theta = 0.07$ occurs at $\sigma_\theta = 26.7$, projecting back to an initial density of $\sigma_\theta = 26.63$.

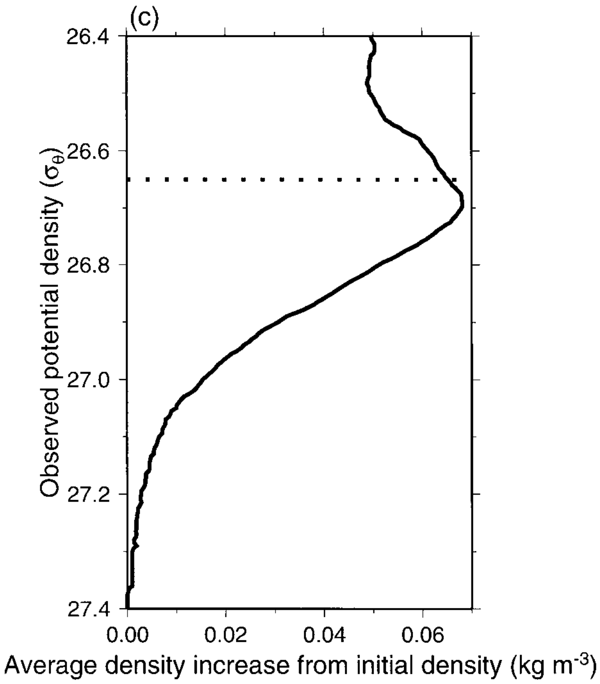

FIG. 3. (*Continued*)

terfaces. In the MWR, the background profile above the NPIW salinity minimum is salt fingering favorable since mixing of Oyashio and Kuroshio waters always produces warm/saline waters at the surface (since the Kuroshio include waters of much lower density than the Oyashio). Therefore we might expect a γ_{eff} less than 1.0.

Interleaving between the strongly contrasting Oyashio and Kuroshio waters occurs throughout the MWR (e.g., Fig. 2a) and is especially pronounced in mesoscale features such as the commonly occuring warm core ring near Honshu (Talley et al. 1995). Density ratios in the MWR indicate that double diffusion can be active as a result of this interleaving (Fig. 4 for all stations shown in Fig. 1). Gaussian smoothing with halfwidths of 5, 15, and 25 dbar were applied to the profiles before vertical differencing. The heaviest smoothing (used in Fig. 4) is most useful for determining regions robustly dominated by double diffusion, while the lightest smoothing reveals the full range of density ratios. Density ratios between 1 and 2, hence favorable for salt fingering (Fig. 4a), are generally found above the NPIW salinity minimum core, with a major concentration along a curve stretching from the average subtropical toward the average subpolar profile from σ_θ = 26.4 to 26.55. Active diffusive interfaces, with density ratios from of 0.5 to 1.0, are primarily located below the main NPIW salinity minimum, stretching from the subpolar toward the subtropical source waters from σ_θ = 26.8 to 27.1 (Fig. 4b). Therefore double diffusive processes sandwich the actively mixing NPIW and are likely to affect its evolution.

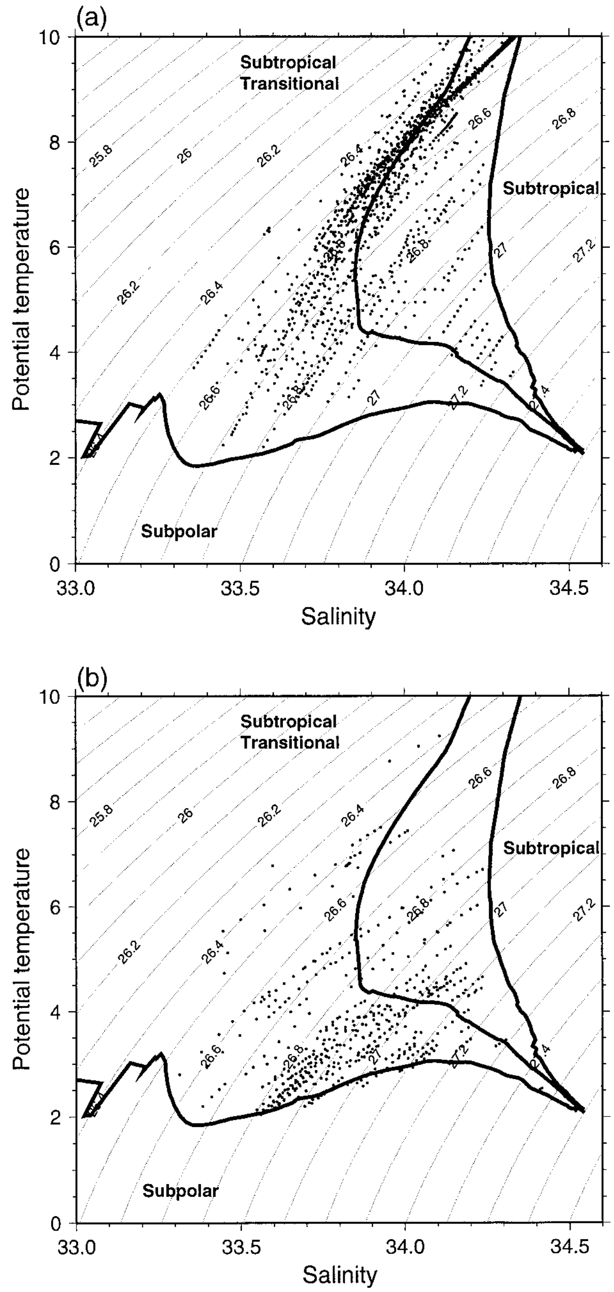

FIG. 4. (a) Density ratios R_ρ between 1.0 and 2.0, indicating active salt fingering for the stations of Fig. 1. Prior to computing R_ρ, temerature and salinity were smoothed vertically using a Gaussian of half-width of 25 dbar. This heavy smoothing reveals regions robustly favorable to salt fingering. (b) Density ratios R_ρ between 0.5 and 1.0, indicating an active diffusive regime, for the same stations.

In contrast to the interleaving profiles of the MWR, density ratios in the Oyashio and Kuroshio source waters are mostly out of the range for active double diffusion, presumably because these water masses have been mixing for a long time, thus reducing the potential for double diffusion. That is, most density ratios for the pure Oyashio stations close to Hokkaido (heavy circles

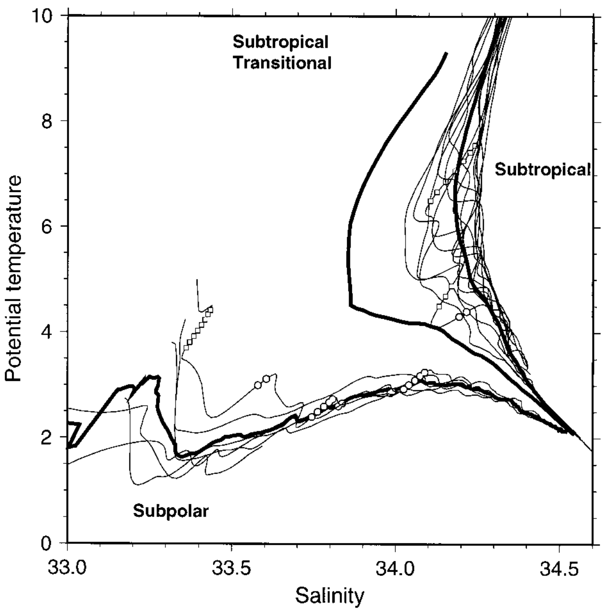

FIG. 5. Potential temperature–salinity profiles from the Oyashio source waters (stations marked with ×'s in Fig. 1) and from in and south of the Kuroshio (subtropical stations in Fig. 1). Circles mark density ratios between 0.5 and 1.0 (diffusive layering) and squares mark density ratios between 1 and 2 (salt fingering). Very few points in these profiles fit in these regimes compared with the profiles shown below in Fig. 6, indicating that double diffusive processes are weak in the source waters.

in Fig. 1) are less than 0.5 (fresh, cold profiles in Fig. 5), while most density ratios in Kuroshio and other subtropical gyre profiles are mostly greater than 2 above the salinity minimum (saline profiles in Fig. 5).

The most vigorous potential for salt fingering, measured by density ratios less than 1.5 in a layer more than 100 dbar thick, even when subjected to the strongest 51-dbar smoothing, is in the warm core ring (WCR) centered at 37°30′N, 143°E (large squares in Fig. 1). The CTD profiles for these twelve WCR stations are shown in Fig. 6. The remnant winter mixed layer, at about 9°C, is about 500 m thick in the center of the ring. [The mixed layers in these rings are the thickest observed in the North Pacific and are a likely source of thickness for the North Pacific Central Mode Water (Suga et al. 1997; Nakamura 1996), previously referred to by Roden (1977) as the stability gap.] Just beneath the remnant mixed layer in Fig. 6, intrusions of subpolar water are wrapped around and into the ring. [See Talley et al. (1995) for a much more detailed description of this particular ring and for references to many other papers showing similar intrusions in other years in Kuroshio warm core rings.] The center station of the WCR contains nearly pure Oyashio water (profile with the thickest mixed layer and the freshest water at 600–700 m deep and $\sigma_\theta = 27.2$). Note that this low salinity layer is also a pycnostad, evidenced by lower stratification between 600 and 700 m (Fig. 6c).

The low density ratio (salt fingering) regime for these WCR stations covers the whole warm water layer connecting the center of the intrusion and the overlying mixed layer (red dots in Fig. 6), and produces the cluster of low density ratios seen in Fig. 4a. This interfacial layer is of remarkably uniform density over the 12 stations, from $\sigma_\theta = 26.43$ to 26.50, and of thickness ranging from a little less than 100 dbar to 280 dbar. Although the density ratio is low, steps like those observed in other salt fingering regions were apparent at only one station (in the center of the ring, with the deepest remnant mixed layer and freshest subpolar intrusion, as in Fig. 6b), so salt and buoyancy fluxes could not be computed using empirical formulas developed for salt fingering steps. The subpolar intrusions are also temperature minima (Fig. 6a). Thus a diffusive regime, with density ratios between 0.5 and 1, occurs at the bottom of the intrusions, so buoyancy fluxes cannot be computed based on salt fingering alone.

The ensemble of potential temperature–salinity profiles from the center of the ring suggests that the salt fingering dominates over diffusive mixing—except for the most extreme station, the mixing intrusions cluster noisily about uniform salinity through a potential temperature gradient (thermocline). These and other profiles when averaged produced the subtropical transitional profile (new NPIW) of Fig. 2, which also has nearly uniform salinity through the NPIW salinity minimum. (In contrast, mixing dominated by a diffusive regime would likely tend toward uniform potential temperature through a salinity gradient or halocline.)

Since the effective flux ratio is unknown, extreme bounds on the density change of the freshest intrusion in the center of the WCR as it mixes to become the new subtropical type of NPIW can be calculated by assuming purely salt fingering and purely diffusive layering. This intrusion is taken to be typical of the initial intrusions of pure Oyashio waters into the MWR and hence typical of the waters that mix to produce the salinity minimum. Ruddick's (1992) effective flux ratios can also be applied to provide a better estimate of the density change. (The fresh intrusions in the warm core ring are embedded in a background of Kuroshio water that has a tendency toward salt fingering, which should therefore cause the effective flux ratio to tend more toward salt fingering.) Salt fingering can occur above the intrusion and diffusive layering below it. The salinity change from the fresh intrusion to the average NPIW salinity is 0.4–0.5 psu. If mixing were only due to salt fingering, with a flux ratio of 0.6, the maximum possible density increase, from (3) and using $\beta = 0.8$, would be $\sigma_\theta = 0.13$. On the other hand, if the intrusion mixes only through the diffusive interface until it is isothermal with the warmer water in the temperature maximum below, hence a change of 1° to 1.5°C, then the density decrease would be $\sigma_\theta = -0.13$ to -0.16 from (4), using $\alpha = 0.15$. Ruddick (1992) observed an effective flux ratio of 0.9 for the meddy's salt fingering side; if this is applied to the fresh MWR intrusion, then the density in-

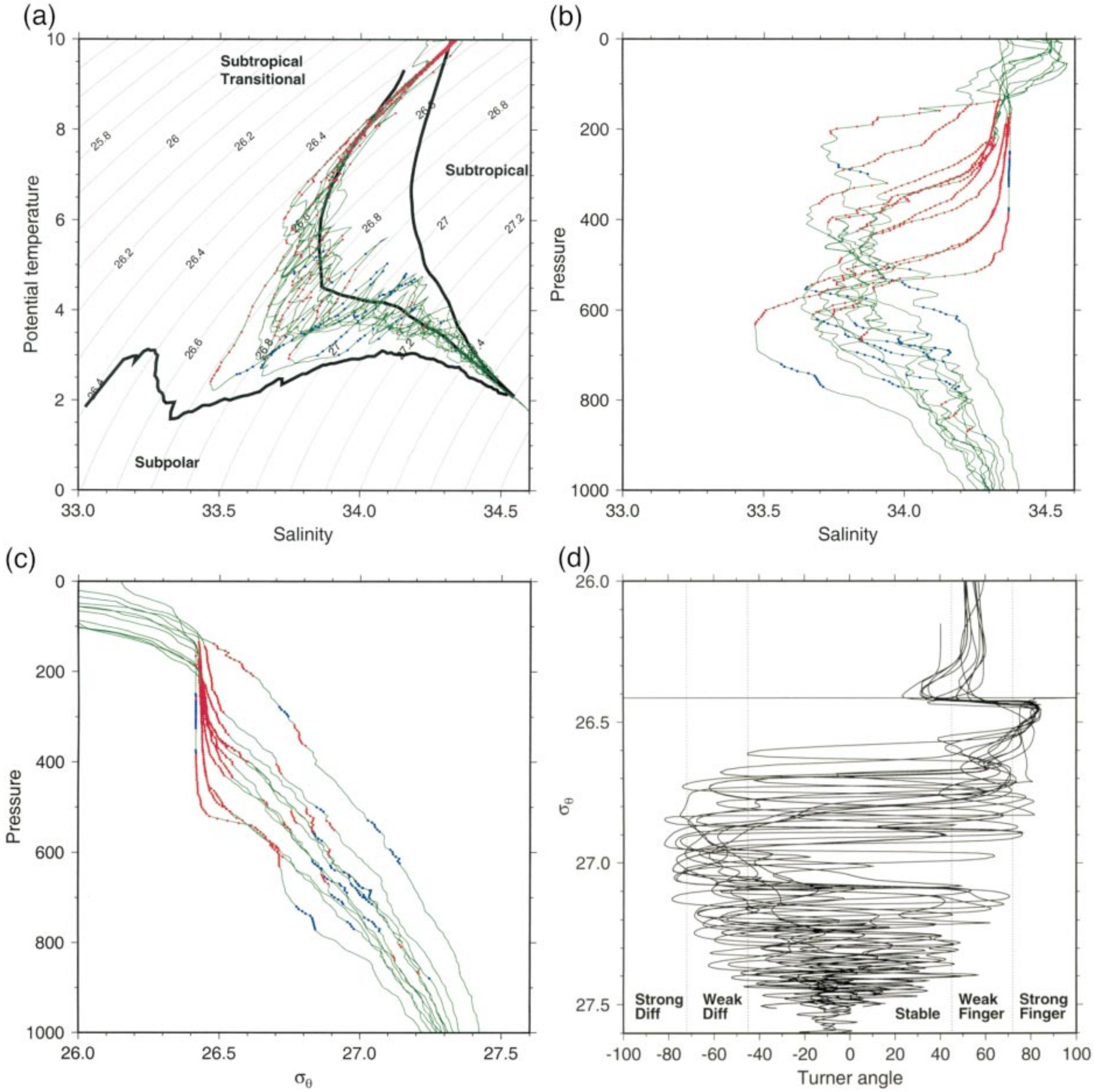

FIG. 6. Profiles from CTD stations in the warm core ring north of the Kuroshio in April 1989 (Fig. 1), showing intrusive layering between low salinity subpolar water wrapped around and into the ring and high salinity warm core ring water from the Kuroshio. Density ratios between 1 and 2 (salt fingering) are indicated with red. Density ratios between 0.5 and 1 (diffusive regime) are indicated with blue. [CTD profiles are displayed with a Gaussian smoothing of 10-dbar half-width. Density ratios and Turner angles were calculated with a larger smoothing of 25-dbar half-width to highlight the major double diffusive features and deemphasize the fine structure.] (a) Potential temperature–salinity, (b) salinity, and (c) potential density σ_θ as a function of pressure for the same stations. (d) Turner angle Tu (Ruddick 1983) as a function of potential density σ_θ for Tu between 72 and 90: active salt fingering, Tu between 45 and 72, weak salt fingering, Tu between −45 and 45: stable to double diffusion, Tu between −45 and −72: weak diffusive regime, and Tu between −72 and −90: strong diffusive regime.

crease as the fresh intrusion mixes to become new NPIW would be 0.03 σ_θ.

An effective flux ratio for the mixing in this region can be estimated if it is hypothesized that the subpolar near-surface layer of nearly uniform salinity 33.3 psu and density range σ_θ = 26.5 to 26.65 mixes double diffusively to become the NPIW salinity minimum layer of salinity 33.85 psu and density σ_θ = 26.65–26.85 (the "subpolar" and "subtropical transitional" curves in Fig. 2). The density change is σ_θ = 0.15 and the salinity change is 0.55 psu. The effective flux ratio is

$$\gamma_{\text{eff}} = 1 - \delta\sigma_\theta/(\beta\delta S) = 0.66\text{–}0.80, \qquad (5)$$

where the lower number assumes that the entire density change is due to double diffusion, whereas the higher number is calculated by first removing a $\sigma_\theta = 0.06$ density change due to cabbeling, assuming that double diffusion is responsible for a density change of $\sigma_\theta = 0.09$.

In conclusion, density increases associated with double diffusive mixing of fresh Oyashio intrusions with saline Kuroshio waters in the warm core north of the Kuroshio Extension could contribute to the increase of density of the NPIW salinity minimum above the density of the Oyashio winter surface water, which is the hypothesized source of the NPIW salinity minimum (Talley 1993; Talley et al. 1995). The effect of double diffusive mixing on density could be of the same magnitude as the cabbeling effect.

5. Summary

It was previously hypothesized (Talley 1993; Talley et al. 1995) that the main factor setting the density of the renewed NPIW salinity minimum at $\sigma_\theta = 26.7$–26.8 in the Mixed Water Region just east of Japan is the winter surface layer density of $\sigma_\theta = 26.6$–26.65 in the Oyashio region. (The Oyashio properties themselves, including those throughout the depth of the NPIW layer, are set by conditions farther upstream, including ventilation in the Okhotsk Sea.) Densification of the Oyashio surface water as it mixes with more saline Kuroshio water increases the density of the salinity minimum at the top of the NPIW layer. Cabbeling clearly contributes significantly to this densification. It is likely that double diffusion does as well.

The importance of cabbeling is, of course, directly proportional to the difference in temperature and salinity along the isopycnal. The cabbeling effect is large at the sea surface and at $\sigma_\theta = 26.5$–26.7, with a maximum at about $\sigma_\theta = 26.6$, and much weaker at densities greater than $\sigma_\theta = 27.0$. The maximum density increase due to cabbeling is about $\sigma_\theta = 0.07$ at around $\sigma_\theta = 26.65$, thus producing a direct connection between Oyashio winter surface water of this density and new NPIW salinity minimum water of density $\sigma_\theta = 26.7$–26.8.

Double diffusion is likely a major mixing process between the intruding layers of subpolar and subtropical waters as they meet in areas such as the warm core rings of the Mixed Water Region, as demonstrated by the robust, thick regions of density ratios favorable to double diffusion. The near-uniformity of salinity surrounding the salinity minimum in new NPIW (subtropical transitional water) suggests the presence of double diffusion, dominated by salt fingering. The maximum density increase that could result from pure salt fingering acting on an intrusive fresh layer is about $\sigma_\theta = 0.13$. The diffusive regime below the fresh, cold intrusion could decrease the density by about the same amount. If Ruddick's (1992) effective flux ratio for the salt fingering side of a meddy is appropriate, the density increase during mixing of the intrusion is on the order of $\sigma_\theta = 0.03$. Lastly, by assuming that the density difference of $\sigma_\theta = 0.15$ between Oyashio winter surface water and the new NPIW salinity minimum is split between $\sigma_\theta = 0.06$ from cabbeling and $\sigma_\theta = 0.09$ from double diffusion, an effective flux ratio of 0.8 is calculated.

The increase in density as Oyashio and saline Kuroshio waters mix, creating the NPIW that is seen in the subtropical gyre, is not the renewal process for NPIW. Rather, renewal occurs through ventilation of the NPIW densities in the subpolar region. However, densification results in convergence of water into the NPIW layer since the density increase is larger for the lower densities for which the Kuroshio/Oyashio property contrast is largest. The Oyashio surface layer, of densities $\sigma_\theta = 26.65$–26.7, in particular joins the NPIW salinity minimum core layer as its density is increased during mixing. A very rough estimate of the transport of this surface layer into the NPIW layer is obtained by making the reasonable assumption that all NPIW in the density range $\sigma_\theta = 26.7$ to 26.76 in the Mixed Water Region arises from this Oyashio surface layer. The horizontal transport is calculated using stations north of the Kuroshio from the 152°E section of May 1981, as in Talley (1997), obtaining about 0.5 Sv of the total 5.5 Sv in the overall NPIW layer, which extends down to $\sigma_\theta = 27.6$.

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