Distribution and Formation of North Pacific Intermediate Water

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(Manuscript received 1 November 1991, in final form 6 May 1992)

ABSTRACT

The North Pacific Intermediate Water (NPIW), defined as the main salinity minimum in the subtropical North Pacific, is examined with respect to its overall property distributions. These suggest that NPIW is formed only in the northwestern subtropical gyre; that is, in the mixed water region between the Kuroshio Extension and Oyashio front. Subsequent modification along its advective path increases its salinity and reduces its oxygen.

The mixed water region is studied using all bottle data available from the National Oceanographic Data Center, with particular emphasis on several winters. Waters from the Oyashio, Kuroshio, and the Tsugaru Warm Current influence the mixed water region, with a well-defined local surface water mass formed as a mixture of the surface waters from these three sources.

Significant salinity minima in the mixed water region are grouped into those that are directly related to the winter surface density and are found at the base of the oxygen-saturated surface layer, and those that form deeper, around warm core rings. Both could be a source of the more uniform NPIW to the east, the former through preferential erosion of the minima from the top and the latter through simple advection. Both sources could exist all year with a narrowly defined density range that depends on winter mixed-layer density in the Oyashio region.

1. Introduction

A prominent feature of the entire subtropical North Pacific is a well-defined salinity minimum at depths of 300–700 m, with a relatively narrow density range centered at 26.7–26.9 σ_θ. This salinity minimum is defined to be North Pacific Intermediate Water (NPIW), following Sverdrup et al. (1942). This is a very narrow definition of NPIW and will be retained throughout this paper. Several other definitions of NPIW have been used. Reid (1965) said that the salinity minimum characterizes NPIW. Hasunuma (1978) called all water in some density interval around the minimum the NPIW and preferred to refer to the salinity minimum itself as the North Pacific Intermediate Salinity Minimum, while Van Scoy et al. (1991) referred to the isopycnal 26.8 σ_θ throughout the North Pacific as NPIW.

Sverdrup et al. (1942) mapped the distribution of the narrowly defined NPIW, showing its confinement to the subtropical gyre, lowest salinity off northern Japan, and anticyclonic advection around the subtropical gyre. As a pervasive salinity minimum, NPIW is superficially similar to the Labrador Sea Water (LSW) of the North Atlantic and Antarctic Intermediate Water (AAIW) of the oceans north of the Antarctic Circum-

polar Current (ACC). In fact, Wüst (1930) ascribed NPIW to sinking in the Okhotsk Sea, probably in analogy with LSW because very little Pacific data were available. However, there are notable differences between NPIW and LSW/AAIW. NPIW is confined mainly to the subtropical gyre of the North Pacific, unlike LSW, which is found as a salinity minimum primarily in the subpolar gyre of the Atlantic (Talley and McCartney 1982), and also unlike AAIW, which extends northward to about 25°N in the Atlantic, 10°N in the Pacific, and 5°–10°S in the Indian Ocean. LSW and AAIW also can be identified by vertical potential vorticity minima (e.g., Talley and McCartney 1982). NPIW, on the other hand, is not a pycnostad, suggesting that a convective source is unlikely.

Reid (1965) noted the interesting lack of a surface outcrop at the NPIW density, nominally 26.8 σ_θ, in the North Pacific. Using maps of properties at δ_T = 125 cl t^{-1}, he showed that the lowest salinity and highest oxygen occur near the Kuril Islands, in the subpolar gyre. He hypothesized that vertical mixing along the cyclonic path around the subpolar gyre causes these extrema. He then suggested that lateral mixing accounts for the spread of subpolar properties at 125 cl t^{-1} into the subtropical gyre and hence, for the salinity minimum. The first hypothesis was examined by Talley (1991), where it was suggested that while vertical mixing does appear to freshen the 26.8 σ_θ around the subpolar gyre, most of the freshening and oxygenation take place directly in the Okhotsk Sea. The second hypothesis is examined herein, where it is suggested that the

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bulk of the lateral exchange from the subpolar into the subtropical gyre takes place in the northwestern subtropical gyre, which is the mixed water region between the Oyashio and Kuroshio.

While the localization of NPIW formation has not been demonstrated before, Hasunuma (1978) showed that the salinity minimum is formed in the Oyashio/Kuroshio mixed water region, giving a thorough and important account of conditions there. He suggested that the intermediate salinity minimum, rather than being a convectively formed and hence volumetrically important water mass such as LSW, is just the vertical boundary between subtropical and subpolar waters in the subtropical gyre. He indicated that the salinity minimum originates from an overrun of subpolar waters originating in the Oyashio by subtropical waters originating from the Kuroshio. He showed that the warm, saline subtropical waters found in the mixed water region are considerably modified compared with their Kuroshio source and, from their density, originate from 500-m depth just south of the Kuroshio. Hasunuma also showed that the density range of NPIW is quite wide off Japan—it is noted here that the lowest densities that he defines as NPIW actually do outcrop, albeit rarely, in the mixed water region, to be shown below in section 3. Hasunuma did not show that NPIW is not formed anywhere else and did not suggest a selection mechanism for the NPIW density. He did suggest that NPIW is not formed from subpolar surface water because its density in all seasons except winter would then be too low; but it is indicated herein that the winter surface density of the Oyashio waters likely controls the density of NPIW formation.

It is important for the following discussion to clarify the distinction between ventilation of an isopycnal and formation of a salinity minimum at that density, which in this case are separate processes. Ventilation is the process of influencing an isopycnal with surface properties. "Direct" ventilation occurs when an isopycnal outcrops at the sea surface. "Indirect" ventilation occurs through vertical diffusion of surface properties downward to an isopycnal that does not outcrop locally. For clear definition, ventilation through salt rejection during sea ice formation is considered here as direct, since it involves a direct, quantifiable input of surface water. Formation of a salinity minimum need not involve any ventilation process; all that is required is that fresh waters intrude into saltier waters.

For NPIW densities of 26.7–26.9 σ_θ, direct ventilation beneath sea ice formation has been demonstrated to occur regularly in the Okhotsk Sea (Kitani 1973; Talley 1991; Ohtani 1989). Open-ocean outcropping near 26.7 σ_θ is rare but will be shown below for locations near Hokkaido, Japan, and has since been found near northern Honshu (Nagata, personal communication 1992). It is speculated that very rare outcropping to 26.8 σ_θ might also occur in the Alaskan gyre (Van Scoy et al. 1991), but indirect ventilation is likely to be the dominant process there (Talley 1988; Van Scoy et al. 1991). Indirect ventilation is likely to be important in the western subarctic gyre as well (Talley 1988). The two locations of enhanced indirect ventilation coincide with maxima in Ekman upwelling, which pulls these isopycnals up into the lower pycnocline, where enhanced vertical diffusion may be balancing the strong upwelling.

Other than to indicate that direct ventilation of NPIW densities occurs only very locally in the North
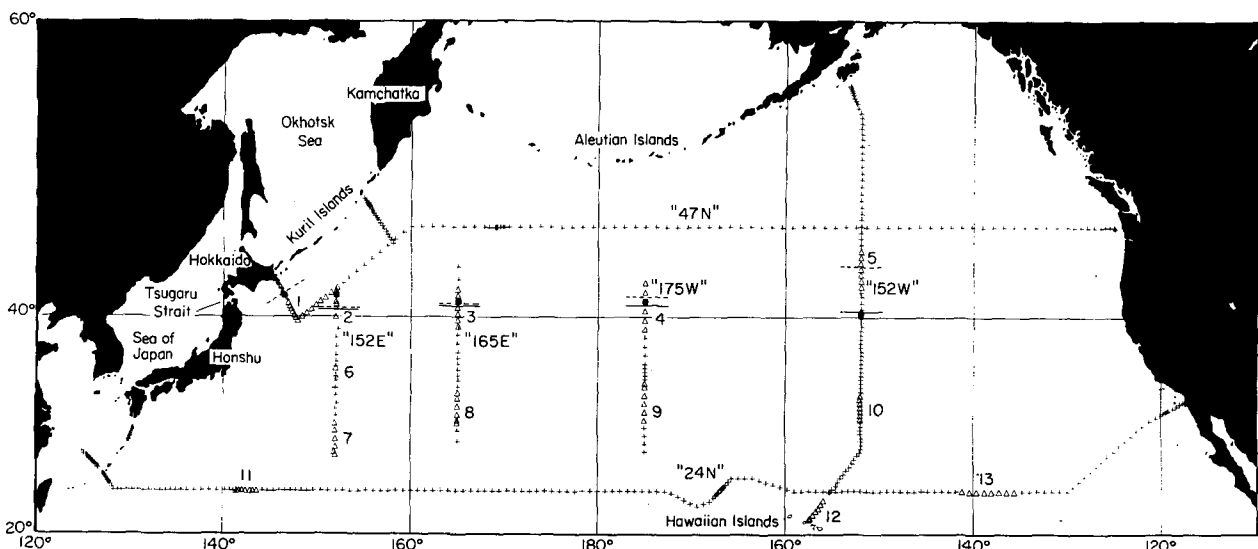

FIG. 1. Map of the region and CTD stations used in sections 2 and 3. Triangles indicate stations used in Fig. 8, listed in Table 1. The small solid horizontal line on each meridional section indicates the location of the subarctic front. At the "152E" section, this is identical to the Oyashio front. The dashed horizontal lines indicate the northernmost occurrence of NPIW.

Pacific outside the Okhotsk Sea, this paper does not deal with ventilation. Instead, the questions are: (i) is the northwestern subtropical gyre the only site for formation of the salinity minimum (NPIW), and (ii) by what process is the salinity minimum formed? An important part of the latter question is what sets the density of the salinity minimum, since it is observed to lie within such a limited range over the entire subtropical gyre. Neither Reid (1965) nor Hasunuma (1978) showed the actual process whereby the salinity minimum is formed and hence a mechanism for setting the density. In this paper, it is concluded that the dominant formation process is subsidence at a front (primarily the Oyashio Front) of relatively fresh subpolar surface water beneath warmer, saltier water. It is hypothesized that the resulting very intrusive salinity minimum, which initially lies at the density of the local subpolar winter mixed layer, is quickly eroded from above, resulting in a salinity minimum at a higher density, which is the NPIW. This last process is not demonstrated here; CTD data from the region is currently being used to substantiate this hypothesis.

The lateral distribution of NPIW and properties on an intersecting isopycnal are presented in section 2, showing that the most extreme properties, suggesting formation of the salinity minimum, occur in the mixed water region between the Kuroshio Extension and Oyashio front, just east of Japan. Also considered in the second section are vertical CTD profiles crossing the NPIW's boundaries, showing that the most intrusive behavior at the NPIW density coincides with the lowest salinity and highest oxygen in the lateral distribution, hence strengthening the designation of the mixed water region as the formation site. The third section details hydrographic conditions in the mixed water region, to show that the winter surface properties of the subpolar waters may be the most important factor in determining the NPIW's density.

A map showing the principal geographic features and CTD stations used in the paper is shown in Fig. 1. The reader is referred to Reid (1965) for a discussion of the general circulation of the North Pacific in the NPIW density range and to Kawai (1972) for an exposition of the most common configuration of the complicated currents in the mixed water region, lying between the Kuroshio Extension and the Oyashio front.

2. North Pacific Intermediate Water properties

a. Horizontal maps

Using a selected, high-quality bottle dataset from J. Reid and A. Mantyla, augmented by bottle data from
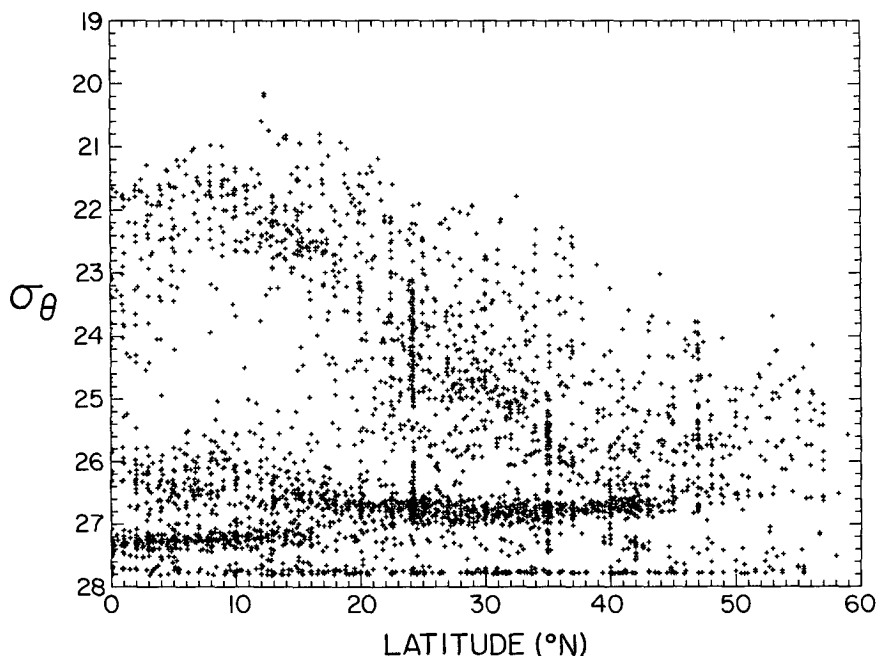

FIG. 2. All salinity minima in the North Pacific, using the data contoured in Figs. 3–7, regardless of longitude and excluding the Okhotsk and Japan seas. Salinity minima were obtained directly from the bottle data, regardless of magnitude of the minimum. NPIW is the dominant cluster, between 26.6 and 27.0 σ_θ and about 14°N and 45°N. Antarctic Intermediate Water is the cluster between 27.0 and 27.4 σ_θ, south of 16°N. The shallow salinity minimum is the group at lower densities with strong dependence of density on latitude. The SSM essentially follows the surface density. The tropical salinity minimum is the cluster between 25.9 and 26.7 σ_θ, south of about 17°N.
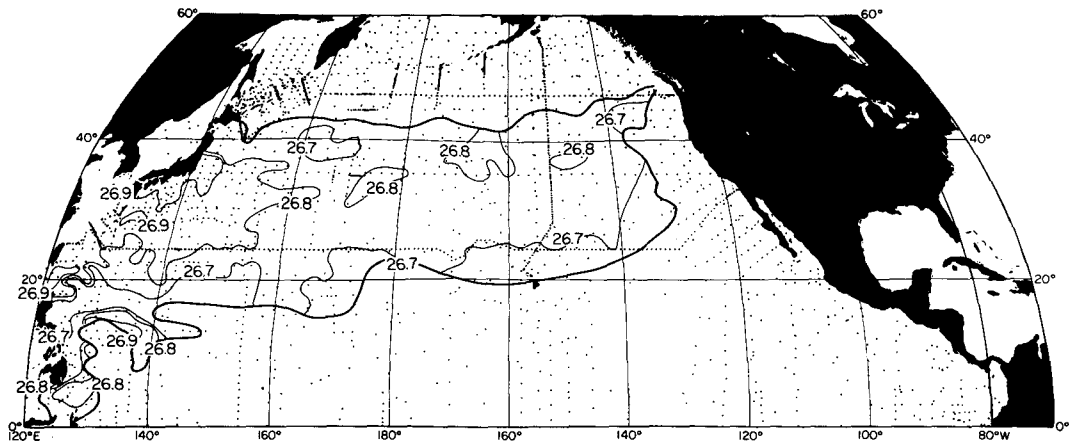
FIG. 3. Potential density, σ_θ, of North Pacific Intermediate Water, defined as all salinity minima in the density range 26.6 to 27.0 σ_θ, excluding salinity minima with very low oxygen near the eastern boundary. Multiple minima near Japan are discussed in section 3.

several recent trans-Pacific cruises, salinity minima in the North Pacific were identified and plotted as a function of latitude for all longitudes (Fig. 2). There are four identifiable groups of minima: Antarctic Intermediate Water (AAIW) south of about 16°N at σ_θ > 27.0; NPIW between about 14° and 45°N at 26.6 < σ_θ < 27.0; a diffuse tropical minimum south of 12°N with a broad density range of 25.8 to 26.6 σ_θ; and a shallow minimum (SSM) at all latitudes with a broad density range of 21 to 26.8 σ_θ. The SSM north of 20°N and the tropical salinity minimum were assumed to be directly connected by Reid (1973), Tsuchiya (1982), and Talley (1985). However, in Fig. 2, in which a large amount of well-distributed, high-quality data is used, the subtropical SSM is connected instead with a very shallow, low-density salinity minimum above the strong tropical salinity maximum, and the tropical salinity minimum appears connected to the NPIW. Yuan and Talley (1992) show that the tropical minimum is

created when very saline water from the eastern tropics undercuts the low salinity water mass created by merging NPIW and SSM on the southern side of the subtropical gyre.

Based on Fig. 2, a wide density range of 26.6 to 27.0 σ_θ was chosen in which to search for NPIW. All salinity minima in this density range were used to map NPIW properties (Figs. 3–5). Remarkably few multiple minima at individual stations were found and the resulting density and salinity distributions were easy to contour. Most multiple minima occurred in the mixed water region between the separated Oyashio and Kuroshio fronts just east of Japan; these will be discussed in section 3. Where multiple minima occurred, the selection for Figs. 3–5 was based on continuity with surrounding stations.

The location of NPIW is clear from the contoured region of Fig. 3. It is confined primarily to the subtropical gyre and, in particular, to north of 15°–20°N,
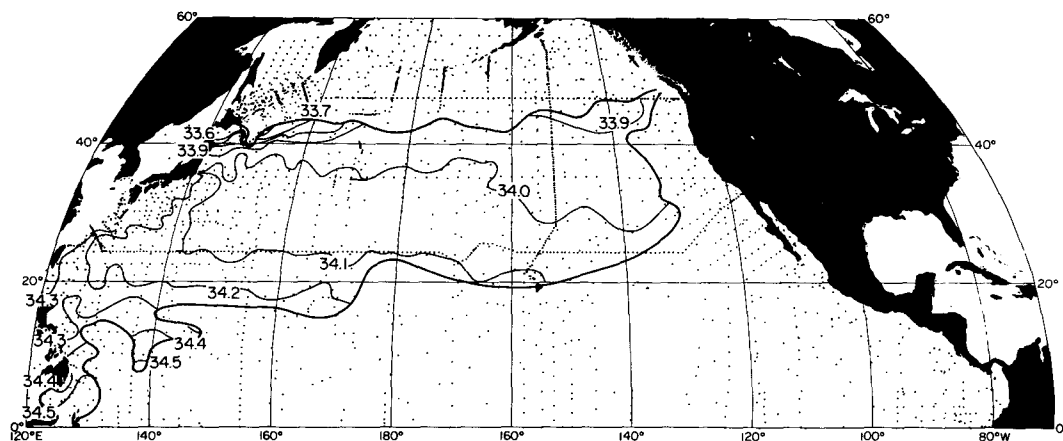

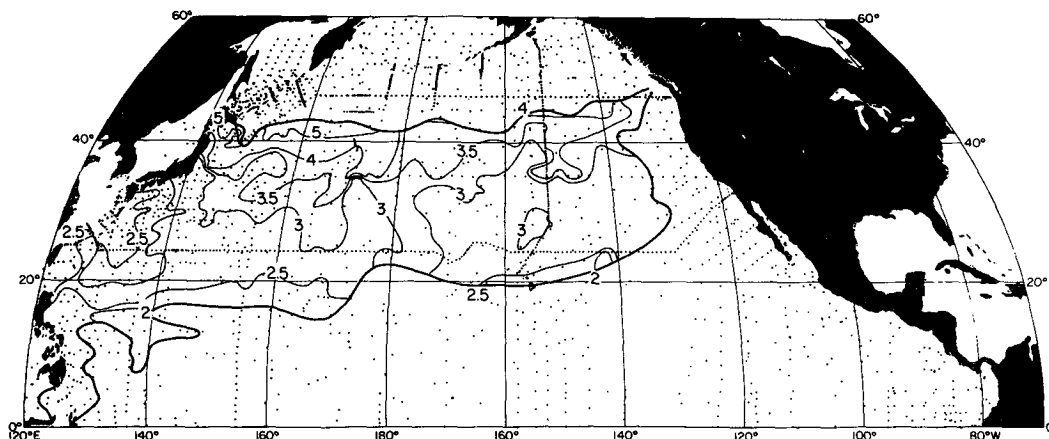FIG. 4. Salinity (‰) of the North Pacific Intermediate Water as defined in Fig. 3.

FIG. 5. Oxygen (ml/l) of the North Pacific Intermediate Water as defined in Fig. 3.

even though the gyre extends southward to about 12°N at the sea surface (Wyrtki 1975). This reflects the northward shift of the southern edge of the gyre with increasing density, which is evident in the potential vorticity distribution on the relevant isopycnals (Talley 1988). (It is noteworthy that the salinity minimum identified as NPIW does not extend south of the gyre, except at the western boundary.) The exact location of the southern boundary of the NPIW is likely to be time dependent; very recent CTD sections at 135° and 150°W (summer 1991) show it several degrees farther south than in the dataset used for Fig. 3.

At its northwesternmost location in Fig. 3, the NPIW is found in the mixed water region between the Kuroshio and Oyashio fronts just east of Japan. This region is also called the "perturbed area" (Kawai 1972). Large-scale dynamic topographies (Reid 1965; Wyrtki 1975) show an overall dividing "streamline" between the subtropical and subpolar gyres originating at about 40°N off the coast of Japan, in the northern mixed water region near the usual location of the Oyashio intrusions, where the Oyashio leaves the western boundary (Kawai 1972). This is close to the zero of annual mean Sverdrup transport (Talley 1985) although the seasonal migration of this zero is large (Hellerman and Rosenstein 1983). The mixed water region is mainly located south of the zero Sverdrup transport but is also north of the zero of wind-stress curl. The mixed water region is therefore technically in the subtropical gyre, although Sverdrup transport is northward in this region. Inertial dynamics is likely to overwhelm Sverdrup dynamics here, but the coincidence of the mixed water region and the region between the zeros of wind curl and Sverdrup transport is intriguing.

NPIW is found throughout this mixed water region. By the formal definition of the previous paragraph, this is within the subtropical gyre. The farthest north that NPIW has been observed in this area is in the warm core eddy that is often located between the first

and second intrusions of the Oyashio, just east of Hokkaido (e.g., Talley et al. 1991).

The eastern termination of NPIW is just west of the broad California Current region. Although there are scattered and weak salinity minima in the appropriate density range in the California Current (about one station with a salinity minimum for four without), oxygen saturation is much lower than in the contoured region. Because of the great coherence of NPIW from station to station within the contoured NPIW region, the lack of coherence, and the weakness of the salinity minima in the California Current as well as their low oxygen, these scattered stations have been excluded from the contoured region. These minima may be created locally (Huyer, personal communication 1991). The exact location of the eastern NPIW boundary can shift several degrees but is well defined and near the location shown, based on several synoptic CTD sections over the years through the area (Yuan, personal communication, 1991).

The northern boundary of the NPIW is roughly coincident with the subarctic front, particularly in the western Pacific, as discussed below. In the eastern Pacific, however, NPIW extends several degrees north of the subarctic front. The extension of the NPIW region to the northeast appears to be real, based on the stations at 47°N (Fig. 1) and others. Musgrave et al. (1992) have reported that a salinity inflection at the NPIW density is found around the eastern side of the Gulf of Alaska, which may be the result of this apparent northward intrusion into the subpolar gyre in the east.

An interesting part of the NPIW distribution in Fig. 3 is the tongue along the Philippines, coinciding with the Mindanao Current. Careful examination of stations in this region indicated that the contoured salinity minimum is not being confused with AAIW and that it is confined near the western boundary. Lukas et al. (1991) remarked on the presence of NPIW in this region and showed that much of it is of lower density than shown in Fig. 3 due to truncation from below.
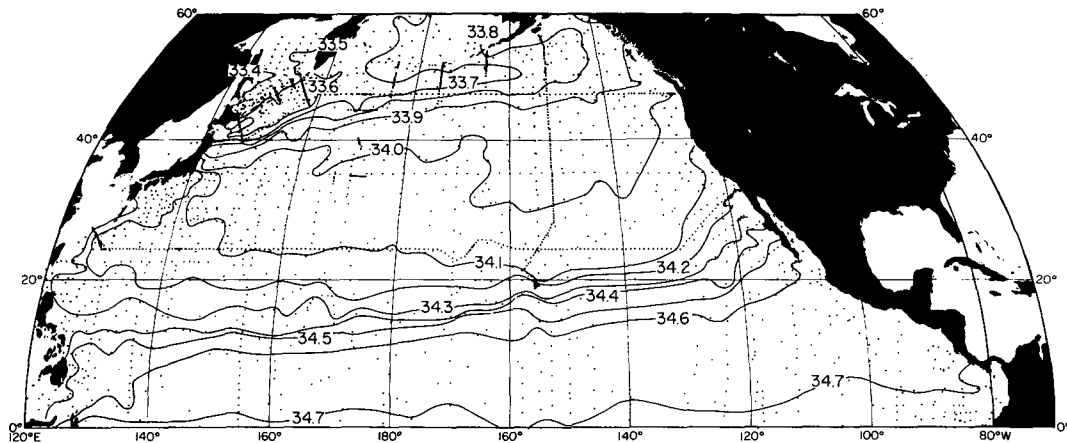
FIG. 6. Salinity (‰) at 26.8 σ_θ.

The density of NPIW is mainly between 26.7 and 26.8 σ_θ (Fig. 3), with lower density on the northern side. In the western part of the gyre, its density exceeds 26.8 σ_θ; near the western boundary, its density can exceed 26.9 σ_θ. Similarly high density NPIW off southern Honshu was mapped by Yang and Nagata (1992).

NPIW salinity (Fig. 4) is lowest (<33.8 psu) in the northwest, in a narrow band stretching eastward from Hokkaido, and is less than 34.0 psu all along the northern and eastern sides. Salinity increases in the interior and is highest in the North Equatorial Current (along 18°N) and Kuroshio (along the western boundary). The highest salinities are found in the Mindanao Current, but this water does not appear to flow back into the subtropical gyre.

Dissolved oxygen concentration in the NPIW (Fig. 5) shows a pattern similar to that discussed for salinity, with the highest values off Hokkaido, generally high values in the north and lowest values in the south and west.

It is not appropriate to consider the NPIW to be a

surface of flow since the density of the salinity minimum can be changed by mixing. It is useful, therefore, to look at properties on isopycnals that intersect NPIW, since density is expected to be better conserved following a water parcel than a vertical salinity minimum. Reid (1965) chose the 125 cl t^{-1} isanostere, which corresponds to 26.83 σ_θ using the 1980 equation of state. Because most of the NPIW lies between 26.7 and 26.9 σ_θ, Reid's choice was reasonable. Hence, properties are displayed at 26.8 σ_θ (new equation of state) in Figs. 6 and 7; salinity at 26.8 σ_θ (Fig. 6) is slightly different from Reid's (1965), mainly because new datasets are included rather than because of the new equation of state. An important feature is the southward extension of low salinity in the eastern subtropics, which was also mapped by Sverdrup et al. (1942). This is found on all neighboring isopycnals and also at the NPIW (Fig. 4). The high meridional salinity gradient south of 20°N coincides with the southern extent of NPIW. As remarked in Reid (1965), high salinity is found in the California Current region since this isopycnal lies in
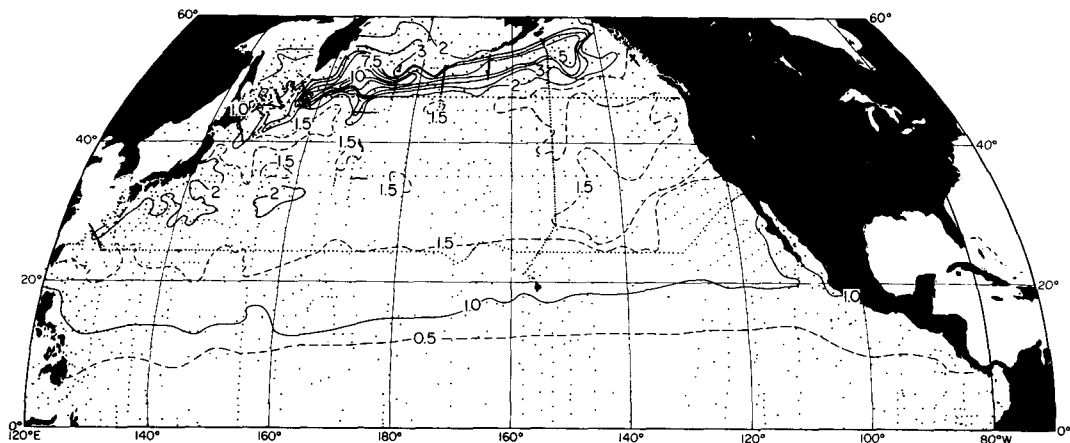
FIG. 7. Isopycnic potential vorticity, $(f/\rho)(\partial\rho/\partial z)$ ($\times 10^{-12}$ cm^{-1} s^{-1}) at 26.8 σ_θ.

the poleward undercurrent. The oxygen distribution at 26.8 σ_θ is not shown because it does not differ in any significant way from Reid's except in the Okhotsk Sea (Talley 1991).

Thus, the salinity and oxygen distributions both in the NPIW and on intersecting isopycnals show freshest and most oxygenated water in the northwestern part of the NPIW; that is, in the northern part of the mixed water region. This suggests that this region is the source of NPIW for the subtropical gyre.

Isopycnic potential vorticity $(f/\rho)(\partial\rho/\partial z)$ independently indicates the extent of surface influence. It is conserved following isopycnic flow, assuming the flow is inviscid and nondiffusive and that relative vorticity is small. Maps of this vertical stretching part of potential vorticity, Q, at many densities were shown by Talley (1988). The previous maps were based on the heavily smoothed Levitus (1982) data and hence, are most accurate in midocean. The 26.8 σ_θ map showed a broad region of reduced Q gradients between 20° and 45°N. The new map based on individual stations (Fig. 7) differs in some remarkable ways from that based on averaged data. For instance, not only is the gradient of Q low in midocean in Fig. 7, but it was nearly impossible to contour Q between the values 1.25 and 2.0 $\times$ 10^{-12} (cm s)$^{-1}$—that is, in most of the region between 20° and 45°N. Relative vorticity is negligible in the interior of the gyre, so the mapped quantity is representative of the full potential vorticity. The region of nearly homogeneous Q is predicted by the Rhines and Young (1982) circulation model for interior (nonoutcropping) isopycnal layers and is identified as the location of the wind-driven circulation at this density. The high meridional gradients to the south indicate the southern extent of the subtropical circulation at 26.8 σ_θ, south of which the wind-driven flow is expected to be small.

The band of very high Q in the subpolar gyre, on the other hand, does not indicate a boundary for wind-driven flow on a subsurface isopycnal. The isopycnal 26.8 σ_θ is close to the sea surface here, so the high Q suggests influence from surface processes. This identification is strengthened by noting that Q is highest where the isopycnal is shallowest. [See Reid (1965) for the depth of the 125 cl t^{-1} surface.] While calculations show that open-ocean outcropping at 26.8 σ_θ may occur in the northeast Pacific (VanScoy et al. 1991), such outcropping has not been observed, and vertical mixing is indicated as the main process modifying properties at this density (also Van Scoy et al. 1991). This isopycnal has thus far been observed to be separated from the surface by an intense pycnocline, so I suspect that the high Q band is a subsurface expression of Ekman pumping and perhaps enhanced vertical mixing.

A remarkable feature of the potential vorticity map based on individual stations is its structure near the western boundary where relative vorticity is expected to be important. The subtropical gyre's western boundary current, the Kuroshio, and its offshore extension are marked by high Q. The subpolar gyre's western boundary current, the Oyashio, has low Q: the lowest Q north of 15°N is found in the Okhotsk Sea and in its outflow in the Oyashio. The Bering Sea also has relatively low Q, but this may only be in contrast with the central subpolar gyre's very high Q. This observed pattern of isopycnic Q is the opposite of what is expected for the total potential vorticity, with the Kuroshio advecting low potential vorticity northward and the Oyashio advecting high potential vorticity southward. Similar patterns are found at 26.7 and 26.9 σ_θ. The neglect of relative vorticity in calculating Q probably causes the observed pattern in these strong currents.

The Q distribution at 26.8 σ_θ thus indicates wind-driven circulation isolated from outcropping in the open North Pacific; details in the Okhotsk Sea and near the western boundary are obscured because of the lack of relative vorticity in the calculation. Strong forcing at 26.8 σ_θ occurs in the northern subpolar gyre, where the isopycnal is pulled up into the intense halocline, where it must be subject to strong vertical diffusion. The uniformity of Q in the subtropical gyre suggests that if there is a steady leakage of water from the subpolar gyre near the western boundary, isopycnic mixing overwhelms whatever potential vorticity signature is carried by the northern water, suggesting that the southward transport of northern water is possibly low, certainly in comparison with the Labrador Sea Water in the North Atlantic.

b. Vertical structure through the NPIW

CTD profiles collected along meridional and zonal sections (Fig. 1 and Table 1) provide additional evidence of the importance of the mixed water region in the formation of NPIW. Figure 8 is a mosaic of selected σ_θ/salinity profiles from each of the cruises in Fig. 1; in each panel, all stations are adjacent and were collected in no more than four consecutive days. Except for the stations at 152°E (Fig. 8.6), the center row (Fig. 8.7–8.10, numbers following decimal identity panels) is archetypical NPIW; at these locations, the profiles are very smooth through the salinity minimum, with little station-to-station variability. A slight tendency toward higher salinity in the west, as seen in Fig. 4, would be apparent if the panels were overlain.

The bottom row (Fig. 8.11–8.13) shows NPIW in various stages of being broken up or modified at its southern and eastern periphery. Here the salinity minimum is more variable from one station to the next than in the central subtropical gyre. (At the scale of Fig. 8, this variability is difficult to distinguish.) In the east and just north of the Hawaiian Islands, the σ_θ/ salinity profile is "blocky" due to breakup of both NPIW and the overlying shallow salinity minimum (Reid 1973). Lukas and Chiswell (personal commu-
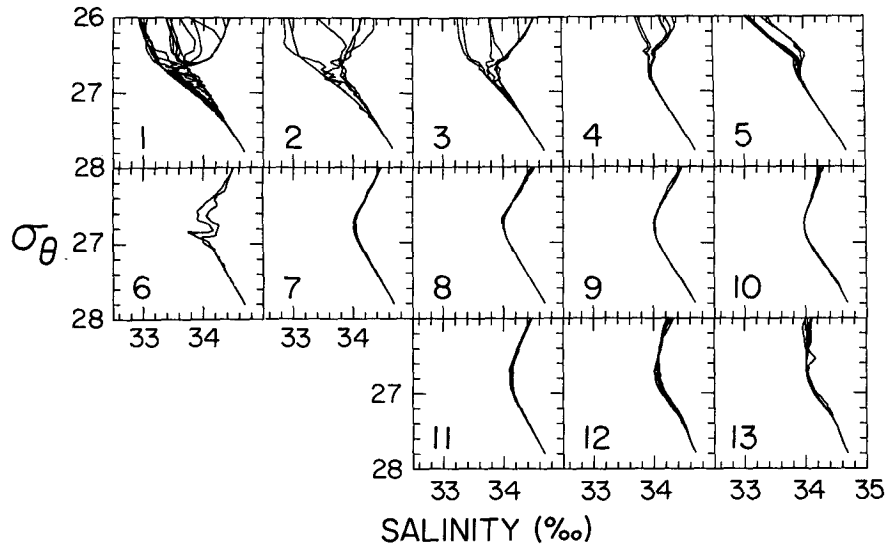
FIG. 8. Properties from the CTD sections shown in Fig. 1 and listed in Table 1. Stations for the top row (1–5) were chosen to be from 1° north to 2°S of the northernmost occurrence of NPIW. The Kuroshio stations (6) were chosen from the very center of the current. Stations in the second row (7–10) cover approximately three degrees of latitude in the central NPIW. Stations in the bottom row (11–13) were chosen from close to the southern boundary of the NPIW.

nication, 1991) report singular intrusions at the NPIW density at the Hawaii Ocean Time Series (HOTS) at 22°45'N, 158°W. Given the proximity of HOTS to the NPIW boundary, the observation is very likely of the breakup of NPIW. A hydrographic section southeast of the island of Hawaii, in September 1991, showed similar intrusive NPIW structure at 17°20'N, 153°20'W. The NPIW disappeared 30 n mi south of that station. This southern NPIW boundary is several degrees south of the NPIW boundary shown in Fig. 5 and probably reflects time dependence as well as much better spatial sampling on the 1991 section. A similarly well-defined eastern boundary for the NPIW was found along the densely sampled section at 24°N, for which data are included in Figs. 4–7.

The upper row (Fig. 8.1–5) shows NPIW at its northern boundary. For each section, the northernmost station with NPIW was identified, and all stations within 1° north and 2° south were plotted. This provides examples of subpolar water north of the NPIW for comparison. The Oyashio Extension or subarctic front, whichever is appropriate, is indicated for each meridional section in Fig. 1. The front was identified by the onset of a sharp halocline and temperature minimum to the north in the uppermost layer—it occurred at nearly the same latitude on all of these sections. The most obvious observation from Fig. 8.1–5 is that the two westernmost groups of stations, from "47N" and "152E", have the widest range of salinity at NPIW densities and the most intrusive-looking, sometimes

TABLE 1.

Section	Ship	Dates	Reference	Station group (Figs 1 and 8)	Station numbers
47°N	T. Thompson	8/5/85–9/7/85	Talley et al., 1991	1	14–28
152°E	T. Thompson	5/25/82–6/5/82	Niiler et al., 1985	2	24–29
152°E	T. Thompson	5/25/82–6/5/82	Niiler et al., 1985	7	3–8
152°E	T. Washington	5/13/81–5/28/81	Niiler et al., 1985	6	15–16
165°E	T. Thompson	9/23/84–10/28/84	Joyce, 1987	3	21–27
165°E	T. Thompson	9/23/84–10/28/84	Joyce, 1987	8	5–10
175°W	T. Thompson	10/30/83–11/8/83	Joyce, 1987	4	3–8
175°W	T. Thompson	10/30/83–11/8/83	Joyce, 1987	9	17–22
152°W	T. Washington	5/5/84–6/2/84	Talley et al., 1991	5	60–66
152°W	T. Washington	5/5/84–6/2/84	Talley et al., 1991	10	28–34
152°W	T. Washington	5/5/84–6/2/84	Talley et al., 1991	13	1–7
24°N	T. Thompson	3/29/85–6/4/85	Roemmich et al., 1991	11	293–305
24°N	T. Thompson	3/29/85–6/4/85	Roemmich et al., 1991	12	62–74

multiple, salinity minima. Both groups cross the Oyashio, at the northern boundary of the mixed water region of the Oyashio and Kuroshio. The "47N" stations also cross into a warm core ring that is often present off Hokkaido, separating the two Oyashio intrusions (Kawai 1972).

The σ_θ/S relations at the northernmost station groups at 165°E, 175°W, and 152°W are progressively smoother to the east. While the NPIW terminates at about 41°N at 165°E and 175°W, coinciding with the subarctic front, at 152°W it terminates (44°N) several degrees north of the front (41°N) where it lies under a pronounced layer of subpolar surface water. There are at least two possible explanations for this lack of coincidence: (i) subtropical waters are moving northeastward below the surface layer across the annually averaged subtropical–subpolar gyre boundary or (ii) the subarctic front lies south of the gyre boundary, as suggested by the dynamic topographies and Sverdrup transport, while the northern limit of NPIW is more closely linked to the gyre boundary.

Thus, NPIW along its northern boundary in the central and eastern Pacific has the same character as NPIW in the central subtropical gyre, differing only slightly in properties, as already seen in Figs. 3–5. In the western North Pacific, on the other hand, NPIW is very "intrusive" at its northern boundary, with sharp features in σ_θ/S and superimposed smaller-scale variability. The northwestern region of the subtropical gyre is also where the NPIW has the lowest salinity and highest oxygen laterally (Figs. 4 and 5); hence the conclusion that NPIW is formed in this region and advected eastward, while subject to mixing that reduces its intrusiveness and extreme properties. Vertical and lateral mixing may continue to affect NPIW after it is smoothed, but the mixing acts on much lower salinity gradients.

3. Oyashio/Kuroshio mixed water region

A more detailed examination of the Oyashio/Kuroshio mixed water region is warranted by the extrema in salinity, oxygen, and "intrusiveness" that characterize NPIW there; this region is bounded by the Oyashio Extension at about 42°N, the Kuroshio Extension at about 36°N, and Honshu to the west. The eastern "boundary" of the mixed water region is ill defined but is located around 150°E. The extrema described in the previous section suggest that NPIW formation occurs primarily in this region, as suggested by Hasunuma (1978). The features of the circulation in the upper waters in this zone were described by Kawai (1972). Dynamic topography at the sea surface relative to 500 dbar for late winter 1966 (Fig. 11a) is typical. This dataset was also used in Hasunuma's account of the region, to which the reader is referred for a more thorough description. The Kuroshio Extension separates from the Japan coast at about 141°E, often with

a large northward meander before heading eastward. In the north, the Oyashio commonly forms two lateral intrusions, the "first" just off the coast of Hokkaido and the "second" offshore at about 146°E. When present, the two Oyashio intrusions are separated by anticyclonic flow around water of much more subtropical properties than the subpolar Oyashio waters. At 150°E, the Oyashio Front extends eastward about 5° north of the Kuroshio Extension.

As mentioned above, only one salinity minimum identified as NPIW is found throughout most of the subtropical Pacific, allowing NPIW properties to be easily mapped. However, in the mixed water region the simple procedure of choosing all salinity minima in the density range of, say, 26.4 to 27.2 σ_θ, in order to find the NPIW, results in multiple minima that were simplified to produce Figs. 3–5. Multiple minima are best described from CTD data, but such data were more difficult to obtain in quantity for this region than the archived bottle data, of which there are tens of thousands of stations. As seen below, most of these multiple minima arise from slight variations in the surface mixed layer, overlying a single significant minimum, with true multiple minima found at only a few stations.

a. Composite data in the mixed water region

The many bottle observations in the mixed water region can be combined in composite property plots showing the average behavior of waters there. Potential density, σ_θ, plotted versus salinity (Fig. 9a) for all available National Oceanographic Data Center (NODC) data in March from each 2° lat by 2° long box shows how the properties vary on average across the region. March oxygen is a good independent property (Fig. 9b), indicating recent ventilation and clearly differentiating the water masses. Composite potential temperature/salinity relations (not included) show one additional important feature: a temperature minimum characteristic of subpolar water. Based on the relations shown in Fig. 9, four water "masses" were identified (Fig. 10). The nomenclature refers to portions of the vertical profiles, rather than to a full station. This differs from Hasunuma's (1978) approach, in which full stations were grouped as subtropical, subpolar, and interfrontal and is somewhat more precise in defining the source of water in the mixed water zone where a given station might have "subtropical" water at the surface, a layer of "transition" water below, and "subpolar" water below that. The water masses are

1) *Subpolar water:* monotonically increasing salinity with increasing density/high oxygen at low density proceeding smoothly to the oxygen minimum. An example is 42°–44°N, 148°–150°E. Subpolar water is present alone in the northeast but is also found throughout the mixed water region, as far south as the 34°–36°N box just east of Japan.
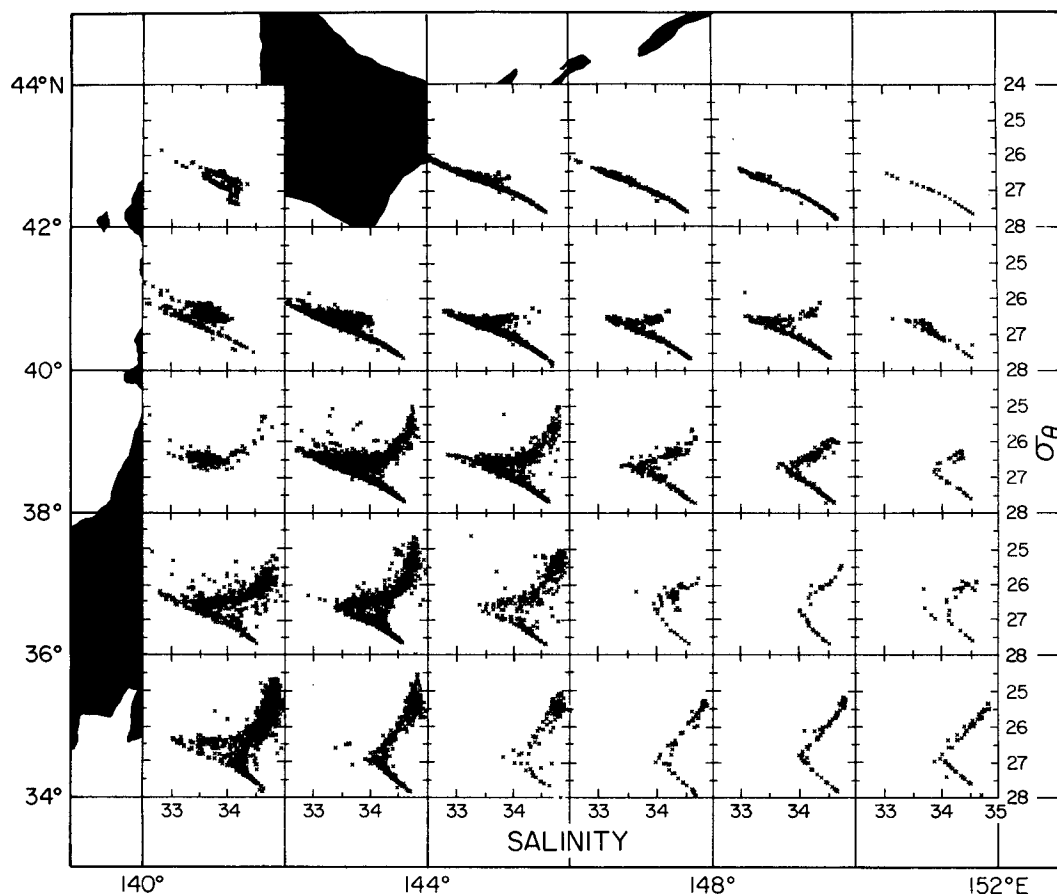
FIG. 9. (a) March σ_θ vs salinity and (b) March oxygen vs salinity
from all Japanese bottle data in the NODC archives.

2) *Subtropical water:* well-defined but rounded sa-
linity minimum (NPIW), with NPIW salinity greater
than about 33.8‰ and high oxygen at high salinity,
proceeding around a curve through the NPIW salinity
minimum to the oxygen minimum. An example is
34°–36°N, 144°–146°E. Subtropical water is found
south of 36°N (the Kuroshio Extension) and is ad-
vected up into the mixed water region, to 40°N west
of 146°E, by the warm core ring often found there.

3) *Transition water:* well-defined branch connecting
low-density, low-salinity, high-oxygen subpolar near-
surface water to lower-density, high-salinity, high-ox-
ygen subtropical near-surface water. Good examples
are 40°–42°N, 148°–150°E, and 36°–38°N, 140°–
142°E. It appears to be a mixture of the winter surface
subpolar and subtropical waters. Winter modification
of warm-core ring surface water is also an important
process in producing the portion of the transition water
that is actually of higher salinity than subtropical water
at the same density (Yasuda et al. 1991), as seen in
Fig. 9a for 36°–38°N, 142°–144°E.

4) *Tsugaru water:* cluster at 26.1–26.6 σ_θ, 33.5–34.0
psu, 6.5–8.0 ml l^{-1}. An example is the cluster at 40°–

42°N, 140°–142°E. Tsugaru Water matches the fresher
part of the transition water, so it is difficult to determine
how much of the transition water has Tsugaru origin.
Tsugaru Water is significantly more saline than sub-
polar water at the same density, because of the high
salinity of the Sea of Japan. At 40°–42°N, 140°–142°E,
near Tsugaru Strait, superposition of Tsugaru and sub-
polar waters leads to a pronounced salinity maximum
and minimum at the interface between them. The
density of the interface is set by the 130-m deep sill in
Tsugaru Strait. The density at the sill is about 26.5 σ_θ,
based on examination of historical data in the strait;
this matches the density of salinity minima found just
east of the strait. Because of low transport through
Tsugaru Strait (Kawai 1972), Tsugaru Water is not
commonly found east of the southernmost point of
Hokkaido, and the warm saline water commonly found
separating the two Oyashio intrusions is generally of
subtropical rather than Tsugaru origin (Nagata, per-
sonal communication 1991).

The gap in the center of the average property plots,
between subtropical, subpolar, and transition waters,
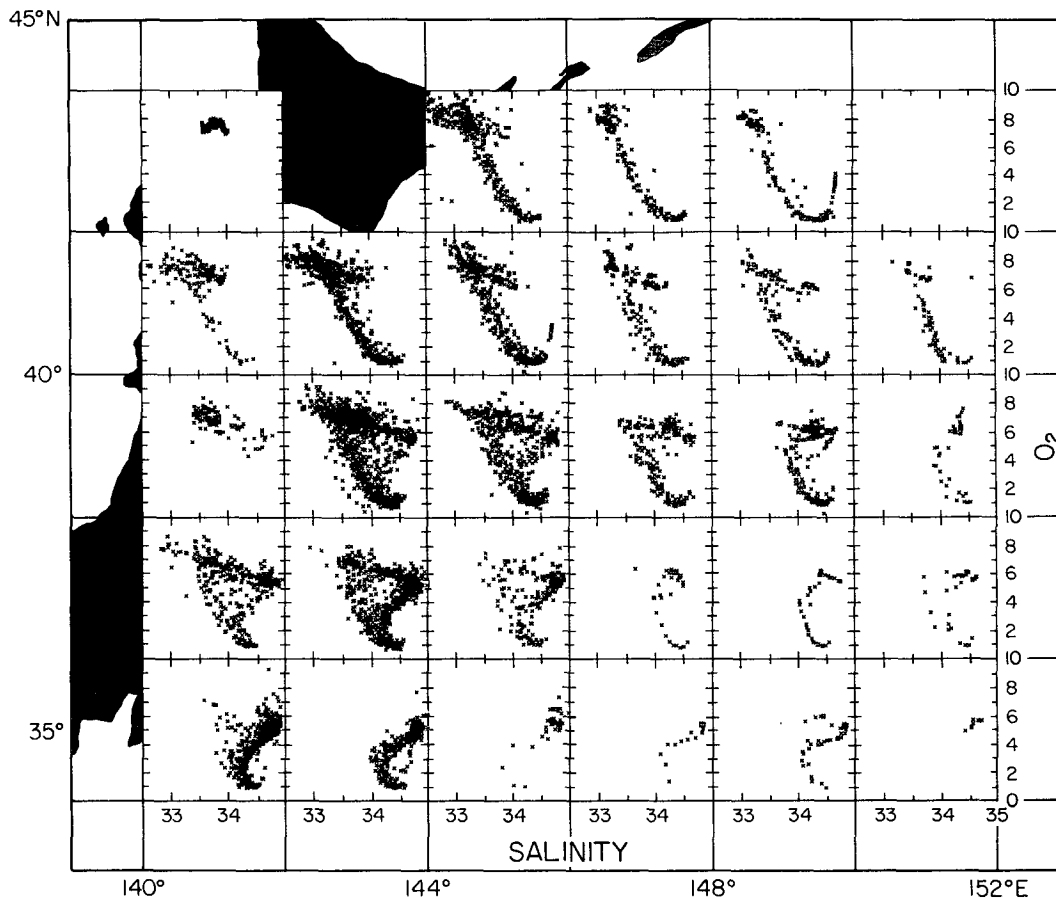is remarkable given the vigorous mixing in the region

FIG. 9. (Continued)

and indicates that most mixing and modification occurs near the surface layer. However, vertical juxtoposition of the different water masses is common. A typical station in the mixed-water region will contain a surface point at relatively high salinity, proceed down through the transition water to a salinity minimum, still at high oxygen, and then follow the subpolar relation on downward to higher density and lower oxygen. The local salinity minimum is thus often at the base of the high-oxygen surface layer, which itself is a mixture of subtropical and subpolar surface waters.

Stations in the region 38°–40°N, 148°–152°E and 36°–38°N, 146°–150°E cannot be classified by the four types listed above. Instead, these can be taken to include archetypical new NPIW, formed from erosion of the sharper, low-density salinity minima lying close by to the west and north. In the basinwide distributions of salinity and oxygen at the NPIW (Figs. 4 and 5), it is apparent that this is the appropriate latitude and region for NPIW origination, and the oxygen and salinity values of the composite stations' NPIW matches the basinwide distributions in this region. However, if a definition of NPIW is based on Figs. 4 and 5, that is, with salinity less than 34.0 psu and oxygen greater than 4.0

ml l^{-1}, new NPIW is found in all 2° squares in the mixed water region.

b. Synoptic data in the mixed water region

Because of the prevalence of large eddies and meanders in the mixed water region, detailed study requires quasi-synoptic surveys. The February, March, and April stations were selected because of the expected importance of winter conditions. The years 1966, 1971, 1972, and 1973 were chosen. The first was chosen because of good spatial station coverage; these data were used in Hasunuma's (1978) work and in a previous study of the Okhotsk Sea's influence (Talley 1991). The latter three years were chosen because they were densely sampled, although not as far east as in 1966. The great majority of the stations are from a few Japanese ships that routinely make measurements in this region, with a few stations from the R/V Argo in 1966 (Reid 1973).

Potential density as a function of latitude for all salinity minima from the four winters (Fig. 12) has three rough clusters, which vary little from one year to the next. South of the Kuroshio Extension (35°–36°N),
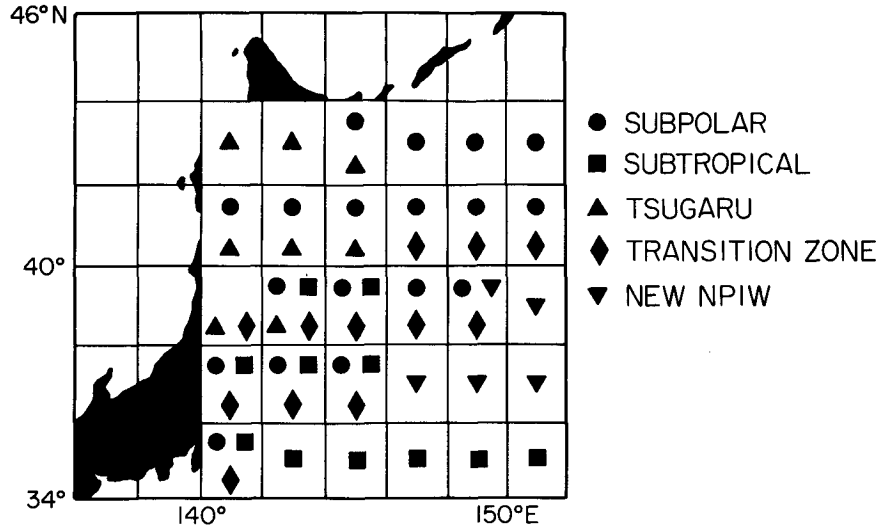
FIG. 10. Classification of the types of water present in 2° latitude by 2° longitude regions, based on properties in Fig. 9. "New NPIW" is a very loose definition and could be indicated in most 2° squares in the mixed water region.

minima are in the rough ranges of 26.6–27.2 σ_θ or 24.4–25.5 σ_θ. The latter less dense group is in the thick, well-mixed upper layer where minima are not well defined, arising only from fluctuations in the low, vertical salinity gradient. The denser cluster is old, classical NPIW, with salinity between 34.1 and 34.3 psu and oxygen mostly below 60% saturation (Fig. 13). In the mixed water region north of the Kuroshio Extension, the minima cluster roughly between 26.2 and 26.8 σ_θ, thus are slightly less dense than to the south. Salinity is much lower and more scattered here than south of the Kuroshio; oxygen is correspondingly high.

Winter 1966 was selected for greater description because station coverage extended east to 148°E. All salinity minima, in 0.01 σ_θ ranges from 26.2 to 27.2 σ_θ, were found and plotted (Fig. 14). The outermost ranges

(26.2–26.3 and 27.1–27.2 σ_θ) had few minima and are not shown. In each σ_θ range, regions where a minimum was found were connected, if not separated, by stations without a minimum; because of the gappy coverage this could be misleading, but the results are probably fairly representative of how widespread and coherent the minima are in each density range. As was apparent in Fig. 12, salinity minima less dense than 26.7 σ_θ are found in the mixed water region, with minima at 26.7–26.8 and 26.8–26.9 σ_θ found both north and south of the Kuroshio Extension. The densest salinity minima are found only in and south of the Kuroshio Extension. The minima north and south of the Kuroshio Extension are quite separate, based on salinity and oxygen on isopycnals intersecting them, such as at 26.74 σ_θ (Fig. 15).
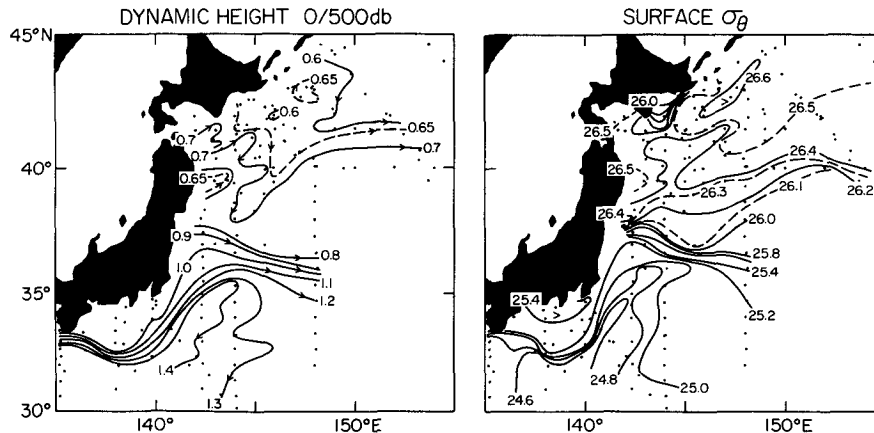

FIG. 11. (a) Dynamic height at the sea surface relative to 500 dbar and (b) surface density σ_θ for February, March, and April 1966 bottle data.
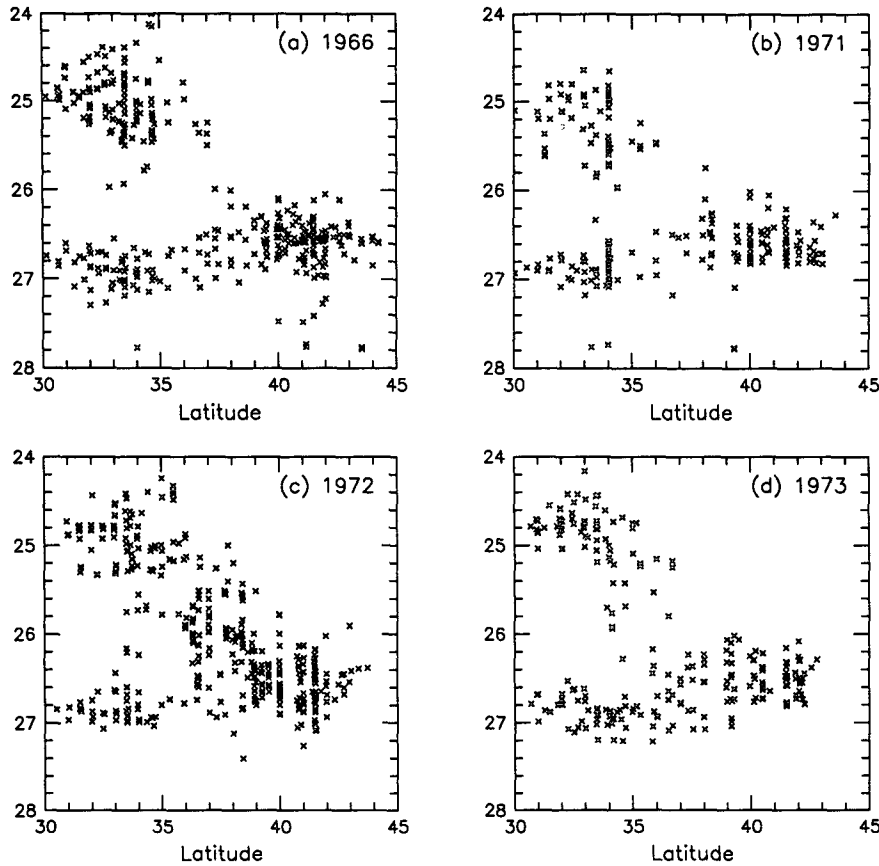
FIG. 12. Density σ_θ of all salinity minima in the Kuroshio/Oyashio region, using data from February, March, and April for (a) 1966, (b) 1971, (c) 1972, and (d) 1973.

In Fig. 14, minima in the range 26.6–26.7 σ_θ in 1966 in the mixed water region were very patchy compared with higher and lower densities. This was also true for the winter 1973 survey and to a lesser extent for 1971 but not for 1972. This suggests different formation mechanisms for the minima, less dense than about 26.6 σ_θ and denser than about 26.7 σ_θ; this happens to be the division between isopycnals that outcrop regularly

in winter from those that do not. To better study this, a representative group of the 1966 stations (80 of the 253 stations) was examined, examples of which are shown in Fig. 16. Oxygen saturation was also essential in categorizing minima.

Salinity minima in the region just east of Japan in winter 1966 can be separated into five types as indicated below. At the 80 closely examined stations from winter
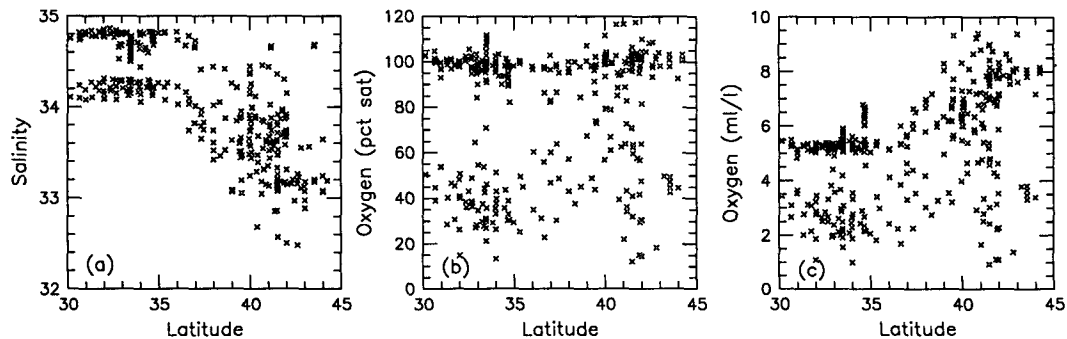

FIG. 13. (a) Salinity, (b) oxygen (% saturation), and (c) oxygen (ml l^{-1}) of all salinity minima for the February, March, and April 1966 dataset used for Fig. 11a.
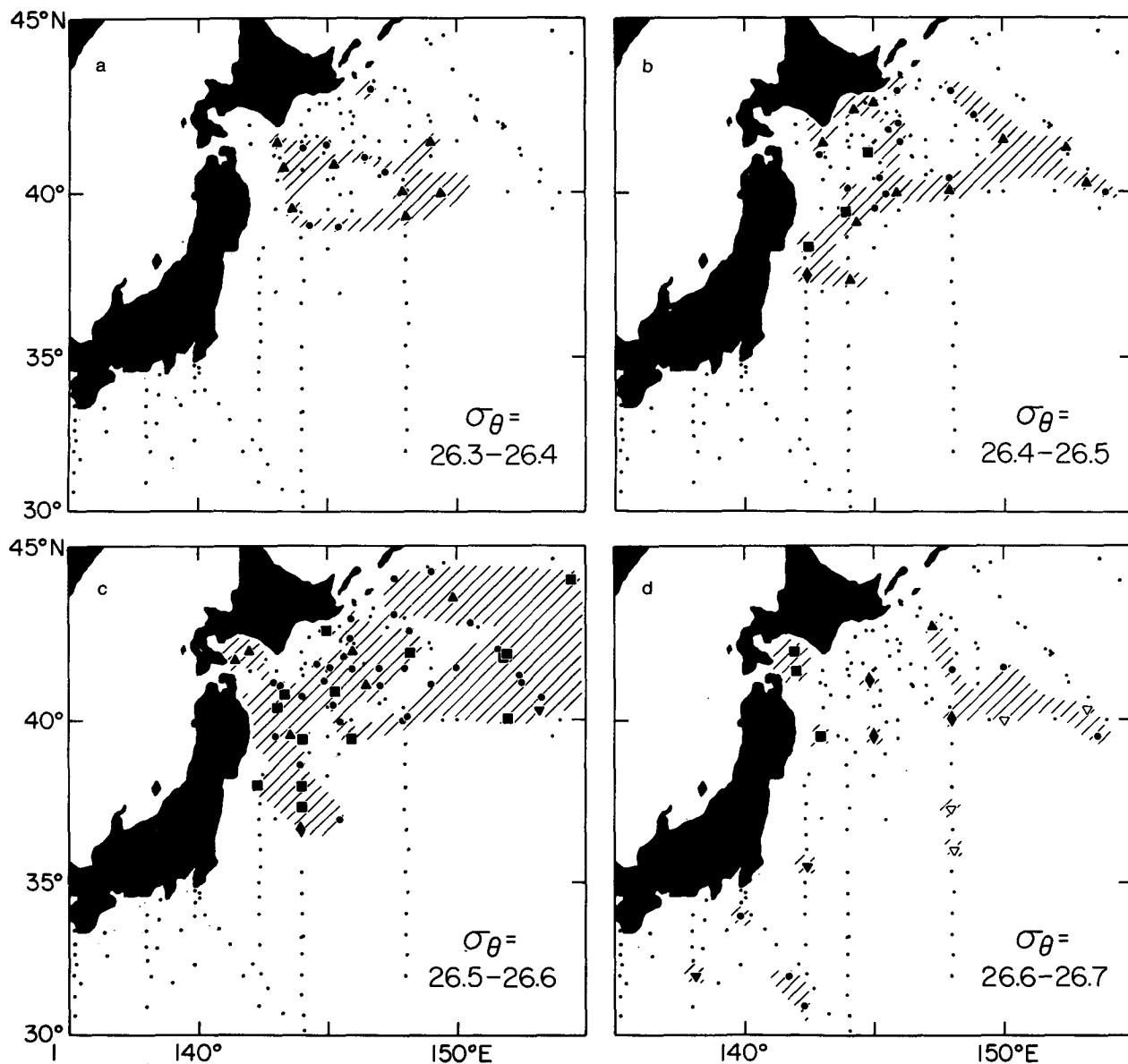
FIG. 14. Salinity minima for February, March, and April 1966 found in potential density ranges of 0.01 σ_θ: (a) 26.3–26.4 σ_θ, (b) 26.4–26.5 σ_θ, (c) 26.5–26.6 σ_θ, (d) 26.6–26.7 σ_θ, (e) 26.7–26.8 σ_θ, (f) 26.8–26.9 σ_θ, (g) 26.9–27.0 σ_θ, and (h) 27.0–27.1 σ_θ. Large symbols indicate stations at which salinity minima occurred. Based on the latter stations, the type of salinity minimum was identified as a negligible surface mixed-layer minimum (triangle); strong minimum near the base of the mixed layer (square); intrusive minimum below the mixed layer, with temperature minimum (diamond); sharp salinity minimum (NPIW), with no temperature minimum (open inverted triangle); and smooth salinity minimum (NPIW), with no temperature minimum (inverted triangle). Large circles are minima that were not examined individually so were not classified.

1966 the type of salinity minimum is indicated on the maps in Fig. 14. In this highly variable region, almost every station is unique and classification as one of these five types is sometimes quite subjective.

1) *Slight variations in the well-mixed layer* produce insignificant salinity minima (Figs. 16c, f and triangles in Fig. 14). Comparison of the density of these minima and the surface density (Fig. 11b) shows that all are within 0.01 σ_θ of the surface density; many are actually

reported at lower density than the surface density, suggesting that the salinity differences are within the measurement error. All minima with oxygen saturation in excess of 100% north of the Kuroshio Extension, all minima in the least dense cluster south of the Kuroshio Extension (in Fig. 12a), and all minima with potential density less than 26.45 σ_θ are in this category.

2) *Minima at the base of the oxygen-saturated surface layer* (example in Fig. 16a and squares in Fig. 14)
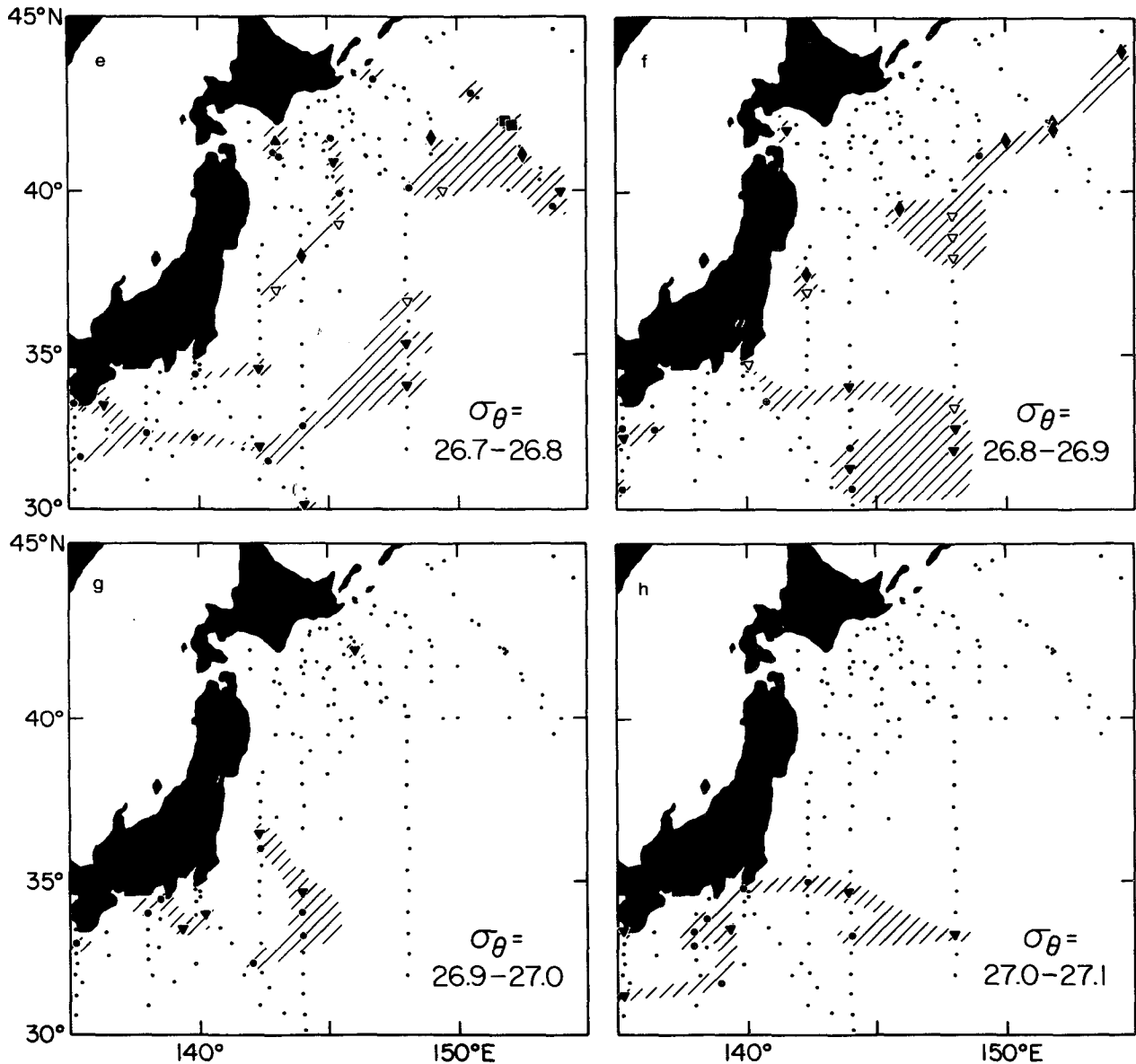
FIG. 14. (*Continued*)

are found at many stations in the northern and western parts of the mixed water region. These minima are very sharp or "intrusive" in the vertical (large $\partial^2 s/\partial \rho^2$). Stations just east of Japan, where the minima occur in association with the Tsugaru warm current and the Kuroshio warm core ring, have temperature minima associated with the salinity minima, but those associated with the Oyashio front do not. The density of these salinity minima in 1966 was 26.45–26.62 σ_θ. Surface density greater than 26.45 σ_θ occurred in the subpolar water in both Oyashio intrusions (subpolar water), just east of Tsugaru Strait in Funka Bay, and just off the Honshu coast at about 35°N, where there is also often strong Tsugaru influence. (Funka Bay is

the horseshoe-shaped bay on the southwest side of Hokkaido just east of Tsugaru Strait.) Surface density higher than 26.6 σ_θ was found in a small region in the first Oyashio intrusion, with the maximum being 26.625 σ_θ. Where surface density was higher than about

TABLE 2. Stations used in Fig. 16.

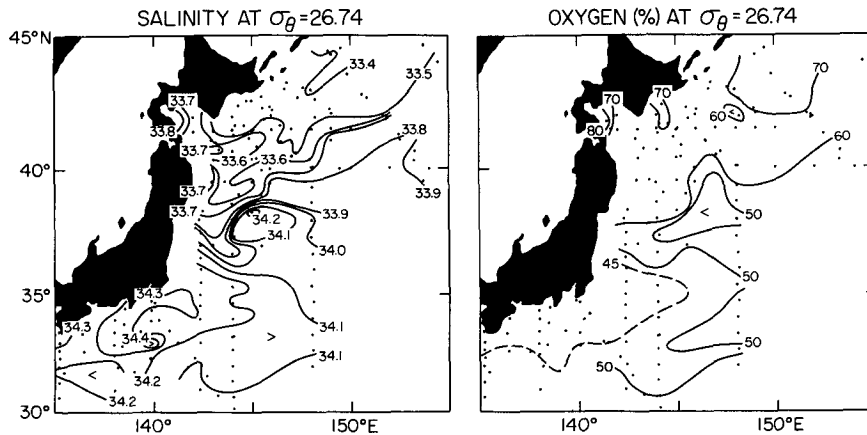|				
a	38°01'N	142°19'E	3/12/66	Takuyo
b	41°31'N	149°0'E	4/29/66	Kofu-maru
c	39°17'N	148°1'E	3/1/66	Ryofu-maru
d	32°2'N	142°23'E	3/10/66	Takuyo
e	37°28'N	142°23'E	3/12/66	Takuyo
f	33°21'N	148°2'E	3/4/66	Ryofu-maru

FIG. 15. (a) Salinity at 26.74 σ_θ and (b) oxygen (% saturation)
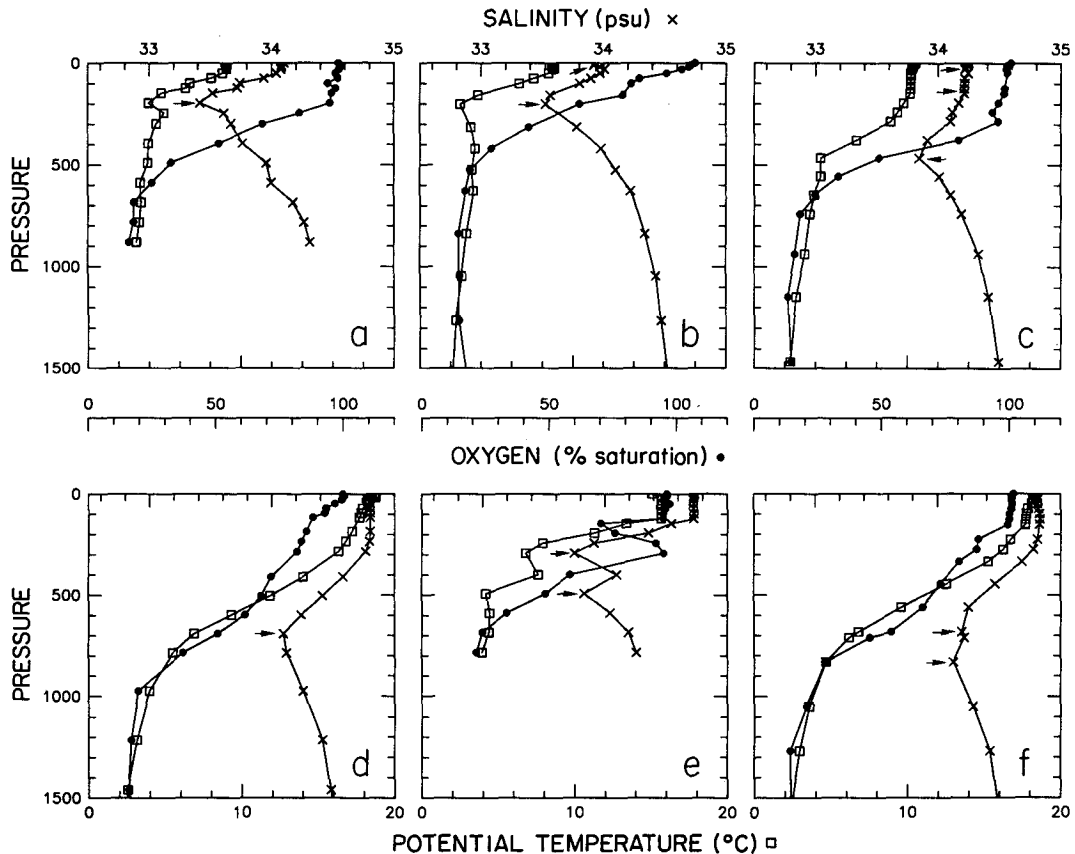for February, March, and April 1966.

FIG. 16. Examples of salinity minima from the February, March, and April 1966 dataset with salinity, potential
temperature, and oxygen (% saturation) plotted as a function of depth. Stations used are listed in Table 2. Arrows
indicate salinity minima. (a) Minimum at the base of the oxygen-saturated surface layer (squares in Fig. 14), with
temperature minimum; (b) single intrusive minimum below the surface layer with temperature minimum (diamonds
in Fig. 14); (c) sharply defined NPIW, characteristically found north of the Kuroshio Extension (open inverted triangles
in Fig. 14), insignificant mixed-layer minima also present (filled triangles in Fig. 14); (d) smooth, "classic" NPIW,
characteristically found south of the Kuroshio Extension (filled inverted triangles in Fig. 14); (e) double minimum
with temperature minima (diamonds in Fig. 14), mixed-layer minima also present (filled triangles in Fig. 14);
(f) double minimum in the Kuroshio Extension, with an insignificant mixed-layer minimum as well (diamond in Fig.
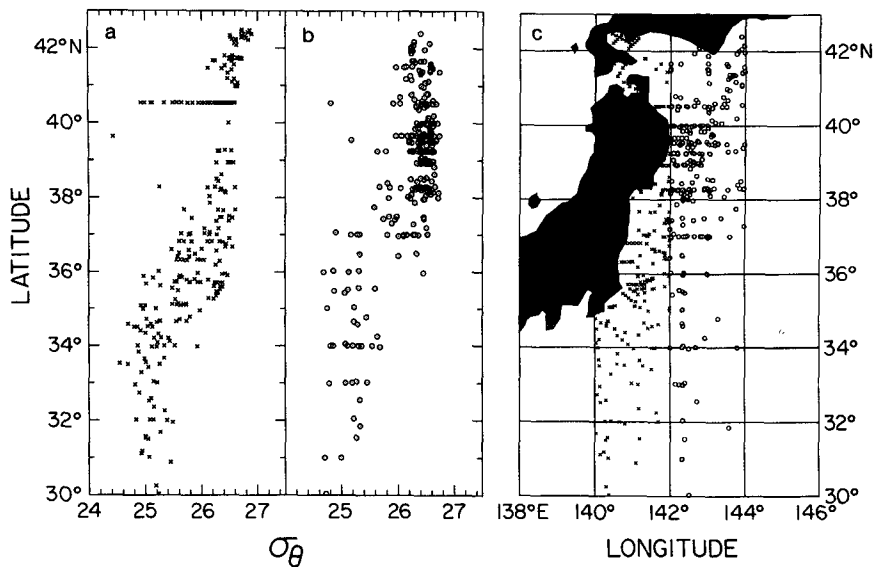14).

FIG. 17. Surface density for all March observations between (a) 140°
and 142°E, (b) 142° and 144°E, and (c) station locations.

26.5 σ_θ, the vertical salinity structure indicates subpolar origin, with freshest water at the sea surface, and salinity increasing monotonically with depth. Density of the surface water overlying these minima was 26.0–26.57 σ_θ. Thus, the surface-layer–base minima were at the density of the subpolar surface waters that enter the region from the Oyashio, while the overlying warmer, saltier surface water had a subtropical component. The formation mechanism for the minima is only conjectured: the cold, fresh subpolar surface water is denser than the warm, salty subtropical surface water; so lateral juxtaposition at local, continually evolving fronts could result in subsidence of the denser, fresher surface waters below the lighter, saltier ones.

3) "Intrusive" salinity minima (examples in Figs. 16c and 16e and diamonds in Fig. 14) are defined as sharp minima that are well below the oxygen-saturated surface layer and are generally associated with a temperature minimum or abrupt change in $\partial T / \partial Z$. In 1966, intrusive minima were found throughout the same region as the surface-layer–base minima; that is, in the northern and western parts of the mixed water region. Intrusive minima have also been found in the Kuroshio Extension (next paragraph). The total density range of the minima was 26.53–26.89 σ_θ, with oxygen saturation of 40%–86%. All of the few significant multiple minima in the 1966 survey were of this intrusive type. Dynamic height throughout this region (Fig. 11a) is convoluted; the multiple minima occur where the frontal structures are most intense, based on dynamic topography and also on salinity at 26.74 σ_θ (Fig. 15a). The intrusions thus may be formed as waters are juxtaposed at fronts separating subpolar, subtropical, and Tsugaru waters. Strong double minima, such

as shown in Fig. 16e, are found at several stations on the north side of the warm core ring just east of Japan, and in the Tsugaru outflow. They appear to be due to intrusion of a warm, salty layer into subpolar water. Warm core rings just east of Honshu are frequently observed and may be the primary site for modification of Kuroshio waters in the mixed water region (Yasuda et al. 1992). The mechanism that sets the density of the intrusive minima is unknown.

Sharp, intrusive, double salinity minima are also found in the Kuroshio Extension itself. Only one station in the 1966 survey, at 33°21'N, 148°02'E (Fig. 16f), has a suggestion of it. However, CTD sections (Fig. 1) at 152°E (1981 and 1982) and 165°E (1983 and 1984) showed the double minimum very clearly (Fig. 8f) in each crossing of the Kuroshio Extension and any warm core rings that were present. In these four CTD surveys, the double minimum occurred only in or just north of the strong eastward shear. Occurrences in warm core rings could be a means for producing minima in the northern part of the subtropical gyre. Whether the double minimum structure can be eliminated in favor of a single minimum at the "right" density is the primary unanswered question.

4) Clearly defined single salinity minima categorized as NPIW (Fig. 16c and open inverted triangles in Fig. 14) were found north of the Kuroshio Extension but in the eastern part of the maps. These minima were located well below the oxygen-saturated surface layer but did not have associated temperature minima so are not categorized as "intrusive." Density of these minima was 26.56–26.85 σ_θ, and oxygen saturation was 42%–80%. The shape of these salinity minima as a function of density was sharper than that of NPIW

south of the Kuroshio Extension. This water is iden-
tified as new NPIW.

5) "Classic" NPIW (Fig. 16d and filled inverted tri-
angles in Fig. 14) was found south of and in the Ku-
roshio Extension, which was located roughly at 36°N
(Fig. 11a). The density range was 26.7–27.1 σ_θ, with
oxygen saturation of 15%–55%.

In summary, all salinity minima south of the Ku-
roshio Extension were "classic" NPIW in winter 1966
with relatively high density and low oxygen. North of
the Kuroshio Extension the significant salinity minima
were much more pronounced and ranged from intru-
sions with temperature minima just at the base of the
oxygen-saturated surface layer, to deeper intrusions
with temperature minima and slightly lower oxygen,
to sharp salinity minima with no temperature mini-
mum. The first two of these northern minima were
found in the western and northern part of the mixed
water region (this may define the actual "mixed water
region") and the latter in the eastern part of the maps
in Fig. 14.

Given all these types of salinity minima, where does
the NPIW come from? By about 160°E, all stations
except those in the Kuroshio Extension have only a
single significant salinity minimum, in the density
range 26.7–26.8 σ_θ (Fig. 3). Based on dynamic topog-
raphy (Reid 1965; Wyrtki 1975), NPIW north of the
Kuroshio Extension should come from the mixed water
region. The salinity minima, characterized as newer
NPIW in the mixed water region (sharper vertical sa-
linity structure and higher oxygen than minima south
of the Kuroshio Extension) in the above classification,
have densities in a wider range than to the east, ranging
from 26.62 to 26.89 σ_θ with most lying between 26.7
and 26.85 σ_θ.

Can NPIW arise directly from surface water in the
mixed water region? Maximum surface density in the
region just east of the Tsugaru Strait, Hokkaido, and
the southern Kuril Islands averages between 26.6 and
26.7 σ_θ (Fig. 17, based on all NODC data from March
for the strips 140°–142°E and 142°–144°E) and the
average winter surface density is generally somewhat
lower, as seen in the winter 1966 data (Fig. 11b). Win-
ter surface waters farther north along the Kuril Islands
are slightly less dense than off Hokkaido (Talley 1991).
Observations of surface densities higher than 26.7 σ_θ
are rare in this region, even though it is one of the most
intensively observed in the World Ocean. Indeed, the
only surface densities higher than 26.7 σ_θ east of Japan
in the NODC database are in Funka Bay.

[All Funka Bay stations in the NODC database with
density higher than 26.7 σ_θ were occupied in March.
There were only two sets of stations in Funka Bay in
March in the NODC dataset, one in 1959 (1 station)
and the other in 1980 (19 stations). The single 1959
station and 11 of the 1980 stations showed surface den-
sity greater than 26.7 σ_θ, with 4 greater than 26.8 σ_θ.
Surface density in Funka Bay can be higher than farther

east because of its proximity to Tsugaru Strait and hence
a source of saline water. Confirmation that this is a
common March occurrence has been found in the reg-
ular observations in Funka Bay which are not reported
to NODC (Ohtani 1971; Talley and Nagata 1991). Even
though the winter, 1966, survey had one anomalous
station in this region, there was no evidence of wide-
spread influence of Funka Bay waters on the NPIW.]

Additional evidence that densities 26.7–26.8 σ_θ are
not locally ventilated comes from the oxygen distri-
bution. In winter 1966, oxygen saturation at 26.74 σ_θ
(Fig. 15b) was less than 75% everywhere in the region,
with the exception of one station in Funka Bay near
the Tsugaru Strait outflow. Oxygen at 26.74 σ_θ is highest
in the north, arising from its ventilation in the Okhotsk
Sea (Kitani 1973; Talley 1991) and possible vertical
diffusion as well (Reid 1965), since it is close to the
bottom of the mixed layer along the Kuril Islands. Ox-
ygen is reduced and salinity increased southward
through the mixed water region as the subpolar waters
commingle with the low oxygen, saline Kuroshio wa-
ters. The low oxygen saturations at 26.74 σ_θ indicate
the unlikelihood of NPIW arising directly from the type
of surface-layer mechanism that produces the 26.4–
26.6 σ_θ minima, whose oxygen saturations generally
exceed 95%.

Thus, the least dense, new NPIW in the mixed water
region could have a source in the winter surface layer
based solely on the winter surface densities; but this is
not true of the bulk of the newer NPIW, which is denser
than 26.7 σ_θ. However, even the less dense NPIW has
relatively low oxygen (less than 75%). The less dense
varieties of NPIW also seem to disappear east of the
mixed water region. Thus, a mechanism for either
eliminating the less dense NPIW and for increasing its
density is sought.

One possible subsurface source of new NPIW in the
mixed water region is the "intrusive" minima (type 3
above) at 26.7–26.8 σ_θ found as vertical intrusions
strung around the lateral Oyashio intrusions and also
north of the first Kuroshio meander (warm core ring
at about 37°N). The juxtaposition of warm, subtropical
waters brought into the region by the Kuroshio and
cold, fresh, subpolar Oyashio waters occurs year-round
in this region, and so presumably could be a nearly
constant source of NPIW. However, there does not
appear to be an obvious mechanism that preferentially
selects the NPIW density for this subsurface source.
The sharp minima found here are also often double
minima, arising from intrusion of a warm, saline layer
into subpolar water. Shallower intrusions could be re-
moved either through direct elimination at the surface
in winter (if less dense than about 26.6 σ_θ) or by pref-
erential erosion from above, as mentioned in the next
paragraph. However, there is no clear mechanism to
select the density of the deeper minima since lateral
gradients of salinity are maintained in the North Pacific
through the NPIW density range and higher, through
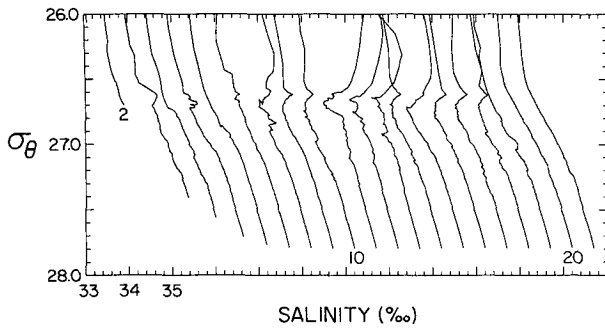direct freshening at the sea surface in the northwestern

FIG. 18. Profiles of σ_θ vs salinity from "47N", from northwest to southeast, each offset by 0.05‰. The large salinity minimum at stations 8–13 occurs in an anticyclonic warm core eddy that separates the two Oyashio intrusions (Talley et al. 1991).

Pacific, including the Okhotsk Sea (Talley 1991). Therefore, there appears to be no particular reason for intrusions to appear at 26.7 σ_θ, rather than, say, 26.9 or 27.0 σ_θ.

A second potential source of NPIW is the intriguing surface-layer–base minima, with densities 26.45–26.65 σ_θ. These minima appear restricted to the mixed water region, although dynamic topography (Fig. 11a) suggests that waters in this region eventually escape to the east. Since the winter surface density to the east does not exceed the density of these minima, winter surface processes cannot destroy them. Formation of the minima at the base of the surface layer from a combination of subpolar and transition waters, where the former has denser surface water than the latter, could be imagined by either (a) two-point mixing along isopycnals, which would create a saline upper layer originating

from the transition waters above a fresher, high oxygen layer that is a mixture of the two, or (b) geostrophic adjustment of the two water types brought into contact with each other along the several strong, constantly moving fronts in the region.

Creation of denser NPIW from the surface-layer–base minima could be conjectured through erosion from above, perhaps by salt fingering or by turbulence intensified at the base of the mixed layer. Maximum density of the erosion might be set by the initial intrusion density and the natural limitation on salt fingering when the density ratio becomes too high, or a limitation on turbulent mixing when the intrusion is smoothed or becomes too deep to be subject to surface-enhanced mixing. It is not possible to estimate the occurrence or potential strength of these processes from the bottle data used in the present study; CTD data are required to compute the density ratio to look for telltale steps in salinity and temperature and to compute other relevant quantities, such as Brunt–Väisälä frequency and Cox number. One counterindication of this mixing mechanism could be the limited occurrence of salinity minima in winter 1966 in the 26.6–26.7 σ_θ range, through which the eroding minima would have to pass as they progress to NPIW. However, the other winter surveys yield mixed results on the prevalence of minima in this density range, with very few in 1973, but nearly as many as in higher and lower density ranges in 1971 and 1972.

The intrusion-eroding mechanism could be a year-round source of NPIW; intrusions could be formed constantly through lateral juxtaposition of remnant subpolar winter mixed layers and subtropical waters. The remnant subpolar winter mixed-layer density
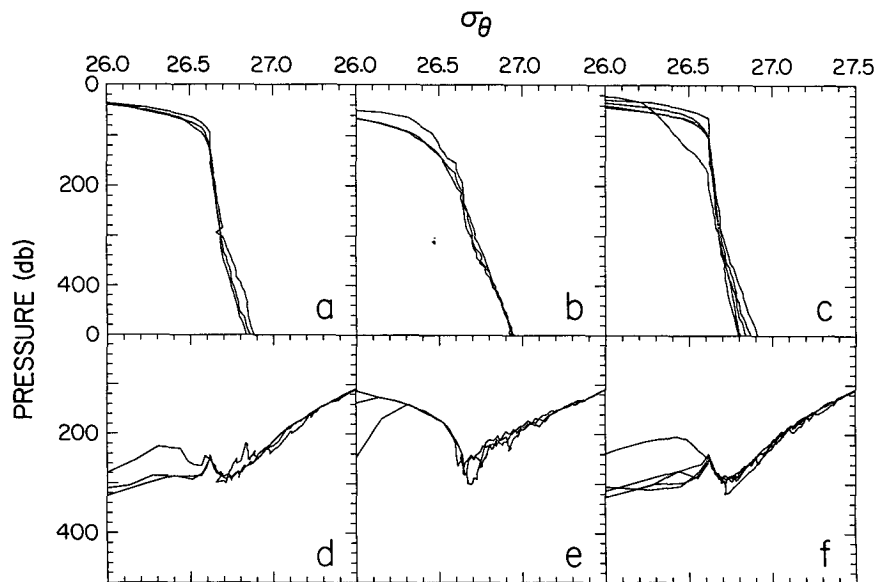

FIG. 19. (a) σ_θ as a function of pressure from "47N" stations 7 to 10, (b) from stations 11–13, and (c) from stations 14 to 18, and (d) σ_θ vs salinity from stations 7 to 10, (e) from stations 11–13, and (f) from stations 14–18.

would not change much through the year since the winter surface density in the entire Oyashio/Kamchatka Current region is about 26.5–26.6 σ_θ (Reid 1969; Talley 1991). The CTD section off Hokkaido in August 1985 (Fig. 1, designated "47N") clearly revealed the presence of such remnant winter mixed layers with NPIW just below the bottom of the layers; the density of the mixed layers matches the density of the local surface mixed layers seen in the four winter bottle data assemblages. Offset σ_θ/S profiles from "47N" stations 1–21 (Fig. 18) show that the most intrusive features are located near the center of the section. The "47N" profiles show warm, subtropical water at stations 8 to 18, which is due to the presence of a warm core ring during this particular survey (Talley et al. 1991), separating the two lateral intrusions of the Oyashio—a common occurrence in this region (Kawai 1972). On the western and eastern flanks of the warm core ring, vertical juxtaposition of the subtropical and subpolar water is evident. Superimposed vertical profiles of σ_θ as a function of pressure (Fig. 19) show a sharp summer thermocline above a remnant winter mixed layer between 100 and 360 dbar, whose density is 26.62–26.72 σ_θ. The mixed layers overlay almost completely on the west side (station 8 to 11, hence over 59 km; Fig. 19a) and on the east side (station 14 to 17 and into the top of 18, hence, over 125 km; Fig. 19c) of the warm, salty ring core. NPIW is found just at the base of this remnant mixed layer even at the stations in the center of the ring, where remnant winter mixed layers are not as sharp as on the eddy flanks.

In concluding that winter surface mixed layers could not be the source of NPIW, Hasunuma (1978) showed that the properties of NPIW vary only slightly seasonally, from warmer, saltier, and lower oxygen in November–April to colder, fresher, and higher oxygen in May–October. This suggests in the present context, however, that the remnant winter subpolar mixed layer source of NPIW is the most likely. In the winter, salinity minima at surface densities would be found with very high oxygen just below the mixed layer. The density of these minima would be too low to be classified as NPIW. As the year proceeds, these minima would be eroded down to higher density, becoming NPIW sometime later. The minima identified as NPIW in the months just after winter would have quite high oxygen. Those found later in the year (fall and early winter) would derive from either subsurface intrusions or from remnant winter mixed layers, both of which would have lower oxygen and perhaps a greater component of subtropical water, since there would have been time to mix some of it in.

4. Summary

NPIW was shown to occur throughout the subtropics in the region where potential vorticity suggests wind-driven circulation, thus north of about 20°N. It appears to "leak" into the subpolar gyre near the eastern

boundary and into the Mindanao Current. It is not found consistently in the broad California Current. Throughout most of its domain, NPIW is a vertically smooth salinity minimum (Fig. 8) with gradual spatial variations in density (Fig. 3). Its density shifts from lowest in the northwestern subtropical gyre to highest in the Kuroshio, presumably along a very long path around the gyre [Fig. 3 and acceleration potential in Reid (1965)]. Oxygen is highest and salinity lowest in the northwest as well (Figs. 4 and 5). Vertical profiles through the NPIW in the northwestern subtropical gyre are markedly different from elsewhere, being strongly intrusive and sometimes having associated temperature minima (Fig. 8).

These observations lead to the conclusion that NPIW is "formed" as a salinity minimum in the northern part of the mixed water region just east of Hokkaido and the northern coast of Honshu.

Examination of late-winter surveys of the mixed water region and Kuroshio Extension suggests two potential sources for the NPIW:

(i) subsurface intrusions at the strong Oyashio and Kuroshio fronts and warm core rings and also near the Tsugaru Warm Current; and

(ii) erosion from above of salinity minima found just at the base of the oxygen-saturated surface layer; minima could be formed by adjustment or lateral mixing of fresh, subpolar mixed layers and saltier transition-zone surface waters when they are juxtaposed at the strong fronts created by the warm core rings and Oyashio.

The first could occur at any density, so unless a mechanism can be suggested for preferentially selecting 26.7–26.8 σ_θ, it is difficult to argue that it is the primary mechanism. The second could have a fairly steady density since the Oyashio winter mixed-layer density is in a fairly tight range (26.5–26.6 σ_θ) and the Oyashio could be a year-round source of remnant, winter mixed layers of this density because of the large area in which this density outcrops (Talley 1991), since it relies only on the outcropping density for a large region, rather than on incidental intrusions.

It has often been noted that NPIW appears in the subtropical gyre at the density slightly greater than the maximum sea-surface density in the North Pacific and appears to mark the transition from directly ventilated to unventilated waters. However, it has been emphasized recently (Talley 1991) that direct ventilation at these densities does occur in the Okhotsk Sea (Kitani 1973), where the lowest salinity and highest oxygen at 26.7 to 27.6 σ_θ is found. Thus, NPIW is not a boundary between ventilated and unventilated waters in a strict sense; it is rather an imprecise marker of the densest direct ventilation in the open North Pacific, which occurs just east of northern Japan. Densest winter surface water sets the density of the overrun of subpolar by subtropical water, hence the local salinity minimum;

vertical mixing erodes the salinity minimum so that it is found at a slightly higher density, where it is identified as NPIW.

While salinity minima occur at many densities in the North Pacific, and especially in the mixed water region, NPIW is a large-scale salinity minimum because it reflects the bulk, large-scale outcropping properties of a fairly large region of the western subpolar gyre; that is, cold, fresh subpolar waters at densities greater than 26.6 σ_θ are advected into the mixed water region by the Oyashio to meet warmer, more saline subtropical and Tsugaru waters. Cooling of the latter and an increase in salinity of the former produce winter surface waters at all densities between 26.2 σ_θ and 26.6 σ_θ, with salinity decreasing with increasing density. The coldest, freshest, densest surface layer then either slides beneath or mixes laterally beneath the saltier surface layers, forming the salinity minimum that erodes from above to produce NPIW. NPIW, thus, is just below the boundary between the densest outcropping subpolar waters of the western Pacific outside the Okhotsk Sea and the part of the water column that is not ventilated outside the Okhotsk Sea.

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