North Pacific Intermediate Water in the Kuroshio/Oyashio Mixed Water Region

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ABSTRACT

The North Pacific Intermediate Water (NPIW) originates as a vertical salinity minimum in the mixed water region (MWR) between the Kuroshio and Oyashio, just east of Japan. Salinity minima in this region are examined and related to the water mass structures, dynamical features, and winter mixed layer density of waters of Oyashio origin. Stations in the MWR are divided into five regimes, of which three represent source waters (from the Kuroshio, Oyashio, and Tsugaru Current) and two are mixed waters formed from these three inputs. Examination of NPIW at stations just east of the MWR indicates that the mixed waters in the MWR are the origin of the newest NPIW. Multiple salinity minima with much finestructure are seen throughout the MWR in spring 1989, with the most fragmented occurring around the large warm core ring centered at 37°N, 144°E, suggesting that this is a dominant site for salinity minimum formation. The density of the NPIW in the MWR is slightly higher than the apparent late winter surface density of the subpolar water. It is hypothesized that the vertical mixing that creates interfacial layers above the salinity minima also increases the density of the minima to the observed NPIW density.

Transport of new intermediate water (26.65–27.4 σ_θ) eastward out of the MWR is about 6 Sv (Sv $\equiv 10^6 \mathrm{m^3 s^{-1}}$), of which roughly 45% is of Oyashio origin and the other 55% of Kuroshio origin. Therefore, the transport of subpolar water into the subtropical gyre in the western North Pacific is estimated to be about 3 Sv.

1. Introduction

The region between the Kuroshio Extension and the Oyashio Front is commonly referred to as the mixed water region (MWR) because it is a location where waters of subtropical, subpolar, and Sea of Japan origin meet and are transformed. This area is also referred to as the "perturbed region" (Kawai 1972). In this region is formed the main intermediate salinity minimum of the subtropical gyre (Hasunuma 1978), which we refer to as the North Pacific Intermediate Water (NPIW). This name often is used more generally, referring to all waters in about the same density range throughout the subtropical and subpolar gyres (Reid 1965; VanScoy et al. 1991) regardless of whether there is a salinity minimum or not.

Sverdrup et al. (1942), Reid (1965), and Talley (1993) discuss the properties of the NPIW throughout the subtropical gyre. Because its most extreme properties (lowest salinity and highest oxygen) are found in the northern part of the MWR, and because CTD profiles through the NPIW in the MWR have much more vertical structure than elsewhere in the subtropical gyre, Talley (1993) concluded that the MWR is the only formation site for the salinity minimum. However, modification of the NPIW occurs throughout the subtropical gyre, such that the density and salinity of the oldest NPIW, which is found in the Kuroshio, is higher than that of the newest, which is found in the MWR; oxygen is correspondingly lower in the older NPIW. There is evidence that part of the intermediate salinity minimum escapes to the south in the Mindanao Current (Bingham and Lukas 1994; Talley 1993) and to the north into the Gulf of Alaska (Talley 1993).

The low salinity and high oxygen at the density of the NPIW are attained in the subpolar gyre, through vertical diffusion in the open North Pacific (Reid 1965; VanScoy et al. 1991; Musgrave et al. 1992) and direct

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ventilation in the Okhotsk Sea as a result of sea ice formation (Kitani 1973; Talley 1991). Formation of the actual salinity minimum occurs when the cold, fresh waters brought south by the Oyashio into the MWR are overrun by warmer, more saline, less dense waters that have their origin in the Kuroshio and Tsugaru Warm Current (Hasunuma 1978). The latter are modified in the MWR and do not have the same properties as the original Kuroshio and Tsugaru waters (Hasunuma 1978). In Talley (1993), it was hypothesized that the winter surface density of the subpolar waters in the MWR sets the original density of the salinity minimum; since this density (26.6–26.7 σ_θ) is somewhat lower than that of the NPIW found east of the MWR (>26.7 σ_θ), erosion of the minimum preferentially from the top was also hypothesized.

Discussion of NPIW in the MWR in Hasunuma (1978) and Talley (1993) was based on bottle data. However, the conclusion regarding the uniqueness of the MWR in producing NPIW was also based on several CTD sections acquired by U.S. investigators: one east of Hokkaido, two at 152°E, and several farther to the east. A characteristic of the NPIW in and near the MWR is a high level of vertical variability (finestructure), which suggests intrusive formation in that region. Fujimura and Nagata (1992) examined CTD datasets from October to November 1989 and February 1990 and showed that NPIW with high vertical variability occurred in the MWR, particularly near a warm core ring (WCR) at 37°40′N, 143°E, which is an area where a WCR is often observed; they also showed that the density of the NPIW increases from north to south in the MWR.

Throughout this paper, it is assumed therefore that the newest NPIW is relatively fresh and that old NPIW is relatively saline, that is, the origin of NPIW is subpolar water that has been overrun by saltier subtropical and Tsugaru waters.

Many questions remain regarding NPIW formation, including the relative importance of various possible sites in the MWR, whether the NPIW density really is linked to the winter surface density of subpolar water, the importance of vertical and horizontal mixing, and how much NPIW is formed. In this paper, we suggest that the interaction between Oyashio intrusions and the westernmost warm core rings in the MWR is an important source of NPIW. We do not have evidence for how the new NPIW might escape the WCRs. We show further evidence of the relation between new NPIW density and Oyashio surface density. We quantify the amount of NPIW transported out of the region and show that it is consistent with the amounts of subtropical and subpolar waters that enter the region.

The dataset we use is a group of quasi-synoptic CTD stations from late spring 1989. It includes one occupation of the regularly repeated section at 144°E examined by Fujimura and Nagata (1992) as well as data from three other vessels. The information added by this CTD dataset is a dramatic and clear indication of new salinity minima and their relation to the semipermanent features in the MWR.

2. Background

The general features of the mixed water region are illustrated by Kawai (1972), who refers to this region as the perturbed area. The water mass and current structures of this region are undeniably complex. The reduction to just five water masses and five regimes in this paper is possible because we do not concern ourselves with the details of the coastal waters. There are three sources—the Oyashio, the Kuroshio, and the Tsugaru Current—and two types of mixtures of these waters; further reduction is not sensible. Likewise, the "permanent" dynamical features important for this problem cannot be reduced to less than the Oyashio, the Kuroshio, and the Tsugaru Current and the WCRs.

The Kuroshio Extension and Oyashio Fronts bound the MWR to the south and north, separating it from subtropical and subpolar waters. The Kuroshio Extension is approximately 150–200 km wide and usually includes two fronts (Nagata et al. 1986); its northern front is the southern boundary of the MWR and the Kuroshio Extension itself is composed mainly of subtropical water. The Kuroshio Extension often meanders northward as it separates from the coast of Honshu and produces a WCR, which is then a dominant feature of the MWR. It also produces other WCRs farther offshore, which advect westward and interact with the westernmost ring (Yasuda et al. 1992). The one to two rings formed each year near Honshu continue to interact strongly with the Kuroshio after formation, often recoalescing with it (Tomosada 1986). Thus, the rings are not always closed, nor are they circular. Following wintertime cooling and deep convection, the WCR's core temperature is usually reduced from 16°–18°C to 9°–12°C (Tomosada 1986).

The Oyashio Front is defined for our purposes as the southern limit of waters that we characterize as "subpolar" based on their temperature–salinity relation (see below), and which are often referred to as "subpolar water." The Oyashio commonly meanders twice (the "first and second intrusions" after Kawai 1972) after leaving the coast of Hokkaido. The meanders are separated by a warm core feature shown to originate from northward movement of WCRs produced by the Kuroshio, possibly with interaction from westward propagating offshore WCRs (Yasuda et al. 1992), and with considerable modification due to winter cooling and mixing with surrounding water. The warm core separating the Oyashio "intrusions" is not necessarily always a closed ring. The Oyashio is fairly barotropic, with little vertical shear, and has apparently more transport than can be inferred from a shallow reference level calculation (Miyake et al. 1991; Sekine 1988; Kono 1994). The Oyashio Front, if defined as a water mass boundary, continues eastward across the Pacific along 40°–42°N as the Subarctic Front, forming the boundary between the subarctic and modified subtropical water masses (Kono 1994; Zhang and Hanawa 1993). The modified subtropical water mass is identified by its NPIW salinity minimum; the main purpose of the current study is to show where this modified subtropical water originates. Much farther east, past the date line, the surface Subarctic Front and the deeper front that forms the northern boundary of the subtropical water become separated, with the surface front found farther south (Talley et al. 1991; Zhang and Hanawa 1992).

The third influence on the MWR is the Tsugaru Warm Current, which introduces relatively warm and saline water from the Sea of Japan. This water originates in the Tsushima Current, which splits off from the Kuroshio and enters the Sea of Japan through Tsushima Strait where it is modified before exiting through Tsugaru Strait. In summer and autumn, the Tsugaru Current often expands eastward and into a small anticyclonic gyre as it meanders eastward past the northern tip of Honshu and then turns southward along the Sanriku coast (Conlon 1982; Kawasaki and Sugimoto 1984). In winter and spring, it usually turns directly southward along the coast. The front between the subpolar and Tsugaru waters is very sharp in the upper ocean. Ejection of a warm core ring from this front has never been reported.

Water properties for all observations in March in the MWR were shown in summary property–property diagrams in Talley (1993). One 2° square (38°–40°N, 144°–146°E) that includes the main water masses is reproduced in Fig. 1. MWR waters offshore of coastal waters consist of subpolar water, subtropical water, Tsugaru water, and transition water. We are not being very exact about defining subtropical and subpolar waters—they are used in the sense of waters that primarily originate from the subpolar and subtropical gyres and are slightly modified in the MWR, mainly by air–sea interaction. In section 4c, we define five station regimes in a similar way: 1) subpolar, 2) subtropical, 3) Tsugaru, 4) subtropical transitional, and 5) subpolar transitional regimes. A given winter, noncoastal station classified as one of these regimes has various combinations of the four water masses.

Subpolar (Oyashio) water is relatively fresh at the sea surface, with salinity increasing monotonically with depth and a temperature minimum at about 100–200 m. It is advected into the MWR by the Oyashio and is found throughout the study region north of the Oyashio Front (meandering eastward extension of the Oyashio) and east of the Tsugaru Warm Current front. The waters in the Oyashio originate in the Okhotsk Sea and the subarctic gyre, with the former being colder, fresher, and more oxygenated below 150 m than the latter (Yoshida 1988). The Oyashio's first intrusion sometimes extends far south along the coast of Honshu, as far as the latitude of the Kuroshio, and subpolar water can be found there as a subsurface salinity minimum (Yang et al. 1993a,b); this is the case in the spring 1989 data we examine. Various studies of maximum southern extent of subpolar water show it to be related to the strength of the Oyashio (Okuda 1989; Yoshida 1992). The Oyashio transport is correlated with the Sverdrup transport of the subpolar gyre (Sekine 1988).

Subtropical (Kuroshio) water is the most saline branch of the property plots (Fig. 1). It originates in the subtropical gyre and is distinguished by low density, warm, high salinity surface waters, and by a smooth NPIW salinity minimum. More careful distinctions between saline water masses could be drawn, as in Fujimura and Nagata (1992), who show that the NPIW in the Kuroshio Extension itself is slightly saltier than NPIW south of the Kuroshio Extension. Subtropical water is carried into the MWR by WCRs, which are then cooled in winter, producing saltier water at 9°–12°C than is found south of the Kuroshio. We do not distinguish here between subtropical water found south of, in, and north of the Kuroshio.

With respect to the WCRs, there is no evidence, either in the literature or in the extensive datasets we have examined, for cooling the centers of WCRs to the density of NPIW. The WCRs are characterized by a deep pycnostad, which is subtropical mode water (17°–18°C) right after formation, and which cools to 9°–11°C after one winter and 4°–5°C after the second winter. The cores remain relatively salty and thick and can be distinguished from surrounding waters of Oyashio origin.

Tsugaru Water originates from the Sea of Japan, flowing eastward through the 130-m deep Tsugaru Strait (Kawai 1972). Based on our own search using all stations in the U.S. National Oceanographic Data Center dataset, in winter it has a density of 26.4–26.7 σ_θ, despite the proximity of much denser water at similar depths in the Sea of Japan. Hanawa and Mitsudera (1986) defined Tsugaru Water in the MWR as all water warmer than 5°C with salinity between 33.7 and 34.2 psu. They noted that this water is identical in properties to that which can be created by mixing subtropical and subpolar waters. In Talley (1993), the ambiguity was also noted, and Hasunuma's (1978) term "transition water" was adopted for water on the branch between the surface subpolar and subtropical waters, with an uncertain amount of Tsugaru water identified separately near Tsugaru Strait. In the absence of another parameter that can be used to distinguish between water of Tsugaru origin and the simple mixture of subtropical/subpolar waters, perhaps it is simplest to refer to all of this branch as transition water.

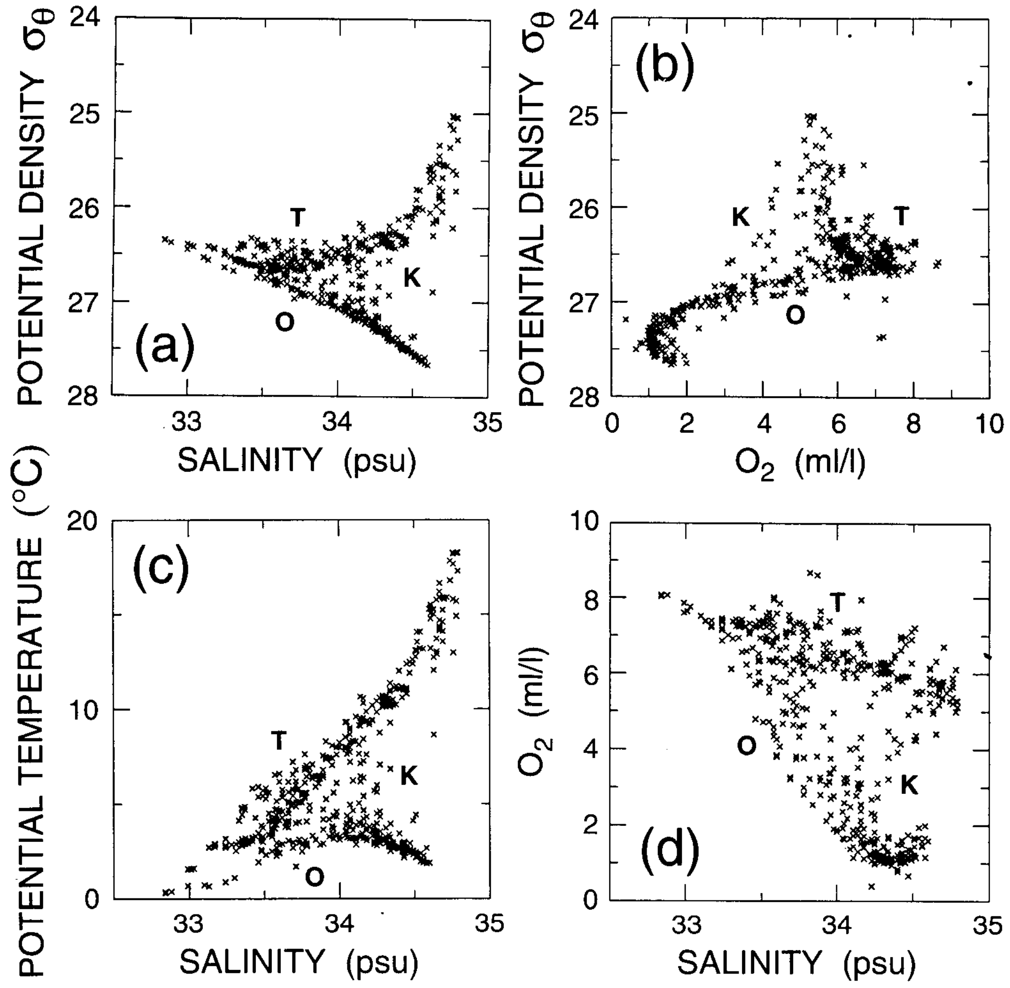

FIG. 1.(a) Potential density vs salinity, (b) σ_θ vs oxygen, (c) potential temperature vs salinity, and (d) oxygen (ml l^{-1}) vs salinity for 38°–40°N, 144°–146°E. (a) and (d) are reproduced from Talley (1993). The subtropical water (K), subpolar water (O), and transition water (T) are labeled, and refer to curves in the property relations rather than single points. Tsugaru water corresponds to the least saline portion of the transition water (Talley 1993). A given station may include parts of several of these water masses.

Transition water appears to be mainly a mixture of the surface portions of subpolar and subtropical waters. It has the highest oxygen of all the water masses, with the water being close to saturation. The noisy gap in the center of the March property diagrams, which is a feature of every 2° square in the MWR (Talley 1993) and which is most evident in the oxygen–salinity relation in Fig. 1d, suggests that transition water arises from vertical mixing when the subpolar water column is overrun by the least dense subtropical water. The waters both below and above the overrun are nearly saturated in oxygen, suggesting that near-surface subtropical water overruns near-surface subpolar water. An alternate possibility is that it is mainly Tsugaru water that mixes with surface subtropical water.

The intermediate salinity minimum, NPIW, has several manifestations in the MWR. Old NPIW is a typical and identifying characteristic of subtropical water, with a vertically smooth salinity minimum; the salinity of old NPIW is much higher than the salinity of subpolar water at the same density. Newest NPIW is found at the water mass connection point between transition water and subpolar water (Fig. 1), centered broadly around 33.5 psu, 26.7 σ_θ, and oxygen of 7 ml l^{-1}. It is considerably fresher than old NPIW in subtropical water.

Formation of new NPIW is thought to occur through overrun of the subpolar water by the saltier surface waters of the MWR (Hasunuma 1978). By "overrun" is also meant "lateral intrusion" of subpolar water into subtropical water. There are several hypotheses about where the overrun occurs and what sets its density. Four mechanisms were suggested by Talley (1993): subduction of subpolar water beneath modified sub-

TABLE 1. Station summary.

Ship	Institution	Investigators	Dates	Number of stations
Kofu Maru	Hakodate Marine Observatory	Iwao and Fujimura	10 Apr–9 May 1989	54
Tankai Maru	Hokkaido Fisheries Research Institute	Kono and Okuda	14 Apr–3 Jun 1989	167
Wakataka Maru	Tohoku Fisheries Research Institute	Hirai	2 May–31 May 1989	37
Soyo Maru	Central Fisheries Research Institute	Inagake	15 May–23 May 1989	20

tropical water at the Oyashio Front, entrainment and intrusion of subpolar water into the warm (saline) core ring, overrun of subpolar water by Tsugaru water, and intrusions into the Kuroshio Extension itself. These all involve vigorous currents. The first two mechanisms were deemed more important in Talley (1993) since the latter two are observed only in limited regions, near Tsugaru Strait and in the Kuroshio Extension. Subduction at the Oyashio Front was considered to be the most likely, since it would result in a steady source of NPIW at a well-determined density, that of the remnant Oyashio winter mixed layer (26.6–26.7 σ_θ). Since this density is a little too low for NPIW, a vertical mechanism is required to selectively erode the NPIW from the top and produce a minimum at 26.7–26.8 σ_θ. In Talley (1993), this was hypothesized to be either enhanced turbulence at the top of the intrusion, which lies near the bottom of the mixed layer, or double diffusion. However, simple diffusion acting on a sharp interface between salty subtropical water and fresher subpolar water would also selectively erode from the top. In the dataset examined here, entrainment of subpolar water into the main WCR may be the most important possibility for creating this interface. Muto et al. (1975) and Muto (1977) show a large number of examples of relatively fresh salinity minima in and around the WCR in the MWR that is often found just north of the first Kuroshio meander. A vertical mixing mechanism is still required for this source.

Winter surface density in the subducted water is hypothesized to be the most important factor in setting the NPIW density. Winter surface water in the NPIW density range (slightly greater than 26.7 σ_θ) has been reported in limited parts of the MWR: Funka Bay on the south side of Hokkaido (Talley and Nagata 1991; Talley 1993) and at 40°N just off the coast of northern Honshu (Nagata 1993). Both are substantiated by very long and regularly sampled time series, with the high densities occurring almost every March. Winter densities are high in both regions because of the influence of high salinity Tsugaru water, which can be cooled to this density in winter without freezing. The Funka Bay source of dense water might be too small and localized to be important; its characteristic high salinity is not observed far from Tsugaru Strait. The high winter density east of Honshu is more intriguing, because it suggests a mechanism for setting the density of fresh intrusions in this dynamic part of the MWR, where a Kuroshio WCR is often located (Kawai 1972).

3. Data

Observations of the MWR are made on a regular basis by several Japanese government agencies. We selected April–June 1989, because of the good coverage of the MWR with CTD stations just after winter and because we started this cooperative study in 1990. Most routine observations since 1988 have employed a CTD, and reasonably good coverage of the MWR is available in late spring and in autumn of each year. We have supplemented the CTD observations with bottle data to improve spatial coverage off the northern coast of Honshu.

The CTD observations from April–June 1989, are listed in Table 1. Station locations are shown in Fig. 2. Many of the sections in this survey are regularly repeated sections, including the 144°E section. Bottle data and standard level CTD data are regularly reported to the Japan Oceanographic Data Center but the high resolution CTD data are not archived centrally. Not all of the stations were used in the maps in this paper because of the high density of stations from the *Tankai Maru* and repeated stations from the *Soyo Maru* and *Wakataka Maru*.

4. The mixed water region in April–June 1989

The area studied encompassed the Kuroshio Extension, a warm core ring which was not completely detached from the Kuroshio Extension, the Tsugaru Warm Current, both Oyashio intrusions southeast of Hokkaido, and an old WCR (4°–5°C) between the Oyashio intrusions in late spring 1989. Most features are apparent in the 100-m temperature analysis for April 1989 produced by the Japan Meteorological Agency (Japan Meteorological Agency 1989) and reproduced as Fig. 2c; the Kuroshio Extension is the high meridional gradient of temperature at about 35°N, the semidetached WCR is the 14°–16°C

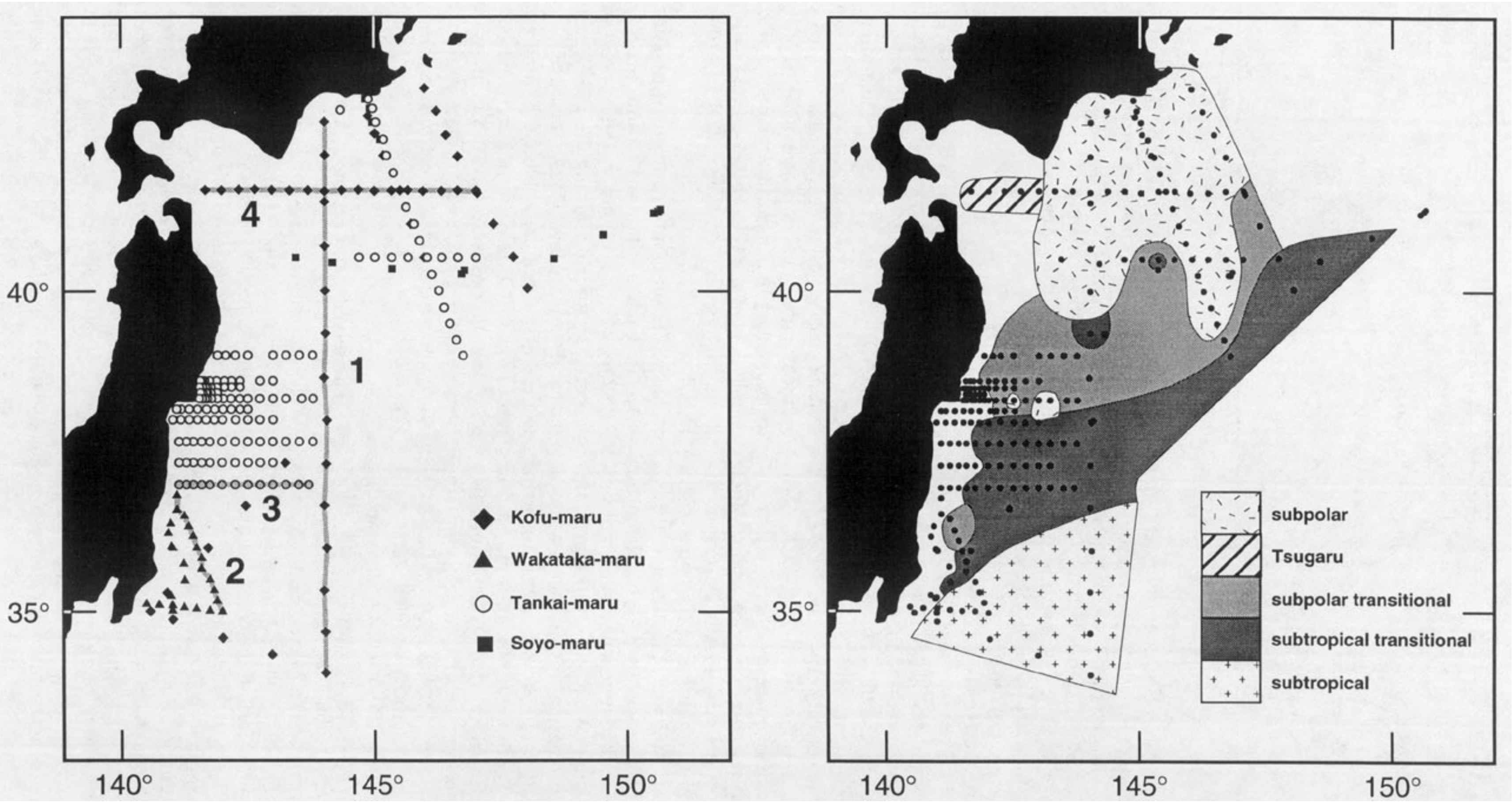

FIG. 2.(a) Station locations for the *Kofu Maru* (diamonds), *Wakataka Maru* (triangles), *Soyo Maru* (squares), and *Tankai Maru* (circles) for April–June 1989. The four sections used in Figs. 3–6 are indicated with dashed lines. (b) The subtropical, subpolar, subtropical transition, subpolar transition, and Tsugaru regimes (see section 3c). (c) Temperature at 100 m (reproduced from Japan Meteorological Agency analysis for April 1989).

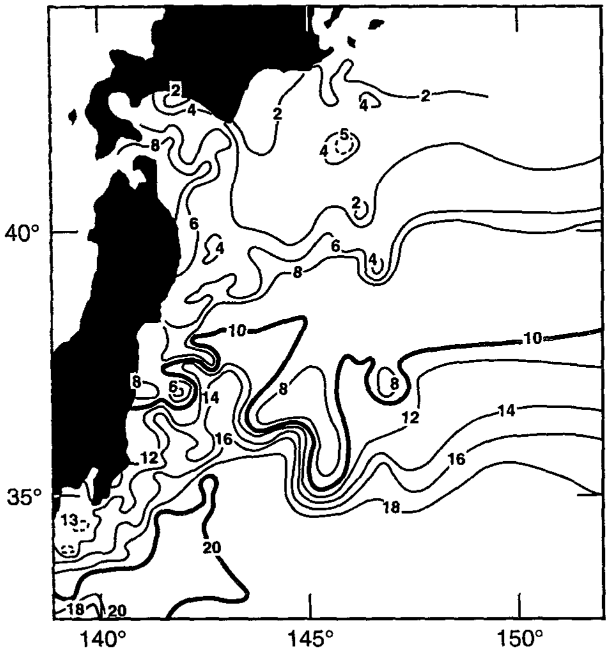

FIG. 2. (*Continued*)

feature at 36°N, 143°E elongated to the northeast into a region of 10°C, the Tsugaru Warm Current is the 8°C water east of Tsugaru Strait at about 42°N, 141°E, the old WCR between the Oyashio intrusions is the 4°–5°C feature at about 42°N, 146°E. In the following, we refer to the southern WCR as the "main" WCR. Based on the Japan Meteorological Agency (JMA) monthly analyses, this main WCR was distinct in November 1988 (100-m temperature 15°C), cooled to 10°C by February 1989, reattached to the Kuroshio Extension in April 1989, and separated again in May 1989 with an infusion of 13°C water. This progression of WCR temperatures through one winter is typical (e.g., Tomosada 1986; Yasuda et al. 1992). It is seen in section 4a that the 100-m analyses might be too shallow to capture the true extent of the main WCR. Most of the features apparent in spring 1989 occur in various forms most of the time; temperatures of each feature change dramatically through the winter, but the basic configuration of currents, WCRs, and water masses can usually be identified.

We first examine CTD sections with particular attention to the water masses and occurrence of salinity minima, and then examine maps of properties on an isopycnal, 26.7 σ_θ, which characterizes NPIW and properties of the salinity minima. As part of the analysis we also consider the apparent winter mixed layer density as suggested by these spring observations.

a. Vertical profiles and sections

Several vertical sections through the study area are shown in Figs. 3–6. Because it cuts through most of the water mass regimes, our primary section is along 144°E; this is a repeated section and two later occupations were analyzed by Fujimura and Nagata (1992). The 144°E potential density section clearly shows the Kuroshio Extension at 35°30′N to 36°30′N and the WCR situated just to the north. The warm core pycnostad is 9°–11°C, 26.4–26.5 σ_θ, and up to 450 m deep, with its greatest contrast with the surroundings below the standard mapping depth of 100 m (Fig. 2c). The isopycnal deflections associated with the WCR extend below the maximum observation depth of 1000 m. A small warm feature is found north of the main WCR, at station 49 (39°30′N). The small undulation in isopycnal depths at 40°N is the Oyashio Front, which is nearly density compensated, hence much more dramatic in temperature and salinity (Figs. 3b,c). These features are also evident in the 100-m temperature analysis for April 1989 (previous section and Fig. 2b). The configuration of the Kuroshio Extension, a deeply extending WCR with pycnostad temperature of 9°–11°C after one winter, and the nearly density-compensated Oyashio Front is common for this region.

Different types of salinity minima are found at 144°E (Figs. 3b,d): a clean, sharp minimum in the center of the WCR (sta. 46 at 37°20′N, 600–700 m, 26.71 σ_θ), vertically noisier minima on either side of the ring (200–500 m, minimum salinity at various densities between 26.0 and 27.1 σ_θ), vertically smoother minima in the Kuroshio Extension (sta. 41–43), and weak minima at the northern end (sta. 51–54). The sharp WCR salinity minimum is also a temperature minimum with temperature less than 2.8°C (Fig. 3a); its properties (see Fig. 7 below and Fig. 1) indicate that it is pure subpolar water, matching properties in the Oyashio. It is the only station in this dataset with such a clean salinity minimum of pure subpolar water (part d of Figs. 3–6), and it sits directly in the middle of the WCR. The northern salinity minimum appears to extend southward from the Oyashio Front; however it is a 4° to 5°C thermostad with slight temperature minima and not pure subpolar water so its source may be more complicated than a simple subduction southward from the front. The complicated salinity minima south of the WCR are embedded in the northern part of the Kuroshio Extension; station 45 has a double salinity minimum, with the deeper at 26.8 σ_θ and the shallower at 26.5 σ_θ. Salinity minima are typical of the Kuroshio Extension (Shin et al. 1988, 1991) and double salinity minima are also often observed (Fujimura and Nagata 1992; Talley 1993). Thus, on this one section we see salinity minima at the NPIW density arising from 1) presence of subpolar water in the Kuroshio Extension, 2) intrusion of subpolar water in a large WCR, and 3) intrusion of modified subpolar water beneath a weak warm core feature.

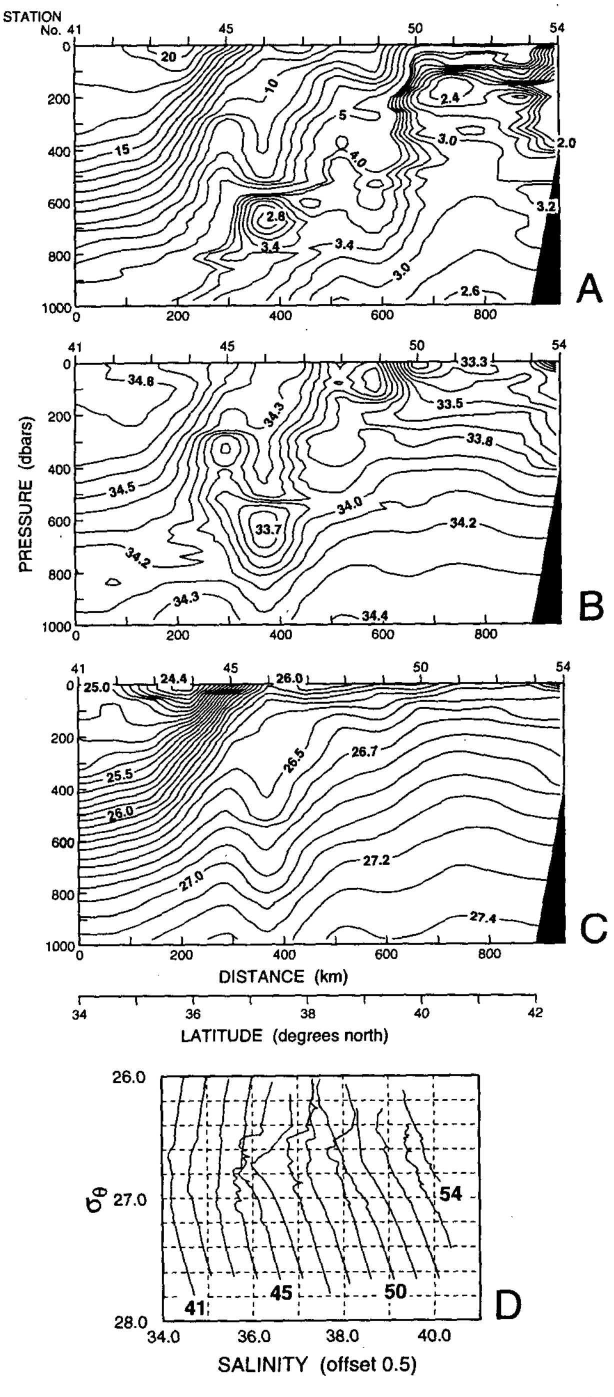

FIG. 3.(a) Potential temperature, (b) salinity, (c) potential density σ_θ, and (d) profiles of salinity for the *Kofu Maru* stations along 144°E. Salinity profiles are offset 0.5 from each other; the scale is correct for sta. 41.

To further examine the minima in the Kuroshio Extension (Kuroshio Extension), the slanted *Wakataka Maru* section at about 142°E, just downstream of the Kuroshio Extension separation point, is shown (Fig. 4). Its close station spacing (Fig. 2a) resolves the Kuroshio Extension well and shows that it is about 120 km wide here, just past its separation point from Honshu. The maximum shear shifts southward about 40 km at 400-m depth, in accord with Nagata et al.'s (1986) observation of such southward shift on average. At the depth of the shift, a salinity and temperature minimum is found in and north of the Kuroshio Extension. The properties indicate that the minima originate from nearly pure subpolar water, which therefore penetrated far south along Honshu to where it was entrained by the Kuroshio. Similar southward penetration has been reported by Yang et al. (1993a,b).

Of the many available zonal *Tankai Maru* sections, the southernmost at 37°N was selected for display (Fig. 5) because it cuts into the center of the main WCR seen already in the 144°E section. Except at the most coastal stations (58–60), all stations have subtropical surface water and a well-developed salinity minimum with much finestructure (Fig. 5d). The main WCR is evident east of station 65, with a fresh, cold intrusion centered at 500 m. Inshore of the WCR, there is a much shallower salinity minimum, at 200–300 m. Despite the great difference in depth between the salinity minima inside and outside the ring, they are at nearly the same density of ~26.7 σ_θ. The two minima are separated from each other by a more saline strip at station 66 in which the salinity minimum is at ~26.8 σ_θ, similar to the north side of the ring along the 144°E section (Fig. 3b). Temperature minima are associated with the salinity minima; the lowest minimum temperature is 3.2°C at station 64 inshore of the WCR, where the salinity is less than 33.7 psu, indicating that this is nearly pure subpolar water. This section thus shows that the similar structure observed on the north side of the WCR at 144°E (Fig. 3) extends around to the west side of the ring.

The *Tankai Maru* sections farther north are not shown because of space limitations. The section at 37°40′N is similar to the 37°N section although the salinity minimum inshore of the WCR is more fractured than at 37°N. The northern edge of the WCR is at 38°N on the 144°E section (Fig. 3); however, the easternmost *Tankai Maru* stations at 38°N, 38°20′N, and 39°N all show some influence of the same WCR and have salinity minima and associated temperature minima at about 26.7 σ_θ.

Last, the *Kofu Maru* section at 41°30′N is shown (Fig. 6) to illustrate the strong effect of the Tsugaru Current and the structure associated with the two intrusions of the Oyashio, separated by the weak, old WCR. The westernmost six stations (1–6) have strong Tsugaru water influence, identified as the upper water salinity maximum. The water exiting Tsugaru Strait overruns the subpolar water south of Hokkaido, creating a salinity minimum at a density of 26.7–26.8 σ_θ and temperature of less than 3.0°C, as illustrated by

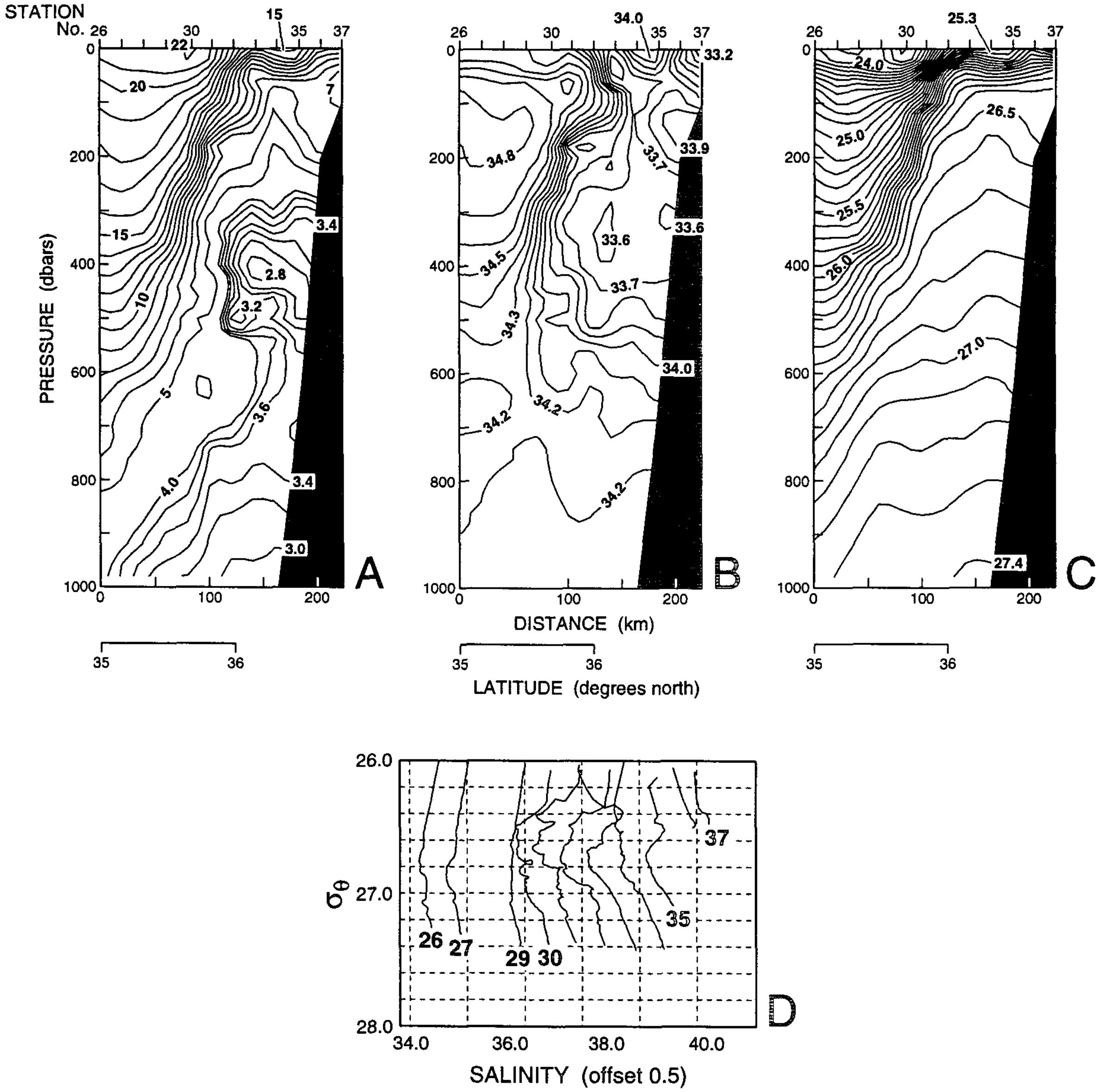

FIG. 4.(a) Potential temperature, (b) salinity, (c) potential density σ_θ, and (d) profiles of salinity for the *Wakataka Maru* stations along about 142°E. Salinity profiles are offset 0.5 from each other; the scale is correct for sta. 26.

these *Kofu Maru* stations. The salinity maximum and minimum are equally remarkable in the vertical profiles (Fig. 6d). The edge of the Tsugaru water is a strong front (stations 5–6), east of which is subpolar water from the first Oyashio intrusion. At stations 12–14 is found a warm core thermostad, with a temperature of 4–5°C; this is a weak manifestation of the WCR that is often located here, separating the two Oyashio intrusions. The thermostad has a salinity of 33.5 psu with a very weak salinity minimum at its base. East of the warm thermostad is found more subpolar water, of the second intrusion.

The weak 4°–5°C WCR separating the Oyashio intrusions can be traced back to an 8°–10°C ring prior to winter using the monthly JMA 100-m temperature analyses (JMA 1988, 1989). Fast evolution of the 100-m temperature in September–October 1988 makes it more difficult to trace the ring farther back in time. It could have been the remnant of Yasuda et al.'s (1992) WCR86B or WCR88A, or it might have been an offshore ring that propagated westward into this area in August 1988 and interacted with WCR88A.

Based on these sections, the southern WCR emerges as an important contender for the formation site for

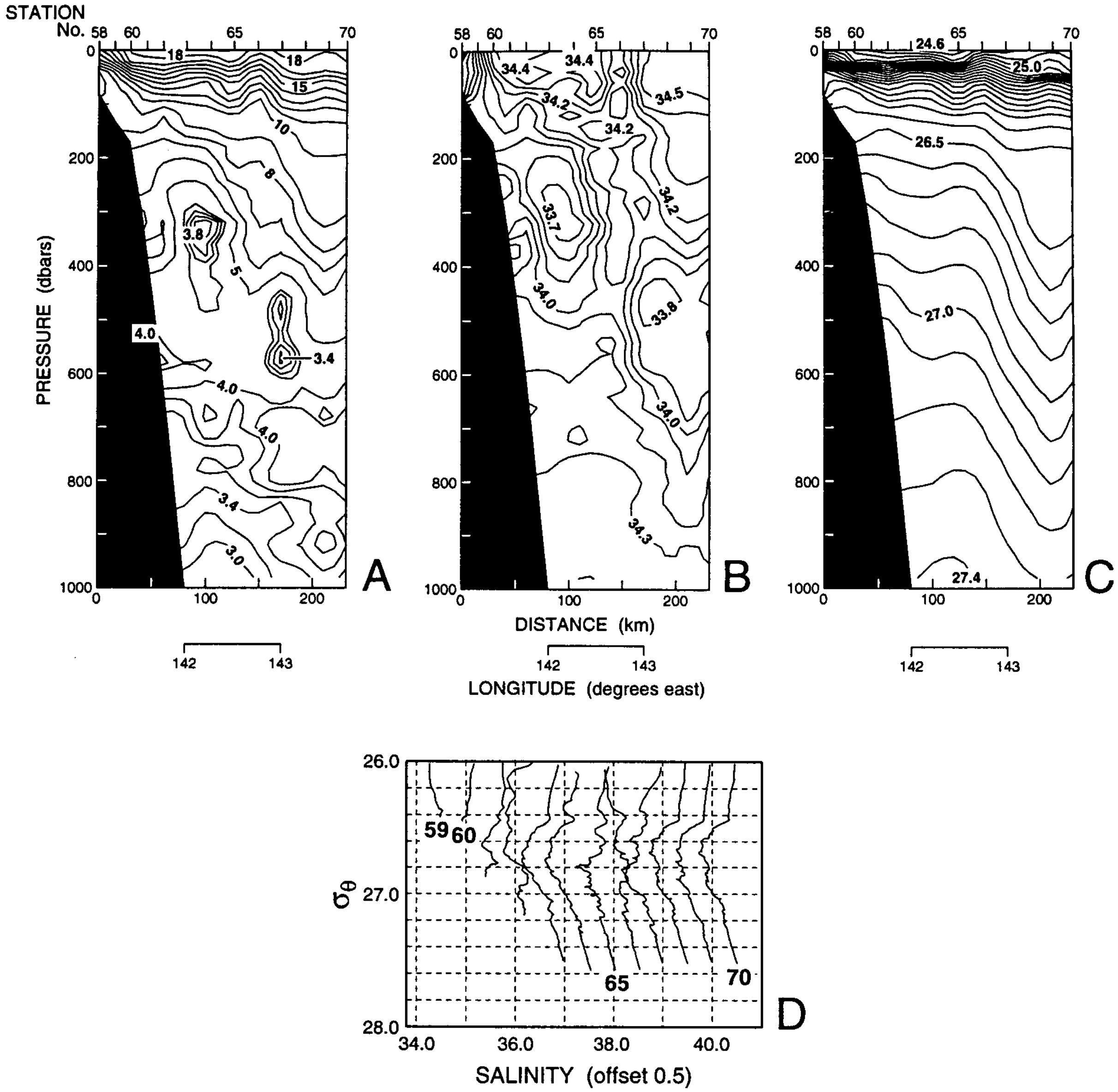

FIG. 5.(a) Potential temperature, (b) salinity, (c) potential density σ_θ, and (d) profiles of salinity for the *Tankai Maru* stations along 37°N. Salinity profiles are offset 0.5 from each other; the scale is correct for sta. 58 but its salinities were all lower than 33.8 psu so it does not appear.

NPIW. The nearly pure subpolar water in the center of the WCR (Fig. 3b) in spring 1989 was somewhat unusual in both its salinity and location in the very center, but the many examples of salinity minima of nearly this freshness in and surrounding this main WCR in Muto et al. (1975) and Muto (1977) suggest that it was just an extreme example of intrusions commonly found in the WCRs at this location. On the other hand, the weak northern 4°–5°C WCR has only a tiny remnant of the NPIW structure. It is common to find 9°–12°C water in this northern location since the main southern WCR advects northward (Yasuda et al. 1992). Such a 9°–12°C feature in summer 1985 was described by Talley et al. (1991); its NPIW salinity was too high to be pure subpolar water, suggesting that the intrusions of subpolar water had occurred sometime earlier, perhaps when the ring was at the southern location. The 1989 CTD data examined here show no new NPIW in the northern WCR; rather it appears that during its winter cooling and modification, it had incorporated so much subpolar water as to almost eliminate the NPIW. Intrusions of subpolar water di-

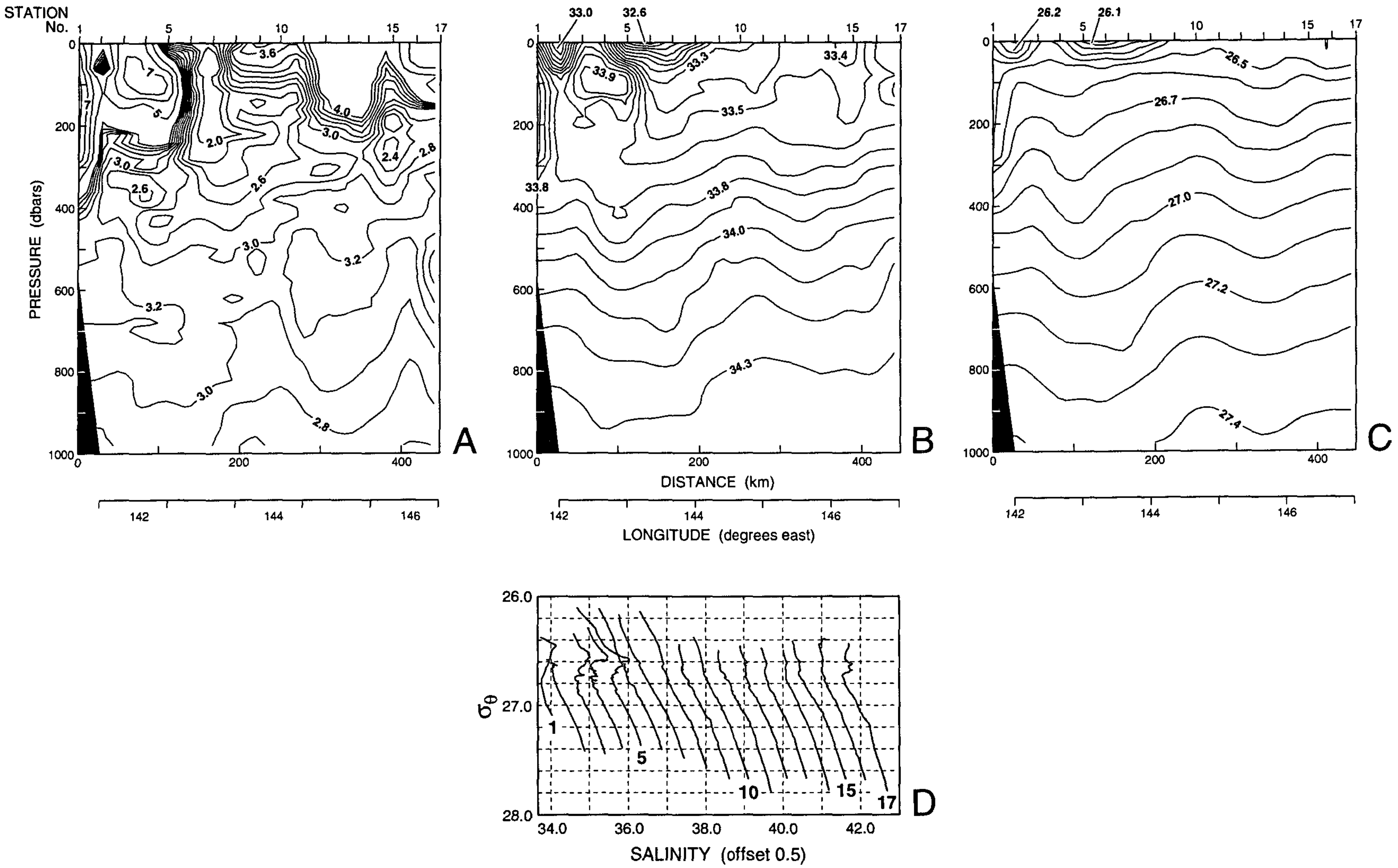

FIG. 6.(a) Potential temperature, (b) salinity, (c) potential density σ_θ, and (d) profiles of salinity for the *Kofu Maru* stations along 41°30′N. Salinity profiles are offset 0.5 from each other; the scale is correct for sta. 1.

rectly into the Kuroshio, such as seen on the *Wakataka Maru* section (Fig. 4) may be important, and in fact may be linked to NPIW formation in the main WCR since the ring is formed from a meander of the Kuroshio just east of the site shown in Fig. 4. The relative importance of the Tsugaru outflow is even more difficult to gauge.

b. Properties at 26.7 σ_θ

New NPIW east of the MWR is characterized by densities slightly greater than 26.7 σ_θ (Talley 1993). The origin of this large-scale, single salinity minimum outside the MWR is assumed to be in the multiple, fractured minima found in the MWR. It is also assumed that flow is more or less along isopycnals, so consideration of properties at 26.7 σ_θ should illuminate something of the origin of the NPIW.

Pressure at 26.7 σ_θ (Fig. 7a) reflects the main dyamical features of the MWR. The isopycnal is deepest south of the Kuroshio and shoals to less than 300 dbar in the western MWR. The large WCR is evident in the depression of the isopycnal to 585 dbar, centered at 37°20′N, 144°E. The 200-dbar contour closely follows the boundary between subpolar and transitional waters (next section). In the region southeast of Hokkaido, the 150-dbar contour nicely traces the two Oyashio intrusions with the depressed warmer core between them.

Salinity at 26.7 σ_θ (Fig. 7b) shows the low salinity influence of subpolar waters reaching southward into the WCR area, with salinity lower than 33.6 psu in the center of the WCR (37°20′N, 144°E) and far down along the coast of Honshu near the Kuroshio separation point. The highest salinity is in the Kuroshio core (>34.2 psu). A patch of salinity higher than 34.0 psu is found north of the main Kuroshio axis. Otherwise salinities in the MWR are between 33.8 and 34.0 psu. The slightly saline remnant of the old WCR between the Oyashio intrusions (40°N, 145°E) is evident. With the addition of the 152°E section from May 1981, one can see that these intermediate salinities cover most of the region between the Kuroshio Extension and Subarctic Front.

In section 4c, we see that these domains (Oyashio, Oyashio influence, Kuroshio, Kuroshio influence) are identifiable and discrete.

c. Regime classification

Two different kinds of classifications of waters are used. These are 1) the actual water masses (several different ones are often observed at a given station) or 2) regimes based on the entire vertical profile. The water masses were discussed in the introduction and illustrated in Fig. 1. Total vertical profile classification is as 1) subtropical regime, 2) subpolar regime, 3) Tsugaru regime, 4) subtropical transitional regime, or 5) subpolar transitional regime (Fig. 8). "Subtropical regime" profiles originate in and south of the Kuroshio and are somewhat modified in the MWR through winter cooling. "Subpolar regime" profiles are full-column Oyashio profiles. The "Tsugaru regime" contains a strong signature of warm, salty Tsugaru water overlying subpolar water. The "transitional regime" contains various superpositions of these three, and also includes transition water. In Talley (1993) no distinction between stations in the transitional regime was made, but here the profiles can be divided into two groups, one with stronger subtropical influence and the other with stronger subpolar influence. Both have salinity minima (NPIW), but the subpolar transitional profiles are fresher than the subtropical transitional profiles; the NPIW is generally less marked in the subpolar transitional profiles.

The five regimes are mapped in Fig. 2b. Coastal waters along Hokkaido and Honshu are blanked out. The transition between regimes is generally abrupt, taking place between adjacent stations, even though currents, particularly the Kuroshio Extension, are spread over several adjacent stations. The regimes are related to the features apparent in the 100-m temperature (Fig. 2c), and pressure and salinity at 26.7 σ_θ (Fig. 7).

The subtropical regime (Fig. 8a) is in and south of the Kuroshio Extension. The noisy envelope of salinity in the NPIW range is due to the older, saltier NPIW in the Kuroshio Extension compared with south of it. No purely subtropical profiles were found north of the Kuroshio Extension, reflecting the one-winter age of the southern WCR.

The subpolar regime (Fig. 8b) is located north of the Oyashio Front (~40°N). These profiles are not all "pure" subpolar water, as a group of them has slightly higher salinity at densities less than 26.7 σ_θ than original subpolar water. However, they were all easy to distinguish from subpolar transitional profiles, which have a salinity minimum.

The Tsugaru regime (Fig. 8c) lies west of the front separating Tsugaru and subpolar waters and contains strong salinity minima in the NPIW range.

Subtropical transitional stations (Fig. 8d) were found in the southern WCR and to the east, south of the Oyashio Front. These stations contained the new NPIW which is found east of the MWR (section 4f below). The deep salinities and the NPIW salinities were higher than in the subpolar transitional waters. Many of these stations had nearly pure subtropical surface water.

Subpolar transitional stations (Fig. 8e) were slightly fresher below the NPIW salinity minimum than subtropical transitional stations and saltier than subpolar stations. Salinity minima with a lot of vertical structure at and above the NPIW density were also characteristic of these stations. The stations in the weak northern

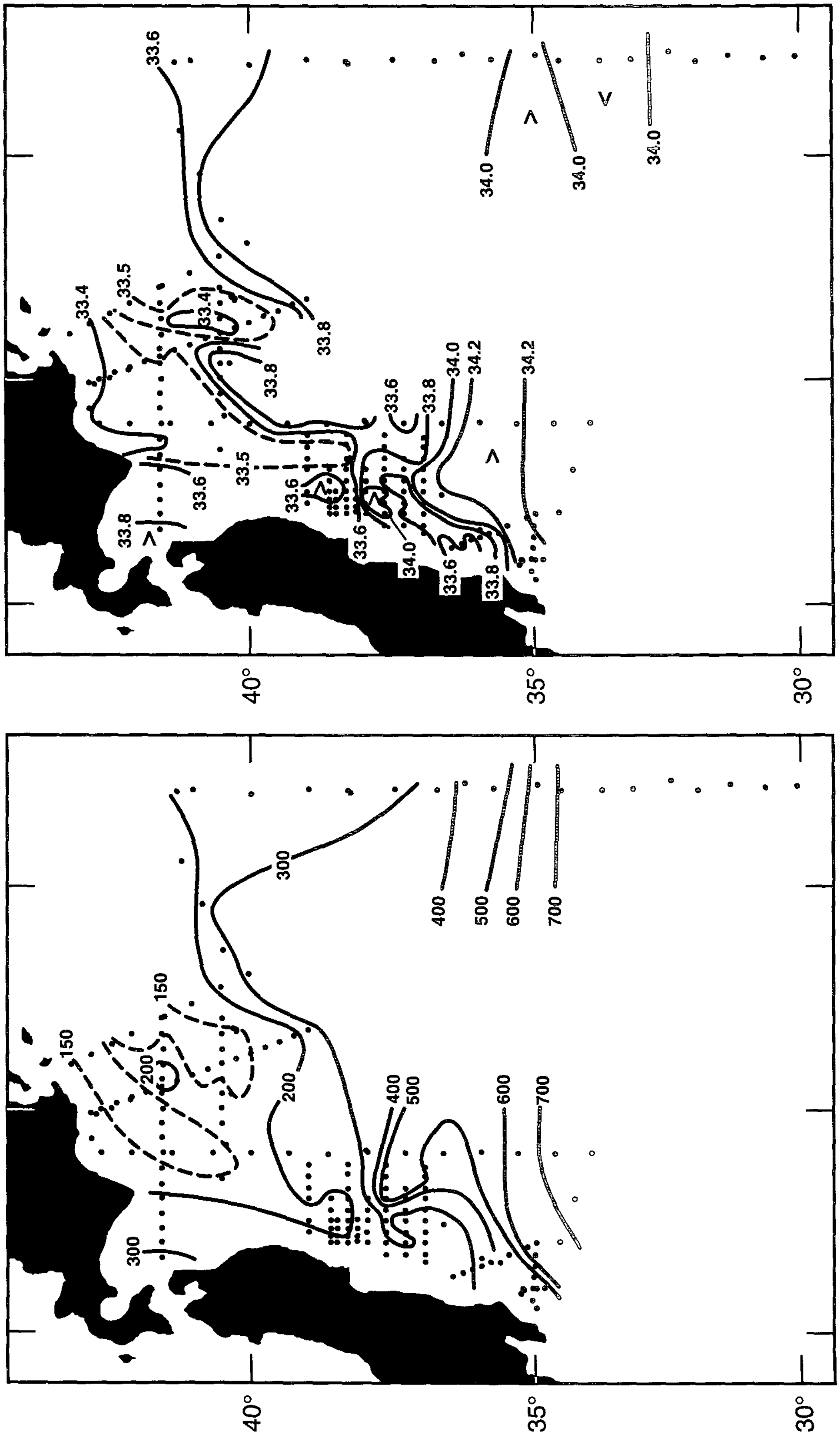

FIG. 7.(a) Pressure and (b) salinity at 26.7 σ_θ.

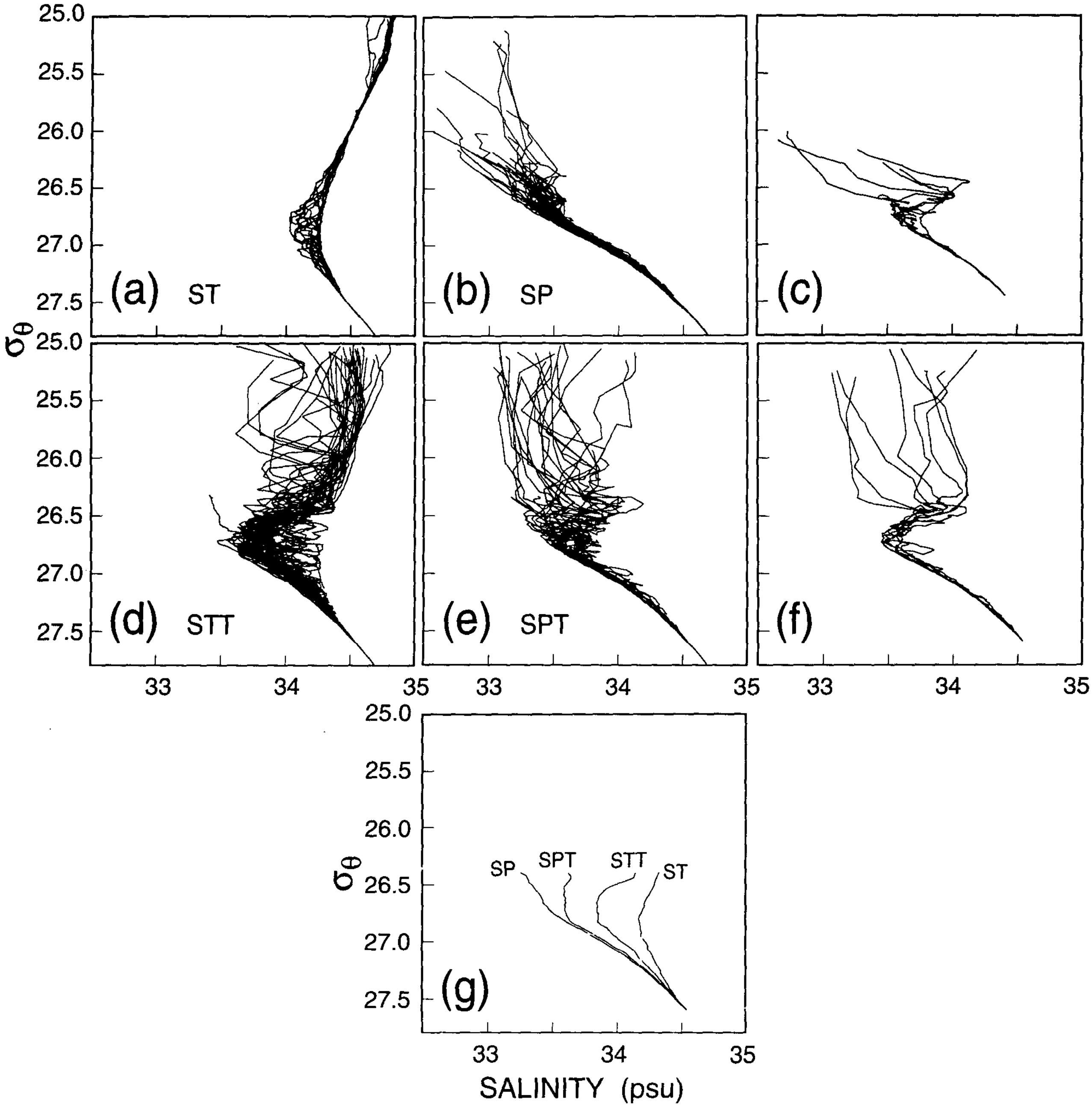

FIG. 8. Potential density vs salinity for the four regimes using all stations in Fig. 2: (a) subtropical regime (ST), (b) subpolar regime (SP), (c) Tsugaru regime, (d) subtropical transitional regime (STT), (e) subpolar transitional regime (SPT), (f) group of *Tankai Maru* stations along 39°N between 143°E and 143°40'E, and (g) average profiles.

WCR are mainly classified as subpolar transitional, since they resembled subpolar profiles but had very weak salinity minima in the NPIW range. It is assumed that this WCR had much stronger NPIW prior to its winter cooling and near-obliteration by entrained subpolar waters. Subpolar transitional profiles were also found next to the Honshu coast where Oyashio influence is common.

One group of stations at 39°N, 143°E (Fig. 8f) could not be classified as easily as the others: the deep property relations were similar to the subtropical transitional profiles, but the rounded salinity minimum was markedly fresher (closer to subpolar water) than the other subtropical transitional profiles. These properties may have resulted from Tsugaru influence or from local dense outcropping in winter (Nagata 1993).

d. Salinity minima

Salinity minima of many different magnitudes and vertical scales occurred throughout the region (see Figs. 3–6d). A great deal of finestructure is characteristic of all of the larger-scale intrusions and will be the subject of a later study. In order to study only the most important minima, those of relatively large vertical scale, the data were first smoothed vertically with a Gaussian filter of 50 dbars half-width. This suppressed the finestructure and retained the visually most dominant minima.

Subsurface salinity minima were found at 130 of the 195 stations deep enough for the smoothing (Fig. 9). Even with this strong smoothing, multiple salinity minima were common, being found at 64 stations located throughout the MWR. Three or more minima were found at only 23 stations, all of them located in and west of the main WCR and to its southwest towards the Kuroshio separation point.

The properties of all filtered salinity minima are displayed in Fig. 10. Absolute (lowest), shallowest, deepest, and intermediate salinity minima are indicated with different symbols. The deepest minima tend towards the subpolar side of the properties, with the densest cluster also including subtropical water. The shallow minima are found scattered across the lower densities, roughly corresponding to transition water. The absolute minima tend to fall more on the subpolar side of the properties, but there are absolute minima throughout the property ranges.

The shallower salinity minima in the WCR and surrounding area were at 26.55–26.67 σ_θ, which is similar to the local maximum winter surface density (section 4e). In the WCR, most minima were multiple and had a lot of finestructure; the only exception was the *Kofu Maru* station 46 (37°20′N, 144°E) at the center of the ring, which had a single salinity minimum of very low salinity, composed of nearly pure subpolar water at 26.71 σ_θ.

At stations with multiple minima, the shallowest minimum was freshest in the Kuroshio Extension. However, in the MWR the pattern of whether the shallower or deeper minima were fresher appeared at random.

It is not clear which of the minima to identify as NPIW at stations with multiple minima, and perhaps identification of just one minimum as NPIW is not necessary. The simplest strategy is to plot properties at the absolute salinity minimum (Fig. 9), with the assumption that these are the most likely to survive further mixing and contribute the most to the new NPIW. (At a number of stations, the salinity difference between multiple minima is slight, so this strategy has some problems.)

The highest densities (>26.9 σ_θ) of the absolute salinity minima are found in the Kuroshio Extension, with some scattered high densities elsewhere. Densities between 26.8 and 26.9 σ_θ are found in the Kuroshio Extension and up into the MWR, on the west side of the WCR. Densities between 26.7 and 26.8 σ_θ are found on the east side of the WCR, down along the Honshu coast, along the Subarctic Front, and in the Tsugaru outflow. The few densities less than 26.7 σ_θ are found mainly in the northwest corner of the WCR study area and up into the Oyashio intrusions and the old WCR north of 40°N. Salinities of the minima follow the same pattern, with highest salinities in the south and lowest in the north.

The absolute salinity minima can be classified using the average regimes (Fig. 8g). The resulting map differs from that of the regimes (Fig. 2b) because Fig. 2b was based subjectively on the whole station profile, whereas Fig. 8g is based on which average profile the salinity minimum itself fits best. When regimes for the shallowest and densest salinity minima are mapped (not shown), approximately the same pattern emerges. The absolute salinity minima are subtropical water only in the Kuroshio Extension and southward. In the southern MWR around the WCR, they are mainly subtropical transitional water, with some subpolar transitional water along the coast near 36°N. The Tsugaru outflow registers as subpolar transitional because a separate test for Tsugaru water was not included. The absolute salinity minima exiting the region towards the east along the Subarctic Front (40°N between 146° and 150°E) are subtropical transitional. This is the prototypical NPIW, as discussed in the next section.

e. Relation of salinity minima to winter surface conditions

The density of the fresh, new salinity minima in the MWR is close enough to the usual maximum winter (March) surface density in the region to suggest further exploration of their relationship. Regular ventilation, to 27.1–27.2 σ_θ, occurs farther north in the Okhotsk Sea under sea ice (Talley 1991). Local MWR outcropping slightly denser than 26.7 σ_θ has been found in Funka Bay (Talley 1993; Talley and Nagata 1991) and close to the coast of northern Honshu (Nagata 1993). As seen in this 1989 data, late-winter data often reveal one or two stations near the southeastern Hokkaido coast with surface density this high. However, average March surface density in the MWR north of 40°N is more on the order of 26.5–26.65 σ_θ (Talley 1993) and so perhaps generalizations about what sets the density of new NPIW should rely more on this density range than on the maximum surface density.

Surface density from the April–June 1989 stations is difficult to interpret because of nonsynopticity and rapid warming after winter. Two surface densities higher than 26.5 σ_θ (26.56 and 26.75 σ_θ) were observed at the southeastern coast of Hokkaido in early April

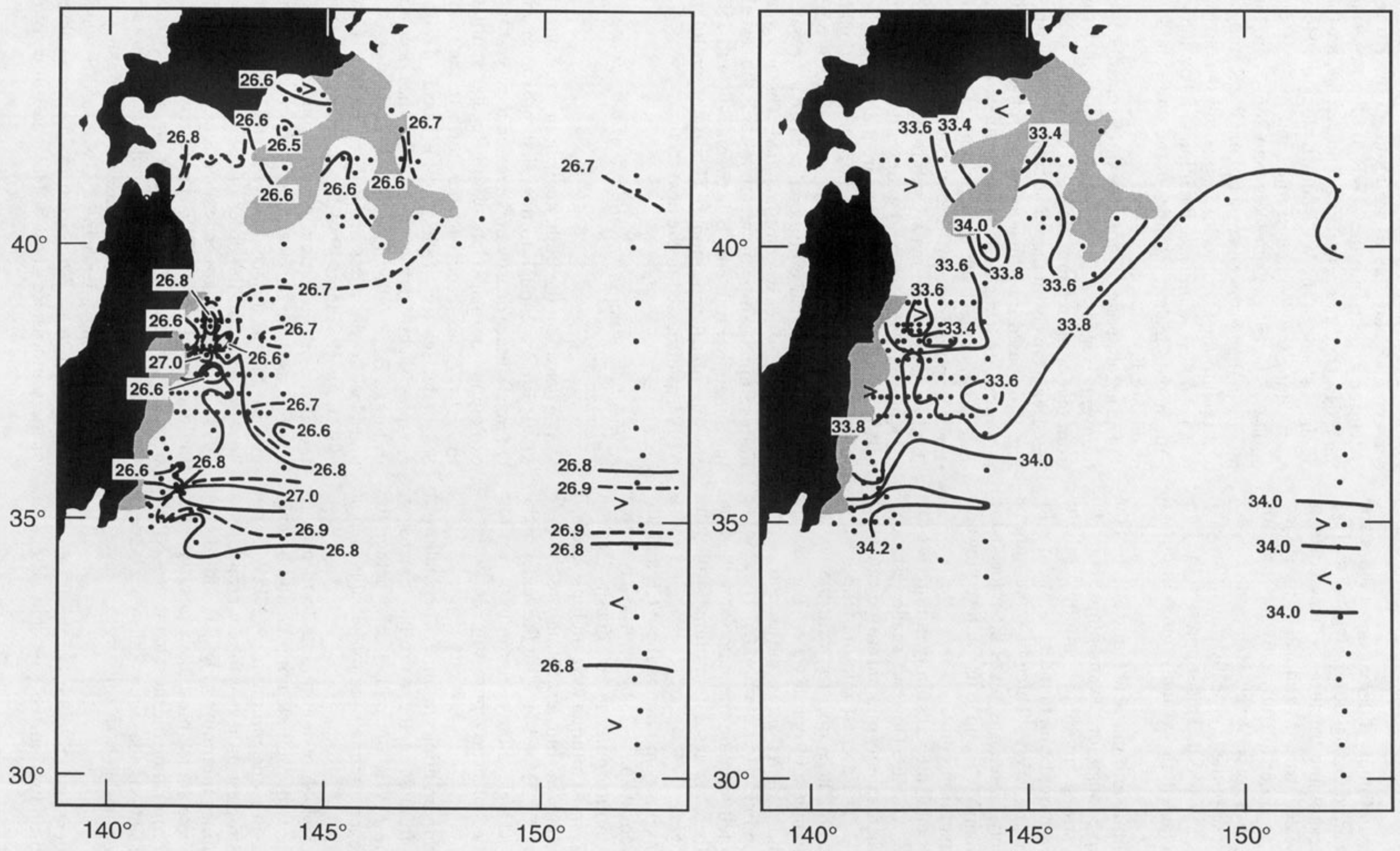

FIG. 9.(a) Potential density, (b) salinity, and (c) regime of the absolute salinity minimum at stations where there was a subsurface salinity minimum. CTD profiles were smoothed with a Gaussian filter of 50 dbar half-width prior to selection of minima. Data from the 152°E section from May 1981 are also included. There is no subsurface salinity minimum in the shaded regions. The "regime" was chosen by comparison with the average profiles of Fig. 8g, within the standard deviation of the mean salinity at the density of each stations' salinity minimum. No regime is shown for the southernmost stations along 152°E and in a band just south of 35°N; salinity at the minimum for these stations was fresher than "subtropical" and more saline than "subtropical transitional."

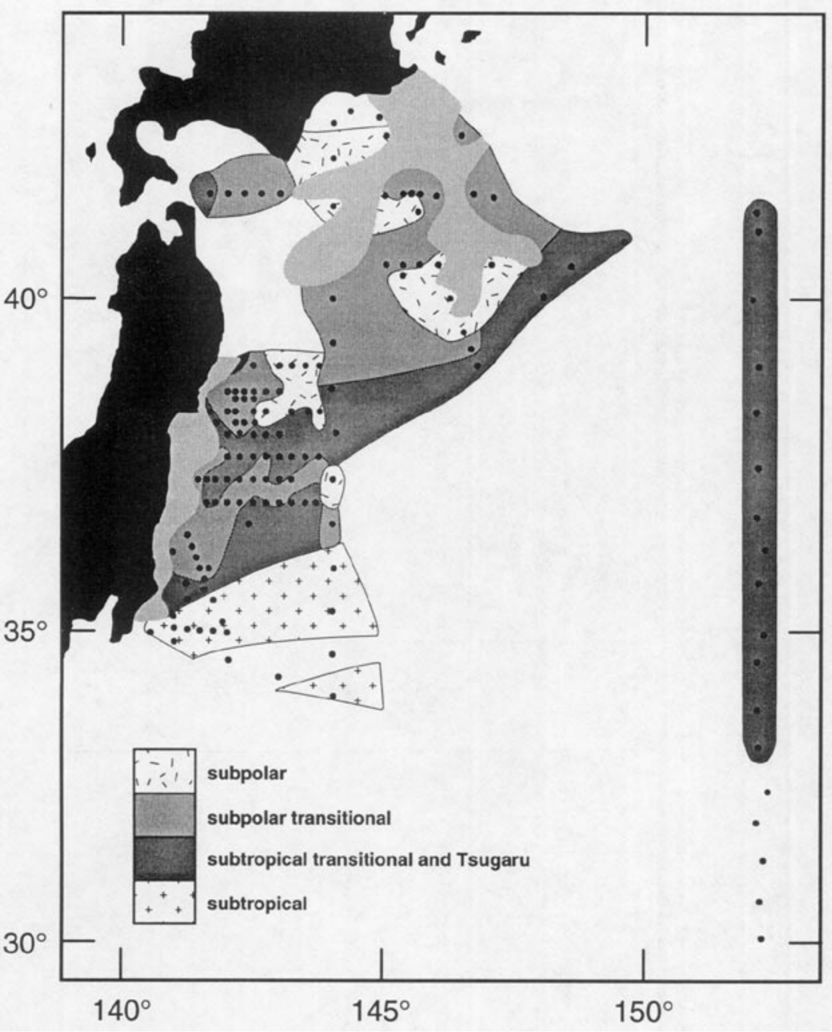

FIG. 9. (*Continued*)

on the *Tankai Maru*. These data are somewhat suspect since they were at the first stations on the cruise. Since the full dataset extends into June, winter density can only be inferred subjectively from either oxygen (Reid 1982) or Brunt–Väisälä frequency profiles. In the absence of oxygen data, we have used the latter. Squared Brunt–Väisälä frequency

$$-\frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

was calculated by a least squares fit to the slope of in situ density, after first smoothing with a Gaussian filter of 10 dbar half-width. The shallowest Brunt–Väisälä frequency minimum is expected to mark the local mixed layer; for post-winter stations, the winter mixed layer could therefore be the second minimum. In practice such selection was difficult, as some stations were made in early April and others through June. Profiles without a dominant minimum were deleted; most were in the Kuroshio Extension. The resulting subjective maps of "winter mixed layer" density, temperature, and Brunt–Väisälä frequency are shown in Fig. 11.

Dramatically low Brunt–Väisälä frequency occurred in the southern WCR (37°20′N, 144°E) and may be the best indicator of the limits of this ring, in which 9°–11°C water centered at a density of 26.45 σ_θ was found in a near-surface layer 300–400 m thick. This overlaid the jagged salinity minimum layer, in which there was usually a double minimum, with the upper slightly denser than 26.5 σ_θ and the lower nearer 26.7 σ_θ.

In the Oyashio region, where most stations were made in April, there were two superimposed surface layers 70–100 m thick, with the upper one at a density of 26.4–26.5 σ_θ, lying above one at 26.6–26.7 σ_θ. It was difficult to decide which to call the "winter mixed layer"; we have chosen the denser. It is therefore likely that we have really selected the

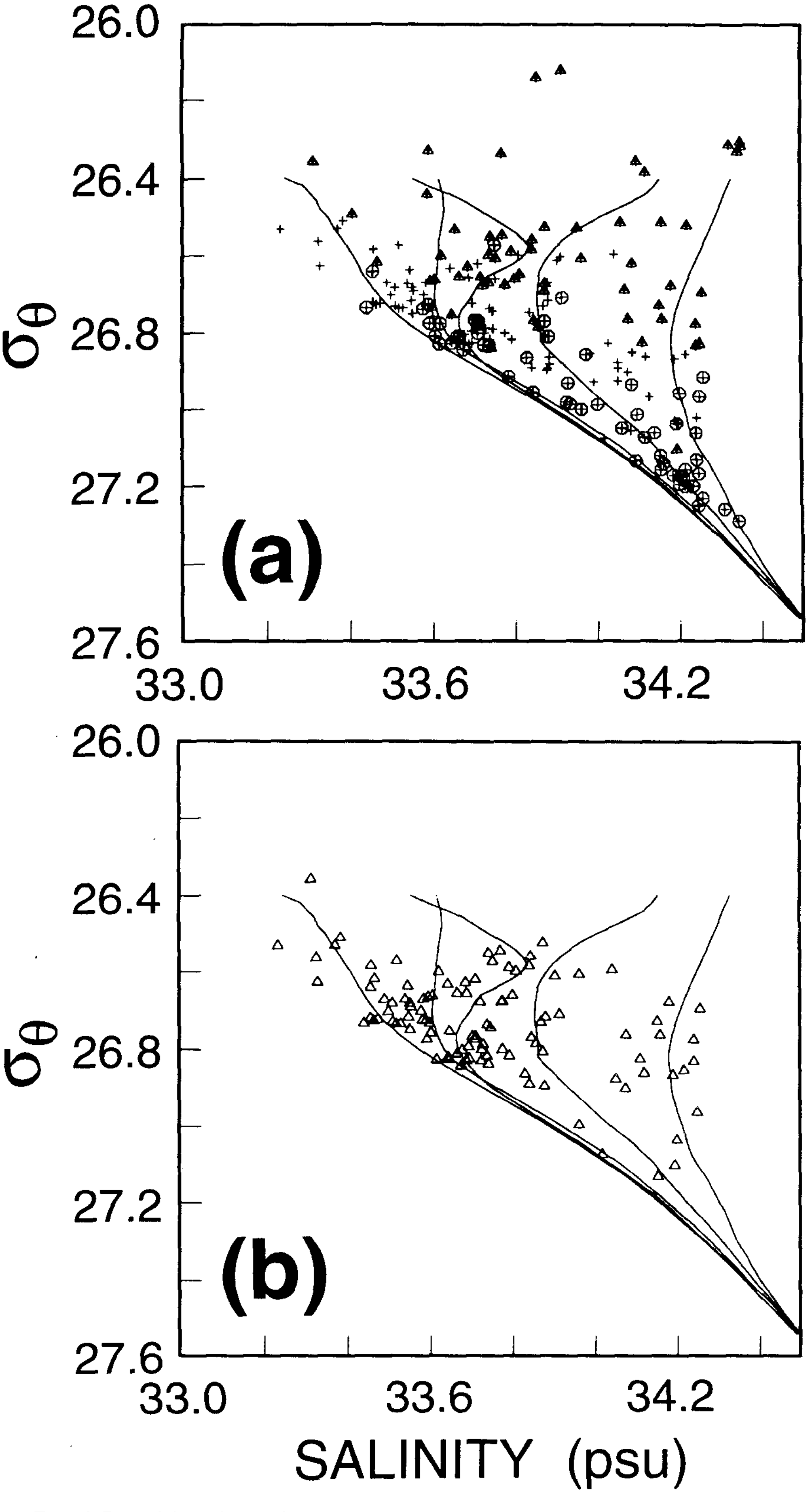

FIG. 10. Potential density as a function of salinity for (a) all salinity minima and (b) the absolute salinity minima. In (a) a plus sign marks each minimum; for stations with multiple minima, the upper minima are marked by triangles and the lower minima by circles, which therefore also include a plus sign. CTD profiles were smoothed with a Gaussian filter of 50 dbar half-width prior to selection of minima. (The 152°E stations are not included.)

densest mixed layer from upstream along the Kuril Islands.

Even with a prejudice towards choice of the highest possible surface density, densities exceeded 26.7 σ_θ only at the two coastal stations just south of Hokkaido where the actual surface density was this high. Densities exceeded 26.65 σ_θ in the area most directly affected by the Oyashio, north of 39°N and east of 143°E, in precisely the region indicated as "subpolar" in Fig. 2b. These densities were associated with temperatures less than 5°C. Densities between 26.5 and 26.6 σ_θ were found down along the Honshu coast to about 38°N, coinciding with the subpolar transitional and Tsugaru regimes. South of this was the main WCR (37°20′N, 144°E), with a winter density of about 26.45 σ_θ; the influence of the latter extended southwestward along the northern edge of the Kuroshio; these were the subtropical transitional stations of Fig. 2b. In the coastal waters along Honshu, the density was considerably lower (predominantly 26.2–26.3 σ_θ), although no data along the northern coast of Honshu were included—this may also be a region where winter surface density often exceeds 26.7 σ_θ (Nagata 1993).

Are the density of the salinity minima and "winter surface layer" density related? The newer, fresher salinity minima, that is, subtropical transitional and subpolar transitional minima, are at slightly higher densities (Figs. 9a,c) than the general winter surface density of the subpolar waters in the MWR (Fig. 11a). It is assumed that these fresh salinity minima are newer than the saltier ones found in the subtropical water, based in part on their higher oxygen and assumed formation mechanism (Talley 1993). In a later study, we will show details of the vertical structure of these minima, which often are overlain by a layer of sharply increasing salinity. This interfacial layer will be shown to be about 100 m thick. If half of this thickness comes from subpolar water, the final density of the fresh intrusion would be that which lies about 50 m below the late-winter mixed layer; in the average subpolar profile, this density is about 26.7 σ_θ. Thus, intrusion of the winter subpolar waters of density 26.6 σ_θ beneath any saltier, less dense waters in the MWR, with rapid mixing producing an interfacial layer, could result in the salinity minimum being at the NPIW density.

f. Relation of salinity minima in the mixed water region to NPIW found to the east

Comparison of NPIW from CTD data east of the MWR with the salinity minima described above suggests which of the minima actually persist towards the east, and hence is the true precursor to the NPIW. CTD stations along 152°E in May 1981 and May 1982 and along 165°E in September 1984 are considered. The 152°E sections were discussed by Niiler et al. (1985) and the 165°E section by Joyce (1987). The 1982 section at 152°E and the 1984 section at 165°E are reproduced here in Fig. 12. To check that interannual variability does not obscure the comparison, properties for the bottle data at 144°E section in spring 1981 and 1982 were compared and found to be essentially the same as in spring 1989.

Both of the 152°E sections crossed the Kuroshio Extension. The 1981 section did not cross the Subarctic Front to the north. The 1982 section (Figs. 12a,b) crossed the Subarctic Front and also contained a Kuroshio WCR. In Talley (1993) the northern NPIW on these sections was seen to be jagged relative to profiles from farther east and from the center of the subtropical gyre. This difference in NPIW structure was taken to be evidence that NPIW is formed as an intrusive minimum in the MWR. The double salinity minimum from these data in the Kuroshio core was also noted in Talley (1993).

Three distinct types of potential density–salinity structure are apparent at 152°E (Figs. 13a,b): relatively smooth and salty salinity minima, from stations south of the Kuroshio Extension; noisier, fresher salinity minima with salinity less than 34.0 psu, from stations between the Kuroshio Extension and Subarctic Front; and subpolar profiles with lowest salinity at the sea surface (the two northern stations in 1982). The profiles with fresher NPIW between the Kuroshio Extension and the Subarctic Front closely resemble the MWR profiles labeled subtropical transitional (Fig. 8d) and therefore their NPIW is assumed to originate in the MWR. One station (28) just south of the Subarctic Front in 1982 had even fresher, more jagged NPIW and may therefore indicate new NPIW formation near this location.

As described above, the WCR near the western boundary appears to be important in initial formation of NPIW. Are rings that form farther offshore also important? At 152°E in 1982 (Figs. 12a,b and Fig. 13b), stations 13–16, between the Kuroshio Extension and the WCR, had subtropical water below 26.7 σ_θ, a relatively fresh intrusion between 26.0 and 26.7 σ_θ, and surface waters fresher than subtropical and saltier than subpolar water. In the WCR itself (stations 17 to 20), the structure was the same except that the surface waters were subtropical. North of the WCR (stations 21–25 and 29), all profiles matched the subtropical transitional profiles for the MWR (Fig. 8d). Station 28 just south of the Subarctic Front in 1982 could be classified as either subpolar transitional or subtropical transitional, with a strong and jagged NPIW salinity minimum. The 152°E WCR therefore appears to have been subtropical water that entrained subtropical transitional water. We do not consider this to be "new NPIW formation" since the subtropical transitional water with new NPIW apparently was already present when the WCR began entraining. However, the entrainment

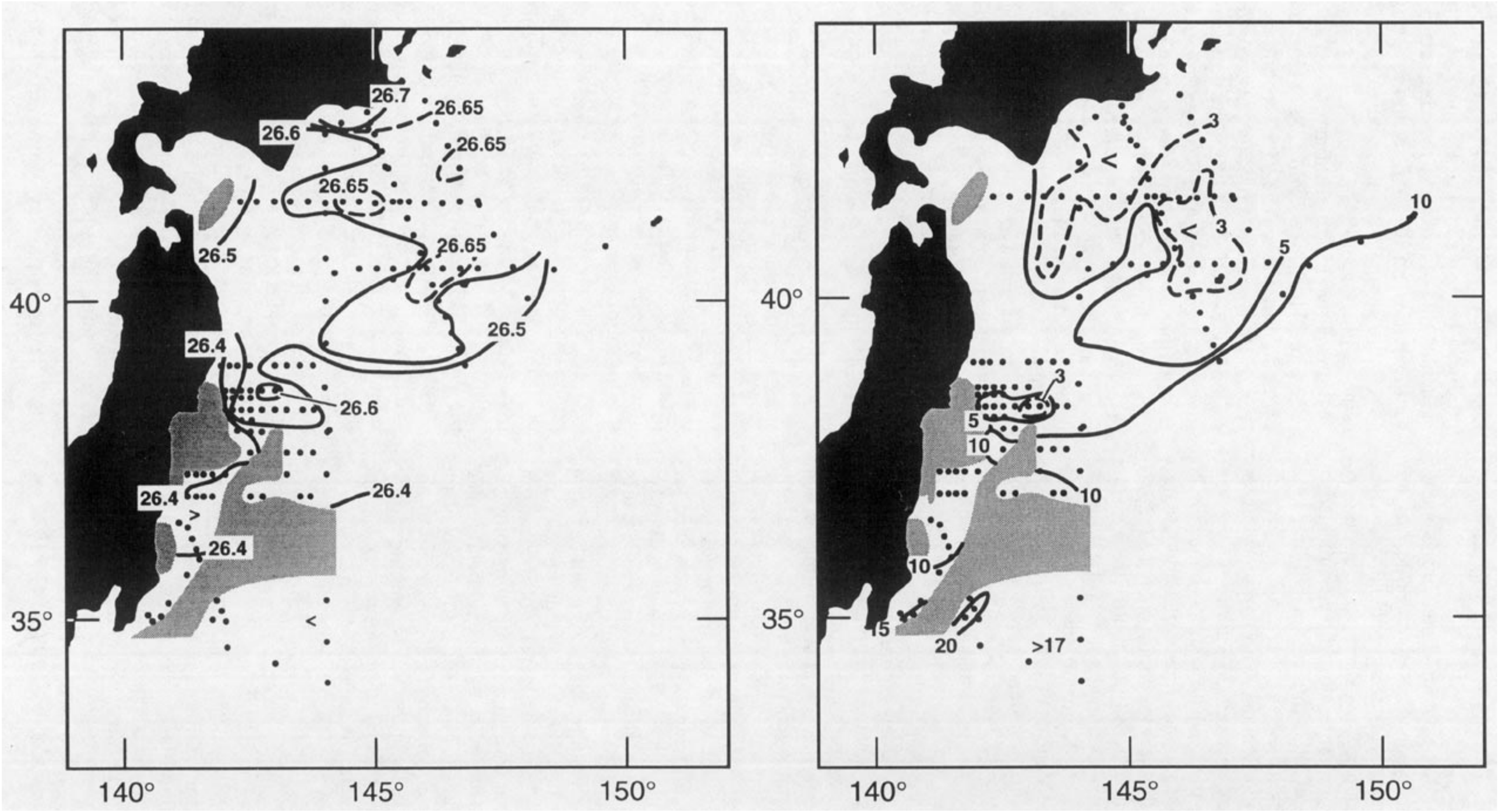

FIG. 11.(a) Potential density, (b) potential temperature (°C), and (c) Brunt–Väisälä frequency (cycles/hr) at the near-surface Brunt-Väisälä frequency minimum. It is suggested that this minimum approximately represents the remnant winter mixed layer. There is no minimum at the shaded stations.

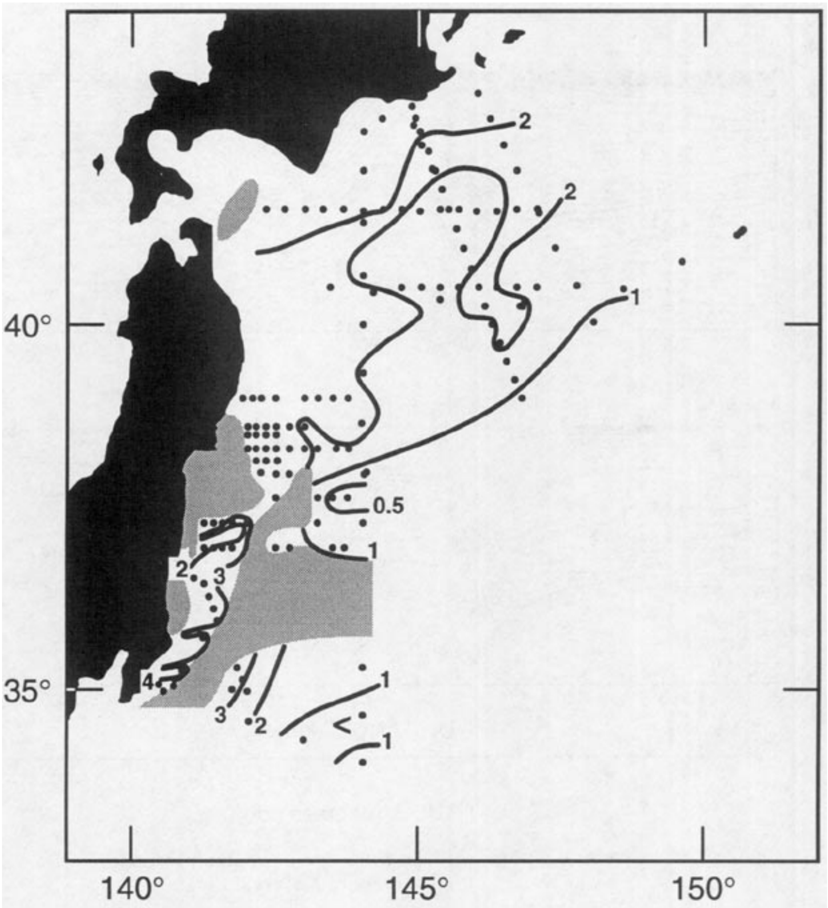

FIG. 11. (*Continued*)

process did create sharper interfaces above and below the layer of subtropical transitional water.

In and south of the Kuroshio Extension, the 152°E NPIW salinity was actually fresher than at 144°E. Thus, the saline, old NPIW in the Kuroshio core near the western boundary was freshened before reaching 152°E; the only remnant at 152°E of the original Kuroshio core was in the high salinity separating the double salinity minima in the profiles directly in the high speed Kuroshio core. The double salinity minima in the core were subtropical transitional water, and so originated in the MWR.

The 1984 section at 165°E is described in Joyce (1987). It crossed the Kuroshio Extension (34° to 35°N), a WCR (37° to 41°N), and the Subarctic Front (42°N) (Figs. 12c,d). Sigma theta–salinity relations (Fig. 13c) can be divided into four regimes: 1) stations 3 to 11 south of the Kuroshio Extension, 2) stations 12 to 23 between the Kuroshio Extension and across the WCR, 3) two stations (24 to 25) just south of the Subarctic Front, and 4) stations north of the Subarctic Front. South of the Kuroshio Extension, the NPIW most resembles the saltiest subtropical transition water (Fig. 8d) or the freshest subtropical water (Fig. 8a). It is similar to the relatively fresh NPIW found just south of the Kuroshio Extension at 152°E in 1981 but is vertically smoother. None of the saltiest NPIW from 144° or 152°E is found on the 165°E section, indicating that all of the old NPIW found near the western boundary had been mixed away by this longitude. NPIW north of the Kuroshio Extension at 165°E was slightly fresher than that south of the Kuroshio Extension. This water likewise resembled the saltier subtropical transition water and is assumed to be the downstream expression of what was found at 152°E. It was much smoother vertically at 165°E than at 152°E. The two stations south of the Subarctic Front were subpolar transitional (Fig. 8e), based on our MWR definitions. The water north of the Subarctic Front at 165°E was not the purer subpolar water of the MWR, based on its somewhat high surface salinity. If classified according to the MWR definitions, this also would be subpolar transitional water.

From the 152° and 165°E sections, we conclude that the subtropical transitional water in the MWR is the source of new NPIW. The very narrow band of

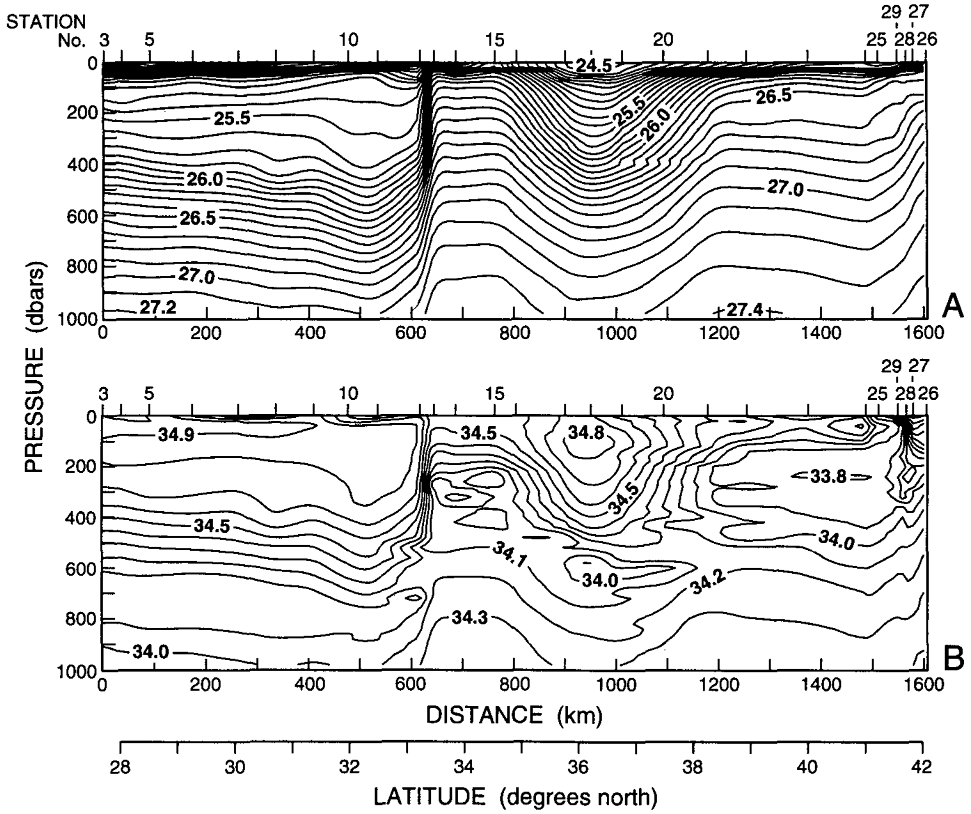

FIG. 12. Vertical sections of (a) potential density σ_θ and (b) salinity at 152°E in May 1982 (Niiler et al. 1985).

subpolar transitional water adjacent to the Subarctic Front at 152° and 165°E indicates that intrusions across this front may still also be active at these longitudes, but the limited area of these intrusions and the fact that the bulk of NPIW in the MWR and at 152° and 165°E looks like subtropical transitional water suggests that the latter is the primary source.

We also conclude that the high salinity core of the Kuroshio Extension is mixed away rapidly once it separates from the western boundary (see also Fujimura and Nagata 1992); a particular but unspecified process is suggested by the observation of fresh intrusions above and below the old NPIW in the Kuroshio core, as partially demonstrated by Shin et al. (1988; 1991). The 1981 152°E section also shows evidence of southward flux of newer NPIW across the Kuroshio. Since similarly freshwater was found at all stations in and south of the Kuroshio Extension at 165°E in 1984, and the water south of the Kuroshio Extension at 144°E is also fresher than the oldest NPIW, but saltier than that found at 152°E, we hypothesize that exchange across the Kuroshio Extension occurs between 144° and 165°E. Since the water north of the Subarctic Front was somewhat saltier at 165°E than farther west, we also hypothesize exchange across this front.

5. Transport of new NPIW out of the mixed water region

How much subpolar water is transported into the subtropical gyre in the western North Pacific? The Okhotsk Sea produces the freshest water at densities of about 26.7–27.6 σ_θ. This is carried southward in the Oyashio to the MWR, where some portion mixes into the MWR, hence significantly freshening the subtropical water that comes into the MWR from the south. This mixture exits to the east and is part of the subtropical gyre circulation. The remainder of the subpolar water presumably continues on around the subpolar gyre north of the extended Oyashio Front (Subarctic Front in the western North Pacific). For the purposes of this discussion, "intermediate waters" refers to this full density range. Lateral and vertical mixing of subtropical and subpolar waters in the MWR changes the density of the incoming subpolar and subtropical waters, so it is best to make this transport calculation for the complete affected layer rather than for a narrow density range.

The intermediate waters exiting the MWR are apparent on the 152°E sections between the Kuroshio Extension and Subarctic Front and are identical to the

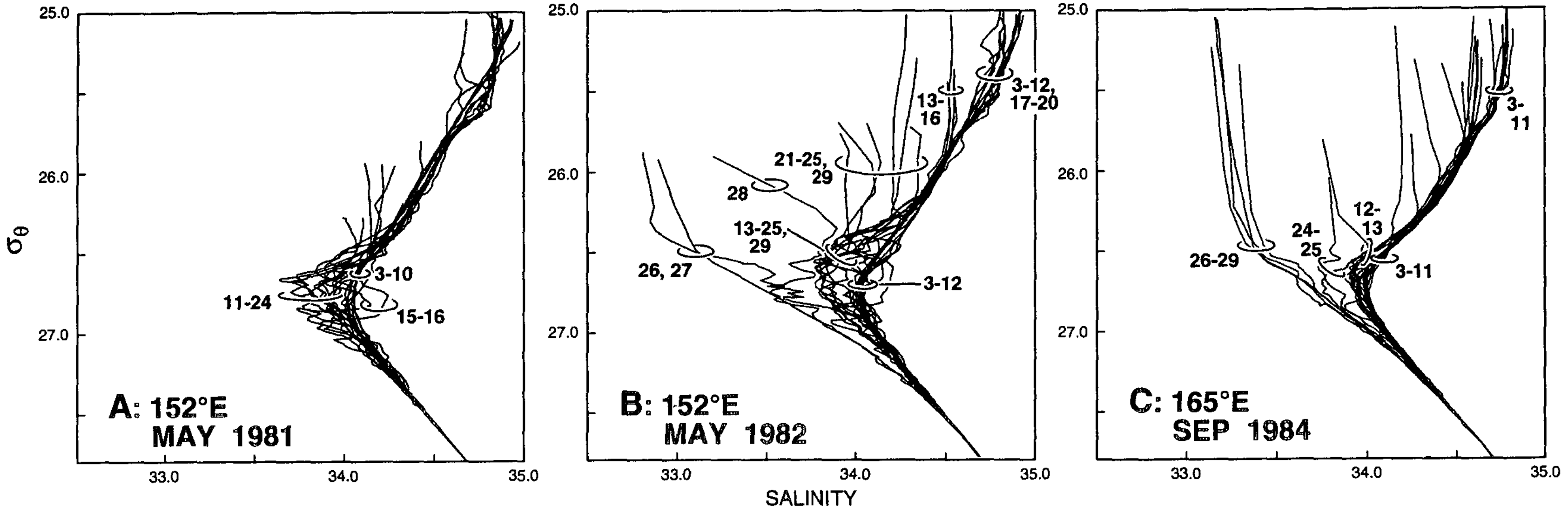

FIG. 13. Potential density salinity for all CTD profiles along 152°E and 165°E: (a) 152°E between 27°40′°N and 41°16′N in May 1981, (b) 152°E between 30°N and 41°34′N in May 1982, (c) 165°E between 29°N and 44°N in September 1984. Vertical sections for the latter two were shown in Fig. 12.

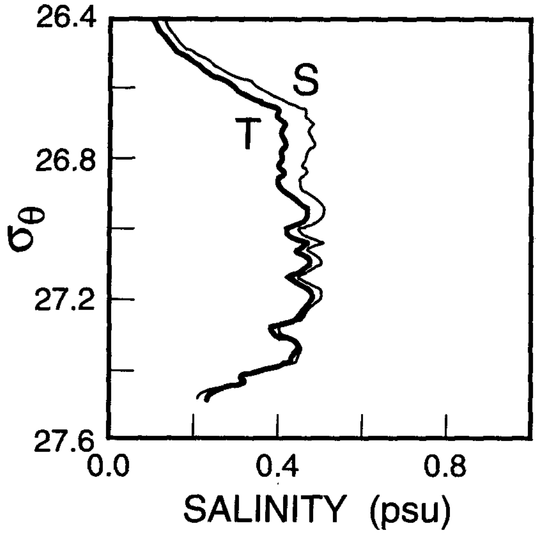

FIG. 14. Relative proportion of subpolar water in subtropical transition water, assuming the latter is a mixture of subtropical and subpolar waters only. The heavy curve bases the proportions on potential temperature and the light curve on salinity. See Fig. 8g for the average curves for the three regimes.

subtropical transition regime defined for the MWR. Based on the average subtropical and subpolar profiles (Fig. 8g), and assuming conservation of density during mixing, subtropical transition water is about 40% subpolar and 60% subtropical water for the density range 26.65–27.4 σ_θ using temperature for the proportions. Using salinity, subtropical transition water is about 45% subpolar water (Fig. 14). The difference between the temperature and salinity results is due to cabelling, which affects the density by up to 0.04 σ_θ.

The 152°E section in May 1981 did not contain any WCRs, so it is the easiest to use for calculating eastward transport of new intermediate water. Stations 17–24, north of the Kuroshio Extension, have the freshest, hence newest, intermediate water. It is assumed that there is little new intermediate water between the northernmost station and the Subarctic Front. Niiler et al. (1985) showed that transport relative to the bottom has little shear below about 2000 m. Using two years of current meter measurements, they inferred a level of no eastward flow at 1000–1200 m. The transport in the range 26.4–27.4 σ_θ at stas 17 to 24 is 6.9, 8.1, 8.4 Sv eastward, for reference levels of 1000, 1200, 2000 dbar, respectively (Sv ≡ 10^6 m^3 s^{-1}). The eastward volume transport relative to 2000 dbar for 26.4–26.65 σ_θ and 26.65–27.4 σ_θ is 2.3 and 6.1 Sv, respectively. New intermediate water is assumed to be in the denser category. Thus, it is estimated that 2.7 Sv (45%) of the new intermediate water is of Oyashio origin.

How does this compare with the transport of subtropical water into the mixed water region? It is estimated that one to two WCRs form each year just off Japan (e.g., Tomosada 1986). Assuming that rings formed farther offshore also contribute some subtropical water to the MWR, we take the higher estimate of two rings per year. With an average diameter of 200 km, and an average thickness of 700 m for the range 26.65–27.4 σ_θ (e.g., Fig. 3), the transport of subtropical water into the MWR is 1.4 Sv for two rings per year. If the eastward flowing intermediate water is 55% subtropical water, then the total transport eastward is 2.5 Sv, of which 1.1 Sv is from the Oyashio. This estimate does not take into account formation of offshore rings, which might occur as frequently as formation of the first ring. If two offshore rings form each year and their subtropical water becomes part of the overall mixture as they advect westward, the eastward transport of new intermediate water could be 5.0 Sv, with 2.2 Sv from the Oyashio. This total transport is consistent with the 6.1 Sv estimate of the previous paragraph, suggesting that the assumption of most northward transport across the Kuroshio being in WCRs may be reasonable, that the contribution of the first offshore ring may be important, and that the proportions of subtropical and subpolar waters in the outgoing intermediate water are also reasonable. The transport of the Oyashio along the western boundary is 10–15 Sv for the upper 1000 m based on direct current measurements (Miyake et al. 1991). About 80% of this is in the density range 26.65–27.4 σ_θ; if 2.0–3.4 Sv enter the subtropical gyre, then 7–13 Sv remain in the subpolar gyre, north of the Subarctic Front, as the Oyashio meanders and turns eastward.

6. Discussion

The main dynamical and water mass structures that influenced the MWR in spring 1989 were the Kuroshio Extension, the Oyashio Front, the Tsugaru/Oyashio Front, and a large, semidetached WCR centered at 37°20′N, 144°E. All of the stations in the survey area could be grouped by eye in four distinct regimes, termed the subtropical, subpolar, subtropical transitional, and subpolar transitional regimes. Subpolar transitional stations were fresher at all densities than subtropical transitional stations. The fresh, new salinity minima considered to be prototypical NPIW were found in the latter two transitional regimes.

Subtropical water enters the MWR in WCRs. The lack of any purely subtropical stations in the MWR in spring 1989 may reflect the fact that the WCR was formed before winter and therefore had ample time to entrain surrounding water, modifying the original subtropical water.

Intrusions of low salinity water into more subtropical water were found near all of these dynamical structures, with the preponderance of multiple minima found in and around the WCR. Most of the salinity minima had a large amount of finestructure (apparent in the

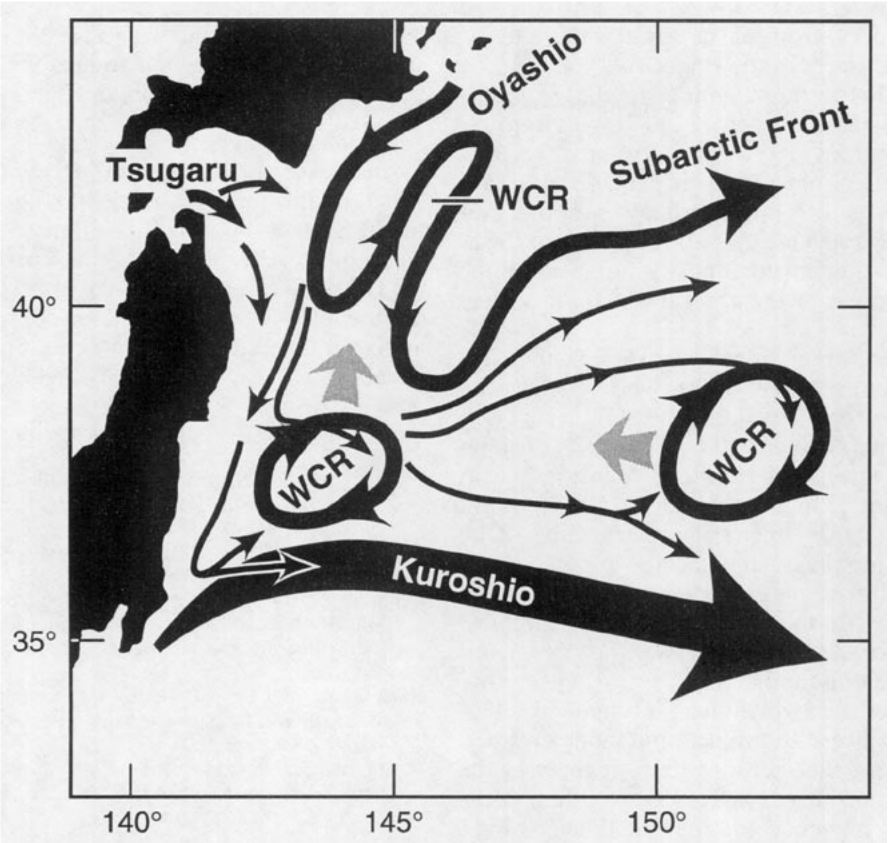

FIG. 15. Schematic diagram for formation of NPIW. For a similar view of the region, see Kawai (1972). The heavy arrowed curves are the major currents and the light curves are general directions of water movement, including intrusion into the rings and the Kuroshio. The large dashed arrows show the propagation direction of the rings. It is emphasized that this region is extraordinarily variable, and that an important aspect of this region is how much each of the features shown is changing continuously. Other important aspects of the region that are not depicted are air–sea interaction, which increases the density of surface waters in winter, and the general direction of migration of the warm core rings: offshore ring to the west, onshore ring to the south where it may recoalesce with the Kuroshio Extension and to the north where it degenerates into the water separating the Oyashio intrusions.

vertical profiles but not quantified in this paper). After smoothing to remove the smallest vertical scales, the minima were largely in the density range 26.5 to 27.0 σ_θ. The large number of multiple minima and lack of a strong preference towards fresher or saltier shallow salinity minima suggests that the simplest hypothesis of NPIW formation—subduction of fresh surface water with subsequent erosion of this single minimum—cannot be validated.

Most of the absolute salinity minima, which one might expect to be new NPIW because of their freshness, were between 26.7 and 26.82 σ_θ. A subjective attempt to determine the late-winter surface mixed layer density using the Brunt–Väisälä frequency minimum showed that the subpolar water had a fairly thick layer near the surface at 26.6–26.65 σ_θ, which is somewhat less dense than most of the absolute salinity minima. These surface densities are characteristic of Oyashio waters well northward along the Kurils (Talley 1993), so it is presumed that the timing of the spring 1989 observations did not bias the conclusion about late-winter density of subpolar water. Two coastal stations off Hokkaido had surface densities higher than 26.7 σ_θ; similarly high surface densities are found in Funka Bay near Tsugaru Strait (Talley and Nagata 1991; Talley 1993); Nagata (1993) has shown that coastal waters in a small region off northern Honshu also reach this density in late winter. We have not estimated the volumetric significance of these very local sources, assuming that they represent the extreme rather than the mean winter subpolar surface density because of the small regions that they occupy.

Stations with the freshest NPIW at 152° and 165°E were identical to the subtropical transitional stations in the MWR. Relatively fresh intrusions in a WCR at 152°E were not actually newest (freshest) NPIW, but were intrusions of subtropical transition water into the older subtropical water in the ring.

Transport of the newest intermediate waters (26.65–27.4 σ_θ) eastward across 152°E was approximately 6 Sv in May 1981. The properties of this intermediate water suggest that it is made up of approximately 55% subtropical and 45% subpolar water. Therefore, we suggest that about 3.0 Sv of freshened subpolar water in this density range enter the subtropical gyre, renewing the intermediate waters there.

Based on these observations, we suggest that formation of the newest NPIW occurs when the Oyashio introduces fresh subpolar water to the MWR (Fig. 15). These surface waters cool in winter to a density of about 26.6–26.65 σ_θ with some localized densities (near coasts) that might be higher than 26.7 σ_θ due to input of higher salinity from the Tsugaru Current. At all fronts between modified subpolar and modified subtropical waters, intrusions of low salinity into the more subtropical water are found. In spring 1989 the most active location for these intrusions was the large, semidetached WCR at about 37°20′N. Intrusions are obvious at all densities at which there is a marked difference in salinity between subtropical and subpolar water.

We hypothesize that because the thickness of the remnant late-winter mixed layer is greater than of the overlying seasonal pycnocline, that the thicker winter water produces thicker intrusions which do not mix away as rapidly as the seasonal surface layers. We also hypothesize that the input of higher salinity from the Tsugaru Current at densities lower than 26.6 σ_θ means that on the whole, the freshest water in the northern MWR is at densities greater than 26.6 σ_θ.

The interfacial layers between the fresh intrusions and surrounding saltier water are 50–100 m thick at the stations with the sharpest intrusions; this is not demonstrated herein however. If the major shallowest intrusion is at the winter mixed layer density to start with, this mixing alone could deepen the salinity minimum to densities of about 26.7 σ_θ.

We then hypothesize that the subtropical transition water formed through these intrusions and mixing escapes the WCR and fronts and is advected toward the east. There it may encounter other WCRs formed farther east and be entrained by them. These rings propagate westward and interact with the WCR and other structures in the MWR. This recycling process lengthens the time in which subpolar and subtropical waters interact. The observations at 165°E also suggest that there is some flux of subtropical transitional water across the Kuroshio Extension and the Subarctic Front, thereby freshening the subtropical and increasing the salinity of the subpolar waters.

Further work is necessary to identify and quantify the mixing processes and rates in the MWR. With the large number of high resolution CTD stations that have been collected routinely since 1988, it should be possible to begin making statements which are independent of a particular season and survey.

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