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An Okhotsk Sea water anomaly: implications for ventilation in the North Pacific

LYNNE D. TALLEY*

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Abstract—An unusually cold, fresh and oxygenated layer of water centered at a pressure of 800 dbar and σ_θ of 27.4 was found at a CTD station in the western Pacific at 43°5'N, 153°20'E in August 1985. The anomaly was part of a larger pattern of less dramatic but nevertheless higher variance at densities up to 27.6 σ_θ in the mixed water region of the Oyashio and Kuroshio, south of the Bussol' Strait, which connects the Sea of Okhotsk and the open North Pacific. Isopycnal maps indicate that the source of the anomaly, which was embedded in a cyclonic flow, was the Okhotsk Sea. Surface properties in the Okhotsk Sea, based on all available NODC observations, and isopycnal maps indicate that the layer probably did not originate at the sea surface in open water. Instead, the principal modifying influences at densities of 26.8–27.6 σ_θ in the North Pacific are sea-ice formation and vertical mixing, the latter primarily in the Kuril Straits. A simple calculation shows that most of the low salinity influence at these densities in the North Pacific can originate in the Okhotsk Sea and that vertical mixing in the open North Pacific may be much less important than previously thought.

1. INTRODUCTION

IT IS well known that North Pacific waters below the thermocline are lower in salinity than waters in the tropical Pacific at the same densities. In the subtropical gyre, one manifestation of the lowered salinity is the North Pacific Intermediate Water (NPIW), which is a salinity minimum at densities of about 26.7–26.9 σ_θ. In the subpolar gyre, salinity increases monotonically from the sea surface downward and is lower than in the subtropical gyre at all densities less than about 27.6 σ_θ. REID's (1965) composite meridional section at 165°E shows the low salinity water and its lateral minimum in the subpolar North Pacific. Closer examination of properties such as salinity and potential vorticity on isopycnals shows a strong meridional gradient at densities lower than 26.8 σ_θ, particularly at the subtropical–subpolar gyre 'boundary', a discernible gradient at densities between 26.8 and 27.6 σ_θ, and a nearly vanishing gradient at higher densities.

It is evident from maps of winter surface density in the North Pacific (e.g. REID, 1969; HASUNUMA, 1978; LEVITUS, 1982), a further iteration of which is included in this paper, that densities greater than 26.8 σ_θ do not outcrop in the open North Pacific. While this may partially explain the decrease in isopycnic gradients below the 26.8 σ_θ surface, it does not explain why the contrast in salinity disappears entirely below the 27.6 σ_θ surface. It may be that the effect of vertical mixing of low salinity from the surface waters down into the unventilated waters diminishes with increasing density, and that we are simply seeing the

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* Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, U.S.A.

increasingly weak effects with depth. This was REID's (1965, 1973) reasonable solution, an assumption of general vertical mixing throughout the subpolar gyre without intermediate water formation or enhanced mixing at specific sites.

On the other hand, the Okhotsk Sea has lower salinity and higher oxygen at the intermediate densities of 26.8–27.6 σ_θ than any other site in the North Pacific. The density at its deepest sill depth is about 27.65 σ_θ; the coincidence of this range of densities with those which have measurable large-scale salinity gradients in the open North Pacific is intriguing. In fact, based on very limited data, WÜST (1930) suggested that the Okhotsk Sea was the source of low salinity at intermediate depths; he assumed that these waters outcrop in the Okhotsk Sea. REID (1965, 1973) concluded that direct ventilation was not possible and moreover felt that the Okhotsk Sea could not contribute enough low salinity flux to account for the modified properties in the open North Pacific. FAVORITE *et al.* (1976), on the other hand, concluded that "discharge from the Okhotsk Sea" both forms the core of the Oyashio and also joins with the southward-flowing East Kamchatka Current and turns offshore to form the Subarctic Current. Evidence for the latter was a tongue of low salinity at 27.0 σ_θ extending northeastward from the southern Kuril Islands. KITANI (1973), in a careful study of intermediate waters of the Okhotsk Sea, focuses on modification of water properties beneath sea-ice formation. His data showed saline shelf waters as dense as 27.05 σ_θ formed from fresher surface waters in the northwestern Okhotsk Sea. (The 'saline' shelf waters have lower salinity than the ambient waters at the same density because they are so close to the freezing point.) Kitani suggested that this mechanism could be the source of low salinity water at densities up to 27.05 σ_θ in the northwest Pacific. His treatment of higher densities was confined to a few statements about vertical mixing in the Kuril Straits.

CTD/hydrographic data collected in 1985 and 1987 in the northwest Pacific prompted a new look at the question of the source of low salinity in the northwest Pacific. In particular, a marked anomaly of low salinity, low temperature and high oxygen, centered at a density of 27.4 σ_θ, was found near the exit from the Okhotsk Sea; the source of the anomaly could only have been the Okhotsk Sea. The existence of the anomaly and tracing of its source to the Okhotsk Sea may contradict the hypothesis of the greater importance of vertical mixing in a large region of the subpolar gyre compared with local mixing in the Okhotsk Sea. Subsurface anomalies have been found at the exits of other semi-enclosed seas, which have long been known to be the source of strong property signals. One such source is the Mediterranean Sea, which produces high salinity at mid-depth in the North Atlantic without a large volume flux through the Strait of Gibraltar. These 'Meddies' are compact lenses which are found in greatest abundance near the Strait, but which have also been found far to the west in the Gulf Stream region along with many other lens-like structures of rather distant origin (e.g. EBBESMEYER *et al.*, 1986). Meddies may carry a large share of the salt flux that is responsible for increasing the North Atlantic salinity (ARMI and STOMMEL, 1983). A recent study in the Beaufort Sea (D'ASARO, 1988) showed anomalous, compact lenses produced by flow out of a submarine canyon. It is reasonable to expect that, in general, discharge through narrow topographic features will result in pinched-off, compact anomalies, and it is possible that these anomalies carry much of the discharged transport.

Unfortunately, the large-scale North Pacific survey that revealed the anomalous Okhotsk Sea water could not possibly have resolved the shape and volume of the anomaly. Nor could it determine anything about the regularity of the occurrence and geographical distribution of anomalies at this and nearby densities. Therefore the focus of this paper is the source of the anomaly and the importance of the Okhotsk Sea in modifying North Pacific properties at intermediate depths.

2. AN OKHOTSK SEA WATER ANOMALY

In August 1985, 115 hydrographic/CTD stations to the ocean bottom were collected between Hokkaido, Japan and Seattle, Washington. An additional 21 stations were collected in the northwest Pacific in June 1987, by the Saga II expedition of the *Akademik Korolev* (Fig. 1). The cruises are henceforth referred to as 'TPS47' and 'Korolev'. Vertical sections from both cruises are included as color plates in this issue of *Deep-Sea Research*, as is a paper describing the property distributions (TALLEY *et al.*, 1991). Details of the data collection and processing as well as a complete set of vertical profiles are available in TALLEY *et al.* (1988a,b). Final processed CTD data included temperature and salinity at 2 dbar intervals, with precisions of 0.001°C and 0.002‰.

At Sta. 30 on TPS47, an unusual temperature, salinity and oxygen layer of 100 m thickness was found (Fig. 2); the station was located along the northeastward jog of TPS47 nearly opposite Bussol' Strait, which is the deepest passage through the Kuril Islands. The isolated layer at Sta. 30 is too thin to have been resolved properly by standard bottle spacing, although it is recognizable in the bottle data; it is unlikely, however, that it would

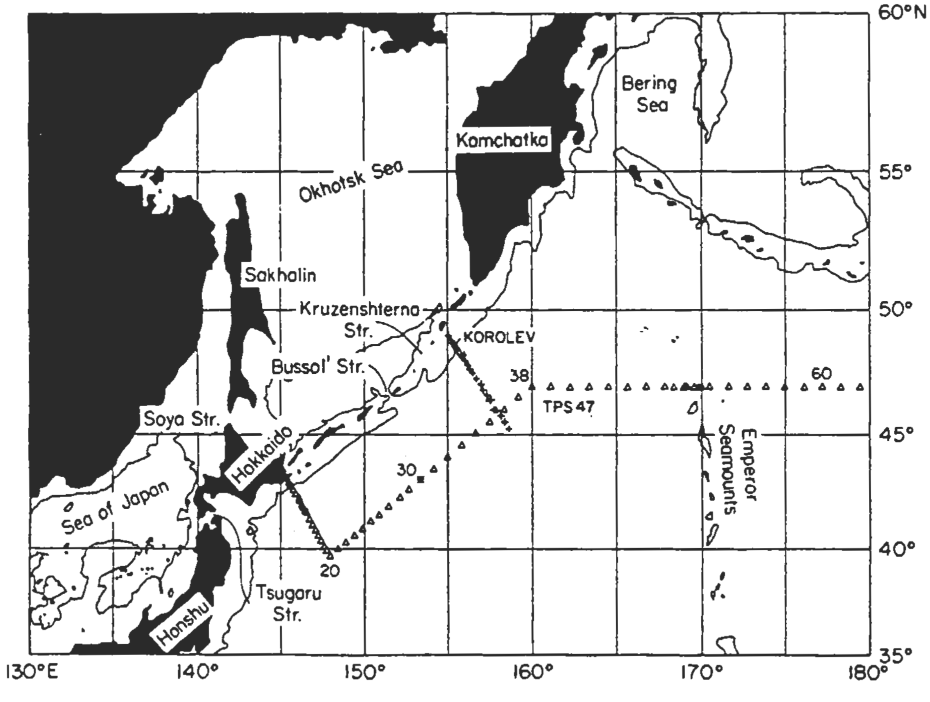

Fig. 1. Stations occupied by R.V. *T. Thompson* in August 1985 (triangles) and by the *Akademik Korolev* in June 1987 (+s).

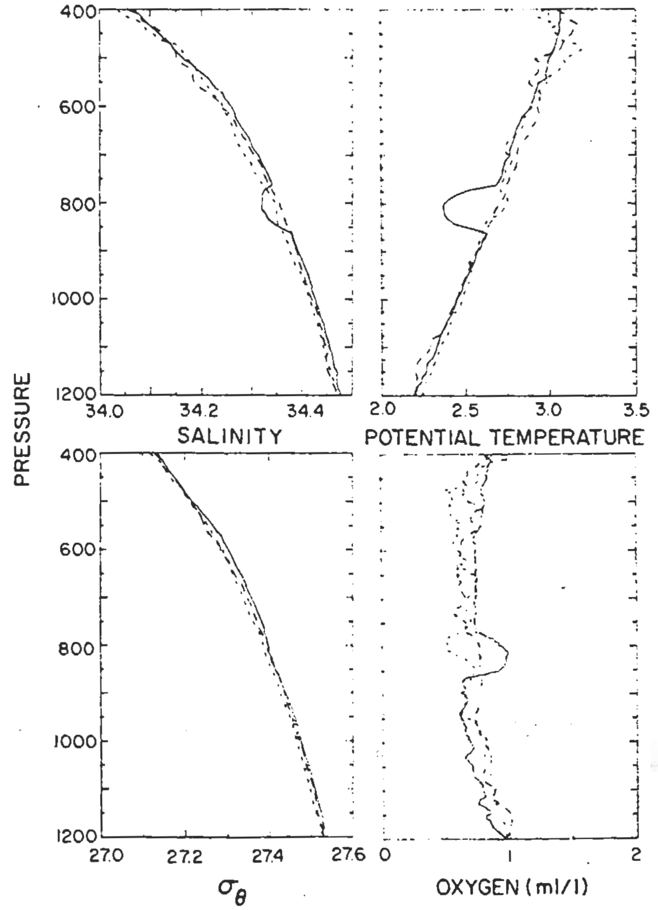

Fig. 2. (a) CTD salinity, (b) CTD potential temperature, (c) CTD density σ_θ, (d) CTD oxygen for TPS47 Stas 29, 30 and 31.

have been noticed except in a CTD trace. The 110 dbar thick layer is centered at 800 dbar at a density of 27.4 σ_θ; it is 0.2–0.5°C and 0.07‰ lower than water at the adjacent stations, which show nothing unusual at this density. (A simple curve through the CTD data above and below the layer at Sta. 30 would have resulted in traces nearly identical to Stas 29 and 31.) The layer is equally striking as a local maximum in the CTD oxygen data. The vertical profile of σ_θ shows no density inversion in the layer, indicating that there was no CTD malfunction. Although there appears to be little signature of the anomalous layer in density, there is a very slight minimum in potential vorticity and hence Brunt–Väisälä frequency (not shown). Armi and Zenk (1984) also found a minimum in Brunt–Väisälä frequency in well-measured Meddies.

Since there was no sign of the anomaly at either of the adjacent stations, its width along the TPS47 track must have been less than 150 km. Using the 110 m thickness of the anomaly and its Brunt–Väisälä frequency of 0.96 cph, the internal deformation radius was

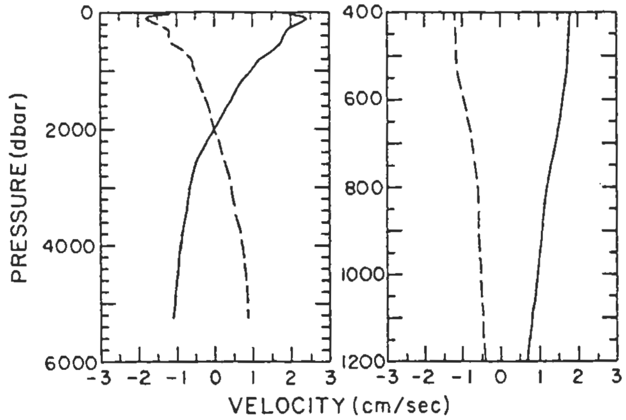

Fig. 3. Geostrophic velocity (cm^{-1}) relative to 2000 dbar at Stas 29–30 (dash) and 30–31 (solid). Positive is to the northwest.

2 km; if the anomaly width was at all related to this internal deformation radius, it must have been very small and the measurement which found it fortuitous indeed. [As a general rule, Killworth (1983) indicates that lens radii should be $\sqrt{2}$ larger than the internal deformations radius; Armi and Zenk's (1984) and d'Asaro's (1988) well-measured lenses in fact conform to this size.] If the Sta. 30 anomaly were this small, then geostrophic flow based on the adjacent stations does not yield information about flow in the anomaly, but at least yields the larger-scale flow in which it was embedded.

The smallness of the density anomaly is reflected in the geostrophic velocity profiles relative to 2000 dbar between Stas 29/30 and Stas 30/31 (Fig. 3). No unusual feature is found at the layer's depth; however, the two profiles are strongly antisymmetric, as if Sta. 30 were near the center of a cyclonic flow. None of the velocity profiles from nearby station pairs exhibits the same detailed vertical shear pattern, which obviously is unaffected by choice of reference level. Choice of zero velocity at 2000 dbar was for convenience; Roemmich and McCallister (1989) indicate a velocity of about 0.2 cm s^{-1} at 2000 dbar at both station pairs as a result of inverting the CTD velocities for the entire section.

3. ANOMALY SOURCE

A number of possible sources for the 27.4 σ_θ anomaly are considered and eliminated, with the only remaining possibility the Sea of Okhotsk, through Bussol' Strait. The first, most obvious, source to consider for strong property variations is a sea-surface outcrop. Although it has been shown that outcropping at 27.4 σ_θ occurs only (and rarely) in the isolated Sea of Japan, section 3.1 is a full treatment of the possibility, in order to completely eliminate it. The second possible contribution is ice formation along the Okhotsk Sea continental shelf, as proposed by Moroshkin (1966), Kitani (1973) and Alfultis and Martin (1987). A third mechanism is vigorous vertical mixing within the Okhotsk Sea and extrusion of the resulting fresher waters through straits in the Kuril Islands. Sections 3.2 and 3.3 treat firstly the spatial variability on various isopycnals in the northwest Pacific, using CTD data from TPS47 and Korolev, and secondly the sources of cold, low salinity water on isopycnals denser than 26.7 σ_θ, using a larger, selected hydrographic data set, to show the importance of both ice formation and localized vertical mixing.

3.1. *Maximum sea surface density*

Since variable surface forcing is the easiest way to produce a property anomaly, the first place to look for the source of the Sta. 30 anomaly is the sea surface. It is apparent from winter surface density maps (REID, 1969; LEVITUS, 1982) that surface water as dense as 27.4 σ_θ has not been found in the North Pacific. REID's (1969) map uses a selected, high-quality data set; the maximum surface density is in excess of 26.6 σ_θ in a long narrow region east of the Kuril Islands, stretching from Hokkaido to the western Bering Sea, and in the eastern central Okhotsk Sea near the deepest passages connecting it with the North Pacific. The maximum surface density in LEVITUS' (1982) objective map of all available, quality-controlled data from the National Oceanographic Data Center (NODC) is in excess of 26.5 σ_θ in a relatively large region of the northwest Pacific, including the Okhotsk and Bering Seas. Clearly, neither method specifically produces the maximum observed surface density, nor was either intended to do so.

A map of nominal maximum sea-surface density (Fig. 4b) was produced using the large hydrographic data set maintained by Reid at SIO. The data base contains virtually all of the data available at NODC and is updated yearly. The data set was searched for all Japanese and U.S. stations made in February, March or April, which included at least two observations per station, and for which temperature and salinity were reported to at least two decimal places. Stations were eliminated that had either no observation in the top 10 m, a quality indicator showing bad data at the surface observation, or a density inversion in excess of 0.02 g cm^{-3} between the top two bottles. Of the 16,457 observations found in the initial search, 6495 were eliminated, largely because of density inversions, leaving 9962 stations for final comparison in 2° squares. Almost all of the observations (Fig. 4a) are Japanese; however, U.S. stations are essential in the Bering Sea and the eastern portion of the region shown. The greatest limitation in determining the 'maximum' surface density is the greatly unequal distribution of data—near Japan, the values can be expected to be extremal because of the large number of observations, while in many other areas, the 'maximum' density is based on one or two stations and is most likely an underestimate. No late winter data are available in much of the (ice-covered) Sea of Okhotsk.

With these caveats, the highest surface densities occur in the western Sea of Japan, with values of 27.3–27.5 σ_θ (Fig. 4b). Because the sill depth and density in Tsugaru Strait, between the Sea of Japan and the open North Pacific, are 130 m and about 26.5–7 σ_θ, these high surface densities are not responsible for the variability of which the Sta. 30 anomaly is a part. (Although the density of waters at 100–200 m in the Sea of Japan just west of Tsugaru Strait is in excess of 27.0 σ_θ, there is a front which apparently prevents these dense waters from entering the Strait, based on 33 stations, available from NODC, located directly in Tsugaru Strait and collected between 1941 and 1981 in all months.) The warm, salty (>33.8‰) waters of the Tsugaru Warm Current entering the North Pacific may be partially responsible for the high winter surface densities observed southeast of Hokkaido (Fig. 4b), where five adjacent 2° squares show densities in excess of 26.7 σ_θ. Because of heavy sampling over the years in the region, it is likely that the densest events were observed here, certainly more likely than in the Okhotsk and Bering Seas. In the Okhotsk Sea, the highest densities occur in the east, with one square in excess of 26.7 σ_θ, and at Soya Strait where two stations have densities between 26.8 and 27.0 σ_θ. [Soya Strait,

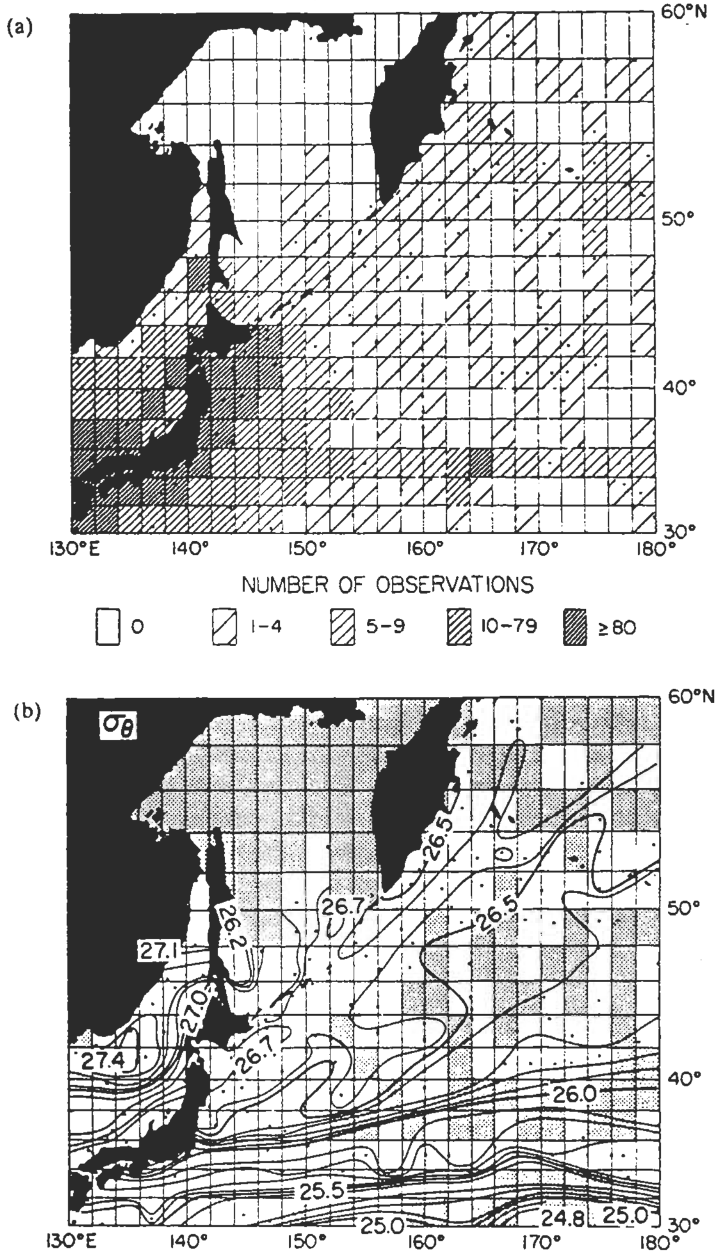

Fig. 4. (a) Distribution of all available Japanese and U.S. quality-controlled, hydrographic stations from February, March and April. (b) Nominal maximum surface density using these stations.

between the Sea of Japan and the Okhotsk Sea, is 50 m deep with a sill density of about 27.0 σ_θ (Favorite *et al.*, 1976) and contributes high salinity water to the Okhotsk Sea.] There is one extremum denser than 26.7 σ_θ just south of the Aleutian Islands.

In contrast to the small number of squares with densities greater than 26.7 σ_θ, a much larger region is encompassed by the 26.6 σ_θ contour, including much of the Bering Sea, a long strip parallel to Kamchatka and the Kuril Islands, the eastern Okhotsk Sea, and an eastward tongue centered at 42°N. All features are apparent in Reid's (1969) map, although the eastward tongue is not pronounced.

A fairly strong 'front' separates the subpolar and subtropical outcropping regions, starting at about 36°N at Japan and moving to 40°N at 180°. This coincides with the Subarctic Boundary (Favorite *et al.*, 1973). Densest outcropping within this 1°-wide band occurs at 26.0–26.2 σ_θ; outcropping at these densities has never been observed any farther south. A second high gradient region is perceptible at about 32°N, but is in a data-poor region; this coincides with the ridge in dynamic topography separating the eastward-flowing Kuroshio and its westward-flowing countercurrent (Hasunuma and Yoshida, 1978).

One remarkable feature of the maximum surface density map is that dense water occurs in the southwestern corner of the subpolar 'gyre', where the cold waters of the Oyashio mix with saltier, warmer waters. Because the surface water is near freezing, especially in the Okhotsk Sea, the salinity of surface waters denser than 26.6 σ_θ exceeds 33.1‰ and those denser than 27.7 σ_θ have salinities higher than 33.3‰. Salinity of the dense surface waters in the Japan Sea exceeds 34‰; where σ_θ is greater than 27.3 σ_θ, salinity is greater than 34.0‰ and ranges up to 34.3‰. The rather large region of densest surface water southeast of Hokkaido results from the mingling of cold, fresh Oyashio waters with saltier waters from the Tsugaru Current and the Kuroshio, together with winter cooling which keeps the temperature of the mixture low. This is likely to have an influence on the formation of North Pacific Intermediate Water (Hasunuma, 1978).

The high winter densities in Soya Strait suggest further exploration of the flow of saline water via the Soya Current from the Japan Sea into the Okhotsk Sea. Salinity in the shallow Soya Current, which enters through the Soya Strait and flows along the northwest coast of Hokkaido, is much higher than elsewhere in the Okhotsk Sea (Takizawa, 1982). Using data from all seasons in the Okhotsk Sea, almost all surface salinities which exceed 33.3‰ are in the Soya Current (Fig. 5a). Winter data alone in the Soya Current (not shown) include only a few salinities higher than 33.3‰, near Soya Strait, with lower salinity Okhotsk Sea 'waters' prevailing along the Hokkaido coast. This may reflect the winter weakening of the Soya Current (Takizawa, 1982). For the remainder of the Okhotsk Sea, only winter data are displayed in Fig. 5. This small set of data available from NODC was all collected in 1939, 1956–58, and 1964–66. A definite gap in salinity separates the Soya Current waters from Okhotsk Sea waters (Fig. 5b). This gap is just as apparent when data from all seasons are used.

If surface water of salinity greater than 33.3‰ is cooled to the freezing point, its density easily exceeds 26.8 σ_θ (Fig. 5b). However, water in the Soya Current is relatively warm as well as being saline, even in the 'Forerunner' phase of later winter (Takizawa, 1982), with temperatures in excess of 2°C. None of the winter observations show cooling of the warm Soya Current waters to freezing (Fig. 5b), although there were many winter observations of surface waters near freezing throughout the central Okhotsk Sea where there was open water or open ice. The salinities of the latter cold waters were lower than 33.3‰ even near Hokkaido. Thus it appears from the limited data that Soya Current waters mix with less

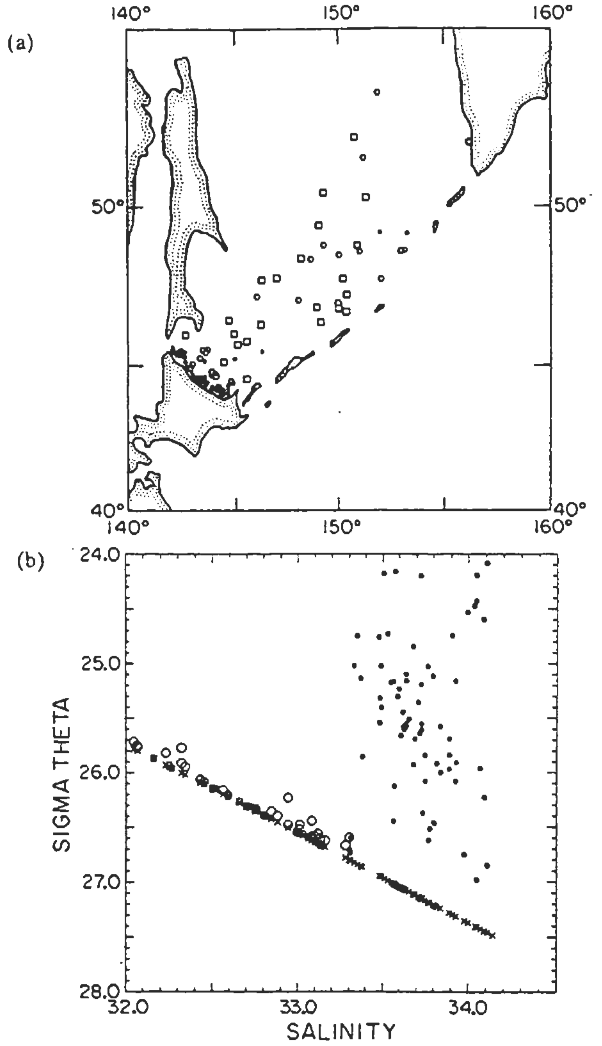

Fig. 5. Surface observations in the Okhotsk Sea. Filled circles (●) are *all* stations from all seasons with surface salinity greater than 33.3‰, hence $\sigma_\theta > 26.8$ if cooled to the freezing point. Squares are all *winter* observations (February, March, April) with surface σ_θ less than 0.015 from the freezing point σ_θ. Open circles are all other winter stations which meet neither of these criteria. In (b), the ×s show σ_θ if the water at each observation were cooled to the freezing point.

saline Okhotsk Sea waters before they can cool enough to produce the densities we are seeking ($>26.8\ \sigma_\theta$).

The Soya Current however is important for water mass processes in the Okhotsk Sea since it provides high salinity which permits water mass modification at much higher densities than if there were no such salinity source. That is, it seems unlikely that surface densities even as high as 26.7–26.8 σ_θ would be observed without the salt input. On a larger scale, we note that the highest surface salinity in the subpolar North Pacific is in the northwest (even though salinity on isopycnals is lowest there); the Japan Sea is a most likely source for this high salinity, via the Tsugaru and Soya Currents, and therefore may be important in determining the maximum winter densities in the subpolar gyre.

In conclusion, the TPS47 anomaly of 27.4 σ_θ could not have originated at the sea surface in the open waters of the North Pacific. The other remote possibility for sea-surface formation is the South Pacific: here REID's (1969) maps of winter surface density show an outcrop at 65°S, south of the Antarctic Circumpolar Current, with a temperature of about −1.5°C. There is no possibility of continuity between this outcrop and the anomaly at Sta. 30, based on any maps of salinity at this density (e.g. REID, 1965).

3.2. *TPS47/Korolev salinity*

The anomaly at Sta. 30 is a remarkable vertically isolated feature of TPS47 and Korolev; it is also part of a general pattern of property disturbance along isopycnals south of its location. Aside from the dramatic decrease in salinity range with increasing density, all isopycnals from TPS47 have similar features (Fig. 6): (a) large amplitude variations in the west, (b) lowest salinity between 148°E and about 160°E, (c) overall rise in salinity toward the east, and (d) highest salinity (hence temperature) at the eastern boundary. The last is possibly an intrusion of subtropical water over the Cascadia Basin. The salty, warm water found at 26.6, 26.8, 27.0 and 27.2 σ_θ between 146°05′E and 147°34′E (Stas 8–18) in the west is a warm eddy of subtropical water between the two southward intrusions of Oyashio

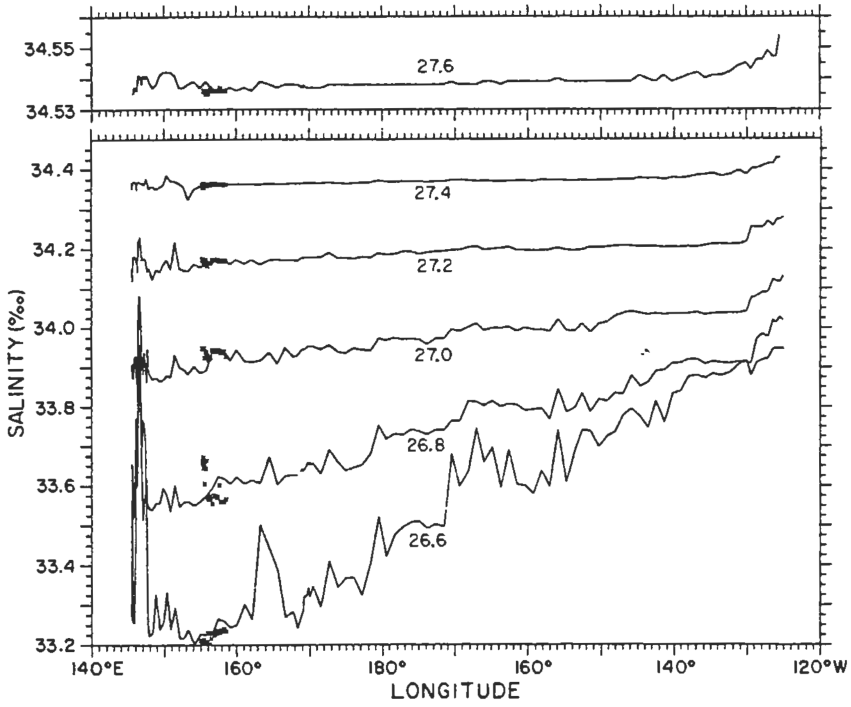

Fig. 6. Salinity at 26.6, 26.8, 27.0, 27.2, 27.4 and 27.6 σ_θ for all TPS47 stations (continuous) and for Korolev stations (×s).

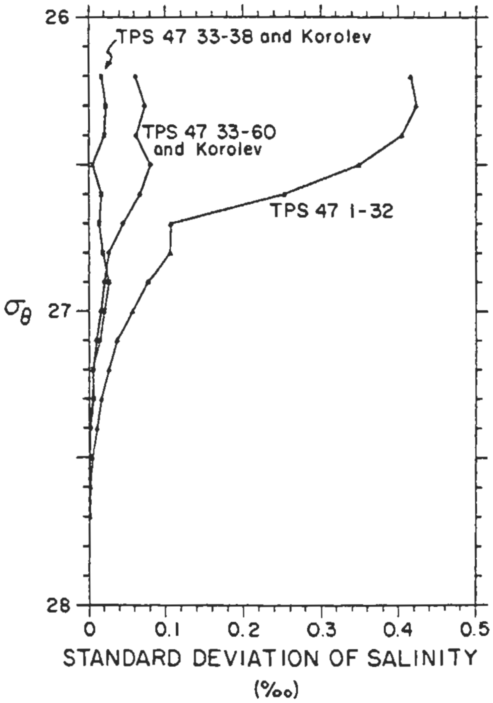

Fig. 7. Standard deviation of salinity along isopycnals for (i) TPS47 Stas 1–32, (ii) TPS47 Stas 33–38 and all Korolev stations shown in Fig. 1, and (iii) TPS47 Stas 33–60 and the Korolev stations.

water (Kawai, 1972; Talley *et al.*, 1991), a common situation in the region. The freshest, coldest water is of Oyashio origin.

At 27.4 and 27.6 σ_θ, there is a dramatic difference in salinity noisiness between water west and east of 154°30′E (Sta. 31 or 32); this is also true to a more limited extent at 27.2 σ_θ. The anomaly at 27.4 σ_θ at Sta. 30 stands out slightly as the freshest water at this density; at both 27.4 and 27.6 σ_θ, salinity east of Sta. 30 is nearly uniform for a long distance. To quantify the change in property variations, the standard deviation of salinity along isopycnals is shown (Fig. 7): (1) for TPS47 Stas 1–32, to be contrasted with (2) the standard deviation for TPS47 Stas 33–38 and Korolev, and then (3) with Stas 33–60 and Korolev. The second group consists of stations north of the anomaly in the dogleg of TPS47 plus the Korolev stations, while the third group extends east of the Emperor Seamounts and is representative of the interior of the western subpolar gyre.

Highest salinity variance is obtained for Stas 1–32 at all densities down to 27.5 σ_θ. A marked shift occurs at 26.7 and 26.8 σ_θ, below which the variance drops off nearly exponentially. At the lower densities high variance is due primarily to the subtropical water found in the center of the first leg (Stas 8–18). At higher densities, fresh anomalies also contribute. Although the Sta. 30 anomaly stands out in the vertical and isopycnal profiles, the variance at 27.4 σ_θ is in line with that at 27.3 and 27.5 σ_θ, possibly indicating that the anomaly we observed is just an extreme example of a continual process.

Variances at densities less than 26.8 σ_θ on TPS47 33–38/Korolev differ from those on TPS47 33–60/Korolev, with greater variability occurring in the latter, larger group of stations. This arises because these isopycnals outcrop in the open-ocean subpolar gyre, allowing large variations as well as a trend in properties, and because the smaller group of stations occupies a limited region. The relatively low and similar variance at densities greater than 26.8 σ_θ for these two groups of stations compared with TPS47 suggests that the sources which create variability in these relatively dense waters occur near the southern portion of the station rectangle along the Kurils and Hokkaido rather than, say, near the Bering Sea. As shown in the next section and by Favorite *et al.* (1976), the source of fresh water variability is the passages through the Kuril Islands; the source of salty, warm water is the Kuroshio intrusion seen at Stas 8–18.

3.3. *Isopycnal maps*

In order to clarify the source of isopycnal variability which includes the Sta. 30 anomaly, isopycnal maps based on a restricted hydrographic data set were constructed. Data used were from TPS47, Korolev, a 1982 section at 175°E (Warren and Owens, 1988), the 1966 Boreas expedition (Reid, 1973), Japanese stations from the Sea of Okhotsk in 1966–1968, Japanese stations in the Sea of Japan, and Japanese stations between 140° and 150°E from 1966. Only stations with temperature and salinity reported to at least two decimal places and with oxygen measurements were used. Although Japanese surveys of the Okhotsk Sea were made in the 1930s, in the summers of 1966–68, and in the autumns of 1976–78, only data from the 1960s surveys were used in order to produce the most coherent maps; few data are as yet as easily available from the mid-1980s. Data from the 1960s surveys were presented by Yasuoka (1967, 1968) and Kitani (1973); the earlier surveys had similar station coverage. The juxtaposition of the 1966–68 and 1980s data sets did not create many problems; in overlapping regions, they agree fairly well. The hydrographic data were interpolated to 10-m intervals using a cubic spline, followed by linear interpolation to isopycnals.

The apparent source of fresh, cold water and high oxygen on the isopycnals is emphasized because the Sta. 30 anomaly was fresh and cold. (Within the Okhotsk Sea, higher salinity water has two sources: inflow through the Kuril Islands and through Soya Strait. The latter transport is low, but the effect of the relatively high salinity is clear on the isopycnal maps and was discussed in section 3.1. Wüst (1930) hypothesized, with very little data, that the low salinity intermediate waters originate in the Okhotsk Sea. Because none of the involved isopycnals had been observed to outcrop in the North Pacific, Reid (1965) suggested that vertical mixing throughout the subpolar gyre creates the lower salinity. However, Moroshkin's (1966) Okhotsk Sea study suggested vigorous mixing and hence water mass transformation in the Kuril Straits, and Kitani (1973) showed the importance of dense shelf water formation during freezing in lowering the salinity of Okhotsk waters at densities up to at least 27.05 σ_θ. Thus we have returned to the Okhotsk Sea as the source of low salinity in the North Pacific.

The four isopycnals shown in Fig. 8 (salinity) and two isopycnals in Fig. 9 (oxygen) yield the following qualitative scenario. On the denser isopycnals (26.8, 27.0 and 27.4 σ_θ), the primary source of fresh water in the open ocean, including Sta. 30 anomaly, is the Okhotsk Sea through Bussol' Strait. The lowest salinity contour outside the Okhotsk Sea at 27.4 σ_θ is based only on the TPS47 station, which could or should have been contoured as an isolated eddy. However it is part of a more general pattern of relatively low salinity based on many stations, so a continuous contour was drawn. The 0.1‰ difference in salinity across Tsugaru Strait at 27.0 σ_θ reflects the isolation of the Japan Sea. The confluence of the East Kamchatka Current and discharge from Bussol' Strait results in the formation of both the Oyashio flowing to the southwest along the Kurils and the Subarctic Current to the east, according to Favorite *et al.* (1976); their interpretation of local flow is amply supported by the TPS47 low salinity anomaly some 400 km southeast of Bussol' Strait and by the low salinity stretching in the directions of each of the two currents. On a larger scale, horizontal mixing is obviously important as the low salinity water eventually melds with the higher salinity water from the south. The low salinity in the Subarctic Current increases to the east and curves back around to the west along the Aleutians. On the largest (hemispheric) scale, highest salinity occurs in the tropics (Reid, 1965) where these isopycnals never outcrop, thus indicating that vertical mixing must play a role there.

Within the Okhotsk Sea at densities of 26.8–27.4 σ_θ a marked gradient from salty and warm in the northeast to fresh and cold in the west and center is seen. The saltiest water is the input from the North Pacific through Kruzenshterna Strait. At 27.0 σ_θ, a plume of fresh, cold water originates near the side of Sakhalin, and is advected cyclonically to the southeastern Okhotsk Sea. This supports the conjecture of property modification through shelf processes (brine rejection) in the northwestern Okhotsk Sea (Moroshkin, 1966; Kitani, 1973; Alfultis and Martin, 1987). The isopycnals shown in Figs 8 and 9, as well as 27.3, 27.5, 27.6 σ_θ and 37.7 σ_2, indicate that the plume is most visible at 27.0 σ_θ, which may thus be the predominant density of modification. Kitani's (1973) observations actually

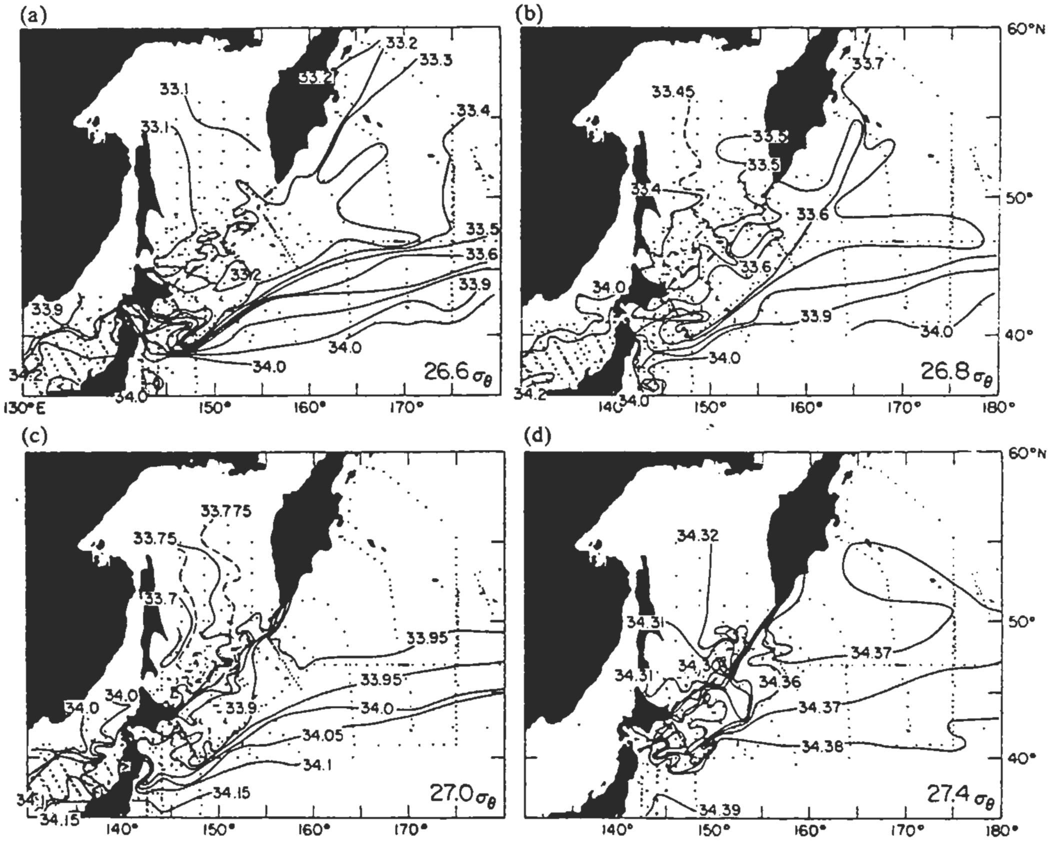

Fig. 8. Salinity on isopycnals (a) 26.6 σ_θ, (b) 26.8 σ_θ, (c) 27.0 σ_θ and (d) 27.4 σ_θ.

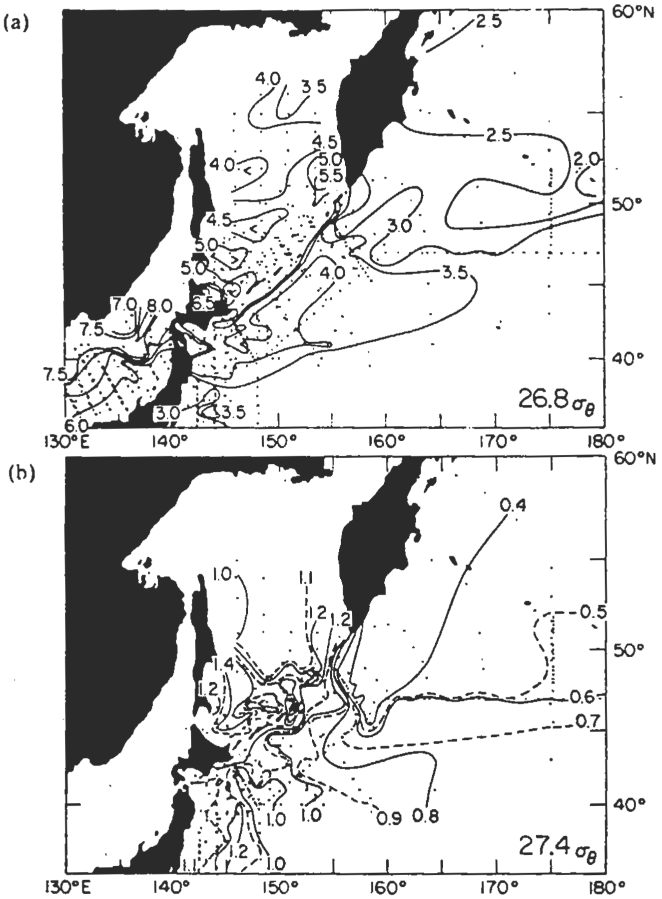

Fig. 9. Oxygen on isopycnals (a) 26.8 σ_θ and (b) 27.4 σ_θ.

include an example of shelf water formation, from which he drew his conclusion regarding the density of shelf modification. The data set available for the present work is even more limited and does not contain any shelf observations, hence any shelf water formation. However, there is enough data to show that properties are noisier at densities lower than about 27.3 σ_θ in the northern and western Okhotsk Sea (Fig. 10a), which may imply active processes in addition to straight mixing below this density. Knowledge of the precise density range of shelf water formation must await much more extensive data collection on the Okhotsk Sea shelf. Further evidence that there might be shelf water formation to 27.2 σ_θ is that the lowest salinity at this density (not shown in Fig. 8) occurs in the same region as lowest salinity at 27.0 σ_θ (Fig. 8c), whereas the lowest salinity at 27.3 σ_θ and higher densities occurs near Bussol' Strait, illustrated by the similar 27.4 σ_θ (Fig. 8d). Low salinity at 27.2 σ_θ however is not as pervasive as at 27.0 σ_θ; there is also an isolated patch of low salinity near Bussol' Strait at 27.2 σ_θ, possibly indicating vertical mixing there.

At 27.4 σ_θ, lowest salinity and highest oxygen are found in an isolated region near Bussol' Strait, indicating vertical mixing of low salinity water from above. This is also true of 27.3, 27.5 and 27.6 σ_θ (not shown). Further indication of vertical mixing is provided by property/property relations, for instance potential temperature–salinity (Fig. 10b) for the northwestern Okhotsk Sea and the Bussol' Strait regions. For salinity greater than 34‰, three distinct regimes are apparent: North Pacific water (highest temperature with a maximum at 3.3°C), water from the northwestern Okhotsk Sea (middle temperature and almost no temperature maximum), and Bussol' Strait water (lowest temperature with a temperature maximum at 2.2°C). The last is the coldest, hence freshest, on an isopycnal, and plausibly arises from mixing the northern Okhotsk water with North Pacific water. At Bussol' Strait, the mixing has apparently proceeded to the point of creating the observed temperature maximum, which occurs at a density of about 27.4 σ_θ. Enhanced mixing near the Strait has been noted before (MOROSHKIN, 1966; YASUOKA, 1967; KITANI, 1973).

Explaining properties at 26.8 σ_θ is more difficult than at higher densities. This isopycnal is often chosen to represent the main salinity minimum of the subtropical gyre (REID, 1965) although the minimum's density ranges from 26.7 to 26.9 (HASUNUMA, 1978). Within the Okhotsk Sea, processes are essentially the same as at 27.0 σ_θ, based on the relative location of fresh and salty water in the Sea and the fresh-water tongue exiting Bussol' Strait. However, east of the Kurils, the region of lower salinity is much larger than at 27.0 σ_θ and is not preferentially directed southwest or northwest of Bussol' Strait. I suspect that this reflects vertical mixing with the overlying fresher waters in the region along the Kurils; the vigor of mixing at 26.8 σ_θ may be higher because it lies very close to the domed, outcropping 26.6 σ_θ surface. That is, because the Ekman pumping is large and upward in this region in winter (HELLERMAN and ROSENSTEIN, 1983), and because outcropping occurs at 26.6–26.7 σ_θ in this region in winter, the 26.8 σ_θ surface lies very close to the surface and is subject to upwelling and downward diffusion. [Similar phenomena are clear in other regions of large Ekman pumping, for instance in the potential vorticity field in the northeast Pacific shown in TALLEY (1988).] Salinity is reduced at 26.8 σ_θ all along the Kuril Islands as a result.

At 26.6 σ_θ, which outcrops throughout most of the region, including the Okhotsk Sea, the pattern of salinity in even the Okhotsk Sea differs from the denser isopycnals, with low

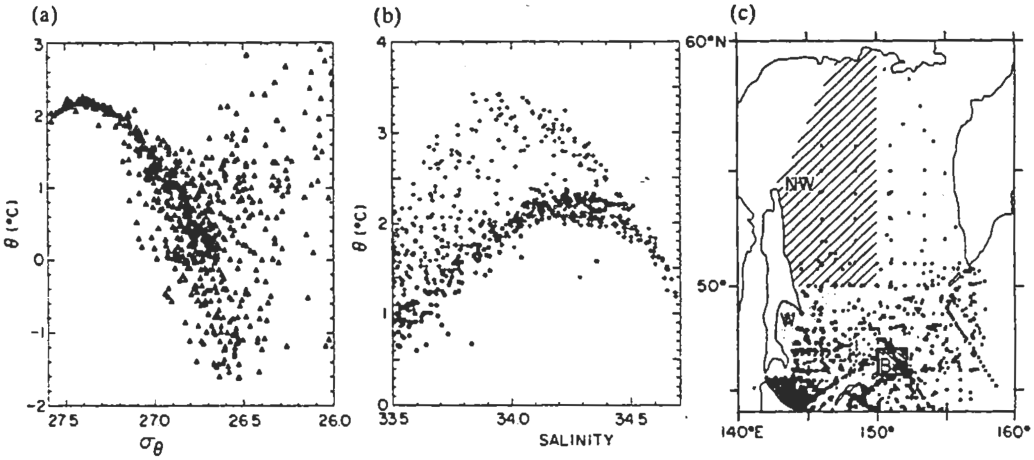

Fig. 10. (a) Potential temperature as a function of σ_θ, for the region 47°–50°N, 142°–147°E, ('W' in c). (b) Potential temperature as a function of salinity for the northwestern Okhotsk Sea, 50°–60°N, 142°–150°E (circles, 'NW' in c) and for Bussol' Strait, 46°–47°N, 150°–152°E (+, 'B' in c). For salinity greater than 34‰, the highest temperature is North Pacific water near Bussol' Strait. (c) NODC stations used for (a) and (b) and other analyses.

salinity ringing the northern and western sides; direct surface forcing is responsible for properties on this surface.

4. DISCUSSION

In this paper it is shown that:

(1) The Okhotsk Sea through Bussol' Strait was the source of the cold, fresh, oxygenated anomaly at TPS47 Sta. 30 and of cold, fresh, oxygenated water in the open North Pacific at densities of about 26.7–27.4 σ_θ. The anomaly was part of a pattern of higher salinity variance which reflects preferential spread of Okhotsk sea waters to the southwest.

(2) Winter surface densities in the ice-free part of the Okhotsk Sea have never been observed to be denser than 26.7 σ_θ; although this may be due to lack of observations, it is more likely that transformation of surface waters to densities of 26.8 to 27.1–27.2 σ_θ is due to brine rejection during sea-ice formation in the northwest Okhotsk Sea (Kitani, 1973), and that water mass modification at densities 27.1–27.2 to 27.6 σ_θ is due to vertical mixing, primarily near Bussol' Strait.

Thus, variability in water properties in the North Pacific at densities between 26.8 and about 27.6 σ_θ and the ventilation of these observed by means of oxygen and CFM measurements (Warner, 1988), including large-scale gradients of salinity and oxygen, is attributable to processes in the Okhotsk Sea; the processes are dense shelf water production during sea-ice formation, north of Sakhalin, and vertical mixing, primarily near Bussol' Strait. Open water convection is not a candidate because of the low salinity of the inflowing surface water.

Because there was only one station on TPS47 with a marked Okhotsk Sea anomaly, it is only possible to say that its maximum width along the station track was 150 km (the distance from Sta. 29 to 31); we know nothing about its length perpendicular to the track. An estimate of the internal Rossby deformation radius indicates that the anomaly may have been less than 10 km wide. Regardless of its shape, the anomaly must have been advected by the larger scale flow from Bussol' Strait to its observed location since all theories of movement of compact lenses indicate westward self-advection (McWilliams *et al.*, 1986). Previous dynamic topographies and circulation schemes east of the Kurils indicate the requisite southwestward advection out of the Okhotsk Sea (Reid, 1965; McAlister *et al.*, 1970; Favorite *et al.*, 1976). Using Favorite *et al.*'s (1976) nomenclature, the convergence of the southeastward East Kamchatka Current and the Okhotsk Sea outflow through the central Kuril Islands is the source of both the Oyashio and the eastward-flowing Subarctic Current. The latter is marked by low salinity and is obvious on the isopycnal maps of Fig. 7.

The formation 'mechanism' for the anomalous layer at TPS47 Sta. 30 is unclear, especially since nothing is known about its shape or volume. Since water exists through Bussol' Strait at all densities lower than 27.75 σ_θ, it is not obvious why only a small part of the water column was found at Sta. 30 unless there was large vertical shear in the outflow.

Implications of the Okhotsk Sea outflow for ventilation of the North Pacific are clear. Current analytical models of ventilation of the subtropical and subpolar gyres are based entirely on sea-surface outcropping with wind and/or buoyancy forcing. Vertical mixing which transports surface properties downward, whether geographically widespread or localized, and the regional process of sea-ice formation are missing. The latter is not likely

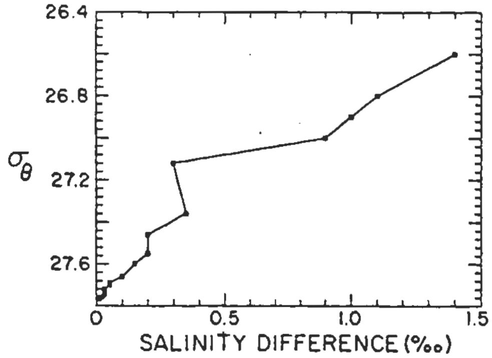

Fig. 11. Difference in the highest salinity at the equator and lowest salinity (near the Kuril Islands) in the North Pacific. All values at densities higher than 27.0 σ_θ were actually calculated at densities relative to the nearest 100 m depth.

to be incorporated in analytical models but should be included in numerical models if the models are intended to simulate the actual ocean. In interpreting observations of oceanic properties, these results suggest that the widespread vertical mixing which has been required to account for the North Pacific fresh, cold intermediate/mid-depth water in the north (REID, 1965) may include a large component of local mixing in straits.

The equator-to-Kurils salinity difference in various density ranges reflects the processes which modify the salinity. This difference as a function of density (Fig. 11) was calculated using LEVITUS' (1982) data. Salinities at densities higher than 27.0 σ_θ were mapped on σ_1, σ_2, σ_3 and σ_4 surfaces and then converted roughly to σ_θ for this figure. Three rough regimes are apparent: (1) $\sigma_\theta < 27.1$, (2) $27.1 < \sigma_\theta < 27.66$, and (3) $\sigma_\theta > 27.66$. In the first, salinity differences exceed 0.8‰; in the second, they range from 0.1 to 0.4‰; in the third, they are less than 0.05‰. These regimes may correspond to (1) directly ventilated at the sea surface or as a result of sea-ice formation, (2) mixed in the Kuril Straits, and (3) mixed in the open North Pacific.

Is there enough low salinity water exiting the Okhotsk Sea to produce most of the low salinity signal in the North Pacific at densities 26.8–27.6 σ_θ? KURASHINA *et al.* (1967) have made the only quantitative transport estimate for the full island chain of which I am aware. KITANI (1973), YASUOKA (1967, 1968) and FAVORITE *et al.* (1976) indicated that flow is predominantly into the Okhotsk Sea at the shallower Kruzenshterna Strait and out at Bussol' Strait, with the Okhotsk Sea a part of the cyclonic subpolar circulation. MOROSHKIN (1966), however, commented on the 'two-sided' (bi-directional) currents in most passages; KURASHINA *et al.* (1967) broke the flow in the two main passages into inflow and outflow with 3.6 Sv in and 2.5 Sv out at Kruzenshterna and 4.8 Sv in and 4.3 Sv out at Bussol' Strait. The basis for the latter calculations was a variety of geostrophic, GEK and 'two current-meter' measurements, with only geostrophic measurements used at these two main passages. Since non-geostrophic flow is probably important in the Straits, errors in the estimates are probably large.

To check very simply on net salt balances in the North Pacific at 26.7–27.65 σ_θ, assume that there is no vertical mixing, that 5 Sv cycles through the Okhotsk Sea, and that approximately the same amount of high salinity water at these densities crosses from the tropics into the subtropical gyre. Reid's (1965) maps of salinity at roughly 26.8 and 27.3 σ_θ indicate salinities of 34.4 and 34.5‰ at the southern side of the subtropical gyre, respectively. The salinities at Bussol' Strait at 26.8 σ_θ (Fig. 6) and 27.3 σ_θ (not shown) are 33.5 and 34.15‰. The mean salinities at 26.8 and 27.3 σ_θ are then roughly 33.95 and 34.3‰ respectively, which are close to the mean salinity found on Reid's (1965) maps. While this argument is not rigorously quantitative, it illustrates that the Okhotsk Sea can discharge enough low salinity water to produce the observed salinity pattern, much as the Mediterranean Sea affects the North Atlantic salinity without a large mass exchange. A better estimate would require accurate estimates of flow through the principal Kuril Straits and an accurate estimate of exchange across the equator. The other extremum of salinity on these isopycnals is a lateral maximum at the equator (Reid, 1965); since it has no apparent lateral source, vertical diffusion is necessary to maintain it. However, it may be likely that 'localized' equatorial upwelling and diffusion account for much of the maximum.

Therefore, based on the isopycnal maps, maximum surface density map, observations of high variance and anomalies at densities to 27.4 σ_θ and Kitani's (1973) careful analysis of Okhotsk Sea water mass transformation, it is concluded that the subpolar gyre is 'ventilated' between 26.7 and 27.6 σ_θ by waters from the Okhotsk Sea. Within the Okhotsk Sea, open water convection occurs to about 26.7 σ_θ and sea-ice formation on the shelf in the northwest Okhotsk Sea produces cold, saline 'bottom' water to densities of at least 27.05 σ_θ (Kitani, 1973). Bussol' Strait is about 2300 m deep, allowing free passage of water to densities of 27.65 σ_θ and also providing a location for vigorous vertical mixing which decreases salinity and increases oxygen, with the most apparent effect at densities greater than 27.1 σ_θ.

In conclusion, sea-ice formation with associated cold, saline bottom water formation and localized vertical mixing should be added to convection and wind-driven subduction and broad vertical diffusion as important ventilation processes in the North Pacific. Of these, sea-ice formation and vertical mixing are the only processes which affect densities higher than 26.8 σ_θ.

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