

Distribution, formation, and seasonal variability of Okhotsk Sea Mode Water

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[1] Russian historical data and recently completed conductivity-temperature-depth surveys are used to examine the formation and spread in the deep Okhotsk Sea of dense shelf water (DSW) produced in the Okhotsk Sea polynyas. Isopycnal analysis indicates that all of the main polynyas contribute to the ventilation at $\sigma_\theta < 26.80$, including the Okhotsk Sea Mode Water (OSMW), which has densities $\sigma_\theta = 26.7\text{--}27.0$. At densities greater than $26.9 \sigma_\theta$ the northwest polynya is the only contributor to OSMW. (Although Shelikhov Bay polynyas produce the densest water with $\sigma_\theta > 27.1$, vigorous tidal mixing leads to outflow of water with a density of only about $26.7 \sigma_\theta$). In the western Okhotsk Sea the East Sakhalin Current rapidly transports modified dense shelf water along the eastern Sakhalin slope to the Kuril Basin, where it is subject to further mixing because of the large anticyclonic eddies and tides. Most of the dense water flows off the shelves in spring. Their average flux does not exceed 0.2 Sv in summer and fall. The shelf water transport and water exchange with the North Pacific cause large seasonal variations of temperature at densities of $26.7\text{--}27.0 \sigma_\theta$ (depths of 150–500 m) in the Kuril Basin, where the average temperature minimum occurs in April–May, and the average temperature maximum occurs in September, with a range of $0.2^\circ\text{--}0.7^\circ\text{C}$. The average seasonal variations of salinity are quite small and do not exceed 0.05 psu. The Soya Water mixed by winter convection, penetrating to depths greater than 200 m, in the southern Kuril Basin also produces freezing water with density greater than $26.7 \sigma_\theta$. Using a simple isopycnal box model and seasonal observations, the OSMW production rate is seen to increase in summer up to 2.2 ± 1.7 Sv, mainly because of increased North Pacific inflow, and drops in winter to 0.2 ± 0.1 Sv. A compensating decrease in temperature in the Kuril Basin implies a DSW volume transport of 1.4 ± 1.1 Sv from February through May. The residence time of the OSMW in the Kuril Basin is 2 ± 1.7 years. **INDEX TERMS:** 4223 Oceanography: General: Descriptive and regional oceanography; 4243 Oceanography: General: Marginal and semienclosed seas; 4283 Oceanography: General: Water masses; 4536 Oceanography: Physical: Hydrography; 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; **KEYWORDS:** Okhotsk Sea, North Pacific Intermediate Water, Mode Water, water mass, marginal sea

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1. Introduction

[2] The Okhotsk Sea (Figure 1) is a marginal semienclosed sea that is the main source of cold, less saline, and oxygenated intermediate water in the western North Pacific

[Moroshkin, 1966; Kitani, 1973; Favorite *et al.*, 1976; Talley, 1991, 1993; Talley and Nagata, 1995; Yasuda, 1997; Watanabe and Wakatsuchi, 1998; Freeland *et al.*, 1998; Wong *et al.*, 1998; Itoh, 2000]. There are no direct observations of deep dense convection penetrating to intermediate density range ($26.7\text{--}27.6 \sigma_\theta$) in the open Okhotsk Sea. Talley [1991] showed that saline Soya Water (SW) entering in the southern Kuril Basin from the Japan Sea could be a source of dense convection, but also showed that vigorous mixing with low-salinity Okhotsk water significantly reduces the maximum winter density in the Kuril Basin. The principal source of ventilation at $26.7\text{--}27.0 \sigma_\theta$ is dense shelf water (DSW) produced by brine rejection in coastal polynyas during ice formation [Kitani, 1973; Alftutis and Martin, 1987; Talley, 1991; Martin *et al.*, 1998;

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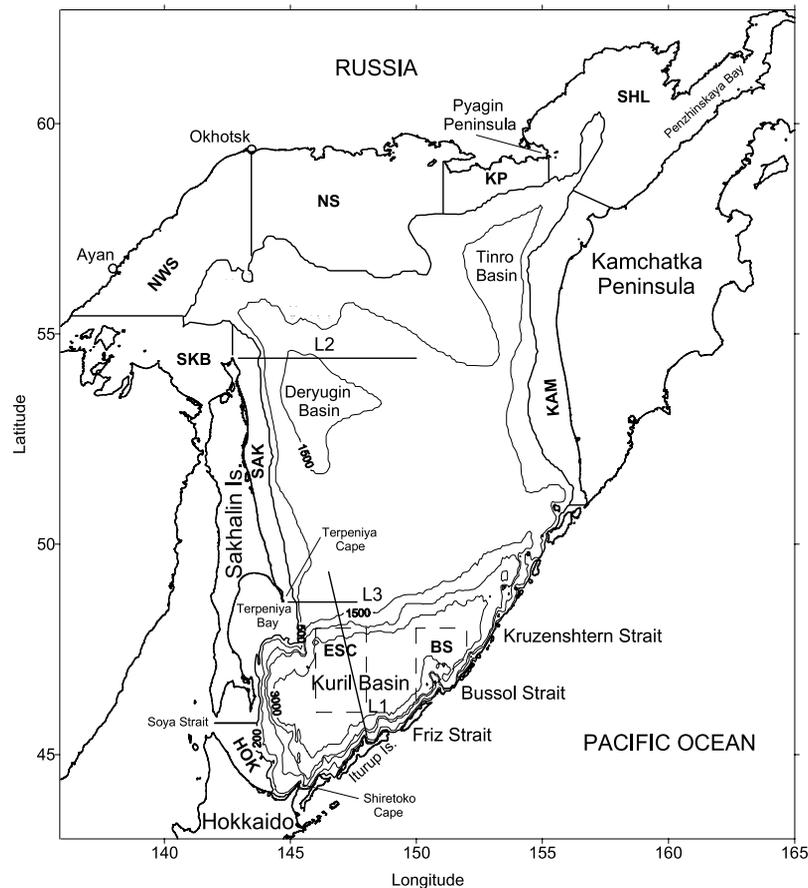


Figure 1. Chart of the Okhotsk Sea. The 200 m depth contour defines the shelves. The abbreviations are Hok for Hokkaido, Sak for Sakhalin, Skb for Sakhalin Bay, NWS for northwest shelf, NS for northern shelf, Kp for Koni-Pyagina, Shl for Shelikhov, and Kam for Kamchatka. Sections along L1, L2, and L3 are shown in Figures 5 and 11.

Watanabe and Wakatsuchi, 1998; Wong et al., 1998; Gladyshev et al., 2000]. Water in this density range is the upper part of the Okhotsk Intermediate Water. *Yasuda [1997]* called this Okhotsk Sea Mode Water (OSMW), because of its thickness (low potential vorticity). We use a slightly more restricted density range for OSMW than *Yasuda* ($26.6\text{--}27.0\ \sigma_\theta$). The low potential vorticity of the OSMW reflects convection and mixing in the Kuril Basin but does not explain the strong ventilation of the entire intermediate layer.

[3] Generally, the OSMW is a mixture of three components. The first and maybe largest is North Pacific Water (NPW) entering the Okhotsk Sea through the Kuril Straits. The quantitative contribution of this component to the OSMW is unknown and presents the biggest gap in oceanographic observations in this region. Repeat sections in Bussol' and Kruzenshtern Straits, the two largest Kuril Straits, clearly show the dominance of tidal variability, rendering geostrophic transport estimates meaningless [*Riser, 1996*]. Recent theoretical estimates of tidally generated transport give a value of about 3.4 Sv of NPW flow into the Okhotsk Sea through Bussol', Kruzenshtern, and Friza Straits [*Nakamura et al., 2000a*]. It is not clear, however, what part of this transport occurs in the OSMW density range.

[4] The second component contributing to the OSMW is produced in winter coastal polynyas. This is the coldest and least saline component of the OSMW. Using satellite data, [*Alfultis and Martin [1987], Martin et al. [1998], and Gladyshev et al. [2000]*] showed that polynyas on the northern shelves start to form in January and end at the end of March. Using a relation between ice formation and brine rejection, the northwest shelf (NWS) polynya is always the main brine water producer, contributing more than 50% of the total production, and the Shelikhov Bay polynya is usually the second with about 25% of the total, regardless of large interannual variability. Recently, [*Gladyshev et al. [2000]*] analyzed extensive conductivity-temperature-depth (CTD) surveys on the northern Okhotsk shelves and found water with density greater than $26.9\ \sigma_\theta$ and close to the freezing point on the NWS and in Shelikhov Bay in 1996–1997. A gravity current was hypothesized to transport this DSW to Sakhalin Bay from the NWS, generating cyclonic circulation over the northern shelf, while Shelikhov dense water drained directly to the Tinro Basin. In 1996–1997 the estimated annually averaged volume flux of the DSW was 0.5 and 0.24 Sv at densities $26.6\text{--}26.9\ \sigma_\theta$. However, most of this water left the shelves before July, with a volume transport of about 0.8 Sv, and further flux did not exceed 0.2 Sv. A slow offshore DSW flux during the second half of the

year and cyclonic circulation over the northern shelves explain the existence of DSW on the NWS even in September. The general scheme of DSW expansion in the deep Okhotsk Sea was proposed by *Kitani* [1973] and had been confirmed by a number of other investigators. *Kitani* showed that DSW flows off the continental shelf and spreads southward along the western Okhotsk Sea margin, diffusing into the OSMW through enhanced horizontal mixing in the central Okhotsk Sea.

[5] The third component of the OSMW is the Soya Water (SW) [*Takizawa*, 1982; *Talley*, 1991; *Watanabe and Wakatsuchi*, 1998; *Itoh*, 2000]. This is the warmest and saltiest component of the OSMW, flowing through the narrow (about 42 km) and shallow (about 55 m) Soya Strait [*Talley and Nagata*, 1995]. *Watanabe and Wakatsuchi* [1998] referred to the OSMW as Kuril Basin Intermediate Water. They showed that the Forerunner SW is an important source of dissolved oxygen for OSMW in the Kuril Basin. The SW transport into the Okhotsk Sea varies from about 0.1 Sv in December–February to about 1.2 Sv in June [*Takizawa*, 1982; after *Aota*, 1975].

[6] The OSMW differs from the North Pacific Water (NPW) in the same density range [*Moroshkin*, 1966; *Yasuda*, 1997]. OSMW is significantly thicker by about 250 m than NPW and has been identified as a pycnostad or low potential vorticity water [*Yasuda*, 1997]. *Talley* [1993] attributed the low potential vorticity of OSMW entering the North Pacific to relative vorticity, but Okhotsk Sea convection and mixing is the most likely origin of the low potential vorticity. According to *Moroshkin* [1966], who referred to the OSMW as the Transitional Water Mass, its greatest thickness is 450–650 m in the Kuril Basin (between 150–200 m and 600–800 m). Its thickness decreases northward to about 250 m (between 150–200 m and 300–400 m). *Moroshkin* [1966] explained the deepening of OSMW lower boundary in the Kuril Basin by intensive downwelling. The OSMW is characterized by temperature 0.1° – 2° C and salinity 33.3–33.8 psu. Oxygen saturation decreases from 60–70% (6.5 mL/L) at the upper OSMW boundary to 15–20% (2.5 mL/L) at the lower OSMW boundary. However, oxygen saturation can exceed 70% in the western OSMW [*Moroshkin*, 1966].

[7] *Gladyshev et al.* [2000] showed that the estimated DSW outflow implies a residence time of OSMW at 26.7 – $26.8 \sigma_{\theta}$ of about 4 years, and at 26.8 – $26.9 \sigma_{\theta}$ of about 14 years. However, *Wong et al.* [1998], using chlorofluorocarbon data, found that the OSMW, which they referred to as upper Okhotsk Sea Intermediate Water, is renewed within 1.4 years, with a correspondingly larger estimated DSW flux. The disagreement in residence time estimates indicates that further work is necessary.

[8] Although winter convection occurs in the upper 100–150 m layer in the central Okhotsk Sea and in the 300–400 m layer in Kuril Straits according to *Moroshkin* [1966], *Kitani* [1973] reported that seasonal variations of thermohaline structure extend to 500 m depth in the Okhotsk Sea. This depth corresponds to a density of about $27.0 \sigma_{\theta}$, that is, the maximum density of the DSW on the NWS; this consistency is intriguing. On the other hand using five oceanographic surveys obtained in summer–fall during 1977 through 1979, *Wakatsuchi and Martin* [1991, Figure 6] showed large seasonal changes in the upper 1200 m of

Table 1. Acronyms

Acronym	Definition
DCW	Dense Cold Water
DSW	Dense Shelf Water
MDSW	Modified DSW
MNPW	Modified NPW
NPW	North Pacific Water
OSMW	Okhotsk Sea Mode Water
SW	Soya Water
ESC	East Sakhalin Current
NS	Northern shelf
NWS	Northwest shelf

the anticyclonic eddy located in the eastern Kuril Basin. They explained the variations by summer advection of cold, less saline and oxygen-rich water from Terpeniya Bay and the east Sakhalin shelf.

[9] In this paper we examine the DSW formation on the shelves, its further spread toward the deep Okhotsk Sea, and related seasonal OSMW variability in the Kuril Basin. The residence time of the OSMW is estimated on the basis of these seasonal changes. Section 2 briefly describes our data set. Section 3 shows the sources of dense cold water in the Okhotsk Sea contributing to the OSMW formation. Section 4 describes the distribution of the average temperature and salinity on isopycnals using the historical data and synoptic surveys. Section 5 discusses the seasonal changes on the northern shelves and in the OSMW, in the DSW and NPW fluxes, and in the OSMW production rate, using a simple isopycnal box model. The residence time of OSMW is also estimated.

[10] Acronyms are listed in Table 1.

2. Data

[11] The data set consists of historical bottle data taken between 1930 and 1995 and archived at Pacific Oceanographic Institute in Vladivostok, Pacific Scientific Research Fisheries Center in Vladivostok, Research Institute of Fisheries and Oceanography in Yuzhno-Sakhalinsk, Russia as well as the recently completed CTD surveys (Table 2) whose results are being published in more detail elsewhere. Extensive sea ice in winter reduces the number of stations between December and March. The CTD data have 1 dbar vertical resolution, and temperature and salinity accuracy of 0.01° C and 0.01 psu or better. The salinities were calibrated with water bottle samples. Cruises marked by asterisks in Table 2 are at WOCE standard quality [*Freeland et al.*, 1998; *Riser et al.*, 1996].

[12] For bottle data quality control and processing, we followed the procedure described by *Boyer and Levitus* [1994]. Quality control was made separately for the deep and shelf parts of the Okhotsk Sea, divided by an isobath of 200 m. In the deep part, data were averaged for statistical checks by 2° squares. In the shelf region, we distinguish the Hokkaido, Sakhalin, Sakhalin Bay, Northwestern Shelf (NWS), Northern Shelf (NS), Koni-Pyagin shelf (KP), Shelikhov Bay (SHL), and Kamchatka shelf (KAM) (Figure 1), where the stations were sorted into depth bins between 0 and 25 m, 25–50 m, 50–100 m, 100–150 m, and 150–200 m within each 2° box. Following the statistical check, the historical data were averaged by 1° squares in the deep part

Table 2. CTD Data Summary

Ship	Date	Number of Stations	Institution
<i>Akademik Lavrentyev</i>	September 1989	11	POI
<i>Akademik Nesmeyanov</i> ^a [<i>Freeland et al.</i> , 1998]	September 1993	33	POI-IOS
<i>Akademik Lavrentyev</i>	July–Aug. 1994	135	POI
<i>Pulkovo</i>	March–April 1995	119	PSRFC
<i>Akademik Lavrentyev</i> ^a [<i>Riser et al.</i> , 1996]	April–May 1995	155	POI-UW-SIO
<i>Professor Levanidov</i>	Nov.–Dec 1995	116	PSRFC
<i>TINRO</i>	April–June 1996	355	PSRFC
<i>Professor Gagarinskii</i>	June–July 1996	117	POI-RIFO
<i>TINRO</i>	March–June 1997	393	PSRFC
<i>Professor Levanidov</i>	July–Aug. 1997	137	PCRFC
<i>TINRO</i>	Aug–Sept. 1997	126	PSRFC
<i>Professor Khromov</i> ^a	July–Aug. 1998	64	Hydromet, HU, UW
<i>Professor Khromov</i> ^a	Aug–Sept. 1999	79	Hydromet, HU, SIO

^aWOCE standard quality cruises. The abbreviations are Hydromet for Far-Eastern Hydrometeorological Research Institute (Russia), IOS for Institute of Ocean Sciences (Canada), HU for Low Temperature Science Institute, Hokkaido University (Japan), PSRFC for Pacific Scientific Research Fisheries Center (Russia), POI for Pacific Oceanological Institute (Russia), RIFO for Research Institute of Fisheries and Oceanography (Russia), SIO for Scripps Institution of Oceanography (USA), UW for School of Oceanography, University of Washington (USA).

and by the given depth bins within 1° squares on the shelves for input to objective analysis. For the distribution of bottom density on the shelves, we used only measurements taken within 20 m of the bottom.

[13] After quality control, we chose 20,447 hydrographic stations, in addition to the 1840 CTD data stations (Figure 2). The Okhotsk Sea is well sampled except in Penguinskaya Bay, the northeasternmost part of the Shelikhov Bay, and the central Okhotsk Sea ($50\text{--}54.5^\circ\text{N}$ and $146^\circ\text{--}149^\circ\text{E}$). Sampling is denser in the shelf areas. 7529 stations are

included for the shallowest analyzed surface, $26.7 \sigma_\theta$, decreases to 3341 on the densest OSMW surface, $27.0 \sigma_\theta$. The temporal distribution of historical data (Figure 3) reflects a weak exploration of the Okhotsk Sea before World War II, with a rapid increase in the 1950s during the *Vityaz* expeditions, which were the observational basis for *Moroshkin* [1966]. Field measurements were intensive in the 1960–1970s, with more than 200 stations per year. Much lower coverage from the late 1970s to late 1980s may reflect incompleteness of our data set.

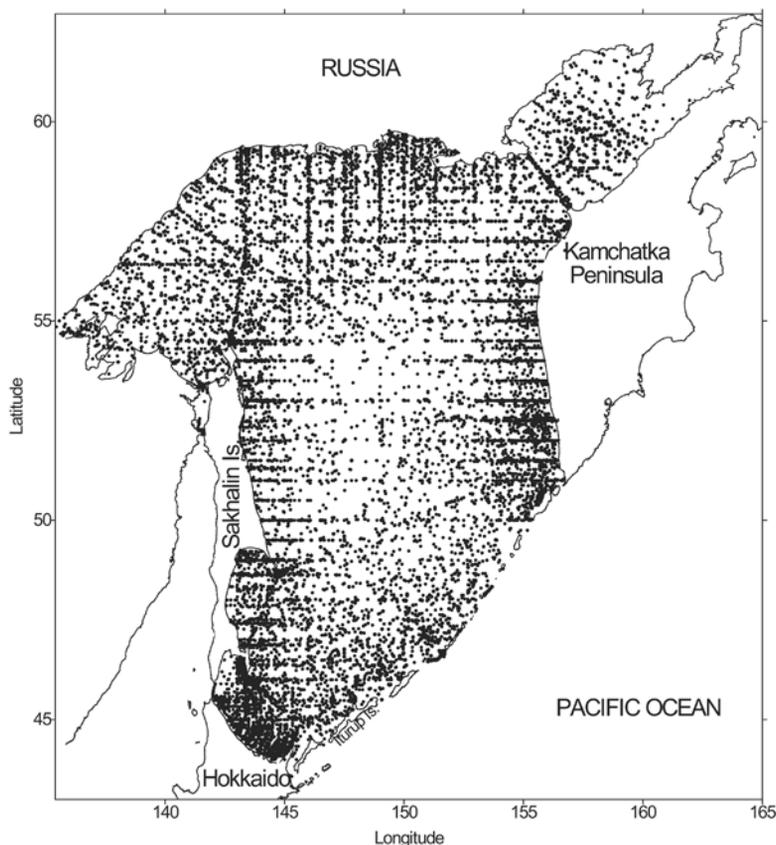


Figure 2. The distribution of historical data in the Okhotsk Sea including CTD cruises listed in Table 2.

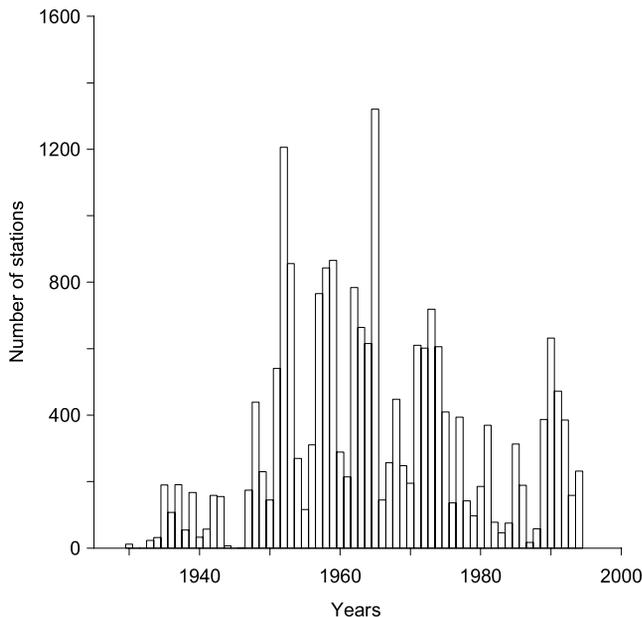


Figure 3. The year-to-year distribution of the historical data.

[14] Potential temperature and potential density referenced to the sea surface are used throughout the following text. The words “temperature” and “density” mean “potential temperature” and “potential density”.

3. Sources of Dense Cold Water in the Okhotsk Sea

[15] *Talley* [1991] discussed possible sources of dense cold water (DCW) in the Okhotsk Sea using data from the World Data Center, most of Japanese origin. We use our expanded data set to clarify the dominant processes. We define the DCW and DSW as water with temperature below 0°C and density greater than $26.7 \sigma_{\theta}$. However, in contrast to the DSW, the DCW can form not only on the shelves but also in the open Okhotsk Sea and, hence this term is more general. Winter convection and brine rejection during ice formation in polynyas [*Alfultis and Martin*, 1987; *Martin et al.*, 1998] are considered including the contributions of the Shelikhov Bay and Sakhalin polynyas. *Gladyshev et al.* [2000] described DSW production on the NS and NWS, so our discussion of this region is confined to section 5, where the seasonal variability of OSMW is considered.

3.1. Potential for Winter Convection in the Deep Okhotsk Sea

[16] Since ice cover has prevented direct observations of winter convection in the western and central Okhotsk Sea until very recently, investigators have used indirect methods, such as density of the temperature minimum in the dichothermal layer [*Kitani*, 1973], to infer the density of convection. *Talley* [1991], using late winter and spring data in the ice-free regions, found $26.7 \sigma_{\theta}$ outcropping close to the northern Kuril Islands and at Soya Strait, where the surface densities exceeded $26.8 \sigma_{\theta}$. The latter is due to inflow of the spring Soya Warm Current (SWC) [*Takizawa*,

1982; *Talley and Nagata*, 1995; *Watanabe and Wakatsuchi*, 1998; *Itoh*, 2000]. Spring (“Forerunner”) SW [*Takizawa*, 1982] spreads along the Hokkaido coast between March and May with a 0.2 Sv transport concentrated at $26.8\text{--}26.9 \sigma_{\theta}$ [*Watanabe and Wakatsuchi*, 1998]. Although the spring SW is important for water mass modification in the Kuril Basin, its temperature exceeds 2°C [*Takizawa*, 1982] and its transport is small.

[17] The Soya Warm Current flows from March through November with a considerably larger volume transport of about 1 Sv in summer–fall [*Takizawa*, 1982; *Talley and Nagata*, 1995; *Itoh*, 2000]. Consequently, the summer–fall contribution of the SW to the southern part of the Okhotsk Sea is greater. The summer SW salinity is greater than 33.6 psu , but its density is less than $26.3 \sigma_{\theta}$ because of high temperature and spreads in the upper layer in the Kuril Basin. The behavior of the SW after passing the tip of Cape Shiretoko is not clear [*Talley and Nagata*, 1995], and it probably mixes through eddies into the Kuril Basin [*Takizawa*, 1982; *Bobkov*, 1993]. SW outflow to the North Pacific was observed through Friza Strait in August 1989. The saline SW is a tantalizing potential source of dense cold water in winter. However, *Talley* [1991] hypothesized, on the basis of limited winter surface data in the Kuril Basin, that SW mixes with less saline Okhotsk Sea water before cooling, reducing the density of the convected surface water to less than $26.8 \sigma_{\theta}$.

[18] To examine winter convection in the deep Okhotsk Sea, we use the *Prof. Levanidov* November–December 1995 cruise (Table 2), when winter convection had already begun in the upper $50\text{--}80 \text{ m}$. The September *Ak. Nesmeyanov* 1993 and *Prof. Khromov* 1999 data were used to fill a data gap in the Deryugin Basin, where fresh Amur River water dominates the surface salinity field (Figure 4a). There are two regions where surface salinity exceeds 33.0 psu and so the density would exceed $26.6 \sigma_{\theta}$ if cooled to the freezing point. The first is Bussol’ Strait in the central Kuril Islands where strong tidal mixing in the Kuril Straits brings higher-salinity water to the surface [*Moroshkin*, 1966; *Kowalik and Polyakov*, 1998; *Nakamura et al.*, 2000b]. The second region is the Southern Kuril Basin where SWC is widely distributed in fall [*Itoh*, 2000] and actively mixes with low-salinity water from the East Sakhalin Current (ESC). A low-salinity tongue intrudes southeastward to Iturup (Etorofu) Island and almost splits the surface SW in two. Most of the Okhotsk Sea surface salinity is between 32.4 and 32.9 psu at the beginning of winter, with lowest salinity in the west where the ESC transports the Amur River water along Sakhalin to the Hokkaido coast, where it is often observed in November [*Watanabe*, 1963].

[19] We estimate the density of potential winter convection using this December salinity distribution, assuming that surface salinity does not change in winter and that upper layer density varies only because of local convection. We also assume for the calculation that ice-covered areas are all at the freezing point, although some of the Okhotsk Sea ice cover, particularly at the southern edges, is exported from ice production areas and is melting. Thus the estimated densities are the maximum possible and are likely high, particularly along the southern edge of the ice region. First, the maximum density of the convectively mixed layer is calculated for each station as $\rho_c = f(T_w, S_{sr})$, where S_{sr} is the

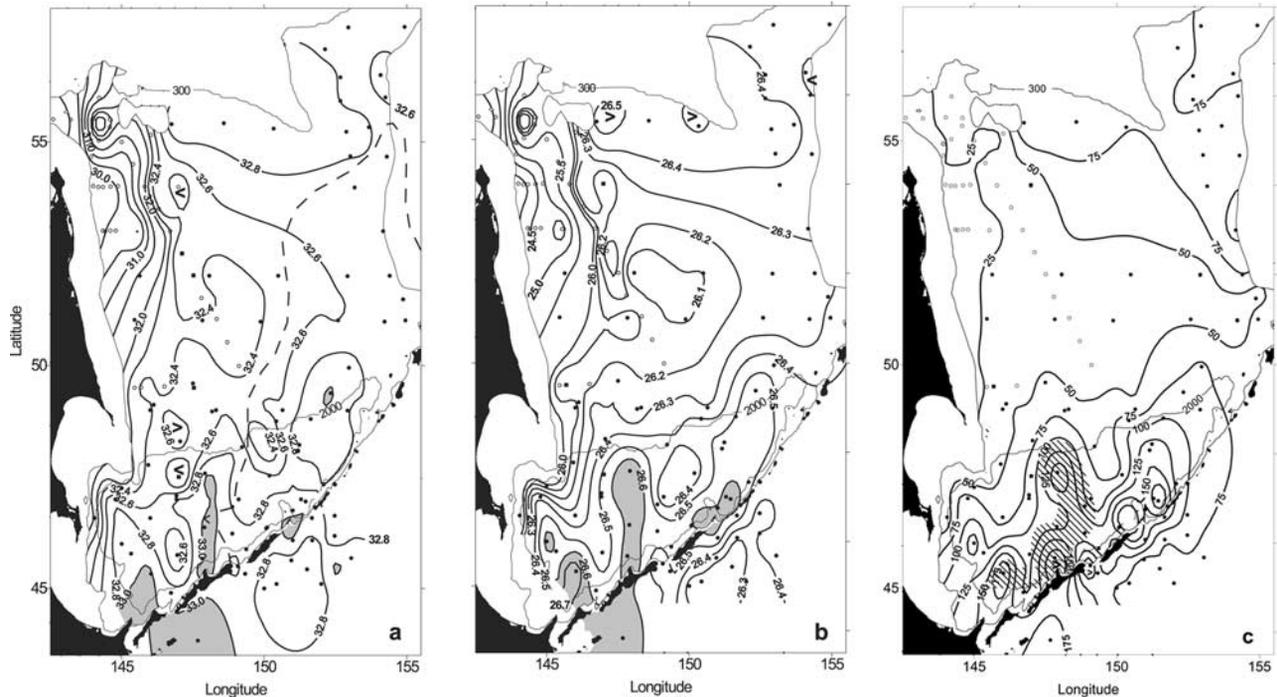


Figure 4. (a) Surface salinity, (b) surface density, and (c) mixed layer depth based on the data of November–December *Prof. Levanidov* 1995 cruise (solid circles) and September *Ak. Nesmeyanov* 1993 and *Prof. Khromov* 1999 cruises (open circles). The dashed line shows the long-term mean ice boundary in March. Shaded areas encompass the regions where salinity (Figure 4a) and density (Figure 4b) exceed 33 psu and $26.6 \sigma_\theta$, correspondingly. The cross shaded area denotes the DCW region in April–May 1995. The contour interval is 0.5 for salinity 30–32 psu and 0.2 for salinity greater than 32 psu. The contour interval is 0.5 for density 24–26 σ_θ and 0.1 for density greater than $26.0 \sigma_\theta$. The thin line is the 300 m isobath.

surface salinity (Figure 4a) and T_w is the winter surface temperature. The latter is taken at the freezing point for the given salinity if the station is covered by ice in winter, or as 0°C for open water in accord with winter observations [Talley and Nagata, 1995] (Figure 4a). The mean Okhotsk Sea ice extent for 1971–1990 [Talley and Nagata, 1995] was used. The depth of ρ_c on each actual vertical profile is a first iteration of the mixed layer thickness. Then the average salinity is calculated in the estimated mixed layer and ρ_c is calculated again with the new salinity to produce an estimate of the density and thickness of winter convection (Figures 4b and 4c). (Although ice formation increases the salinity (density) of the mixed layer, we do not include this effect. For example, formation of 0.5 m ice, which is typical for the central Okhotsk Sea, will increase salinity of a 50 m (100 m) layer by about 0.3 (0.15) psu.)

[20] The estimated convection is relatively shallow in the northern and central Okhotsk Sea, with a thickness of 50–75 m and densities 26.2 – $26.4 \sigma_\theta$ that could be 0.1 – $0.2 \sigma_\theta$ higher depending on ice formation. This is consistent with numerous summer observations of depth and thickness of the dichothermal layer, which is generally shallower than 100 m and with a density of about $26.5 \sigma_\theta$ (not shown). The estimated convection is shallowest along the Sakhalin shelf, with the lowest density of about 24 – $25 \sigma_\theta$. Note however that September data are used in the northwestern Okhotsk Sea, and hence our estimates may be most uncertain for this region. It is evident that the low-salinity surface water

derived from the Amur River could inhibit DCW formation in the northern and central Okhotsk Sea.

[21] In contrast to the northern area, estimated winter convection could reach to greater than 200 m in the Kuril Straits and in the region adjacent to the southern Kuril Islands (Figure 4c). However, this estimated depth is meaningless in the straits, as surface temperatures remain well above freezing all winter. The higher salinity here is due to strong tidal mixing with the warmer, saltier North Pacific water, so the high salinity cannot create favorable conditions for convection.

[22] The relatively dense estimated winter convection in the southern Kuril Basin is caused by the saline SW (Figure 4b). Mixing of the SW with the low-salinity ESC water in the Kuril Basin's vigorous eddy field causes large spatial variations of the depth and density of the dichothermal layer. A Kuril Basin section from May 1995 (Figure 5a) shows two different dichothermal layers. In the region adjacent to Sakhalin, the dichothermal layer is shallow (<100 m) and low density (26.4 – $26.5 \sigma_\theta$) because the winter convection occurred in the low-salinity surface water. The dichothermal layer adjacent to Iturup has a density of 26.6 – $26.7 \sigma_\theta$ and a depth of 150–250 m because of saline SW, spreading in this region in the previous fall (not shown). High dissolved oxygen and low dissolved silicate at $26.7 \sigma_\theta$ in the vicinity of the Iturup (not shown) are also consistent with an hypothesis of the local formation of this water.

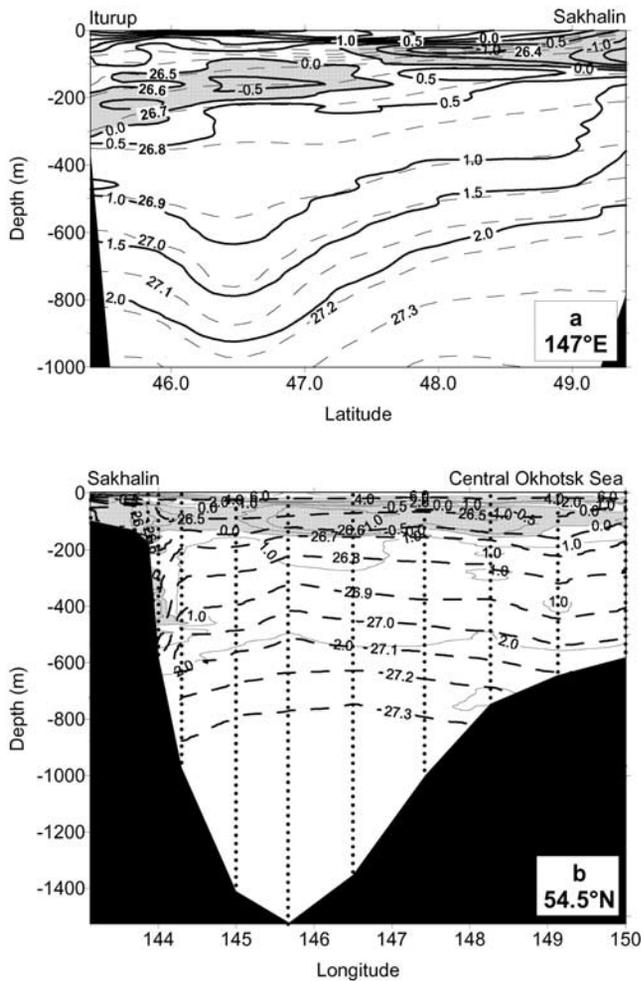


Figure 5. (a) The distribution of potential temperature (solid lines) and potential density (dashed lines) on the vertical section crossing the Kuril Basin between Sakhalin and Iturup Islands. The location of the section is shown in Figure 1 as L1. (b) The same for a section at 55°N from the shelf north of Sakhalin eastward to the central Okhotsk Sea (section L2 in Figure 1). Temperature below zero is shaded.

[23] The location of DCW in April–May 1995 is shown in Figure 4c. On the basis of the direct CTD measurements, its thickness exceeds 30 m near Iturup and is greater than 50 m at the southernmost station (44.99°N, 146.59°E). It is likely that the convective DCW forms in February–March, when ice extends to the southeastern Kuril Basin [Talley, 1991; Wakatsuchi and Martin, 1991; Yasuda, 1997]. Using the Lavrentiev April–May 1995 cruise, we estimate a volume of the DCW produced by the winter convection in the Kuril Basin of about 500 km³, which gives its February–March production rate of about 0.1 Sv. We note that this is a very crude estimate because there are few winter observations south of 45°N in the Kuril Basin. Although the DCW production due to convection is apparently low in comparison with the DSW production on the northern shelves [Gladyshev et al., 2000], we need a more accurate estimate using reliable data. We have to caution that it is difficult to separate the DCW from the DSW in the Kuril Basin using only temperature and salinity. We are not able

to do this employing our historical data, although we find water with temperature below 0°C at 26.7 σ_θ along the southern Kuril Islands in spring. Hydrochemical tracers would be helpful, keeping in mind that the advective DSW loses its properties because of mixing en route to the Kuril Basin.

3.2. Shelikhov Bay

[24] Shelikhov Bay, in the northeastern Okhotsk Sea, is a site of dense (>26.9 σ_θ) shelf water formation in winter [Gladyshev et al., 2000]. The DSW extends southward to a neck of Shelikhov Bay and could drain directly to the Tinro Basin. However, the two available cruises showed only lower densities (<26.7 σ_θ) outside the Shelikhov entrance, from which we conclude that Shelikhov Bay does not really contribute to the OSMW formation, as follows.

[25] Bottom temperature, salinity, and density in March–May 1997 and bottom oxygen for July–August 1997 reveals two separate areas where the bottom density exceeds 26.7 σ_θ , with considerably different water properties. The northern area includes the Shelikhov DSW [Gladyshev et al., 2000], with $\theta < 0^\circ$ and $S > 33.2$ psu. The southern, much larger area is filled by OSMW with $\theta > 1^\circ\text{C}$ and $S > 33.3$ psu. In the Shelikhov neck, bottom salinity and density are less than 32.9 psu and 26.5 σ_θ , presumably because of vigorous tides [Kowalik and Polyakov, 1998]. Water of the same properties as in the neck is widely distributed over the bottom of Koni-Pyagin shelf (Figure 6d) to the west of Pyagin Peninsula. There is no sign of DSW on the continental slope of the Koni-Pyagin shelf and in the Tinro Basin in March–May 1997 (Figure 6). These indicate that water exiting Shelikhov Bay flows westward along the shelf in accordance with the general cyclonic circulation in the Okhotsk Sea.

[26] In Tinro Basin, oxygen is low at the bottom (Figure 6c). Moreover, at 26.9 σ_θ oxygen is lower (<80 $\mu\text{M}/\text{kg}$) here than elsewhere in the Okhotsk Sea, while silicate (>150 $\mu\text{M}/\text{kg}$) is the highest (not shown). At depths greater than 600 m, Sagalevich and Ivanenkov [1982] found, from submarine observations, extremely low visibility, of 2–3 m, and very high turbidity due to the high concentration of organic matter, up to 100–200 mg/L. This was associated with high biological productivity of the western Kamchatka shelf. The organic matter sinks to the bottom, producing 6 km thick layer of deposits, which is the thickest in the Okhotsk Sea. This suggests a large amount of remineralization of organic matter in the Tinro Basin. It seems likely that this process also occurs in the Deryugin Basin, where very high (low) silicate (oxygen) has been observed at the bottom [Freeland et al., 1998]. In contrast to Tinro Basin, oxygen in the tidally mixed bottom water in Shelikhov Bay is highest in summer (Figure 6c). The enormously large tides completely mix the DSW in Shelikhov Bay between May and August [Gladyshev et al., 2000].

3.3. Sakhalin Shelf

[27] The Sakhalin and Terpeniya Bay polynyas may contribute slightly to the DSW production according to Martin et al. [1998] using Chapman and Gawarkiewicz's

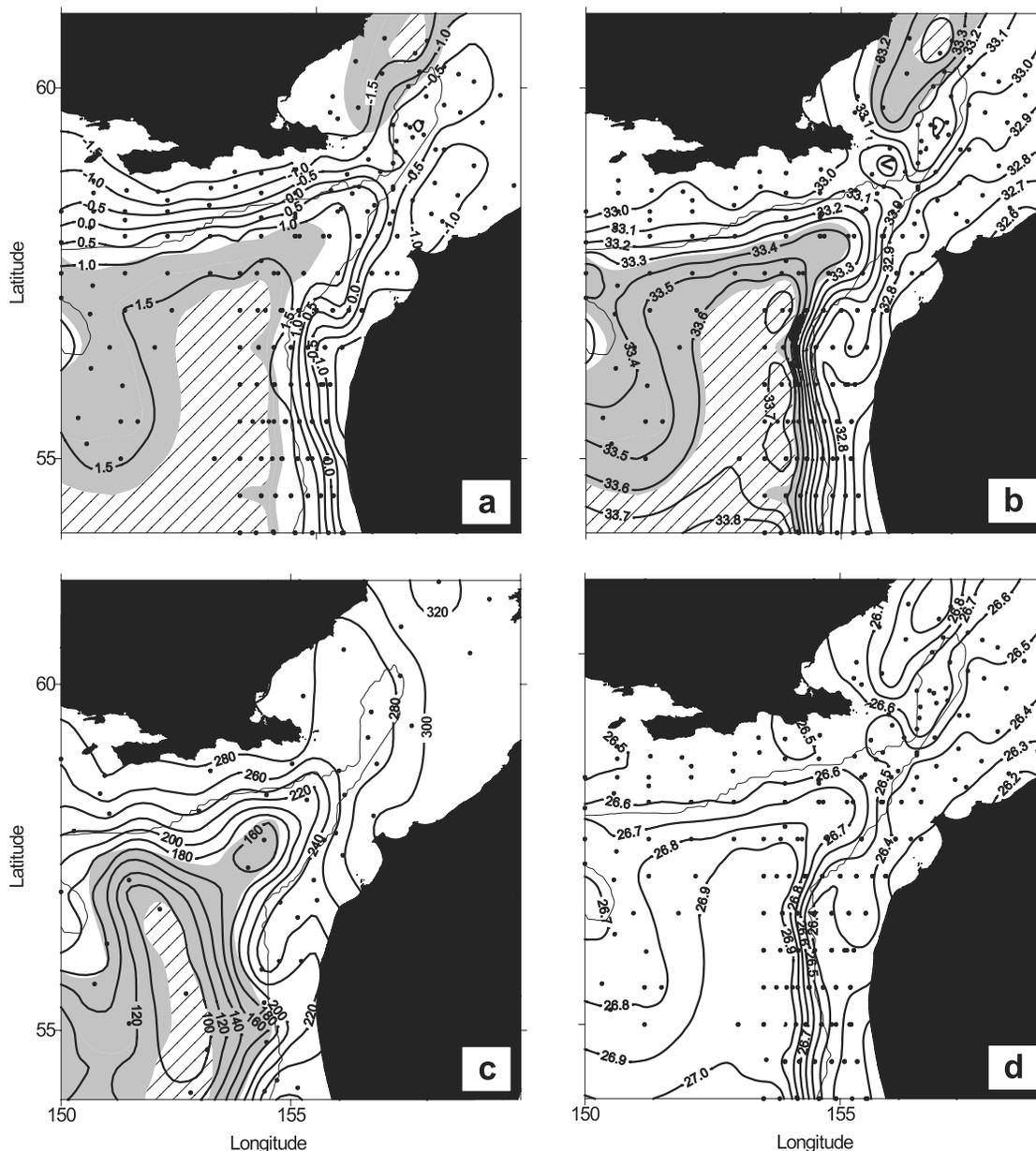


Figure 6. Bottom (a) potential temperature ($^{\circ}\text{C}$), (b) salinity, (c) dissolved oxygen ($\mu\text{M}/\text{kg}$), and (d) potential density (kg m^{-3}) in Shelikhov Bay and adjacent area. Station locations: from March to May 1997 (Figures 6a, 6b, and 6d) and from July to August 1997 (Figure 6c). Shading indicates potential density exceeding $26.7 \sigma_{\theta}$. Cross hatching indicates potential density exceeding $26.9 \sigma_{\theta}$. The thin line indicates the 200 m isobath.

[1997] theoretical results. All available in situ data for April–June (Figure 7) are used here to examine this potential contribution. Ice cover over the Sakhalin shelf north of Terpeniya Cape continues into May [Martin *et al.*, 1998; Talley and Nagata, 1995], so these data represent the earliest period after ice melt. DSW is found only in Sakhalin Bay and on the eastern Sakhalin shelf north of 53°N (Figure 7), and originates from the northern shelves [Gladyshev *et al.*, 2000]. This dense cold water at northern Sakhalin is illustrated in Figure 5b, which is a section (L2 in Figure 1) along 55°N . The rest of the Sakhalin shelf has no DSW, excluding the narrow area adjacent to the 200 m

isobath where it is nevertheless difficult to identify the origin of water of density $>26.7 \sigma_{\theta}$.

[28] There are at least two reasons why DSW is not found on the Sakhalin shelf even just after ice melt. First, the eastern Sakhalin shelf is only 20–50 km wide and the DSW, which is produced before the end of March [Martin *et al.*, 1998; Gladyshev *et al.*, 2000], could be removed from the shelf by currents before May–June. Also, strong tidal currents [Kowalik and Polyakov, 1998] intensively mix the DSW in the coastal area shallower than 50 m [Moroshkin, 1966]. Second, the Amur River fresh water dominates the surface in the western Okhotsk

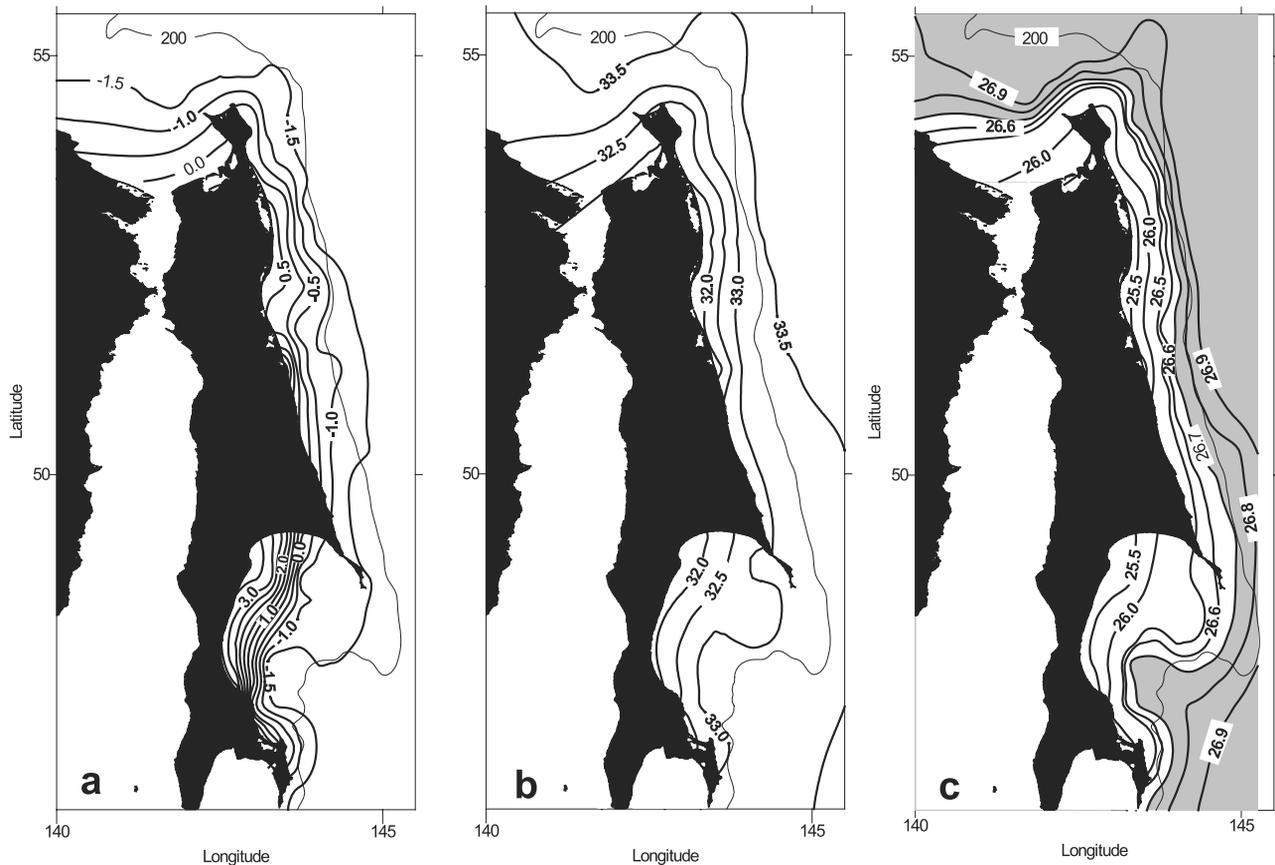


Figure 7. Mean bottom (a) potential temperature, (b) salinity, and (c) potential density on the eastern Sakhalin shelf in April–June based on the historical data. Shading indicates density greater than $26.7 \sigma_{\theta}$. The thin line is the 200 m isobath.

Sea as is evident in the sharp surface salinity front formed in June–July 1996 near Sakhalin (Figure 8). The Amur runoff spreads in Sakhalin Bay over the northwestern escarpment of the Deryugin Basin and over the eastern Sakhalin shelf north of 50°N . Further, the ESC transports the low-salinity water southward along the shelf, causing its appearance at the Hokkaido coast in November [Watanabe, 1963]. When convectively mixed in winter with shelf bottom water, the fresh surface water considerably decreases the water column salinity, such that the brine rejection in polynyas may not be able to produce DSW.

[29] Winter density on the Sakhalin shelf can be inferred from the June–July 1996 data, assuming that water shallower than the 150 m isobath completely mixes by winter convection [Moroshkin, 1966] (Figure 8b). For the open Okhotsk Sea we assume that the temperature minimum is the lower boundary of winter convection. This “winter” density varies significantly from $25.5 \sigma_{\theta}$ north of 52°N to $26.4 \sigma_{\theta}$ south of 50°N on the Sakhalin shelf (Figure 8b), hence not dense enough to become DSW. Martin *et al.* [1998], using Chapman and Gawarkiewicz’s [1997] model, estimated that brine rejection in Sakhalin polynyas increases the bottom density by $0.3 \sigma_{\theta}$. Hence the DSW formation density should be about $26.7 \sigma_{\theta}$. The isopycnal analysis in section 4 will shed some light on this problem. Interannual variability in Amur River runoff may be a controlling factor

for DSW formation on the Sakhalin shelf which can change by a factor of two [Rogachev, 2000].

4. Basin-Wide Okhotsk Sea Mode Water Properties

[30] To describe the spatial distribution of the OSMW in the open sea together with the DSW on the shelves, and the density to which the DSW can increase because of brine rejection in polynyas, we first present isopycnal maps of isopycnally averaged potential temperature and salinity using all available data. It is easy to identify the DSW on these maps, because its temperature is well below 0°C on the shelf all year [Gladyshev *et al.*, 2000] as is also apparent in vertical cross sections from the shelf (Figure 5b). However, the freezing DSW rapidly loses its extreme properties near the shelf break as it descends from the shelves, assumed primarily because of tidal mixing [Kowalik and Polyakov, 1998]. Tidal mixing also modifies warm and saline NPW entering through the Kuril straits. You *et al.* [2000] show that diffusive double diffusion also contributes to the transformation of OSMW from 26.8 to $27.4 \sigma_{\theta}$.

[31] In order to trace the influence of DSW and NPW after they have been modified and to differentiate this modified DSW (MDSW) and modified NPW (MNPW) from the OSMW in the deep Okhotsk Sea, we define MDSW and

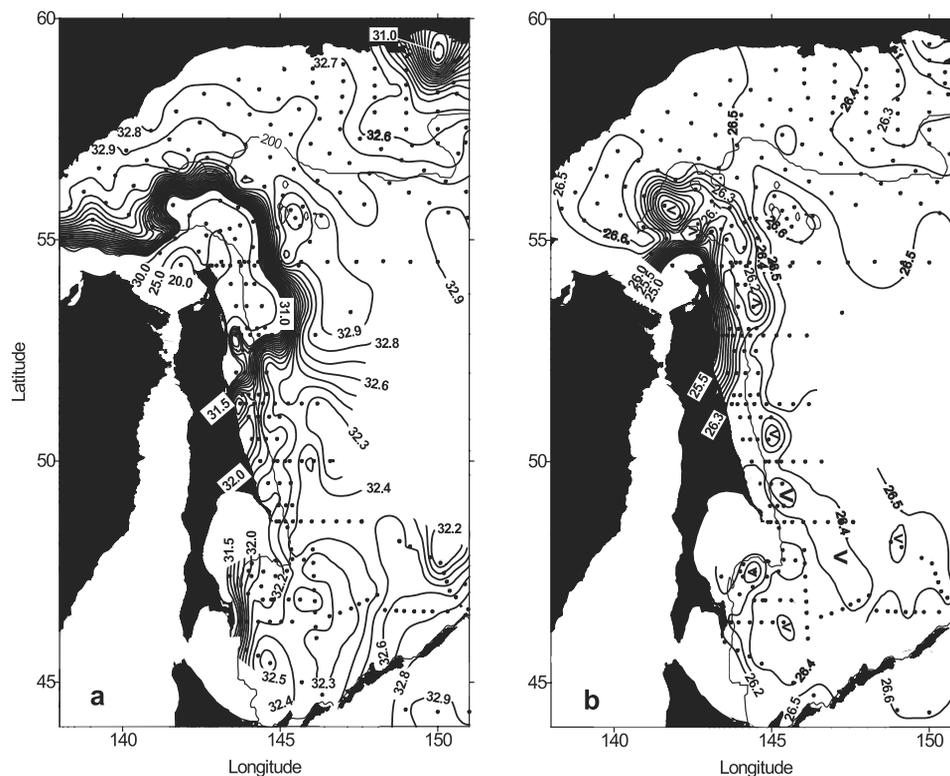


Figure 8. Surface (a) salinity in June–July 1996 and (b) calculated density of winter convection in the western Okhotsk Sea. The dots show the station locations. The contour interval is 5.0 for salinity 20–30 psu, 1.0 for salinity 30–31 psu, and 0.1 for salinity greater than 31 psu. The contour interval is 0.5 for density 25–26 σ_θ and 0.1 for density greater than 26.0 σ_θ . The thin line is the 200 m isobath.

MNPW as follows. (MDSW and MNPW are not traditionally defined water masses, but are useful for tracking the mixed products of DSW and NPW.) MDSW is colder and fresher than OSMW, while MNPW is warmer and saltier. A MDSW (MNPW) upper (lower) bound separately for each isopycnal surface from 26.7 to 27.0 σ_θ is defined as

$$\theta_{MDSW}^u = \bar{\theta}_{OSMW} - 3*\sigma, \quad \theta_{MNPW}^l = \bar{\theta}_{OSMW} + 3*\sigma, \quad (1)$$

and

$$S_{MDSW}^u = \bar{S}_{OSMW} - 3*\sigma, \quad S_{MNPW}^l = \bar{S}_{OSMW} + 3*\sigma,$$

where θ_{MDSW}^u and S_{MDSW}^u are the upper thermohaline bound of the MDSW, θ_{MNPW}^l and S_{MNPW}^l are the lower thermohaline bound of the MNPW, and $\bar{\theta}_{OSMW}$ and \bar{S}_{OSMW} are the isopycnally averaged temperature and salinity of OSMW, and σ is the standard deviation of mean of the OSMW properties (Table 3). The use of 3σ to define the boundaries

is arbitrary but useful. The MDSW and MNPW boundaries are shown only on temperature maps (Figure 9). The boundaries based on salinity are consistent with the temperature boundaries. However, the OSMW salinity range on isopycnal surfaces is small and three standard deviations in salinity just slightly exceed the accuracy of the historical data, which is 0.02 psu. The “MNPW boundary” in the southern Okhotsk Sea along the Hokkaido coast actually shows Forerunner SW. The coldest OSMW is most recently ventilated by the DSW.

4.1. Okhotsk Sea Mode Water Using All Available Data

[32] At 26.7 σ_θ , cold DSW ($\theta < -1^\circ\text{C}$, $S < 33.20$ psu) is widely distributed on the NS, NWS, in Sakhalin Bay where it is transported from the NWS, and in Shelikhov Bay (Figures 9a and 9b), consistent with *Kitani* [1973] and *Gladyshev et al.* [2000]. The DSW rapidly changes its properties in the neck of Shelikhov Bay (Section 3). Along the eastern Sakhalin shelf the DSW descends and forms a

Table 3. Average Isopycnal Values for the OSMW ($\bar{\theta}_{OSMW}$, \bar{S}_{OSMW}) and the Upper and Lower Thermohaline Boundaries of the Modified Dense Shelf Water (θ_{MDSW}^u , S_{MDSW}^u) and Modified North Pacific Water (θ_{MNPW}^l , S_{MNPW}^l) Defined as in the Text

σ_θ	$\bar{\theta}_{OSMW}$, °C	\bar{S}_{OSMW} , psu	θ_{MDSW}^u , °C	S_{MDSW}^u , psu	θ_{MNPW}^l , °C	S_{MNPW}^l , psu
26.7	0.48 ± 0.15	33.29 ± 0.01	≤ 0	≤ 33.26	≥ 1.0	≥ 33.32
26.8	0.91 ± 0.10	33.44 ± 0.01	≤ 0.6	≤ 33.41	≥ 1.2	≥ 33.47
26.9	1.17 ± 0.10	33.59 ± 0.01	≤ 0.9	≤ 33.56	≥ 1.5	≥ 33.62
27.0	1.48 ± 0.08	33.73 ± 0.01	≤ 1.2	≤ 33.70	≥ 1.7	≥ 33.76

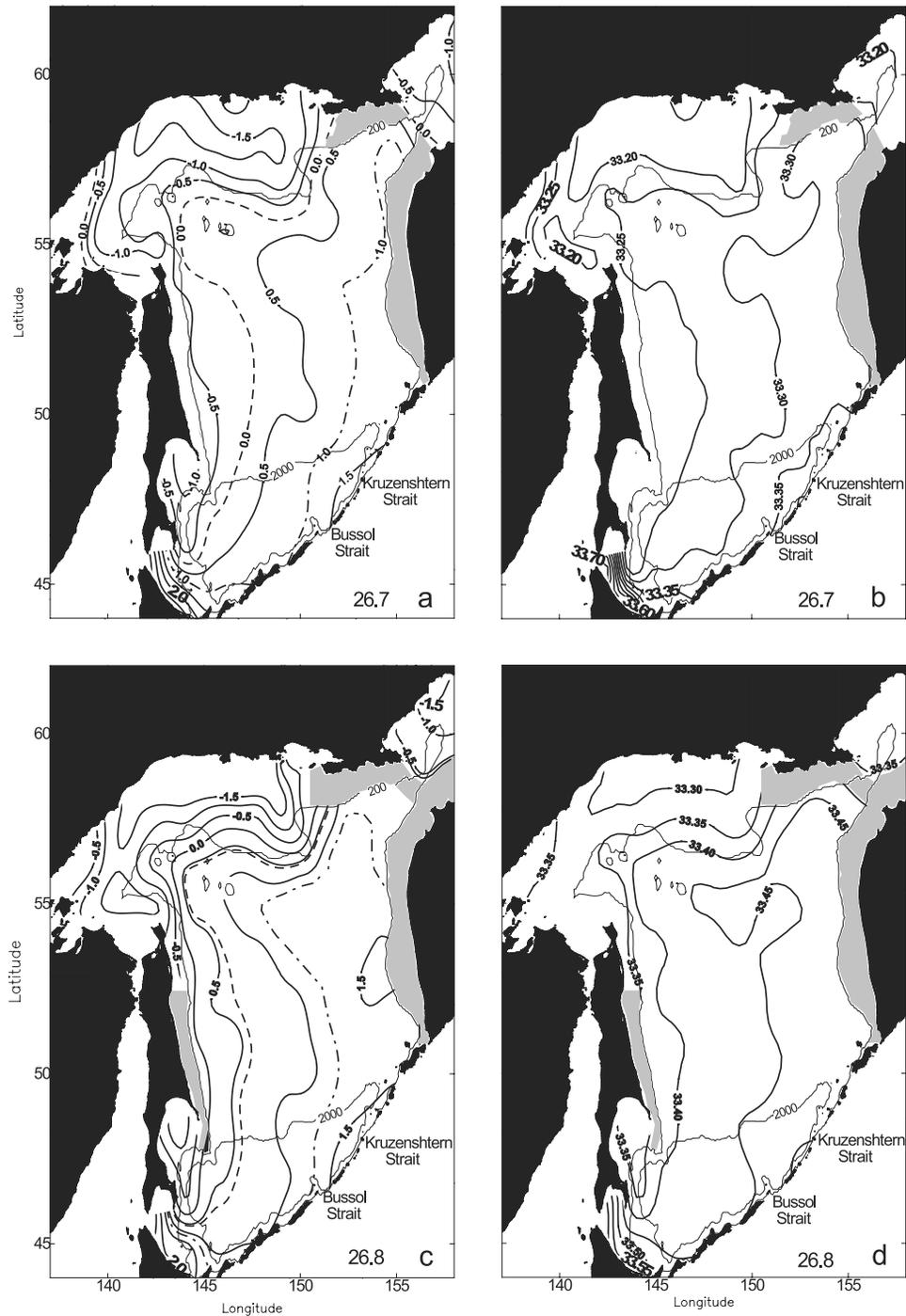


Figure 9. The average distribution of potential temperature and salinity on isopycnals in the Okhotsk Sea: (a) and (b) $26.7 \sigma_{\theta}$; (c) and (d) $26.8 \sigma_{\theta}$; (e) and (f) $26.9 \sigma_{\theta}$; (g) and (h) $27.0 \sigma_{\theta}$. Shading indicates no water with such potential density. The dashed (dot-dashed) line shows the boundary of the MDSW (MNPW). The thin lines are the 200 and 2000 m isobaths.

large, cold pool, longitudinally oriented in the western Okhotsk Sea, with potential temperature below 0°C and salinity less than 33.26 psu. Further transformation of the MDSW along its cyclonic pathway includes gradual mixing with the warmer and saltier MNPW in the central Okhotsk Sea. The latter, indicated by the 1°C isotherm, is widely distributed east of 150°E from Friz Strait in the south to a narrow band along western Kamchatka shelf, up to 58°N in

the north. The MDSW mixing with the warm and saline Forerunner SW occurs in the southern part of the Okhotsk Sea. The Forerunner SW dominates on the Hokkaido shelf in March–May [Takizawa, 1982; Watanabe and Wakatsuchi, 1998] and, according to Figure 9a, spreads to the north along the southern Kuril Islands to 45°N . It is not possible to distinguish the convective DCW in the southern Kuril Basin because of averaging.

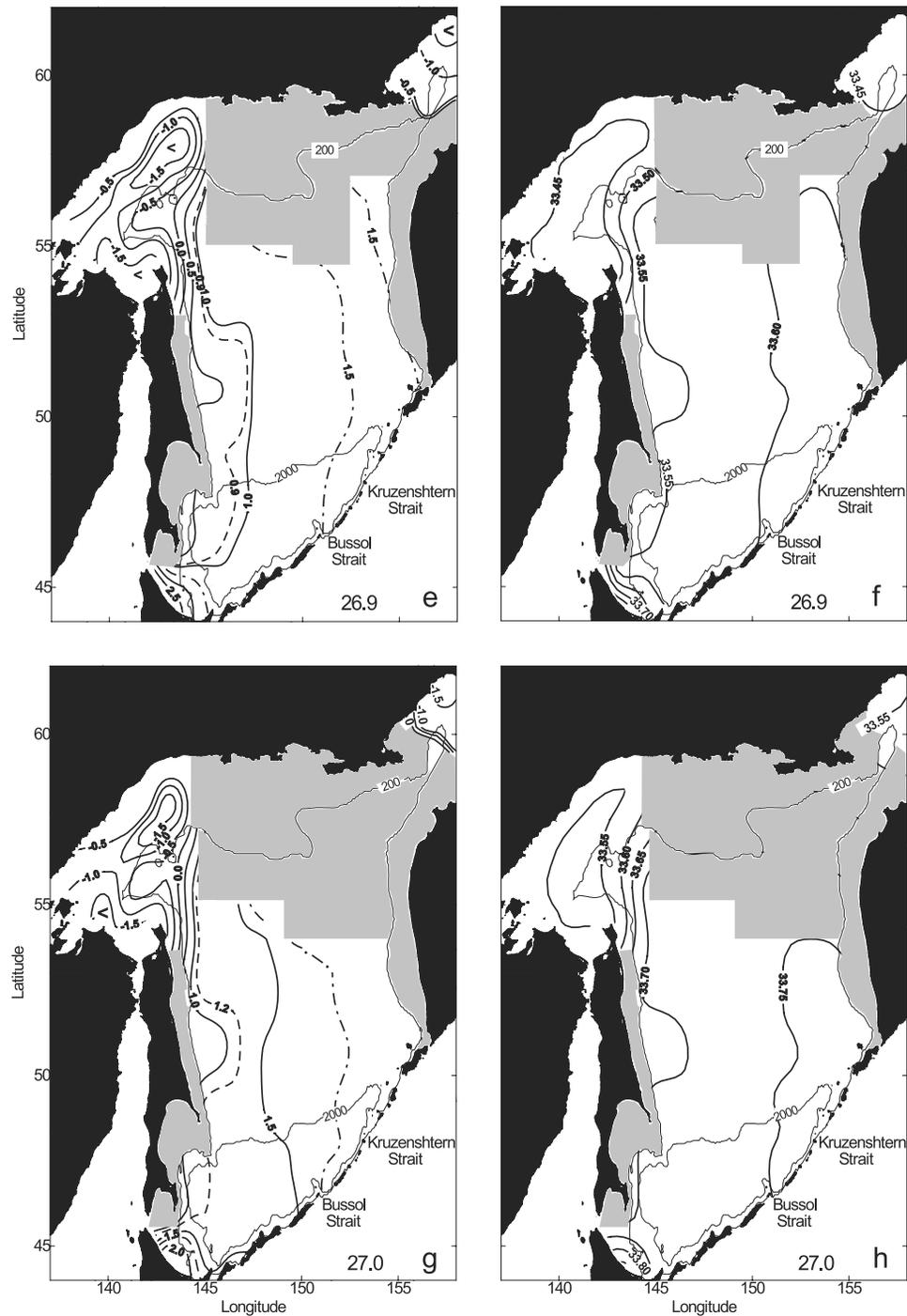


Figure 9. (continued)

[33] At $26.7 \sigma_{\theta}$, the basin-wide variations in temperature and in salinity are about 2°C and less than 0.15 psu. There is no DSW formation and hence no freezing bottom water on the Hokkaido, Koni-Pyagin and Kamchatka shelves because of the lack of polynyas.

[34] DSW with a density of $26.8 \sigma_{\theta}$ forms on the NWS and NS (Figures 9c and 9d). This water has salinity less than 33.3 psu and is close to the freezing point. The DSW is also involved in cyclonic circulation over the northern shelf, turns around Sakhalin to reach the northeastern Sakhalin shelf, north of about 53°N , and cascades toward the

Deryugin Basin [Gladyshev *et al.*, 2000]. On the other hand, no DSW of this density is found on the eastern Sakhalin shelf between 49°N and 53°N . It is clear, however, that DSW with a density of $26.8 \sigma_{\theta}$ sometimes forms in the Terpeniya Bay polynya and flows southward along the southern part of the eastern Sakhalin shelf. At this density, water below 0.6°C with salinity less than 33.41 (Table 3) occurs in a narrow band along the eastern Sakhalin slope, between 45° and 55°N , clearly manifesting the main pathway of the MDSW in the open sea. This pathway reflects the East Sakhalin Current flowing along the entire Sakhalin

slope and transporting the MDSW southward. In section 3, we showed that Shelikhov Bay does not contribute to ventilation of the Okhotsk Sea at densities greater than $26.8 \sigma_\theta$. Fairly homogeneous, warm water in the northeastern Okhotsk Sea supports this conclusion.

[35] At $26.8 \sigma_\theta$, the MNPW penetrates far to the north to the Tinro Basin and further to the Koni-Pyagin shelf. It also flows toward Kashevarov Bank. It appears that the MNPW mixes slightly with the MDSW along the eastern part of the NS continental slope. In the southern Okhotsk Sea, the Hokkaido shelf and slope restrain the SW spreading (Figures 9c and 9d). Generally at $26.8 \sigma_\theta$, the range of salinity in the open Okhotsk Sea, excluding a quite small SW region, just slightly exceeds 0.1 psu, although the temperature range is about 2°C .

[36] Potential temperature and salinity at $26.9\text{--}27.0 \sigma_\theta$ indicate that the only source of DSW in this density range is the NWS polynya, located along the northwestern coast between Ayan and Okhotsk City (Figures 9e–9h). The DSW from the NWS fills up the northwestern escarpment of the Deryugin Basin and flows southward along the eastern Sakhalin slope to the Kuril Basin. MNPW stretches northward from Bussol' Strait along the Kuril Islands and the western Kamchatka shelf. Forerunner SW on the Hokkaido shelf and continental slope is the warmest and saltiest component of the OSMW, consistent with Takizawa [1982], Talley [1991], Watanabe and Wakatsuchi [1998], and Itoh [2000]. Shelikhov Bay DSW can reach a density of $27.1 \sigma_\theta$ (not shown). However, as mentioned before, this dense water does not ventilate the Okhotsk Sea although Shelikhov Bay polynyas may be important for the Okhotsk Sea as ice producers.

4.2. Modified Dense Shelf Water Using Synoptic Data

[37] Detailed study of the MDSW distribution in the open Okhotsk Sea requires quasi-synoptic surveys because its main pathway off the shelves is the narrow region along the eastern Sakhalin slope. We chose 1996 for its good spatial station coverage in the western Okhotsk Sea, and because there is detailed analysis of the DSW formation on the northern shelves during this year [Gladyshev et al., 2000]. Data are combined from two cruises: *TINRO* (the western part of the survey) and *Prof. Gagarinskii*, both during June–July 1996 (Table 2). The thickness of the layer with $\theta < 0^\circ\text{C}$ and $\sigma_\theta < 26.7$ for each station of the combined survey was calculated (Figure 10a). In 1996, the DSW, originating from the NWS, descended from the shelf toward the northwestern Deryugin Basin south of 56°N , where its thickness was greater than 50 m. A DSW cascade also occurred across the shelf break of Sakhalin Bay and across the shelf break of the northeastern Sakhalin shelf, north of 53°N . The ESC then transported the thick lenses of MDSW southward along the eastern Sakhalin slope parallel to the isobaths. The length of these lenses varied between 50 and 160 km and their width was about 20–50 km. Their thickness was 50–200 m, which was greater than upstream at their source, implying active vertical mixing, most likely due to tides. Some MDSW expansion eastward at $51^\circ\text{--}53^\circ\text{N}$ gives the impression that part of this water is involved in the cyclonic circulation over the Deryugin Basin. Flowing to the south, the MDSW enveloped a Kuril Basin anticyclonic eddy, which contained no DSW.

[38] Temperature and salinity at 26.7 , 26.8 , and $26.9 \sigma_\theta$ (Figures 10b–10g) are generally consistent with the MDSW thickness distribution (Figure 10a) and the historical data analysis (Figure 9). We chose these isopycnals because water in this density range formed on the northern shelves in 1996 [Gladyshev et al., 2000]. In Figures 10b–10d, we also plot the MDSW and MNPW boundaries for comparison (Table 3). As in the historical data, DSW colder than -1.5°C occurred only on the shelves in 1996. At $26.7 \sigma_\theta$, the DSW left the shelf in the large region across the Sakhalin shelf break. Consequently, a large cold pool with potential temperature below 0°C existed in the western Okhotsk Sea, where some MDSW was involved in the cyclonic circulation over the Deryugin Basin. A large amount of MDSW occurred in the western Kuril Basin, where it may have coalesced with convectively formed DCW (relatively thick and cold lens close to Iturup Island in Figure 10b).

[39] At $26.8 \sigma_\theta$, the DSW cascaded across the Sakhalin Bay shelf break and northeastern Sakhalin shelf break. The distribution of MDSW in the western Okhotsk Sea was quite similar to that at $26.7 \sigma_\theta$.

[40] In contrast, at $26.9 \sigma_\theta$ (Figure 10d), the MDSW was not as abundant in the western Okhotsk Sea, consistent with Gladyshev et al. [2000]. In 1996, the annually averaged production rate of DSW at $26.8\text{--}26.9 \sigma_\theta$ was only 0.04 Sv or four times less than for $26.7\text{--}26.8 \sigma_\theta$ [Gladyshev et al., 2000]. The MDSW flow at $26.9 \sigma_\theta$ turned eastward near Terpeniya Cape, spreading toward Bussol' Strait in the Kuril Basin. A few separated lenses of MDSW occurred. The MDSW was quite homogeneous in salinity at all densities (Figures 10e–10g), with the lowest salinities along the Sakhalin slope, consistent with the historical data analysis.

[41] MDSW can be clearly seen along 48.6°N from Terpeniya Cape in June 1996 (Figure 11). (Sections through the whole of the Okhotsk Sea to Bussol' Strait were shown by Freeland et al. [1998].) The MDSW spreads over the Sakhalin slope in the upper 500 m layer, recognized by its anomalously low temperature and salinity. A steep slope of isopycnals at the shelf break and in the deeper layers suggests the existence of a strong ESC. The DSW density was greater than $26.7 \sigma_\theta$ on the Sakhalin shelf and likely originated from the Sakhalin polynya. The separate lens of MDSW 100 km offshore suggests that the ESC is subject to the influence of small eddies and other transients, contributing to MDSW spreading and mixing.

[42] To estimate a travel time necessary for the DSW from its source to the Kuril Basin, geostrophic velocities relative to 1000 dbar for June–July 1996 are calculated, recognizing that there is seasonal and interannual variation so the values given here are estimates only. Velocities at 300 dbar correspond to a density of about $26.8 \sigma_\theta$ (Figure 12). Geostrophic velocities at intermediate depth are persistently southward along the Sakhalin slope with speeds in excess of 15 cm/s in the north and are the core of the ESC. This is consistent with average current speed estimates based on the 2 year long current measurements made over the Sakhalin slope at 53°N (G. Mizuta, personal communication, 2001). The average speed between 48°N and 54.5°N was about 10 cm/s at 300 dbar and 15 cm/s at 200 dbar or $26.7 \sigma_\theta$ (not shown). Hence most MDSW from the 750 km between

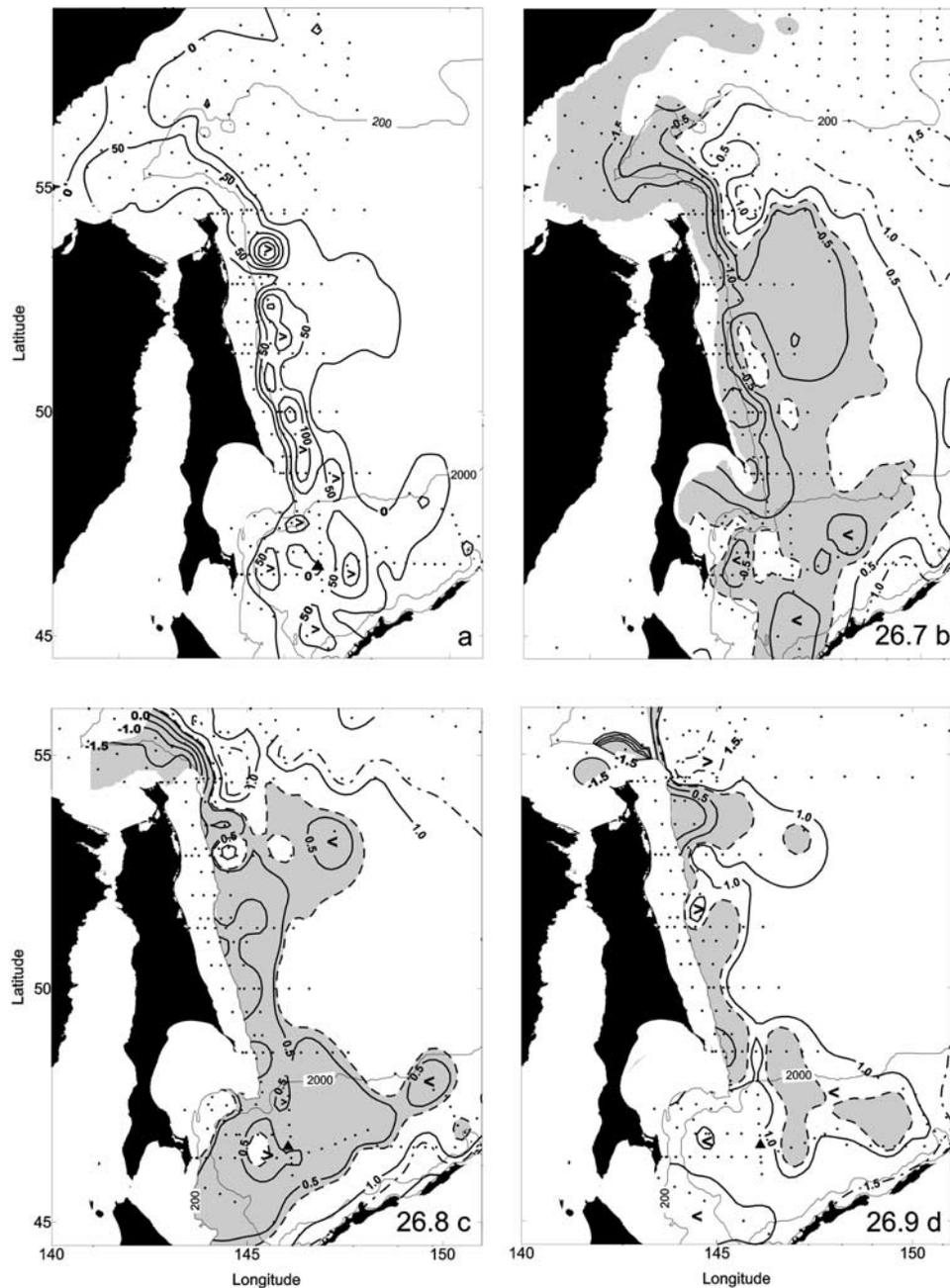


Figure 10. (a) The thickness of the layer with water with $\theta < 0^\circ\text{C}$ and $\sigma_\theta > 26.7 \sigma_\theta$. Potential temperature and salinity at (b) and (e) $26.7 \sigma_\theta$, (c) and (f) at $26.8 \sigma_\theta$, (d) and (g) at $26.9 \sigma_\theta$ for 4 June to 6 July 1996 based on the combined CTD surveys. Regions of potential temperature below 0°C are shaded. The dots show the station locations. The thin lines show the 200 and 2000 m isobaths. The triangle is the center of the anticyclonic eddy in the Kuril Basin.

northern Sakhalin and the Kuril Basin would pass within 2–3 months. For the MDSW at $26.9 \sigma_\theta$, from the northern shelves, 4 months are required to reach the Kuril Basin at an average speed of 7 cm/s. According to Gladyshev *et al.* [2000], the first DSW flows from the NWS to Sakhalin Bay 1.5–2 months after formation. Thus the DSW from the NWS would take 3.5–6 months (depending on density) to reach the Kuril Basin. Given that DSW formation started in mid-January in 1996 [Gladyshev *et al.*, 2000], the first MDSW could reach the Kuril Basin at the beginning of

May. For the DSW from the Sakhalin and Terpeniya polynyas with densities of about $26.7 \sigma_\theta$ the travel time to the Kuril Basin would not exceed 1–2 months. Hence this water could appear in the Kuril Basin as early as March along with the DCW produced by winter convection.

5. Seasonal Variability of DSW and OSMW

[43] As shown in section 4, a large amount of the DSW produced on the Okhotsk shelves at the beginning of each

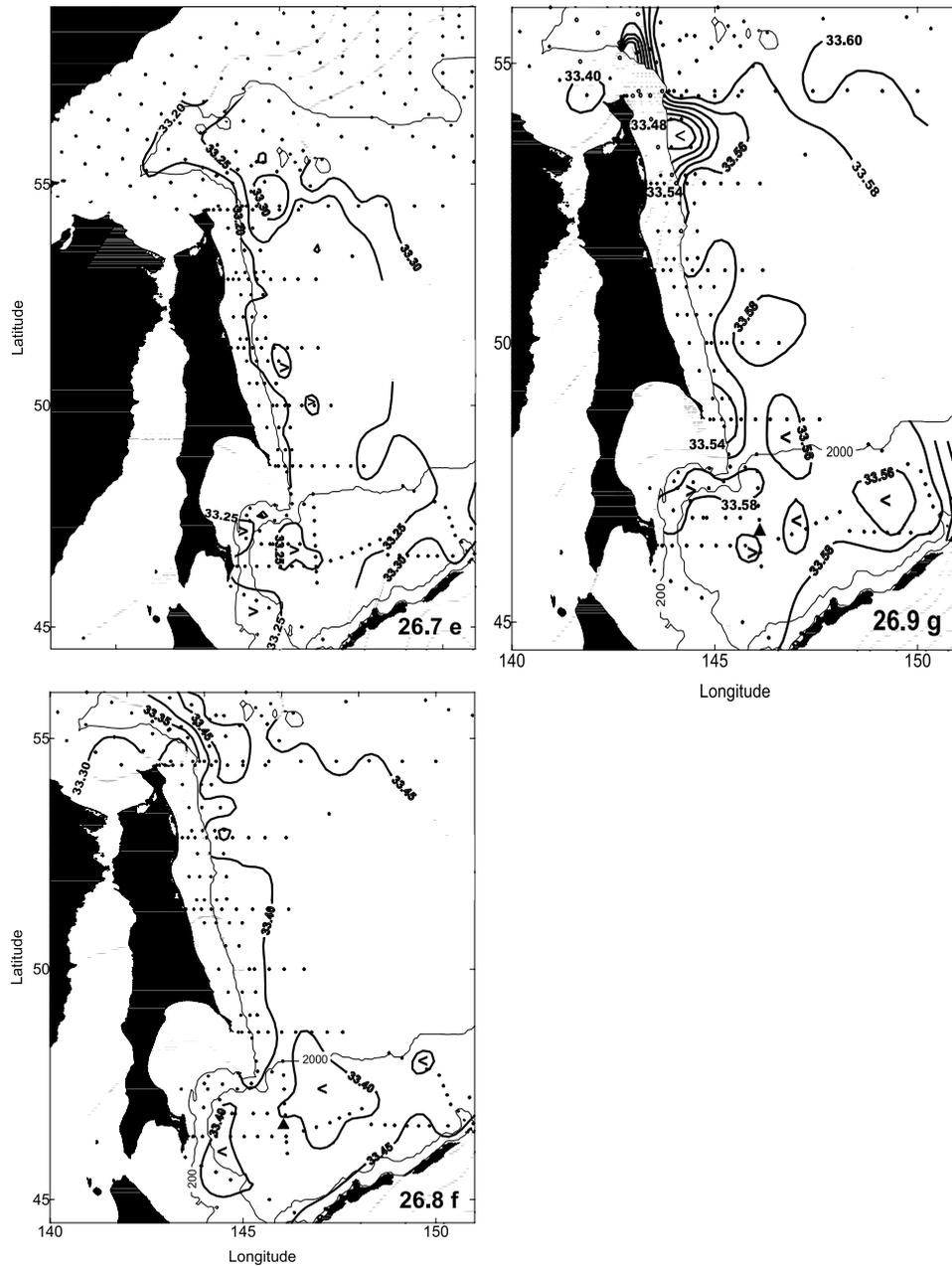


Figure 10. (continued)

year is transported out along the eastern Sakhalin slope to the Kuril Basin. This suggests examining the seasonal variability associated with this outflow. In order to clarify the response of the OSMW to the DSW flux, a detailed examination of the seasonal variations on the northern shelves and in the Kuril Basin from the historical data is undertaken in this section.

5.1. Seasonal Variability on the Northern Shelves

[44] The NWS and NS polynyas are the biggest DSW producers at $26.7\text{--}26.8\sigma_\theta$ (Figure 9). Moreover, the NWS polynya is the only producer at $26.9\text{--}27.0\sigma_\theta$, ventilating the OSMW. The Shelikhov Bay polynyas produce the densest DSW in the Okhotsk Sea but contribute little to OSMW modification (Section 3). Thus we restrict our

further exploration of the shelves to the NS and NWS. We select and average shelf data over the bottom within May–June (spring) and September–October (fall) as representative months to show seasonal variability of the DSW (Figure 13).

[45] In spring, DSW with density exceeding $26.7\sigma_\theta$ occupies the entire NWS, Sakhalin Bay and the NS west of 146°E . It appears that DSW with density greater than $26.9\sigma_\theta$ forms annually on the NWS, while on the NS the DSW usually has densities of $26.7\text{--}26.8\sigma_\theta$. The latter flows cyclonically over the shelf, gradually replacing the DSW on the NWS during spring and summer [Gladyshev *et al.*, 2000].

[46] Bottom density changes in coastal regions exceed $1.0\sigma_\theta$ between spring and fall (Figure 13). At depths shallower

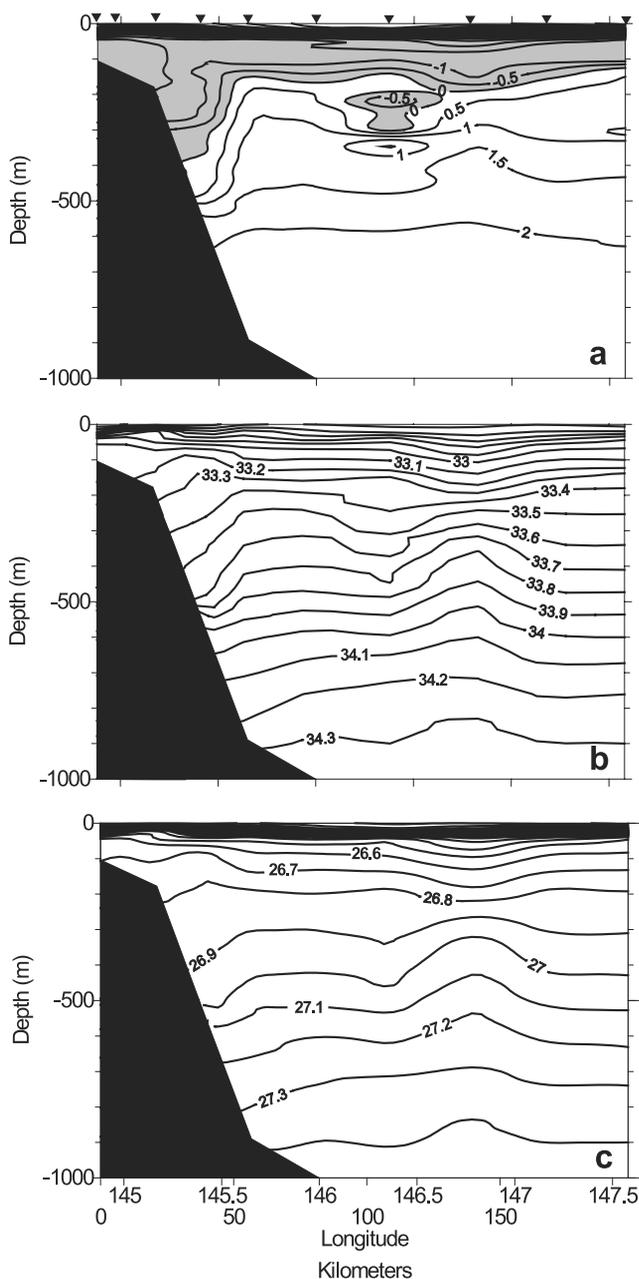


Figure 11. (a) Potential temperature, (b) salinity, and (c) potential density on the vertical section along 48.6°N offshore from Terpeniya Cape for 28 June 1996. The location of section is shown in Figure 1 by L3. Temperature below 0°C is shaded.

than 100 m, strong tides dramatically reduce the density of the bottom layer to less than $26.0 \sigma_\theta$ through mixing with surface water which is seasonally warmed and diluted by melted ice, numerous small rivers and precipitation. The amount of river discharge and precipitation to some degree controls stratification at the beginning of the brine rejection. The river runoff maximum always occurs in spring and depends on the winter snow pack, while precipitation is greatest in summer and fall.

[47] As seen in Figure 8, the Amur runoff does not influence the NWS, which lies upstream, in contrast to

Sakhalin Bay and the Sakhalin shelf. This difference seems to be crucial for formation of the densest water on the NWS. Small rivers entering the NWS bring only $57.2 \text{ km}^3 \text{ yr}^{-1}$ of fresh water [Rogachev, 2000]. Rain gauge data collected by the National Climate Data Center (NCDC) show that maximum precipitation in the north of the Okhotsk Sea occurs in Ayan (Figure 1). The annual long-term mean $84 \pm 24 \text{ cm yr}^{-1}$ for the period 1932–1999 gives a fresh water flux of about $65 \text{ km}^3 \text{ yr}^{-1}$ for the entire NWS. Martin *et al.* [1998] and Gladyshev *et al.* [2000] estimated that annually, more than 100 km^3 of sea ice forms in the NWS polynya. Most of sea ice, however, is thought to be removed from the NWS before melting because of northwestern winds [Kimura and Wakatsuchi, 1999]. Hence melting ice, the small river runoff, and precipitation are the main contributors to the surface salinity variations on the NWS. Variations in freshwater flux, along with winter air temperature and surface wind, produce interannual variability of the dense water production in polynyas. A more detailed analysis of this problem is under way.

[48] Below 100 m on the shelves, seasonal variation of DSW is much less, with DSW with $\sigma_\theta > 26.7$ in both seasons on the NWS, Sakhalin Bay and NS west of 146°E (Figure 13). Although the density of the DSW decreases by about $0.1 \sigma_\theta$ from spring to fall, likely because of outflow from the shelves and also likely because of tidal mixing, Figure 13 gives the impression that not much DSW leaves

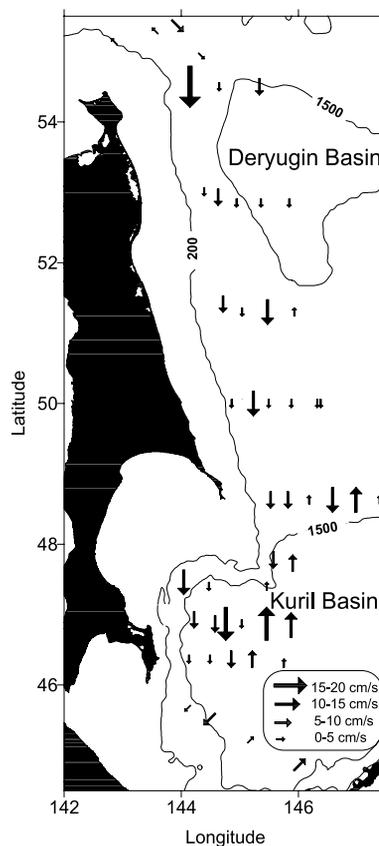


Figure 12. Geostrophic velocity at 300 db relative to 1000 dbar in the region of the East Sakhalin Current for 4 June to 6 July 1996 based on the combined CTD surveys. The thin line is the 200 m isobath.

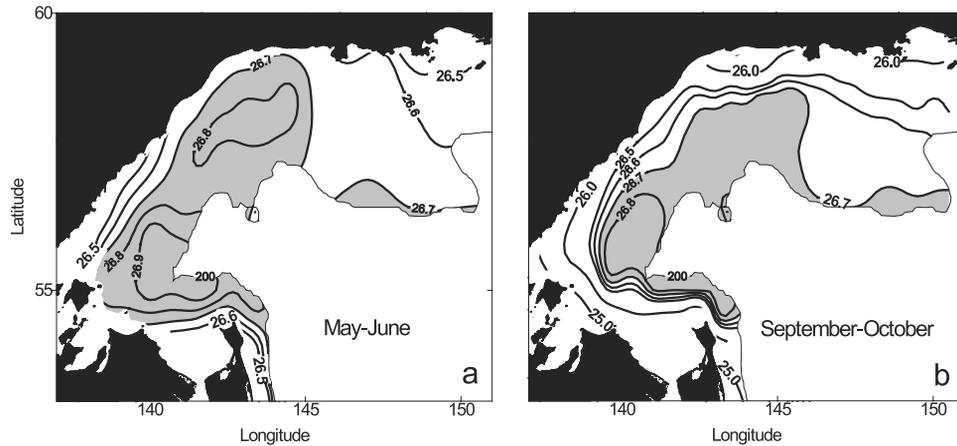


Figure 13. The average distribution of potential density at the bottom on the northern Okhotsk Sea shelves in (a) May–June and (b) September–October based on the historical data. The shaded areas denote regions where the bottom density exceeds $26.7 \sigma_\theta$. The thin line is the 200 m isobath.

the shelf over summer. To check this hypothesis, we estimate the average removal rate U of the DSW from these regions between spring and fall, where we define U as the volume change between 1 June and 1 October. To calculate the volume, we multiply the bottom area encompassed by a given isopycnal and limited seaward by an isobath of 200 m by the seasonally averaged thickness of the isopycnal layer derived from the historical data on the NWS and NS and in Sakhalin Bay. Table 4 lists the average thickness (H) of DSW at 26.7 – $26.9 \sigma_\theta$, their volumes (V), and the summer–fall removal rates (U) with the estimated errors based on standard deviation of mean.

[49] As shown in Table 4, the summer–fall removal rate for DSW with $\sigma_\theta > 26.7$ is about 0.2 Sv. This agrees within the error with the results of Gladyshev *et al.* [2000], who estimated the removal rates for the NWS between July and August 1997 and for the NS between May and August 1997. For these removal rates, we estimate that about $2 \times 10^3 \text{ km}^3$ of the DSW with a density of $26.7 \sigma_\theta$ does not leave the northern shelves until December. Most of this late DSW lying at depths shallower than about 150 m (the lower limit of winter convection according to Moroshkin [1966]) is subject to winter overturning on the shelf, eventually completely mixing with the surrounding water and becoming part of the next year’s new DSW. Because of winter convection the northern DSW flux between November and February would be close to zero.

5.2. Seasonal Variability of the Okhotsk Sea Mode Water

[50] Historical data for April–May (spring) and September (fall) as representative months are used to show seasonal variability of the OSMW (Figure 14). April and May are combined because of the few observations in early spring and because we require at least 7 observations within each 1° square. We display the averaged anomalies of temperature at $26.9 \sigma_\theta$, to highlight the impact of the northern DSW, which is the only source of freezing water that ventilates the deep sea at this density. In general, the distribution and propagation of the anomalies in the OSMW are consistent at all densities (not shown).

[51] In April–May (Figure 14a), a large cold anomaly with ($\theta < -0.4^\circ\text{C}$) exists in the northwestern Kuril Basin, apparently reflecting how rapidly the ESC transports the MDSW southward. A separate cold anomaly is also apparent in the vicinity of Bussol’ Strait, where negative anomalies persist into June–July (Figures 14b and 14c). The strong cold anomaly ($\theta < -0.4^\circ\text{C}$) remains near the Sakhalin coast because of DSW outflow from the northern shelves in June–July (not shown). Beginning in August, warm anomalies rapidly develop in the OSMW (Figure 14d). A large positive anomaly ($\theta > 0.2^\circ\text{C}$) grows along the entire Sakhalin slope indicating that transport of the MDSW to the deep sea dramatically reduces. This anomaly persists into September–November (Figures 14e and 14f). For the same period, the large positive anomaly quickly grows near Bussol’ Strait, occupying about half of the Kuril Basin in September.

[52] In summary, there are two well-distinguished seasons in the OSMW. The cold season occurs between April and July, when the MDSW produces large cold anomalies in the western Okhotsk Sea. Cold anomalies also occur in the eastern Okhotsk between April and July, indicating relatively weak inflow of the MNPW to the Okhotsk Sea. The warm season occurs between August and November, when the DSW flux from the shelves strongly decreases and water exchange between the Okhotsk Sea and North Pacific intensifies.

[53] Seasonal variability of the thermohaline structure through the entire OSMW in the ESC and Bussol’ Strait is shown in Figure 15, using data averaged within areas ESC

Table 4. May–June (V_{SP}) and September–October (V_F) Volumes of the Dense Shelf Water (DSW), Their Average Thickness (H), and Summer–Fall Removal Rate (U) on the Okhotsk Sea Northern Shelves

σ_θ	$V_{SP}, \text{km}^3 \times 10^3$	$V_F, \text{km}^3 \times 10^3$	H, m	U, Sv
>26.7	5.2 ± 0.3	3.2 ± 0.2	57 ± 29	0.19 ± 0.08
>26.8	1.4 ± 0.1	0.4 ± 0.1	41 ± 22	0.1 ± 0.04
>26.9	0.24 ± 0.02	...	29 ± 16	0.02 ± 0.01

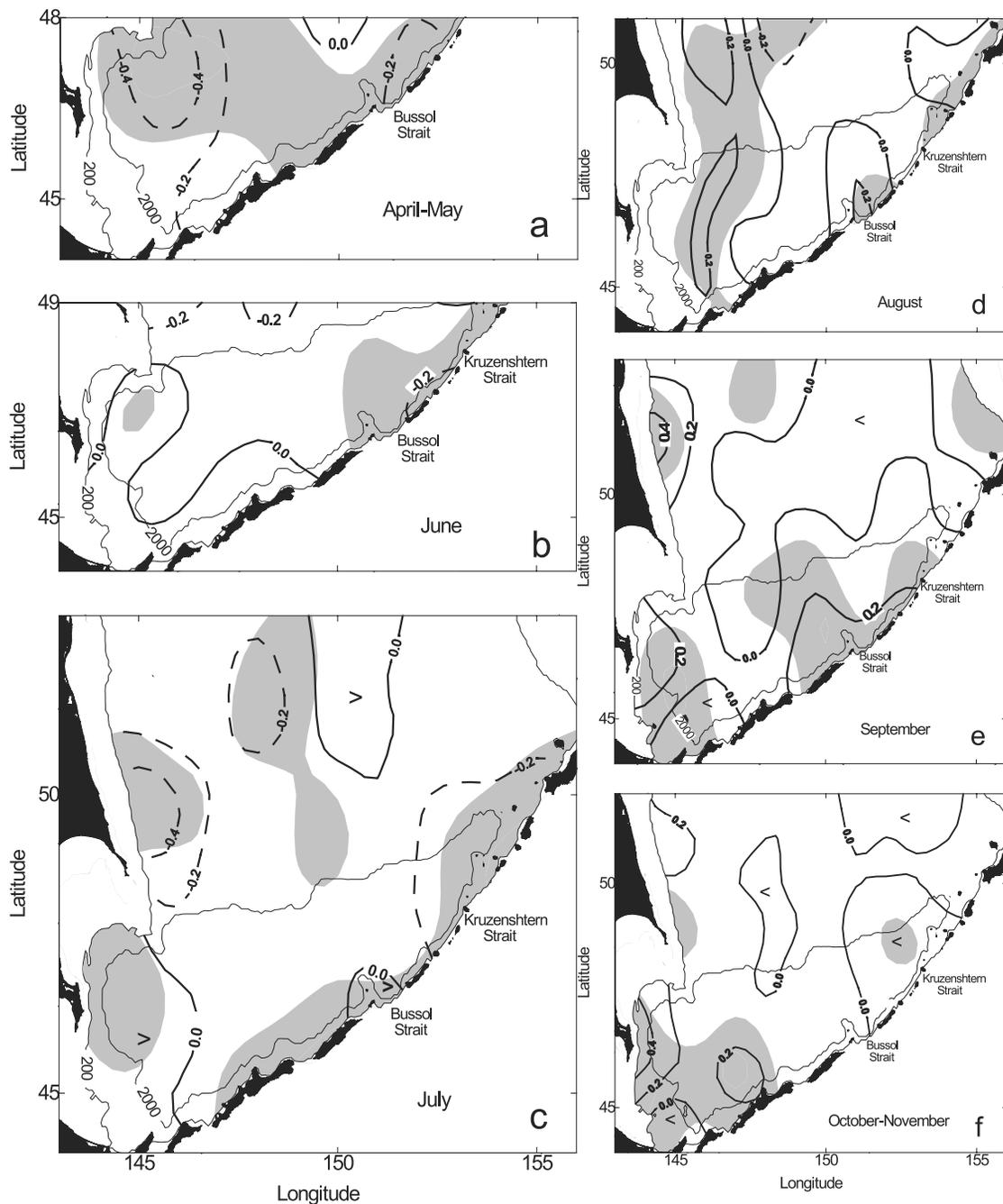


Figure 14. Averaged potential temperature anomalies relative to the annual mean in the deep Okhotsk Sea at $26.9 \sigma_{\theta}$ in (a) April–May, (b) June, (c) July, (d) August, (e) September, and (f) October–November. Shading indicates the statistically significant (95%) anomalies. Solid contours are positive anomalies, and dashed contours are negative anomalies. Contour intervals are 0.2°C .

and BS, encompassed by dashed lines in Figure 1. April–May and August–September were selected as representative months. Within the OSMW ($\sigma_{\theta} = 26.7\text{--}27.0$) the coldest temperature occurs in April–May because of intensive DSW injection from the shelves (Figure 15). The temperature then gradually increases until September, when the largest amount of the MNPW enters the Okhotsk Sea (Figure 15b). It appears that the variations of temperature below the OSMW layer ($\sigma_{\theta} = 27.1\text{--}27.4$) are also related to the North Pacific inflow. This result is consistent

with observations of *Wakatsuchi and Martin* [1991], although we propose a different reason for the variability of this denser water, which is sometimes referred to as lower Okhotsk Intermediate Water. We average gridded values of temperature and salinity south of 49°N (37 gridded points) to estimate the seasonal variability of OSMW in the Kuril Basin. The average seasonal fluctuations in the OSMW are largest at $26.7 \sigma_{\theta}$, with a range of about 0.7°C , and apparently penetrating to $\sigma_{\theta} = 27.0$ (about 500 m depth), with a range of about 0.2°C (Figure 15a). The former is

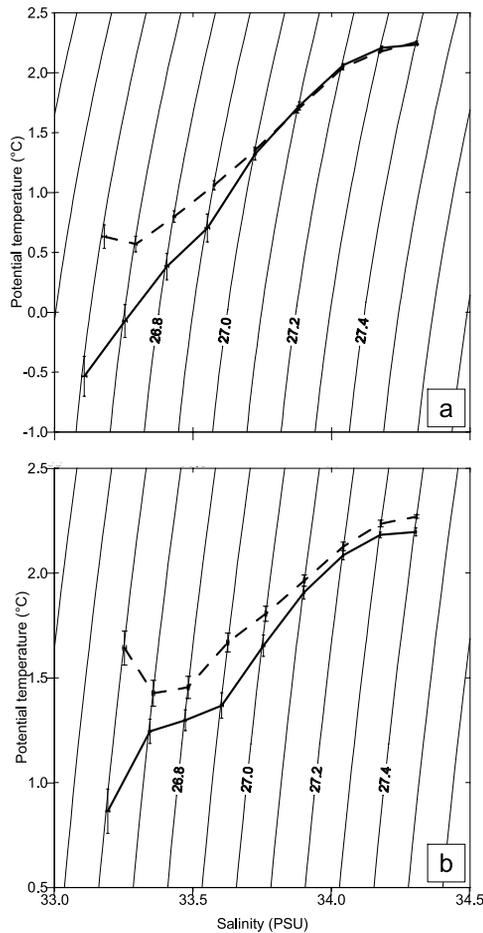


Figure 15. Average potential temperature/salinity curves for (a) ESC and (b) BS. Both regions are encompassed by dashed lines in Figure 1. April–May (solid) and August–September (dashed) curves show the seasonal variations in the region of the East Sakhalin Current and near Bussol’ Strait based on the historical data. Vertical and horizontal bars represent the standard deviation about the means of temperature and salinity, respectively.

significantly different from zero at the 95% confidence level. In contrast to temperature, the average seasonal fluctuations in salinity on isopycnals are quite small south of 49°N with small standard deviation (Figure 15). Within the OSMW ($26.7\sigma_{\theta}$), the maximum annual salinity range is 0.05 psu, but at $27.0\sigma_{\theta}$, the range is only 0.01 psu or less than the accuracy of the salinity measurements.

5.3. Seasonal Cycle of Okhotsk Sea Mode Water in the Kuril Basin

[54] The average temperature of the OSMW in the Kuril Basin increases from May to September and then is unchanged through December (Figure 16). (Only the *Prof. Levaniidov* 1995 cruise is used for December.) The latter means that a relatively weak DSW flux of about 0.1–0.2 Sv from the northern shelves (Table 4) might be equilibrated by the NPW inflow in the fall. This situation might continue until February, when the convective DCW would begin to decrease the temperature of the OSMW. The temperature

would continue to drop until May because of growing DSW flux from the Sakhalin and Terpeniya Bay polynyas and further from the northern shelves. This hypothesis is sketched in Figure 16.

[55] To describe the OSMW seasonal cycle in the Kuril Basin we use a simple box model for the $26.7\text{--}27.0\sigma_{\theta}$ layer. We limit our calculation to south of 49°N because of the scarcity of data to the north due to ice cover in spring. However, this limitation is not important because most DSW descending from the shelves eventually flows to the Kuril Basin south of this latitude. Temperature in the OSMW is governed by

$$V \frac{\partial T}{\partial t} = q_1 T_1 + q_2 T_2 - (q_1 + q_2) T_3, \quad (2)$$

where V is the OSMW volume south of 49°N , q_1 is the DCW/DSW volume transport, including convective DCW in the Kuril Basin (only for *Case III* below) and the DSW from the Sakhalin and northern shelves, q_2 is the NPW volume transport, T_1 is the freezing temperature of the DCW in the Kuril Basin and the DSW from the shelves, T_2 is the average temperature of the NPW for $26.7\text{--}27.0\sigma_{\theta}$, T_3 is the average temperature of the OSMW, $\frac{\partial T}{\partial t}$ is the OSMW temperature fluctuation, and $q_1 + q_2$ is the OSMW production rate. We assume linear increase (decrease) of temperature in the OSMW in summer (in late winter and spring). We do not use salinity because its summer increase in the OSMW is only 0.03 psu or just slightly exceeding the salinity accuracy. From the data, $T_1 = -1.7 \pm 0.06^{\circ}\text{C}$, $T_2 = 2.93 \pm 0.55^{\circ}\text{C}$, and $T_3 = 0.99 \pm 0.17^{\circ}\text{C}$. The volume of the OSMW south of 49°N is $9.5 \pm 0.5 \times 10^4 \text{ km}^3$, based on the depths of $26.7\text{--}27.0\sigma_{\theta}$ isopycnal surfaces and ETOP05 topography.

[56] *Case I: Summer.* From June to September (about 120 days) the average temperature of OSMW increases by 0.37°C from $0.75 \pm 0.24^{\circ}\text{C}$ to $1.12 \pm 0.21^{\circ}\text{C}$ (Figure 16). Since most of Sakhalin DSW leaves the shelf before May–June (Figure 7), q_1 is defined to a large degree by the summer flux of DSW from the northern shelves (Table 4). Hence the only unknown parameter in (2) is q_2 . Solving (2)

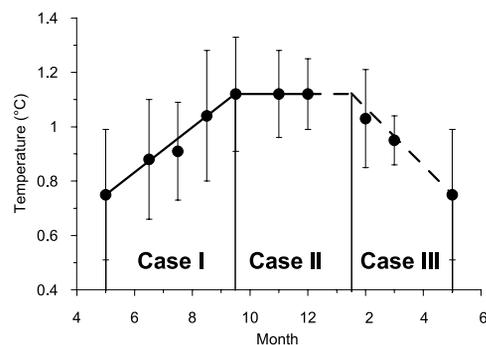


Figure 16. Monthly average potential temperature of OSMW in the Kuril Basin ($26.7\text{--}27.0\sigma_{\theta}$, south of 49°N) based on the gridded historical data. Vertical bars are the standard deviation of the mean. The solid curve is a linear fit to temperature between May and December. The dashed curve is hypothesized behavior of temperature between December and May.

Table 5. Estimated February–May DSW Volume Transport (q_{DSW}) for Given North Pacific Inflow (q_2) in the OSMW Density Range

q_2	q_{DSW} , Sv
0.1	1.4 ± 1.3
0.3	1.6 ± 1.4
0.5	1.7 ± 1.5
0.7	1.9 ± 1.7
0.9	2.0 ± 1.8
1.0	2.1 ± 1.9

yields $q_2 = 2.0 \pm 1.6$ Sv. The known errors in this estimate include temperature uncertainty estimated from standard deviations, a large error from $\frac{\partial T}{\partial t}$, the q_1 uncertainty given in Table 4, and the error associated with the OSMW volume calculation. Our estimate of summer OSMW production rate is 2.2 ± 1.7 Sv.

[57] *Case II: Winter.* Temperature does not change between September and December, so $V\frac{\partial T}{\partial t} = 0$. The solution of (2) thus is $\frac{q_1}{q_2} = 0.7$. Assuming that q_1 drops from 0.2 Sv in October to almost zero in November–December, because it mixes by winter convection, and there is no new DSW formation on the shelves, we take $q_1 = 0.1$ Sv. This yields $q_2 \sim 0.1 \pm 0.1$ Sv. Thus fall–winter OSMW production ($q_1 + q_2$) is estimated as 0.2 ± 0.1 Sv or much less than in summer.

[58] *Case III: Spring.* The average temperature of OSMW decreases between February and May (Figure 16), compensating its summer increase. To account for the Forerunner SW contribution between March and May [Takizawa, 1982; Watanabe and Wakatsuchi, 1998] to seasonal transformation of the OSMW, we rewrite (2) as

$$V \frac{\partial T}{\partial t} = q_1 T_1 + q_2 T_2 + q_3 T_4 - (q_1 + q_2 + q_3) T_3, \quad (3)$$

where q_3 is the Forerunner SW volume transport and T_4 is the average temperature of Forerunner SW in 26.7 – 27.0 σ_θ . We take $T_4 = 3.94 \pm 0.53^\circ\text{C}$ from our data and $q_3 = 0.2$ Sv following Watanabe and Wakatsuchi [1998]. Now there are also two unknown parameters q_1 and q_2 , which cannot be derived from our data. Our principal interest is to estimate the spring DSW production rate, which would cause the hypothesized OSMW cooling. Assuming that the spring NPW flux q_2 is the same as winter (*Case II*), the solution for q_1 is 1.5 ± 1.2 Sv. Separating the DSW from the Kuril Basin DCW, using oxygen and silicate properties, gives for the former 1.4 ± 1.1 Sv, which is greater than the 0.8 ± 0.3 Sv estimate of Gladyshev *et al.* [2000] for spring–summer 1997, for the NWS only. Given q_1 , q_2 , and q_3 , the spring OSMW production rate is 1.8 ± 1.3 Sv. We also solve the equation for different NPW flux values (Table 5), where 0.1 Sv is subtracted from q_1 to exclude the Kuril Basin DCW contribution. Increasing the spring NPW flux up to 0.5 (1.0) Sv requires a corresponding increase in the DSW production up to 1.7 (2.1) Sv. These values might overestimate the spring DSW production rate on the Okhotsk Sea shelves.

[59] Taking 1.4 Sv as a suitable value for the spring DSW production, an annual average DSW flux and OSMW production are estimated as well as a residence time of the OSMW in the Kuril Basin. Averaging the results for the

Cases I–III, the annual average DSW flux from the shelves is 0.6 ± 0.6 Sv, while the annual average OSMW production in the Kuril Basin is 1.4 ± 1.2 Sv. The latter is comparable to the 1.0 ± 0.2 Sv of Gladyshev *et al.* [2000] for 26.7 – 26.9 σ_θ , and to the 2.0 ± 1.5 Sv of Yasuda [1997] for low potential vorticity Oyashio water. However, it is less than the 3.3 Sv of Wong *et al.* [1998].

[60] The residence time of the OSMW in the Kuril Basin is defined as

$$\tau = \frac{V}{F_{OSMW}}, \quad (4)$$

where τ is the residence time, V is the OSMW volume as in (2), and F_{OSMW} is the annual average OSMW production rate in the Kuril Basin. This yields a residence time of 2 ± 1.7 years. This is consistent with the 1.4 year estimate of Wong *et al.* [1998] based on CFC data for $\sigma_\theta < 27.0$. It differs considerably from the 4–14 years of Gladyshev *et al.* [2000]. The latter did not include the contribution of Sakhalin DSW or of Kuril Basin DCW, although they overestimated the contribution of Shelikhov DSW. In addition, DSW outflow from the NWS starts at least at the beginning of March, not in April as was expected by Gladyshev *et al.* [2000]. Rapid winter–spring outflow from the shelves may be due to entrainment of newly formed DSW in polynyas, which forces the DSW formed earlier to flow faster. Shapiro and Hill [1997] have shown that entrainment is able to accelerate the DSW spreading on the shelves by a factor of 2.

6. Conclusion

[61] Using Russian historical data and recently completed CTD surveys from the Okhotsk Sea, the formation and subsequent expansion of dense shelf water that forms in coastal polynyas during winter has been described and the potential for open water deep convection has been evaluated. In spring, most of the dense shelf water drains rapidly from the northwestern and Sakhalin shelves to the deeper sea and is transported by the East Sakhalin Current to the Kuril Basin. It was shown that Shelikhov Bay is not an important site of OSMW ventilation, likely because of vigorous tidal mixing. It is also shown that the DSW descending from the northern shelves occurs most of the year. Winter transformation of the Soya Water can produce a convected water with density greater than 26.7 σ_θ in the southeastern Kuril Basin, providing another, minor contribution to OSMW transformation. This cold input as well as water exchange with the North Pacific leads to large seasonal fluctuations of temperature in the OSMW ($\sigma_\theta = 26.7$ – 27.0), while the seasonal salinity changes are significantly smaller.

[62] Using the observed seasonal variations in temperature in the Kuril Basin and applying a simple isopycnal box model, the summer OSMW production rate is estimated to be 2.2 ± 1.7 Sv. The OSMW production rate decreases considerably to about 0.2 ± 0.1 Sv in winter. Assuming that temperature of the OSMW decreases from February through May to compensate its summer increase, we estimate that at least 1.4 ± 1.2 Sv of total DSW volume transport is necessary to provide these changes. The summer DSW

volume transport is about 0.2 ± 0.1 Sv. The residence time of the OSMW in the Kuril Basin is 2 ± 1.7 years. This estimate is consistent with Wong *et al.* [1998] but significantly shorter than that of Gladyshev *et al.* [2000] for $26.8 - 26.9 \sigma_\theta$.

[63] Winter observations on the Sakhalin shelf and early spring measurements along the southern Kuril Islands would be very useful for better estimating the Sakhalin DSW production and to better quantify the contribution of winter convection. Monitoring properties and currents in the neck of Shelikhov Bay is also desirable. Because tidal mixing is crucial for Okhotsk Mode Water formation, it should be included in theoretical models.

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