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Warming of Intermediate Water in the Sea of Okhotsk since the 1950s

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Okhotsk Sea Intermediate Water (OSIW), the source water for ventilation of North Pacific Intermediate Water, exhibits a multidecadal warming trend. Historical data show that OSIW temperatures increased by 0.28, 0.57, 0.31 and 0.10°C during 1955 to 2003 at potential densities of 26.8, 27.0, 27.2 and 27.4σ_θ, at depths of approximately 250, 500, 700 and 900 m, respectively. This rate of warming is much faster than that of the global ocean. This OSIW warming is likely linked to the reduced ventilation of cold Dense Shelf Water associated with brine rejection during sea ice formation.

Keywords:
· Warming,
· intermediate water,
· Okhotsk Sea.

1. Introduction

In the northern hemisphere, the Sea of Okhotsk is the southernmost sea with significant seasonal ice cover. Over the northwest shelf, offshore winds associated with the Siberian high are dominant during winter, bringing cold continental air in contact with the sea. This results in a very active coastal polynya domain and large sea ice production (Martin *et al*., 1998). Surface cooling and brine rejection in the coastal polynyas leads to rapid water mass transformation, with surface densities increasing to 27.05σ_θ as cold Dense Shelf Water (DSW) (Kitani, 1973; Shcherbina *et al*., 2003). DSW is transported southward along the Sakhalin coast by the East Sakhalin Current (Mizuta *et al*., 2003; Ohshima *et al*., 2004), then brought into the Kuril Basin where it mixes with Western Subarctic Water originating from the North Pacific. This mixing, together with the vertical mixing around the Kuril Straits (Wong *et al*., 1998; Yamamoto *et al*., 2002), forms Okhotsk Sea Intermediate Water (OSIW), the coldest, freshest and most oxygen-rich water in the North Pacific in the density range of 26.8–27.4σ_θ (Talley, 1991; Yasuda, 1997). Maps of winter surface density in the North Pacific show that densities greater than 26.8σ_θ do not outcrop in the open North Pacific (Reid, 1965), so discharge of OSIW through the Kuril Strait is believed to be the only ventilated source water for North Pacific Intermediate Water (NPIW) (Talley, 1991; Yasuda, 1997).

Recent examinations of global ocean temperatures have shown substantial warming in the upper 1000 m (Levitus *et al*., 2000), and this warming is likely due to the increase of greenhouse gases in the earth's atmosphere (Levitus *et al*., 2001). Levitus *et al*. (2005) found that the largest changes occurred in the upper 700 m, averaging about 0.1°C between 1955 and 2003. Warming of the North Pacific also averaged about 0.08°C over the same period of time (see table A1 in the auxiliary material of Levitus *et al*., 2005). With regard to the Sea of Okhotsk, Hill *et al*. (2003) compared hydrographic data from 1949 to 1952 with data from 1993 and inferred a basin-wide warming between 0.1 and 0.3°C and a freshening between 0.05 and 0.10 psu of OSIW at a depth of 500 m, which corresponds to a density of approximately 27.0σ_θ. However, OSIW also shows a large bidecadal oscillation in temperature that is explained by changes in the vertical mixing near Kuril Strait forced by diurnal tides, as noted by Osafune and Yasuda (2006). In view of this oscillation, it is not clear whether the warming suggested by Hill *et al*. (2003) is a long-term warming trend or a part of the decadal oscillation. We focus here on evidence for interannual to decadal variability, and especially for long-term trends in OSIW properties.

2. Data

The base set of temperature and salinity profiles comes from the CD-ROM of World Ocean Data Base (WOD1998) (Levitus *et al*., 1998). We included data collected by R/V Oyashio Maru of Hokkaido University from 1969 to 1976. Intensive CTD/hydrographic and profiling float observations, which were carried out as a part of the

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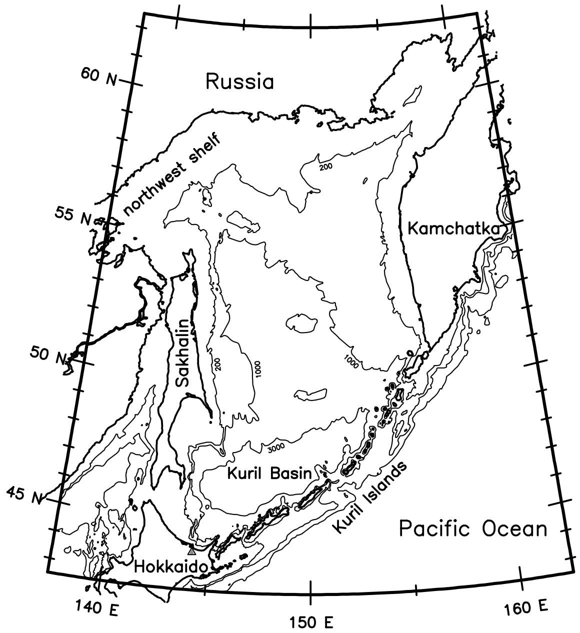

Fig. 1. Bottom topography of the Okhotsk Sea from General Bathymetric Chart of the Oceans (GEBCO). The location of Abashiri is marked by a solid triangle.

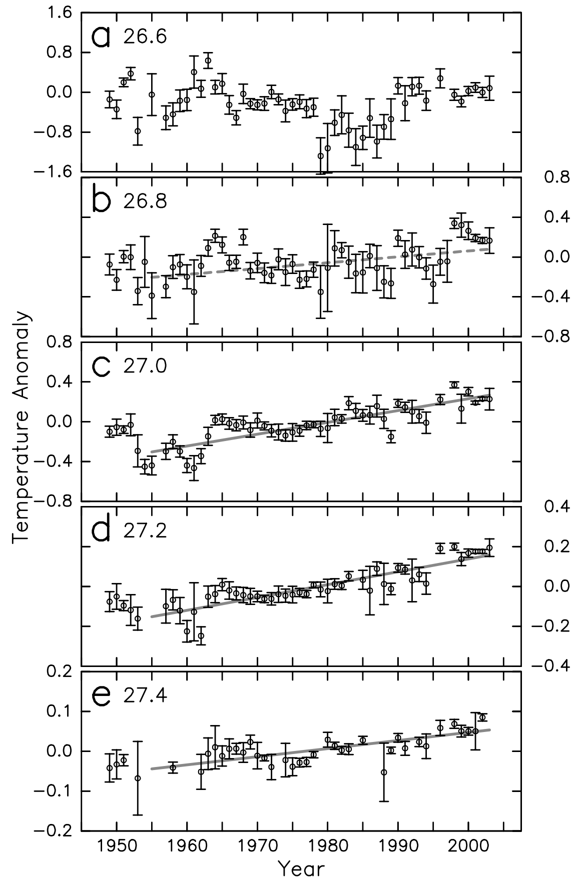

Fig. 2. Time series of anomaly in potential temperature of dichothermal water (a) $26.6\sigma_\theta$, and Okhotsk Sea Intermediate Water (OSIW) at densities of (b) $26.8\sigma_\theta$, (c) $27.0\sigma_\theta$, (d) $27.2\sigma_\theta$ and (e) $27.4\sigma_\theta$ from 1945 to 2003. Circles are one-year averaged anomaly data. Anomaly data in the basin having depths greater than 1000 m were averaged. Error bars show the 95% confidence interval for the averages using the t-distribution. Lines are linear regression lines for the period of 50 years from 1955 to 2003. Error of warming trend shows the 95% confidence interval for the linear trend using the t-distribution. Linear warming trends are (b) $\Delta T = 0.0059 \pm 0.0058$°C/yr, (c) $\Delta T = 0.0119 \pm 0.0037$°C/yr, (d) $\Delta T = 0.0065 \pm 0.0017$°C/yr, (e) $\Delta T = 0.0020 \pm 0.0009$°C/yr, respectively.

international Japan-Russia-United States study of the Sea of Okhotsk from 1998 to 2003, were also included, which enabled us to examine the variability in recent years. The resulting data set is 30% larger than that extracted from WOD1998. In total there are approximately 2200 points from 1945 to 2003.

To construct a gridded climatological data set on nine selected isopycnals (26.6, 26.7, 26.8, 26.9, 27.0, 27.1, 27.2, 27.3, 27.4σ_θ), an objective analysis procedure similar to that used by Itoh *et al.* (2003) was applied. We made a data grid to represent annual average climatology using all observations, but note that only 10% were acquired in the months January through April. We argue that seasonal variations are small even at the lower densities because outcropping is short-lived and occurs over a limited area. Isopycnal surfaces less than 26.7σ_θ outcrop in the western half of the Okhotsk Sea only in winter (Itoh *et al.*, 2003). This cold layer near 0°C temperature between 26.6 and 26.7σ_θ is remnant of winter convection and is called the "dichothermal layer" (Kitani, 1973). The outcropping of deeper water in the density range 26.8–27.4σ_θ (OSIW in this study) is even more limited, occurring only over the northwestern shelf and only for a period of less than three months.

A grid spacing of 20 km and an e-folding scale of 75 km were taken in the domain bounded by 135–165°E and 43–63°N (Fig. 1). The temperature anomaly for each observation was defined as the difference between the observed value and the climatological mean at the grid point which includes the observational point. We then averaged all the anomaly data in a year to calculate one-year averaged anomaly data. For the calculation of one-year averaged anomaly data, we have excluded data from the shelf and shelf slope regions having depths shallower than 1000 m, where seasonal and spatial variations are very large. If the number of observations in a year was less than five, we omitted that year. Observational stations were widely distributed in the Okhotsk Sea, except for the latter half of the 1980s, when observations were limited to the south-

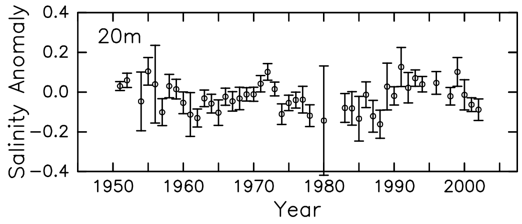

Fig. 3. Time series of anomaly in sea surface salinity (20 m) during summer and fall seasons (July–Dec.) in the Okhotsk Sea from 1945 to 2003. Circles are one-year averaged anomaly data. Error bars show the 95% confidence interval for the averages using the t-distribution.

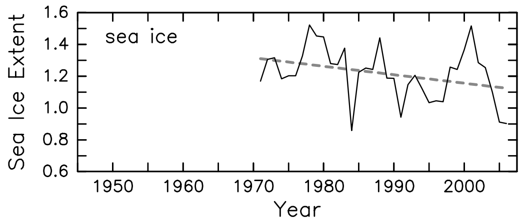

Fig. 4. Time series of maximum sea ice extent (unit in 1000 km^3) in the Okhotsk Sea for the period 1971 to 2006, derived from Japan Meteorological Agency (JMA) data. Lines are linear regression line. The area of the Okhotsk Sea is 16000 km^3.

western Okhotsk Sea off Hokkaido.

Monthly mean averages on depth surfaces (0, 10, 20, 30, 50 m) were also determined to examine the variability of salinity in the Okhotsk Sea. The same objective analysis and grid spacing were used as for the isopycnal climatology described above. The salinity anomaly for each observation was defined as the difference between the observed value and the monthly mean at the grid point which includes the observational point. We then averaged all the anomaly data from the summer and fall (July to December). If the number of observations in a year was less than ten, we omitted that year.

3. Long Term Warming Trend of Okhotsk Sea Intermediate Water

Figures 2(a), (b), (c), (d) and (e) show the time series of potential temperatures in the Okhotsk Sea for the roughly 60-year period from 1945 to 2003 on densities of 26.6, 26.8, 27.0, 27.2 and 27.4σ_θ. The lines in Figs. 2(b), (c), (d) and (e) are linear regressions between 1955 and 2003.

At 26.6σ_θ, the dichothermal water temperature shows large decadal variability, but with no significant trend. At 26.8σ_θ, OSIW temperature shows a decadal variability superimposed on the longer-term warming trend ($\Delta T = 0.0059 \pm 0.0058$°C/yr). The warming trend at this density level is less evident than at the denser potential density levels. At 27.0σ_θ, the OSIW temperature shows a larger long-term warming trend ($\Delta T = 0.0119 \pm 0.0037$ °C/yr), but with a weaker decadal variability than at 26.8σ_θ. At 27.2σ_θ, the long-term warming trend ($\Delta T = 0.0065 \pm 0.0017$°C/yr) is significant although smaller by half than at 27.0σ_θ. At 27.4σ_θ, the warming trend ($\Delta T = 0.0020 \pm 0.0009$°C/yr) is still significant although the value is small.

The historical data clearly indicate that OSIW has warmed from 1955 to the present. From the regression analysis, the increased value of the OSIW temperature between 1955 and 2003 is 0.28, 0.57, 0.31, and 0.10°C at 26.8, 27.0, 27.2, and 27.4σ_θ, respectively. OSIW salinity at the potential density surface has increased to compensate the OSIW warming. The increased value of the OSIW salinity over the same time period is 0.021, 0.048, 0.032 and 0.020 psu at 26.8, 27.0, 27.2, and 27.4σ_θ, respectively. The OSIW salinity trends are small because potential density is mainly controlled by the salinity value in the temperature range of OSIW.

In the East Kamchatka Current region of the North Pacific, from which upstream water flows into the Okhotsk Sea, the warming trend at 27.0σ_θ is about $\Delta T =$ 0.003°C/yr (Osafune and Yasuda, 2006), much smaller than that observed at the same density level in the Okhotsk Sea. The warming from 26.8 to 27.2σ_θ (about from 250 to 700 m) averages about 0.4°C in the Okhotsk Sea between 1955 and 2003 and is nearly five times the North Pacific trend and four times the world ocean trend for the upper 700 m of the ocean over the same time period, reported in Levitus *et al.* (2005). Thus the mid-depth Okhotsk Sea has warmed more rapidly than the global ocean as a whole.

The cold property of OSIW comes from newly ventilated DSW from the northwest Okhotsk shelf (Kitani, 1973) and vertical mixing with the dichothemal water and DSW around the Kuril Straits (Yamamoto *et al.*, 2002). Because dichothermal water has no significant temperature trend and the OSIW warming trend is concentrated within density levels 26.8 to 27.4σ_θ, it implies the warming is caused by the reduced ventilation of cold DSW. We note that Osafune and Yasuda (2006) found bidecadal oscillations in OSIW and suggested that this can be explained by changes in the vertical mixing near Kuril Strait forced by diurnal tides whose amplitudes are modulated by the 18.6-year nodal cycle. However, the long-term warming trend is not likely to be caused by the change in the strength of vertical mixing, which has no linear trend.

What are the oceanographic consequences of intermediate waters warming in the Okhotsk Sea? A decrease in oxygen concentration of NPIW since the 1970s has been identified in the Oyashio region, downstream of the Okhotsk Sea, suggesting a weakening of the overturning down to the intermediate layer (Ono *et al.*, 2001; Watanabe *et al.*, 2001). Ono *et al.* (2001) suggested that the warming trend in waters averaging from 26.7 to 27.2σ_θ is about $\Delta T = 0.007 \pm 0.004$°C/yr in this region. Watanabe *et al.* (2003) suggested that warming in NPIW from 26.8 to 27.4σ_θ is about $\Delta T = 0.005$°C/yr between 1968 and 1998. If the warming trend of OSIW occurs through the reduction of DSW production, this implies the weakening of overturning in the Okhotsk Sea. Given the fact that the Okhotsk Sea is the ventilation source of NPIW, this would further result in weakening of the NPIW overturning. In this way, variability of OSIW could be a key factor governing the variability of the intermediate water of the North Pacific.

4. Discussion

What could have caused the reduced ventilation of DSW in the Okhotsk Sea during the past 50 years? The changes in salt input, i.e. sea ice formation in the northwest shelf (Alflutis and Martin, 1987) and changes in sea surface salinity, i.e. preconditioning of DSW formation (Nakamura *et al.*, 2004), could potentially influence the volume of DSW production. Sea surface salinity in the Okhotsk Sea shows large decadal variability, but no trend, as shown in Fig. 3, but there may have been a reduction of sea ice formation in the Okhotsk Sea over the last 50 years.

Sea ice extent in the Okhotsk Sea shows large interannual variability (Cavalieri and Parkinson, 1987). Although the volume of sea ice cannot be estimated due to the lack of ice thickness observations, it is expected that sea ice production also undergoes large interannual variability. Due to relatively longer residence time of OSIW, estimated to be between 1.4 years (Wong *et al.*, 1998), 7 years (Itoh *et al.*, 2003) and 14 years (Gladyshev *et al.*, 2000), OSIW would be affected by the averaged variability of sea ice for several years. Parkinson *et al.* (1999) have reported a decreasing in winter sea ice extent in the Okhotsk Sea between 1978 and 1996, based on satellite observation. We have now analyzed a longer time record (1971 to 2006) and also find a decreasing trend, but this is not statistically significant (90% level), because year-to-year variability is large (Fig. 4).

Before the era of satellite observations, quantitative information of sea ice extent in the Okhotsk Sea did not exist. Ship and aircraft observations by the Japan Coast Guard showed that in the years 1935, 1936, 1938, 1939 and 1940, 78%, 70%, 87%, 87% and 78% of the Okhotsk Sea was covered by sea ice in February, respectively (Kurashina *et al.*, 1967). These estimates of sea ice extent are comparable to the larger estimates in the era of satellite observations. Aota *et al.* (1993) and Aota (1999) examined the time series of the annual accumulated ice amount from visual ice observation at Abashiri, located on the coast of Hokkaido, and suggested that sea ice cover here has decreased during the past half century or more. Collectively, although the data are limited, they allow us to infer that sea ice extent over the whole Okhotsk Sea has also decreased over the past 50 years or more. If this is the case, then the apparent warming of OSIW over the past 50 years may possibly be caused by the reduction of DSW production owing to the decrease of sea ice formation.

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