

Changes in the Sea of Okhotsk due to global warming – Weakening pump function to the North Pacific

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Introduction

It is known that North Pacific Intermediate Water (NPIW), characterized by a salinity minimum at $26.8\sigma_\theta$, is a major water mass at the intermediate level of the North Pacific (*e.g.*, Reid, 1965). Figure 1 shows the distribution of potential temperature and oxygen content on the $27.0\sigma_\theta$ isopycnal surface in the North Pacific. Cold, high oxygen water seems to originate from the Sea of Okhotsk. High chlorofluorocarbon concentrations (Warner *et al.*, 1996) also originate from the Sea of Okhotsk. These distributions suggest that the ventilation source of intermediate water in the North Pacific, including NPIW, is the Sea of Okhotsk. Since large amounts of sea ice are formed in the Sea of Okhotsk, the densest water in the North Pacific (or to be exact, the densest water on the surface of the North Pacific) is produced there. Sinking of this dense water creates an overturning down to the intermediate depths in the North Pacific. The Okhotsk thus plays a role as the pump of the North Pacific.

Figure 2 shows the annual mean cumulative sea ice production calculated from microwave ice information and heat budget (Ohshima *et al.*, 2003). The northwestern shelf is found to be the far highest ice production region in the Sea of Okhotsk. Over the northwestern shelf, a large amount of sea ice is produced due to severe winds from northeastern Eurasia in winter. The sea ice production leads to the formation of cold, oxygen-rich dense shelf water (DSW) with densities of up to $27.0\sigma_\theta$ (Shcherbina *et al.*, 2003). The DSW is transported southward into the intermediate layer in the southern Okhotsk Sea, and is mixed with intermediate water coming from the North Pacific. This mixing forms the coldest, freshest and oxygen-richest water in the North Pacific in the density range of 26.8 – $27.4\sigma_\theta$ (Talley, 1991), which is called Okhotsk Sea Mode Water (Yasuda, 1997) or Okhotsk Sea Intermediate Water (OSIW) (Itoh *et al.*, 2003). The signal of OSIW

extends downward to $27.4\sigma_\theta$ owing to diapycnal mixing caused by strong tidal currents around the Kuril Straits (Wong *et al.*, 1998). The OSIW outflows to the North Pacific through the Kuril Straits and then mixes with East Kamchatka Current Water to form the Oyashio water. The Oyashio water reaches the confluence of the subtropical and subarctic gyres, and then part of the Oyashio water flows northeastward as the Subarctic Current (SAC), bounding the subarctic gyre on the south.

Warming and Oxygen Decrease Trend

The results of the analyses in this section are based on Nakanowatari *et al.* (2007). For the trend analyses, we have used all available data for

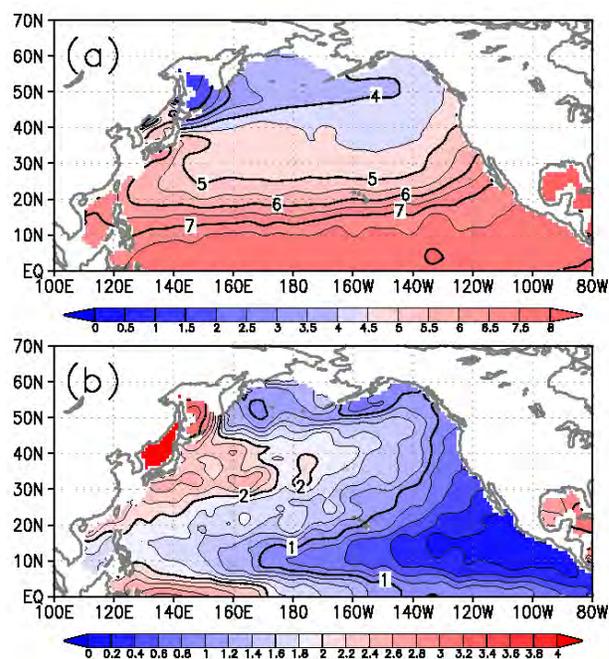


Fig. 1 Horizontal distribution of (a) potential temperature ($^{\circ}\text{C}$) and (b) dissolved oxygen content (ml/l) on the $27.0\sigma_\theta$ isopycnal surface in the North Pacific. These maps are based on World Ocean Atlas 1994 (Levitus *et al.*, 1994).

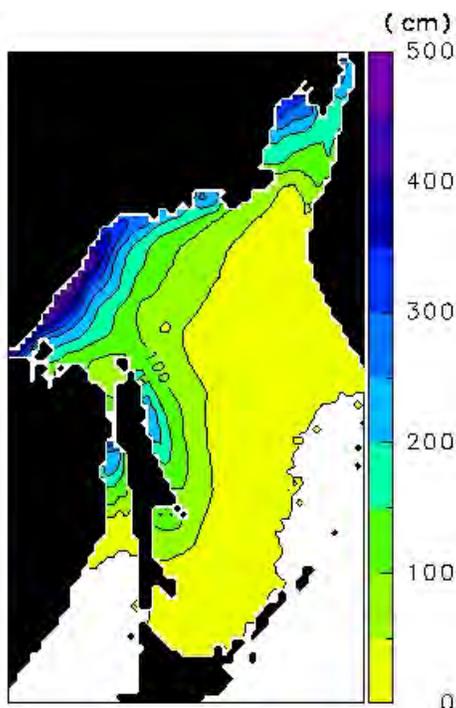


Fig. 2 Annual mean cumulative sea ice production, represented by the ice thickness (cm). Estimation is based on the sea ice information from the satellite microwave and heat budget calculation. After Ohshima *et al.* (2003).

temperature, salinity and dissolved oxygen, taken from the World Ocean Database (WOD01), observational data obtained by the Japan–Russia–

United States international joint study of the Sea of Okhotsk from 1998 to 2004, data archived by the Japan Oceanographic Data Center, and profiling float data obtained by the international Argo program from 2000 to 2004. After the quality control, a gridded dataset of potential temperature anomalies on isopycnal surfaces was then prepared for the period 1955–2004, and one of dissolved oxygen for the period 1960–2004.

Figure 3 shows linear trend maps of intermediate water temperature on the $27.0\sigma_\theta$ isopycnal surface for the past 50 years. Significant warming trends are observed in the northwestern North Pacific and the Sea of Okhotsk. The warming trend in these regions is most prominent at density $27.0\sigma_\theta$, and the largest warming area exists in the western part (47.5° – 55° N, 145° – 147.5° E) of the Sea of Okhotsk with an average of $0.68^\circ\text{C}/50\text{-yr}$. The warming trend at $27.0\sigma_\theta$ seems to extend along the pathway of the OSIW (see the acceleration potential at $27.0\sigma_\theta$, indicated by green contours in Figure 3). A significant warming trend is observed in the Oyashio and SAC regions, but not in the East Kamchatka Current region, *i.e.*, upstream of the Sea of Okhotsk. Since the intermediate water masses in the Oyashio and SAC regions are largely affected by the OSIW (Yasuda, 1997), these results indicate that the warming trend in the northwestern North Pacific may be caused by advection of warmed OSIW.

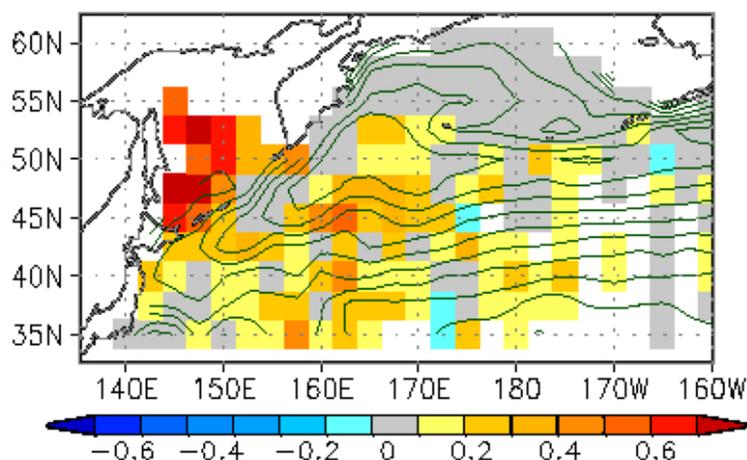


Fig. 3 Linear trends (colors in $^\circ\text{C}/50\text{-yr}$) of potential temperature anomalies at density $27.0\sigma_\theta$ (approximately 300–500 m deep) from 1955 to 2004 in the North Pacific. Green contours indicate acceleration potential at $27.0\sigma_\theta$ relative to 2000 dbar, derived from our dataset. Modified from Nakanowatari *et al.* (2007).

Figure 4 shows the time series of temperature and oxygen content anomalies at $27.0\sigma_\theta$, averaged over the Sea of Okhotsk. A positive and negative linear trend is the most significant feature for temperature and oxygen content, respectively. The temperature has increased by $0.62 \pm 0.18^\circ\text{C}$ (significant at a 99% confidence interval) during the past 50 years from 1955 through 2004. A similar result is obtained by Itoh (2007). The oxygen has decreased by 0.58 ± 0.34 ml/l (significant at a 95% confidence interval) for the past 45 years. The Oyashio and SAC regions also show a warming trend with the magnitude being about half of that for the Okhotsk and a decreasing trend for oxygen with a value less than that for the Okhotsk. The decreasing trend for oxygen in the Oyashio is consistent with Ono *et al.* (2001).

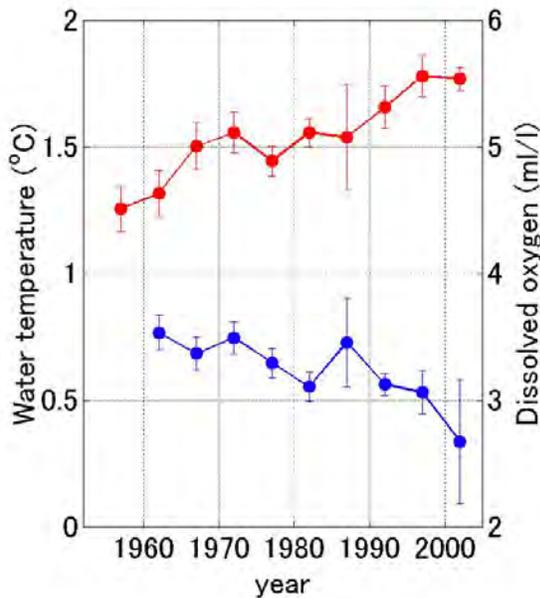


Fig. 4 Time series of potential temperature (red line) and dissolved oxygen content (blue line) of the intermediate water at $27.0\sigma_\theta$, averaged over the Sea of Okhotsk, during the past 50 years. Closed circles show a 5-yr average with errors at the 95% confidence interval for the averages.

It is shown that warming and oxygen-decreasing trends in the intermediate water are most prominent in the Sea of Okhotsk. Moreover, these trends appear to extend to the northwestern North Pacific along the pathway of the water mass originating from the Sea of Okhotsk. These facts suggest that the trends in the northwestern North Pacific are due to preceding changes of water-mass properties in the Sea of Okhotsk. Intermediate water in the Sea of Okhotsk retains its cold and oxygen-rich properties by mixing with dense shelf water (DSW) associated with sea ice

production in the coastal polynya of the northwestern shelf. The largest warming trend occurs in the western part of the Sea of Okhotsk (Fig. 3), to which DSW is transported from the northwestern shelf (Fukamachi *et al.*, 2004). Therefore, we suppose that the main cause of the warming and oxygen-decreasing trends is the weakening of DSW production.

Global Warming and the Sea of Okhotsk

DSW formation is caused by sea ice production. Thus we examine the change of the sea ice extent or production in the Sea of Okhotsk. Over the last three decades since accurate observation by satellite became possible, sea ice extent in the Sea of Okhotsk has decreased by approximately 150,000 km², corresponding to about 10% of the entire area of the Sea of Okhotsk (blue line in Fig. 5). It has been also revealed that yearly variability of sea ice extent in the Sea of Okhotsk is highly correlated with that of surface air temperatures in the upwind region of the Okhotsk (red line in Fig. 5). Of particular note is that this temperature has risen by approximately 2.0°C over the past 50 years ($2.0 \pm 1.4^\circ\text{C}/50\text{-yr}$, significant at a 99% confidence level). This value far exceeds the rate of average temperature increase worldwide (0.74°C over the past 100 years), thereby clearly indicating that the region is significantly affected by global warming. The correlation between this temperature and the sea ice extent ($r = -0.61$, significant at a 95% confidence level) suggests that decreases in the sea ice preceded the beginning of satellite observations.

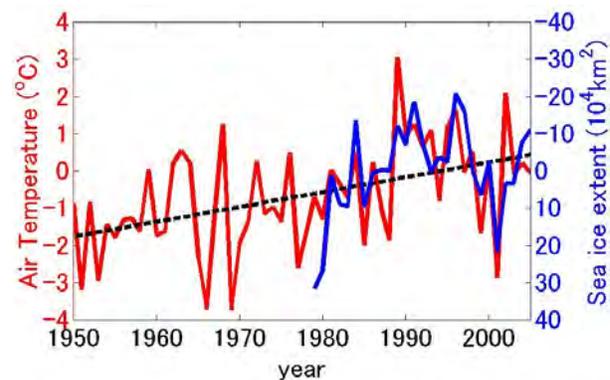


Fig. 5 Time series of sea ice extent anomaly in February (blue line) and surface air temperature anomaly in the upwind region ($50^\circ\text{--}65^\circ\text{N}$, $110^\circ\text{--}140^\circ\text{E}$) (red line) for the Sea of Okhotsk. Note that the scale of the sea ice extent is inverted (the axis on the right). Surface air temperatures are the mean values between October and March. Modified from Nakanowatari *et al.* (2007).

Although satellite measurements have been available only since the 1970s, visual observations at the Hokkaido coast, located on the southern boundary of sea ice extent in the Sea of Okhotsk, show the decreasing trend in the length of the sea ice season during the past 100 years (Aota, 1999). These trends of air temperature and sea ice season suggest that sea ice extent, accordingly sea ice production, has likely decreased during the past 50 years. During the current global warming, the surface air temperature anomaly in autumn and winter is particularly large over northeastern Eurasia (Serreze *et al.*, 2000). The DSW production area of the northwestern shelf in the Sea of Okhotsk is located where the winter monsoon from northeastern Eurasia directly transports cold air masses. Therefore, intermediate water in the Sea of Okhotsk, which is ventilated through DSW, may be sensitive to the global warming.

Possible Scenario

In a nutshell, the Sea of Okhotsk is highly sensitive to global warming: over the past 50 years, the level of sea ice production has decreased and the amount of dense water sinking has thus declined, thereby weakening the overturning in the North Pacific scale. To put it simply, the recent global warming has weakened the Sea of Okhotsk's workings as a pump.

Recent studies suggest that OSIW has a significant role in material circulation of the intermediate layer in the North Pacific. Hansell *et al.* (2002) indicated that dissolved organic carbons in NPIW originate from the Sea of Okhotsk. Nakatsuka *et al.* (2004)

showed that large amounts of dissolved and particulate organic carbons are exported from the highly productive northwestern shelf into the intermediate layer in the Sea of Okhotsk through the outflow of DSW. Moreover, recent observational data show that in the northwestern North Pacific, iron may come from the intermediate water of the Sea of Okhotsk (Nishioka *et al.*, 2007). Iron is an essential micronutrient for phytoplankton and is thus considered an important factor in determining biological productivity. It has been recently revealed that when dense shelf water sinks to the intermediate layer in the Sea of Okhotsk, iron is also brought to this layer. We hypothesize that this iron is also supplied to the western area of the North Pacific and supports high biological productivity there. If that is the case, it is also suggested that if global warming weakens sea ice production in the Sea of Okhotsk, iron supplies will decrease in the North Pacific as well as in the Sea of Okhotsk, thus reducing levels of biological productivity and fishery resources.

Figure 6 summarizes our proposal with schematics. Because the Sea of Okhotsk is an area sensitive to the current global warming, it has experienced a decrease in the production of sea ice and dense shelf water in the northwestern shelf during the past 50 years. This possibly causes a decrease in the supply of iron in the intermediate layer in the Sea of Okhotsk and further in the North Pacific. Finally, this might induce the decrease in primary biological production, fishery resources, and capacity of CO₂ absorption.

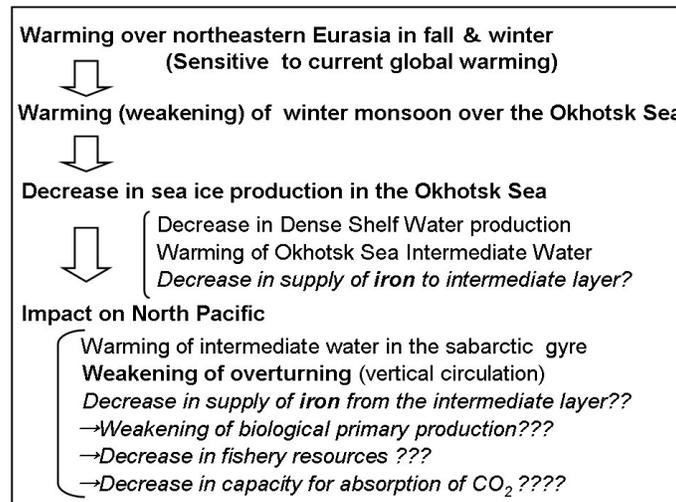


Fig. 6 Schematic showing the impact of the Sea of Okhotsk on the North Pacific through global warming. Bold letters indicate a fact evidenced by observations and analyses. Italic letters indicate a hypothesis. The larger the number of question marks indicates the larger the uncertainty.

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