DECREASE OF SEA ICE PRODUCTION IN THE OKHOTSK SEA CAUSES WEAKENING OF OVERTURNING IN THE NORTHWESTERN NORTH PACIFIC ?

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INTRODUCTION

It is known that North Pacific Intermediate Water (NPIW), characterized by a salinity minimum at 26.8σ_θ, 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 on the 27.0σ_θ isopycnal surface in the North Pacific. Cold water seems to originate from the Sea of Okhotsk. High oxygen content (Talley, 1991) and high CFC concentration (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.

Then where is the specific region of the ventilation in the Sea of Okhotsk? Figure 2 shows the distributions of potential temperature and oxygen content on the 26.8σ_θ isopycnal surface in and around the Sea of Okhotsk. Cold and high oxygen water appears to originate from the northwestern shelf region, suggesting that the ventilation occurs there. Figure 3 shows the annual mean cumulative sea ice production calculated from the 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

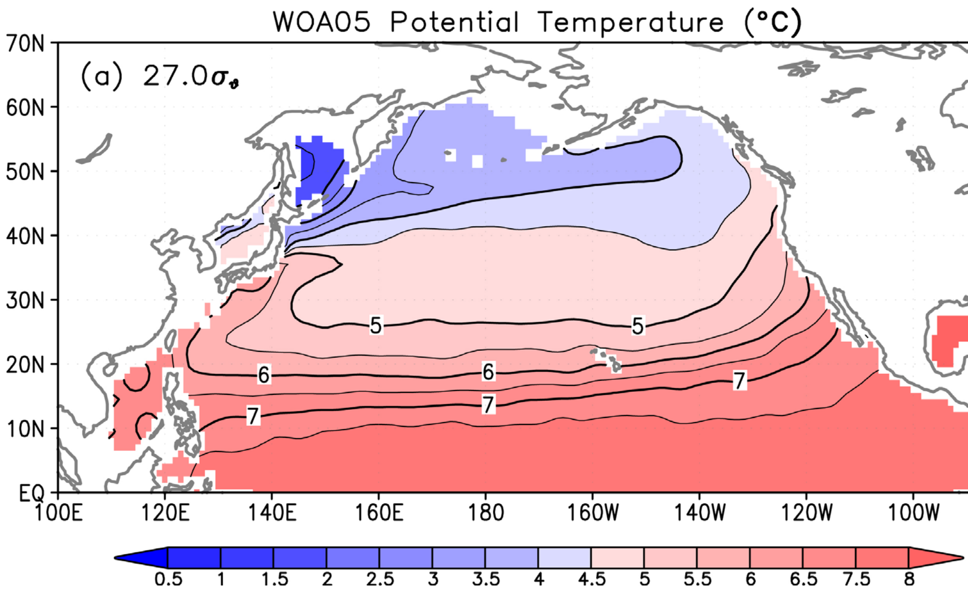


Figure 1: Horizontal distribution of potential temperature on the 27.0σ_θ isopycnal surface in the North Pacific.

sea ice is produced due to severe winds from northeastern Eurasia in winter. The sea ice production leads to production of cold, oxygen-rich dense shelf water (DSW) with densities of up to 27.0σ_θ (Shcherbina et al., 2003). The DSW is transported southward (Fig. 2) into the intermediate layer of the deep Okhotsk basin in the southern Okhotsk Sea, and 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 26.8-27.4σ_θ (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 27.4σ_θ 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, mainly Bussol' Strait (Talley, 1991), and then mixes with East Kamchatska Current Water, which flows southwestward along the northern Kuril Islands, forming the Oyashio water. The Oyashio water extends to the intermediate layer, flowing southwestward along the Kuril Island chain as the western boundary current of the subarctic gyre. 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.

In this study, through the trend analyses of temperature and oxygen in the intermediate water, we suggest that the weakening of ventilation (overturning) in the northwestern North Pacific during the past 50 years, caused by a decrease in sea ice production in the Sea of Okhotsk.

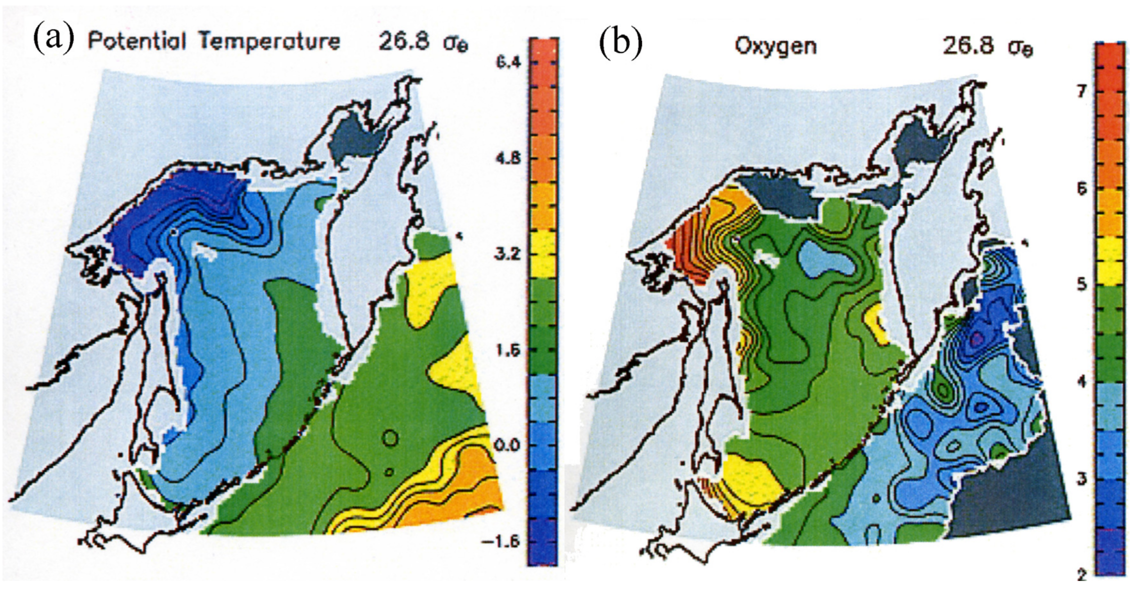


Figure 2: Horizontal distributions of (a) potential temperature (C) and (b) oxygen content (mL/L) on the 26.8σ_θ isopycnal surface in and around the Sea of Okhotsk. After Itoh et al. (2003).

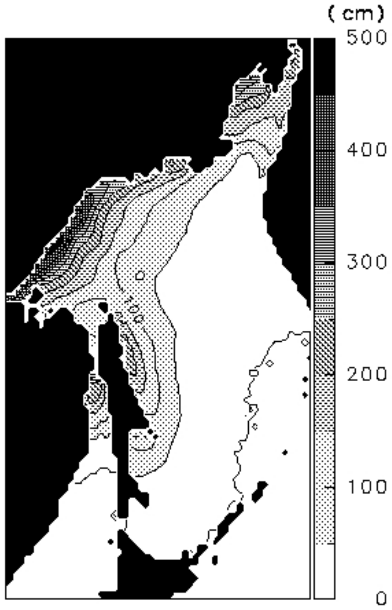
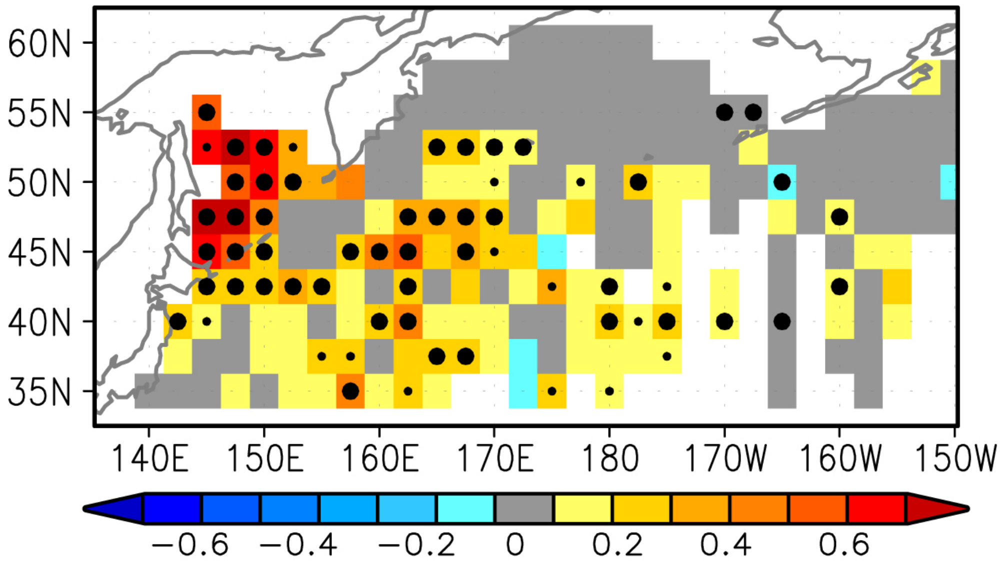


Figure 3: Annual mean cumulative sea ice production, represented by the ice thickness (cm). Estimation is based on the sea ice information from the satellite microwave and heat budget calculation. After Ohshima et al. (2003).

1. WARMING AND OXYGEN-DECREASE TRENDS

For the trend analyses, we have used all available data of 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 4a shows linear trend maps of intermediate water temperature on the $27.0\sigma_\theta$ isopycnal surface for the last 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°C/50-yr. The warming trend at $27.0\sigma_\theta$seems to extend along the pathway of the OSIW. Climatology of the acceleration potential at $27.0\sigma_\theta$ (Figure 4b) shows that the western subarctic gyre, which consists of the Oyashio and Subarctic Current (SAC), extends to the intermediate depth of $27.0\sigma_\theta$. A significant warming trend is observed in the Oyashio and SAC regions, but not in the East Kamchatska 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



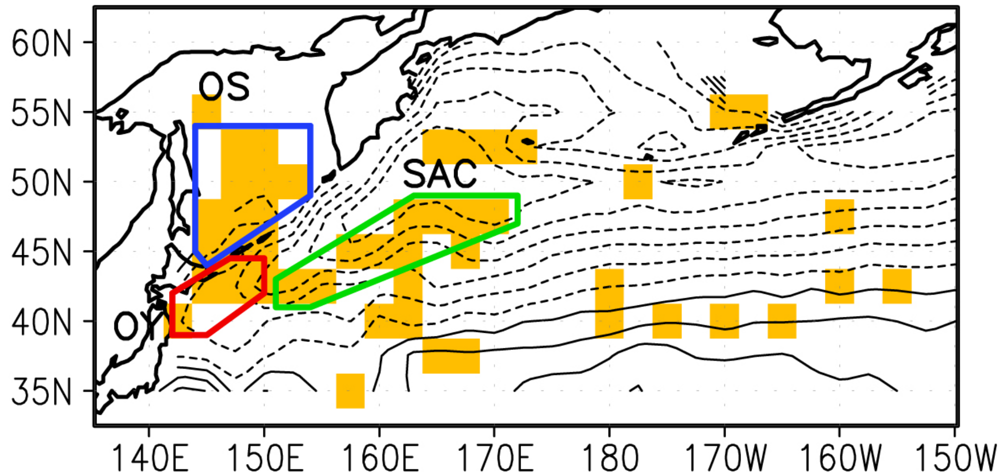


Figure 4: (a) Linear trends (colors in °C/50-yr) of potential temperature anomalies at density 27.0σ_θ from 1955-2004 in the northwestern North Pacific. Large and small dots indicate grid boxes in which the linear trend is significant at the 95% and 90% confidence levels, respectively. White color indicates the grid boxes where yearly temperature anomalies are not available for more than 10 years throughout the respective periods. The significance of the linear trend estimate is based on a Student t distribution. (b) Map of acceleration potential (contours) at 27.0σ_θ relative to 2000 dbar, derived from our dataset. Boundaries of the Sea of Okhotsk (blue), Oyashio (red), and SAC regions (green), for which area-averaged quantities are displayed in Figure 3, are indicated. Shading (yellow) indicates areas where the positive linear trend of potential temperature at 27.0σ_θ exceeds the 95% confidence level. After Nakanowatari et al. (2007).

(Yasuda, 1997), these results indicate that the warming trend in the northwestern North Pacific may be caused by advection of warmed OSIW.

Figure 5a shows the time series of temperature anomalies at 27.0σ_θ for the Sea of Okhotsk, Oyashio and SAC regions (Figure 4b). A positive linear trend is the most significant feature in all three regions. The temperature has increased by 0.62±0.18°C (significant at 99% confidence interval) in the Sea of Okhotsk during the past 50 years from 1955 through 2004. The magnitude of the warming trend in the other two regions is about half of that.

We next examine the linear trend of dissolved oxygen content. For all three regions, significant negative trends are found (Figure 5b). Decreasing trend of dissolved oxygen content in the Oyashio is consistent with Ono et al. (2001). The decrease of dissolved oxygen is most prominent at 26.9-27.0σ_θ, where the warming trend is most prominent. At 27.0σ_θ, the linear trend in the Sea of Okhotsk is -0.58±0.34ml/l (significant at 95% confidence interval) for the past 45 years. The Oyashio and SAC regions have the value less than that for the Sea of Okhotsk.

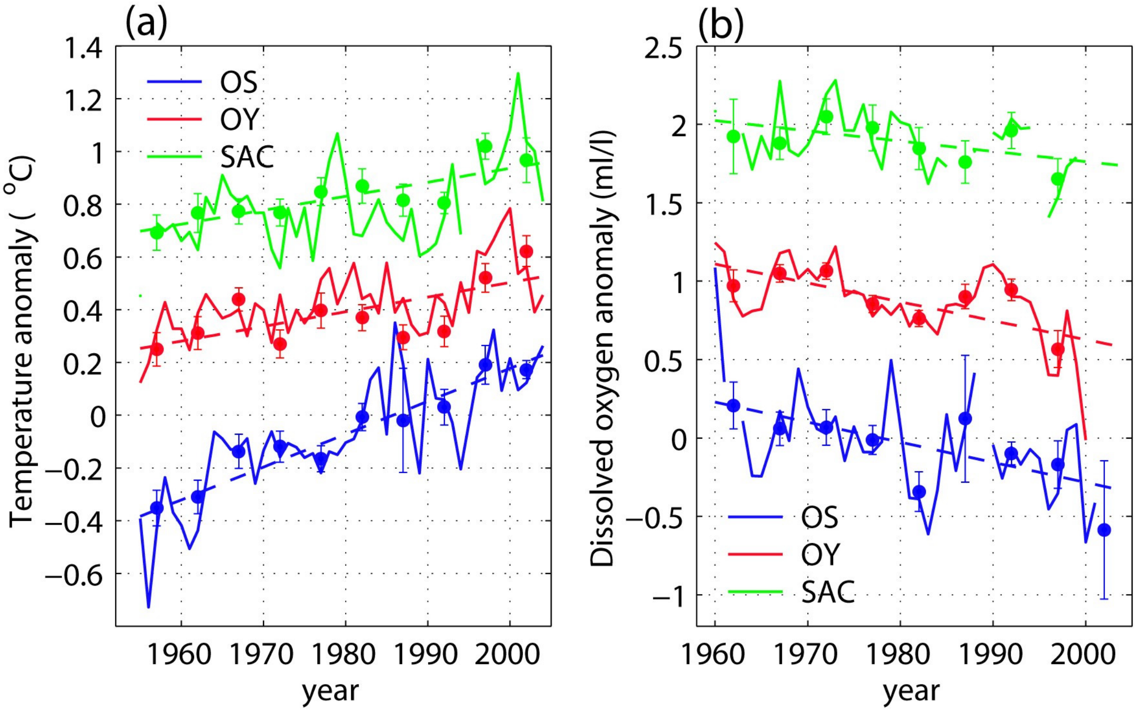


Figure 5: Time series of (a) potential temperature (°C) and (b) dissolved oxygen (ml/l) anomalies at 27.0σ_θ averaged over the Sea of Okhotsk (blue), Oyashio (red), and SAC (green) regions, respectively (see Figure 2 for locations of these three areas). Closed circles show 5-yr averaged anomalies with errors at the 95% confidence interval for the 5-yr averages. Linear regression line for each time series is also indicated by a dashed line. Note that in panel a (b) 0.4°C (1.0 ml/l) and 0.8°C (2.0 ml/l) has been added to the time series for the Oyashio and SAC regions, respectively. After Nakanowatari et al. (2007).

2. POSSIBLE SCENARIO

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 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 Sea of Okhotsk (Figure 4a), 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.

Although reliable estimation of DSW production is not yet available, there is some indirect evidence for a decrease trend in DSW production. Figure 6 shows the time series of surface air temperature anomaly in the cold season averaged over northeastern Eurasia, which is upwind of the Sea of Okhotsk; this air temperature can be an index of sea ice extent. This air temperature has increased considerably during the past 50 years (2.0±1.4°C/50-yr, significant at 99% confidence level). Sea ice extent in the Sea of Okhotsk derived from satellite measurements, which is highly correlated with this air temperature (r=-0.61, significant at 95% confidence level), has decreased (-9.2%/27-yr) (Figure 6). Although satellite measurements have only been available since the 1970's, visual observations at Hokkaido coast, located on the southern boundary of sea ice extent in the Sea of Okhotsk, show the decreasing trend of sea ice season length 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, have 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

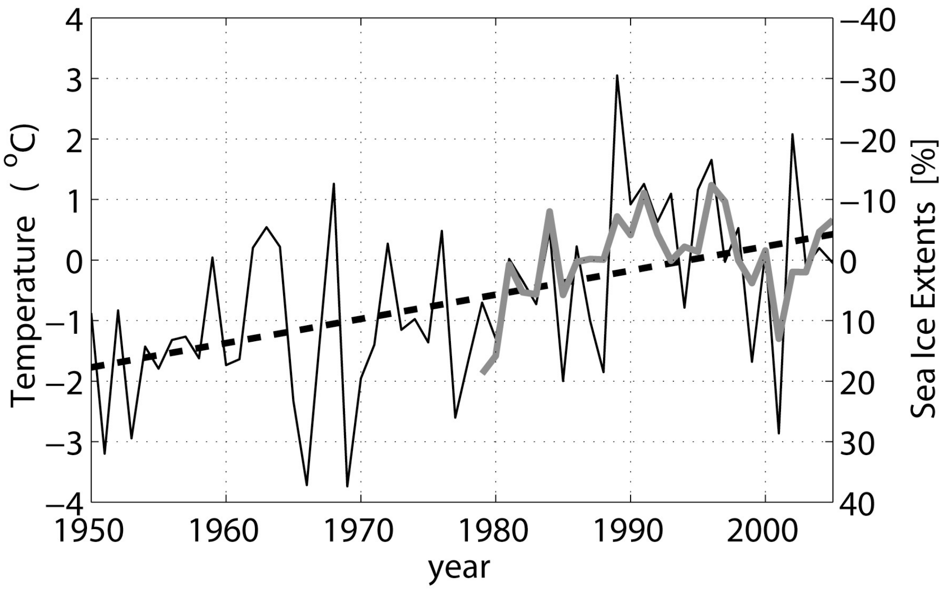


Figure 6: Time series of surface air temperature anomaly in the cold season (October to March) and the linear trend over northeastern Eurasia (50º65ºN, 110º140ºE) from 1950 to 2005 (solid and dashed lines, respectively), and the annual sea ice extent anomaly in the entire Okhotsk Sea from 1979 to 2005 (blue line). The scale of the sea ice extent anomaly is indicated on the right axis and inverted. The surface air temperature anomaly is derived from (Jones, 1994), and the sea ice extent anomaly is derived from the Met Office Hadley Centre's sea ice data set (Rayner et al., 2003). The surface air temperature anomaly with respect to the 27-yr average from 1979 to 2005 is shown for the benefit of comparison with the sea ice extent anomaly. After Nakanowatari et al. (2007).

is ventilated through DSW may be sensitive to the global warming.

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, which is an essential micronutrient for phytoplankton, may come from the intermediate water of the Sea of Okhotsk (Nishioka, 2004). The co-occurrence of warming and decrease in dissolved oxygen concentration in the northwestern North Pacific, originating from the Sea of Okhotsk, implies that overturning in the northwestern North Pacific has weakened in the sense of material cycle. Therefore, such a trend has a possibility of substantial impacts on the material cycle and biological productivity in the North Pacific.

Figure 7 summarizes our proposal with schematics. Because the Sea of Okhotsk is a sensitive area to the current global warming, production of sea ice and dense shelf water in the northwestern shelf has decreased during the past 50 years. This possibly causes a decrease in 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.

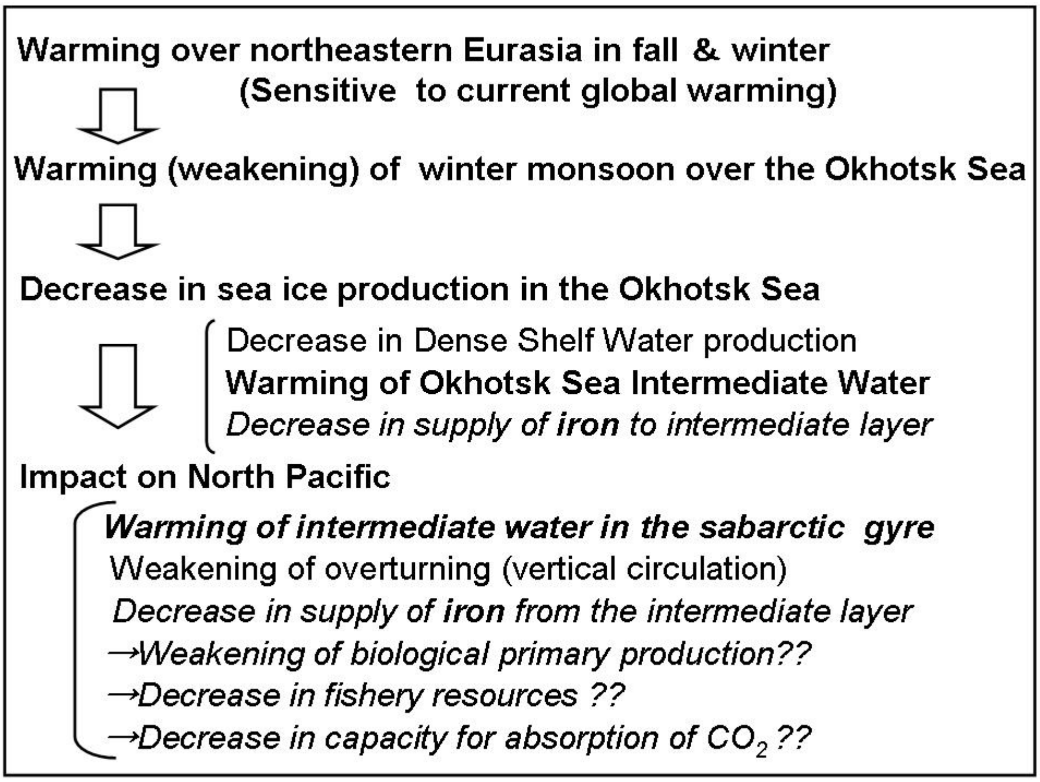


Figure 7: Schematics for impact of the Okhotsk Sea on the North Pacific through global warming. Thick letters indicate a fact evidenced by observations and analyses. Italic letters indicate a hypothesis. Larger number of question mark indicates larger uncertainty.

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