50-yr scale change in the intermediate water temperature in the western North Pacific simulated by an eddy resolving sea ice coupled OGCM

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Introduction

The global ocean dataset shows that water temperature has significantly increased during the past 50 years (Levitus *et al.*, 2005). Since the increase in ocean temperature is prominent at upper levels, the cause of the warming seems to be related to global warming.

Recently, it was reported that a warming trend is found in the western North Pacific, including the Sea of Okhotsk at the intermediate layer, which is not affected by local surface heat flux (Nakanowatari *et al.*, 2007). Since the warming trend originates from the Sea of Okhotsk, which is known to be the ventilation source of North Pacific Intermediate Water (NPIW) (*e.g.*, Talley, 1991), it is suggested that overturning in the North Pacific has weakened during the past 50 years.

On the other hand, ocean temperature at 40°N in the western North Pacific has significantly decreased in the upper and middle layers during the past 50 years (Levitus *et al.*, 2005). The significant decrease in ocean temperature occurs at isopycnal level (*e.g.*, Wong *et al.*, 1999; Nakanowatari *et al.*, 2007). Thus, it is considered that cooling in the intermediate layer is related to the change in water mass property.

Several studies have shown that the significant decrease in upper ocean temperature in the western North Pacific is related to the change in surface heat flux, Ekman transport, and ocean circulation associated with the Pacific Decadal Oscillation (PDO) (*e.g.*, Miller and Schneider, 2000). However, the effect of atmospheric forcing on the 50-yr scale decrease in ocean temperature at intermediate layers has not been investigated.

In this study we investigate the effect of atmospheric forcing on a 50-yr scale change in intermediate water temperature in the western North Pacific by using observational data and hindcast data of an eddy resolving sea ice coupled Ocean General Circulation Model (OGCM) driven by realistic atmospheric forcing.

Data and Methods

Model description and experiment

The hindcast data used in this study is integrated by the sea ice coupled OGCM developed at the Meteorological Research Institute (MRI.COM: Ishikawa *et al.*, 2005). The ocean model is described by a primitive-equation system with a vertical depth coordinate, free surface, Boussinesq and hydrostatic approximations. The model domain occupies the entire North Pacific from 100°E to 75°W and from 15°S to 65°N. Horizontal resolution is 1/12° (eddy resolving) in the zonal and meridional direction, respectively. Thus, ocean circulation in the Sea of Okhotsk and narrow features in the Oyashio front and Kuroshio–Oyashio confluence can be resolved.

In this model, the sea ice model is coupled to realistically simulate vertical mixing in the Sea of Okhotsk. Thermodynamics is based on Mellor and Kantha (1989), and dynamics is based on elastic-viscous-plastic rheology (Hunke and Ducowicz, 1997). In addition, the tidal mixing process is represented in the form of parameterization of the vertical diffusive coefficient (St. Laurent *et al.*, 2002).

As a boundary condition for the hindcast experiment of the sea ice coupled model, 6-h NCEP-NCAR reanalysis data (Kalnay *et al.*, 1996) are used. Heat flux is calculated by bulk formula (Kara *et al.*, 2000). Freshwater flux is estimated from E – P + river runoff. Sea surface salinity (SSS) is restored with an 8-day damping timescale to avoid the SSS drifting problem.

Observational data sets

Temperature and salinity are taken mainly from the World Ocean Database 2001 (Conkright *et al.*, 2002). In addition, we used observational data obtained by the Japan–Russia–United States international joint study of the Sea of Okhotsk from 1998 to 2004 and data archived by the Japan Oceanographic Data Center. We also used profiling float data obtained by the international Argo program from 2000 to 2004.

From these observational data, we made new isopycnal grid data for potential temperature in the North Pacific on the method similar to previous studies (Itoh *et al.*, 2003; Nakanowatari *et al.*, 2007). Annual mean climatology was calculated on a 1° × 1° latitude/longitude grid by a weighted averaging with a Gaussian window of 150 km. Then, we calculated annual mean anomalies from 1955 to 2004 based on this climatology. All the calculated anomalies were gridded by using simple averaging in a yearly 2.5° × 2.5° grid box, taking account of the trade-off between spatial and temporal resolution.

Results

50-yr scale change in potential temperature in the North Pacific from model and observations

Figure 1a shows the 1977–2004 minus 1955–1976 difference in annual mean potential temperature at $26.8\sigma_\theta$ for observational data. The 50-yr scale decrease in potential temperature is observed in the western North Pacific, including the subtropical region. The maximum decrease is found in the subtropical region with 0.6°C. The decrease in potential temperature becomes weak at deeper depth. Such a decrease is successfully simulated in the hindcast data (Fig. 1b), although the most prominent decrease is found in Oyashio region.

Figure 2 shows the time series of potential temperature at $26.8\sigma_\theta$ averaged over the western North Pacific. The potential temperature is dominated by multi-decadal variation like the Pacific Decadal Oscillation, which is characterized by the regime shift which occurred at the end of the 1970s (Mantua *et al.*, 1997; Minobe, 1997). The model quantitatively simulates the multidecadal variation in the observations. The difference in potential temperature for the model is –0.14, which is similar to that for the observations. The correlation between them is 0.67, which is significant at the 99% confidence level.

From the difference map for observational data, significant warming is found around the western subarctic gyre, including the Sea of Okthosk (Fig. 1a). This warming is prominent in the western part of the Sea of Okhotsk, which is consistent with trend analyses of potential temperature on the isopycnal layer (Nakanowatari *et al.*, 2007). However, the warming is not found in the model data. Although we examine the potential temperature at $27.0\sigma_\theta$, in which the most prominent warming trend is observed, the result is basically the same as in Figure 1b. Figure 2b shows the time series of potential temperature at $26.8\sigma_\theta$ averaged over the Sea of Okhotsk. The significant warming trend is dominant in the observational data, but such a long-term variation is quite weak in this model.

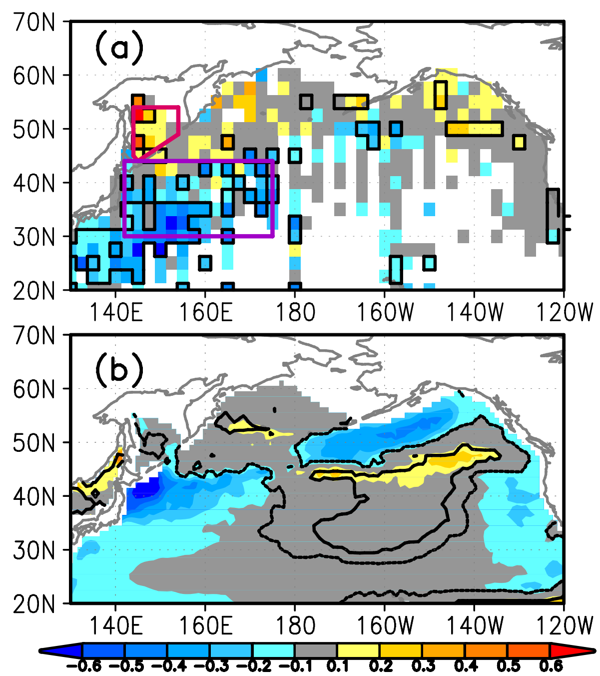

Fig. 1 The 1977–2004 minus 1955–1976 difference (colors) in annual mean potential temperature at $26.8\sigma_\theta$ for (a) observations and (b) model. The black boundaries indicate the regions where the difference is significant at the 95% confidence level. For calculating the significance of the difference, we assume each year is independent. The boundaries of the western North Pacific region (purple) and the Sea of Okhotsk (magenta), for which area-averaged quantities are displayed in Figure 2, are indicated.

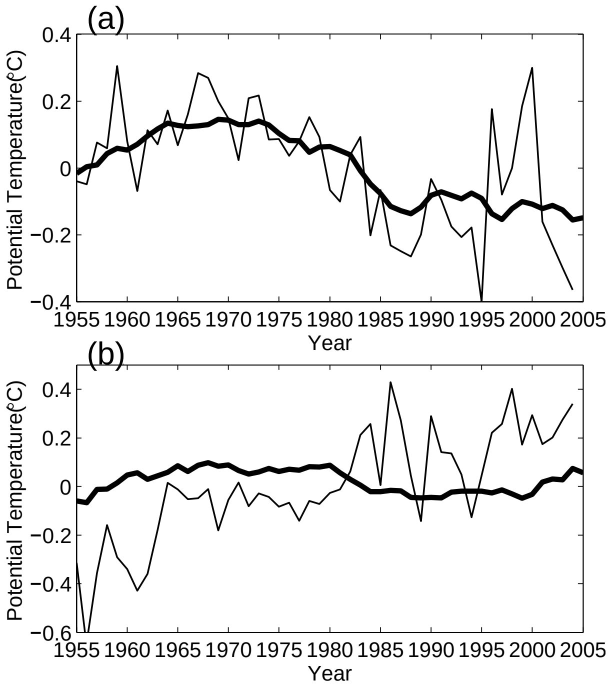

Fig. 2 Time series of annual mean potential temperature for observations (thin line) and model data (thick line) at $26.8\sigma_\theta$ averaged over (a) the western North Pacific and (b) the Sea of Okhotsk. Area averaged region is shown in Figure 1(a).

Effect of Okhotsk Sea Intermediate Water on the 50-yr scale change of intermediate water temperature in the North Pacific

We examine the role of Okhotsk Sea Intermediate Water (OSIW), which is known to be the cooling and freshening source for NPIW, on the 50-yr scale change in intermediate water temperature in the North Pacific by using model data. In order to investigate the water mass property change related to OSIW, we examine potential vorticity, which is defined by $(f + \zeta)\ \rho^{-1}\cdot\partial\rho/\partial z$. Since potential vorticity is minimum in the Sea of Okhotsk at intermediate layer depth, it can be used for a proxy for OSIW (*e.g.*, Mitsudera *et al.*, 2004).

Figure 3 shows the 1977–2004 minus 1955–1976 difference in annual mean potential vorticity at $26.8\sigma_\theta$. A significant decrease in potential vorticity is found in the western North Pacific with a maximum in the Oyashio region. Thus, the spatial pattern of the significant decrease in potential vorticity is very similar to that in potential temperature. On the other hand, the potential vorticity in the Sea of Okhotsk has increased in contrast to the western North Pacific. These results indicate that the cooling in the western North Pacific is not associated with the change in OSIW, but the change in ocean circulation in the North Pacific.

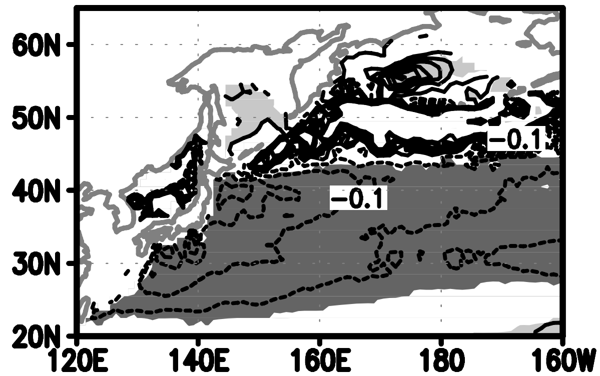

Fig. 3 The 1977–2004 minus 1955–1976 difference in annual mean potential vorticity at $26.8\sigma_\theta$ for the model. The contour interval is 0.05 $m^{-1}s^{-1}$, and the areas with potential vorticity > 0.3 $m^{-1}s^{-1}$ are not contoured. The dense and light shades indicate the region for the negative and positive difference is significant at the 95% confidence level.

Discussion and Summary

In this study, we investigate the influence of atmospheric forcing on the change in the intermediate water temperature in the western North Pacific during the past 50 years by using observational data and the hindcast data of the sea ice ocean coupled model. The model quantitatively represents the 50-yr scale decrease in the western North Pacific. The decrease in the intermediate water temperature is significant at the $26.8\sigma_\theta$ isopycnal surface in the western North Pacific with a maximum in the Oyashio region. The variation is dominated by multi-decadal variation like the Pacific Decadal Oscillation.

The decrease in the intermediate water temperature is accompanied by the decrease in potential vorticity. Since the significant decreases in potential temperature and potential vorticity are found in Oyashio region, it is suggested that the multi-decadal scale change in the intermediate water temperature is due to the variation of the Oyashio. It has been considered that the variation in water temperature in the western North Pacific is related to the change in wind-driven ocean circulation associated with westward Rossby waves (*e.g.*, Deser *et al.*, 1999).

However, the multi-decadal variation in intermediate water originates from the western boundary. Thus, the western boundary current and the associated eddies seems to be important for 50-yr scale cooling in the NPIW.

The coastal region of the western North Pacific is one of the most important fishery regions. It has been reported that consumption of phosphate and chlorophyll-*a* has decreased in the Oyashio region (Ono *et al.*, 2002). Thus, the effect of multi-decadal scale change in the Oyashio on the ecosystem and material circulation in the North Pacific should be examined by using an eddy resolving ecosystem–biogeochemical model.

In this model, the warming trend in the Sea of Okhotsk, reported by Itoh (2007) and Nakanowatari *et al.* (2007), is not simulated. A possible cause for the unrealistic variation in the Sea of Okhotsk is that the amount of sea ice formation is not simulated accurately in the model. A restoring of sea surface salinity may lead to an underestimation of dense shelf water formation associated with sea ice production. Since observational data are very limited in the Sea of Okhotsk, atmospheric forcing data used in this study also may not be satisfactorily realistic.

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 *et al.*, 2007). Thus, realistic simulation for the OSIW and its variability are needed for prediction of the marine environment and ecosystem in the western North Pacific.

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