近年の北極海氷域減少に伴う北半球大気大循環の変調

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Warm Arctic Cold Mid-Latitudes (WACM) associated with the Recent Arctic Sea Ice Reduction

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We examined impacts of the recent environmental changes in the Arctic on the Northern Hemisphere climate by sensitivity experiments using AGCM for the Earth Simulator (AFES) with T79 horizontal resolution and 56 vertical levels up to about the 60 km model top. Perpetual model runs were performed with the global sea surface temperature (SST) and sea ice extent (ICE) of the past period (1979 to 1983, *CNTL*) and the more recent period (2005 to 2009, *Global*). We also performed other cases which are similar to *CNTL*. The *Northern* case changes sea ice extent and SST only in the high-latitudes (north of 50°N) while the *N.ICE* case changes only sea ice extent in the high-latitudes (see the table). We estimated the atmospheric responses by taking respective differences of the 20-year means from the *CNTL* run. For comparison with the model results, we used monthly mean data of ERA-interim Reanalysis datafrom 1979 to 2012. To specify the atmospheric responses to the recent Arctic ice reduction, residual data which is defined as anomalies from the extrapolation of the linear trend of 1979 to 2004 were evaluated in the period of 2005 to 2009.

In winter (DJF mean), all the cases of the model result show a surface temperature warming in the Arctic sea and Okhotsk sea (Fig. 1a-c). The cases with the changes in the global and the northern hemisphere SST (i.e., *Global* and *Northern* runs) show warming signatures in the northern mid- and high-latitudes (Fig. 1a and 1b). In contrast, the cases with the changes in the Northern Hemisphere sea ice, *N.ICE* run, leads to a surface temperature cooling in the Far East, eastern Europe, and eastern North America (Fig. 1c). Such Arctic warming and mid-latitudes cooling are also found in the observation result (Fig. 1d). In both results of model and observation, the cooling anomalies in the mid-latitudes couple with the upper tropospheric cyclonic anomalies. Anomalous geopotential height fields in the upper troposphere and corresponding wave activity flux (WAF) anomalies shows that the Rosbby wave propagation from the Barents Sea to the Eastern Siberia and eastern Europe induces the mid-latitude cyclonic anomalies (Fig. 2). Figure 3a shows polarstereo map of anomalous surface heat flux (i.e., sum of sensible heat and latent heat fluxes), vertical component of the WAF at 700 hPa, and horizontal vector of the WAF at 300 hPa. Southward propagations of the Rossby wave originated from the Arctic region are obvious through three passes over the Europe, the eastern Siberia, and the North America. Especially, two passes in the Eurasian continent side are originated from an upward propagation of the Rossby wave associated with the surface heat flux anomalies over the Barents Sea. These three passes are located to the west of the climatological trough (Figure 3b), corresponding to the southward jet stream (Figure 3c). This is reasonable because the Rossby wave prefers to propagate along the clockwise normal direction of the absolute vorticity gradient (Figure 3d). The result implies that the Arctic ice reduction causes a modulation of the climatological planetary wave. Furthermore, anomalous wave drag associated with the

Table. SST/ICE conditions of perpetual runs. Past (Recent): monthly averaged SST or ICE for a 5 year period of 1979-1983 (2005-2009). SST between 30N and 50N is gradually (e-folding) connected if those periods are different.

	SST and ICE southward of 30N	SST northward of 50N	Northern Hemisphere ICE
CNTL	Past	Past	Past
Global	Recent	Recent	Recent
Northern	Past	Recent	Recent
N.Ice	Past	Past	Recent

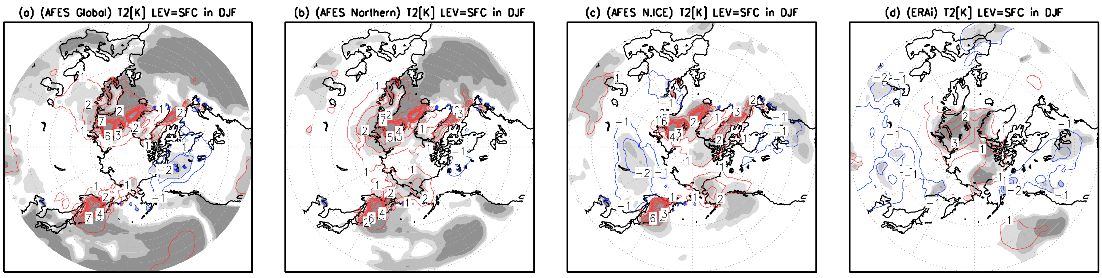

Figure 1. (a) Anomalies of 20 years average of temperature at 2 m in DJF for *Global* run against that for *CNTL* run. Contours indicate the differences in unit of [K]. Light, moderate, and heavy shadings indicate statistical significance with t-test over 90, 95, and 99 %, respectively. (b and c) same as (a) but for *Northern* and *N.ICE* runs. (d) ERA interim residuals (see text in detail) of temperature at 2 m averaged from 2005 to 2009.

modulation of the planetary wave induces anomalous meridional circulation.

The changes in the anomalous meridional circulation in the mid- and high-latitudes strongly correspond to the variation of the Arctic Oscillation (AO). We obtained the DJF mean AO index by applying the empirical orthogonal function (EOF) analysis to 60 years of *CNTL* combined with those of *N.ICE* runs (i.e., total sample number is 120). Mean difference between indices averaged for years of *CNTL* and *N.ICE* is 0.49 σ, indicating the modulation of AO to be negative phase due to the Arctic ice reduction. The observed AO index obtained by EOF analysis applied to the ERA interim residual data shows zero avarge for the period of 1979-2004. An average of the observed AO index for the period of 2005-2009 shows +0.44 σ, in association with the model results. This may indicate the negative phase shift of the observed AO due to the ice reduction. However, accurate and quantitative estimation is still difficult because of quite less samples of years after 2005.

Our results are consistent with the previous studies, Honda et al. (2009) and Inoue et al. (2012), which show the cold Siberian anomalies associated with the sea ice reduction in the Barents Sea. Furthermore, our results suggest that the modulation of the planetary wave in the eastern Siberia affects over the Northern Hemisphere through the changes in the mean meridional circulation.

References

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Inoue, J., M. E. Hori, and K. Takaya, The role of Barents Sea ice on the wintertime cyclone track and emergence of a warm-Arctic cold-Siberian anomaly, Journal of Climate, 25, 2561-2568, 2012

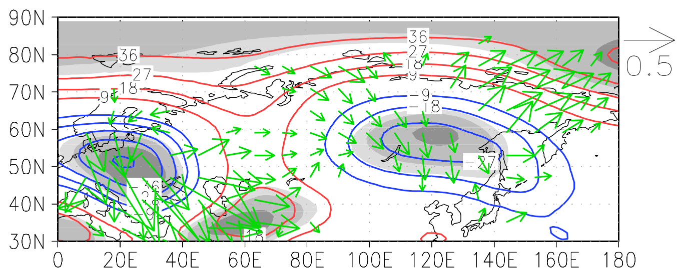

Figure 2. 20-year average of geopotential height anomalies at 300 hPa in DJF for *N.ICE* run against that for *CNTL* run. Indications of contour and shadings are same to Figure 1. Associated wave activity fluxes are shown by green arrows. Corresponding scale to 0.5 m^2 s^{-2} is denoted at top-right corner of the panel.

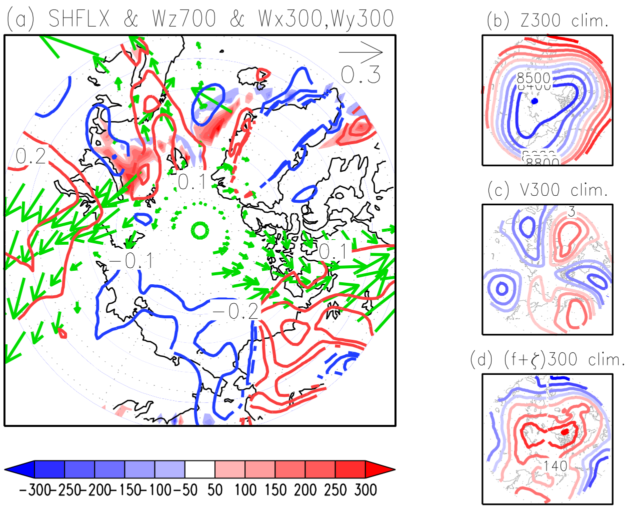

Figure 3. (a) DJF averaged anomalies of *N.ICE* run against *CNTL* run. Shadings, contours, and arrows indicate surface heat flux [W m^{-2}] (i.e., sensible heat plus latent heat, upward positive), vertical component of the wave activity flux [10^{-2} m^2 s^{-2}] at 700 hPa, and horizontal wave activity flux vector at 300 hPa[m^2 s^{-2}], respectively. Arrow length corresponding to 0.3 m^2 s^{-2} is denoted in the top-right corner of the panel. Note that the horizontal wave activity fluxes with northward direction are omitted. (b to d) DJF averaged climatologies of geopotential height [m], meridional wind velocity [m s^{-1}], and absolute vorticity [10^6 s^{-1}] at 300 hPa. Climatology is defined as 20 years average of *CNTL* run.