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Global warming trend without the contributions from decadal variability of the Arctic Oscillation

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Abstract

Climate change associated with recent global warming is most prominent in the Arctic and subarctic. The Arctic Oscillation (AO) is a dominant atmospheric phenomenon in the Northern Hemisphere. Decadal variability of surface air temperature (SAT) associated with the AO index shows high correlation with recent global warming trend. In this study, the SAT variability in the Northern Hemisphere is separated in contributions from decadal variability by the AO and remaining components.

The results indicate that the decadal variability of the AO index shows high correlation with the SAT variation until 1990. The AO index and SAT variabilities show a negative trend during 1949–1969, while the trend is positive during 1969–1989. In addition, the spatial distribution pattern of the SAT linear trend during each period shows the same pattern as AO. However, while the AO index indicates a negative trend, the SAT trend is continuously positive also after 1990. This warming pattern appearing after 1990 is caused by the Arctic amplification.

Although the AO has a large amplitude on local scale, the AO is almost dynamically orthogonal to the hemispheric warming component. However, the AO can be related to the decadal variability of the Arctic and subarctic temperature change through the feedbacks by climate sub-systems.

Keywords: Arctic Oscillation; Global warming; Decadal variability; Ice-albedo feedback

1. Introduction

In recent years, the climate change in the Arctic and subarctic has drawn more attention to global warming. Climate models presented by the Intergovernmental Panel on Climate Change (IPCC) projected large warming trends in the Arctic for the 21st century (IPCC, 2007). On the other hand, Arctic Oscillation (AO) which is the most dominant atmospheric phenomenon in the Northern Hemisphere winter is characterized by the opposite atmospheric pressure anomalies between the high and mid latitudes (Thompson and Wallace, 1998). When the AO index is positive (relatively low pressure over the polar cap and high pressure at mid latitudes), surface air temperature (SAT) is warmer than normal over Siberia and Canada, and cooler around Greenland (Wallace and Thompson, 2002). When the AO index is negative, the spatial pattern is reversed. Thompson et al. (2000) showed that the positive trend of the AO index in the latter 20th century has a high correlation with the positive trend of

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the SAT by the global warming, and about half of the global warming pattern may be explained by the AO. In addition, the SAT pattern related to the positive AO index was similar to the observed trend in the latter 20th century (Chapman and Walsh, 1993).

Miller et al. (2006) examined 14 AOGCM datasets cited by the IPCC and found that the AO index exhibits positive trend due to anthropogenic forcing in the 21st century. In addition, Hori et al. (2007) also showed that the AO index trend reproduced by IPCC (2007) models was controlled by the anthropogenic forcing projected onto the mean climatological state of the Arctic region. On the other hand, Ohashi and Tanaka (2009) suggested that the observed decadal variability associated with the AO can be mostly explained by the internal variability of the atmosphere, and thus the AO index varies chaotically (Hirata et al., 2011).

The increasing trend of the AO index since 1970 has stopped over the last two decades since 1990s, and the AO index trend began to deviate from the global warming trend (Overland and Wang, 2005). Cohen and Barlow (2005) suggested that the AO index variability scarcely correlated with the SAT variability after 1990, and the decadal scale features of the global warming trend over the last 30 years are unrelated to the AO.

Meanwhile, because the global warming seems to have stopped in the 21st century when the AO index shifted to the negative trend, Ohashi and Tanaka (2010) suggested that the AO which is regarded as a natural variability controls, to some extent, the decadal variability of the global warming. Concerning the decadal variability of the AO index, Tanaka (2003) analyzed the time spectra of the AO index for the observed and model atmospheres. Both time spectra are characterized by a red noise spectrum over the higher frequency range and a white noise spectrum for the period longer than 4 months. The observed time spectrum has a minor spectral peak at the decadal time scale Furthermore, Lindsay and Zhang (2005) indicated that the arctic climate system began to enter a new climate regime by the effect of an ice-albedo feedback triggered by the positive AO phase during 1989–1995. However, there are still many unknown factors in the relationship between the AO and global or hemispheric warming, and it is not quantified how much the AO affects the variation of the Northern Hemisphere mean SAT.

In this study, the SAT variability in the Northern Hemisphere is separated in contributions from decadal variability by the AO and the remaining component in order to estimate the hemispheric warming trend with and without the contributions from the decadal variability of the AO.

2. Data and analysis method

The data used in this study are monthly mean sea level pressure (SLP) and SAT of the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis dataset. The period of the data is for 1949–2011. We use the definition of the AO as the first empirical orthogonal function (EOF-1) of the winter (DJF) mean SLP in poleward of 20°N as defined by Thompson and Wallace (1998). The time series of the EOF-1 is referred to as an AO index.

In this study, variability of SAT associated with the AO index is calculated by the standard regression technique using the AO index. We calculate the correlation coefficients of SAT and AO index at all grid points, and multiply the standard deviation of SAT to obtain the regression coefficients. These regression coefficients have a unit of K. The SAT itself is then expanded in the EOFs. The EOF-1 is identified as the SAT associate with the AO. Using this fact, we can analyze the hemispheric warming pattern without the contributions from the AO by removing the EOF-1 and re-synthesizing the rest of the EOFs. Similarly, we can remove the contributions from the AO by removing the SAT pattern regressed by the AO index, instead of the EOF-1 pattern. The time series of the hemispheric mean temperature with and without the contributions from the AO are compared with each other to assess the contribution by the AO to the global warming.

3. Results

Fig. 1 shows the time series of the winter (DJF) mean SAT anomaly (top) and AO index (bottom) for 1948–2010 in poleward of 20°N. The red line shows the 5-year running mean of the time series. Comparing the two time series, the trend of AO index resembles the trend of SAT until 1990. During 1950–1970, the time series of the two components exhibit negative trends. During 1970–1990, the Northern Hemisphere mean temperature increases associated with the positive AO index trend. However, after 1990, though the positive trend of SAT continues, the AO index indicates clear negative trend.

Fig. 2 illustrates spatial distributions of the linear trends of SAT in winter during 1949–1969 (AO index indicated a negative trend), 1969–1989 (AO index indicated a positive trend), and 1989–2009 (AO index indicated a negative trend). During 1949–1969, the spatial pattern exhibits a negative AO pattern which is characterized by warming over the Arctic around

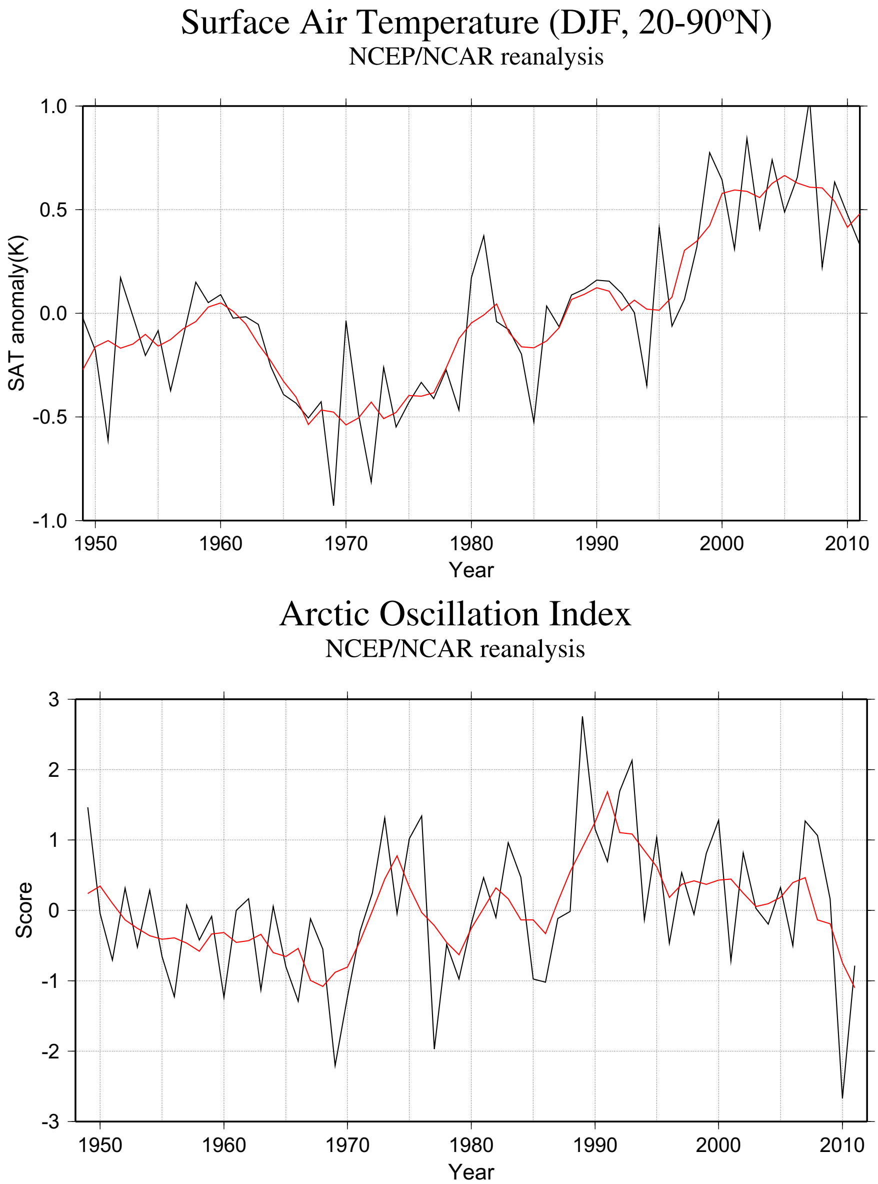

Fig. 1. Time series of the winter SAT anomaly in the Northern Hemisphere (north of 20°N) (top) and AO index (bottom). The red line represents the 5-year running mean.

Greenland and cooling over Siberia and Canada. In contrast, the spatial pattern during 1969–1989 exhibits a positive AO pattern which is characterized by warming over Siberia and Canada, and cooling around Greenland. During 1989–2009, the spatial pattern resembles a negative AO pattern although the region of warming over the Arctic is a little larger than the pattern during 1949–1969. This difference between 1949–1969 and 1989–2009 may be caused by the recent Arctic warming pattern related to the melting Arctic sea ice under the enhanced ice-albedo feedback.

Figs. 3 and 4 illustrate spatial distributions and time series of the EOF-1 and EOF-2 for the winter mean SAT during 1949–2011, respectively. The EOF-1 of the SAT in Fig. 3, which explains 21.0% of the total variance, resembles the typical AO pattern of temperature described by Wallace and Thompson (2002) and Chapman and Walsh (1993). There is a cold anomaly around Greenland and positive anomalies at Siberia and Canada. The detailed analysis shows that the negative anomaly is surrounded by the positive anomaly in an annular structure. This result suggests

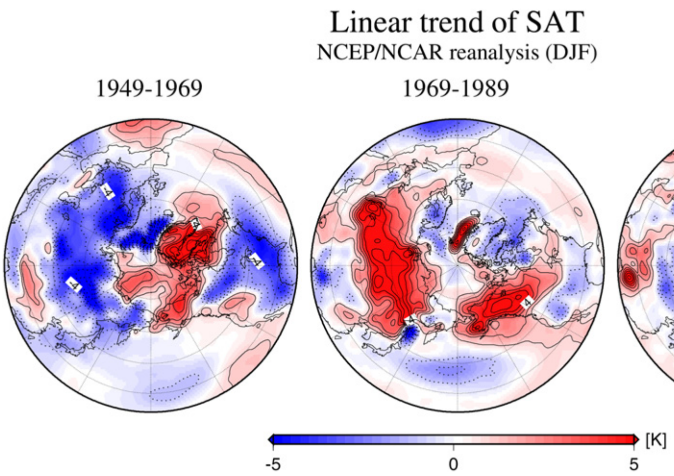

Fig. 2. Spatial distributions of linear trends of SAT in winter during (left) 1949–1969, (middle) 1969–1989 and (right) 1989–2009 in the north of 20°N.

that the AO affects the spatial pattern of SAT, especially for Siberia and Greenland, showing a decadal variation described by red arrows in Fig. 3. The decadal variability can be detected from Fig. 2 by positive, negative, and positive anomalies over Greenland, and negative, positive, and negative anomalies over Siberia for those periods.

The spatial distribution of the EOF-2 (14.8%) is characterized by the warming pattern all over the Arctic region. The score time series indicates a positive trend of the hemispheric warming in parallel with the increasing CO_2, although a part of the variation may contain the natural variability. This Arctic warming pattern looks similar to the structure of the Arctic amplification represented by Manabe and Stouffer (1980) and the IPCC reports due to the doubling CO_2. The pattern is explained by the anthropogenic radiative forcing enhanced by the ice-albedo feedback. In fact, the rapid increase in the score time series after 1990s in Fig. 4 is associated with the recent rapid reduction of Arctic sea ice. The Arctic amplification is largely driven by loss of the sea ice cover, but a part is explained by the strong meridional heat transfers by the ocean and the atmosphere (Serreze et al., 2009). The Arctic amplification pattern in Fig. 4 is not analyzed in the EOF analysis when the data after 2000 are excluded (see Ohashi and Tanaka, 2010). Therefore, this pattern appears prominently only after the year 2000.

Next, the SAT is regressed with the AO index in Fig. 1 to analyze the relationship between the variations of AO index and SAT. Fig. 5 illustrates the spatial distribution of SAT regressed with the AO index. This distribution for the positive phase of the AO index is characterized by warming over Siberia and Canada, and cooling around Greenland, which is almost identical to the EOF-1 of SAT in Fig. 3. The reversed pattern appears in the negative phase of the AO index.

In order to quantify the contributions from the AO for the hemispheric warming, the SAT is expanded in EOFs, and the EOF-1 (i.e., AO in Fig. 3) is subtracted to reconstruct the SAT without the contributions from the AO. The resulting time series of the hemispheric mean temperature is illustrated by blue solid line in Fig. 6. It is found that the blue solid line is almost identical with the original time series for the SAT denoted by black line. Similarly, the regressed SAT pattern in Fig. 5 is subtracted from the original SAT by the same method for the EOF-1 to compare the hemispheric mean temperature time series. The resulting time series is shown by the red solid line in Fig. 6. The red solid line is almost identical with the original time series shown by black line. The contributions from the EOF-1 (blue dotted line) and the regressed time series associated with the AO (red dotted line) to the hemispheric mean are plotted in Fig. 6. The time series are close to 0 K although the temperature distributions in Figs. 3 and 5 indicate large positive and negative values locally. When the spatial mean is taken over the poleward of 40°N, instead of 20°N, the mean SAT becomes twice as large as that of the red dotted line. These results suggest that the AO is almost dynamically orthogonal to the hemispheric warming component. This result is also confirmed by very small spatial means of the EOF-1 and the SAT

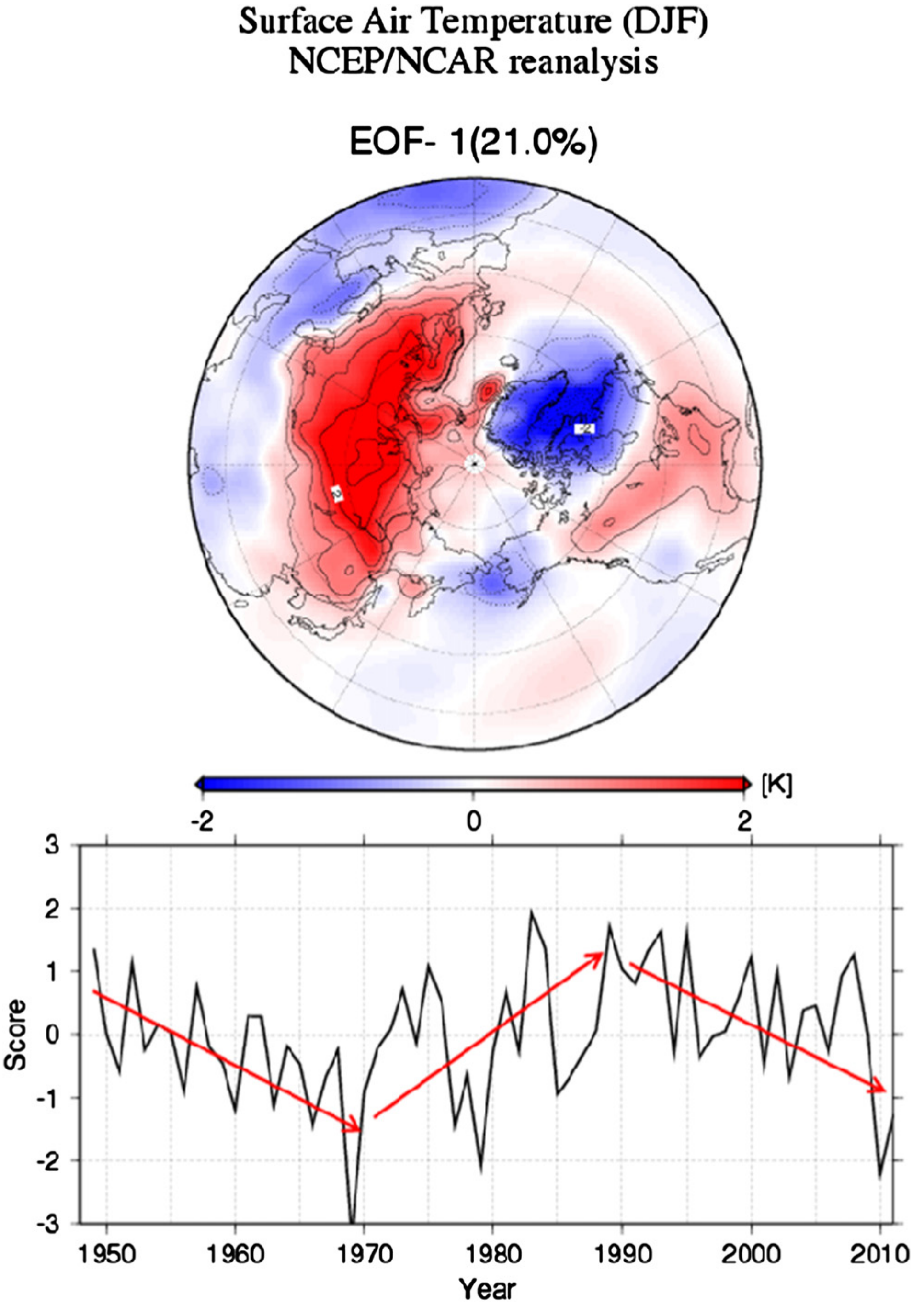

Fig. 3. The spatial distribution (top) and score time series (bottom) of the EOF-1 of winter mean SAT during 1949–2010. Contour interval is 0.5 K.

regressed with AO index in Fig. 5 (0.17 K and 7.66×10^{-2} K, respectively). The hemispheric mean of the EOF-2 for SAT shows the mean value of 1.32 K, but the rest of the EOFs show negligibly small values, because the EOFs are mutually orthogonal under the inner product defined by the hemispheric mean.

The result suggests that only the EOF-2 in Fig. 4 due to the anthropogenic ice-albedo feedback pattern is responsible for the global warming. The result is reasonable because statistical EOFs are mutually orthogonal, although the spatial variances of the EOF-1 and EOF-2 are 0.90 K^2 and 0.63 K^2, respectively.

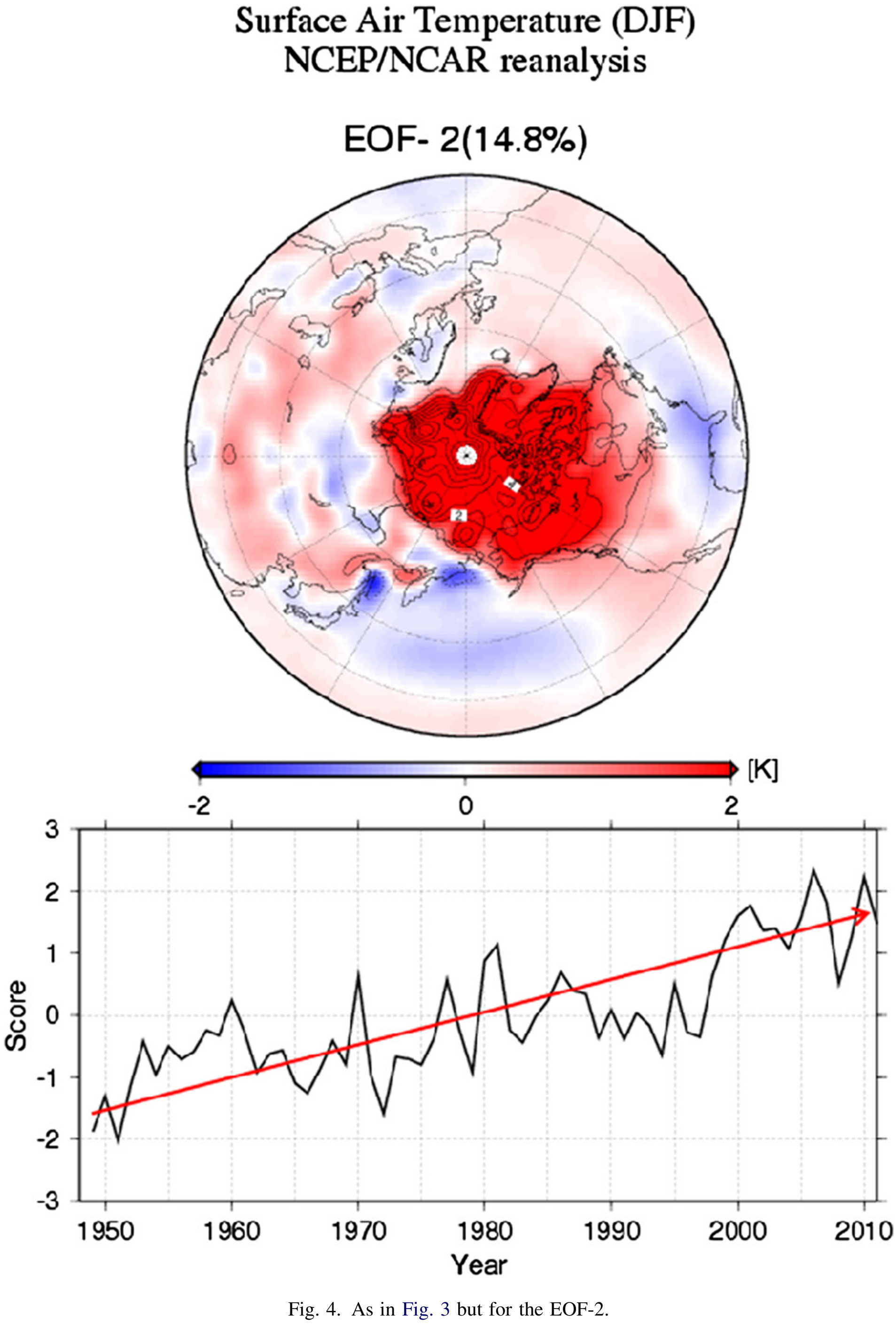

Fig. 4. As in Fig. 3 but for the EOF-2.

4. Summary and discussions

In this study, we analyzed the relationship between the SAT warming pattern in the Northern Hemisphere and the variation of the AO index using NCEP/NCAR reanalysis datasets. During 1949–1969 the negative trends of the SAT is associated with the negative trend of the AO index. During 1969–1989, in contrast, the positive trend of the SAT is associated with the positive trend of the AO index. Therefore, the winter SAT variation in Northern Hemisphere can be explained to some extent by the variations of the AO index. This results support the conclusion of Ohashi and Tanaka (2010). However, the SAT indicates positive trend

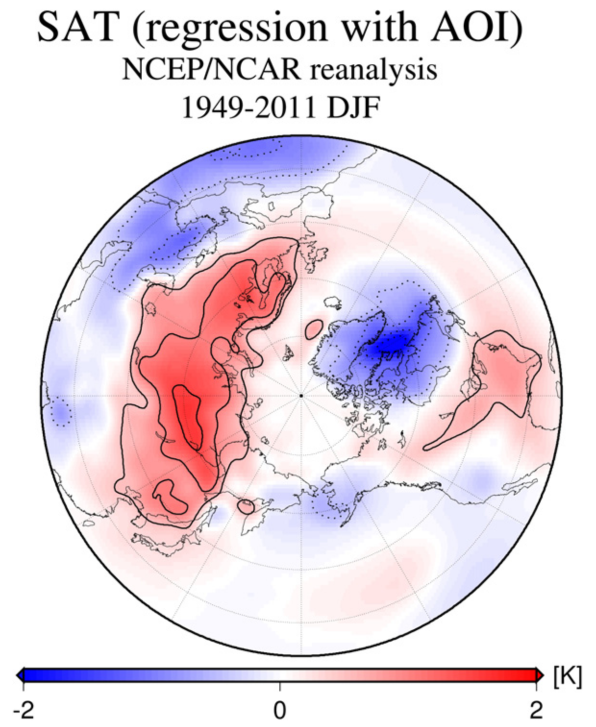

Fig. 5. Spatial distribution of SAT in winter during 1949–2010 regressed with the AO index. Conter interval is 0.5 K.

after 1989 in contradiction with the negative trend of the AO index. This rapid warming after 1990 in the Northern Hemisphere is caused by the ice-albedo feedback, which has resulted from the rapid reduction of the sea ice concentration after 1990. We suggest that the warming after 1990 in the Northern Hemisphere is caused mostly by the ice-albedo feedback pattern. However, because the AO index indicates large negative values and the SAT warming trend seems to have stopped after 2000, the SAT related to AO affects the Northern Hemisphere mean SAT variation.

The spatial distributions of the linear trends of SAT for various periods correspond to the SAT pattern related to AO index variation. Furthermore, the spatial distribution of the EOF-1 for winter mean SAT during 1949–2011 also coincides with the AO pattern. From these results, the AO, which is explained by the natural variability, must be dominant in the real atmosphere not only for SLP but also for SAT.

However, the spatial distribution of the SAT which is related to the AO has a very small contribution when averaged in the Northern Hemisphere and provides only a negligible influence for the mean SAT variation in the Northern Hemisphere. The warming over Siberia and Canada, and the cooling over Greenland for the positive AO index cancel out each other for the

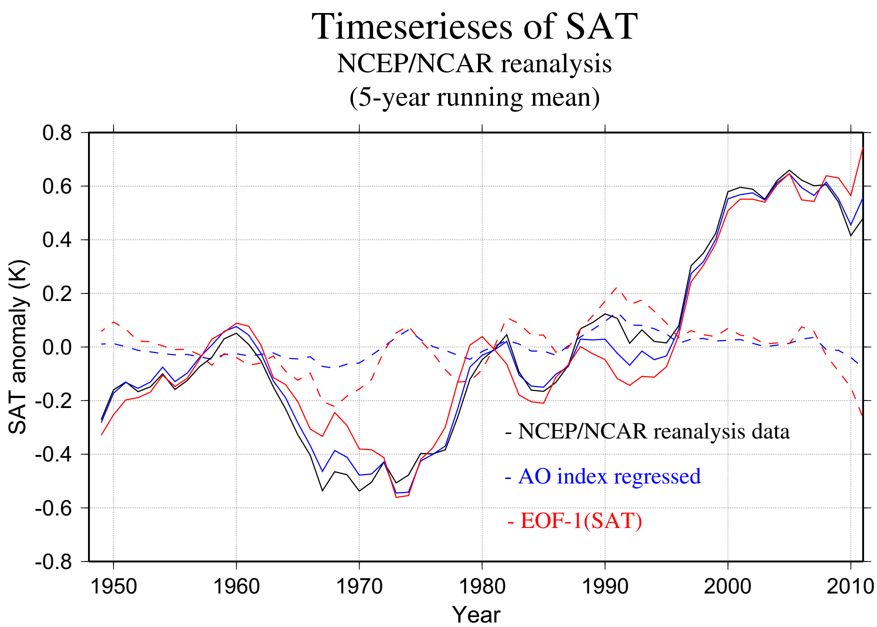

Fig. 6. Time series of the winter SAT anomaly in the Northern Hemisphere (north of 20°N). The black line is SAT variability of Northern Hemisphere mean, the blue dotted line is the Northern Hemisphere mean SAT associated with the AO index, and the red dotted line is the Northern Hemisphere mean EOF-1 of SAT. The solid lines show the variability where the contributions from the AO (blue) and EOF-1 (red) have been removed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Northern Hemisphere mean. Also the small but wide cooling area around 20°N to 40°N appears to be important for the cancellation in the hemispheric mean. Therefore, the AO is almost dynamically orthogonal to the global warming component for the Northern Hemisphere mean. The same result is seen in the spatial distribution of the EOF-1 for the winter mean SAT (Fig. 3, top).

On the other hand, the Northern Hemisphere mean of the spatial distribution of the EOF-2 (Fig. 4, top) has non-zero hemispheric mean (1.32 K) and shows the hemispheric warming trend. The EOF-2 of the SAT influences the hemispheric warming pattern in the statistical analysis, although the spatial variance of EOF-2 is smaller than EOF-1.

In this study we find that the AO contributes to the Arctic warming on local scale, but doesn't contribute to the hemispheric mean temperature. However, since the variance of the AO is largest, it contributes to the Arctic climate change through the complicated interactions and feedbacks with the climate sub-systems such as ocean, sea ice, and eco-systems. The AO can be influenced by the decadal and the multi-decadal variability by the North Pacific and North Atlantic Oceans. For example, Atlantic multi-decadal oscillation (AMO) has a possibility of driving the atmospheric phenomena around Arctic (see Polyakova et al., 2006; Polyakov et al., 2010). Therefore, the AMO coupled with atmosphere may trigger the AO to vary in multi-decadal time scale. This relationship need to be analyzed further as a future study.

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