Mechanism of the Decadal-Scale Variation of the Arctic Oscillation Index

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1. INTRODUCTION

The Arctic Oscillation (AO), or the Northern annular mode, postulated by Thompson and Wallace (1998) has attracted increasing attention in recent years. The AO is a north-south seesaw of the atmospheric mass between the Arctic region poleward of 60°N and a surrounding zonal ring in the mid-latitudes. It is defined as a leading mode of an empirical orthogonal function (EOF) of the sea-level pressure field and has an equivalent barotropic structure extending well into the stratosphere. The AO fluctuations dominate over the weekly and longer time scale, including decadal to long term trends associated with the global warming.

According to the diagnostic analysis of the IPCC AR4 climate models, basically all of the models show that their most dominant variability appears to be the AO both for the 20 century run and for the 21 century projection (Hori et al. 2007). The structure of the AO is robust and is considered as natural variability induced by the model dynamics. Although the structure is consistent with the AO, its score time series, called the AO index, indicates diversified variation for each model, and none of the IPCC models can accurately simulate the observed AO index in the 20 century run.

Yukimoto and Kodera (2005) analyzed the ensemble model experiments of the MRI climate models in the IPCC AR4 20C3M, where the same climate model is integrated using the same external forcing in the 20 century but with slightly different initial data. They interpret that the ensemble mean time series reflects the forced response to the external forcing such as increased CO_2, solar constant variation, and volcanic impact, which are common to each ensemble member. In contrast, the deviations from the ensemble mean for each member are considered as natural variability induced by the nonliniearity of the internal dynamics. With this method of separating variability, they concluded that both of the internal variability and forced response show the AO as the most dominant mode.

In this study, we extend the same analysis as Yukimoto and Kodera (2005) for ten IPCC AR4 climate models using the 20C3M experiments for the 20 century and SRES-A1B experiments for the 21 century. The same experiments are conducted using the barotropic general circulation model, called barotropic S-model, developed at the University of Tsukuba. The results are compared with IPCC AR4 models to find out the mechanism of the decadal-scale variation of the AO index.

2. IPCC MODEL EXPERIMENTS

2.1 Global mean temperature

Figure 1 shows the time series of the global mean surface air temperature for the 20C3M and SRES-A1B for the 5 ensemble members (thin lines) and the ensemble mean (thick line), provided by the MRI-CGCM (Meteorological Research Institute, Japan). For the 20 century run, the global mean temperature increases showing the global warming, especially for the period after 1970s. The global warming continues in the 21 century, and the warming of 2.5°C is projected during the next 100 years.

Since the model is integrated under the same external forcing, the ensemble mean reflects the forced response such as the increasing CO_2, and the deviation from the mean is considered as the internal variability induced by the nonlinearlity of the fluid mechanics. Interestingly, the internal variability is minor in its magnitude, and the long-term trend may be regarded mostly as the response to the external forcing.

2.2 AO index

The result is quite different when the same analysis is applied to the AO index. Figure 2 shows the time series of the AO index for the 20C3M and SRES-A1B by the same MRI-CGCM. For the 20 century run, ensemble mean (thick line) shows increasing trend especially after 1970s. As shown by Hori et al. (2007), the AO index indicates monotonic increasing trend for the 21 century projections. The increasing trend is smooth and monotonic in the 21 century run because the imposed external forcing is only the monotonic increase of CO_2.

In contrast, the time series for the 20 century are more complicated reflecting various kinds of external forcing, such as solar constant variation and volcanic impact, which are common to each ensemble member. The spatial structure of the EOF-1 for the ensemble mean is rather different from the AO.

When the deviations from the ensemble mean are concerned, the spatial pattern is recognized as AO for all of the members both in 20 and 21 century runs. The magnitude of the AO index is comparable to the magnitude of the general trends. Since the spatial pattern has the same vector norm, the AO index has a magnitude comparable to the long-term trends. Moreover, the time series are mutually independent and totally different from the observed AO index in the 20 century run (see Fig. 3) reflecting the fact that the variations are perfectly random implying a realization of the stochastic process.

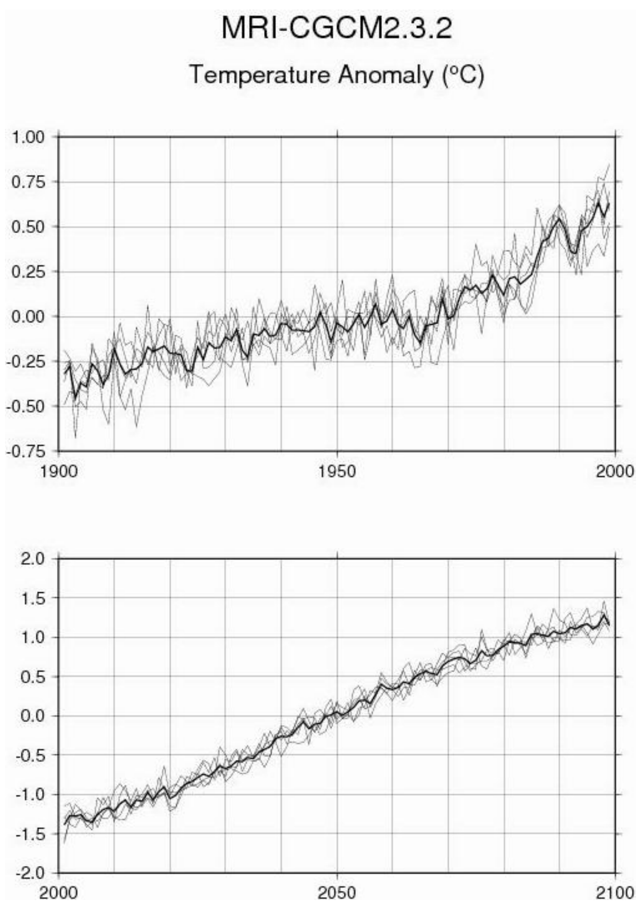

Fig. 1. Time series of global mean temperature for 20 and 21 centuries by the MRI ensemble model.

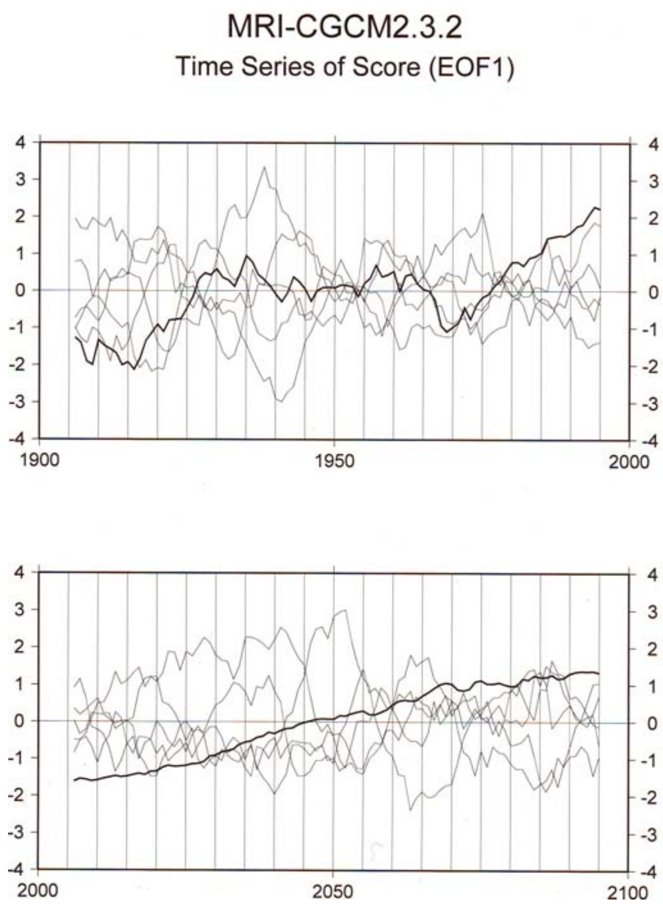

Fig. 2. As in Fig. 1, but for the AO index of the ensemble mean and its deviations.

3. BAROTROPIC S-MODEL

3.1 Singular eigenmode theory of the AO

In order to understand the dynamical cause of the AO, a simple barotropic general circulation model, called barotropic S-model, was constructed, parameterizing the effect of baroclinic instability. The barotropic S-model was integrated for 50 years from 1950 under the perpetual January condition. The EOF-1 of the internal variability was then analyzed to show the robust pattern of the AO as demonstrated by Tanaka (2003).

Because the essence of the dynamics of the AO is apparently contained in the barotropic S-model, a linear stability analysis was performed for the non-zonal climate basic state for January. As a result, it was found that the AO can be understand as an singular eigenmode of the general circulation, whose eignvalue is zero under the proper frictional damping (see Tanaka and Matsueda 2005). Since the eigenvalue is zero for this AO mode, it can be amplified resonantly by any arbitrary quasi-steady external forcing. It is important to note that the transient eddy forcing is an important factor to make the mode singular with the positive feedback between the AO mode and transient eddies. We call it a singular eigenmode theory to explain the dynamics of the AO.

3.2 An experiment with linear trend forcing

In order to understand the mechanism of the decadal-scale variability of the AO index from the viewpoint of the singular eigenmode theory, we conducted an ensemble model experiment using the barotropic S-model by imposing a known linear trend forcing based on the SRES-A1B experiments. The model is identical as used in Tanaka (2003), but the artificial external forcing with the AO pattern is imposed. The forcing varies linearly from negative to positive during the integration period of 50 years, and the magnitude is adjusted to meet with the linear trend analyzed for the 21 century run in Fig. 2.

Figure 3 illustrates the time series of the observed AO index for 50 years after Tanaka (2003), evaluated for the barotropic component of the atmosphere. Values are the 365-day running mean. There are notable climate shifts in 1976 from positive to negative and in 1989 from negative to positive. The AO index is decreasing after the peak around 1990.

Figure 4 shows a sample time series of one member of the ensemble experiment with the barotropic S-model, and Fig. 5 is the composite of the 6 members. In Fig. 5, the ensemble mean is plotted with a thick line. The imposed linear trend of external forcing is evident for the ensemble mean. Yet, more importantly, there are considerable amount of internal variability superimposed on the ensemble mean even for the decadal time-scale.

3.3 An experiment with observed forcing

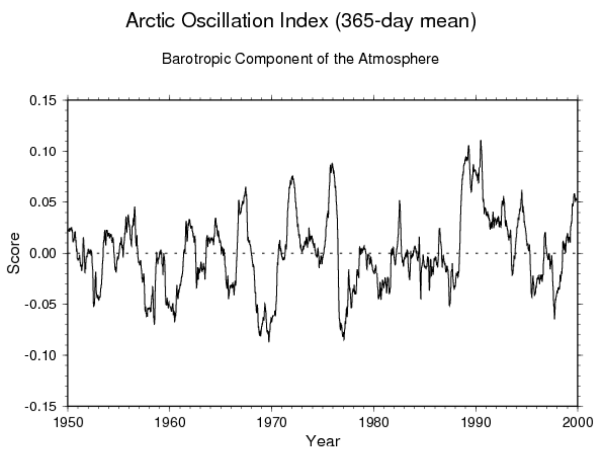

Fig. 3. Time series of observed AO index for 1950 to 2000 for the barotropic component of the atmosphere.

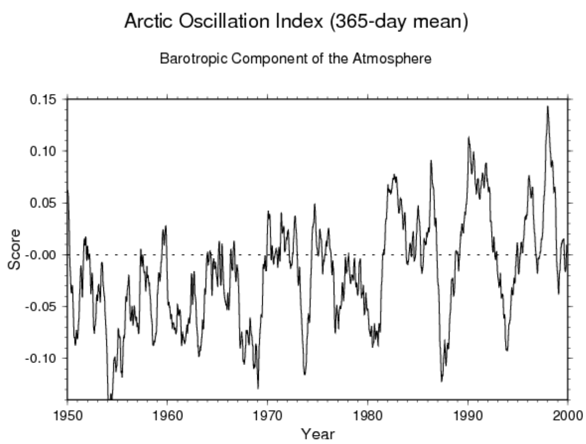

Fig. 4. As in Fig. 3, but for a member of the ensemble experiment with the barotropic S-model.

Finally, the artificial linear trend forcing is now replaced by the observed external forcing in this experiment. The perfect external forcing for the barotropic model was obtained from NCEP-NCAR reanalysis as the residual balance of the model equation for 50 years from 1950. The 365-day running mean of this perfect external forcing is fed to the barotropic S-model in place of the artificial linear trend forcing in the previous experiment.

Figure 6 shows the time series of the 6 ensemble mean of the forced model experiment. According to the result, it is found that the AO index is distinctly different from the observed time series of the AO index in Fig. 3. The result suggest that the observed AO index is not the forced response to some kind of long-term variability, but a realization of the stochastic process of the chaotic fluid mechanics.

4. CONCLUDING SUMMARY

In this study, the barotropic S-model was integrated 50 years, imposing an artificial linear trend to demonstrate the forced response of the model atmosphere. It is confirmed that the AO index indicates an increasing linear trend as shown for the 21 century run in the IPCC AR4 SRES-A1B experiments. More importantly, there are considerable amounts of internal variability superimposed on the trend which is rather similar in nature to the AO index.

The experiment is further extended to replace the artificial linear trend of forcing by the observed perfect external forcing. The result shows that the observed AO index is not simulated by the forced response experiment. Hence, it is concluded that the observed AO index is not the forced response to some kind of long-term variability, but a realization of the stochastic process of the chaotic fluid mechanics. If this is the case, predicting the AO index for long term is essentially impossible by the nature of chaos.

REFERENCES

Hori, M., D. Nohara, and H.L. Tanaka 2007: Influence of Arctic Oscillation toward the Northern Hemisphere surface temperature variability under the global warming scenario. J. Meteor. Soc. Japan. 85, 847-859.

Tanaka, H.L., 2003: Analysis and modeling the Arctic Oscillation using a simple barotropic model with baroclinic eddy forcing. J. Atmos. Sci., 60, 1359-1379.

Tanaka, H. L. and M. Matsueda, 2005: Arctic Oscillation analyzed as a singular eigenmode of the global atmosphere. J. Meteor. Soc. Japan. 83, 611-619.

Thompson, D. W. J. and J. M. Wallace, 1998: The arctic oscillation signature in the wintertime geopotential height and temperature fields. Geophy. Res. Let. 25, 1297-1300.

Yukimoto, S., and K. Kodera, 2005: Interdecadal Arctic Oscillation in twentieth century climate simulations viewed as internal variability and response to external forcing. Geophy. Res. Let, 32. L03707.

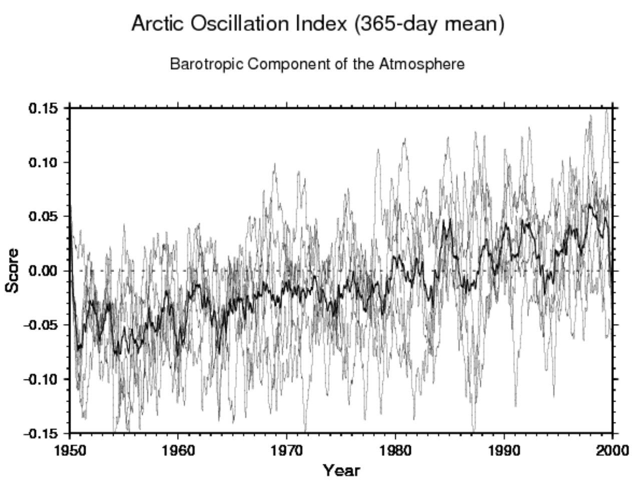

Fig. 5. Composite time series of the AO index for 6 ensemble members and the ensemble mean.

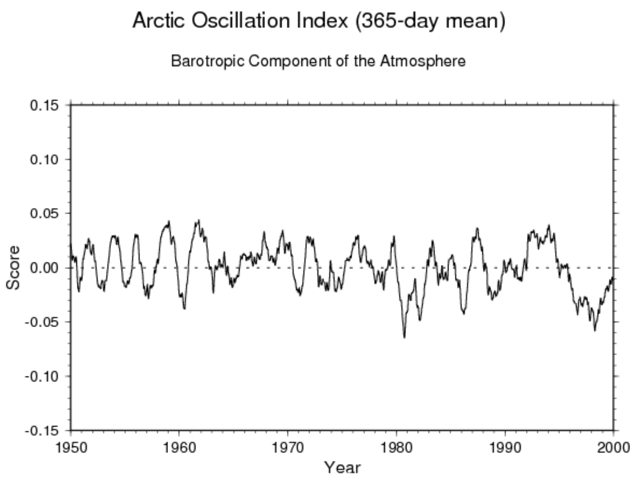

Fig. 6. Time series of the AO index for 6 ensemble mean with the observed external forcing.