A Trial of Predicting the Arctic Oscillation Index using the Barotropic S-Model

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1. INTRODUCTION

The Arctic Oscillation (AO) is a north-south seesaw of the atmospheric mass between the Arctic region pole-ward of 60°N and a surrounding zonal ring in the mid-latitudes. The AO is defined as the EOF-1 of the time variation in sea-level pressure p_s, which is dynamically related to the time variation of the barotropic component of the atmosphere. For this reason, the essential features of the AO are contained in the barotropic component of the atmosphere governed by the 2D fluid mechanics which characterizes the low-frequency variability.

Using a simple barotropic model derived from the 3D normal mode expansion, Tanaka (2003) conducted a numerical simulation of the AO and obtained the same structure as observed in the atmosphere (see Fig. 1 and 2). According to the 50 years time integration of the model, not only the EOF-1 of the AO mode but also the EOF-2 agrees well with the observation which is identified as the Pacific North America (PNA) pattern. The low-frequency variabilities such as the AO and PNA are evidently contained in the internal dynamics of the barotropic component of the atmosphere.

Beside the controversy to recognize the AO as a dynamical mode or a statistical artifact, a dynamical approach has been pursued by Tanaka and Matsueda (2005) by solving a singular mode with the smallest singular value of the linearized dynamical system, which is now referred to as the neutral mode theory (e.g., Kimoto et al. 2001; Watanabe and Jin 2004). Tanaka and Matsueda (2005) identified that the characteristics of the singular mode resembling with the AO are originated from the eigenmode of the dynamical system with nearly zero eigenvalue, i.e., singular eigenmode for the global atmosphere.

It is demonstrated that the singular eigenmode of the dynamical system emerges resonantly as the AO in response to the arbitrary forcing under a moderate linear damping. However, it is still unclear why the atmospheric low frequency variability shows almost no correlation between the Pacific and Atlantic sectors.

The purpose of this study is to examine the correlation between the barotropic heights at the Atlantic and Pacific sectors in the model atmosphere. The results are compared with that of the barotropic heights in the observed atmosphere.

Moreover, 60-day ensemble predictions are attempted in this study using the barotropic S-model developed at the University of Tsukuba. By the theoretical deduction, the Arctic Oscillation may be understood as a singular eigenmode of the global atmosphere induced by steady forcing. The singular eigenmode is amplified resonantly by the steady forcing because the eigenvalue is zero for this mode. If this is the case, the time mean bias near the initial condition of the time integration is essential for the long-term prediction in a monthly range.

Based on this hypothesis, we constructed an ensemble prediction model for the AO index for 60 days using various biases in the external forcing averaged for 10 to 60 days before the initial condition. The results are compare with the actual AOI by the observations in the past.

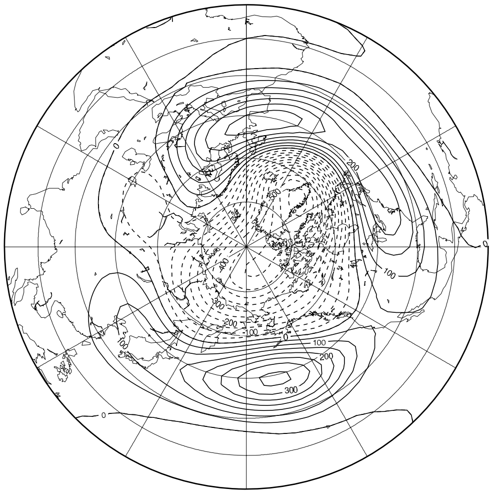

Figure 1: Barotropic height distribution of the EOF–1 evaluated for DJF of the last 51 years by the NCEP/NCAR reanalysis.

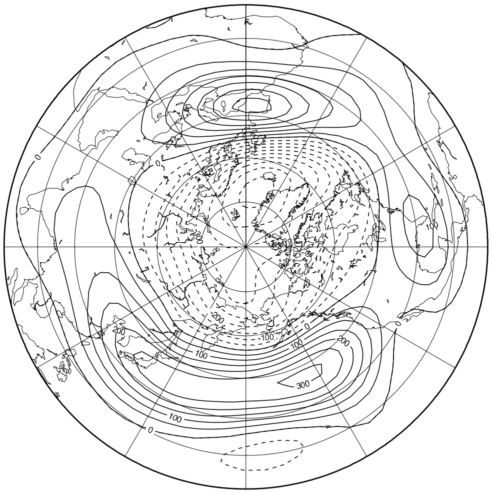

Figure 2: Barotropic height distribution of the EOF–1 evaluated for the 50-year perpetual January run of the barotropic S-model.

2. METHOD AND DATA

According to Tanaka (2003) the 3D representation of the spectral primitive equations on a sphere may be written as:

$$\frac{dw_i}{d\tau} = -i\sigma_i w_i - i\sum_{jk} r_{ijk} w_j w_k + f_i, \qquad (1)$$

where w_i is the complex state variable of the system obtained as the Fourier expansion coefficients of meteorological variables, σ_i is the eigenfrequency of the Laplace's tidal equation, f_i is the expansion coefficient of the external forcing of viscosity and diabatic heating rate, and r_{ijk} is the interaction coefficients for the nonlinear system.

In this study, the external forcing f_i is parameterized by the statistical regression with respect to the state variables w_i, using the 50 years of four times daily data by the NCEP/NCAR reanalysis as in Tanaka (2003):

$$f_i = \tilde{f}_i + \mathbf{A}_{ij} w_j + \mathbf{B}_{ij} w_j^* + \epsilon_i, \qquad (2)$$

where $\tilde{f}_i$ is the climate of f_i with a seasonal change and the asterisk for w_i represents a complex conjugate of w_i.

Because we can evaluate the perfect external forcing of f_i from the observation as the residual of the equation (1), the unknown linear matrices $\mathbf{A}_{ij}$ and $\mathbf{B}_{ij}$ may be obtained by the standard method of the least square fitting to minimize the regression residual ϵ_i. The model with such a forcing is named as "barotropic S-model" since the forcing is obtained statistically from observation.

Although the residual ϵ_i is minimized by this method for the 50-year time span, there remains a considerable bias of $\overline{\epsilon_i}$ for individual winter or monthly time scale. It is this temporal (or monthly mean) bias which is responsible to amplify the singular eigenmode of the AO for each winter. Considering this fact, we evaluated the model bias of $\overline{\epsilon_i}$ from the observation just before the initial condition, and adjust the bias expecting the improved forecasting skill, especially for the AO. Since we do not know the suitable time span to take the average of the model bias ϵ_i, an ensemble prediction technique is applied to the external forcing, setting the time mean for 10 days, 15 days, 20 days, and so on up to 60 days before the initial condition.

The data used in this study are four-times daily NCEP/NCAR reanalysis for 57 years from 1950 to 2006. Once the model is constructed, the nonlinear system was integrated for 50 years from the initial condition of 1 January 1950. The output of the model atmo-

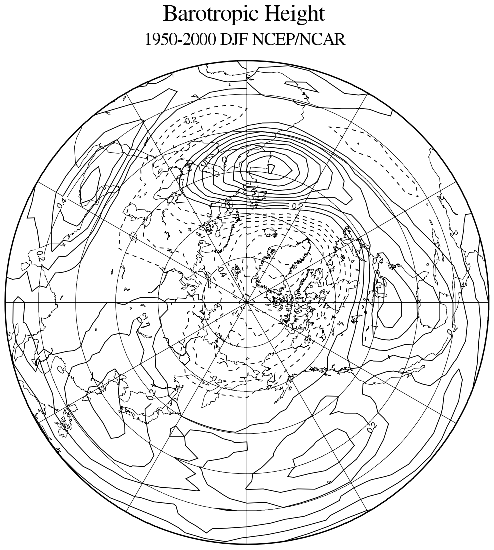

Figure 3: Distribution of the one point correlation centered at the Azores High for the NCEP/NCAR reanalysis.

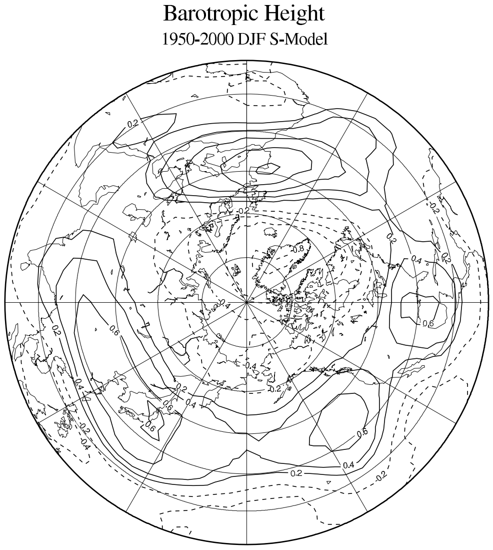

Figure 4: Distribution of the one point correlation centered at the Azores High for the barotropic S-model.

sphere are compared with the observation by the NCEP/NCAR reanalysis.

3. RESULT

Figure 1 shows the barotropic height structure of the AO obtained as the EOF-1 of the observed atmosphere for the 50 winters of DJF mean. The structure is compared with the 50-year perpetual January run of the barotropic S-model in Fig. 2 as demonstrated by Tanaka (2003). Although some differences may be noted, the fundamental annular structure and the Pacific and Atlantic centers of action of the AO are simulated.

Figure 3 illustrates the one point correlation map centered at the Azores High for the NCEP/NCAR reanalysis. As demonstrated by Deser (2000) or Itoh (2002), the one point correlation indicates a teleconnection with the Arctic demonstrating the North Atlantic Oscillation (NAO), and the positive correlation at the Pacific region is hardly seen. In contrast, Fig. 4 is the same one point correlation map for the barotropic S-model. Interestingly, the result clearly shows the AO pattern with apparent positive correlation at the Pacific sector. From this result, we can conclude that the AO in the barotropic S-model is certainly a physical mode inferred from the singular eigenmode theory or the neutral mode theory.

We compared the one point correlation map for the PNA pattern at the Pacific sector. The result shows clear wave-train from the North Pacific to the Southwestern Atlantic for both the NCEP/NCAR reanalysis and the barotropic S-model (not shown). The agreement for the PNA is perfect for the model and real atmospheres.

4. FORECAST OF THE AO INDEX

Next, we applied the barotropic S-model for the actual forecasting of the AO index, considering the model bias which is adjusted by the observations just before the initial condition. Figure 5 demonstrates the forecasting experiment for the winter of 2006/2007 starting from the end of November 2006.

The observed AO index underwent negative values in October, which returned to the normal values at the beginning of November. According to the result of the prediction experiments, all members of the ensemble forecast indicate large positive AO index for the winter of 2006/2007. The prediction appears to agree with what happened during this winter.

Similar experiments of the ensemble prediction of the AO index were repeated for many winters with extreme events of abnormally high AO index, e.g., 1988/1989, and abnormally low

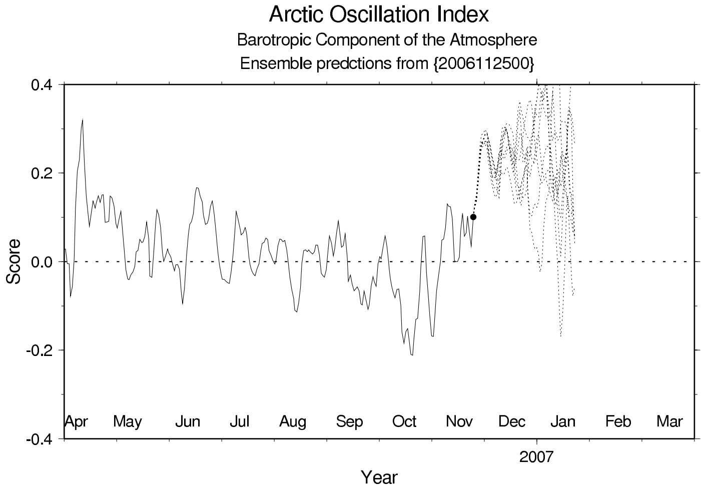

Figure 5: Ensemble predictions of the AO index by the barotropic S-model.

AO index, e.g., 1976/1977. Although the model predictions often failed for certain initial conditions, we found that the predictions were mostly better than we expected.

5. SUMMARY

In this study, we demonstrated the performance of the barotropic S-model to simulate the low-frequency variability occurring in the real atmosphere. It is demonstrated that only the one point correlation maps for the AO disagree between the model and real atmospheres. The one point correlation shows perfect mach with the AO pattern in the model, whereas the one point correlation shows insignificant correlation between the Pacific and Atlantic sectors in the observed atmosphere.

Based on the know performance of the barotropic S-model, ensemble predictions are attempted for the AO index up to 60 days into the future. By a deduction from the singular eigenmode theory, the Arctic Oscillation is amplified resonantly by the steady forcing anomaly. If this is the case, the time mean bias near the initial condition for the time integration is essential for the long term prediction in a monthly range.

Based on this hypothesis, we have constructed an ensemble prediction model for the AO Index for 60 days using various biases in the external forcing averaged for 10 to 60 days before the initial condition.

It is found that the prediction (hindcaste) for the past winter was mostly successful. As the first real trial, the AO index for the winter of 2006/2007 is predicted from the initial condition in November 2006. The result indicates that the AO index is large positive, suggesting warm winter in Japan. Although the prediction must be confirmed many times, the result suggests a possible predictability for the monthly range by the barotropic S-model.

Acknowledgments

The study was supported partly by the International Arctic Research Center (IARC/UAF) and by Asahi Breweries Foundation. The authors appreciate Ms. K. Honda for her technical assistance.

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