Prediction Experiments of the Arctic Oscillation Index Using a Barotropic General Circulation Model

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1 INTRODUCTION

The Arctic Oscillation (AO), postulated by Thompson and Wallace (1998), is one of the dominant atmospheric variabilities characterized as opposing atmospheric pressure patterns in northern middle and high latitudes. The oscillation exhibits a "positive phase" with relatively low pressure over the polar region and high pressure at mid-latitudes.

In the case that the AO is positive, the difference in atmospheric pressure between the Arctic region and mid-latitudes is larger, and jet stream is strengthened. Then it tends to be milder and rainy in Europe, and to be warmer in Japan in winter. On the other hand, in the case that the AO is negative, the difference in atmospheric pressure between the Arctic region and mid-latitudes is smaller, and jet stream is weakened. Then it tends to be sunny in Europe, and to be colder in Japan in winter.

Figure 1 illustrates the time series of the observed Arctic Oscillation Index (AOI) from 1988 to 2007. Values are the 90-day running mean and are calculated by the barotropic component of the atmosphere (to be discussed later). The positive and negative AOI correspond to the warmer and colder winter in Japan, respectively, for example, 1988/89 (warm winter) and 2005/06 (cold winter).

Tanaka (1991) developed a new barotropic general circulation model composed of 3-D spectral primitive equation, using the basis of the horizontal and vertical structure functions. This model predicts the barotropic component of the atmosphere. The barotropic component in this model is defined as follows, introducing the vertical structure functions G_0:

$$(u,\, v,\, \phi')_0^\top = \frac{1}{p_s}\int_0^{p_s} (u,\, v,\, \phi')^\top G_0\, dp$$

where u and v denote wind speeds, and φ' denotes the deviation of geopotential from the global mean.

The AO is characterized by a long-term variation with a barotropic structure. For this reason, it is meaningful to predict its barotropic component. And it is important to predict the AOI, which is a barometer of the strength of the AO in winter from the viewpoint of the seasonal forecast, because the AO is related closely to the climate in the North Hemisphere in winter.

So in this study, we investigated whether long-term (60-days) prediction of the AOI would be possible, using a Barotropic General Circulation Model (discussed later).

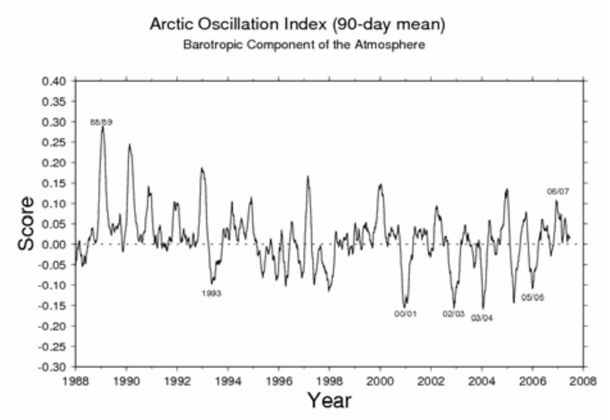

Fig. 1. Time series of the Arctic Oscillation Index (AOI) defined by the barotropic component of the atmosphere from 1988 to 2007.

2 METHOD

2.1 Barotropic S-Model

In this study, we used the barotropic S-Model, in which the optimum forcing of the model is statistically estimated from NCEP/NCAR reanalysis data. The spectral primitive equations in pressure coordinate are expanded by the 3D normal mode functions. When the equation is closed using only the vertical mode zero, we obtain

$$\frac{dw_i}{d\tau} + i\sigma_i w_i = -i \sum_{j=1}^{K} \sum_{k=1}^{K} r_{ijk} w_j w_k + s_i$$
$$i = 1, 2, 3, \ldots, \quad (m = 0)$$

where w_i and s_i are the expansion coefficients of the atmospheric state variable and forcing term (see Tanaka and Nohara, 2001).

However, this S-Model is characterized by slightly weak amplification of baroclinic instability, and cannot reproduce the AO in the model. So, we give additional forcing s_i as follows, introducing the physical processes of baroclinic instability and so on.

$$s_i = \tilde{s}_i + \mathbf{A}_{ij} w_j + \mathbf{B}_{ij} w_j^* + (BC)_{ij} w_i + (DF)_{ij} w_i + (DZ)_{ij} w_j + (DE)_{ij} w_i$$

where BC, DF, DZ, and DE denote baroclinic instability, diffusion, zonal surface stress, and Ekman damping, respectively (see Tanaka, 2004).

2.2 Ensemble forecast

By the parameterization of the forcing, the long-term model bias is eliminated, but it is anticipated that the short-term bias of the model still remains.

So in this study, we constructed the ensemble forecast, adding the bias-adjusted forcing. And we examined the differences between the control run and the ensemble forecasts.

3 RESULT

3.1 2005/2006 winter (cold winter)

In winter of 2005/2006, particularly in December, record breaking low temperature and heavy snow were observed in various regions in Japan.

Figure 2 illustrates the composite chart of time series of the AOI from July 2005 to March 2006 defined in the barotropic component. According to the observed value of the AOI, it began to show the negative value around November. In particular, the AOI shows big drops in early and middle November and in early December. The negative AOI continued until the first half of December.

Figure 2 also shows a result of 60-days predictions of the AOI using the barotropic S-Model with an initial time of 00UTC 1 October 2005 (black circle). The dashed line shows the control run, the dotted lines show each member of the ensemble forecasts which consider the model bias before the initial time, and the thick solid line shows the ensemble mean. All ensemble members can predict the AOI dropping to a lower value. The spread of the members is not so wide. It is thought that the prediction of the AOI was good. In addition, in case of other initial time in October, the prediction of the AOI was good too (not shown).

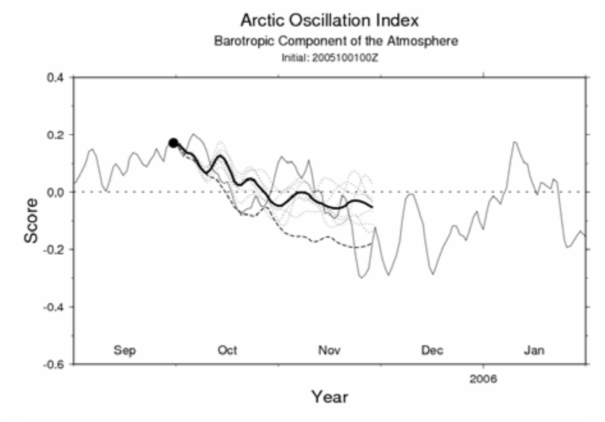

Fig. 2. The 60-days prediction of AOI with an initial time of 00UTC 1 October 2005. Black circle is the initial time. The thin solid line shows the real value of AOI, the dashed line shows control run, the dotted lines show ensemble member, and the thick solid line shows the ensemble mean.

However, in case of the initial time of November, the prediction skill became worse suddenly. Figure 3 illustrates a result of 60-days prediction of the AOI with the initial time of 00UTC 1 November 2005 (black circle). This figure shows that the S-Model can not predict the AOI dropping to a lower value, and any ensemble member can not predict the AOI. The prediction was bad for the initial time of 00UTC 6 November 2005 as well (not shown).

3.2 2006/2007 winter (warm winter)

In contrast to the winter of 2005/2006, the winter of 2006/2007 was the record warm characterized by the lack of snow along the Sea of Japan side around Hokuriku district. According to the real value of the AOI, it began to shift to the positive value around November and was the positive value from late December to early January.

Figure 4 illustrates a result of 60-days prediction of the AOI with the initial time of 00UTC 11 November 2006 (black circle). This shows that the spread among members is wide, but the ensemble mean forecast was improved. It is interesting to note that the forecast by the control run (dashed line) was bad while the forecast by the ensemble mean with the bias correction (thick solid line) is better. In addition, in the case of the other initial time, the forecast skill was hardly affected.

4 DISCUSSION

It is thought that the prediction exceeding two weeks is quite difficult by chaos in the atmosphere in current weather forecast. However, it is found that AOI could be predicted exceeding two weeks by predicting the barotropic component of the atmosphere. And the ensemble forecast in consideration of the bias correction was better than the control run. Therefore it is thought to be effective to use the ensemble forecast.

On the other hand, the forecast occasionally changed a lot depending on the initial time. It is generally said that the prediction skill in new initial value is better than in old initial value, but the result of this study shows it is not necessarily the case.

As a cause of the bad prediction, it is considered that one is the initial value problems and the other is the model problems. It is thought that the model problems relate to the prediction skill in this study because the sensitivity to the initial value is low in the barotropic S-Model (Tanaka and Nohara, 2001).

In the barotropic S-Model, the key point to improve the forecast skill is the parameterization of forcing. Figure 5 illustrates the 60-days prediction of the AOI using the barotropic P-Model, which gives the correct forcing. The black circle shows the initial value, the thin solid line shows the real value of the AOI, and the thick solid line shows the forecast. Thick solid line goes over to the thin solid line, so the forecast is quite similar to the real value. For this result, if we get the correct forcing, the forecast skill will be further improved in the barotropic S-Model.

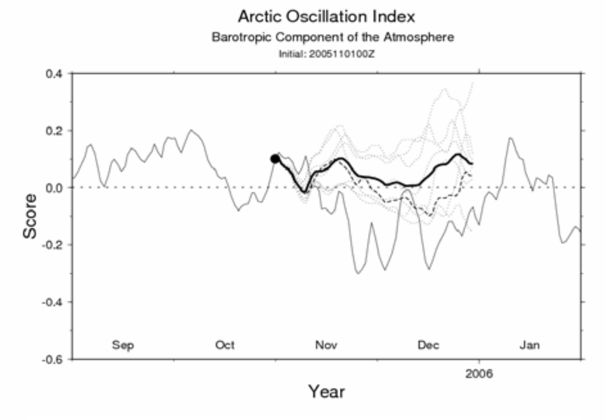

Fig. 3. As in Fig. 2, but for the initial time of 00UTC 1 November 2005.

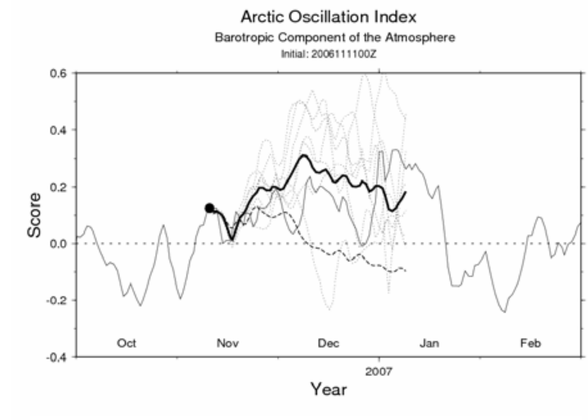

Fig. 4. As in Fig. 2, but for the initial time of 00UTC 11 November 2006.

In this study, we constructed the ensemble forecast adding the bias-adjusted forcing. As a result, the ensemble forecast was better than the control run in many cases. But in some cases, the ensemble forecast shows no improvement in the forecast skill.

Figure 6 illustrates the relations between Root Mean Square Error (RMSE) and spread. It is favorable to be a ratio of 1 to 1 between RMSE and spread in the ensemble forecast. But in this study, spread is approximately half of RMSE. This suggests that the ensemble forecast cannot capture the total of all possible outcomes that affects the prediction skill. In this study, we used "time mean of bias" as the perturbation, but it is thought that this reduced the forecast skill in some cases. For this reason, in order to improve the prediction skill, it is considered that we need to develop another method to correct the bias of the model.

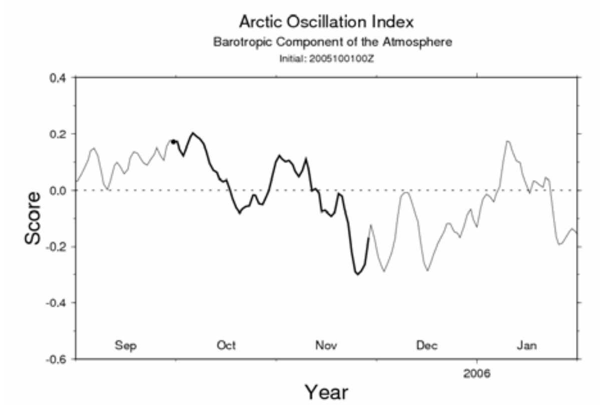

Fig. 5. The 60-days prediction of the AOI with an initial time of 00UTC 1 October 2005 in case of the correct forcing. The thin solid line and the thick solid line show the real value and the prediction of AOI, respectively.

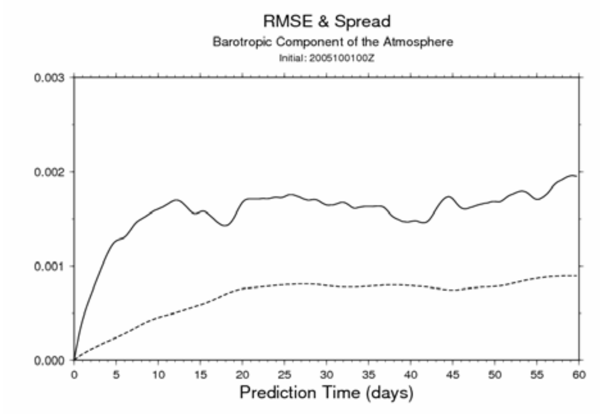

Fig. 6. RMSE (solid line) and spread (dashed line) of the forecast with an initial time of 00UTC 1 October 2005.

5 CONCLUSION

In this study, we investigated the predictability of the AOI with the ensemble technique, using the barotropic S-Model at the University of Tsukuba.

As a result, it was demonstrated that the AOI could be predicted exceeding two weeks in many forecast experiments. And it was suggested that the ensemble forecast was effective. On the other hand, the forecast occasionally changed a lot depending on the different periods of initial conditions.

In order to improve the prediction skill, it is considered that we need to introduce a new parameterization of forcing and another method to correct the bias of the model.

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