Numerical Simulation and EOF Analysis of the Arctic Oscillation in the Boreal Summer using the Barotropic S-Model

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1. INTRODUCTION

Boreal summer of 2003 was characterized by a typical abnormal weather at many regions in the Northern Hemisphere. A large and persistent blocking system stayed over the northern Europe, causing an extremely hot summer. The mean temperature had exceeded 4 times the standard deviation with the normal probability of one in 10,000 events. On the contrary, an abnormal cool summer was recorded in Japan, despite that the prediction by the Japan Meteorological Agency was hotter than normal. A pronounced blocking occurred over the Sea of Okhotsk, blowing a cool maritime northeasterly called Yamase toward the northeastern coast of Japan (Japan Meteorological Agency 2003).

According to the report by Yamazaki (2004), the hot Europe and cool Japan were connected by each other in terms of the Arctic Oscillation (AO) during summer. Yamazaki investigated the seasonally varying Northern Annular Mode (SV-NAM) and compared the winter NAM and summer NAM. Here, the AO and NAM are used for almost the same modal structure. The AO in winter has a nodal structure at about 60°N, whereas that in summer has a nodal structure at about 70°N. As an important characteristic, the AO in winter shows two centers of action over the north Pacific and the north Atlantic, whereas that in summer shows two center of actions over the north Europe and Sea of Okhotsk (see Thompson and Wallace 1998; Tanaka and Tokinaga 2002; Tanaka 2003). Based on the analysis result of the SV-NUM, Yamazaki showed that the extreme events at Europe and Sea of Okhotsk in 2003 were connected and caused by the AO in summer.

The purpose of this study is to investigate the AO in boreal summer to confirm Yamazaki's analysis result. The EOF analyses are conducted for each season and also for each month. Since the low-frequency variability is characterized by the barotropic structure even for summer, attention is concentrated in barotropic component of the atmosphere. A barotropic S-model (see Tanaka 2003) which has a capability to reproduce the AO in winter is applied to simulate the AO in summer in order to understand the low-frequency dynamics of the AO for all seasons.

2. MODEL AND DATA

The model description is given by Tanaka (2003) in detail. In order to obtain a system of 3-D spectral primitive equations, we expand the state variables $U = (u, v, \phi')^T$ in 3-D normal mode functions by a pair of the Fourier transforms:

$$U(\lambda, \theta, p, t) = \sum_{nlm} w_{nlm}(t) X_m \Pi_{nlm}(\lambda, \theta, p), \quad (1)$$

$$w_{nlm}(t) = < U(\lambda, \theta, p, t),\, X_m^{-1} \Pi_{nlm}(\lambda, \theta, p) >, \quad (2)$$

where $\Pi_{nlm}(\lambda, \theta, p)$ is 3-D normal mode func-

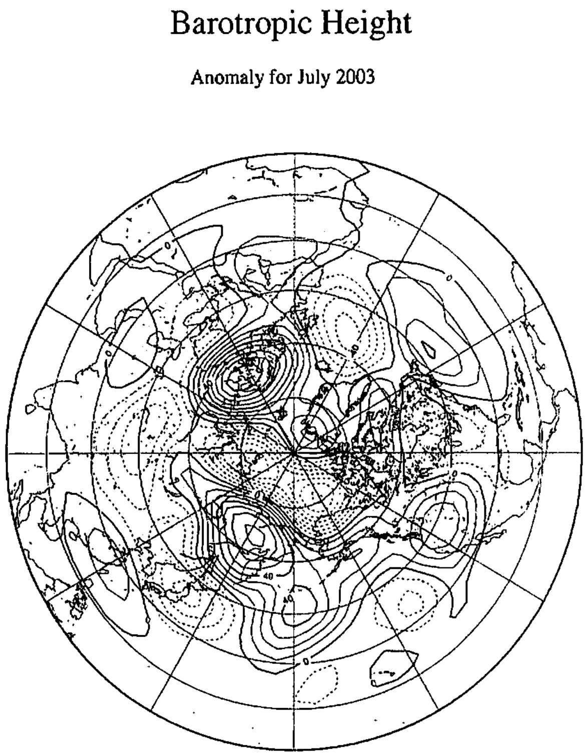

Figure 1: Distribution of the barotropic height anomaly for July 2003 by the NCEP/NCAR reanalysis.

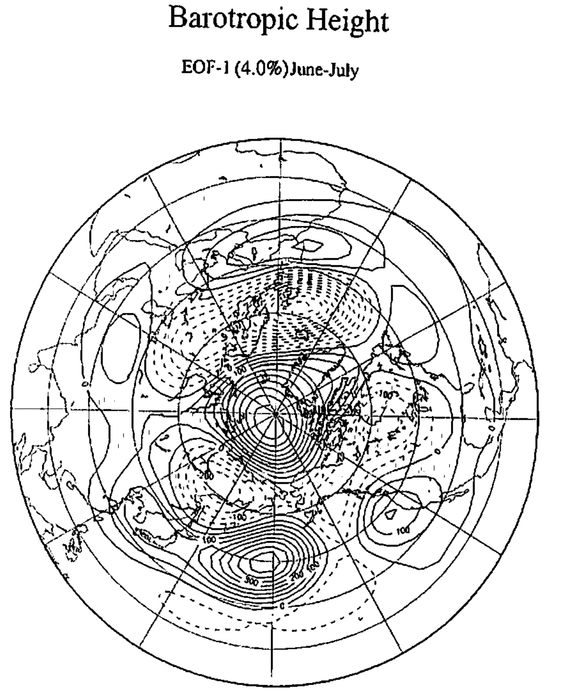

Figure 2: Distribution of the barotropic height of EOF-1 for June and July during 1950-2000.

tions in a resting atmosphere, and the dimensionless expansion coefficients $w_{nlm}(t)$ are the functions of time alone. The subscripts represent zonal wavenumbers n, meridional indices l, and vertical indices m. The scaling matrix X_m is defined at each vertical index. The 3-D normal mode functions form a complete set and satisfy an orthonormality condition under a proper inner product $<, >$, representing a mass integral over the globe.

The EOF analysis is conducted for the state variable w_i in the spectral domain for each month or for each season of the long-term observational data.

By expanding the state variable in 3D normal mode functions, we obtain a system of 3D spectral primitive equations in terms of the spectral expansion coefficients w_i:

$$\frac{dw_i}{d\tau} = -i\sigma_i w_i - i\sum_{jk} r_{ijk} w_j w_k + f_i, \qquad (3)$$

where τ is a dimensionless time, 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 nonlinear wave-wave interactions. The model is referred to as barotropic S-model when the external forcing f_i is evaluated statistically from the long-term observational data.

The data used in this study are four-times daily NCEP/NCAR reanalysis for 51 years from 1950 to 2000 (see Kalnay et al. 1996). The data contain horizontal winds (u, v) and geopotential ϕ, defined at every 2.5° longitude by 2.5° latitude grid point over 17 mandatory vertical levels from 1000 to 10 hPa.

3. AO IN SUMMER 2003

Figure 1 illustrates the anomaly distribution of the barotropic height for July 2003 by the NCEP/NCAR reanalysis. A pronounced positive anomaly of 80 m is seen over the northern Europe associated with the persistent blocking in July. Another marked positive anomaly is seen over the eastern Siberia with the height

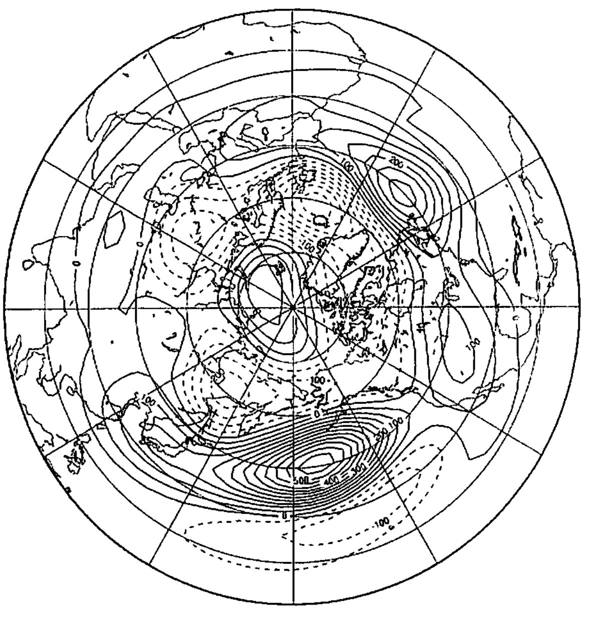

Figure 3: Distribution of the barotropic height of EOF-1 for June during 1950-2000.

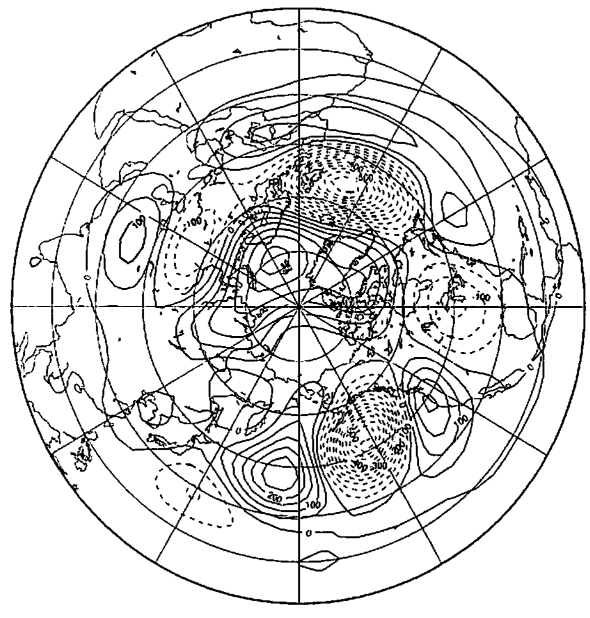

Figure 4: Distribution of the barotropic height of EOF-1 for July during 1950-2000.

anomaly of 60 m. Between these two positive anomalies, there is a negative anomaly over Laptev Sea extending toward the Arctic Ocean, and Japan is also located in a negative anomaly reflecting the cooler than normal summer. A wave-activity flux of quasi-stationary Rossby waves is analyzed from the positive anomaly in Europe via Laptev Sea to eastern Siberia (not shown).

Figure 2 illustrates the distribution of the EOF-1 evaluated for the daily data in June and July for the last 51 years. The variance is 4.0%. The result is consistent with that obtained by Yamazaki (2004), showing a negative anomaly over Europe, positive anomaly over the Arctic Ocean to Laptev Sea, and negative anomaly over the east Siberia. Japan is located in the positive anomaly whose center is seen in the northern Pacific. This characteristic pattern was named by Yamazaki as the AO in summer analyzed as a part of the SV-NAM in summer. The pattern is different from that in winter in that the nodal structure around the Arctic Ocean is located about 70°N. It is important to note the resemblance with the anomaly distribution in July 2003 with opposite sign. According to Yamazaki, the score time series projected onto the AO in summer exceeds 4 sigma during the summer of 2003, explaining how extreme the summer was.

The EOF analysis is conducted for each month in this study. Figures 3 and 4 illustrate the EOF-1 for June and July, respectively. It is found that the pattern is rather different from that in Fig. 2 with respect to the key wave train from Europe to east Siberia. The pattern in June is characterized by the large positive anomaly over the northern Pacific, although a positive anomaly is seen over the Arctic Ocean surrounded by a ring of negative anomaly. The pattern in July is characterized by two negative centers over the north Atlantic and northeast Pacific. The AO in summer appears to be sensitive to the analysis period and is not stubborn compared with that in winter.

4. SIMULATION BY THE S-MODEL

Knowing that the AO in summer is not robust

Barotropic Height

EOF-3 (4.8%)

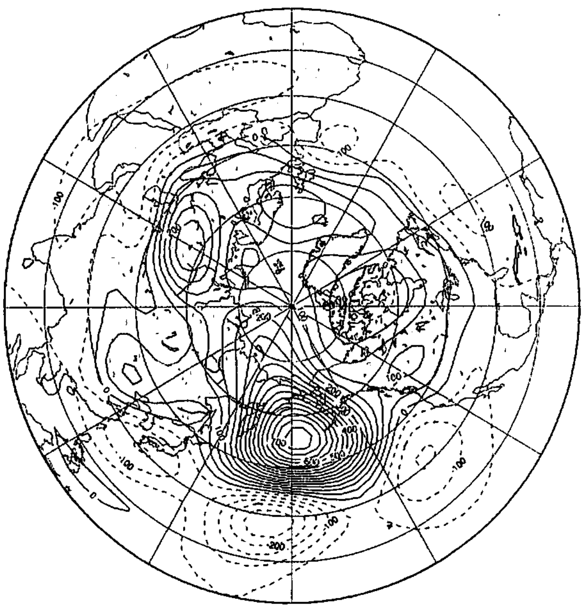

Figure 5: Distribution of the barotropic height of EOF-3 for a perpetual July run by the barotropic S-model.

compared with that in winter, a numerical experiment of the AO in summer is conducted by a perpetual July run for 50 years, using the barotropic S-model. Figure 5 illustrates the result of the barotropic height for EOF-3. We note that the EOF-1 and EOF-2 are recognized as a pare of baroclinic instability in mid-latitudes with a typical scale of zonal wavenumber 6. The distribution shows large positive center over the north Pacific. It is positive in mid to high latitudes and negative in low latitudes. The result is not convincing to reproduce the AO in summer by the same barotropic S-model. More experiments may be required to conclude whether the AO in summer can be reproduced by the barotropic dynamics.

5. CONCLUSION

In this study, the AO in summer is investigated to confirm the result by Yamazaki (2004) and to understand the cause of the abnormal weather in 2003. The EOF analyses are conducted for the barotropic component of the atmosphere in June and July as well as the mean of June to July. It is shown that the AO in summer, which is similar to the anomaly pattern in July 2003, is obtained for the mean of June and July. However, the result is sensitive to the choice of the analysis period and is not robust compared with the AO in winter. A numerical experiment is conducted by a perpetual July run for 50 years. The result is not convincing to reproduce the AO in summer using the S-model applied for the summer case. Further experiments may be required to conclude whether the AO in summer can be reproduced by the barotropic dynamics.

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