Analysis of the Structure and Wave Activity Flux of the Arctic Oscillation in Summer.

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1. Introduction

The Arctic Oscillation (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-latitude. The AO is a notable atmospheric phenomenon in the Northern Hemisphere in winter. The AO is also referred to as the Northern Hemisphere annular mode (NAM).

The study of AO in winter is advanced by Ogi et al. (2004a) for summer. They investigated the seasonally varying Northern Anular Mode (SV-NAM) and compared the NAM in winter and summer. The AO in summer has a smaller meridional scale and is displaced poleward as compared to the AO in winter. The antinode on the lower-latitude side in the AO in summer is at the nodal latitude of the AO in winter. As the important characteristics, the AO in winter shows two centers of action over the north Pacific and the north Atlantic, whereas that in summer shows two centers of action over the north Europe and Sea of Okhotsk. According to Ogi et al. (2005), anomalous weather in summer in the Northern Hemisphere is connected to the summer NAM. Atmospheric circulation anomalies of summer NAM closely resemble the anomalies in the summer of 2003, and the summer NAM index was quite large during the period from mid-July to early Augest when abnormal weather took place in Europe, Canada and Russia.

The purpose of this study is to investigate the AO in summer and winter by applying EOF analyses for each month from January to December. Analyses are consentrated on the barotropic component of the atmosphere since the characteristics of the surface pressure is contained in the barotropic component. Moreover, wave activity flux, derived by Takaya and Nakamura (2001), is analyzed for AO defined for each month in reference to Yamashita et al. (2005). In addition, the analysis is extended to the abnormal summer of 2003 to investigate the cause of the abnormal weather.

2. Data and Method

The data used in this study are four-times daily NCEP/NCAR reanalysis for 54 years from 1950 to 2003. The data contain horizontal winds (u, v) and geopotential ϕ, defined as every 2.5°longitude by 2.5°latitude grid point over 17 mandatory vertical levels from 1000 to 10 hPa.

The EOF analysis is conducted for the

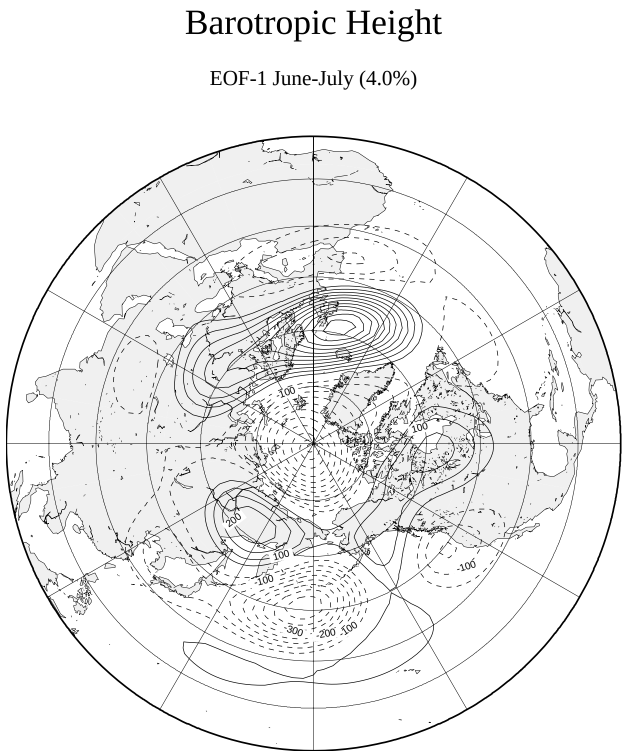

Figure 1: Distribution of the EOF−1 evaluated for the daily data in June and July for the last 51 years by the NCEP/NCAR reanalysis.

state variables of the Fourier expansion coefficients in the spectral domain of the primitive equation for each month of the long-term observational data.

The description of the wave activity flux is given by Takaya and Nakamura (2001). They have derived an approximate conservation relation of the wave activity pseudomomentum for quasigeostrophic eddies on a zonally varying basic flow through averaging neither in time nor in space. The wave activity flux defined as

$$\frac{\partial M}{\partial t} + \nabla \cdot \mathbf{W} = D_\tau, \qquad (1)$$

$$\mathbf{W} = \frac{\sigma}{2|\mathbf{U}|} \begin{pmatrix} U(\psi_x'^2 - \psi'\psi_{xx}' + V(\psi_x'\psi_y' - \psi'\psi_{xy}) \\ U(\psi_x'\psi_y' - \psi'\psi_{xy}') + V(\psi_y'^2 - \psi'\psi_{yy}) \\ \frac{f_0^2}{N^2}\left[(\psi_x'\psi_z' - \psi'\psi_{xz}') + V(\psi_y'\psi_z' - \psi'\psi_{yy})\right] \end{pmatrix}$$

$$+\mathbf{C}_U M, \qquad (2)$$

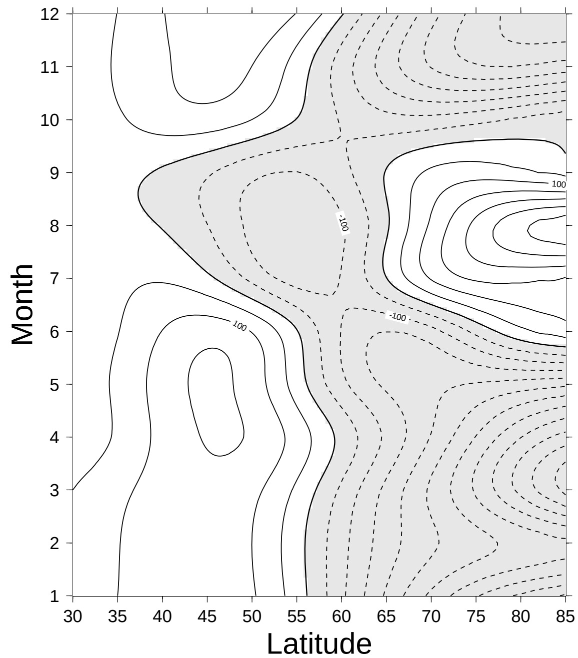

Figure 2: Seasonal variation of the AO as computed by the zonal mean barotropic height anomalies in the Northern Hemisphere over 30°N to 85°N.

where $M \equiv (A + E)/2$ is the phase-independent quantity related to the wave activity pseudomomentum, $\mathbf{U} = (U,\ V,\ 0)^T$ is a steady zonally inhomogeneous basic flow, A is enstrophy derived by the magnitude of the basic potential vorticity gradientand, and E is energy derived by the wave intrinsic phase speed. The conservation law (1) is obtained without any averaging. Therefore, the phase-independent flux $\mathbf{W}$ is suitable for a snapshot analysis of stationary or migratory eddies on a zonally varying basic flow.

3. Result

Figure 1 illustrates the distribution of the EOF-1 evaluated for the daily data in June and July for the last 51 years by the NCEP/NCAR reanalysis. The structure shows a positive anomaly over Europe, negative anomaly over the Arctic Ocean to Laptev Sea, and positive anomaly over the east Siberia. Japan is located in the negative anomaly whose center is seen in the northern

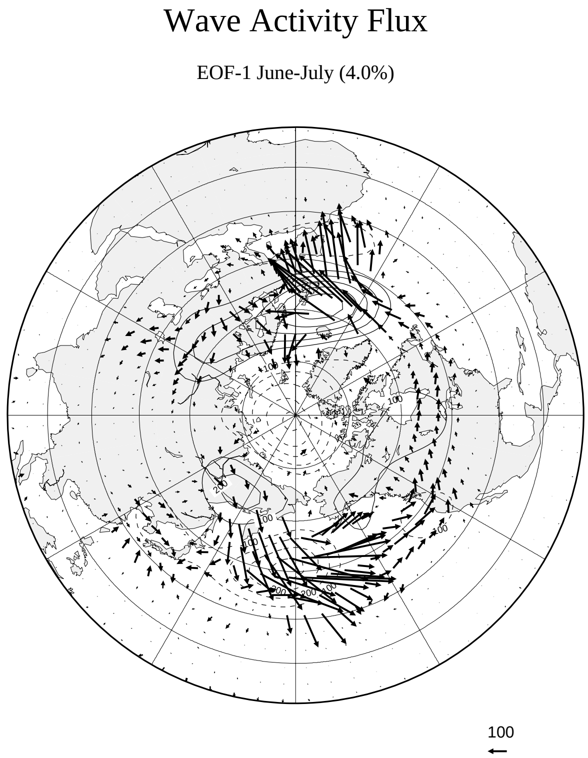

Figure 3: Wave activity flux $\mathbf{W}$ (m^2/s^2) for the AO in summer by arrow superimposed on the pattern of the AO by contour.

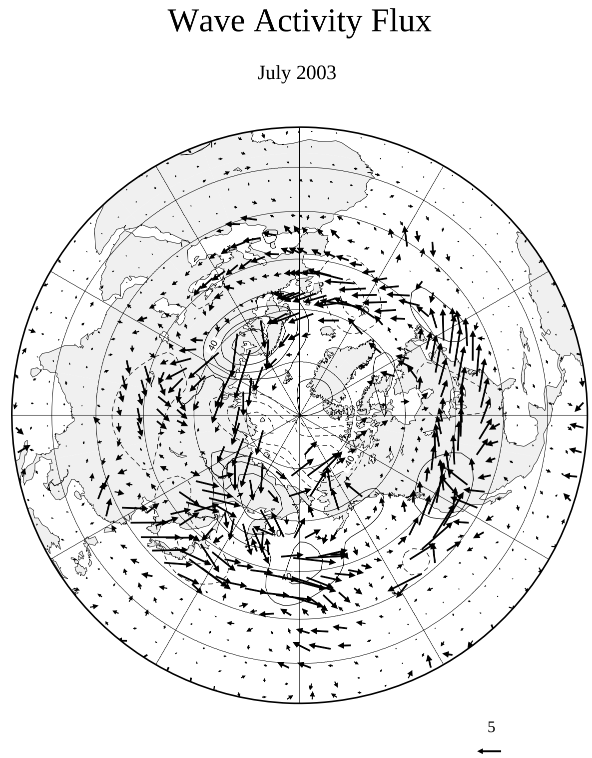

Figure 4: Anomaly distribution of anomaly distribution of the barotropic height and the wave activity flux (m^2/s^2) for July 2003.

Pacific. The variance explaines 4.0 % of the total variance. The result is consistent with that obtained by Ogi et al. (2004a) with opposite sigen. This characterestic pattern was named by Ogi et al. 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.

Figure 2 illustrates the seasonal variation of the AO as computed by the zonal mean barotropic height anomalies in the Northern Hemisphere over 30°N to 85°N. From January to April, the node of the AO is near 55°N. The node moves toward low latitudes in May. At the same time, a positive area appears in June in the Arctic region and expanded southward to 65°N. The AO from June to Octorber shows a tri-pole structure with a negative are centered at 55°N and two positive areas at the north and south of it. The result disagrees with that by Ogi et al. where the seasonal variation of the node moves from 55°N in winter to 65°N in summer. The seasonal shift in May to June is analyzed in detail using 5-day interval and confirmed that the node shifts southward instead of northward.

Next, the wave activity flux is conducted for the AO in winter and summer. The wave activity flux for the AO in winter is consistent with that analyzed by Yamashita et al. (2005), showing a northward flux from the Pacific to the Arctic and a southward flux from the Arctic to Atlantic (not shown). The ave activity flux conducted for EOF-2 in January shows a marked wavetrain of Pasific North Atlantic (PNA) pattern from Pacific to North America (not shown).

Figure 3 illustrates the wave activity flux $\mathbf{W}$ for the AO in summer by arrow superimposed on the pattern of the AO by contour. It shows two independent wavetrains from North Atlantic to Europe and from Eastern Siberia to North Pacific. There is no wavetrain over Siberia.

The analysis is extended to the abnormal summer of 2003. Figure 4 illustrates the anomaly distribution of the barotropic height and the wave activity flux for July 2003. 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 Siberian with height anomaly of 60 m. The wave activity flux during the summer shows a wavetrain from Norh Atlantic via Europe to Eastern Siberia. Compared with Fig. 3, the result shows that the AO in summer can explain the overall distribution of abnormal anomalies in the Northern Hemisphere in 2003. However, it can not explain the characteristics of the wave activity flux in 2003.

4. Concluding summary

In this study, the AO in summer is investigated by applying EOF analysis, and the characteristics of the wave activity flux are examined. The EOF analyses are conducted for the barotropic component of the atmosphere for each month from January to December. It shows that the structure of the AO in summer appears in June by the expansion of the negative anomaly in the Arctic southward, producting a new positive anomaly over Arctic. The wave activity flux associated with the AO in summer shows two independent wavetrains from North Atlantic to Europe and from Eastern Siberia to North Pacific. There is no wavetrain over Siberia. The analysis is extended to the abnormal summer in 2003. It is concluded that the AO in summer can explain the overall distribution of abnormal anomalies in the Northern Hemisphere. However, the characteristic wave activity flux in 2003 from Norh Atlantic via Europe to Eastern Siberia was not understood by the AO in summer.

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