Seasonal Variation of the Arctic Oscillation

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1. INTRODUCTION

The Arctic Oscillation (AO) is a notable atmospheric phenomenon in the Northern Hemisphere in winter, which 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 defined as the primary mode of the empirical orthogonal functions (EOF–1) for the wintertime sea level pressure (SLP) anomaly in the Northern Hemisphere (Thompson and Wallace 1998: TW1998).

The study of AO in winter was advanced by Ogi et al. (2004) for summer. They investigated the seasonally varying Northern Annular 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.

Beside the controversy to recognize the AO as a dynamical mode or a statistical artifact (see Itoh 2002), 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.

The purpose of this study is to investigate the seasonal variation of the AO by applying empirical orthogonal function (EOF) analyses for each month. Moreover, compared with the theoretical AO mode obtained by SVD analysis, we investigate whether the AO in each season, especially in summer, is a physical mode of a dynamical system for the global atmosphere or not.

2. DATA AND METHOD

The data used in this study are monthly data NCEP/NCAR reanalysis for 51 years from 1950 to 2000. 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. Analyses are concentrated on the barotropic component of the atmosphere since the characteristics of the surface pressure is contained in the barotropic component.

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 τ is a demensionless 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.

In this study, only the barotropic compo-

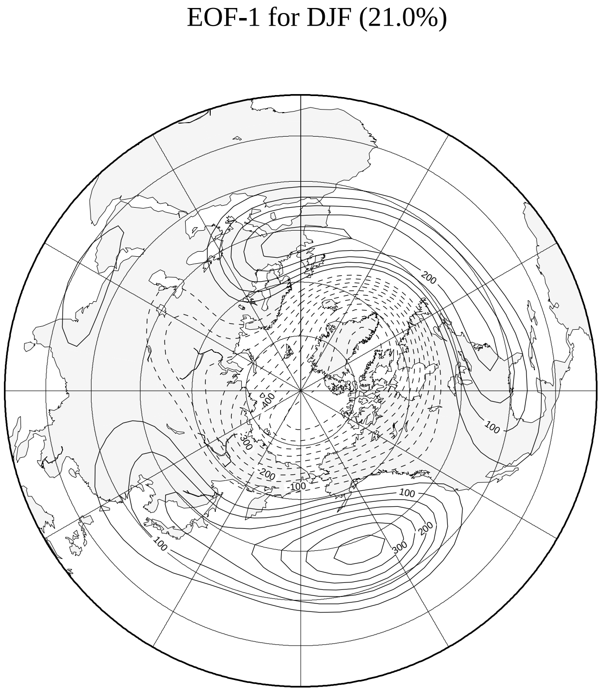

EOF-1 for DJF (21.0%)

Figure 1: Distribution of the EOF–1 evaluated for the climate data in DJF for the last 51 years by the NCEP/NCAR reanalysis.

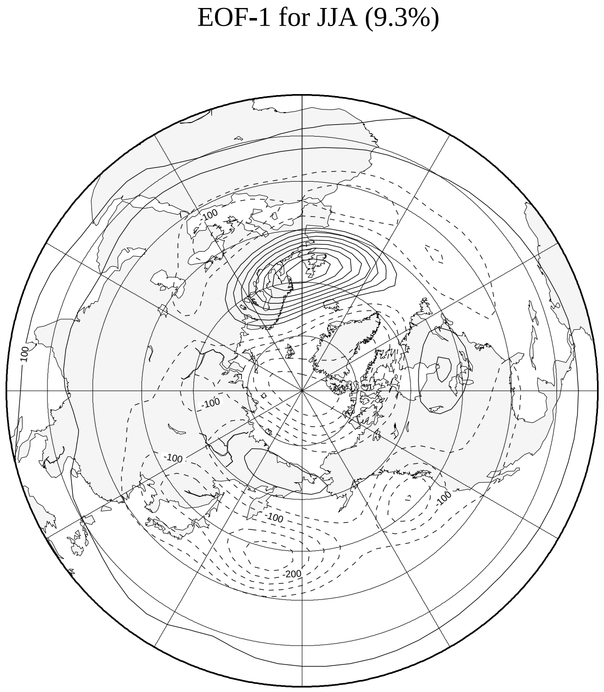

EOF-1 for JJA (9.3%)

Figure 2: Distribution of the EOF–1 evaluated for the climate data in JJA for the last 51 years by the NCEP/NCAR reanalysis.

nent of the 3D spectral model is considered to represent the simple dynamics of the low-frequency variability which indicates equivalent barotropic structure. The frictional forcing d_i in f_i is parameterized by the following hyper diffusion and Rayleigh friction as in Tanaka and Matsueda (2005):

$$d_i = -k_D c_i^{-4} w_i - \nu_S w_i, \qquad (2)$$

where k_D is a diffusion coefficient, c_i is a phase speed of Rossby modes given as:

$$c_i = \frac{\sigma_i}{n} \simeq \frac{-1}{l(l+1)}, \qquad (3)$$

where n and l designate zonal and meridional wavenumbers. The linear damping coefficient ν_S is first set zero and will be added later to shift the eigenvalues so that the system becomes singular.

3. RESULT

The EOF analysis is conducted for each season using the monthly data for the last 51 years by the NCEP/NCAR reanalysis. The structure of the EOF-1 for DJF shows positive anomalies over the northern Pacific and the northern Atlantic, and negative anomaly over the Arctic Ocean (Fig.1). This pattern is identical to the AO pattern defined by TW1998. The structure of the EOF-1 for MAM is similar to the EOF-1 for DJF, but negative area over the Arctic is reduced to northward (not shown). For the EOF-1 for JJA, the characteristic annular pattern of the AO has lost. It is found that the pattern is characterized by the robust positive anomaly over the Europe, week positive anomaly over the eastern Siberia, and negative anomaly over the Arctic Ocean and the northern Pacific (Fig. 2). This pattern is different from summer SV-NAM obtained by Ogi et al. (2004).

The structure for the EOF-1 for SON shows the synoptic-scale waves, and positive anomalies are seen from northern Pacific to Eurasia, from Europe to eastern America (not shown), and a negative anomaly is seen through the north Siberia, Arctic and north America.

Next, the SVD analyses are constructed for each season to compare with the EOF-1 for each

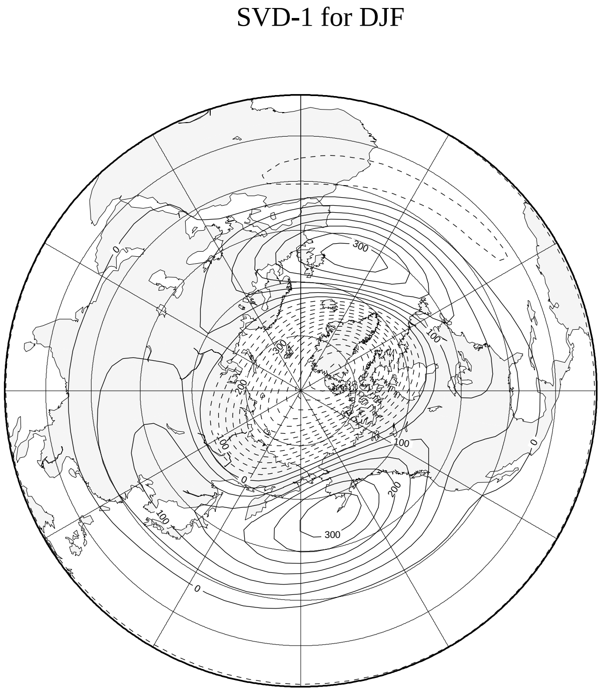


Figure 3: Distribution of the SVD–1 evaluated for the climate data in DJF when the viscosity is the hyperdiffusion with the diffusion coefficient k_D is 2.7×10^{40}.

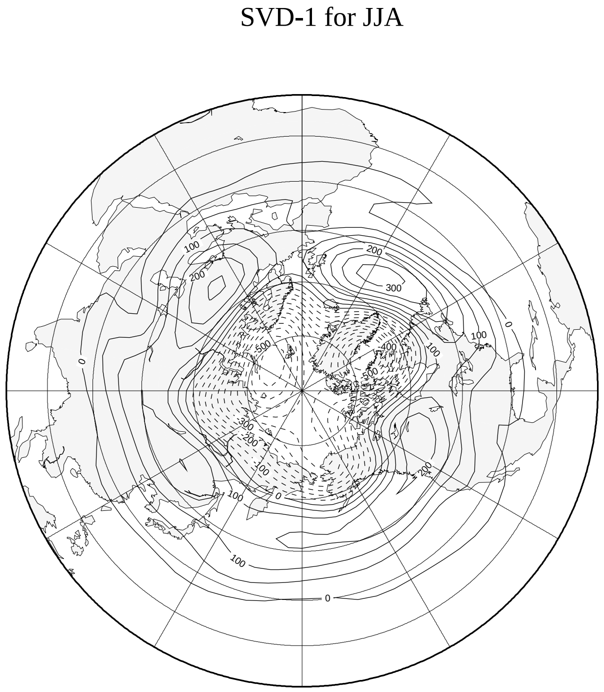


Figure 4: Distribution of the SVD–1 evaluated for the climate data in JJA when the viscosity is the hyperdiffusion with the diffusion coefficient k_D is 2.7×10^{40}.

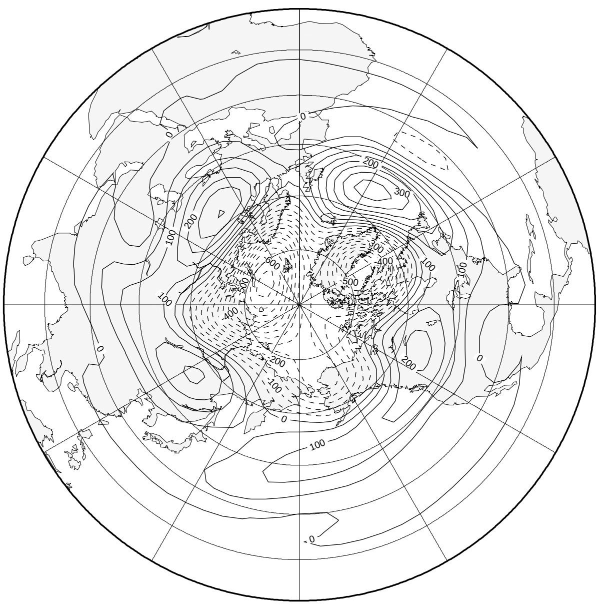
season. First, the eigenvalue problem (EVP) is solved for each season using the frictional forcing d_i in f_i parameterized by the hyper diffusion. In DJF, EVP-1 shows an AO-like pattern with negative pole over the Arctic and positive pole over Pacific and Atlantic (not shown). When the eigenvalue is zero, this mode becomes resonant and is excited dominantly by arbitrary steady forcing.

Second, singular vectors of the linear system is solved for neutral modes with respect to a stochastic random forcing $\boldsymbol{f}$ under the steady state (SVD analysis) for each season using the Rayleigh friction with the same magnitude as the eigenvalue obtained by EVP.

It is found that the AO-like structure appears robustly in DJF when the frictional forcing is parameterized by the scale-dependent hyper diffusion. It is shown that a negative area appears over the Arctic and positive areas over the Pacific and Atlantic (Fig. 4). This pattern is same as EVP-1 for DJF. However, in other seasons, the dynamical SVD-1 mode is different from the observed EOF-1. Therefore, the viscosity is changed to the bi-harmonic diffusion and the diffusion coefficient k_D is set to 4.0×10^{16}, which is same as the numerical experiment of the AO in winter (Tanaka 2003).

It is found that the dynamical SVD-1 mode in DJF is different from the observed EOF-1, which is not an AO-like pattern. The dynamical SVD-1 mode in MAM is similar to the observed EOF-1, which shows positive poles over the eastern America and Europe, and a negative anomaly over the Arctic region (not shown). The dynamical SVD-1 mode in JJA shows a negative anomaly over the Arctic and positive anomaly over the mid-latitude (Fig.5). The pattern shows annular structure, but it is different from the observed EOF-1. The pattern of dynamical SVD-1 mode in SON shows AO-like structure (not shown), but it is different from the observed EOF-1. These results show that the EOF-1 is similar to the SVD-1 in winter, while the EOF-1 is different from the SVD-1 in summer, and autumn.

4. CONCLUTION



SVD-1 for JJA

Figure 5: Distribution of the SVD–1 evaluated for the climate data in JJA when the viscosity is changed to the bi-harmonic diffusion with the diffusion coefficient k_D is 4.0×10^{16}.

In this study, the AO in summer is investigated by applying EOF analysis. The EOF analyses are conducted for the barotropic component of the atmosphere for each season. It shows that the structure of the AO in winter and spring is identified as an annular mode, but in summer and fall, it is not an annular mode. The pattern of EOF-1 in summer is different from summer SV-NAM. It should be noted that the analysis by Ogi et al. (2004) is performed using the data north of 40°N with the monthly and zonally averaged data, while entire Northern Hemisphere data are used in this study. Therefore, the AO in summer appears to be sensitive to the EOF analysis area.

The seasonal variation of the dynamical SVD-1 mode is analyzed for the climate basic states to compare with the EOF-1 for each season. It is found that the AO-like structure appears robustly in DJF. The AO-like pattern obtained by observed EOF-1 appears also in MAM when the viscosity is changed to the biharmonic diffusion with the realistic diffusion coefficient. But the structures appeared SVD-1 in JJA and SON are different from the structure of EOF-1 obtained by observational data. From this result, we can conclude that the AO in winter is a physical mode of a dynamical system for the global atmosphere, however the AO in other seasons is not a physical mode but a statistical mode.

Acknowledgments

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