A Study of Arctic Oscillation Induced by a Positive Feedback between the Polar Vortex and Baroclinic Instability

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1. Introduction

The Arctic Oscillation (AO) advocated by Thompson and Wallace (1998) attracts more attentions in recent years. The AO is a north-south seesaw of the atmospheric mass between the Arctic region poleward of 60°N and the surrounding zonal ring in mid-latitudes. It is defined as the primary mode of the empirical orthogonal function (EOF) for the detrended sea-level pressure field in the Northern Hemisphere (NH).

Yamazaki and Shinya (1999) concluded that the AO is an intrinsic internal mode of the atmosphere, suggesting that the wave-mean flow interactions are responsible for the phase transition between the positive and negative polarity of the AO. They also find that the planetary-scale wavenumbers 2 and 3 play the largest contribution among the zonal eddies, while the synoptic-scale waves contribute destructively. It may be interesting to study the different roles of baroclinic instability in synoptic and planetary waves in the context of the dynamical understanding of the AO.

The purpose of this study is to analyze the baroclinic instability in synoptic and planetary waves given specific zonal basic states with strong and weak polar vortices. Baroclinic instability is in general induced by the baroclinicity associated with the subtropical jet. We are interested more in the baroclinicity associated with the polar vortex in this study. The expected feedback of the unstable eddies to the zonal mean basic states of the strong and weak polar vortices is discussed.

2. Model and data

In this study, a 3-D spectral primitive equation model in terms of the 3-D normal mode expansion developed by Tanaka and Kung (1989) is used in order to solve the linear baroclinic instability for general zonal basic states on a sphere. The zonal mean basic states, which represent both the subtropical jet and polar jet, are constructed from wintertime monthly and seasonal mean observational data. Although the model is based on the primitive equations on a sphere, we can filter out the redundant unstable gravity modes by virtue of the normal mode expansion technique.

The data used in this study are monthly mean reanalysis provided by the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) for 1950 to 1998 (see Kalnay et al. 1996).

3. Result of the unstable modes

The AO is defined by the EOF-1 of the sea-level pressure in the Northern Hemisphere during the winter. Yet, it may be our consensus now that AO has a barotropic structure, in that, the axisymmetric pressure pattern of the EOF-

1 is detected at the whole vertical levels in the troposphere as well as in the lower stratosphere. In this study the strong and weak polar vorticies are identified by the AO index obtained by the EOF analysis of the barotropic component of the atmosphere.

Figure 1 shows (a) a case for the weak polar vortex in 1997/98, (b) the strong polar vortex in 1988/89, and (c) a hypothetical zonal mean zonal wind without the subtropical jet constructed from strong polar vortex for January 1989. The baroclinic instability problem is solved for those zonal mean basic flows.

Figure 2 illustrates the results of the growth rates (day^{-1}) and phase speeds (°day^{-1}) computed for the corresponding basic states in Fig. 1, respectively.

For the weak polar vortex in Fig. 2(a), the most unstable mode at the zonal wavenumber n=7 may be identified as Charney mode which appears for n=3 to 12. The growth rate is approximately 0.4 day^{-1} with its e-folding time 2.5 days. It moves eastward with its phase speed of approximately 8 °day^{-1} advected by the mean westerly. The most unstable mode is replaced by other different mode for the zonal wavenumbers n=1 to 4, which clearly has different modal structure. According to Tanaka and Kung (1989), those unstable modes are labeled as shallow Charney modes M_C, dipole Charney modes M_2, and tripole Charney modes M_3.

We now compare the unstable modes for the strong polar vortex in 1988/89. The most unstable mode at the zonal wavenumber n=7 in Fig. 2(b) is identified as the shallow Charney mode M_C which appears for n=2 to 12. The most unstable mode M_C is replaced now by so-called monopole Charney mode M_1 for n=2 to 5 for the strong polar vortex. According to the original work by Tanaka and Kung (1989), the M_1 mode is clearly distinguished from M_2 mode from the different structure. It has one amplitude peak in the troposphere and is deep in the sense that it can propagate into the stratosphere for small zonal wavenumbers.

Figure 3 illustrates the meridional-height structures of the geopotential amplitude (in arbitrary unit) and phase (in longitude of ridges) for the monopole Charney modes M_1 at n=2 and 3. The monopole Charney mode M_1 at n=3 indicates single amplitude maximum at the tropopause level near 60°N. The name of M_1 mode comes from such a structure in comparison with the M_2 mode. The phase tilt westward with respect to height, transporting the eddy heat energy to the north. It is clearly a mode excited by baroclinic instability. The horizontal phase structure shows the eastward phase tilt with respect to latitudes, indicating the poleward eddy momentum flux.

The meridional-height structure for n=2 exhibits the large amplitude at 10 hPa in addition to the amplitude peak at the tropopause level. Since the structure of the M_1 mode indicates a large meridional extent, the mode can propagate into the stratosphere for planetary scale waves. The common characteristics to M_1 modes is the poleward eddy momentum flux as inferred from the phase structure. It is important to note that the M_1 mode tends to intensify the polar vortex by those poleward eddy momentum flux. Therefore, the M_1 mode shows a positive feedback with the polar vortex because it appears in high latitudes for stronger polar vortex, and it tends to intensify the polar vortex.

The M_1 mode was not identified from the viewpoint of the higher order modes of the M_C mode, such as M_2 and M_3. It has been an open question to identify the M_1 mode. The M_1 mode shows a similar structure to the M_C mode to large extent, but it appears always in higher latitudes with larger meridional structure. In order to identify the M_1 mode, we solve the baroclinic instability for a hypothetical zonal mean zonal wind constructed with the strong polar vortex in January 1989 as shown in Fig. 1(c) The subtropical jet is removed manually from the figure. The polar night jet of 55 m s^{-1} appears at 10 hPa over 65°N.

The solution of the unstable modes is plotted in Fig. 2(c). The most unstable mode appears over n=1 to 10 with its peak growth rate at the zonal wavenumber n=6. The growth rate is approximately 0.4 day^{-1} with its e-folding time 2.5 days. It looks like the shallow Charney mode M_C in Fig. 2(b), but actually we find

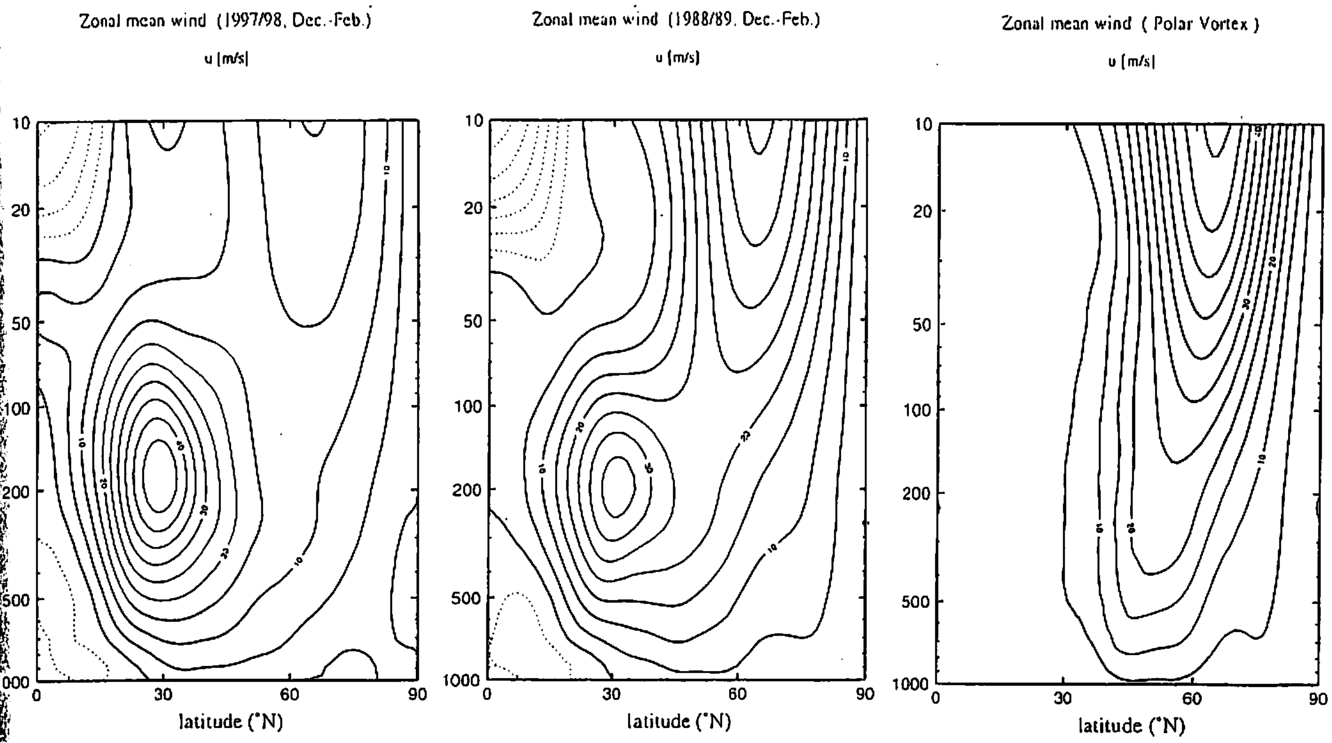

Fig. 1 Meridional-height section of zonal mean zonal wind (m s^{-1}) for (a) a weak polar vortex (DJF 1997/98), (b) strong polar vortex (DJF 1988/89), and (c) hypothetical zonal mean zonal wind constructed with strong polar vortex in January 1989 in the Northern Hemisphere.

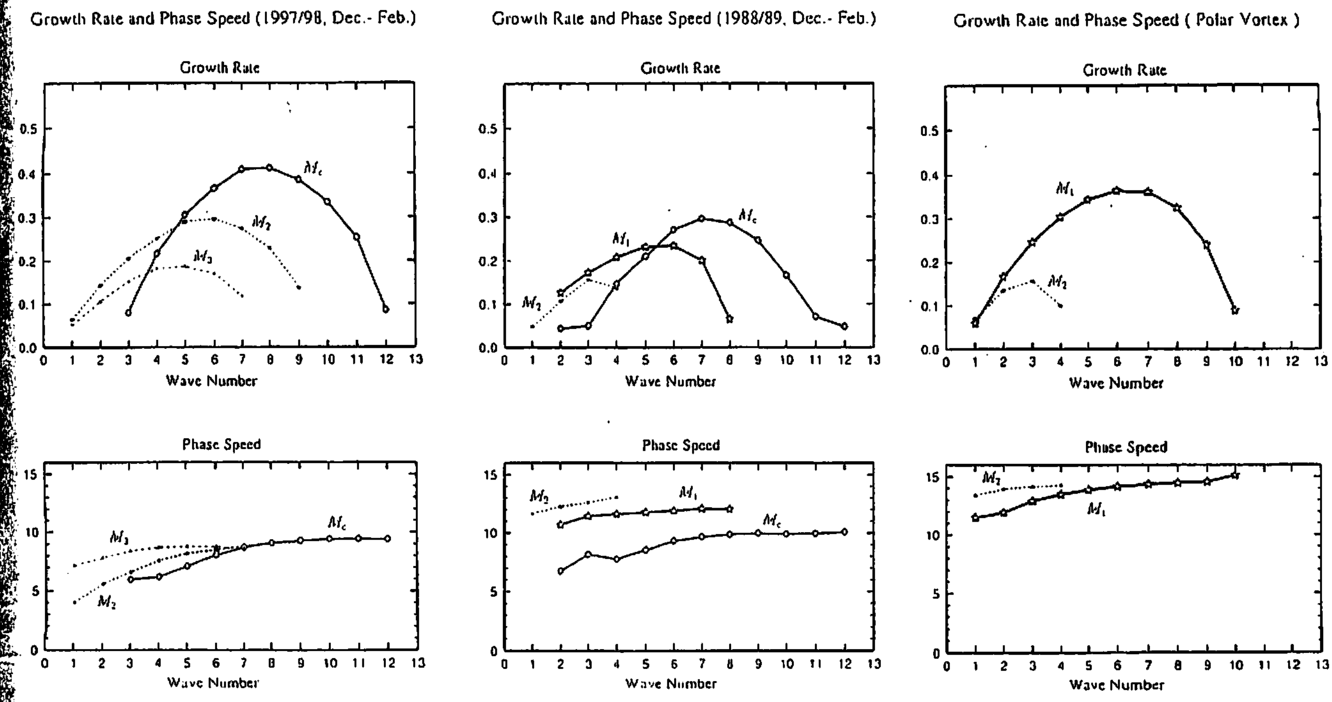

Fig. 2 Growth rates (day^{-1}) and phase speeds ($^{\circ}day^{-1}$) of the unstable modes for the zonal mean basic state of (a) weak polar vortex, (b) strong polar vortex, and (c) hypothetical zonal mean zonal wind shown in Fig. 1. The unstable modes are labeled M_C for shallow Charney modes, M_2 for dipole Charney modes, M_3 for tripole Charney modes, and M_1 for monopole Charney modes.

it is the monopole Charney mode M_1 from its structure. The common finger print of the M_1 modes such as the poleward eddy momentum flux is identified from the structure. From the result, we can clearly identify the M_1 mode as the baroclinic instability excited by the baroclinicity associated with the polar jet. The second unstable mode at n=1 to 4 is identified as M_2 mode from its structure.

4. Summary and discussion

In this study, baroclinic instability of northern winter atmosphere is investigated in the context of the dynamical interpretation of the AO, using a method of 3-D normal mode expansion introduced by Tanaka and Kung (1989). The basic states used for the linear stability analysis are the observed zonal mean wind for strong and weak polar vortices. In addition, a hypothetical basic state which has only the polar jet with no subtropical jet is analyzed.

As a result of the eigenvalue problem for such basic states, we obtain a characteristic unstable solution which is dominant in high latitudes when the polar vortex is strong. The mode is called a monopole Charney mode M_1, which transfers eddy momentum from the low latitudes to the polar region. The stronger the polar vortex is, the faster the growth of the M_1 mode is. On the contrary, the M_1 mode becomes weak or disappear when the polar vortex is weak. The M_1 mode is identified as the ordinary Charney mode excited by the baroclinicity of the polar vortex. Dynamically the M_1 mode is indistinguishable from the Charney mode M_C, but physically, the former is excited by the polar jet and the later by the subtropical jet.

The positive feedback between the polar vortex and the the M_1 mode tends to produce two persistent equilibria of strong and weak polar vortices. This dynamics may result in the appearance of the annular mode of AO. As a future subject, we need to demonstrate the AO using a simple nonlinear model with the parameterized feedback from the M_1 and M_C modes to confirm the proposed scenario in this study.

Acknowledgments

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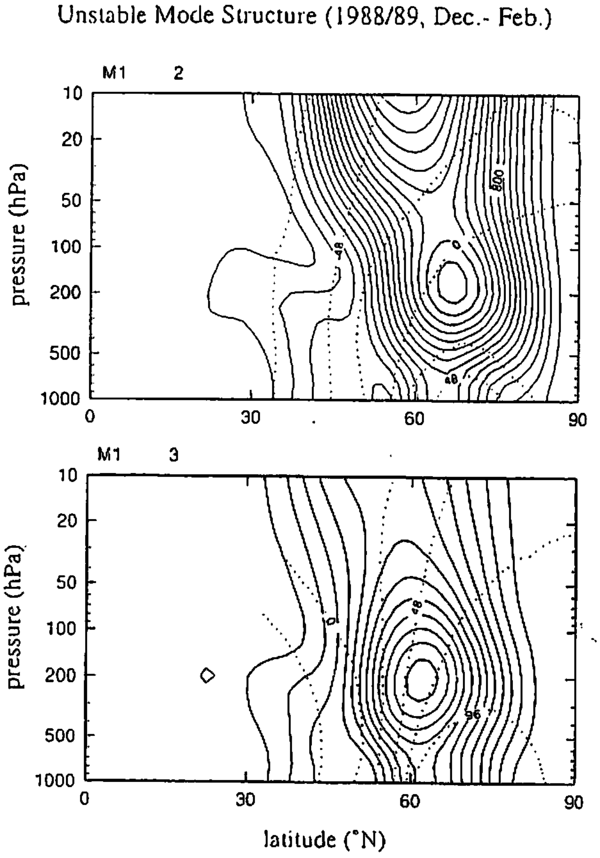

Fig. 3 Meridional-height section of the geopotential amplitude (in arbitrary unit) and phase (in longitude of ridges) for M_1 at zonal wavenumbers 2 and 3.