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Zonal-eddy Coupling and a Neutral Mode Theory for the Arctic Oscillation (Extended Abstract)

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Abstract: This study demonstrates that a dynamical mode that resembles the observed Arctic Oscillation (AO) pattern can be obtained as a least damped mode of a linear operator that expresses the dynamics of the zonally averaged flow interacting with stationary, zonally-asymmetric waves. The spatial pattern of the leading singular mode of the operator bears much resemblance to the observed Arctic Oscillation both in terms of zonal and associated wave components. The mode has a damping time scale of more than a month, and is well separated from subsequent modes. Therefore, it is plausible that it survives on monthly and longer time scales. The simulated zonally asymmetric waves produce a meridional tilt due to advetion by the AO-like sheared zonal flow and positively feed back to the zonal flow through the momentum flux arising from the interplay with the climatological mean waves. The dominant contribution of this feedback is shown to come from the features in the North Atlantic sector, supporting the notion that the AO is a hemispheric extension of the more regional North Atlantic Oscillation.

1. Introduction

Much attention has been paid recently to the so-called Arctic Oscillation (Thompson and Wallace, 1998, 2000 ; Thompson *et al.*, 2000 ; TW collectively), an annular pattern of variability that describes a pressure dipole between the polar cap and middle latitudes. It is identified by TW as a leading mode of the empirical orthogonal function (EOF) of the cold season sea level pressure (SLP) field and has an equivalent barotropic structure of the anomalies extending well into the stratosphere. The AO fluctuations dominate over monthly and longer time scales. In fact, it resembles the trend of the northern SLP field (TW) and the relation between the AO and the global warming is under an active debate (Shindell *et al.*, 1999 ; Fyfe *et al.*, 1999 ; Hartmann *et al.*, 2000). Decadal modulation of the AO time series is also conspicuous; especially, the recent warming in the 1990s coincides with the phase of the AO with lower pressure over the Arctic. Near surface temperature anomalies dominant over the northern Eurasia and East Asia associated with the AO have also been documented (Walsh *et al.*, 1996 ; Watanabe and Nitta, 1999 ; Xie *et al.*, 1999).

It is generally agreed that the AO is essentially a mode internal to the atmosphere. This notion is underscored by the facts that little signature in sea surface temperature anomalies is associated with the AO (Kodera *et al.*, 1996) and that quite a few atmospheric GCMs produce a mode similar to the observed AO with climatological sea surface temperatures (*e.g.*, Yamazaki and Shinya, 1999). However, dynamical understanding of the mode is yet to be reached.

In this study, we attempt to understand the dynamics of the AO in terms of interactions between zonal mean and zonally asymmetric components of the flow.

2. Zonal-eddy coupling and its representation

An approach explored here is to identify a least damped mode of a dynamical operator that governs zonal mean perturbations. A spectral primitive equation model linearized about an observed climatological zonal mean flow is adopted for this purpose (Watanabe and Kimoto, 1999, 2000). A version with 20 vertical levels is employed in this study. Horizontally, spherical harmonic coefficients are truncated at zonal wave number 5 and total wave number 21. Del-forth horizontal diffusion, linear friction, and Newtonean thermal damping are the only diabatic terms included. Both the linear friction and Newtonean damping have time scales of 1 day in the lowest 100 hPa, 2 days in the topmost two levels, and 15 days elsewhere. A December-February (DJF) mean over the recent 40 years was computed using the NCEP/NCAR reanalysis data and is used as the basic state.

We decompose an arbitrary variable X into zonal mean $\overline{(\ )}$, and zonally asymmetric components $(\ )^*$, and further denote climatological mean by $(\ )_c$ and anomaly thereof by $(\ )_a$. We obtain an anomaly pattern that represents the AO by a linear regression on a principal component time series of the first EOF of DJF monthly 1,000 hPa height anomalies during 1949-1998. Figures 1a and 1b show anomalies associated with the observed AO, the former for the latitude-height section and the latter for the horizontal pattern at 300 hPa.

Recent observational studies (Limpasuvan and Hartmann, 1999; DeWeaver and Nigam, 2000a) have shown that stationary component of asymmetric waves, or *eddies*, associated with the AO play a more dominant role than transient component. Although the contribution of the latter is not at all negligible quantitatively, this study explores the possibility that the AO is understood exclusively by the interaction between the zonal flow and stationary eddies.

Arrows in Figs. 1a and 1b represent the E-P flux and horizontal component of E-vector (Hoskins *et al.*, 1983) due to the interaction between the AO-associated and climatological mean wave components. Divergence of the meridional components of the vectors represent zonal flow acceleration due to eddies and it is seen in Fig. 1a that the eddies act to amplify the zonal wind anomalies. Figure 1b shows that such acceleration is dominated by the features in the North Atlantic sector.

The linear model can be used as a 'planetary wave model'; *i.e.*, with a given perturbation in the zonal flow, the model solves for a steady zonally asymmetric response that are forced by interactions between the zonal perturbation and climatological waves, written schematically as

$$L^*(\overline{X}_c)X_a^* = F^*(X_c^*)\overline{X}_a + f^*, \tag{1}$$

where L^* is a linear operator for wave anomalies and is a function of the basic-state zonal flow. On the right-hand side, a linear operator F^* acts on zonal flow anomalies to force wave anomalies. F^* is a function of the climatological mean wave, X_c^*. Precisely speaking, L^* also depends on X_c^*, but this is neglected in the present study, which enables us to solve each zonal wave number separately and results in considerable computational economy. Effects of transients and other forcings, collectively denoted by f^*, are neglected in this study.

This planetary wave model is capable of simulating eddy anomalies given the zonal component of the observed AO (not shown, but see Ting *et al.*, 1996, and DeWeaver and Nigam, 2000b,

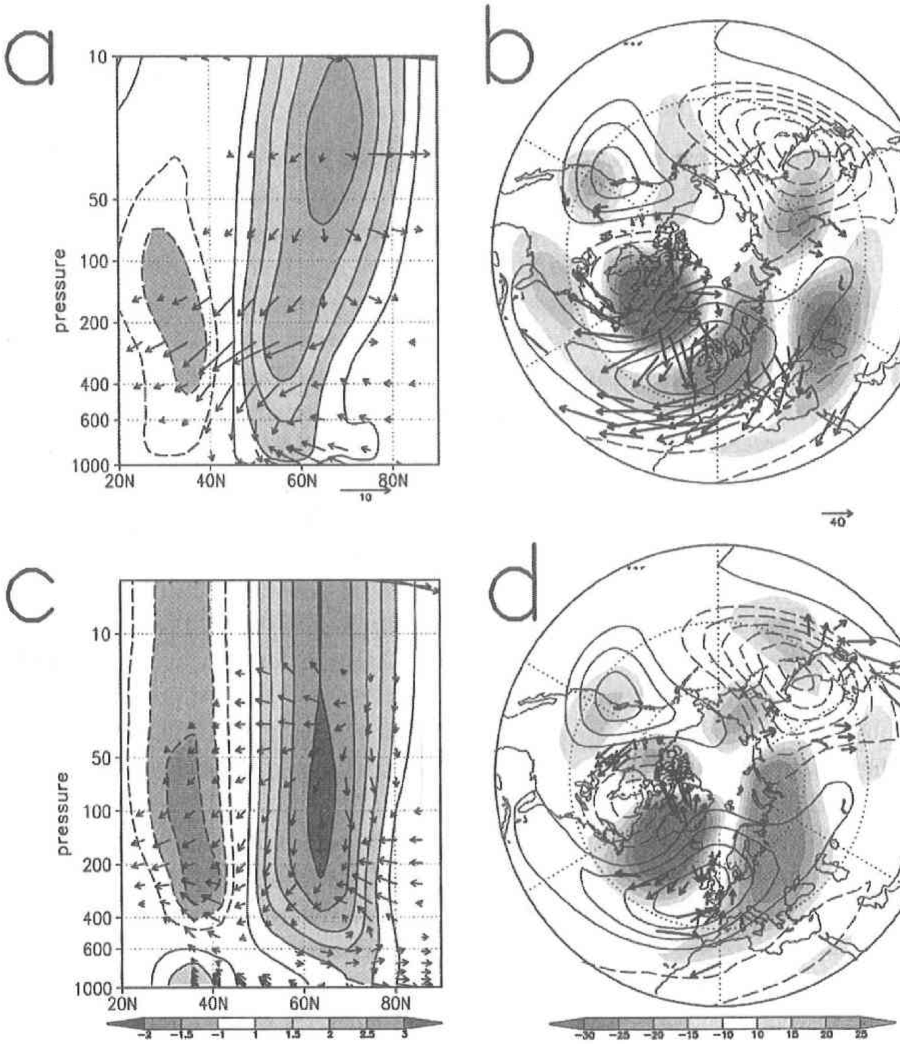

Fig. 1. (a) Observed zonal mean wind (contour; interval is 0.5 m sec^{-1}) and E-P fluxes (arrow; unit: m^2 sec^{-2}) associated with the AO anomalies. The E-P flux only includes contributions from the AO-associated stationary waves. (b) Observed climatological stationary wave height (contour) and zonally asymmetric height anomalies of the AO (shades) at 300 hPa. The contour interval is 50 m. See the color bar for the shadings. The arrows indicate horizontal component of the E-vector (unit: m^2 sec^{-2}) due to the interaction between climatological and AO-associated waves. (c) and (d) As in (a) and (b), but for the leading singular vector of the zonal mean linear operator in Eq. (3).

for similar simulations). The simulated waves are then combined to the climatological waves to obtain forcing for the zonal flow. The equation governing the zonal perturbation can be written schematically as

$$\partial \overline{X}_a / \partial t + \overline{L}(\overline{X}_c)\overline{X}_a = \overline{F}(X_c^*)X_a^* + \overline{f}, \tag{2}$$

where $\overline{L}$ and $\overline{F}$ are linear dynamical operators. The latter acts on X_a^* to represent the forcing for zonal anomalies due to wave-wave interaction. Forcing by transients and other sources is represented by $\bar{f}$. A zonal response model used in this study is formed by neglecting the tendency term and $\bar{f}$ in (2). Again, it is confirmed that such a simulation gives an observed AO like zonal flow anomalies (not shown), substantiating that a positive feedback is at work between the zonal and wave components of the AO pattern.

Using Eq.(1), the zonal equation (2) can be rewritten as

$$\partial \bar{X}_a/\partial t + (\bar{L} - \bar{F}L^{*-1}F^*)\bar{X}_a = \bar{f} - \bar{E}L^{*-1}f^*, \tag{3}$$

which takes into account that the dependence of wave anomaly X_a^* on $\bar{X}_a$. The second term in the parenthesis of the l.h.s. is calculated numerically by a repeated use of the planetary wave model (1) avoiding the burden of inverting L^* (*cf.*, Hoskins and Karoly, 1981). Equation (3) shows that coupled zonal-eddy system is forced by contributions from transients and other sources, the explicit representation of which are beyond the scope of this study.

3. The leading singular mode

Assuming for simplicity that the right-hand side of Eq. (3) is white in both spatial and temporal characters, and the tendency term on the l.h.s. is neglected, the steady response of the system should be dominated by singular modes of the linear operator, $\bar{L} - \bar{F}L^{*-1}F^* \equiv A$ with least singular values (*cf.* Branstator 1990; Navarra 1993; Itoh and Kimoto, 1999). Contours and shadings of Fig. 1c shows zonal mean zonal wind anomalies of the leading singular vector of the zonal operator with the observed DJF basic state. The meridional dipole with mostly barotropic structure is in good agreement with the observed AO shown in Fig. 1a. Associated stationary eddies at 300 hPa are shown in Fig.1d by shadings. The simulated eddies do have the largest component in the North Atlantic sector and the overall agreement with the observed counterpart is excellent, although a tendency is noted for the simulated features are to be displaced somewhat downstream. The neglect of the interactions between anomaly and climatological waves and effects of transients in the planetary wave model should have been the major source of the deficiency. Although the purpose of this report is to demonstrate that the stationary wave —zonal flow interaction is primarily responsible for the formation of an AO-like mode, inclusion of some of the neglected processes appears necessary for a better simulation (*cf.* DeWeaver and Nigam, 2000b).

The E-P fluxes and E-vectors due to the waves are shown by arrows in Figs. 1c and 1d, respectively, and again mimic the observed AO features well. It is noted that the magnitude of the E-P fluxes and E-vectors fall short of the observations probably due to the degradation of simulated waves. Despite this deficiency, however, it is striking for a mode that bears so much resemblance to the observed AO is naturally selected as a result of the positive zonal-eddy feedback. The spectrum of the singular values of A (not shown,, but see Fig. 2 of Kimoto *et al.*, 2001) is dominated by a small number of modes with the smallest singular values, and the first mode is very well separated by the others.

An eigenmode which has an essentially the same structure as the leading singular mode is obtained (not shown). It has a real eigenvalue which is the smallest and has a damping time scale of 47 days. Therefore, the AO-like least damped, or near neutral mode, is expected to be dominant over monthly and longer time scales. As long as the forcing is approximately white, the temporal spectrum of such mode is expected to be redder than any other.

4. A 'tilted-trough' mechanism for the zonal-eddy interaction

The essence of the positive feedback between zonal flow and stationary eddies can be understood by referring to a schematic diagram shown in Fig. 2. Suppose first a dipolar zonal wind anomaly on the leftmost panel. This advects the climatological wave ψ_c^* and produces a dipolar anomaly ψ_a^* downstream. The summation of the climatological and anomaly waves gives a meridional tilt of the wave (the middle panel), which give rise to a northward zonal momentum flux centered at the nodal latitude. Then, the divergence of this flux gives a zonal flow acceleration that projects positively to the original zonal flow anomaly. The meridional component of the E-vector shown in Figs. 1b and 1d corresponds to the northward zonal momentum flux. It is seen that the features in the Atlantic sector dominates in both the observation and the simulated neutral mode (Figs. 1b and 1d). A simple analytical model using barotropic vorticity equation (Kimoto *et al.*, 2001) shows that shorter zonal and meridional wavelengths of the climatological waves are preferred for the positive zonal-eddy feedback, explaining partially the dominance of the Atlantic, rather than Pacific, sector in the neutral mode. A more detailed investigation is necessary to assess the importance of other properties of climatological waves, such as meridional tilt and meridional phase relative to the zonal anomalies, in distinguishing the two sectors.

5. Concluding remarks

The prime objective of this letter is to demonstrate that a positive zonal flow-stationary eddy coupling is able to form the least damped dynamical mode that resembles the observed Arctic Oscillation (AO). Several simplifications have been adopted, mainly for computational reasons; zonal inhomogeneity was not taken into account in the simulation of stationary waves, and effects of transients were neglected both in wave and zonal flow dynamics. Although these processes are not likely indispensable, they are definitely required for a better simulation and their effects should be assessed quantitatively (*cf.* DeWeaver and Nigam, 2000a, b). Limpasuvan and Hart-

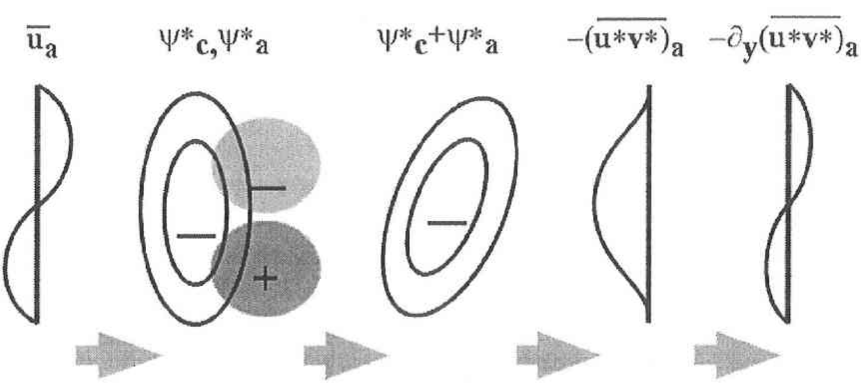

Fig. 2. A schematic diagram illustrating the 'tilted-trough' mechanism for the positive zonal-eddy feedback

mann (2000) among others show that transient eddies play a dominant role in the zonal-eddy coupling in the Southern Hemisphere counter part of the AO, the Antarctic Oscillation (TW). Clearly, the elucidation of zonal-transient eddy coupling should enhance our understanding of annular modes.

Decadal and longer term variability and relation with global warming for the AO are under debate. Although the neutral mode theory advocates that it should be easily excited and long-lived, it is not in contradiction to a search for effective forcing mechanisms, which is an important future subject.

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