Multiple Planetary Flow Regimes and the Eddy Forcing in Northern Hemisphere Wintertime Variability

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Abstract

A cluster algorithm is applied to the zonal mean zonal wind and 500 hPa height from winter monthly means (for the period 1948-2002), obtained from the reanalyses of the National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP/NCAR). Four reproducible and robust clusters are found: two regimes represent the opposite phases the Northern Hemisphere Annular mode (NAM), and two regimes represent the opposite phases of a pattern which can be identified with the Cold Ocean-Warm Land (COWL) pattern. This identification is accomplished by regressing the zonal mean zonal wind on the COWL-index derived from 500 hPa height data by Wu and Straus [2003].

Transformed Eulerian (or Eliassen-Palm) eddy forcing analysis is used to examine the maintenance of these clusters. The results show that barotropic forcing by the eddy momentum fluxes appears to maintain the wind anomalies in the upper troposphere and balance the Coriolis acceleration associated with the anomalous transformed mean meridional circulation, while the Coriolis acceleration maintains the wind anomalies against friction in the lower troposphere. This mechanism holds for both NAM-like and COWL-like regimes.

1. Introduction

The Northern Hemisphere annular mode (NAM) has been shown to be a leading mode of Northern Hemisphere (NH) variability (Thompson and Wallace, 1998, 2000; Wallace, 2000). The zonally symmetric structure of the NAM is remarkably similar to that of the corresponding Southern Hemisphere annular mode (Thompson and Wallace, 2000). In both hemispheres, the annular modes associated with the zonal-mean wind are characterized by a strengthening of the westerly flow poleward of 45°N from the surface to the lower stratosphere and a weakening of the westerlies in the troposphere to the south of 45°N. This kind of annular mode has been simulated in atmospheric models and has been shown to result from the interaction between eddies and mean flow (e.g. Robinson, 1991; Yu and Hartmann, 1993; Hartmann and Lo, 1998). Thus the annular modes are natural variability modes of the climate system that are likely to be observed even in the absence of any external forcing.

The Cold Ocean-Warm Land (COWL) pattern arose from a partitioning of observed winter season time series of Northern Hemisphere averaged monthly mean surface air temperature into a very slow varying "radiative" component, and the remaining "dynamical" component exhibiting rapid year-to-year fluctuations (Wallace et al., 1996). The COWL patterns of 500 hPa height and temperature are defined by regression of these fields onto the "dynamical" time series component. Wallace et al. (1996) argued that the COWL is essentially induced by the land-sea distribution. From GCM test results, Broccoli et al. (1998) confirm that the contrast in thermal inertia between land and ocean is the primary factor for the existence of the COWL pattern, whereas dynamical air-sea interactions do not play a significant role.

COWL-like patterns have also been derived from cluster analyses designed to identify states whose probability distribution stands out from the Gaussian background (Corti et al., 1999; Hsu and Zwiers, 2001), are independent of the occurrence of ENSO events, and have been more prevalent in the past few decades than previously. Recently, Wu and Straus (2003) have applied the partitioning cluster algorithm of Michelangeli et al. (1995), hereafter MVL, to the observed monthly mean NH wintertime (December-March) sea-level pressure (SLP) and 500 hPa geopotential height. They found that the NAM and COWL regimes co-exist in the NH wintertime variability and that both NAM and COWL regimes can be reproduced from conditional one-point correlation maps.

The major goal of this study is to apply the cluster algorithm of MVL to the zonal mean zonal wind in the troposphere and lower stratosphere to determine whether multiple regimes do exist, and to document the dynamical maintenance of these regimes. We find four regimes in the NH wintertime zonal-mean zonal wind. Two of them are associated with the NAM and the other two with COWL mode. The results show that momentum forcing by eddy fluxes and Coriolis acceleration sustains both the NAM and COWL zonal-mean wind anomalies. While our results for the NAM-like regimes are very similar to those reported previously (Yoden et al., 1987; Shiotani, 1990; Karoly, 1990; Hartman and Lo, 1998; Kidson and Waterson, 1999; Limpasuvan and Hartmann, 2000), the existence of zonal-mean regimes associated with COWL mode and their dynamics have not been reported before.

2. Data and analysis techniques

2.1 Data sets

The variables used in this study are once-daily 500 hPa geopotential height, zonal wind (*u*), meridional wind (*v*) and temperature (*T*) at 15 levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50 and 30 hPa. These data are part of the reanalysis archive of NCEP/NCAR (Kalany et al., 1996) and were obtained from Climate Diagnostics Center (CDC) of National Oceanic and Atmospheric Administration (NOAA) on a 2.5^o x 2.5^o lat/lon grid. The January-March (JFM) period for the years 1948 - 2002 was used. These data were combined into monthly means. In addition, the monthly eddy terms described below in Section 3 were obtained by adding the stationary and transient eddy fluxes of momentum and heat computed from daily values.

2.2 EOF Analysis

Empirical orthogonal function (EOF) analysis is applied to the JFM monthly mean fields of 500 hPa height and zonal mean zonal wind (*u*). The climate (55-yr mean) of each month is removed separately. In the EOF analysis, area weighting is accomplished by multiplying height and zonal-mean wind by the square root of cosine of latitude. The zonal-mean wind is also multiplied by the square root of the pressure interval represented by each level (i.e., by their mass-weighted contribution to the variance). All physical fields have been divided by the square root of the cosine of latitude (and the square root of the pressure interval for zonal wind) before plotting. This same treatment of data sets for EOF analysis was reported in Thompson and Wallace (2000).

2.3 Cluster analysis

The partitioning method (Michelangeli et al., 1995) is used here to obtain regimes, or clusters, of JFM monthly mean height and mean fields. The partitioning method agglomerates data around randomly chosen seeds in a reduced dimensional space, classifies all months into a predefined number of clusters (k) and iteratively finds the partition minimizing the ratio of the variance within clusters to the variance between cluster centroids. Reproducibility (Chen and Wallace, 1993) can be used to test the robustness of the clusters by repeating the cluster analysis for many randomly chosen half-length samples. Details are given in the above references and in Wu and Straus (2003).

3. Results

The leading four EOFs of the zonal mean u-wind explain 41.6%, 21.7%, 10.6% and 6.9% of the total variance respectively. According to the method by North et al. (1982), the leading two EOFs are well separated each other and they are also well separated from the other EOFs. The patterns of EOFs are quite similar to the Southern Hemisphere counterparts obtained Hartman and Lo (1998). The first EOF represents variability associated with north/south displacement of the mid-latitude jet in the NH winter. The second EOF of zonal-mean wind is in quadrature with the first EOF. Its positive phase represents the strengthening of the low-latitude and high-latitude westerlies, but weakening of the mid-latitude jet. The patterns corresponding to EOF-1 and EOF-2 are not shown; however they are quite similar to Regime 4 and Regime 2 (respectively) shown in Figure 1.

3.1 Regimes

The reproducibility index is calculated for the number of clusters *k* varying from 2 to 8 in the reduced phase space spanned by various EOFs. For the reduced space spanned by the first two, six and ten EOFs, the reproducibility index lies above 0.98 for all values of *k* between 2 and 7. (An index of 1.0 corresponds to perfect reproducibility.)

If five or more clusters are chosen, two of the anomaly maps corresponding to the cluster centroids are nearly perfectly correlated, with the only difference being the magnitude of the anomalies. They are both similar in pattern to the corresponding single centroid in the four-cluster case. This suggests that we should take $k = 4$ for monthly mean NH wintertime zonal mean flow. This choice is consistent with the results obtained by Wu and Straus (2003), who applied the same partition algorithm to SLP and 500 hPa geopotential height, and found four regimes. This choice is also consistent with the results reported by Corti et al. (1999) who obtained four regimes in the NH wintertime geopotential height.

The corresponding four regimes are plotted in Fig. 1. Regime 4 is associated with the annular mode in Thompson and Wallace (2000) and Limpasuvan and Hartmann (2000). Regime 3 is simply the reverse of regime 4, yielding the negative phase of the NAM. These two regimes represent variability dominated by EOF-1.

Regimes 1 and 2 represent variability dominated by the second EOF of the zonal-mean *u*-wind. Both exhibit a barotropic structure. Regime 2 is marked by westerly anomalies in the equatorward and poleward centers of action and easterly anomalies in the mid-latitude center. The anomalies amplify with height from the surface to the upper troposphere, and exhibit a narrow maximum at 27.5°N and 47.5°N at the 300-hPa level. The westerly anomalies of regime 2 in the high latitude also amplify with height from the surface to the lower stratosphere.

The COWL structure embedded in the zonal-mean *u*-wind field is shown in Fig. 2. This pattern can be obtained as the regression of zonal-mean *u*-wind anomalies on the second standardized principal component of the 500 hPa geopotential height. The corresponding EOF was shown to be the COWL pattern by Wu and Straus (2003). It is clear from Figures 1 and 2 that Regimes 1 and 2 are associated with the COWL mode.

3.2 Eddy forcing analysis

To understand how wind anomalies are maintained in the above four regimes, the forcing of zonal flow tendency during the occurrence of each regime is studied using the transformed Eulerian mean diagnostics of the zonal momentum balance (Edmon et al., 1980). The (quasi-geostrophic) zonal momentum balance is expressed as the sum of two eddy forcing terms, barotropic and baroclinic in nature, plus the Coriolis force acting on the transformed mean meridional circulation. These three terms are balanced in the long term by momentum dissipation.

As in Hartmann and Lo (1998) we calculate the difference between composites during months when the circulation was in Regimes 1 and 2 (Regime 2 minus Regime 1) for the barotropic eddy forcing, the baroclinic eddy forcing, the transformed Coriolis momentum forcing and the net forcing, which is the sum of all three terms (and is balanced by dissipation). The structure of the barotropic eddy momentum flux convergence in Fig. 3(a) consists of three centers of forcing near 300 hPa. The forcing accelerates westerly anomalies at both high and low latitudes but decelerates anomalies in middle latitudes. The transformed Coriolis acceleration, shown in Fig. 3(c), contains three strong local structures which reinforce the regime difference near the surface. The baroclinic eddy forcing shown in Fig. 3 (b) exerts a weaker damping on the anomalies near the surface. The role of frictional dissipation is to balance the net acceleration seen in Fig. 3(d). Note that the acceleration in the upper troposphere due to the barotropic eddy forcing is nearly balanced by the transformed Coriolis acceleration.

Comparable results for the difference between monthly composites in Regime 4 and Regime 3 are shown in Fig. 4. Our results are quite similar to those of Hartmann and Lo (1998) and Limpasuvan and Hartmann (2002), although the composites used in both of these papers were based in a slightly different criterion than used here. Both the barotropic eddy forcing and the transformed Coriolis forcing (see Figs. 4(a) and (c) respectively) have dominant mid-latitude dipole structures with the node about 45^0N. The baroclinic eddy contribution (Fig. 4(b)) is generally the largest below 800 hPa, and causes westerly forcing in the middle troposphere and easterly forcing above 300 hPa.

The centers of the anomalous barotropic eddy forcing in Fig. 3(a) in the upper troposphere and the strong near-surface structures of the transformed Coriolis forcing in Fig. 3(c) in the lower troposphere align very well with the main features of the COWL regimes shown in Fig. 1. These results indicate that forcing by the barotropic eddy momentum fluxes appears to maintain the COWL-like wind anomalies in the upper troposphere and the transformed Coriolis acceleration maintain the wind anomalies in the lower troposphere. The same conclusion holds during the occurrence of the NAM regimes. Such mechanisms indicate a strong coupling between zonal flow and eddy forcing and support the hypothesis that for the COWL pattern, as for the NAM, the eddies are organized to support the anomalous zonal winds associated with zonal flow vacillation (Hartmann and Lo, 1998; Robinson, 1991).

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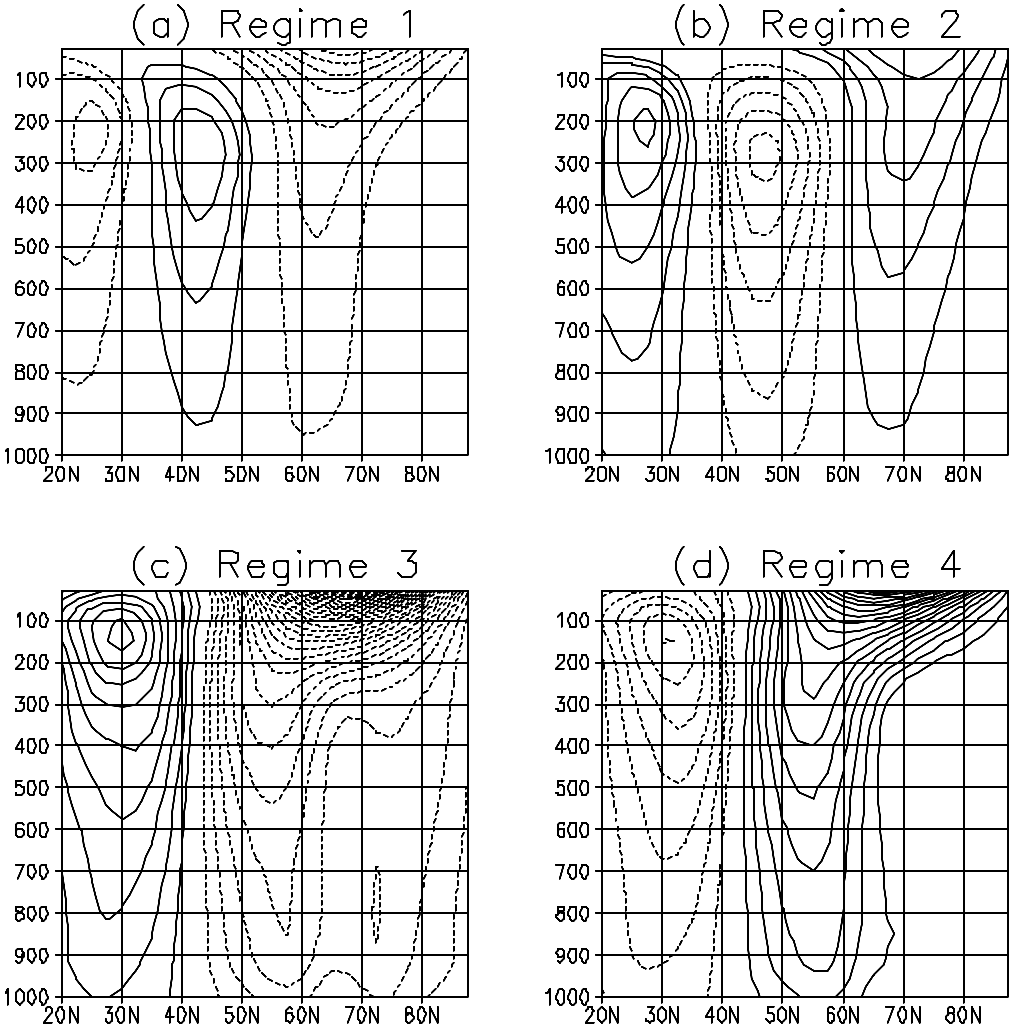


Figure 1. The cluster centroids for the zonal mean zonal wind (u). The cluster analysis retains 6 empirical orthogonal functions (EOFs), which explain about 90% of the variance. Contour interval is 0.25 m/s, with the zero line omitted and negative contours dashed. Regimes (1)-(4) are shown in panels (a)-(d).

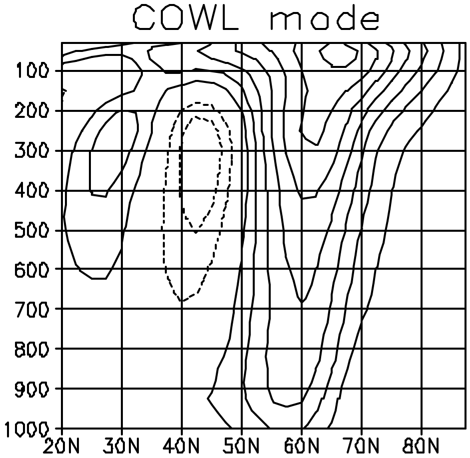
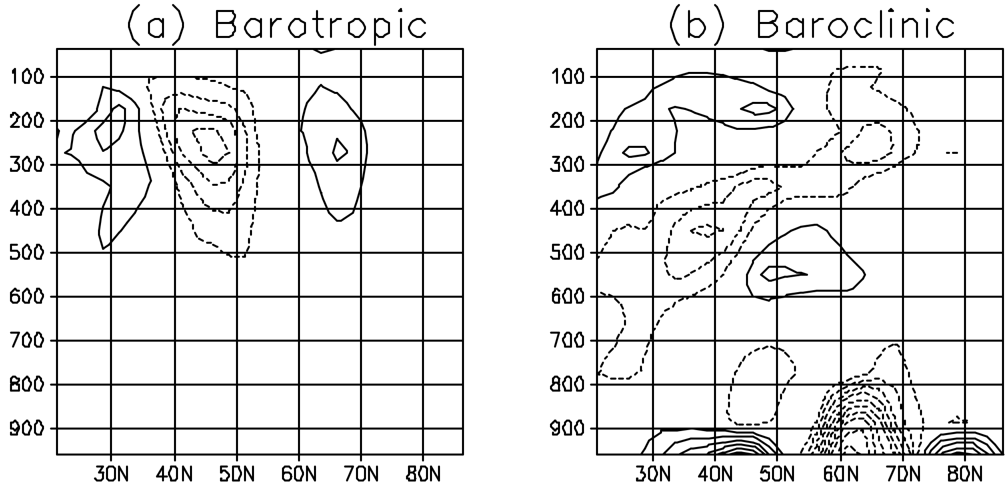


Figure 2. Regression pattern of the zonal mean zonal wind (u) anomalies onto the standardized principal component of 500 hPa height corresponding to the COWL pattern (see text for details). Contour interval is 0.25 m/s.

(a) Barotropic (b) Baroclinic



(c) Coriolis (d) Residual

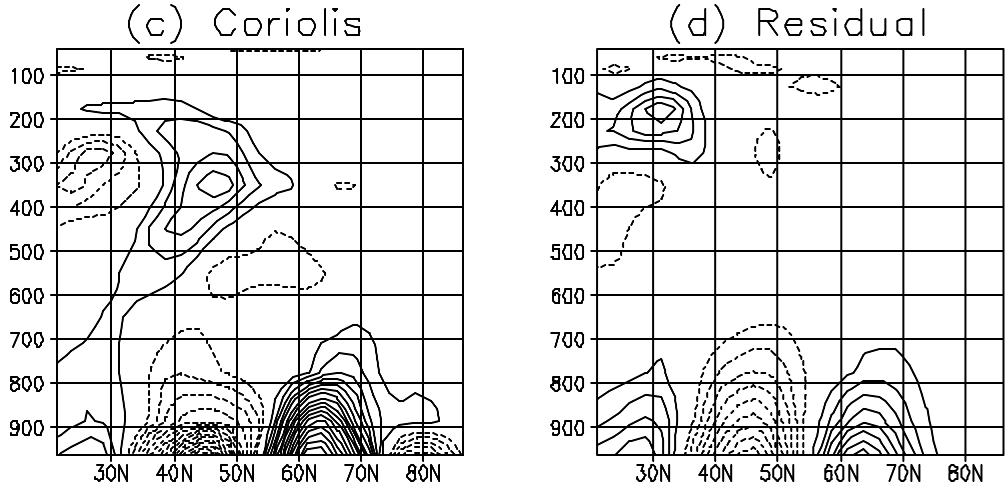


Figure 3. COWL cluster monthly composite difference (Regime 2 minus Regime 1) for: the barotropic eddy forcing (a); the baroclinic eddy forcing (b); the transformed Coriolis forcing (c); the net forcing (d). Contour interval is 0.24 m/(s day), with the zero line omitted and negative contours dashed.

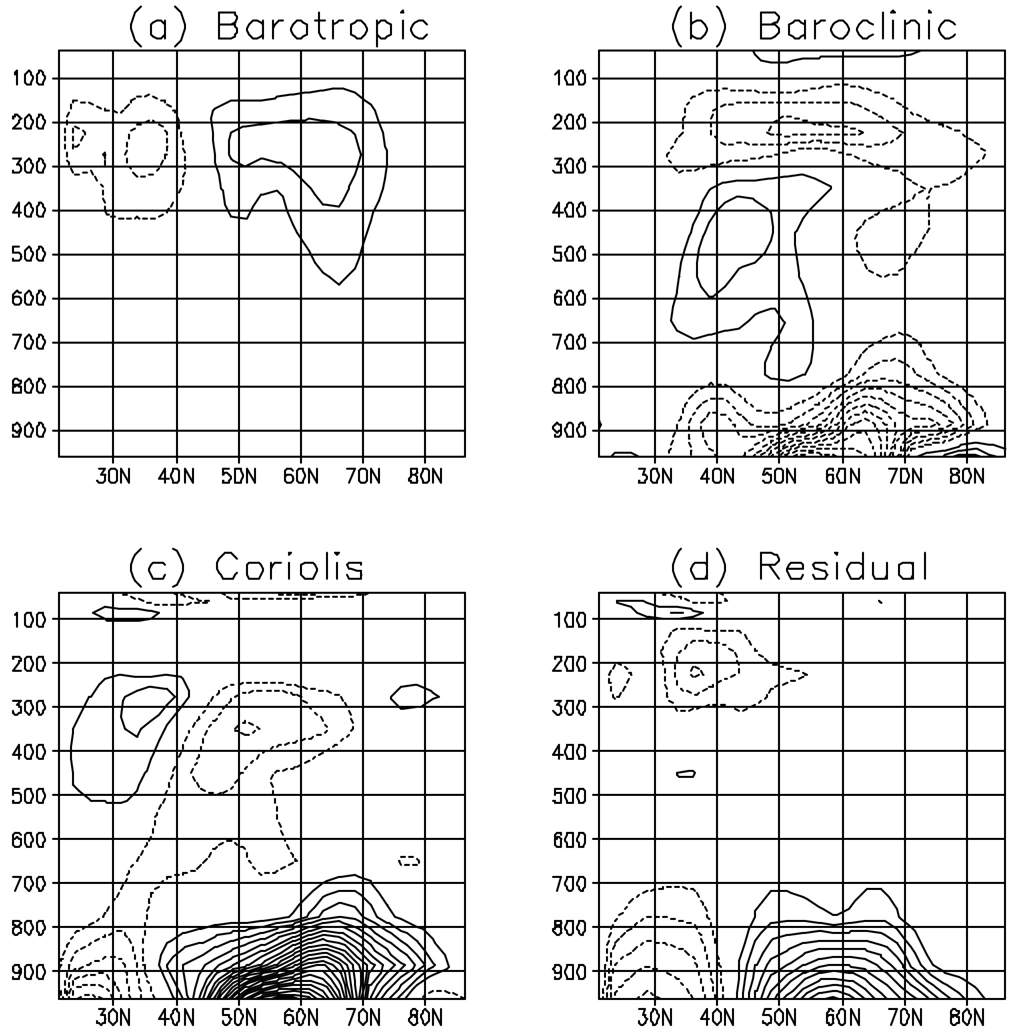


Figure 4. As in Figure 3, but for the NAM cluster monthly mean composite difference (Regime 4 minus Regime 3). Contour interval is 0.5 m/(s day).