

# Eddies and the annular modes of climate variability\*

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**Abstract.** The dominant modes of month-to-month variation of the troposphere can be realistically simulated in a general circulation model forced with realistic topography and seasonally varying, climatological sea surface temperatures. In both hemispheres, these modes describe a nearly zonally symmetric, north-south shifting of the zonal jets as anomalous westerlies vacillate between high (50°-60°) and low (30°-40°) latitudes. The eddy structures evolve with the jets, and the corresponding eddy momentum forcings support the shifts in jet position. In both hemisphere jet movement is supported by transient eddy momentum fluxes. When the jet shifts northward in the North Atlantic, its Southwest-Northeast tilt is accentuated, and the associated stationary wave transports momentum poleward, supporting the jet displacement locally. Transient eddy activity is also more intense when the jet is displaced poleward. Stronger tilt in the North Atlantic jet favors pronounced “mini” ozone hole events over Northern Europe, as low latitude, ozone poor air is readily advected poleward.

## Introduction

The month-to-month tropospheric variations in both hemispheres are dominated by nearly zonally symmetric, north-south movement of momentum and mass across the midlatitudes [Thompson and Wallace, 1998 and 1999a]. We will refer to these modes of variation as the Northern Annular Mode (NAM) and the Southern Annual Mode (SAM). NAM has also been called the “Arctic Oscillation” by Thompson and Wallace, and is related closely to the North Atlantic Oscillation, but its structure covers a larger extent of the Arctic, and its variability is more closely related to surface air temperature fluctuations over the Eurasian continent. SAM describes zonal flow vacillation in the Southern Hemisphere [e.g. Hartmann and Lo, 1998, and references therein].

In this study, we use a realistic numerical simulation to demonstrate the large role of transient and stationary eddy fluxes in the maintenance of these unforced annular modes

of variability. Since the observed NAM variability exhibits a systematic bias toward positive polarity (with an anomalous polar low) in the past 30 years [Thompson and Wallace, 1999b], our study suggests that possible corresponding trends in storm activity over Northern Atlantic should be looked for in observations.

## Model and Analysis

We analyze a 100-year climatological (control) run from the Geophysical Fluid Dynamics Laboratory GCM with rhomboidal 30 horizontal resolution and 14 vertical levels (R30L14), extending up to about 10 hPa. For this particular run, the sea surface temperatures are given seasonally varying climatological values. Interannual variability is thus absent from the model forcing.

The leading low frequency mode is identified by performing an Empirical Orthogonal Function (EOF) analysis on the monthly anomalies. To produce the anomaly fields, the climatological annual cycle for the 100-year run is first removed from the monthly averaged data. In forming the temporal covariance matrix for the EOF calculation, each grid point in the horizontal data domain is weighted by the square root of cosine of the corresponding latitude. The analyzed domains extend poleward from 10 degrees latitude in each hemisphere. Indices of the annular modes are defined as the normalized principal component (PC) time series corresponding to the leading EOF of 1000 hPa geopotential height. Virtually identical indices can be obtained using the sea level pressure fields.

Eddy activity during the extrema of the annular modes are revealed by compositing the eddy fluxes based on the indices of the modes. The high (low) phase composites are averages over months with index values above (below) the +1.5 (-1.5) standard deviation. Baroclinic waves are high-pass filtered transients (<10-day period), and stationary waves are zonal asymmetries associated with the monthly composites.

## Structure of the Annular Modes

To a large extent, the month-to-month variation of the entire troposphere can be followed by examining the near surface height field (Z) fluctuation. In both hemispheres, the leading EOF of the 1000 hPa Z shows anomalous low (high) values poleward (equatorward) of about 60° latitude

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during the high SAM/NAM phase (Fig. 1, top). These modes are well separated from the subsequent modes by the criterion of *North et al.* [1982], and explain 36% and 27% of the total variance in the Southern and Northern Hemisphere, respectively. The structure and amplitude are in good agreement with the observed patterns of *Thompson and Wallace* [1998 and 1999a] in both hemispheres.

Height patterns at upper levels derived by regressing the anomalous height field onto the SAM/NAM index are highly correlated with the leading Z EOF at those levels. Temporal correlation between the leading Z PC at other levels with the SAM/NAM index are also large (Table 1 and Fig. 1, middle). As suggested in Table 1, the entire troposphere appears to vacillate about its climatological state in a near zonally symmetric and barotropic manner. This vacillation is most pronounced during the “cold” months of the respective hemisphere, as illustrated by the annual cycle of the SAM/NAM index variance (Fig. 1, bottom). The seasonal variation is smaller in the Southern Hemisphere, in agreement with observations.

The zonal jets associated with the annular modes undergo meridional displacement in the mid-latitudes at nearly all

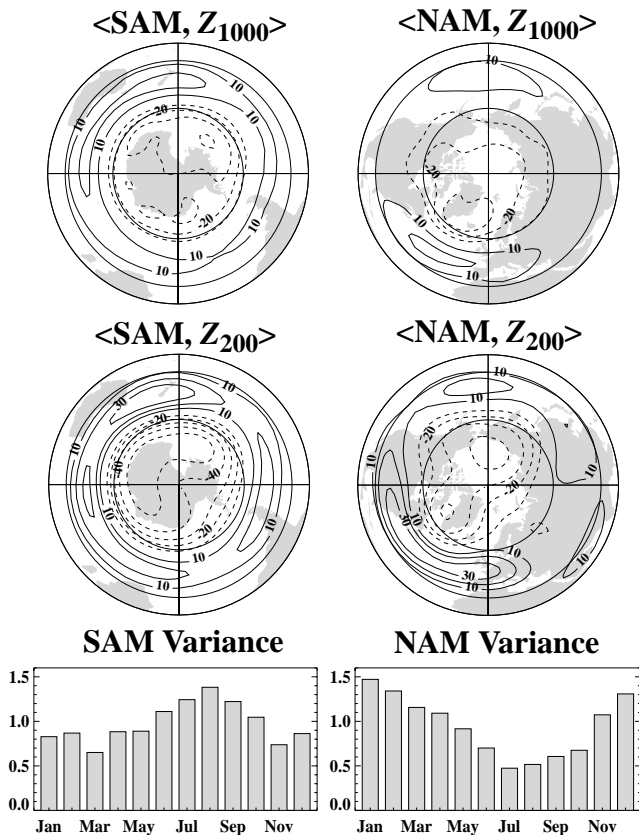
longitudes. Stronger jets tend to reside at higher latitudes during the high phase, consistent with the contraction of the polar vortex. Cross sections of the anomalous zonal mean zonal wind regressed onto the SAM/NAM index demonstrate shifting of the jets near 30°-50°N or 40°-60°S throughout the troposphere (Fig. 2). The associated mean meridional circulation (arrows in Fig. 2) describes the modulation of the Hadley and Ferrel circulations. Strongest descending motions are located at the node of the zonal wind anomalies (near 45°) and coincide with anomalous warming. Near the center of strongest zonal wind anomalies, vigorous meridional motions are present near the surface and the tropopause. This suggests that the anomalous mean meridional circulation helps sustain the surface wind anomalies while eddy momentum fluxes are important in maintaining the winds aloft, as has been demonstrated in a model by *Yu and Hartmann* [1993] and in observations by *Hartmann and Lo* [1998].

### Eddy Activity Related to the Annular Modes

Top panels of Fig. 3 summarize the baroclinic wave activity as  $\mathbf{E}$  vectors [*Hoskins et al.*, 1983] for the NAM composites. The  $\mathbf{E}$  vectors roughly point in the direction of the wave energy propagation, and their divergence approximates the local mean wind acceleration. An equatorward pointing vector indicates poleward eddy momentum flux by the transients. The vertical vector component (shown as contours) reflects poleward eddy heat flux. The baroclinic wave activity, localized over the oceanic sectors, fluctuates with the related jet displacement (see contours in bottom panels of Fig. 3). Wave activity during the high NAM phase is stronger, originates from below at a more poleward position, and tends to propagate more equatorward than activity during the low phase (Fig. 3, top right). Momentum forcing by the baroclinic waves appears to support the zonal wind anomalies, since westerlies winds are accelerated at higher latitudes during the high phase.

Similar contrasts in storm activity between high and low phases are found in the Southern Hemisphere (not shown). However, the SAM related eddies lack longitudinally localized structures due to the greater zonal symmetry of the Southern Hemisphere. The transients tend to propagate more equatorward when the jet is displaced poleward. Transient baroclinic waves account for nearly all of the total eddy forcings. Detailed zonal mean momentum budget calculations thus show that eddy forcing supports the SAM wind anomalies as shown in previous modeling and observational studies of zonal flow vacillation [e.g. *Robinson* 1991, *Yu and Hartmann* 1993, *Feldstein and Lee* 1996, and *Hartmann and Lo* 1998].

While a similar momentum budget is obtained for the Northern Hemisphere mode, significant contributions to the total eddy forcings come from eddy fluxes associated with the zonal variations in the monthly averaged fields (i.e. stationary waves). The fluxes associated with the stationary waves are displayed in the bottom panels of Fig. 3 (arrows)



**Figure 1.** (Top) Leading EOF of geopotential height at 1000 hPa ( $Z_{1000}$ ) shown as regression map of  $Z_{1000}$  anomalies on the SAM/NAM index. Contour interval is 10 m per standard deviation of the index. Orthographic projection is used with 30° latitude interval. (Middle) Same as above, except for 200 hPa. (Bottom) The annual cycle of the index variance averaged over the 100 years.

**Table 1.** Statistics of the normalized leading PCs and EOFs for the geopotential height ( $Z$ ) anomalies above 1000 hPa and their relationship with the annular modes. Here,  $\langle \text{NAM}, X \rangle$ , for example, denotes the spatial pattern derived by regressing  $Z$  anomalies at  $X$  hPa onto the NAM index.

EOF/PC	Variance Exp.(%)		Temporal Correlation w/		Spatial Correlation w/	
	SH	NH	SAM index	NAM index	$\langle \text{SAM}, X \rangle$	$\langle \text{NAM}, X \rangle$
$Z_{500}$	32	22	0.97	0.93	0.99	0.99
$Z_{200}$	29	21	0.94	0.87	0.99	0.99
$Z_{100}$	28	24	0.88	0.67	0.99	0.95

as  $\mathbf{F}_s$  vectors [Plumb, 1985] at 300 hPa. The  $\mathbf{F}_s$  vector is approximately parallel to the wave energy propagational direction and its zonal mean is equivalent to the Eliassen-Palm flux [James, 1994]. The stationary wave activity is stronger and propagates more equatorward during the high phase over the North Atlantic. The associated momentum fluxes conform with the transients in forcing poleward displacement of the westerlies during the high NAM phase.

### Peculiarities over the North Atlantic

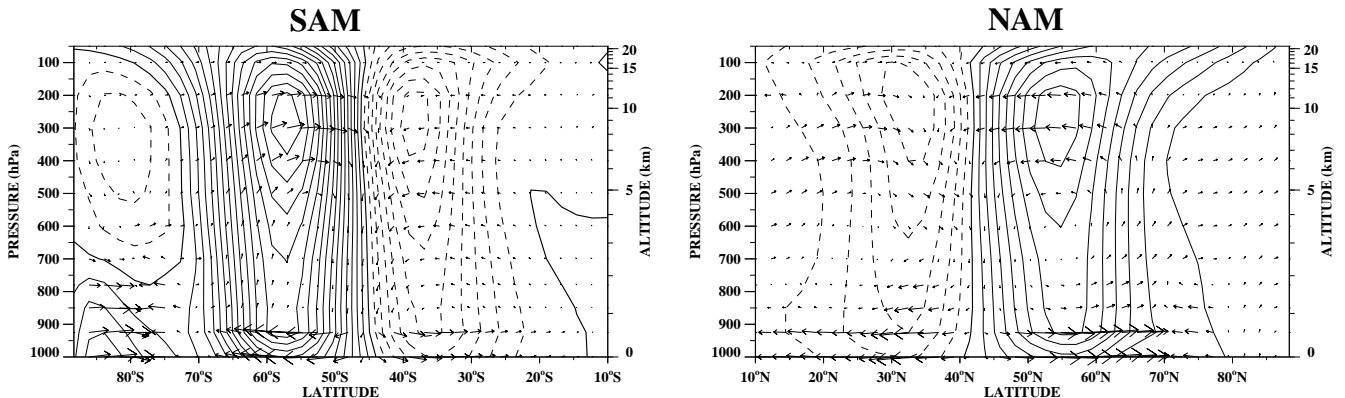
A striking difference between the composite baroclinic waves appears over the North Atlantic in the difference plot in Fig. 3. Baroclinic wave activity generation is much stronger in the high NAM phase, as evidenced by the stronger vertical component of the  $\mathbf{E}$  vectors. The difference in baroclinic eddy activity is much greater in the Atlantic than the Pacific. These differences are consistent with the stronger mode amplitude in the North Atlantic (Fig. 1).

The pronounced zonal asymmetry over the North Atlantic during the high NAM phase is associated with the intensification of the climatological winter stationary wave pattern. The North Atlantic jet structure in the high NAM phase (see Fig. 3, bottom left) has stronger westerlies extending well into Norway and exhibits more Southwest-Northeast tilt than climatology. Similar intensification of the stationary waves has been noted in an observational context by DeWeaver and Nigam [1999]. Conspicuous weakening of the climatological stationary wave pattern is

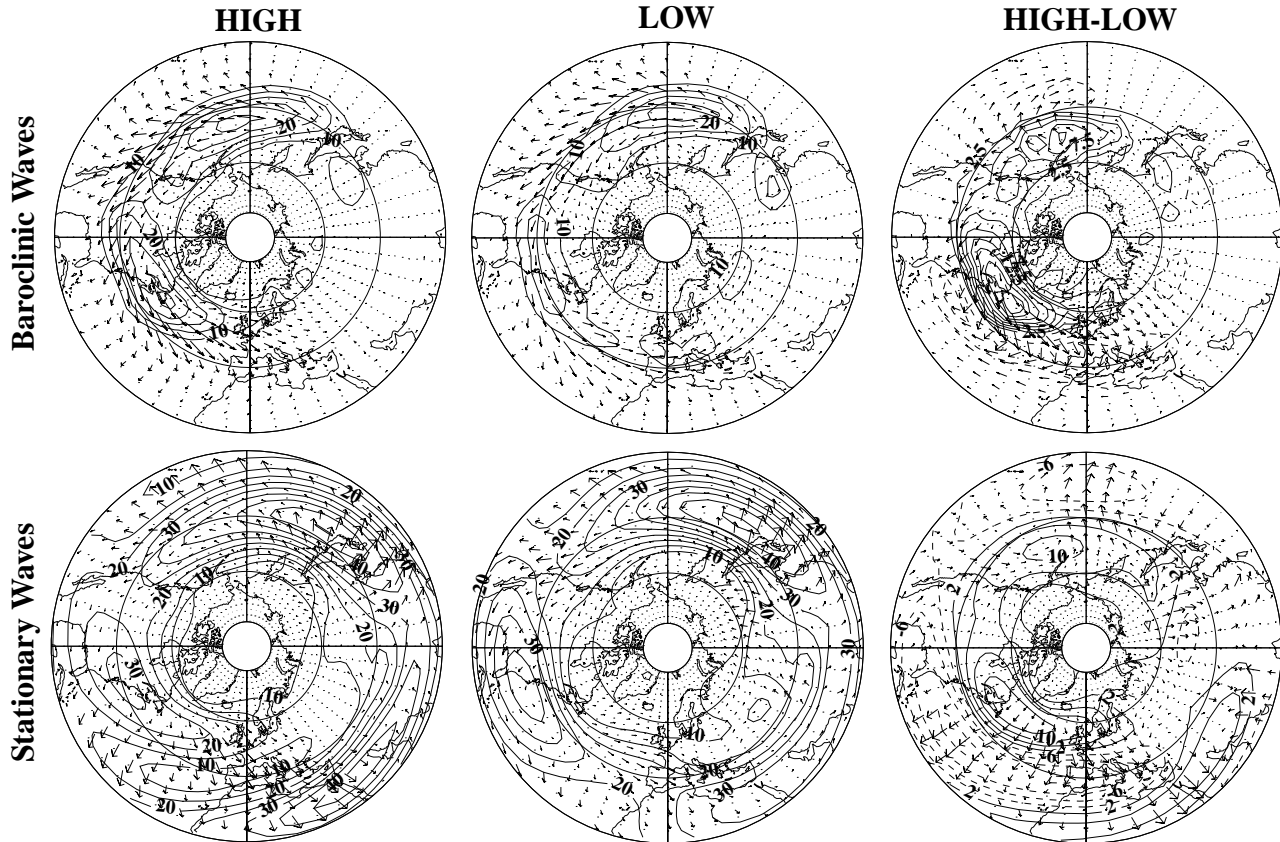
found during in the low NAM phase.

The exaggerated zonal asymmetry and extended protrusion of the jet stream over the North Atlantic appear to induce stronger and more localized baroclinically unstable zones poleward of  $50^\circ\text{N}$ . During the high NAM phase, anomalously cold conditions over the Labrador Sea and mild temperatures in the  $35^\circ\text{--}45^\circ$  belt are reinforced by the NAM related stationary wave anomalies [Wallace, J. M., personal communication]. As the modified stationary wave serves as the background flow for the baroclinic waves, the intensified storm activity over the North Atlantic deviates further poleward from its climatological position. Indeed, observations of Lau [1988] document that the leading low frequency mode of the stormtrack variation in the North Atlantic is characterized by its meridional migration about the time-mean position. Latent heating as well as momentum and heat transport associated with the baroclinic wave systems in turn provide positive feedback to the strong stationary wave anomalies.

The stronger tilt of the North Atlantic jet is associated with an intense anomalous stationary anticyclone over Eastern Europe during the high NAM phase. Such flow configuration may favor anomalous decreases in the total ozone over Northern Europe. As observed by Orsolini *et al.* [1998], sporadic declines in the winter total ozone (“mini” zone hole events) are enhanced by persistent flow that readily advects low latitude, ozone poor air poleward.



**Figure 2.** Cross section of the zonal mean zonal wind regressed onto the SAM/NAM index. Contour interval is  $0.2 \text{ m s}^{-1}$  per standard deviation of the index. Bold contour is zero. The zonal mean vertical and meridional winds regressed onto the index are also shown as vectors in the respective panels (meridional wind in  $\text{m s}^{-1}$ ; vertical wind in  $\text{mm s}^{-1}$ ).



**Figure 3.** (Top) The NAM composite of the baroclinic waves ( $\mathbf{E}$  vectors). The horizontal vector component is shown as arrows at 300 hPa; the vertical vector component is given as contours at 700 hPa. Contour interval is given every  $5.0 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$  (composite) and  $2.5 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$  (difference). The longest vector in the high (low) composite has a magnitude of 110 (100)  $\text{m}^2 \text{ s}^{-2}$ . (Bottom) The NAM composite of the stationary waves ( $\mathbf{F}_s$  vectors) at 300 hPa. Composite zonal winds at 300 hPa are also shown as contours with interval of  $5 \text{ m s}^{-1}$  ( $4 \text{ m s}^{-1}$ , difference). The longest vector in the high (low) composite has a magnitude of 20 (22)  $\text{m}^2 \text{ s}^{-2}$ . The vector length in the low composite is scaled relative to the high. Stereographic projection is used with  $20^\circ$  latitude interval.

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