# A Mechanism and Simple Dynamical Model of the NAO and Annular Modes (A Dynamical Null Hypothesis)

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### The NAO (glossy cartoon from Lamont)



#### Positive NAO Index:

- Stronger than usual subtropical high pressure center and a deeper than normal Icelandic low.
- More and stronger winter storms crossing the Atlantic Ocean, and on a slightly more northerly track.
- Warm and wet winters in Europe, cold and dry winters in northern Canada and Greenland. Mild and wet winter conditions in the Eastern US

### The NAO (continued...)



#### Negative NAO Index:

- Weaker than usual subtropical high pressure center and a deeper than normal Icelandic low.
- Weaker winter storms crossing the Atlantic Ocean, on a slightly more southerly track.
- Cold and dry winters in Northern Europe, perhaps wetter winters in Southern Europe. Milder winters in Greenland, and colder conditions and snowier in the Eastern US.

## **Issues and Observations**

What is the dynamical mechanism underlying phenomena such as the NAO and 'annular modes'?

- (i) There are distinct patterns of variability in the atmosphere, for example the North Atlantic Oscillation (NAO); the Pacific Decadal Oscillation; the Southern Annular Mode (SAM) (Southern *Hemisphere(?)* Annular Mode??).
  - Often identified by EOF analysis, and by teleconnections (analysis of correlations).
- (ii) A particular current (passé?) discussion revolves around whether some of the modes are just regional manifestations of modes of truly hemispheric extent or projections on the zonal mean of regional phenomena. Do different mechanisms exist for zonally symmetric and regional patterns? Do so-called annular modes exist? (Wallace, 2000; Ambaum *et al.,* 2001)
  - This discussion takes place because of the lack of an agreed upon dynamical mechanism for the modes, and is a little ill-defined for that same reason. We would like to reduce the discussion to a quantitative one, not a qualitative one.

## **Issues and Observations - Extra-tropospheric influences**

- (i) Do we *need* the stratosphere (or the ocean) for the NAO or annular modes?
  - In the simplest model we ignore both.
- (ii) Are tropospheric annular modes related to stratospheric annular modes?
  - Do they have the same mechanism?
  - Are they coherent in phase?
- (iii) Does the stratosphere (or ocean) provide a longer timescale than that provided by the troposphere alone?
  - If so, is it a direct effect on the NAO/annular modes, or on the causing mechanism (baroclinic eddies?)?

### The 'timescale' of the NAO





EOF (from Ambaum et al 2001) showing the NAO



and (d) The same as (a) and (b), but for the Pacic sector zonal winds (150 E-120 W).

Zonal wind in low (left) and high (right) AO index states. Atlantic sector (top) and Pacific (bottom) (from Ambaum et al 2001)

## Models

- 1. A full GCM, with various idealized geometries.
  - T42, 14 levels, radiation + moisture + seasonal cycle.
  - Mixed layer ocean as lower boundary condition:
    - (a) Zonally symmetric (40m mixed layer)
    - (b) Zonally asymmetric, either through topography ('Tibet') or variations in mixed layer thickness land (20cm) and ocean (40m).
- 2. A barotropic model. Barotropic vorticity equation, with stochastic forcing (e.g., wavenumbers 8–12, meridionally concentrated in mid-latitudes), representing baroclinic instability. Forcing is:
  - (a) Statistically zonally symmetric, or
  - (b) Statistically longitudinally concentrated in 'storm track' regions  $\sim 60^\circ$  wide.



### Schematic of generation of eddy-driven jet

Stirring produces a *dipole* pattern in the streamfunction (and the pressure).

zonal velocity

streamfunction (or pressure)

## **Generation of Zonal Motion** — **Momentum Fluxes and Rossby Waves**

A Rossby wave,

$$\psi = C \exp[i(k_x x + k_y y - \omega t)]$$

has dispersion relation

$$\omega = ck = \overline{u}k - \frac{\beta k_x}{k_x^2 + k_y^2},$$

The meridional component of the group velocity is given by

$$c_{gy} = \frac{\partial \omega}{\partial k_{y}} = \frac{2\beta k_{x}k_{y}}{(k_{x}^{2} + k_{y}^{2})^{2}}.$$

Must be directed *away* from the source flux,  $\overline{u'v'} > 0$ . region (a radiation condition).

Northwards (southwards) of the source Momentum *converges* in the region of  $k_x k_y$  is positive (negative). the stirring.

$$\begin{split} u' &= -\Re i C k_{\mathcal{Y}} e^{i(k_{x}x+k_{\mathcal{Y}}y-\omega t)} \\ v' &= \Re i C k_{x} e^{i(k_{x}x+k_{\mathcal{Y}}y-\omega t)}. \end{split}$$

The associated momentum flux is

$$\boxed{\overline{u'v'} = -\frac{1}{2}C^2k_xk_y}$$

Northwards of the source Momentum flux,  $\overline{u'v'} < 0$ .

Southwards of the source Momentum flux,  $\overline{u'v'} > 0$ .

#### Generation of Zonal Motion — Stirring and Momentum Fluxes

Zonal motion can generated by random stirring on a  $\beta$ -plane, a crude parameterization of the effects of baroclinic instability on the barotropic mode.

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Zonal momentum equation:

$$\frac{\partial u}{\partial t} = \overline{v'\zeta'} - \kappa \overline{u}$$

Barotropic vorticity equation:

$$\frac{\partial \zeta'}{\partial t} = -\overline{u}\frac{\partial \zeta'}{\partial x} - v'\overline{q}_{y} + S_{\zeta} - D_{\zeta}$$

where  $S_{\zeta}$  is stirring and  $D_{\zeta}$  is dissipation. Multiply by  $\zeta'/\overline{q}_{\gamma}$  and integrate in x:

Pseudo-momentum equation:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial t} \left( \frac{\overline{\zeta'^2}}{\overline{q}_{\mathcal{Y}}} \right) = -\overline{\nu' \zeta'} + S_P - D_P.$$

Statistically steady state:

$$\kappa \overline{u} = S_p - D_p$$

So westerlies are generated in regions of stirring (i.e. baroclinic instability) and these can be expected to vary in strength and in location.



Zonally averaged flow in experiments with varying widths (standard deviations) of the forcing zone. For a wide enough forcing zone, alternating jets can form within the forcing zone.

### Schematic of an anomaly



Anomalous stirring produces a *dipole* pattern of in the streamfunction variability (and so the pressure), and in any measure of this, like an EOF.





Black: jet itself. Red: EOF of  $\overline{u}$ . Blue: EOF of  $\overline{\psi}$ .

(c.f. Sinuous and pulsing modes arise in weakly nonlinear analysis of the variability of a jet.)



## Leading EOFs in statistically symmetric barotropic model



Streamfunction EOF

Zonal velocity EOF



Mean jets and first EOFs for simulations with a narrow stirring region (approximately 6°half-width) and a broader stirring region (approximately 24°half-width) With a narrow stirring region the first EOF is a pulse, and resembles the jet itself. With wider stirring the first EOF is a wobble, almost in quadrature with the jet.

## 1 Pt Correlations, Zonally symmetric barotropic model









# **Effects of Asymmetries**

## Questions:

- As we increase the asymmetry in the model, do the mechanisms of variability change qualitatively?
- Is the EOF (a low frequency phenomena) tied to the location of eddy forcing by baroclinic instability (i.e. a high-frequency events)?

Experiments:

- Use idealised mountains and land-sea contrasts in GCM.
- Vary intensity of stochastic forcing, with longitude, in barotropic model.

### EOF (contours) and EKE (colours).

(a) Case L





Three GCM integrations with differing mountain & land configurations.

## EKE and EOF in asymmetric barotropic model

Eddy Kinetic Energy

EOFS:  $\psi$  (top) and u (bottom)



Stirring is confined to midlatitudes, but zonally asymmetric to represent a single storm track.



### How annular is the annular mode and what does this mean?



The EOF computed from the zonally averaged wind (solid line) and from two distinct quadrants each 45° wide. The structure of the EOFs is the regional quadrants is almost identical to that of the zonally averaged field. The same dynamics is happening around the globe.

#### **Temporal Correlations**

Correlations of the time series of the principal components (Z for zonally average EOF, R for the regional EOFs):

> C(Z, R1) = 0.6249C(Z, R2) = 0.6364C(R1, R2) = 0.1625

If the four quadrants were completely independent, we would have:

C(Z, R1) = 0.5C(Z, R2) = 0.5C(R1, R2) = 0

If there were a perfect annular mode, expect values of 1. This 'same dynamics' is not always in con-

This 'same dynamics' is not always in concert.

## The timescale of intra-seasonal variability

Problems:

- 1. NAO (etc.) has in some sense a longer timescale than weather events (not wholly by definition).
  - (a) There is 'low frequency' (week-toweek) variability.
  - (b) There seems to be some very long term variability in NAO index.

- 2. What gives the power on these longer timescales?
  - (a) The week-to-week timescale?
  - (b) What dynamics gives interannual or interdecadal power (if needed)?
- 3. Do we *need* any exotic dynamics?

### Red Noise

Linear barotropic equation:

$$\frac{\partial \zeta}{\partial t} + U \frac{\partial \zeta}{\partial x} + \beta \frac{\partial \psi}{\partial x} = S - r\zeta$$

Solution of the form

$$\Psi = Re\Psi e^{i(\mathbf{k}\cdot\boldsymbol{x}-\omega t)}.$$

Whence

$$|\Psi|^{2} = \frac{S_{\omega}^{2}}{[(k^{2}\omega^{2} + (\beta - Uk^{2})k_{x})^{2} + r^{2}k^{4}]}$$

A red noise process.



### **Time Series**



Time series shown has 10 day drag. Power spectra are obtained for three different values of the frictional drag: 10 days, 20 days, and 40 days..



Bottom:  $(\partial \zeta / \partial t) = S - r\zeta$ 

#### Power Spectra, EOF 1



Autocorrelation of EOFs

Autocorrelation of EOF of zonally-averaged zonal velocity (left) and of a simple rednoise process (right)

- 1. A typical autocorrelation is of order 10 days (cf observations show a similar value).
- 2. The wobbler is typically as or more persistent than the pulser

## Conclusions

- The NAO and annular modes can be produced by stormtracks.
  - Dipole-like patterns are a natural consequence of forcing by meridionally localized stirring, caused by baroclinic instability in a single baroclinic zone.
  - Stirring produces eddy-momentum fluxes that produce a barotropic jet (the mid-latitude-subpolar jet in the atmosphere). If the stirring is a random process then it produces variability in the this jet. Typical modes of variability are a 'wobbling' and a 'pulsing' of the zonal flow.
  - Both of these produce a dipolar pattern in the EOF (and one-point correlation function) of pressure field, and a dipole or tripole component in the variability of the velocity field.
- Zonally localized forcing produces a correspondingly localized response. NAOlike patterns are readily achievable, in a GCM and in a barotropic model. *Same mechanisms produce an NAO and an AO.* 
  - Suggests there should be a correlation in NAO index and Atlantic storm-track activity.
  - Suggests a NPO should exist, but its signature may be swamped by other activity in the Pacific.

- The (zeroth order) timescale of the response [i.e., 10-100 day ('low-frequency') variability] is produced by redenning of the eddy forcing by friction, limited by nonlinear dynamics. Produces a decorrelation timescale of ~ 10-20 days, as is observed. (No shame in red noise. The NAO really stands for 'Not An Oscilla-tion'...)
  - There need be no intrinsic 'low-frequency' dynamics to produce that lowest order timescale. If there is a longer timescale (e.g. weeks, a tail in the autocorrelation) may be because of baroclinic feedbacks between eddies and mean flow, or 'weather regimes' (e.g. blocks), or the stratosphere. (No shortage of mechanisms.)
- If there is real interannual (or longer) variability in the NAO/AO/SAM etc, then it may be due to influence of SST (or other slowly varying phenomenon) on the baroclinicity, rather than directly on the patterns.

## Role of the Stratosphere and Other Open Questions

- Many kinds of forcing, especially but not only zonally symmetric forcing, will project onto the annular mode and influence it. Significant hemispheric-scale zonal correlations require a zonally symmetric forcing.
- Are annular modes in the stratosphere caused by a similar mechanism?
  - Almost any mid-latitude stirring will give a similar EOFs.
- Does the stratosphere influence the tropospheric annular modes, or vice versa?