The Annular Modes in Weather and Climate: Tutorial/Discussion

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Topics

What are the annular modes?

Observations and features to explain.

Are the annular modes important?

Theoretical and climate significance.

Dynamics & simple models of the annular modes

Eddy mean-flow interactions, timescales, zonal structure.

Climate models of the annular modes & their climate responses

(Time permitting)

What Are the Annular Modes?

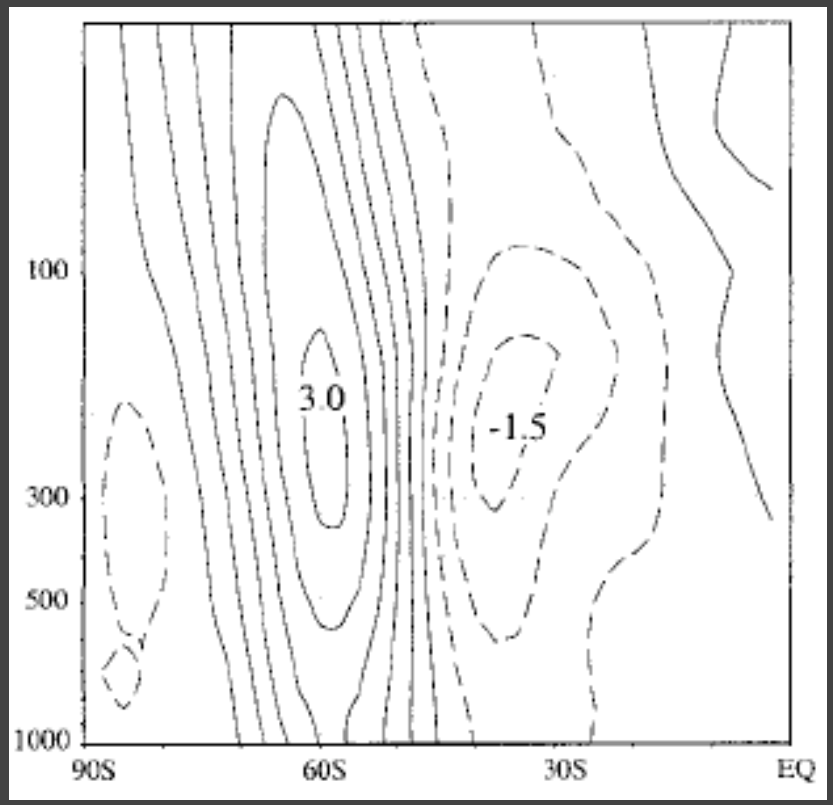
- Annular mode: recent name for long-studied vacillations of zonal mean extratropical atmospheric circulation.

- Thompson & Wallace (1998, 2000, ...) brought out several new points and revitalized the field of extratropical atmospheric dynamics.

- We'll start with a discussion of the AMs from Thompson and Wallace (2000) and other papers.

What Are the Annular Modes?

The annular mode signature in zonal wind, using all months of the year.



What Are the Annular Modes?

Method:

- Extract extratropical zonal mean wind or zonal-mean geopotential at some pressure level: $g(y,t)$
- Apply areal weighting, remove seasonal cycle: $g'(y,t)$
- From $g'(y,t)$, calculate leading EOF $v(y)$ and principal component time series $u(t)$.
- Regress PC time series $u(t)$ on various fields; here we show zonal wind.

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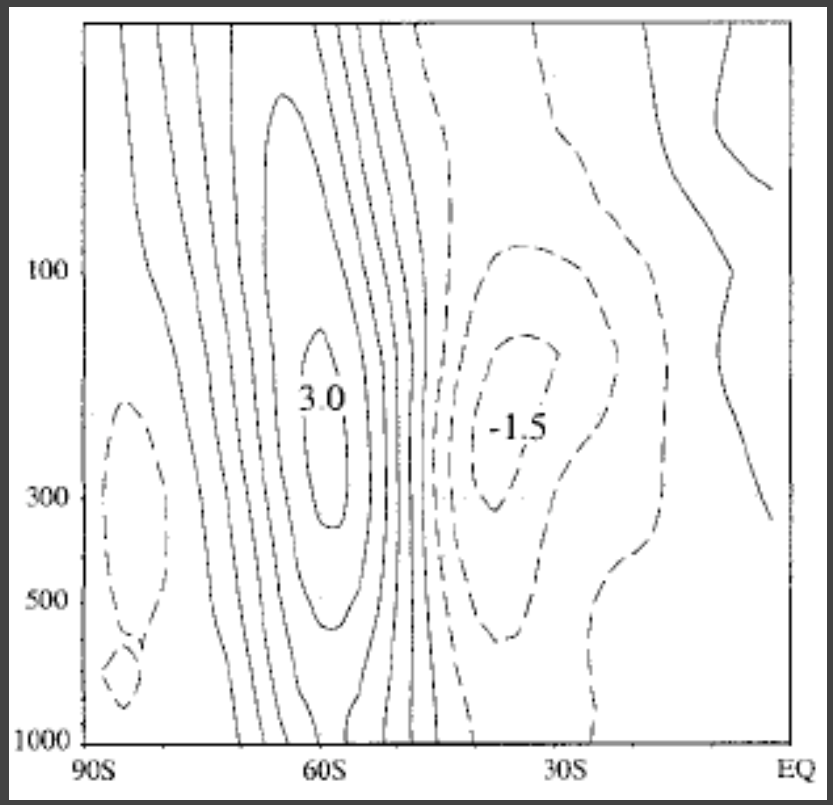

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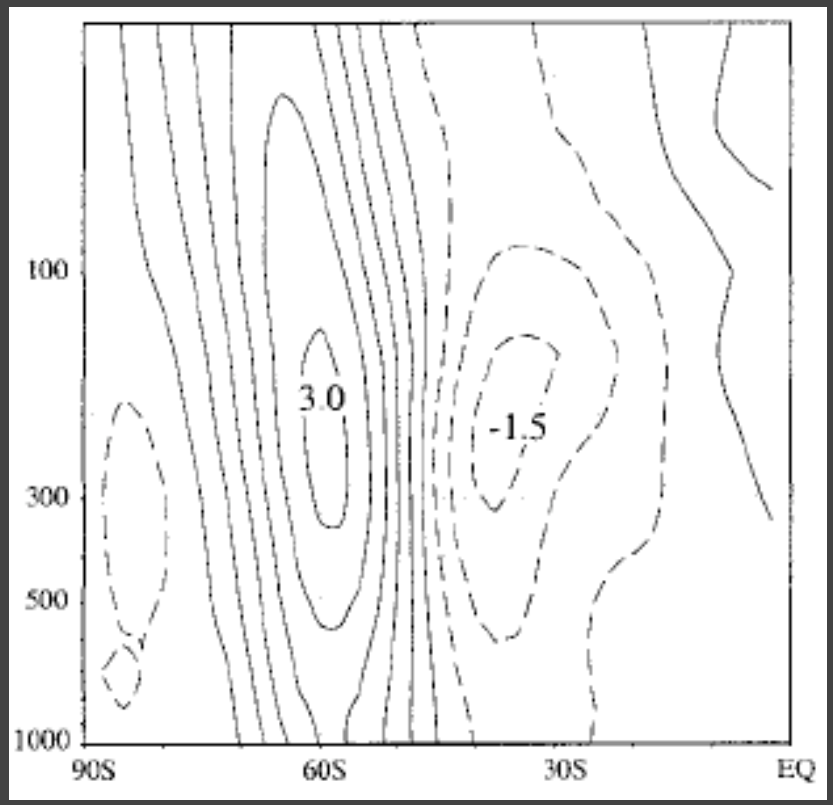

Questions:

- Dipolar structure: what sets the scale of the dipole?
- Node at around 45^0 latitude: what sets this point?
- 2-3 m/s anomalies in month to month variability: what sets this amplitude?

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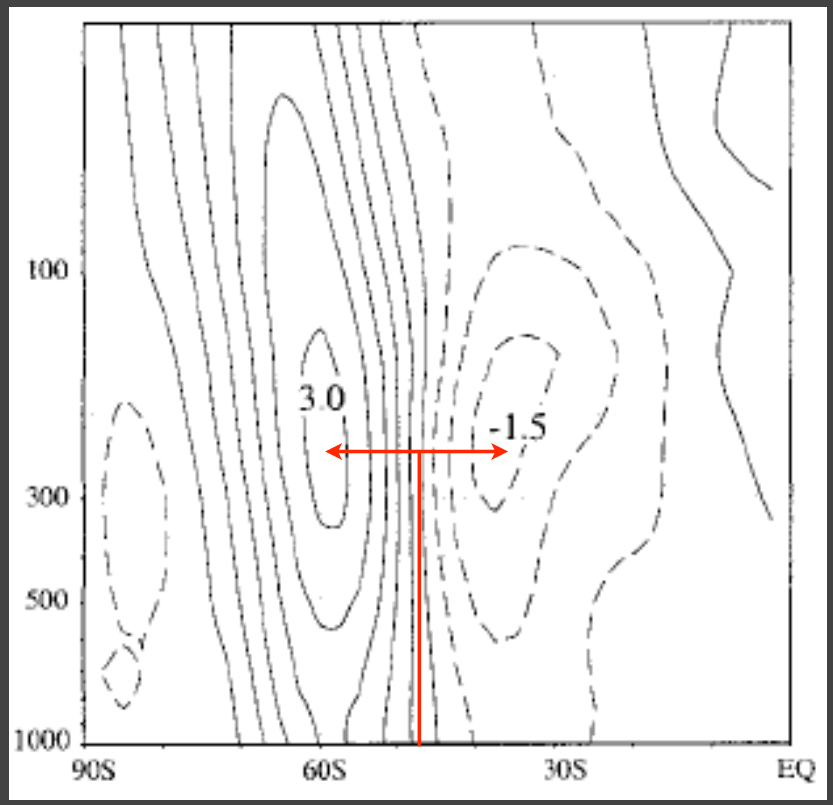

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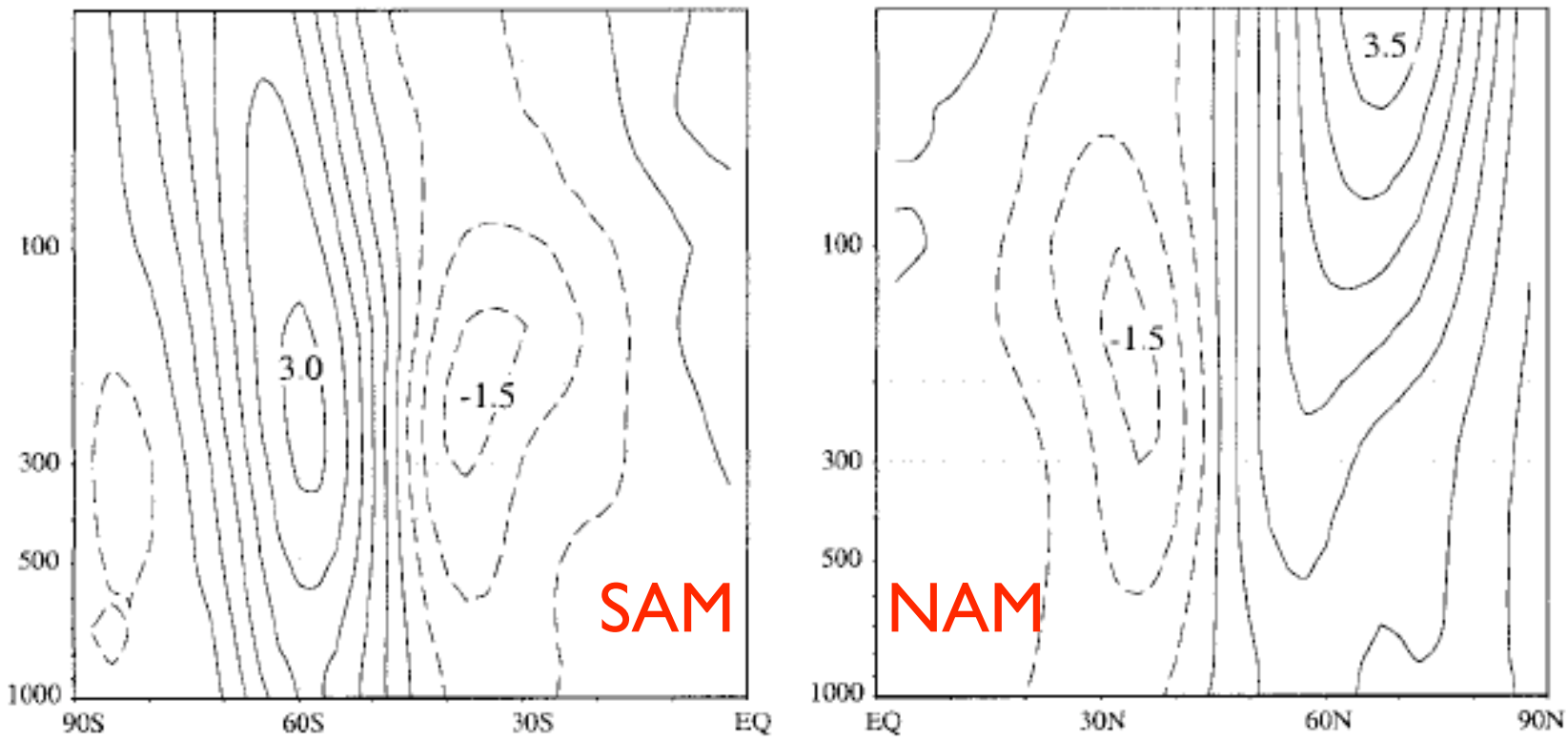
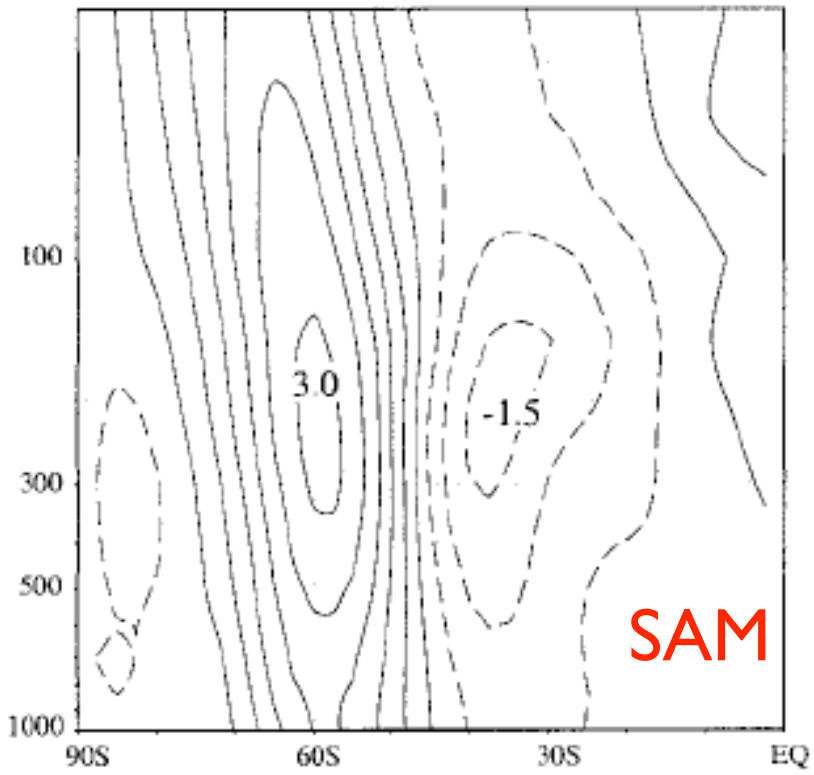
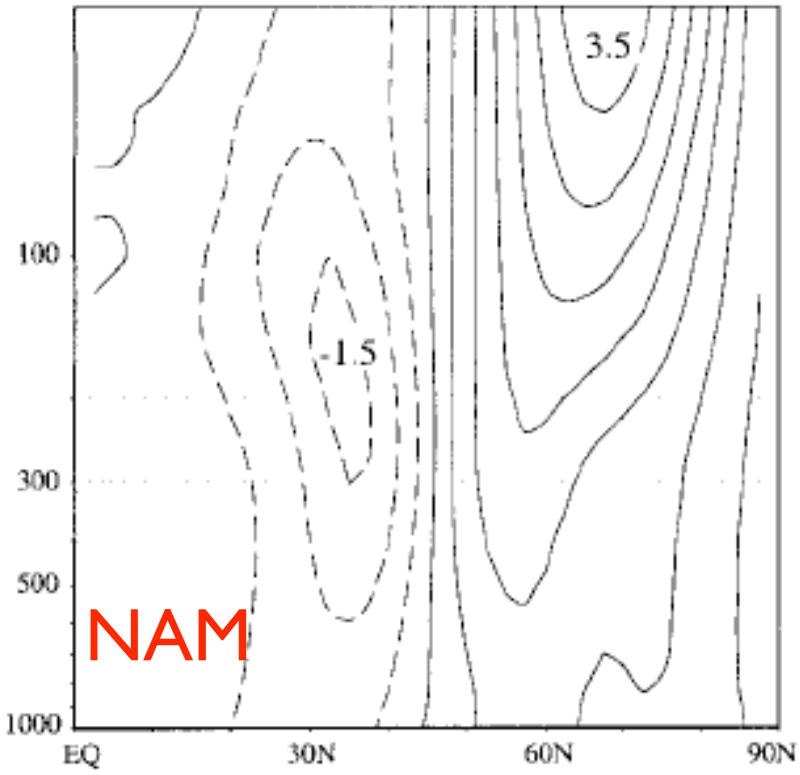


We see tropospheric and stratospheric signatures.
Tropospheric signatures are symmetric about the equator.

What Are the Annular Modes?



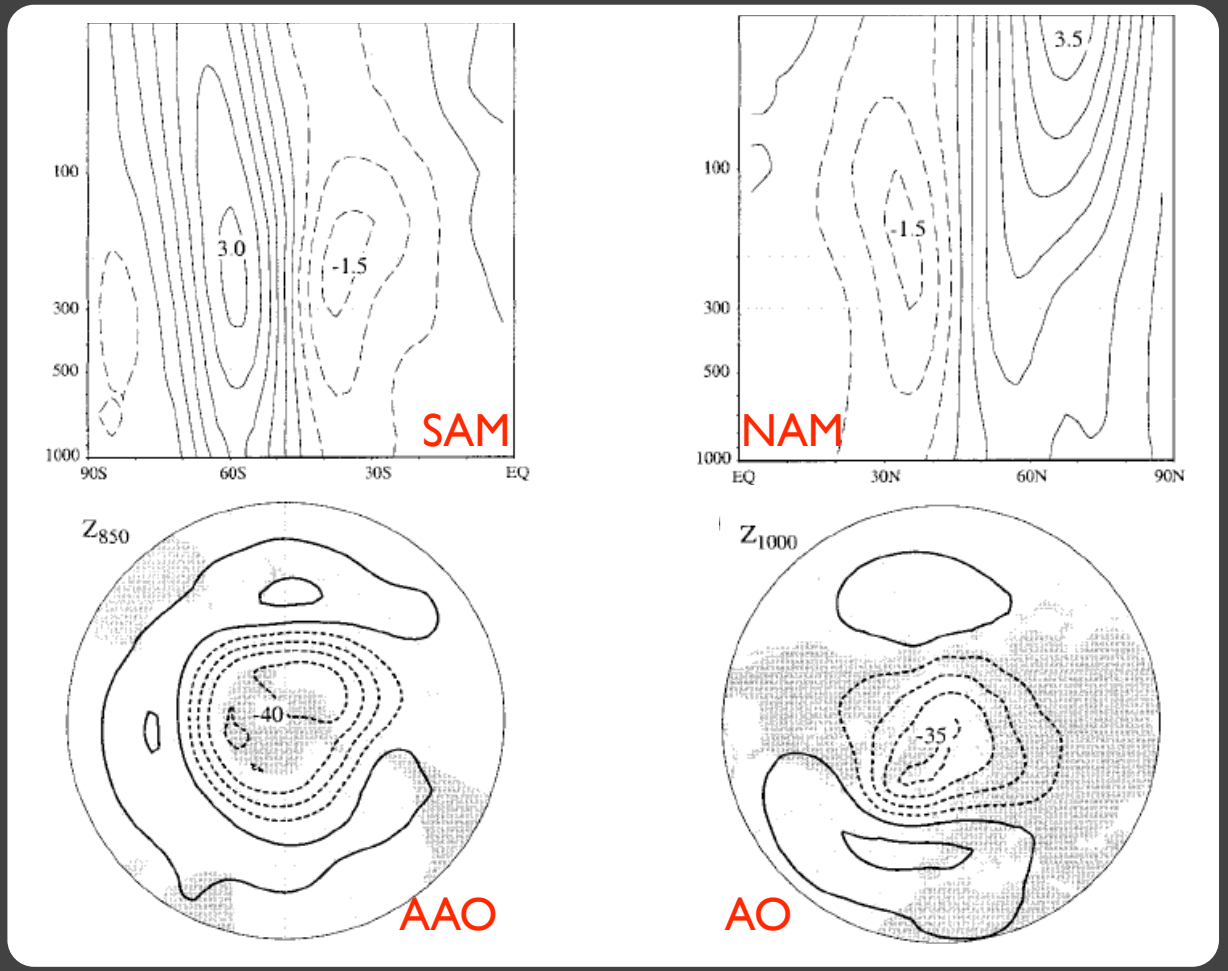


Questions:

What kind of dynamics yields hemispheric symmetry?

Why is this symmetry absent in the stratosphere?

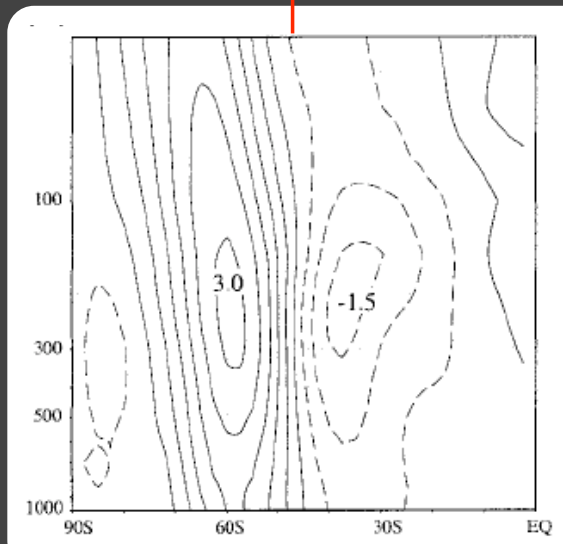
What Are the Annular Modes?



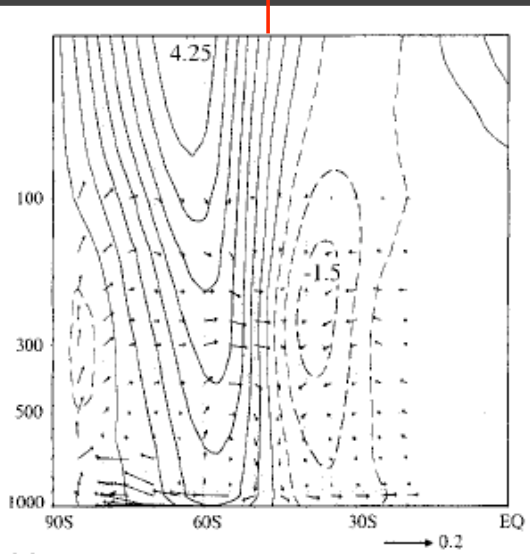
The regional patterns favour ocean basins.
NAM/AO is a hemispheric version of the NAO.

What Are the Annular Modes?

SAM, All Months



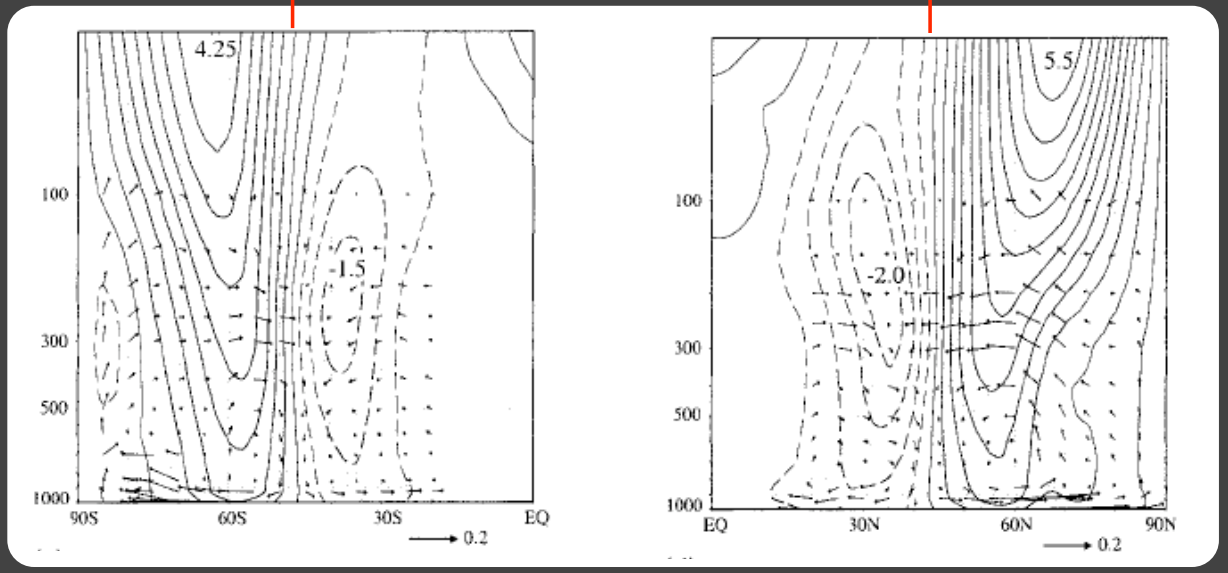
SAM, November



When the SH stratosphere is active, the SAM is no longer tropospherically trapped . . .

What Are the Annular Modes?

SAM, November NAM, January–March



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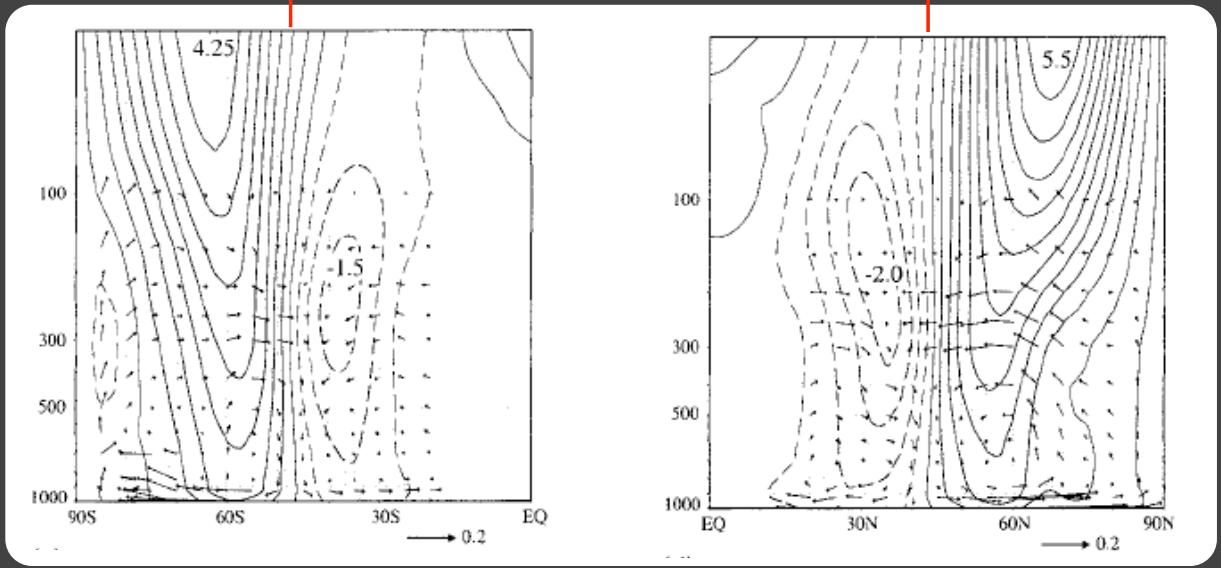
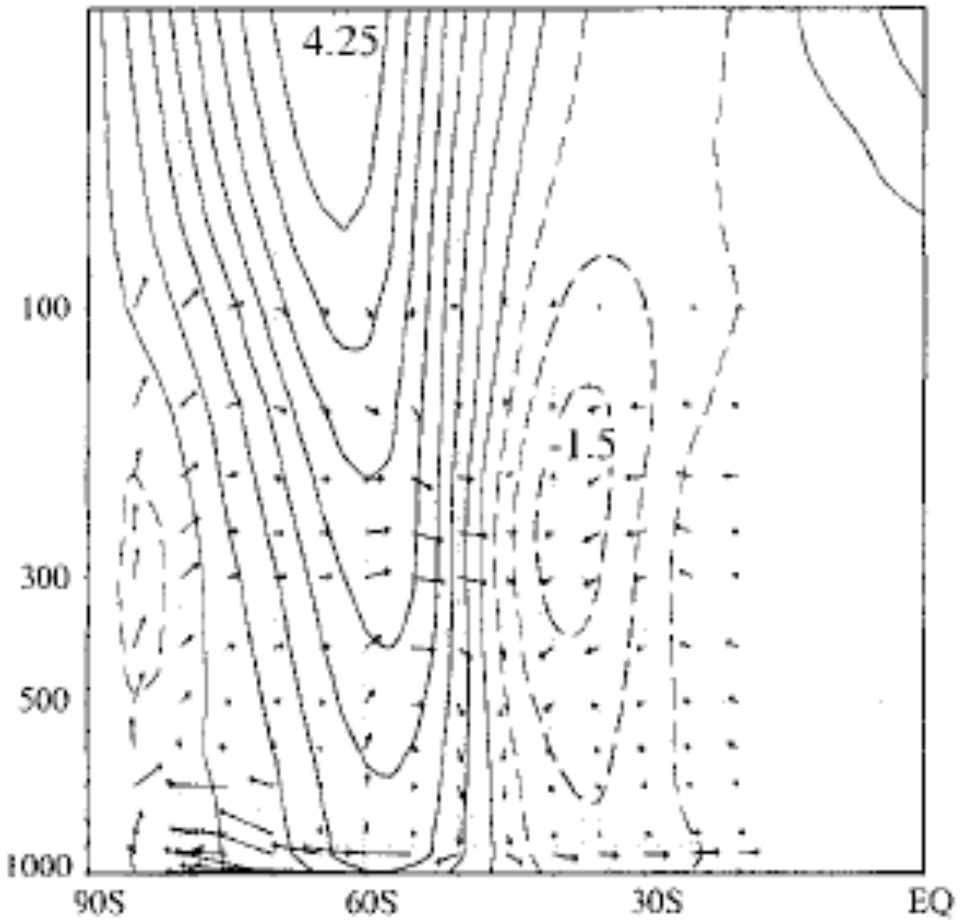


. . . and the hemispheric symmetry is apparent in both stratosphere and troposphere.

Annular Modes: Modulating Jets

SAM, November



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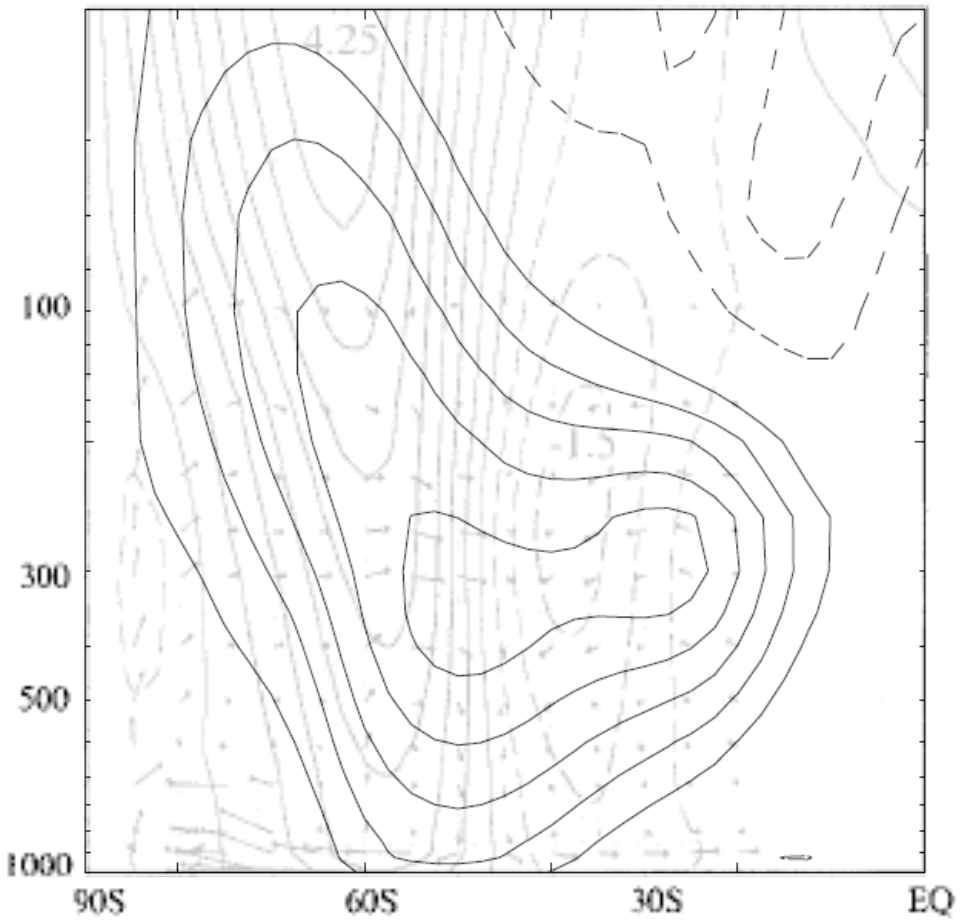

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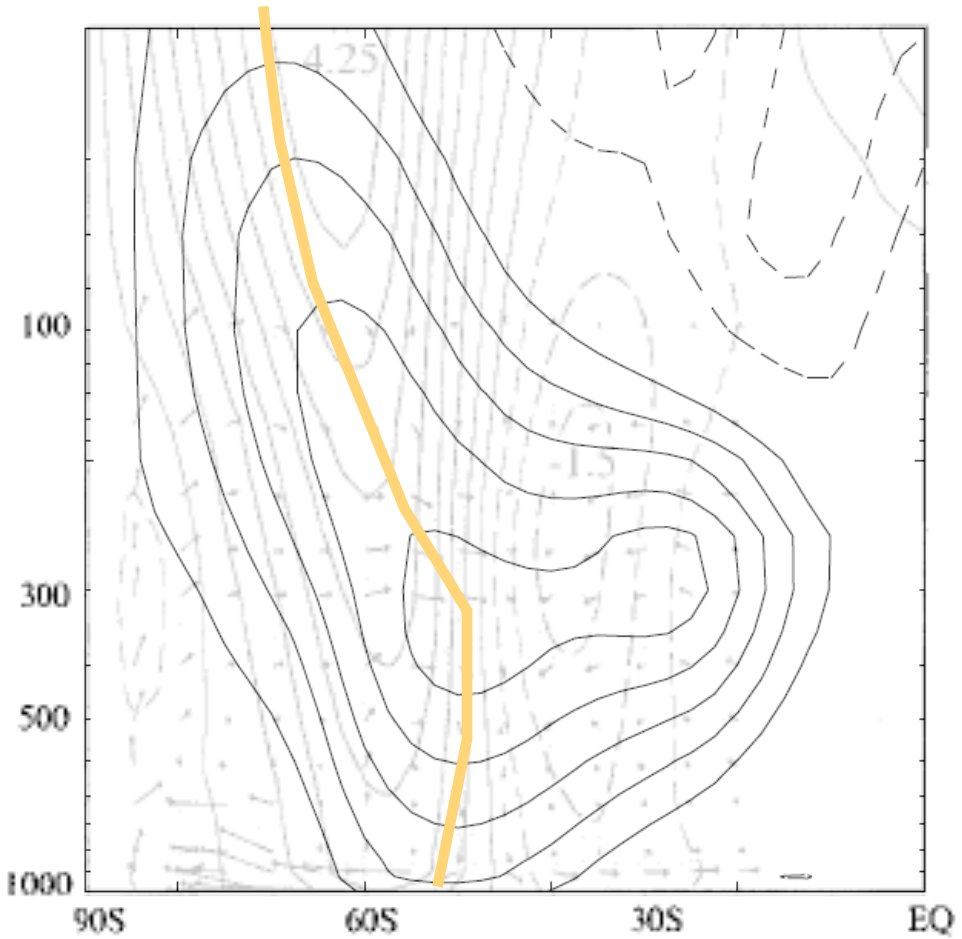
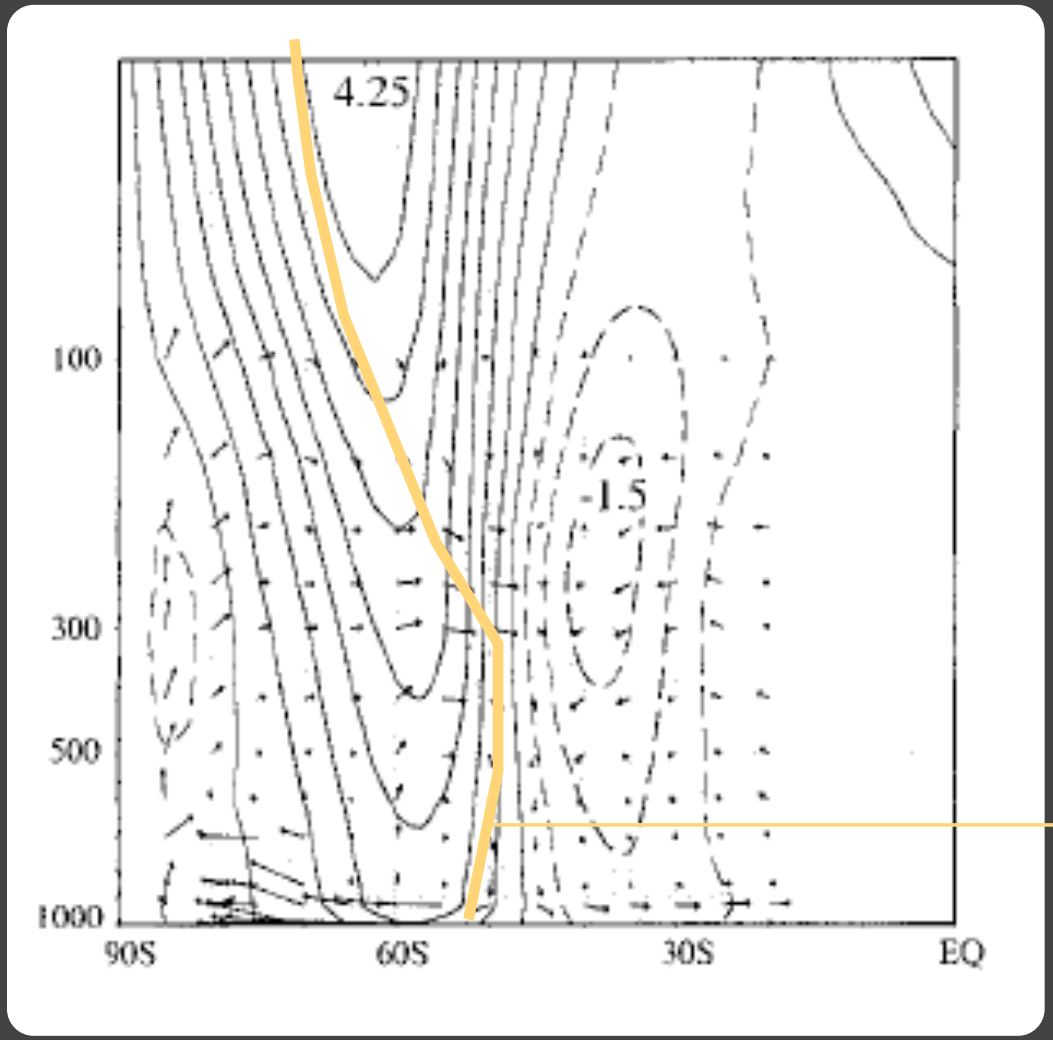
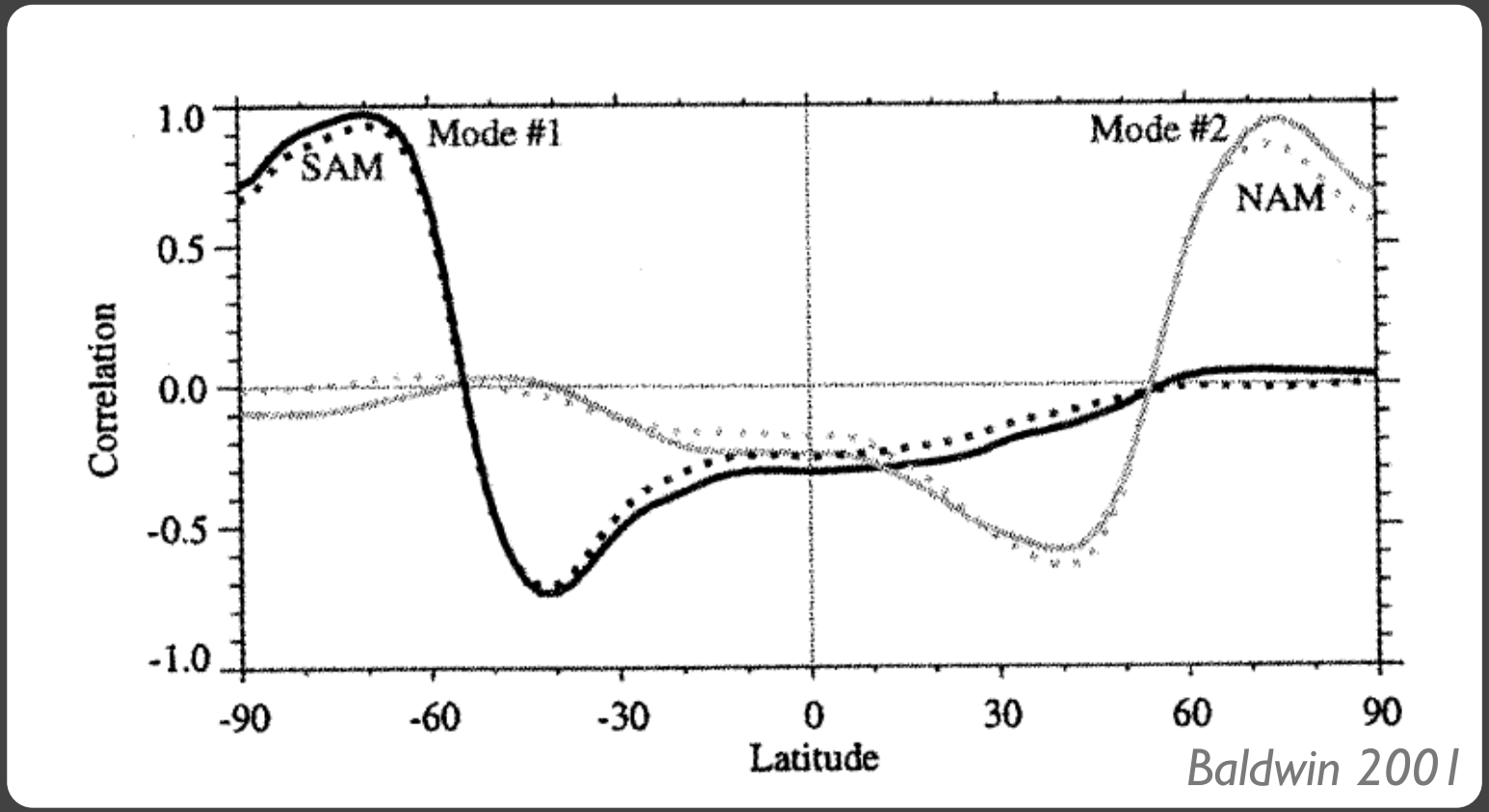


Annular Modes: Modulating Jets

- In the troposphere, the AM is a north-south jet shift (this is a good description of the SAM).
- In the stratosphere, the AM is a weaker or stronger polar vortex.
- Positive AM: poleward shifted jet stream, stronger polar night jet, colder polar stratosphere.



Timescales of the AMs

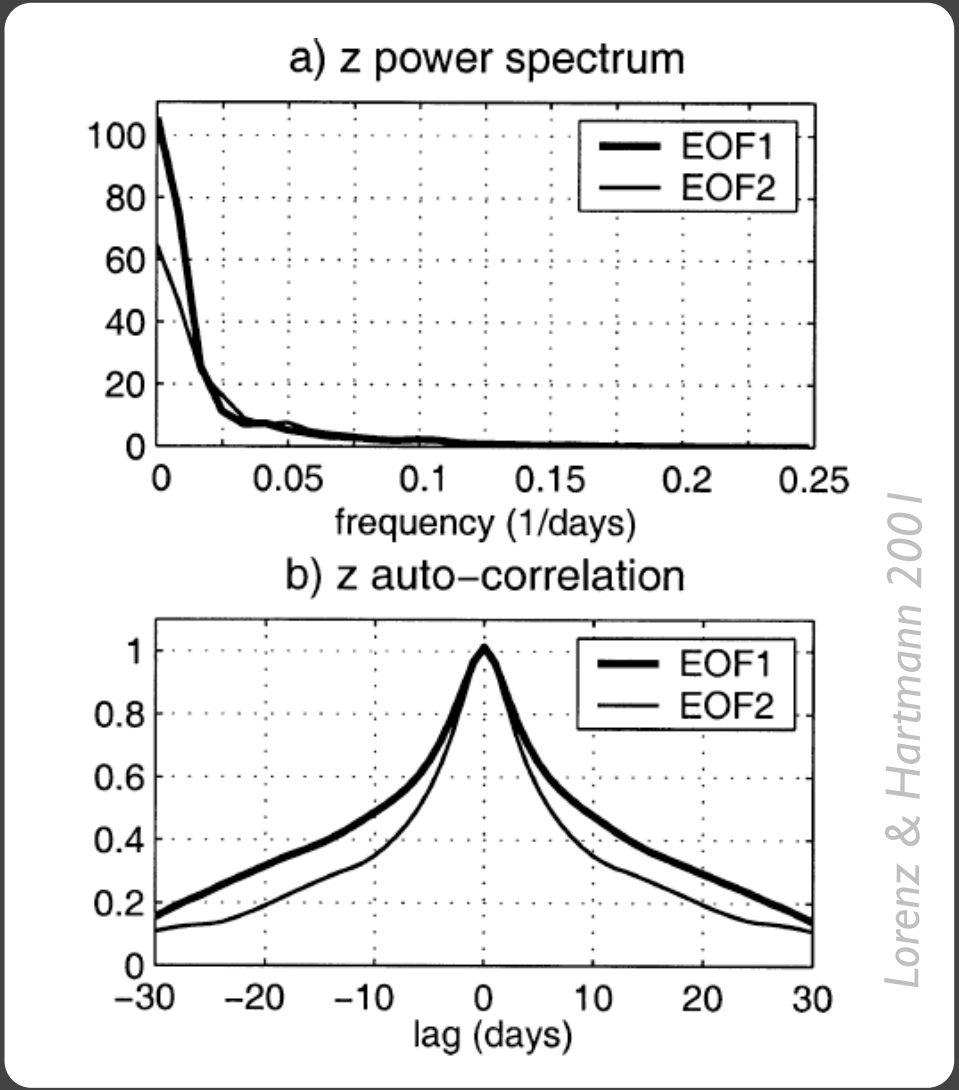


Baldwin 2001

- Baldwin (2001): AM pattern is the same whether daily or monthly data is used.
- AM events occur on sub-monthly scales, and the monthly patterns reflect the average of several of these events.

Timescales of the AMs

- Lorenz and Hartmann (2001), Feldstein, Lee: AMs exhibit red noise behaviour and damp within 14-20 days.
- So the annular mode is considered a mode of low-frequency atmospheric variability.



Lorenz & Hartmann 2001

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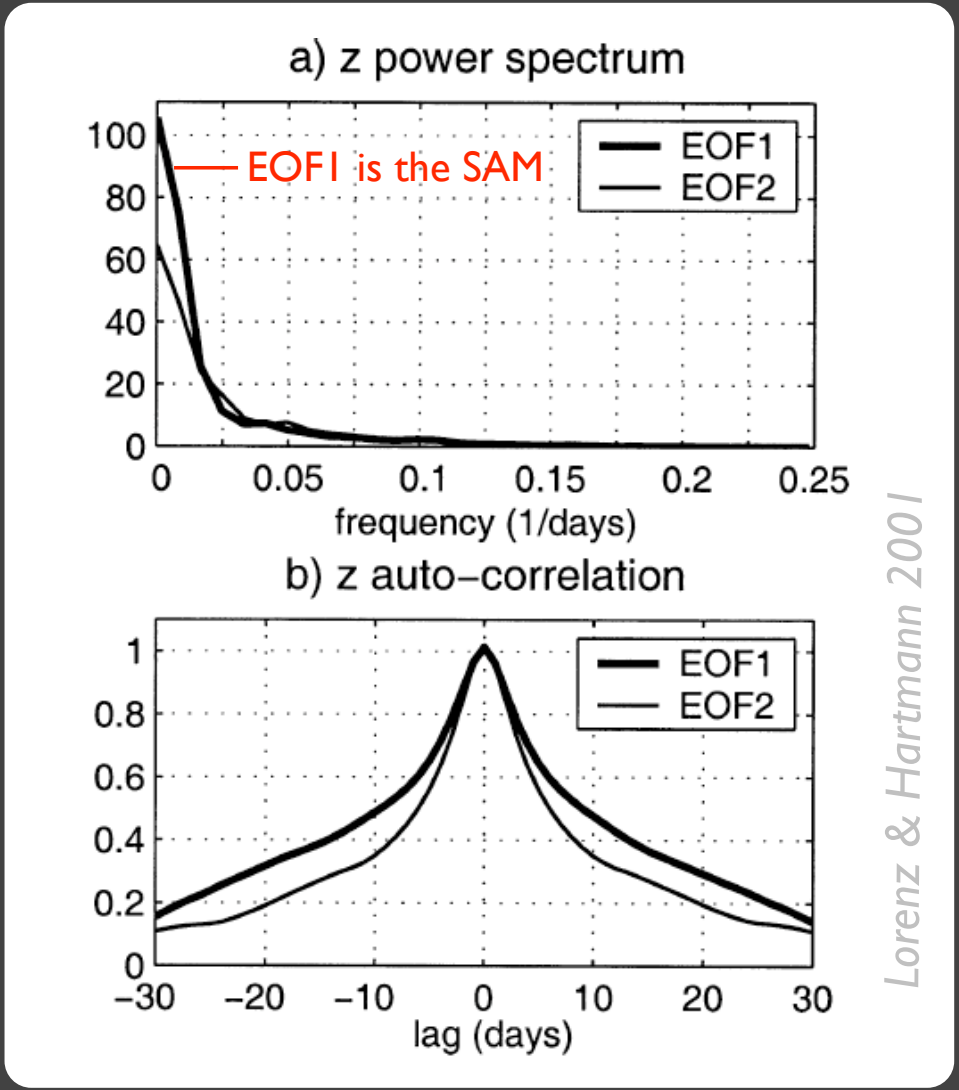

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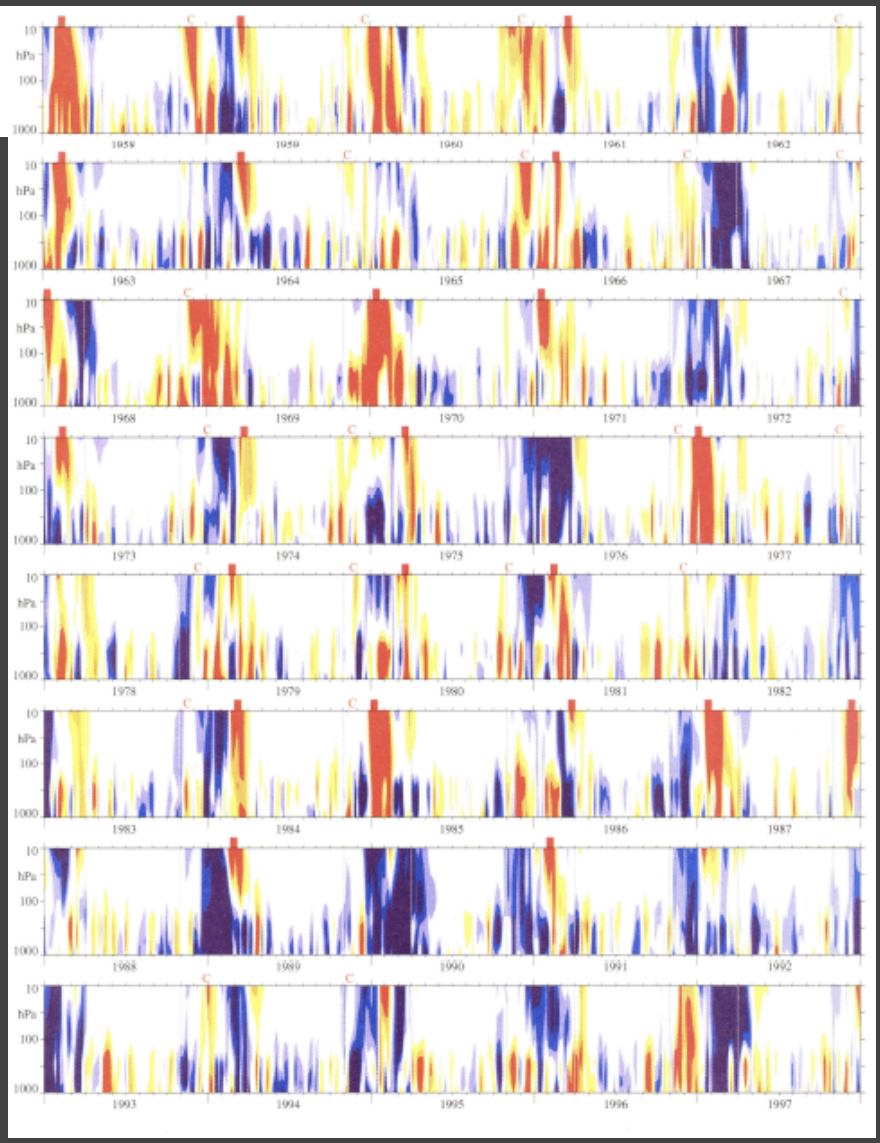
Vertical Coherence of the AMs

Propagation of the Arctic Oscillation from the stratosphere to the troposphere

Mark P. Baldwin and Timothy J. Dunkerton

- Baldwin and Dunkerton (1999) calculate the daily NAM at each level in the stratosphere.
- They find that the stratospheric NAM typically leads the tropospheric NAM.



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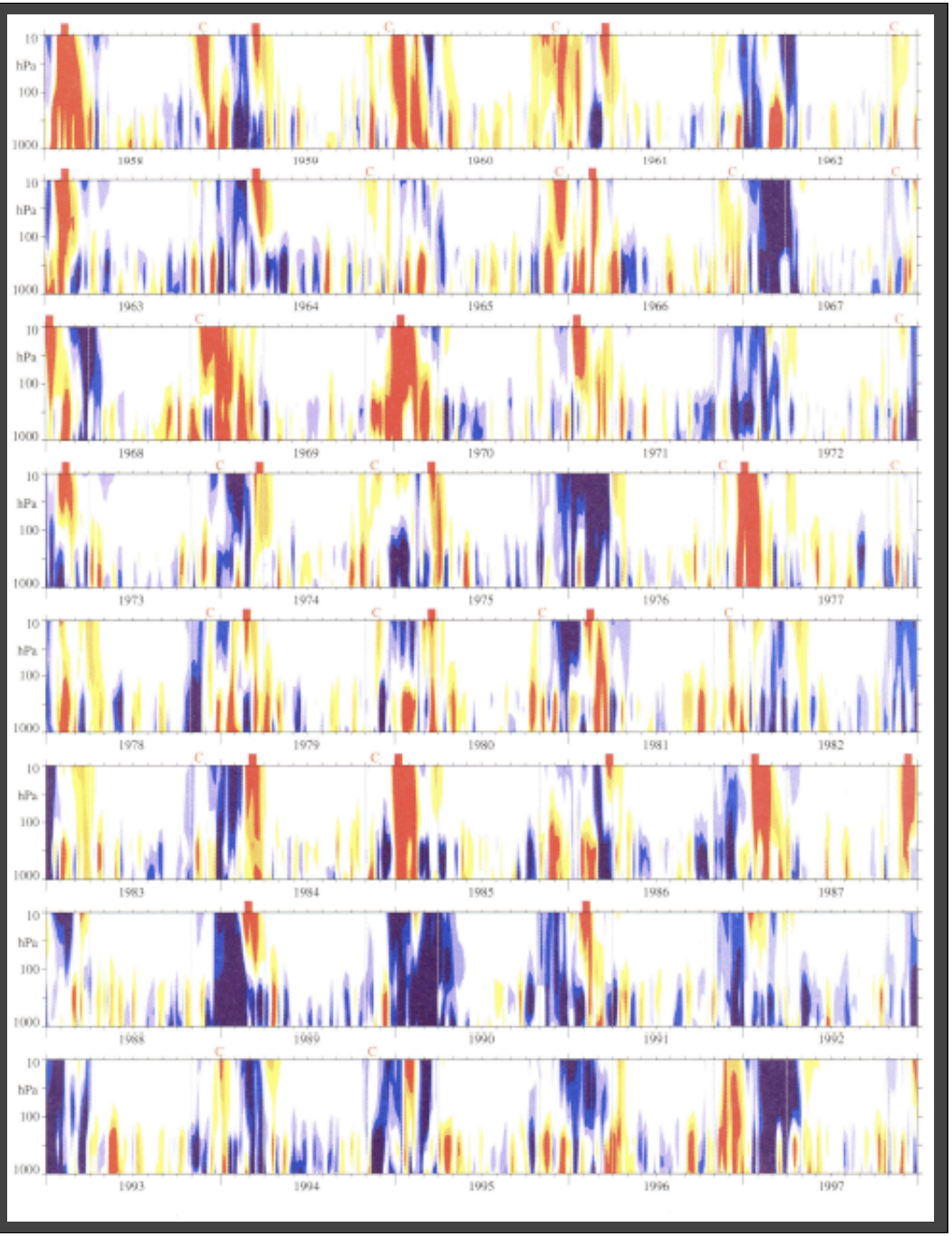

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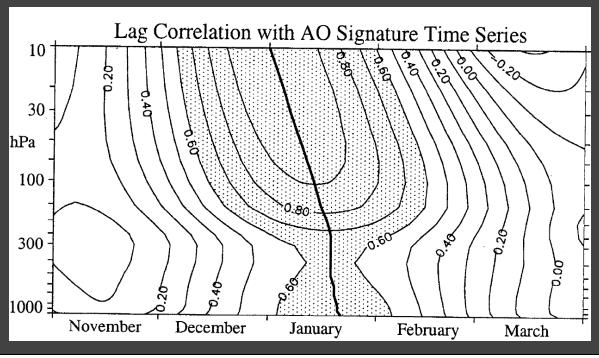

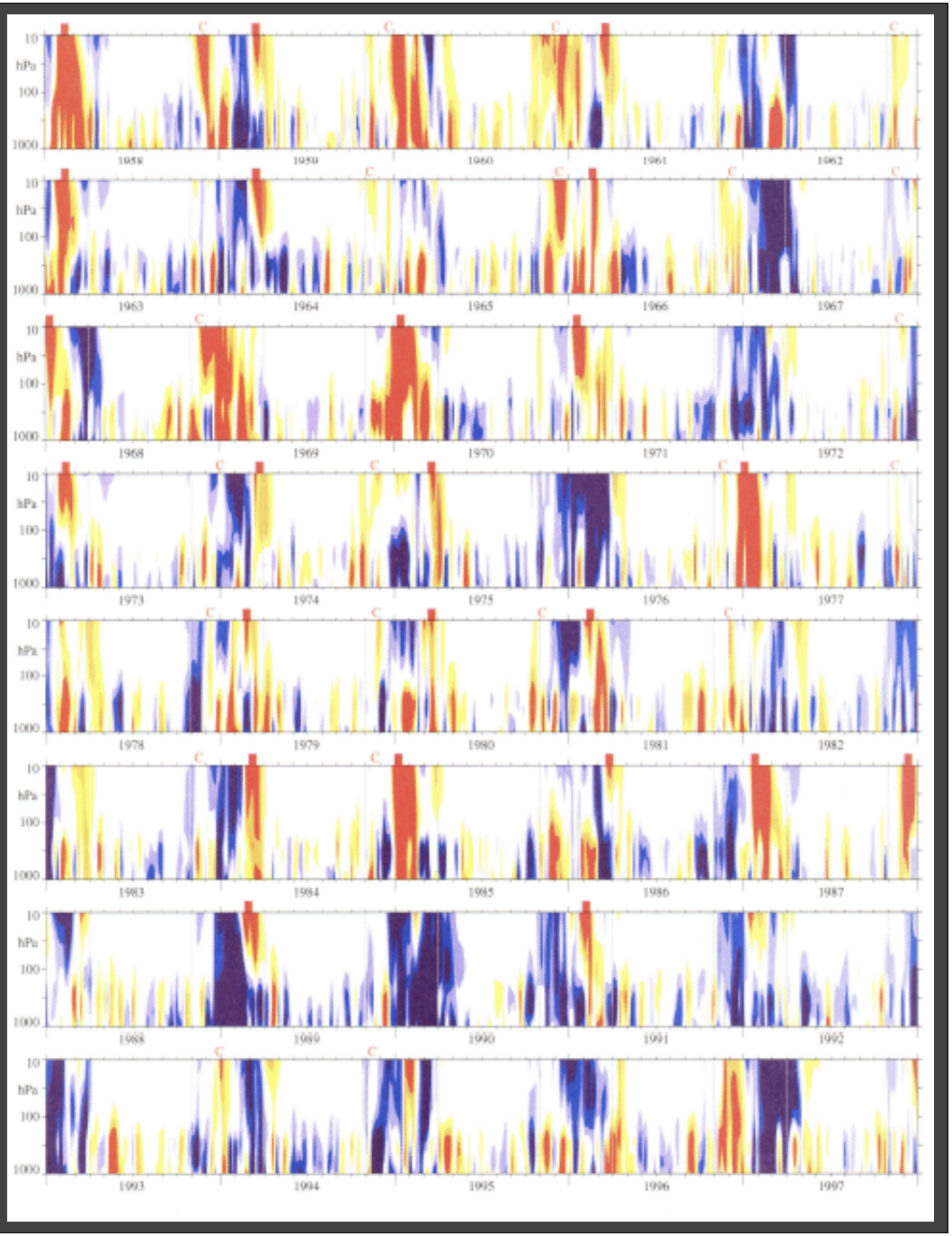

Are the AMs important? If so, why?

- We have so far described meteorological signatures of the AMs.
- What is their significance in the general circulation?
- Why are they important to think about for climate?

Theoretical Significance of AMs

Classical theory of the general circulation

$$\overline{u} = \overline{u}(x, y, p) = [\overline{u}](y, p) + \overline{u}^*(x, y, p)$$

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time mean

zonal mean

stationary eddy

- Extratropical zonal mean circulation: baroclinic instability, wave-mean-flow interactions, hemispherically symmetric.

- Extratropical stationary eddy field: stationary wave theory, predominantly Northern Hemisphere.

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time mean

zonal mean

stationary eddy

- We want a theory for zonal-mean and eddy climate *fluctuations* on various timescales.

- The annular modes account for > 40% of the variance in the extratropical zonal mean circulation, so they are worth trying to understand as dynamical objects.

Climate Significance of AMs

- AM *influences* are ubiquitous in extratropical climate: if we could predict the AMs, we could predict many parameters.
- Some examples . . .

Climate Significance of AMs

AM-related effects that do not strongly affect the AM.

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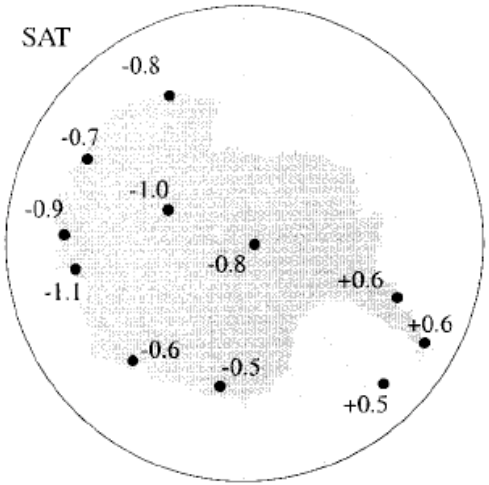
Climate Significance of AMs

SAM & SAT



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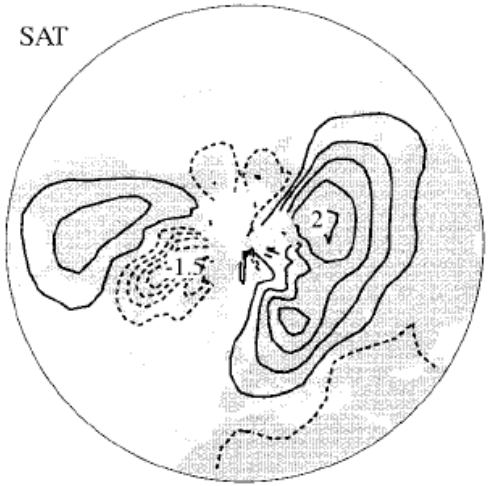
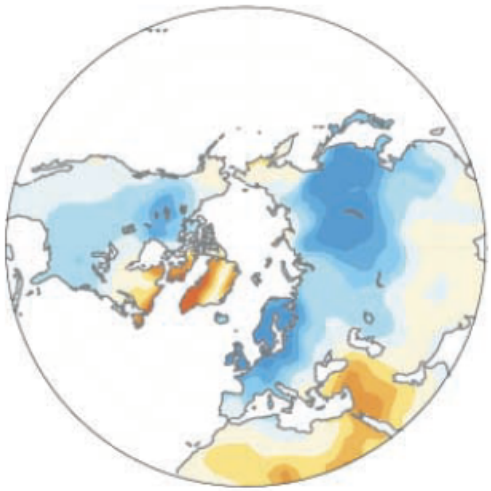


NAM & Cold Extremes



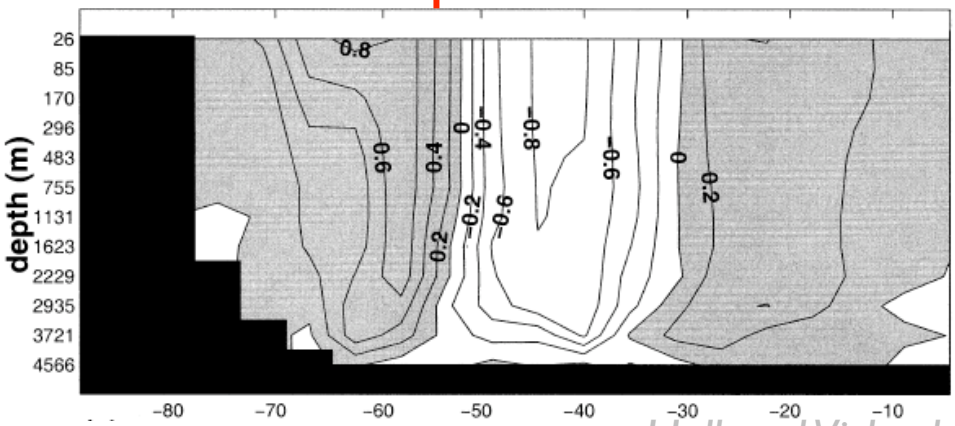
Thompson & Wallace

AMs have a strong link to surface climate variability. This has important implications for surface temperature trends.

Climate Significance of AMs

- SAM signatures in the Southern Ocean.

SAM-related Zonal Currents in a Coupled Model

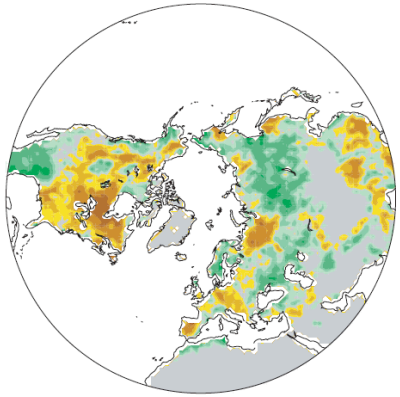


Hall and Visbeck

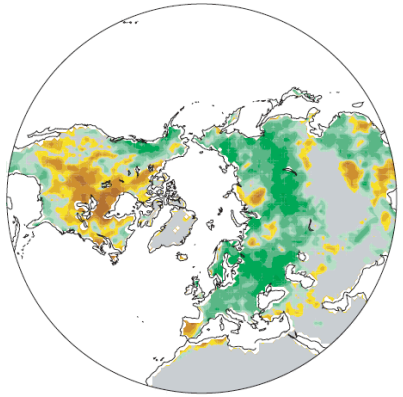
Climate Significance of AMs

- NAM & SAM related variability in the carbon cycle.

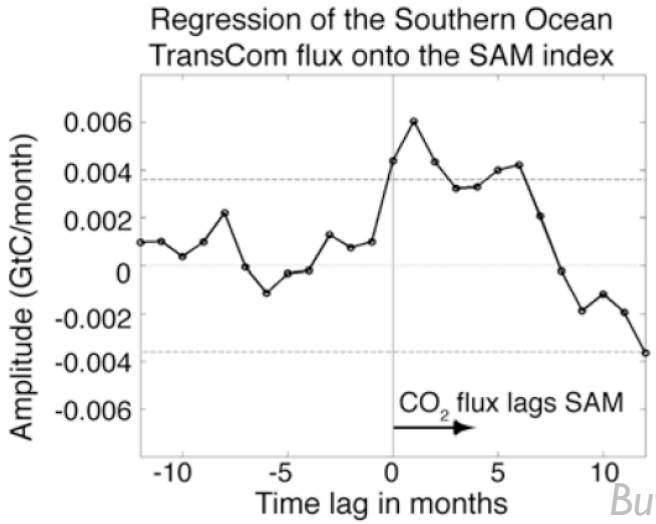
NDVI & EOF1 of NH CO2



NDVI & Springtime NAM



Russell and Wallace

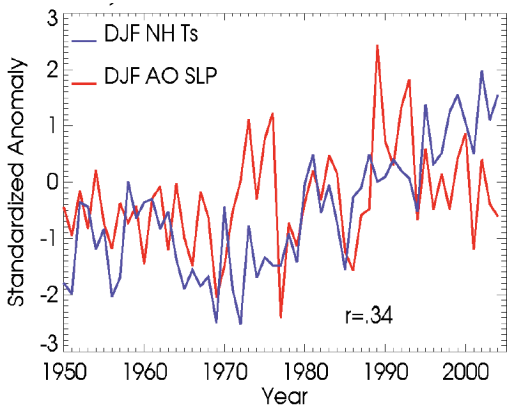


Butler et al.

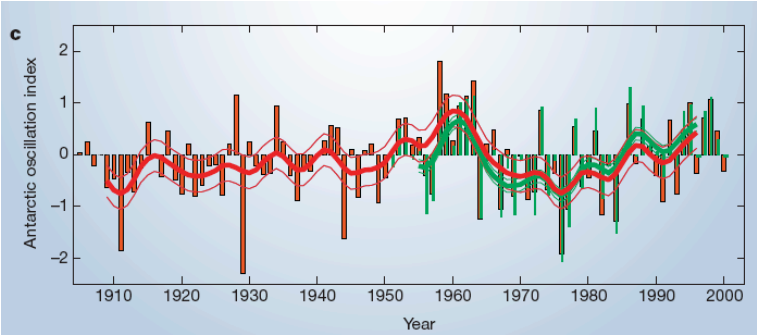
Climate Significance of AMs

- NAM and SAM indices exhibit decadal scale variability.
- We'll talk more about this later.

NAM & NH Ts



SAM



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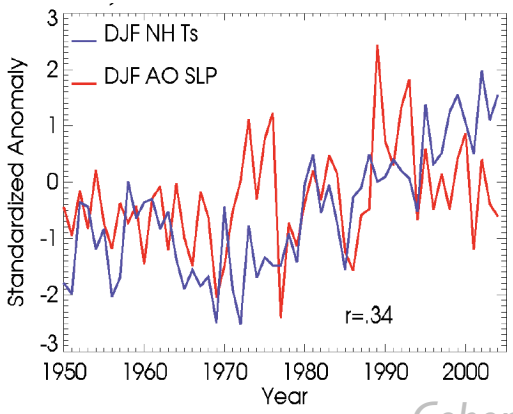
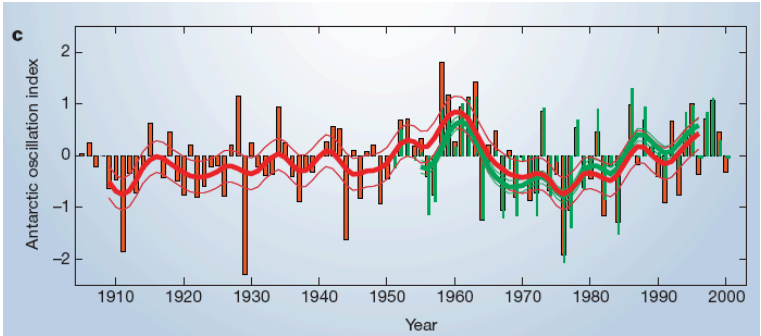


Cohen & Barlow

SAM



Jones & Widmann

Working Definition of AM

- AM is leading principal component of zonal-mean zonal wind.
- The tropospheric AM is insensitive to seasonal cycle and so doesn't hinge crucially on the stratosphere.
- The tropospheric AM is *equivalent barotropic*:

$$a(y,p) = b(y)\, c(p)$$

$c(p)$ positive, peaks in upper troposphere

- The tropospheric AM corresponds to a jet shift (at least in the Southern Hemisphere).

AM Dynamics

- If jet $u(y)$ shifts by an amount δy, then

$$\delta u(y) = u(y-\delta y)-u(y) \approx -\delta y\, du/dy = \delta y\, \zeta,$$

where ζ is zonal mean relative vorticity.

For $\delta u \sim 3$ m/s, $\zeta \sim 10^{-5}$ s^{-1}, $\delta y \sim 300$ km

  - Node is located at jet maximum
  - AM meridional scale is $(d(\log u)/dy)^{-1}$
  - AM amplitude is proportional to δy. There is no simple theory for what sets δy.

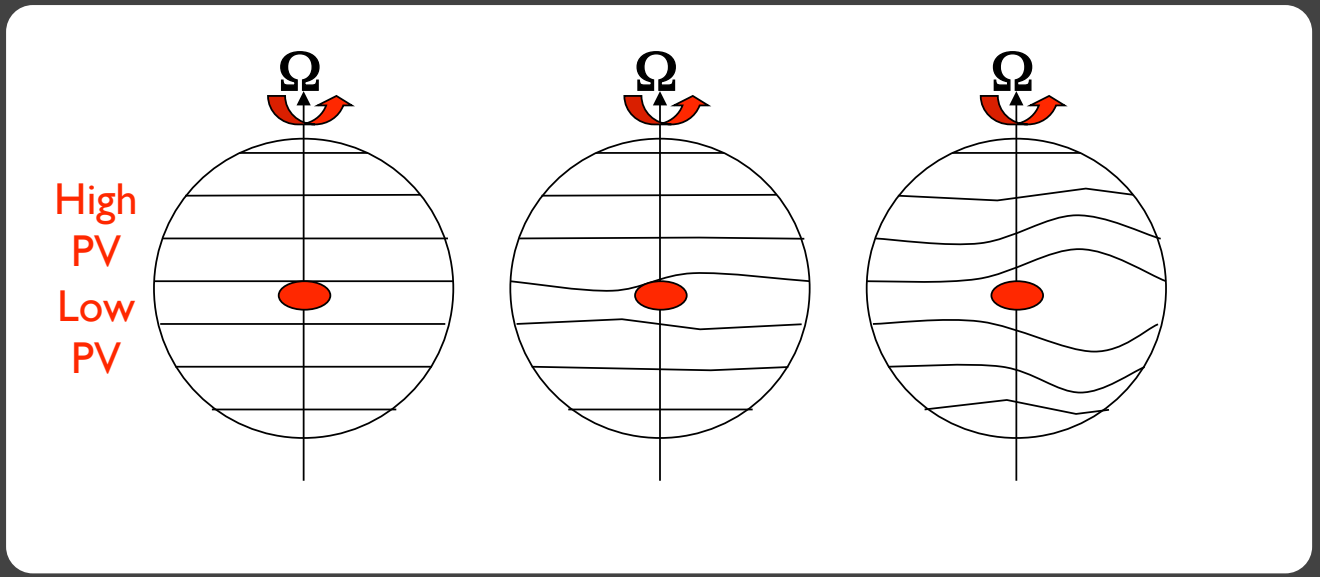
Barotropic Dynamics

- The AMs, like the PNA and NAO, are equivalent barotropic patterns.
- The classical model for barotropic patterns is barotropic potential vorticity dynamics:

$$\frac{\partial q}{\partial t} + \vec{u} \cdot \nabla q = S - D, q = \zeta + \beta y$$
$$\zeta = \nabla^2 \psi, \quad \vec{u} = \left(-\frac{\partial \psi}{\partial y}, \frac{\partial \psi}{\partial z} \right), \quad \psi = \psi(x, y, t)$$

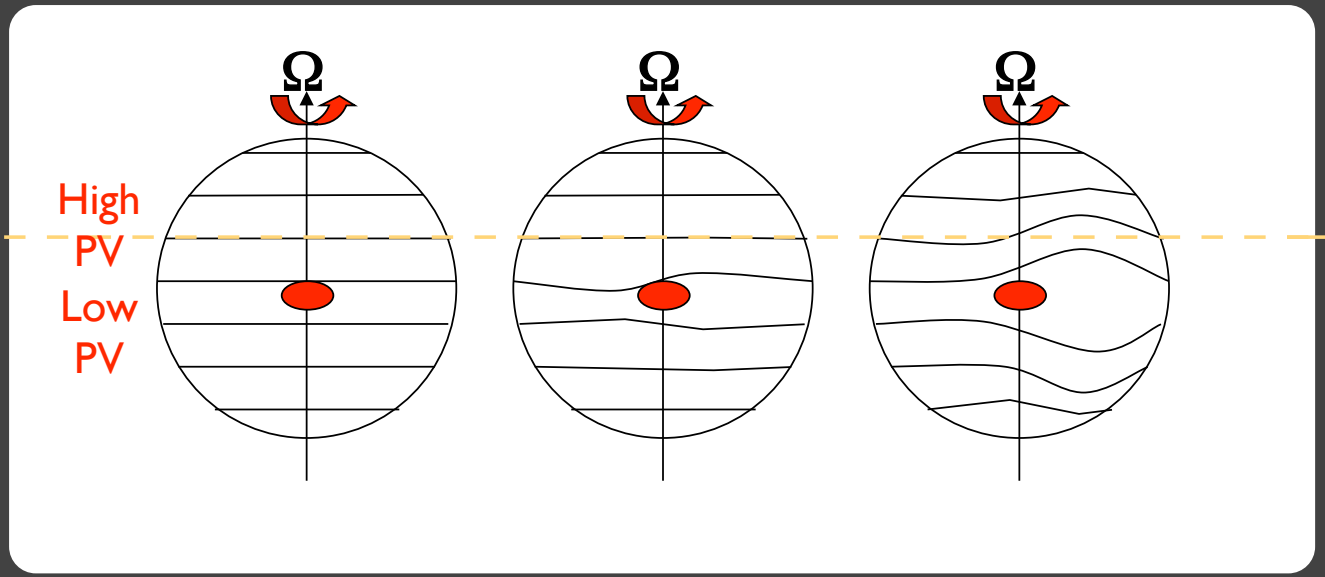
This dynamics was the basis for the first weather prediction models and still has much to tell us about the general circulation.

Barotropic Dynamics



- Consider a shallow layer of fluid at rest on a rotating Earth.
- We'll first think about PV conserving dynamics: $S=0$, $D=0$
- A wave maker switches on and a Rossby pulse propagates away, disturbing material lines.

Barotropic Dynamics



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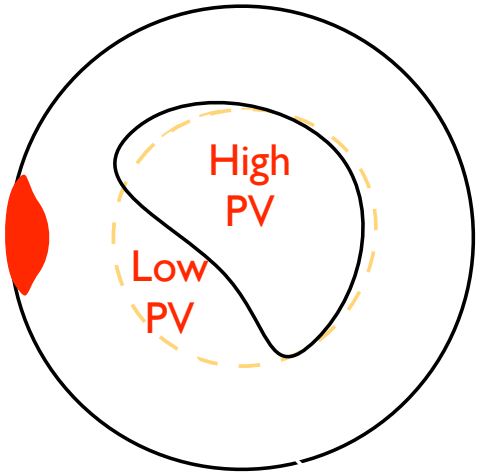
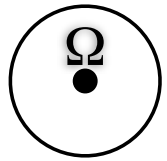
Barotropic Dynamics

$$\frac{Dq}{Dt} = \frac{\partial q}{\partial t} + \vec{u} \cdot \nabla q = 0$$

Stokes: $\oint \vec{u} \cdot d\vec{l} = \int \zeta dA$





Rotation out of page

- Material lines are also PV contours.
- There is a net flux of PV out of the polar cap. The average relative vorticity becomes negative in the polar cap.
- By Stokes relation a westward flow results around the polar cap.
- The PV flux into the wavemaker latitudes leads to an eastward flow.

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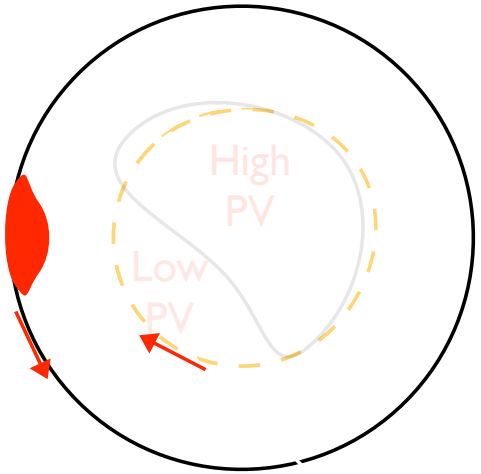

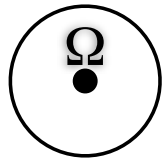

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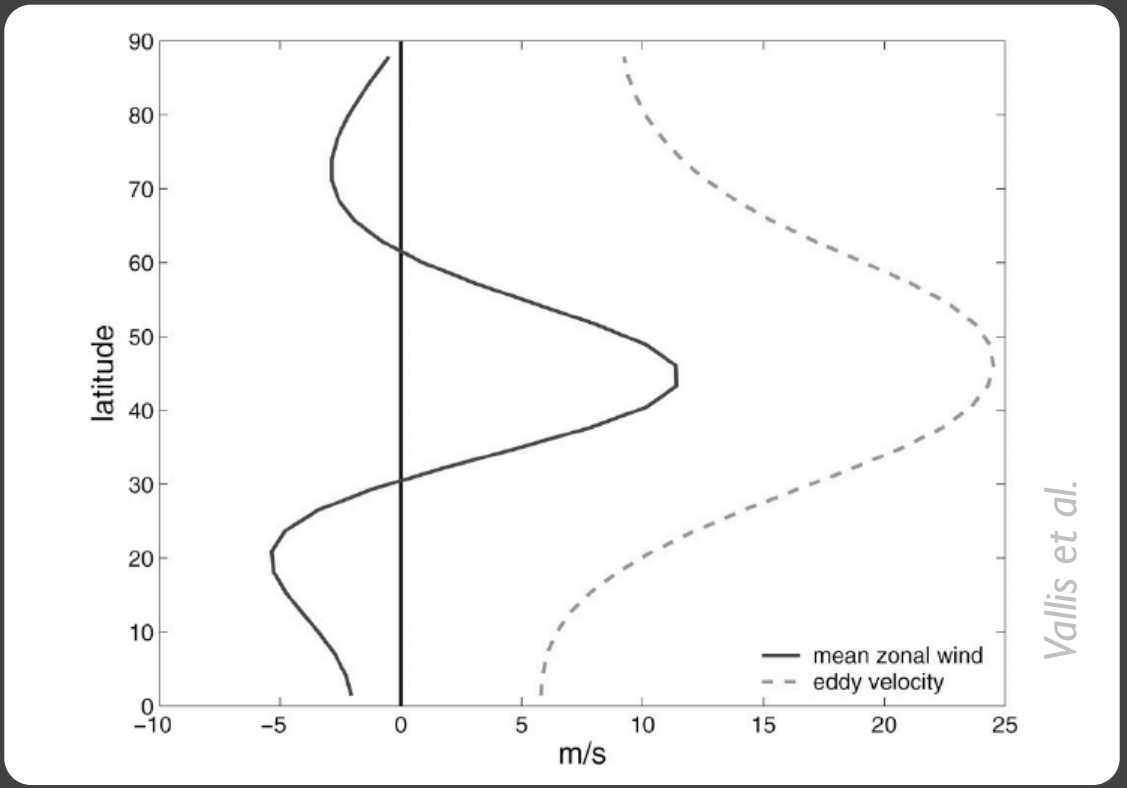

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- In the Vallis et al. model, eddy vorticity fluxes are balanced by eddy damping.

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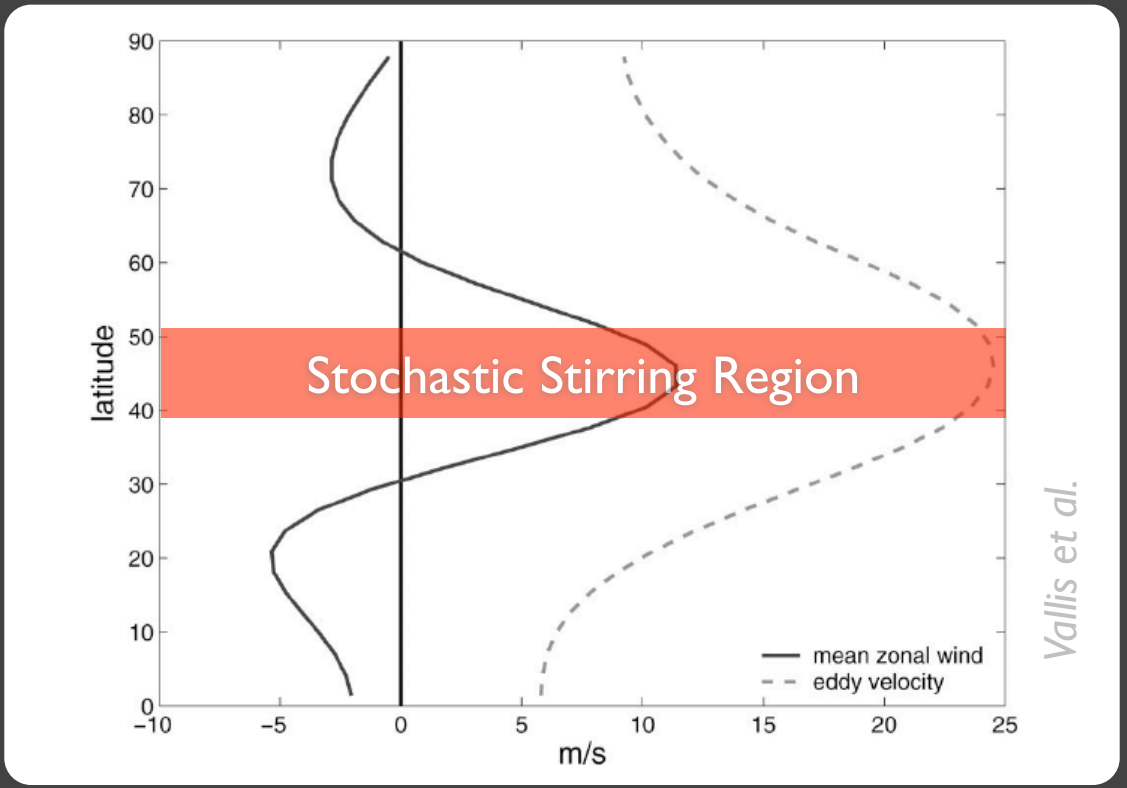

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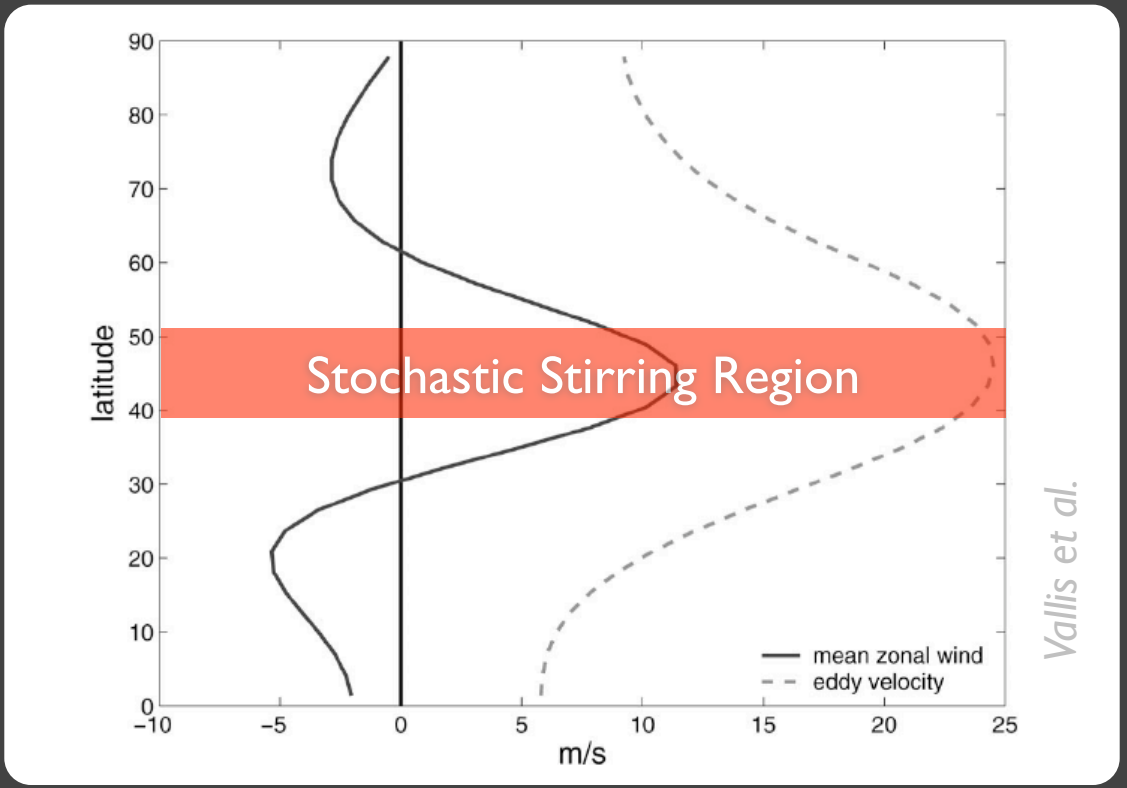
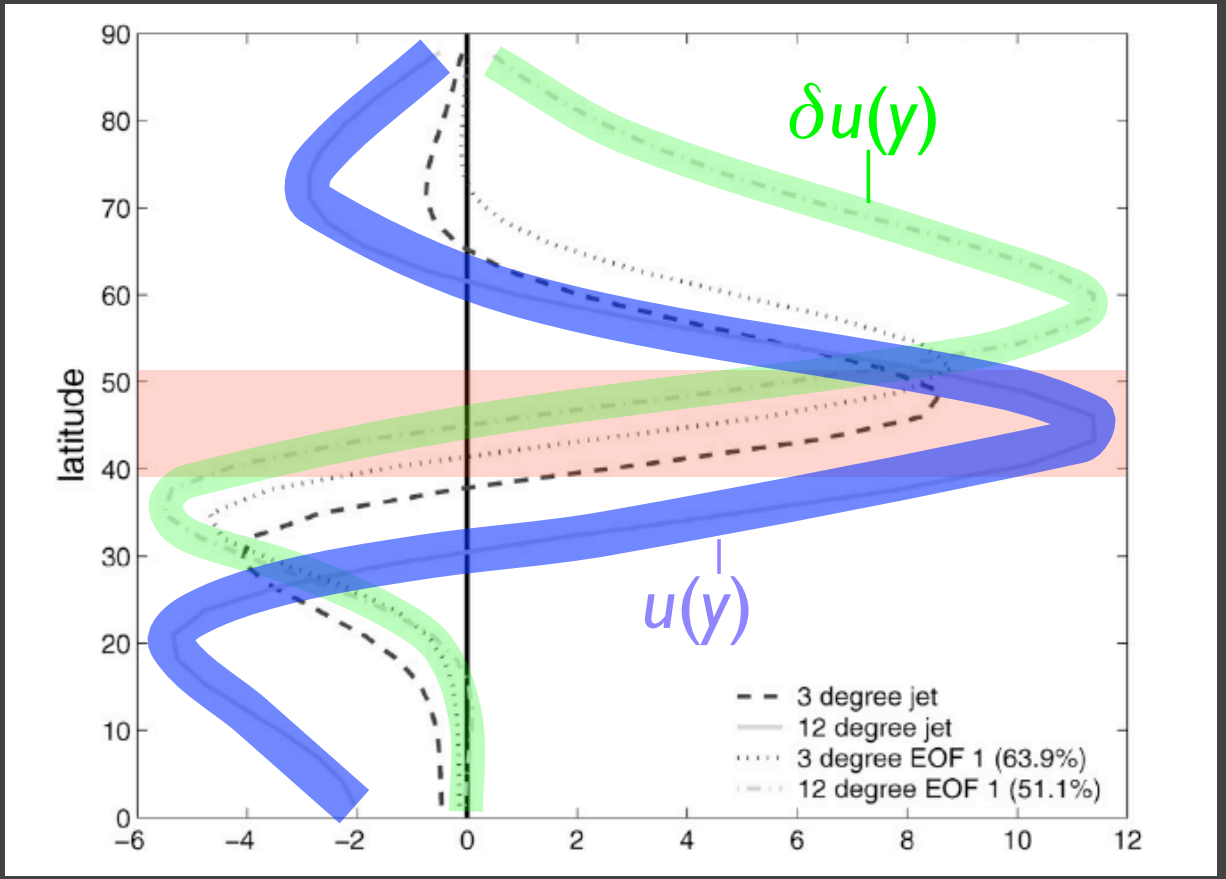


- What do the modes of variability look like in this model?

Barotropic Dynamics



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- This is the simplest realistic representation of the AMs.
- A narrower stirring region gives rise to a pulse instead of a wobble.

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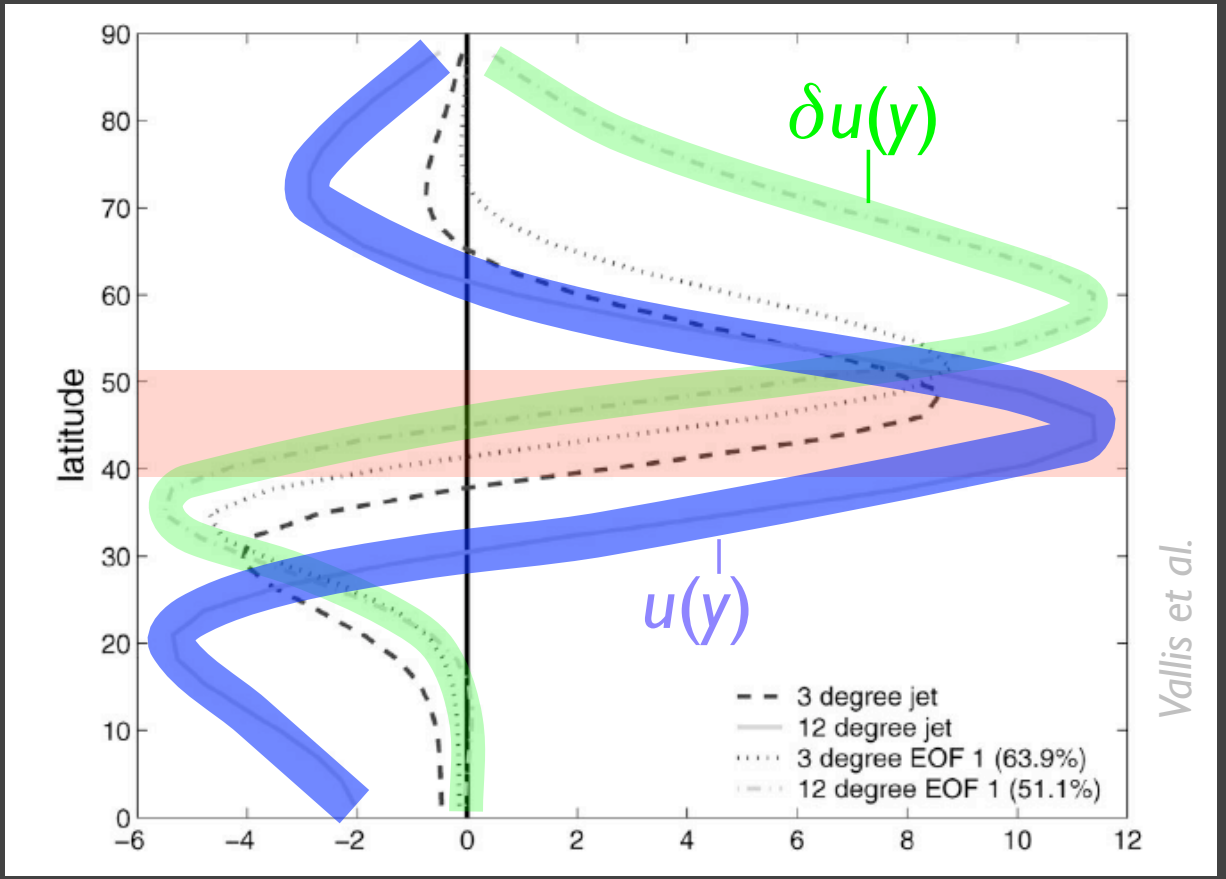

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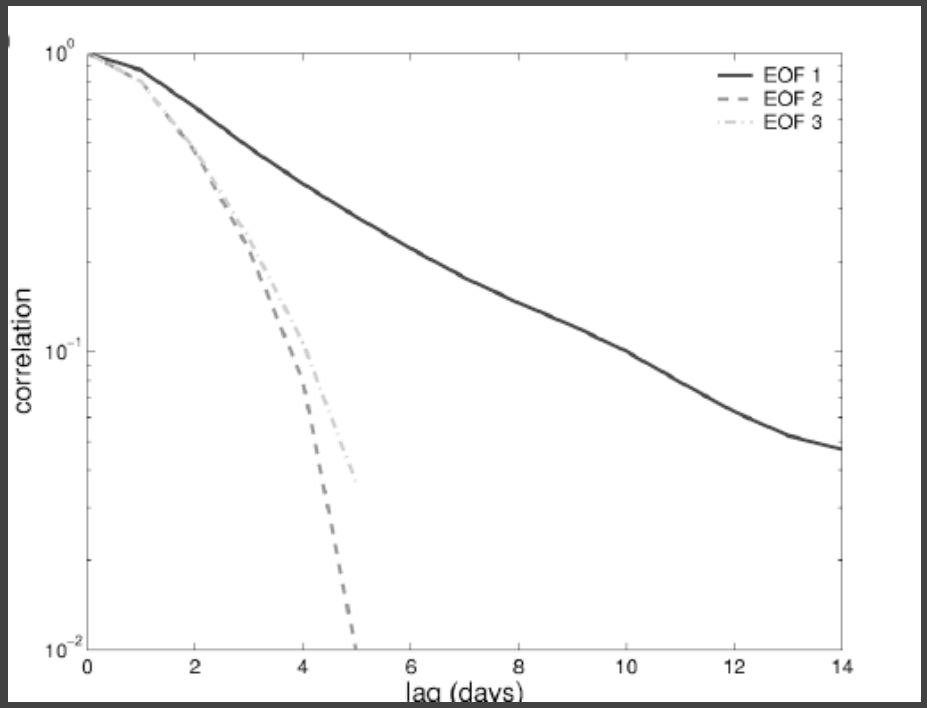

Reality Check

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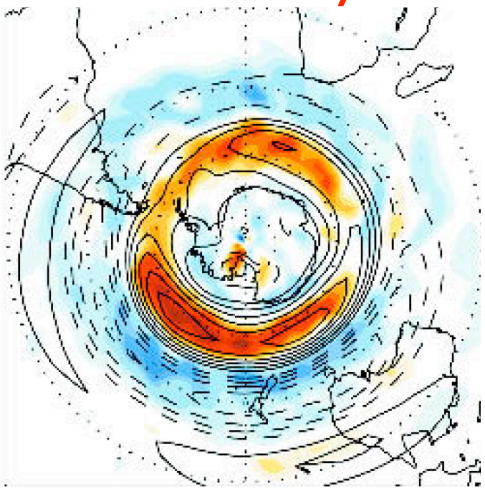
SAM U & Eddy Forcing



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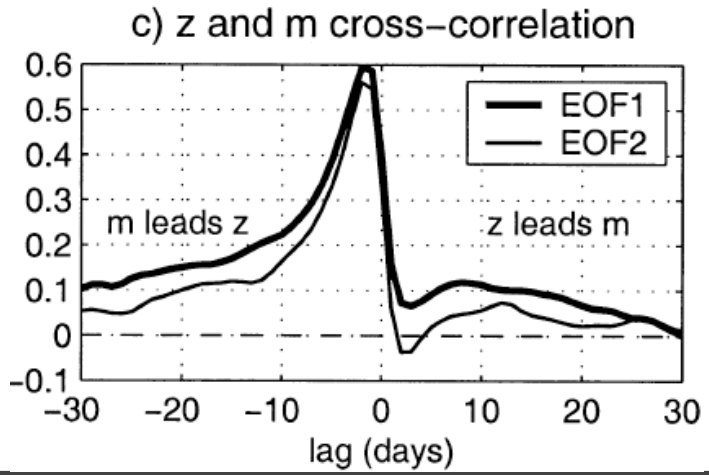

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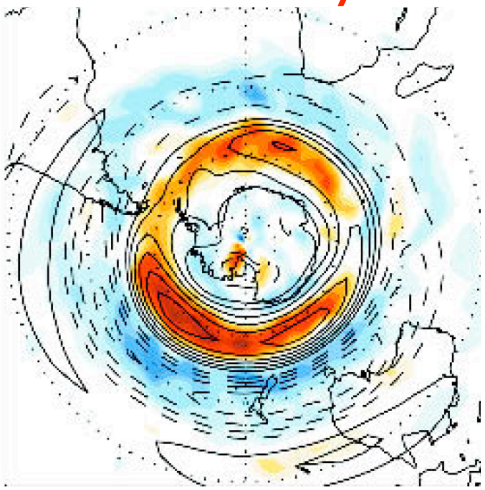

Codron 2005

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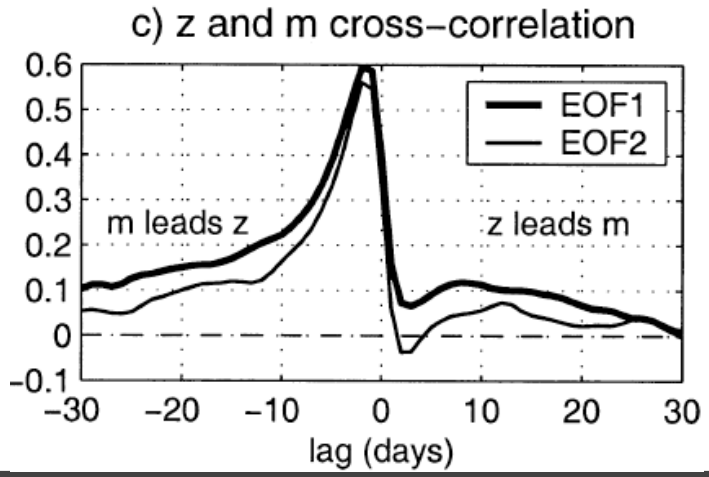

Lorenz & Hartmann

Baroclinic Dynamics

Feldstein & Lee 1996:

- Two layer QG model, internal "stirring" via baroclinic instability.
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$$\frac{\partial Q_j}{\partial t} + J(\psi_j, Q_j) = -(-1)^j r\left(\frac{\psi_1 - \psi_2}{2} - \tau_e\right) - \delta_{j,2}\kappa_M \nabla^2 \psi_2 - \nu \nabla^6 \psi_j,$$

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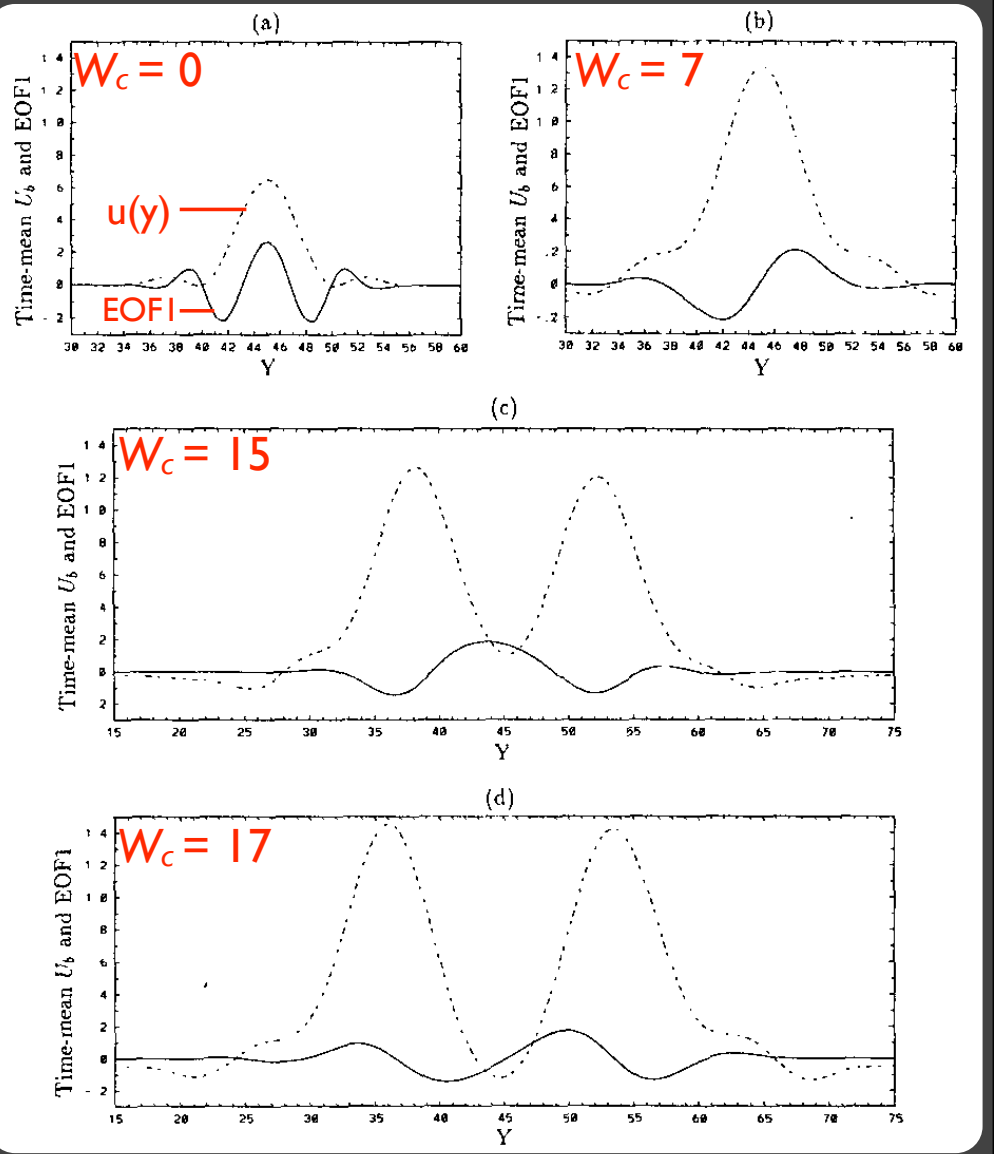

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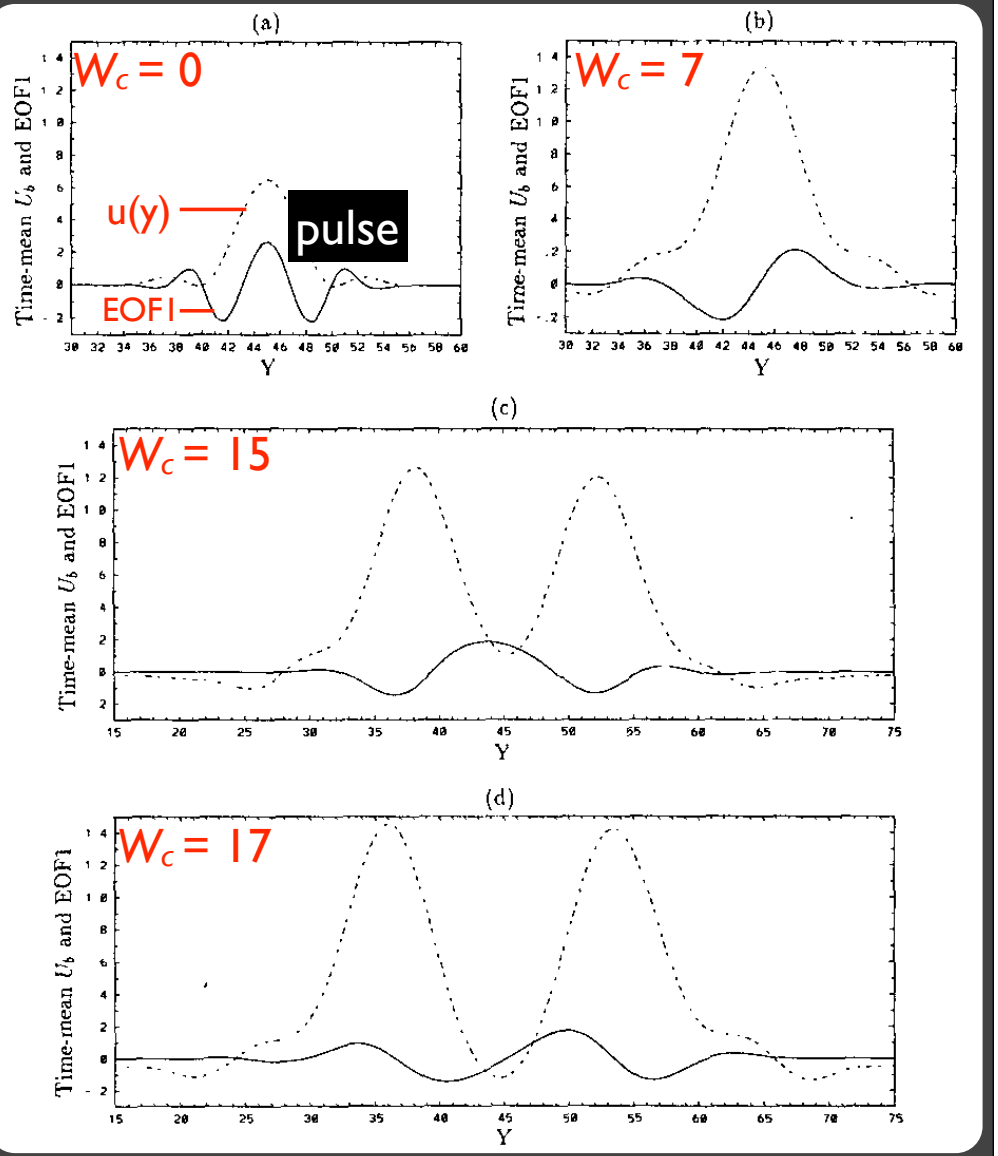

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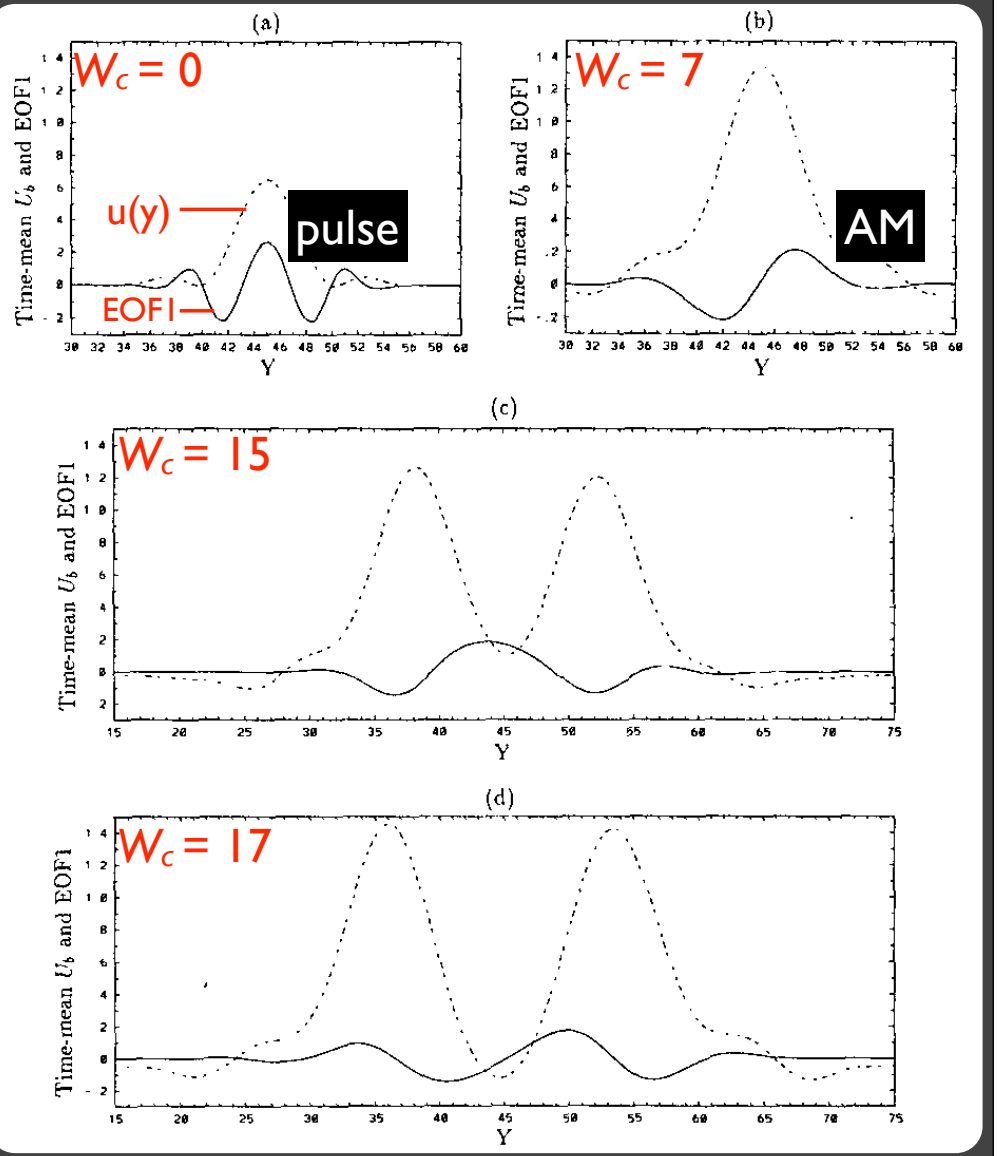

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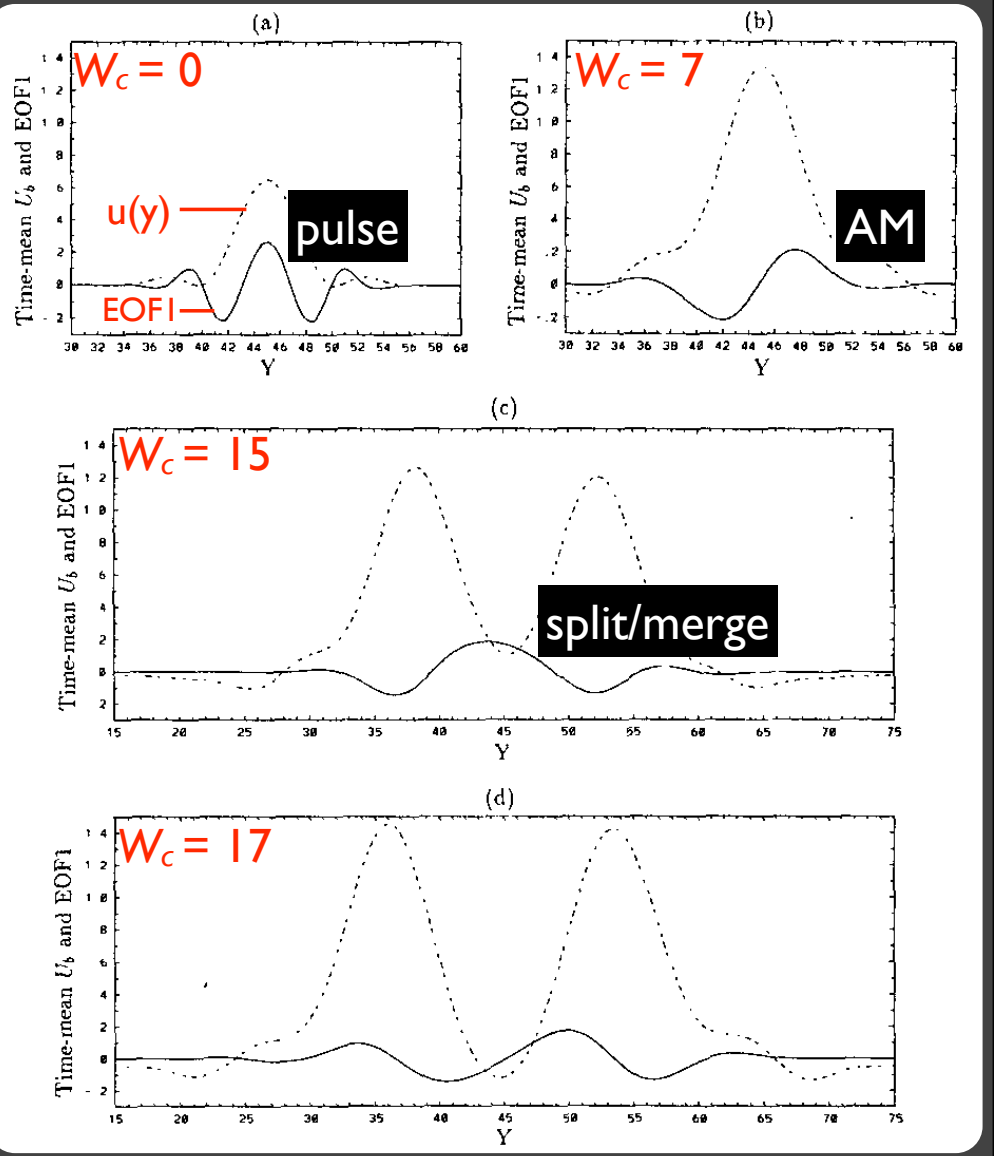

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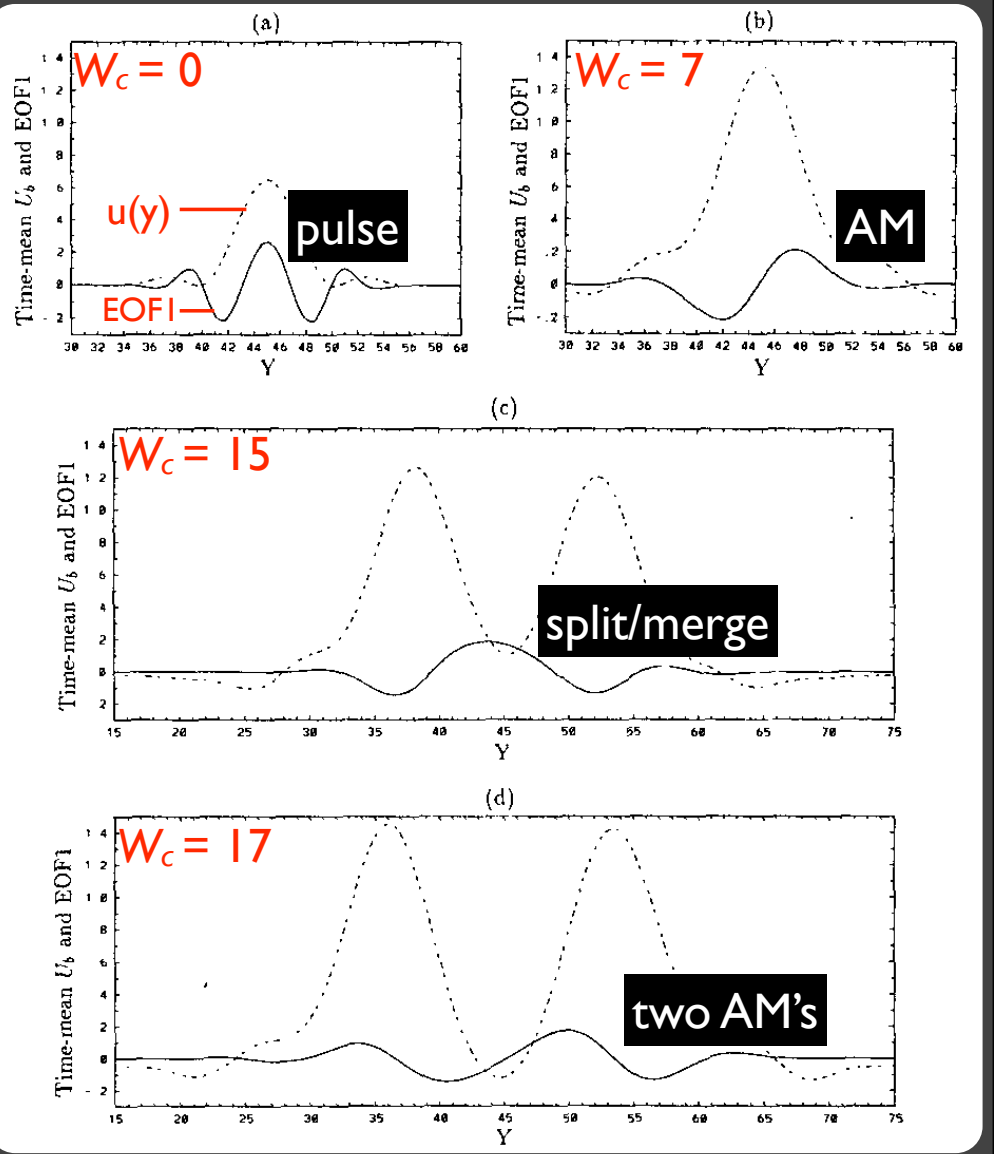
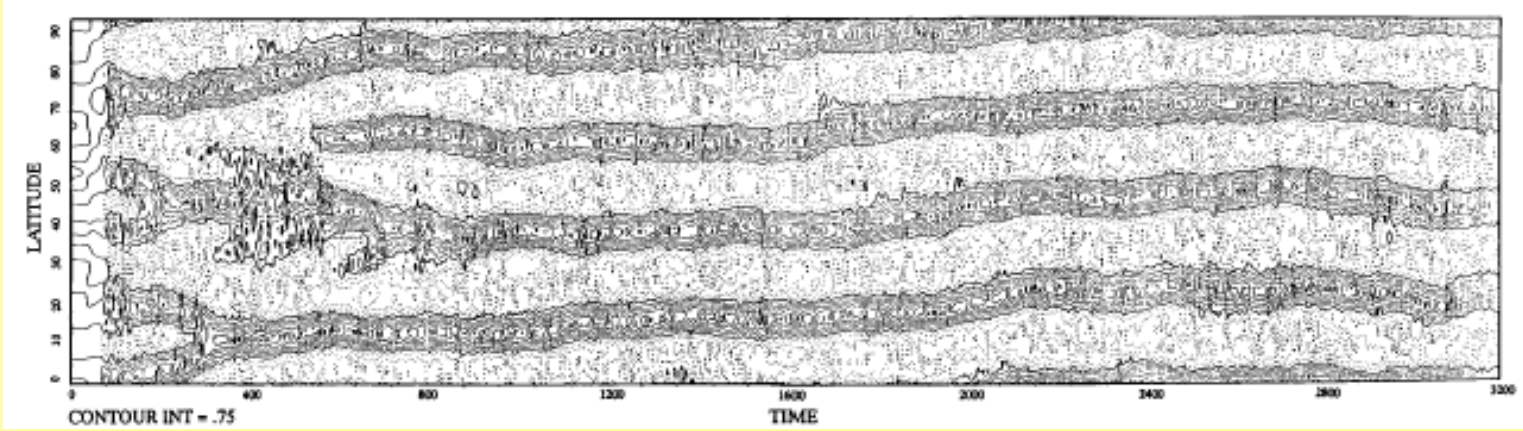


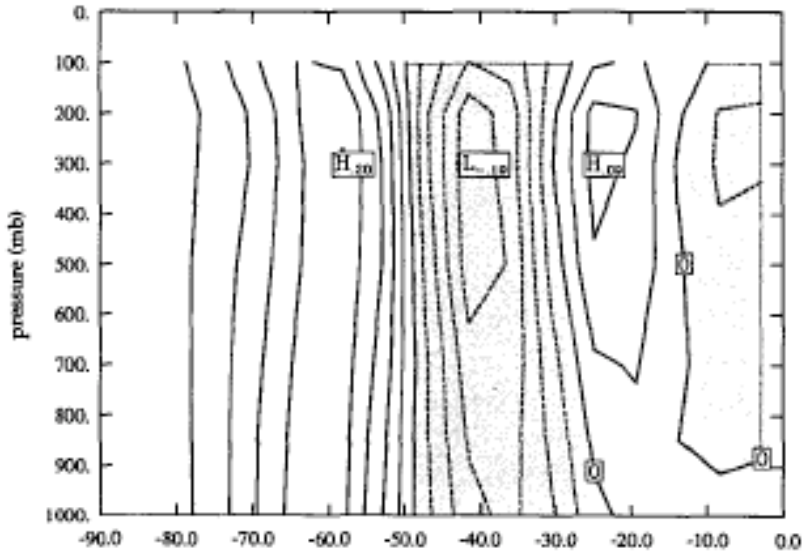
Two Layer Model

Wandering Jets in 2-Layer Homogeneous beta-plane turbulence (Panetta 1991)

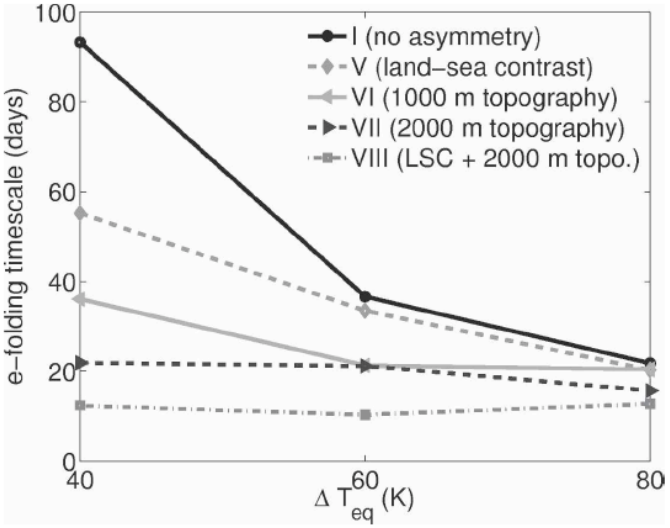


Many Layer Model

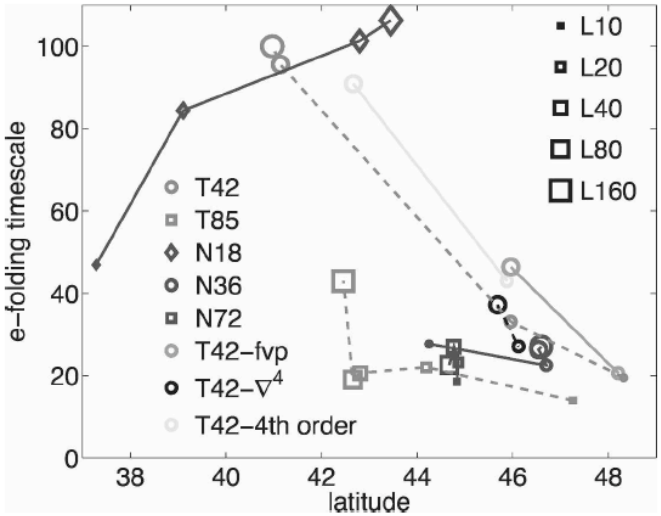
- Simplified "dry" 3-D GCMs simulate a realistic vertical structure of the AMs.
- Gerber et al. show that the AM timescale in these models is very sensitive to details.



Yu & Hartmann 1993



Gerber & Vallis 2007



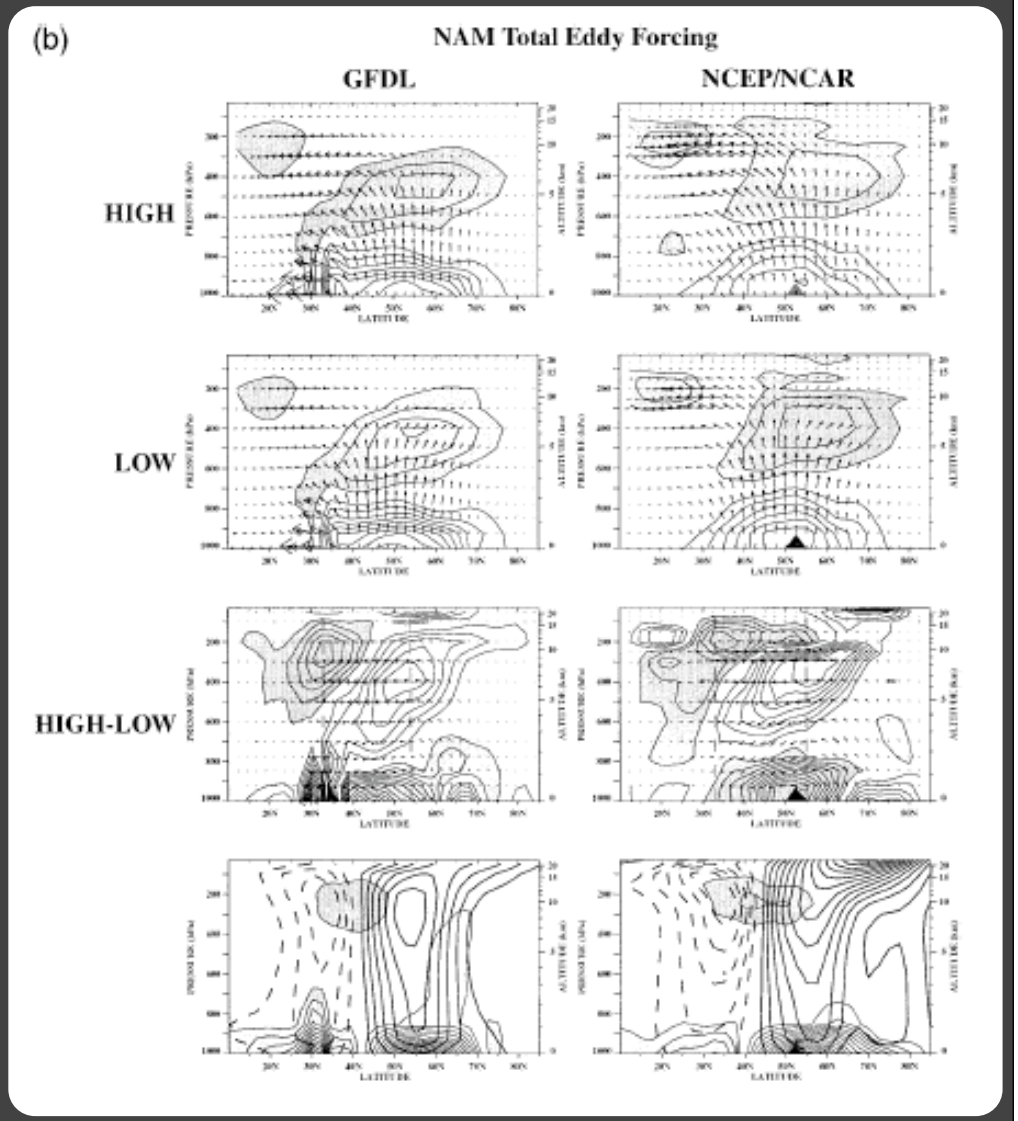
Gerber et al. 2007

Atmospheric General Circulation Model

Limpasuvan & Hartmann:

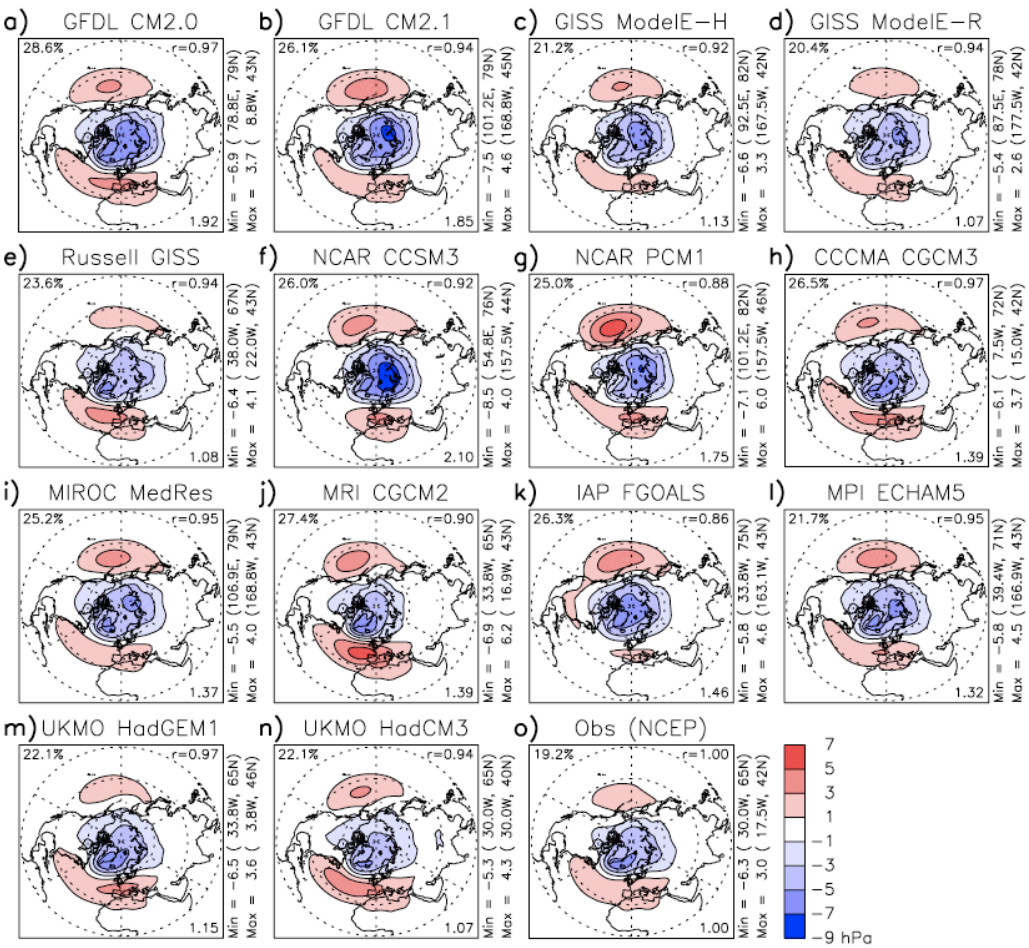
- Comprehensive GCM (GFDL R30) with prescribed SSTs captures the AM structure and signature in wave driving very realistically.

- This highlights the strong link between the AM wind and eddy forcing signatures.



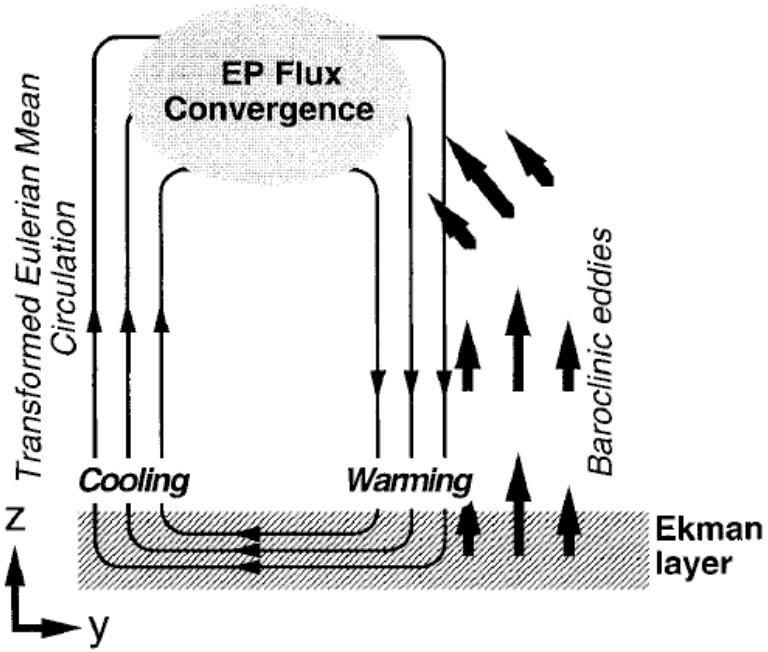
AMs in Climate Models

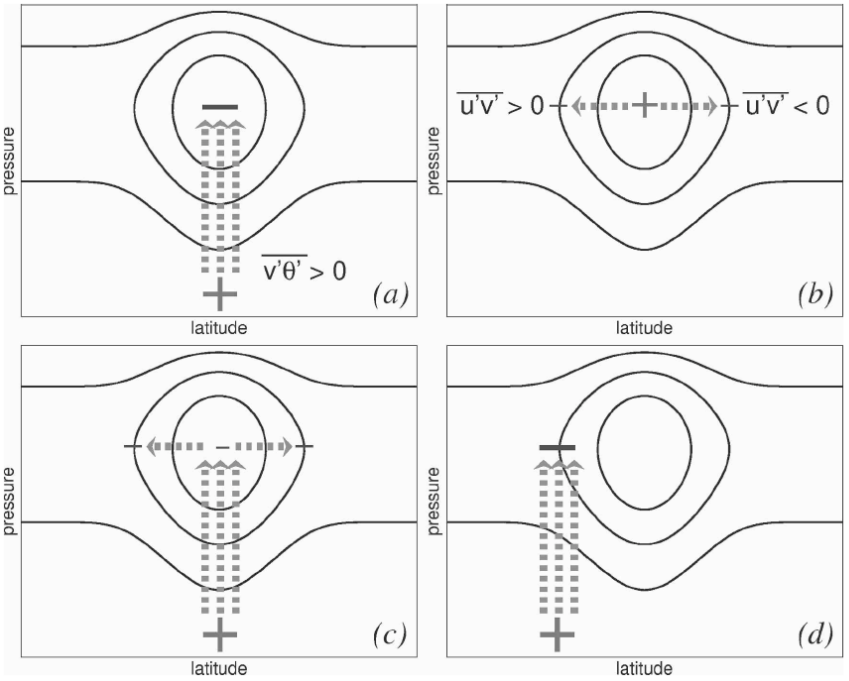
- Coupled ocean atmosphere climate models can accurately simulate NAM and SAM structure.
- Details are not robust: Zonal structure of the patterns varies from decade to decade in the obs and among different realizations of the same model (Raphael & Holland 2006).



Miller et al. 2006

Theory of AMs in the General Circulation





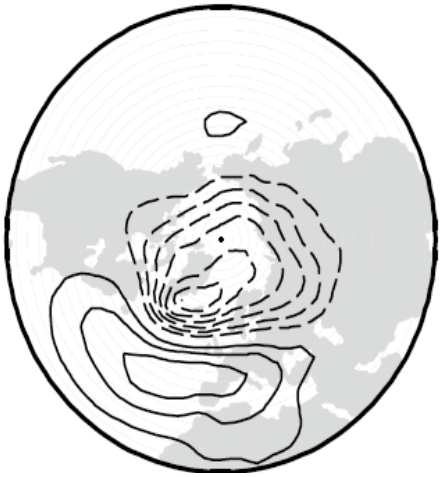
- Robinson (2000) and Gerber and Vallis (2007) present descriptions of how AM lifecycles might work. Index of refraction arguments (Feldstein & Lee, Limpasuvan & Hartmann) also help explain things.

A "Localized" View

Northern Annular Mode (NAM)

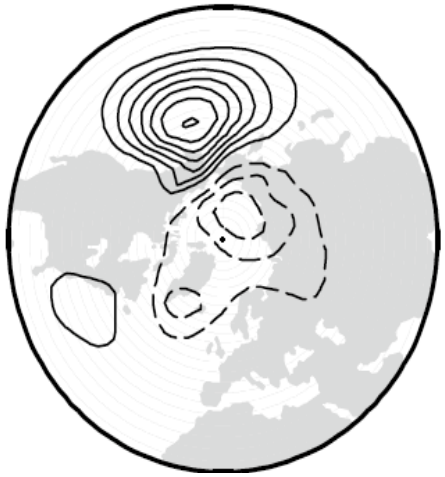
EOF of SLP Poleward of 20N

North Atlantic Oscillation (NAO)



… for the North-Atlantic sector only

North Pacific Oscillation (NPO)



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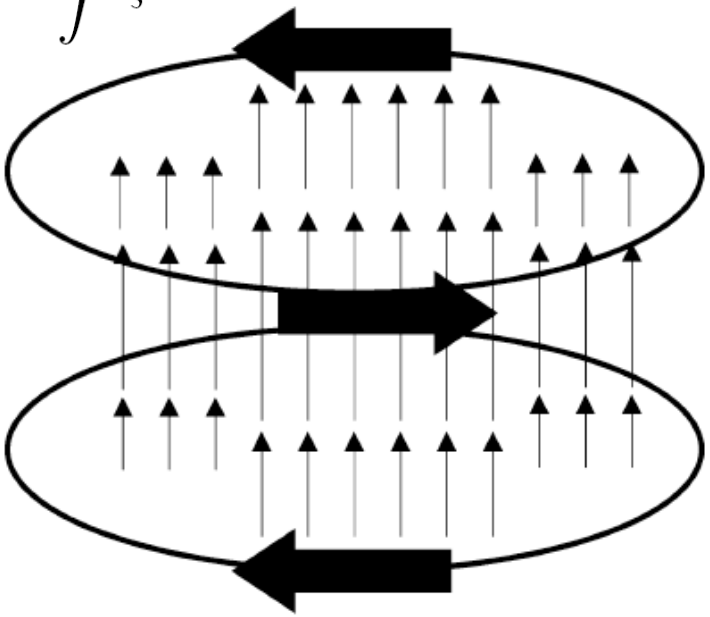
Deser 2000

- What does the hemispheric flow pattern of the AM represent?

Regional AM Dynamics

Stokes: $\oint \vec{u} \cdot d\vec{l} = \int \zeta dA$



- Localized eddy mean-flow interaction.

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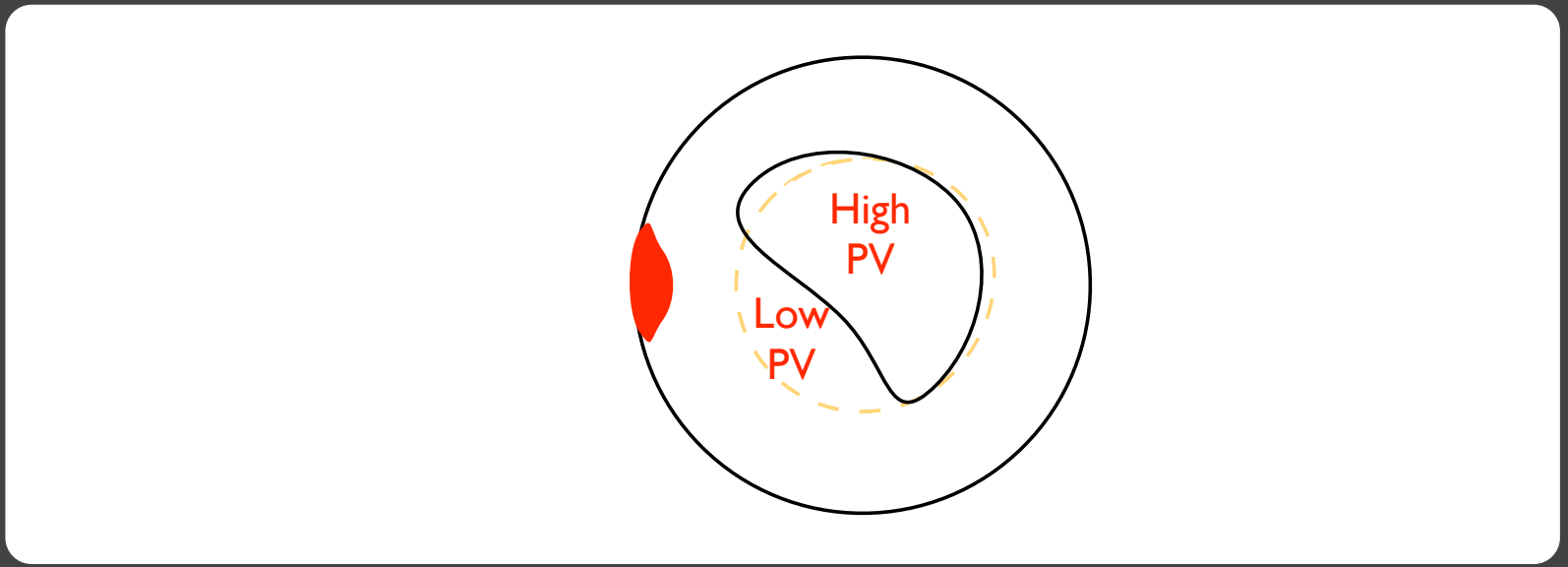

- A similar localization of the circulation response will occur in the transient pulse case.

- Several authors have explored the idea that the annular mode streamflow pattern is a superposition of regional events like this.

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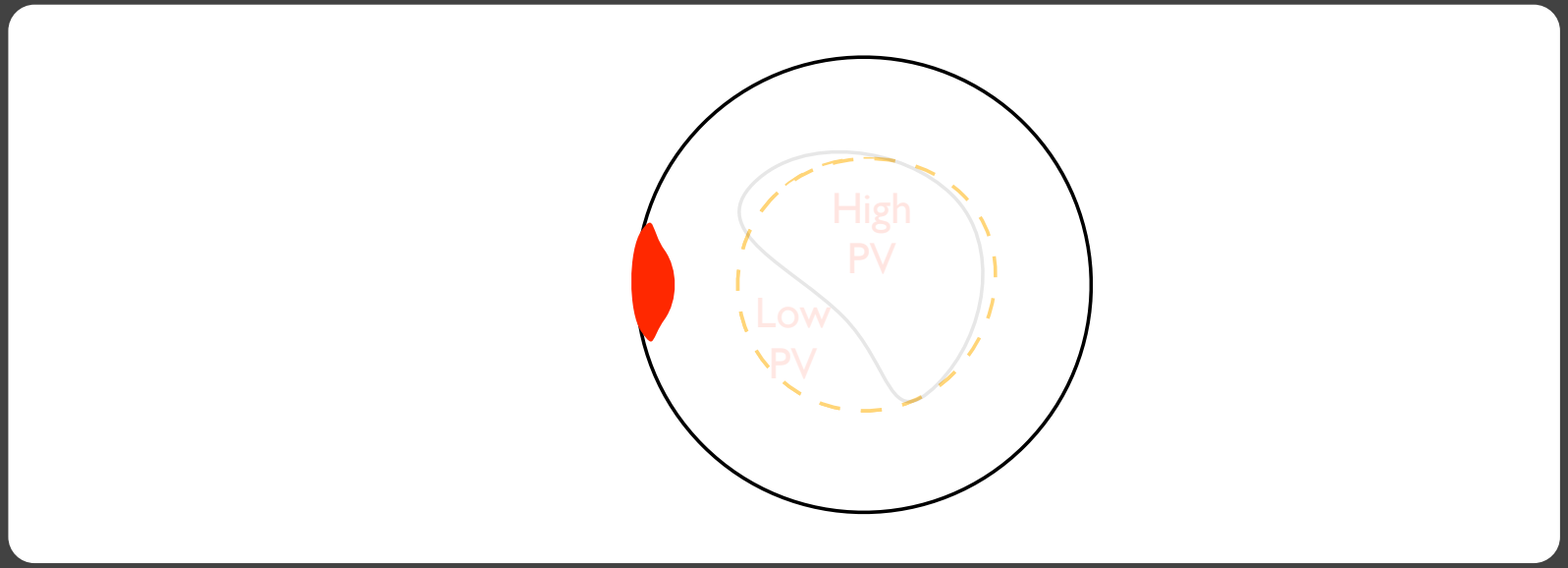

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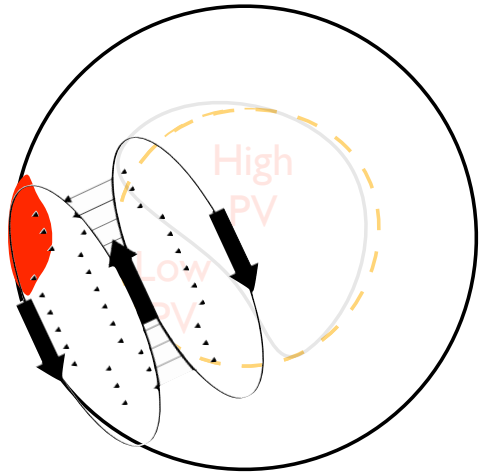

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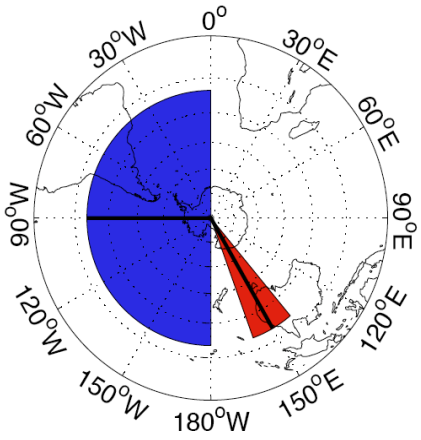
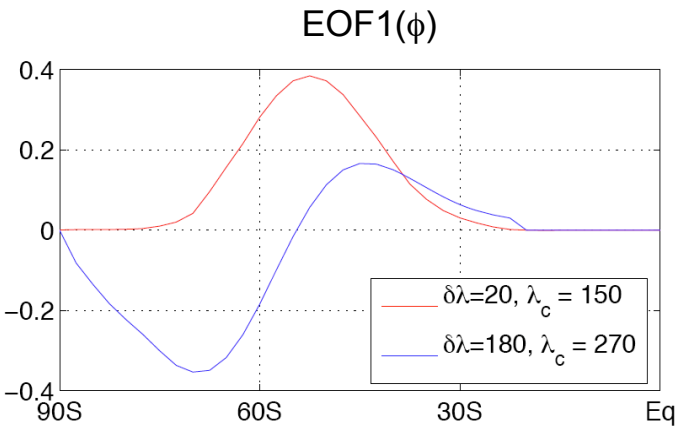
Sector EOF Analysis (Kushner & Lee)





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* We find EOFs of zonal mean p_s in sectors of zonal width $\delta\lambda$, center λ_c.
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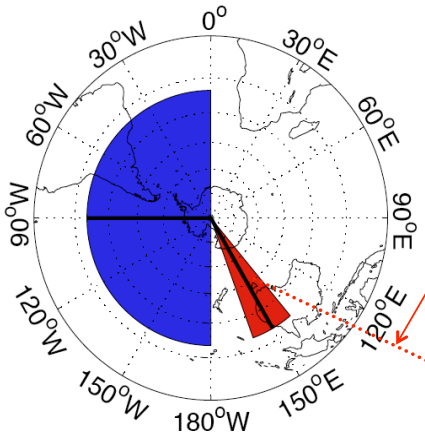
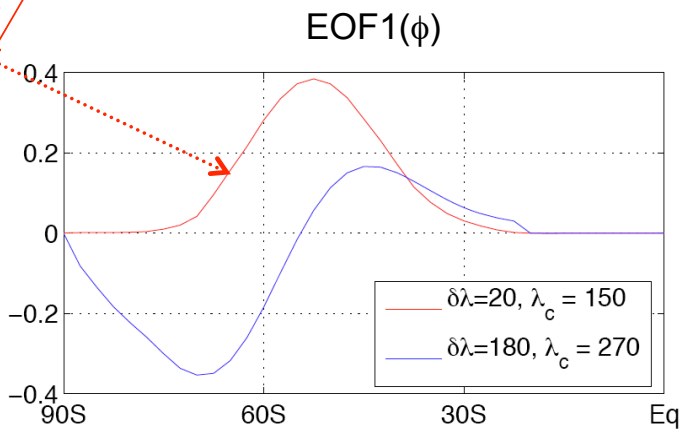


EOF1 for a narrow sector: monopolar function of latitude.



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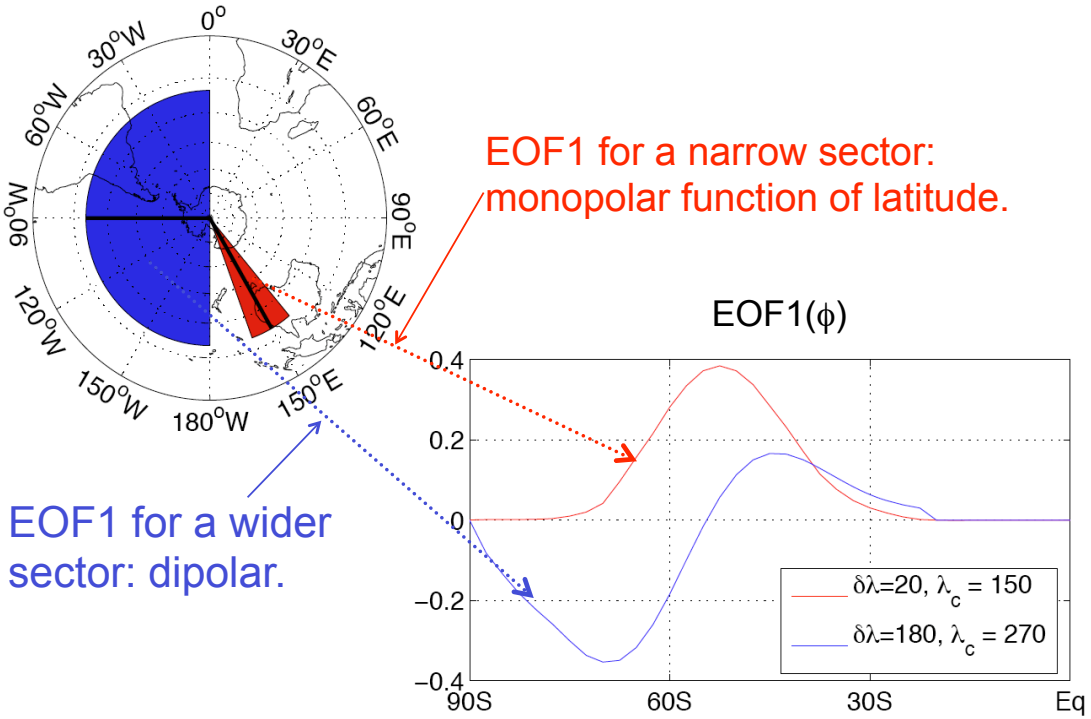

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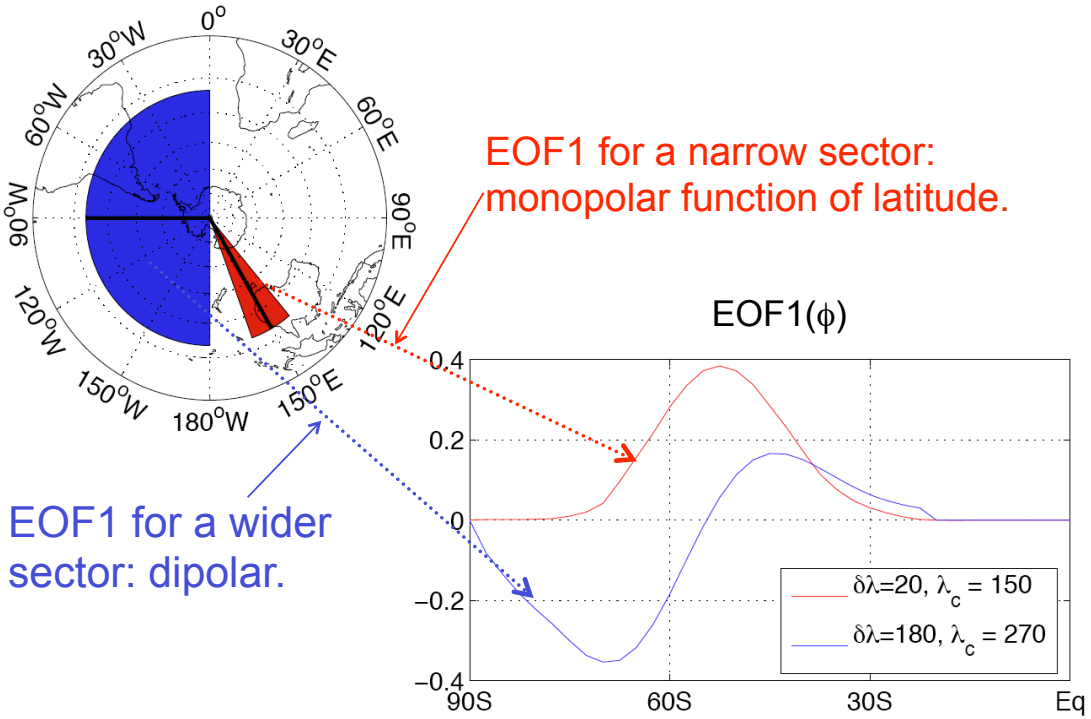

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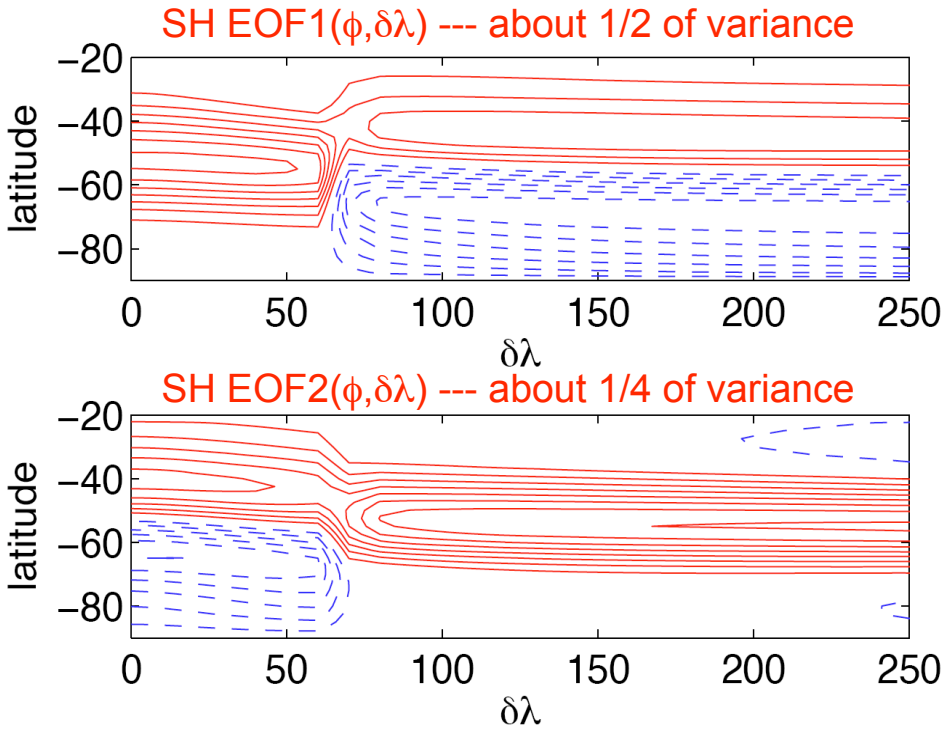
* As the sector width $\delta\lambda \rightarrow 360^o$, EOF1 becomes the SAM or the NAM (Baldwin 2001).
* We now focus on sector-composite SH results.

Sector EOF Analysis

* SH EOF structure goes from monopole to dipole through $\delta\lambda$ ~70^0



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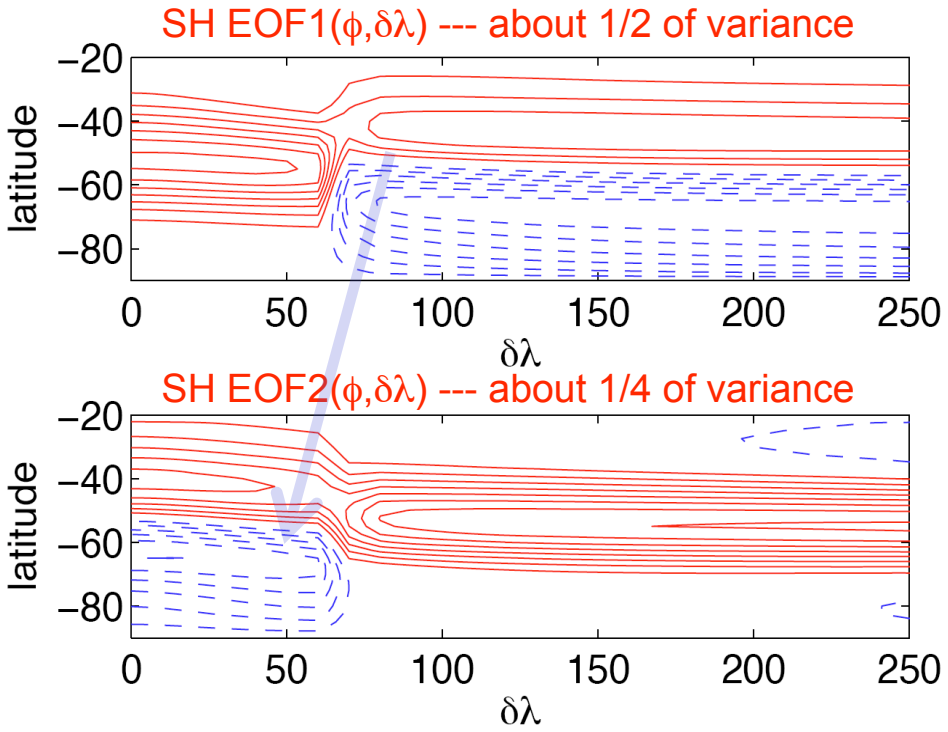

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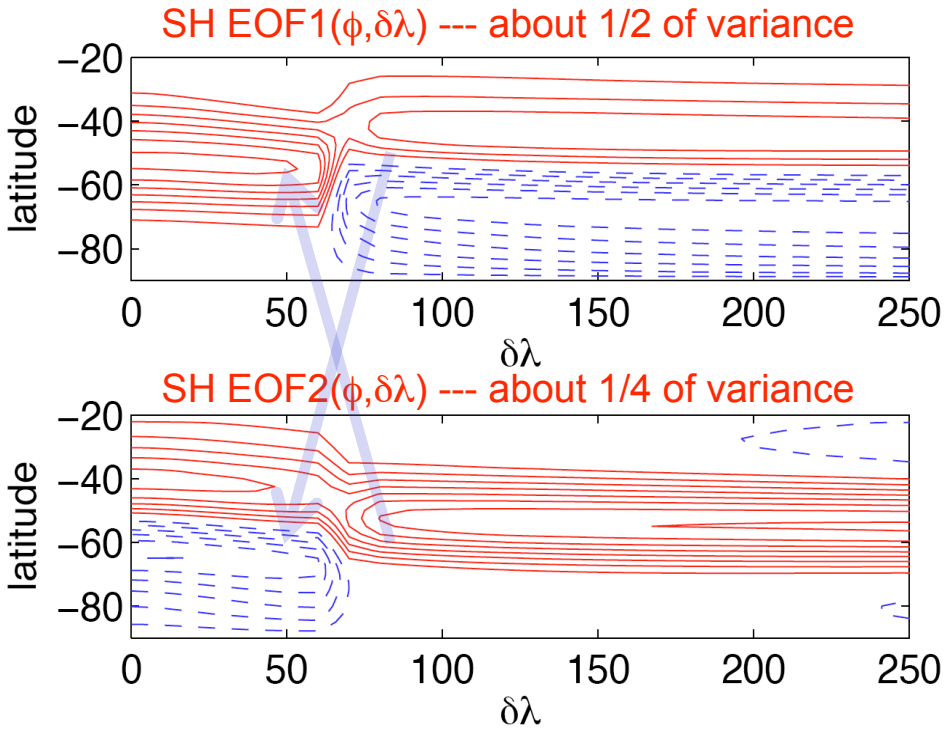

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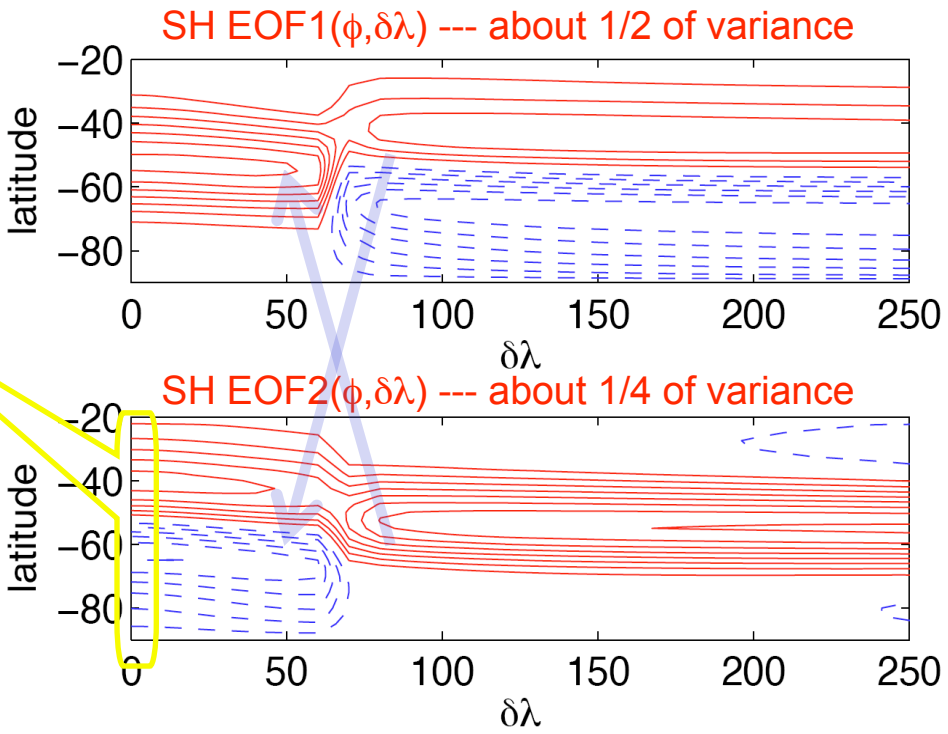
* SH EOF structure goes from monopole to dipole through $\delta\lambda \sim 70^0$

  * At EOF2, $\delta\lambda = 0^0$ we find the dipolar *regional signature of the SAM.*

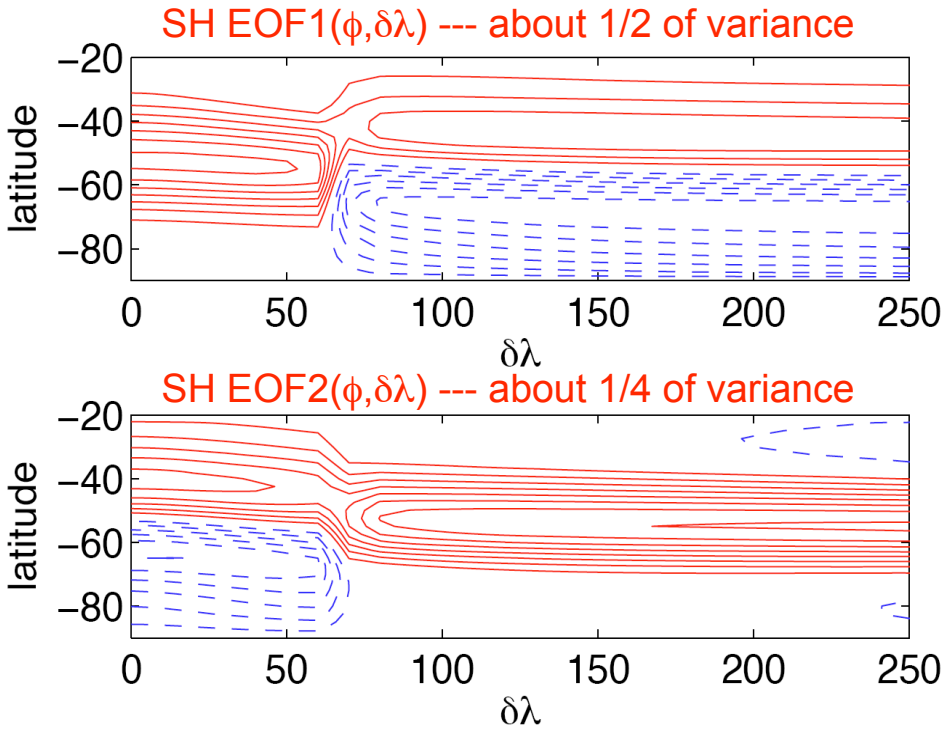


Sector EOF Analysis

* $\delta\lambda=0^0$ EOF2 PC time series is used for regression.

* This time series is equivalent to a dipole index:

  $\Delta p = p_s(40^0 \text{ lat}) - p_s(65^0 \text{ lat})$



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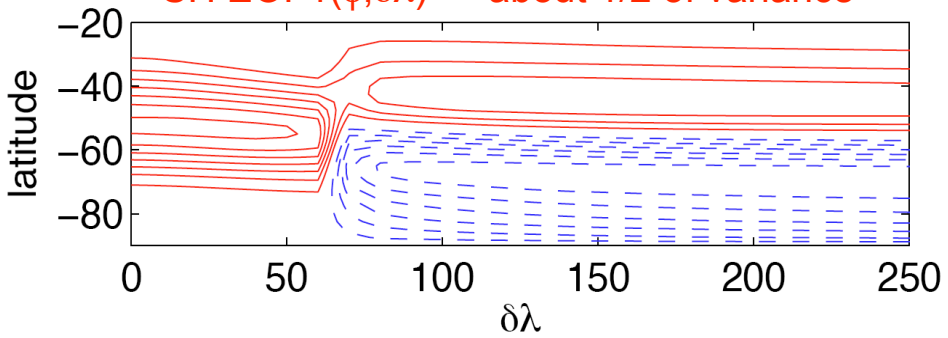
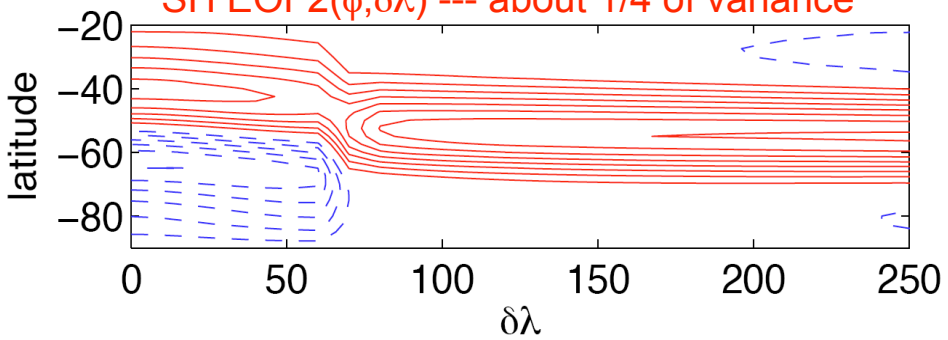
* The regression patterns have the AM dipolar structure but are regional like the NAO.

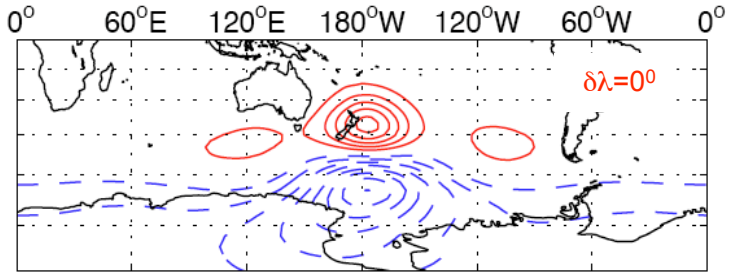
SH EOF1(ϕ,$\delta\lambda$) --- about 1/2 of variance

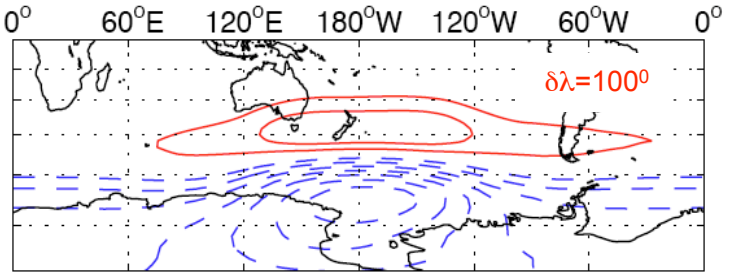


SH EOF2(ϕ,$\delta\lambda$) --- about 1/4 of variance



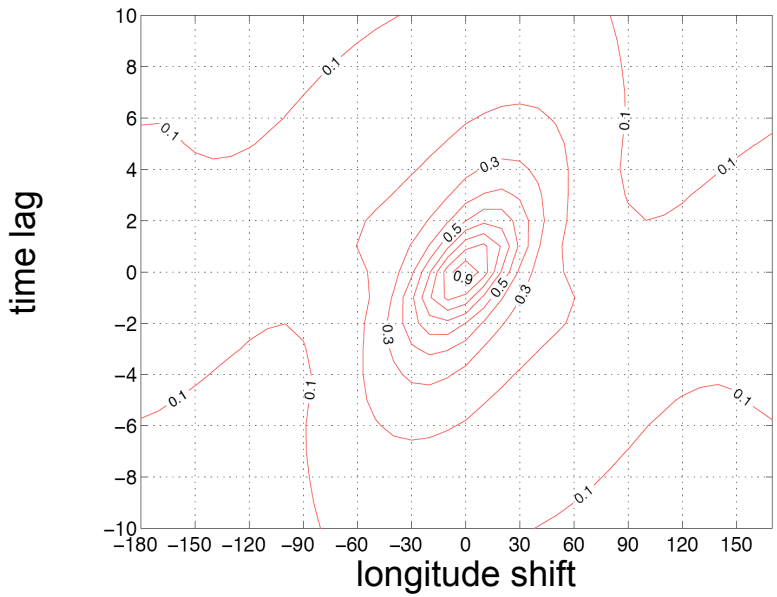
Sector-Composite regressions: local dipole index on p_s



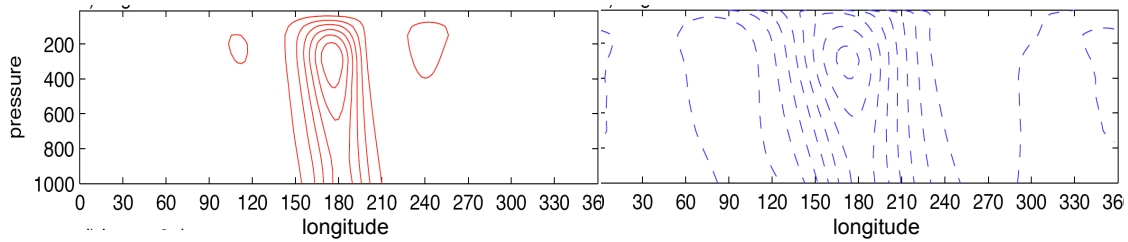


Dipole Patterns

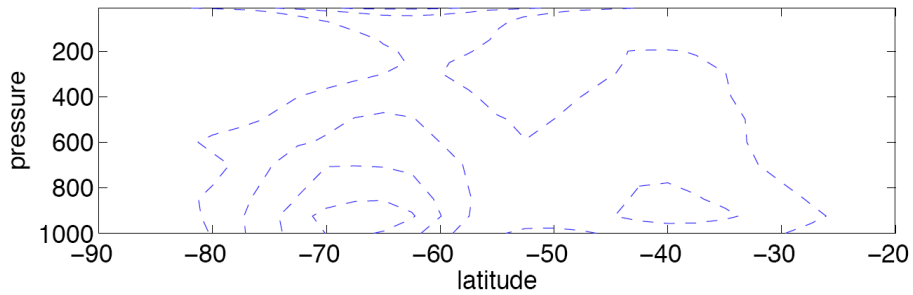
Longitude-Time Lag-Correlation of Dipole Index



Regressions on Geopotential at 40S & 65S



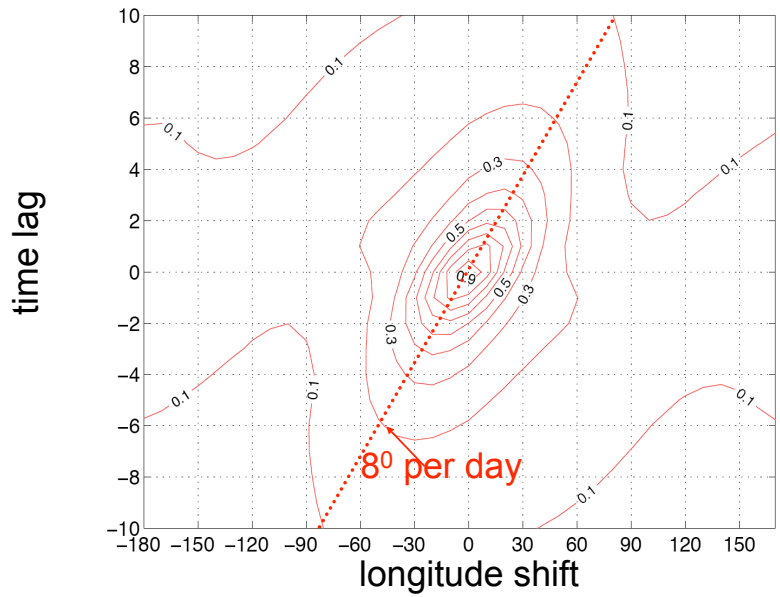
Meridional eddy heat flux from regressions on *v* & *T*



* The dipole patterns propagate coherently, with little dispersion.
* The patterns tilt westward with height and have a meridional heat flux signature.
* So the AMs might involve baroclinic instability.

Dipole Patterns

Longitude-Time Lag-Correlation of Dipole Index



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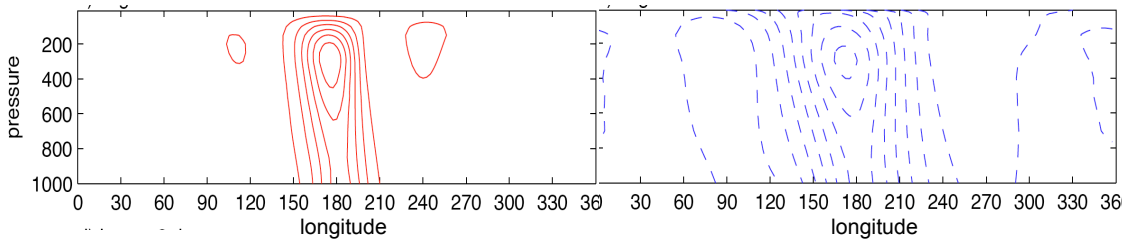

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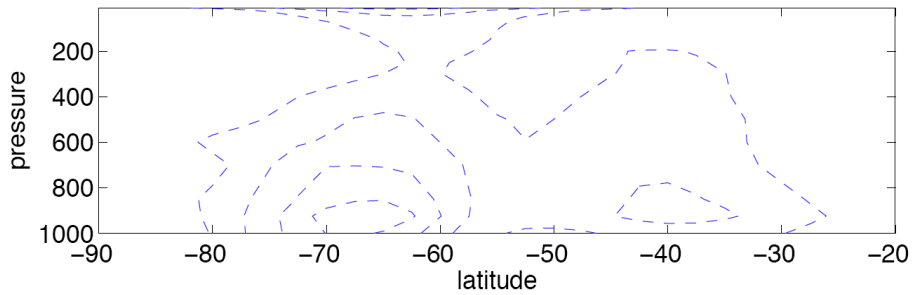

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Recap

What are the annular modes?

Robust hemispherically extratropical modes characterized by north-south shifts of the jet.

Are the annular modes important?

Dominant signals with many climate influences.

Dynamics of the annular modes

Barotropic dynamics gives key insights, but doesn't fully explain AM dynamics.

A regional perspective reveals propagating dipole paterns: "building blocks" of the AMs?