On the time scales of midlatitude atmospheric variability: Eddy-mean flow interactions and coupling from on high

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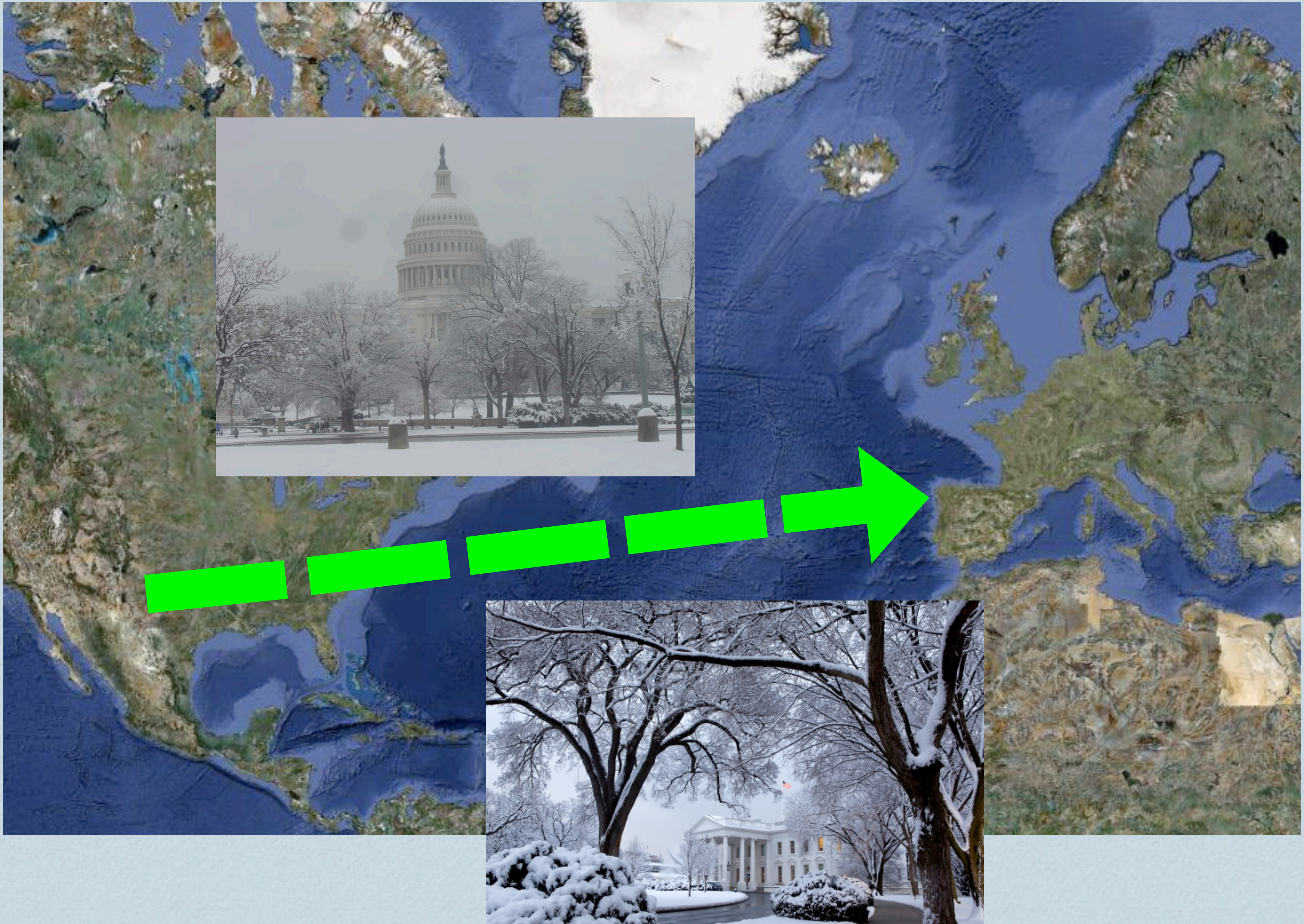
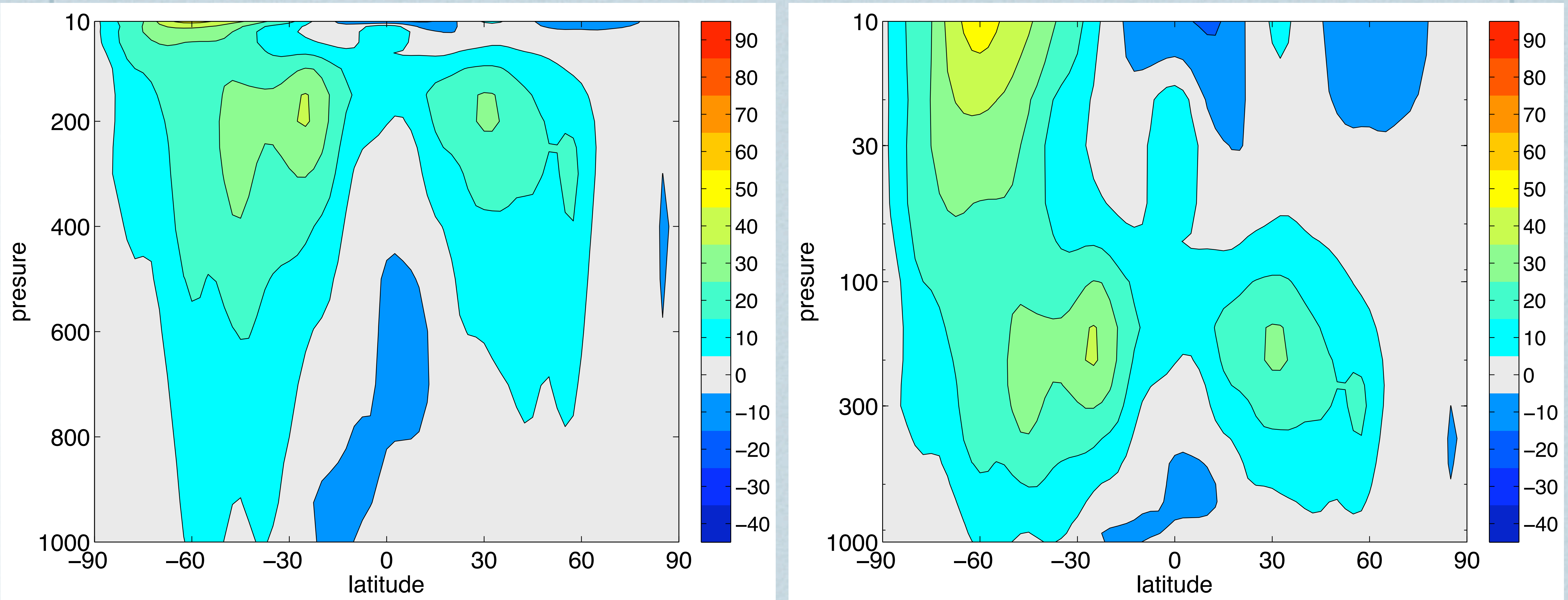
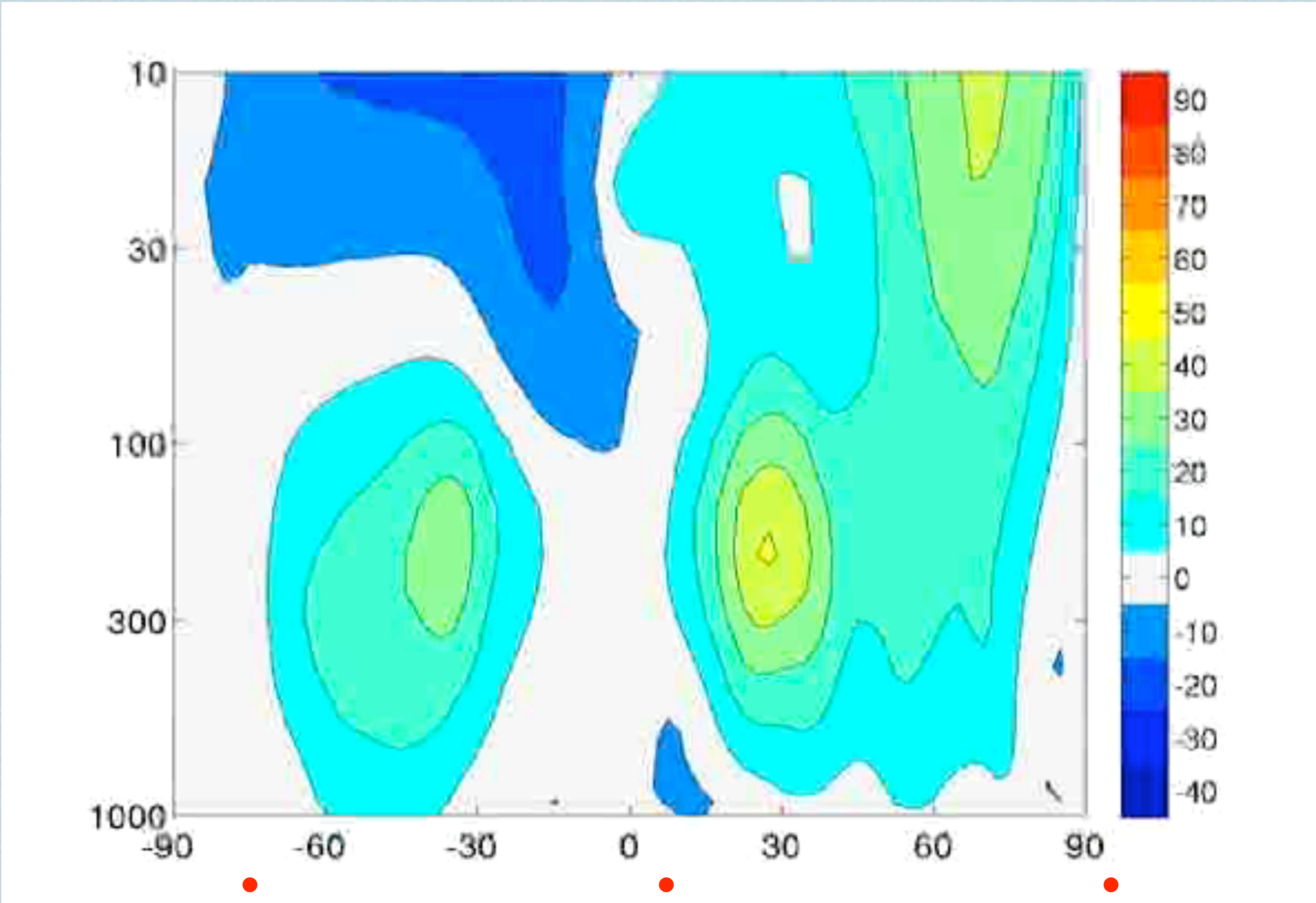


Zonal Mean Zonal Winds: Jets



NCEP-NCAR Reanalyses for 5/18/78



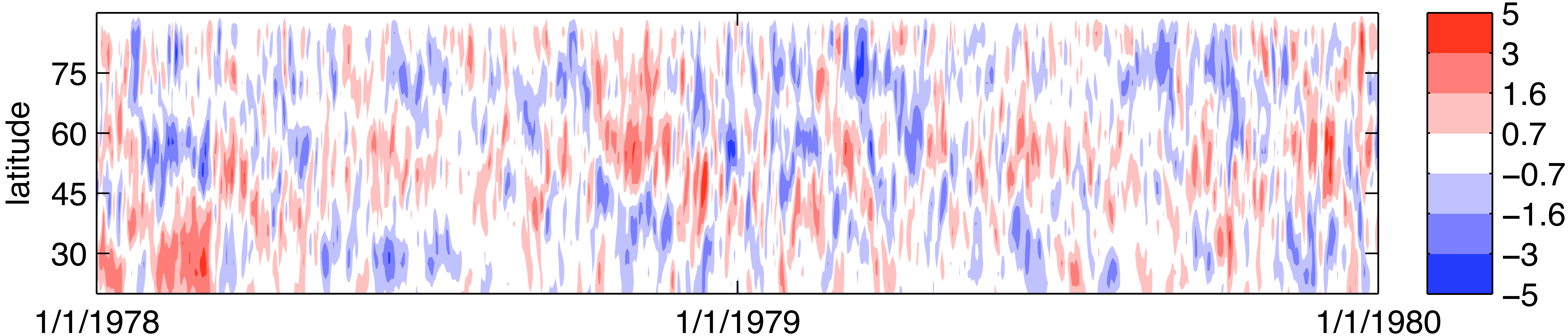
Jan
1978

Jan
1979

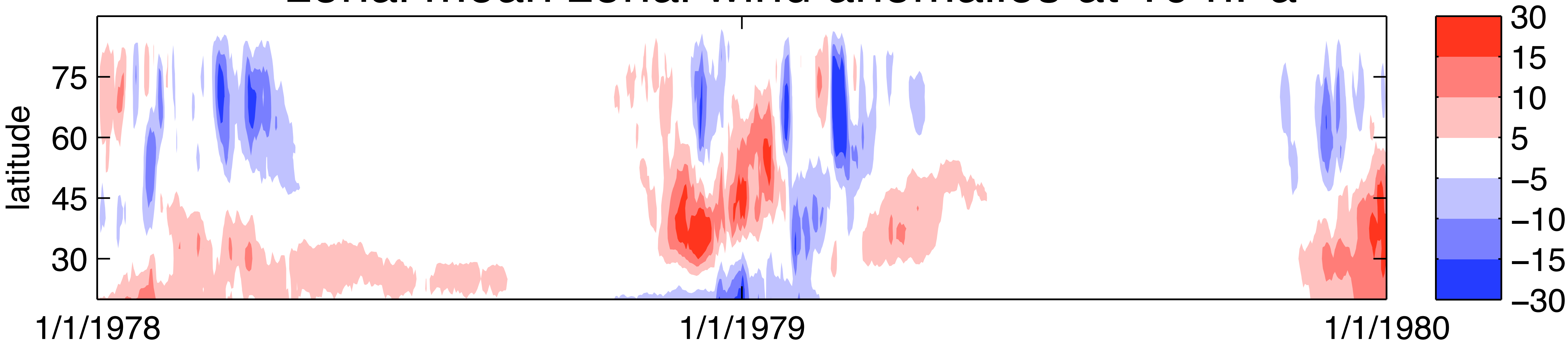
Jan
1980

Variations of the Jets

zonal mean zonal wind anomalies at 1000 hPa

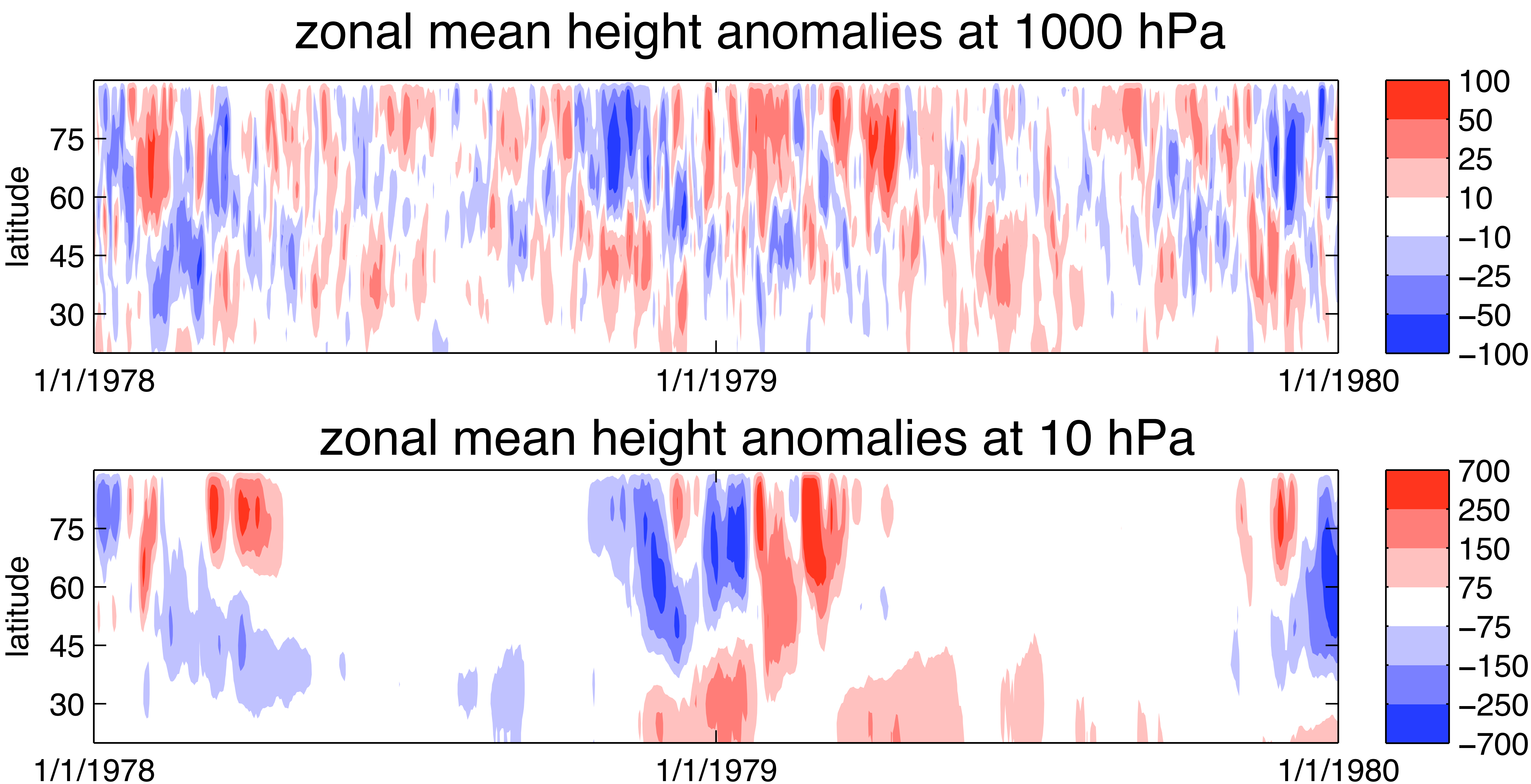


zonal mean zonal wind anomalies at 10 hPa



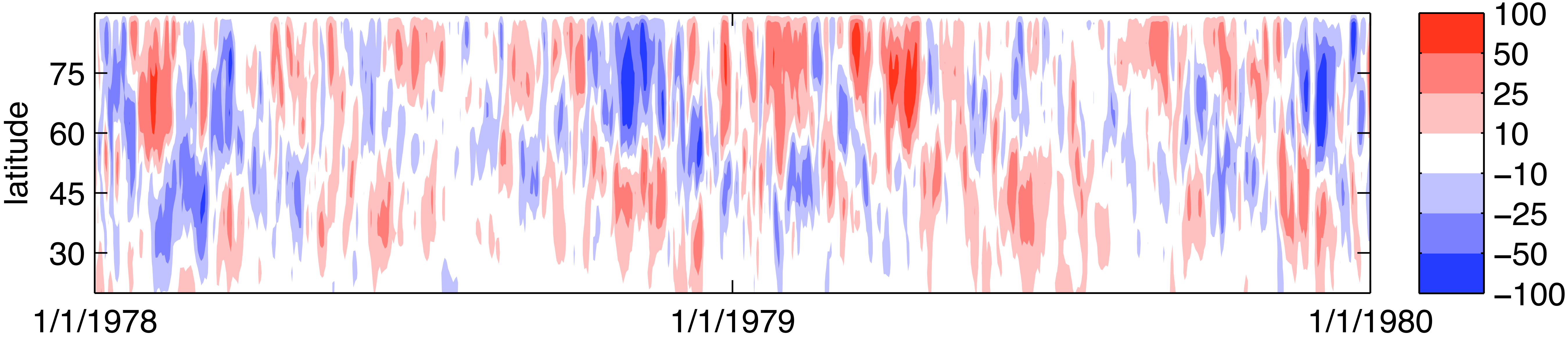
[cos$^{1/2}$(lat) weighted, NCEP-NCAR reanalyses]

Variations of the Jets
(viewed through height anomalies!)

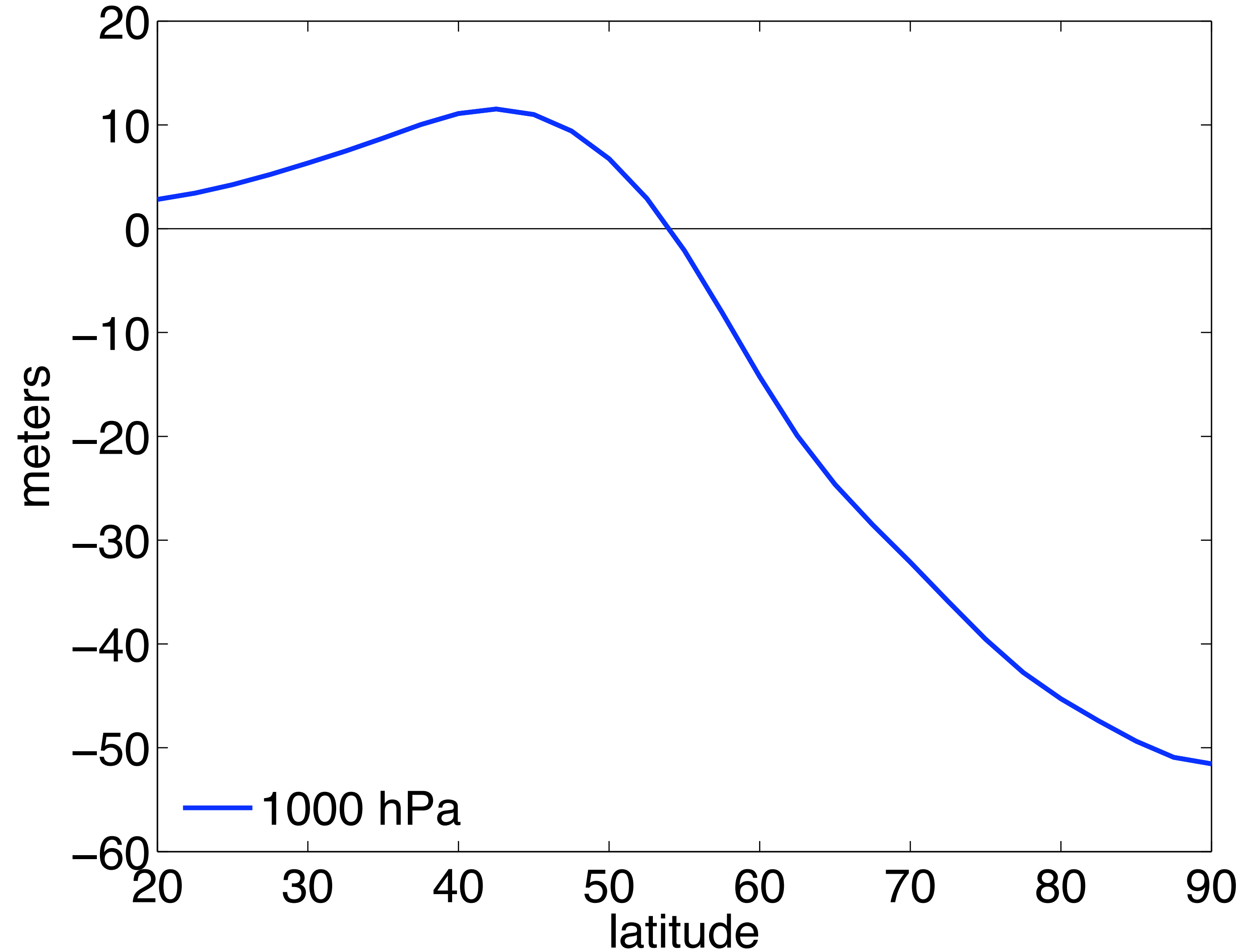


[$\cos^{1/2}$(lat) weighted, NCEP-NCAR reanalyses]

The Annular Mode (AM)

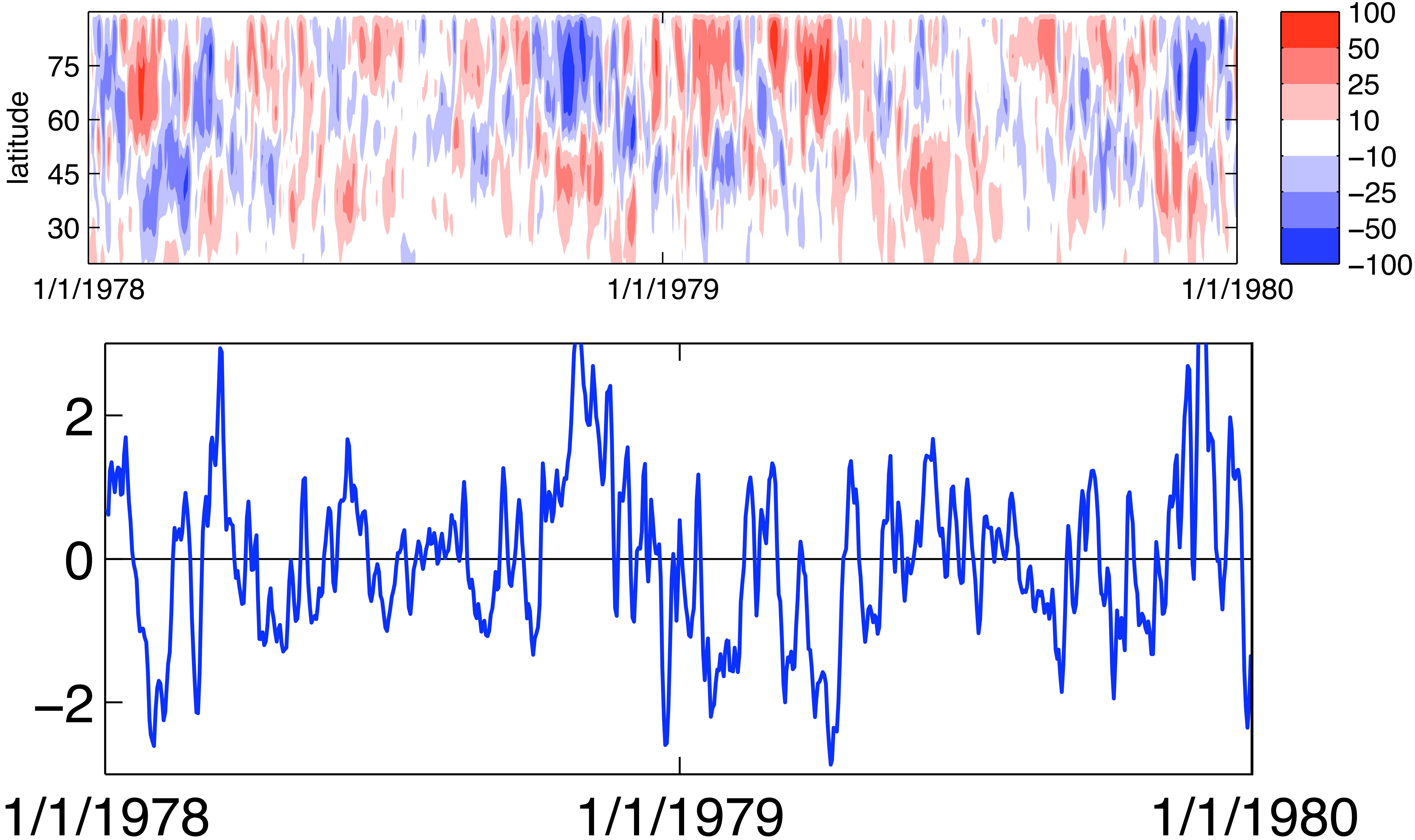


first Empirical Orthogonal Function (EOF) of zonal mean geopotential height



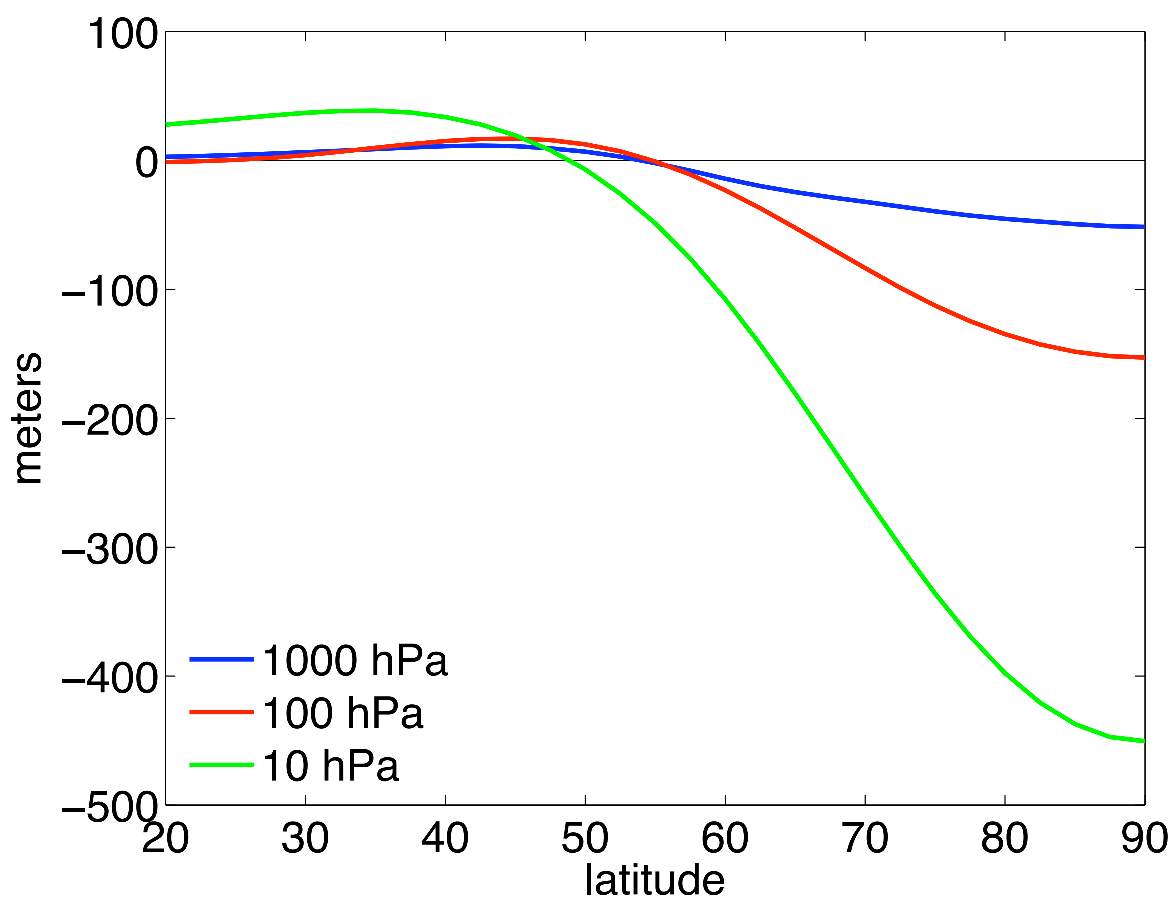
Thompson and Wallace 1998, Baldwin and Thompson 2009

The Annular Mode Index

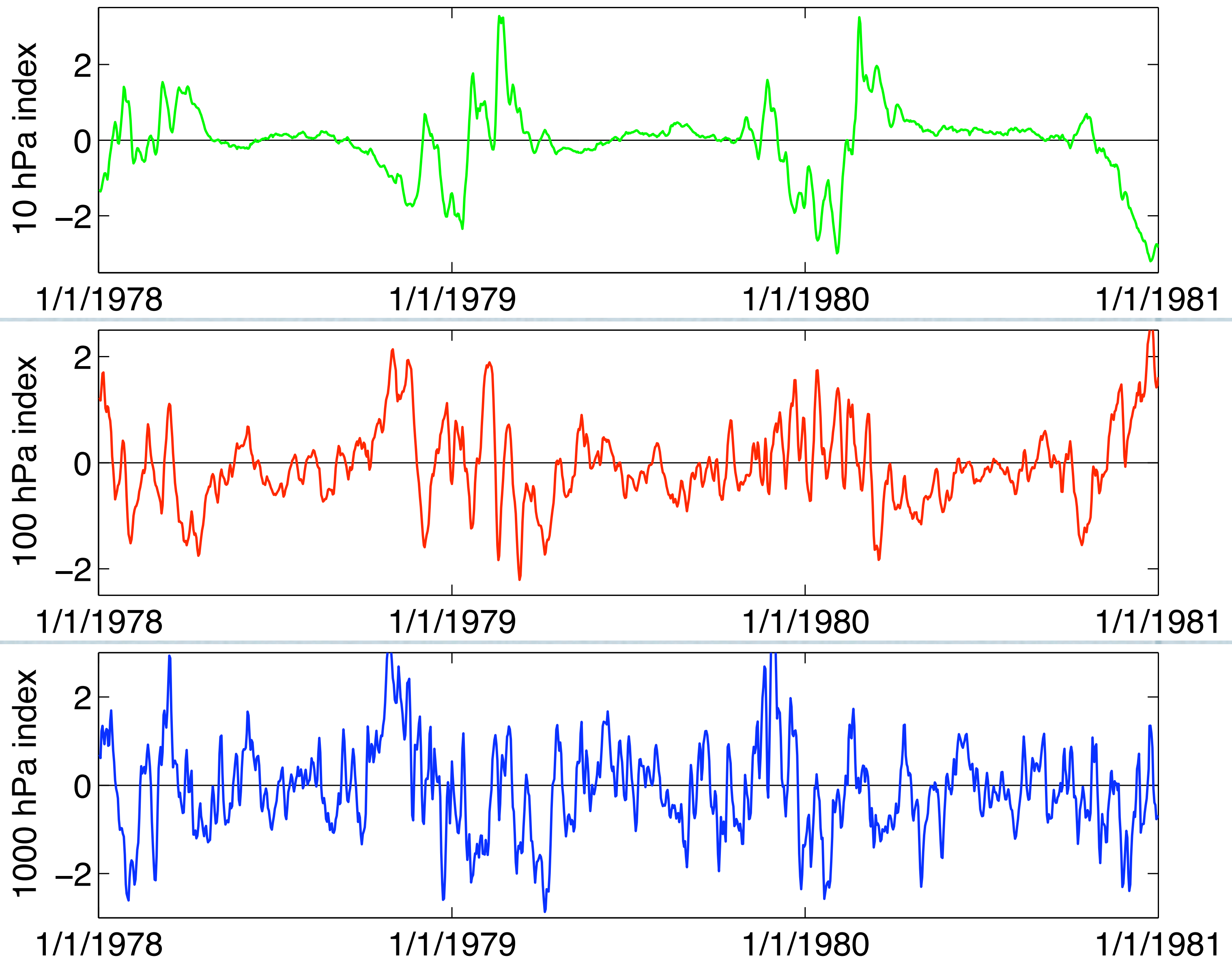


The Annular Mode (AM): as a function of height

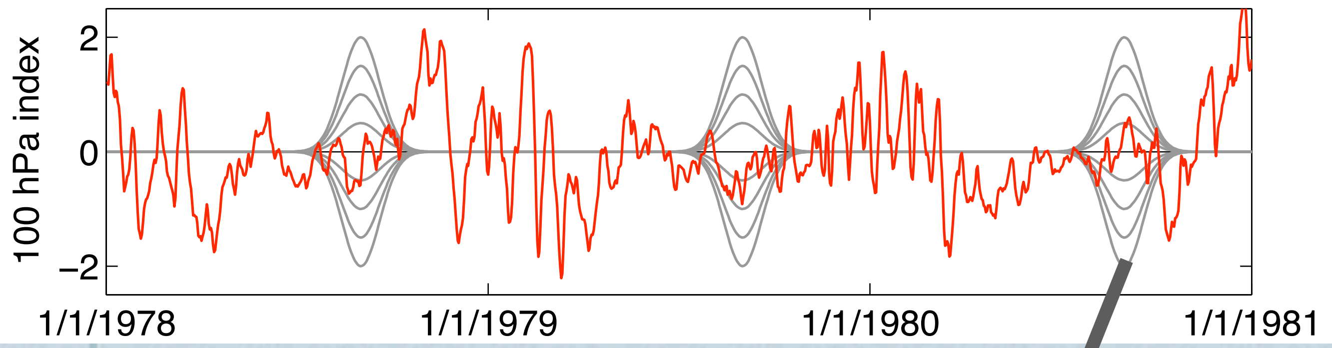
AM patterns

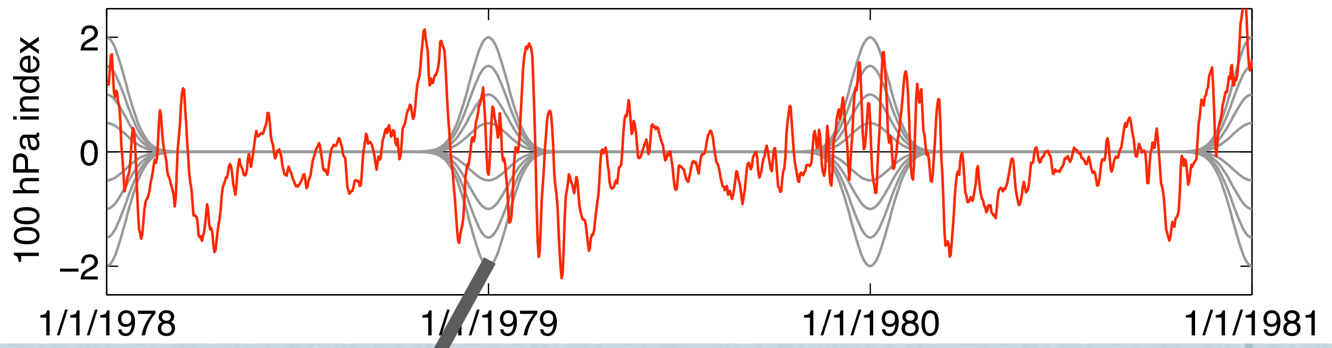


AM Indices

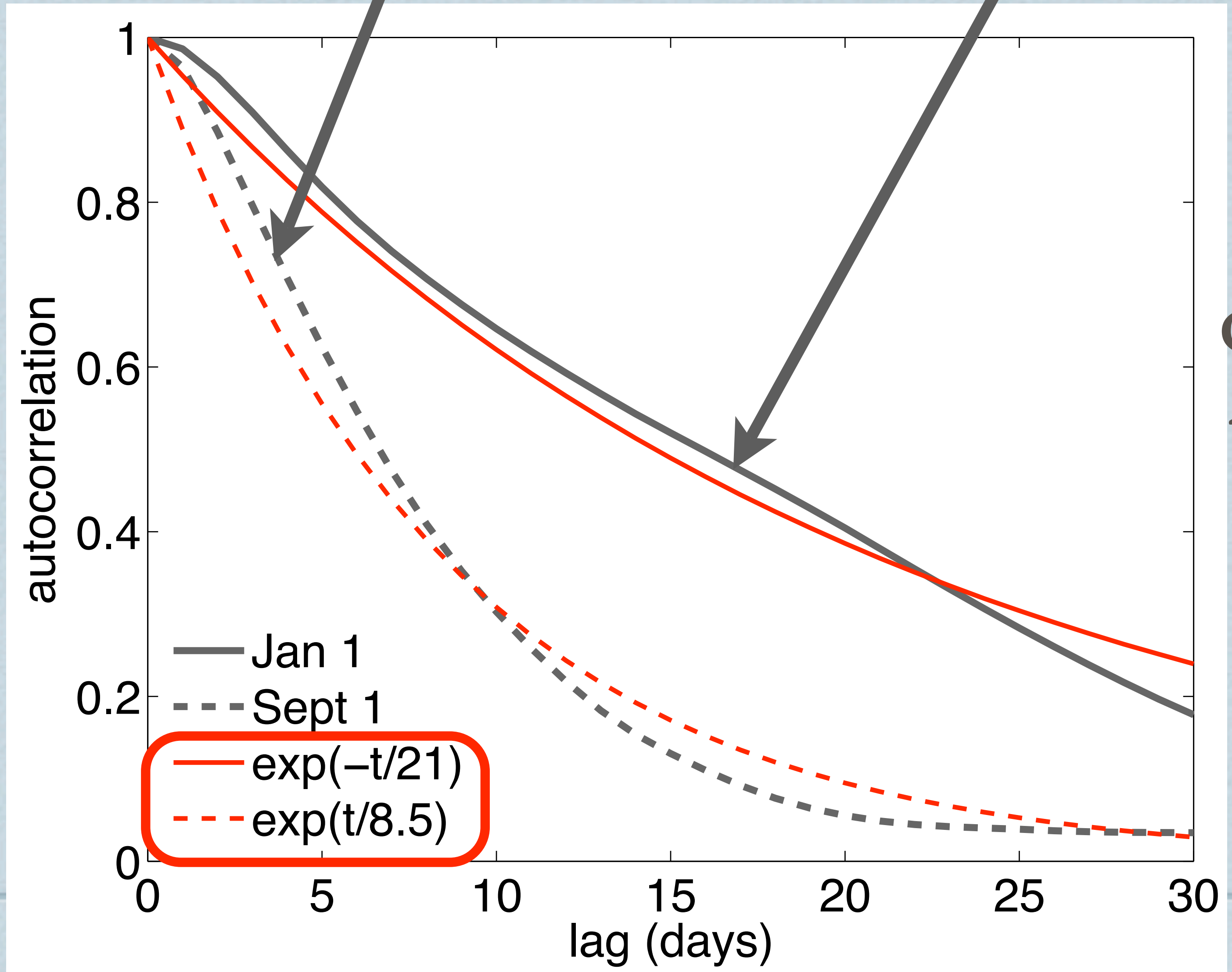


Quantify the correlation: the e-folding time scale





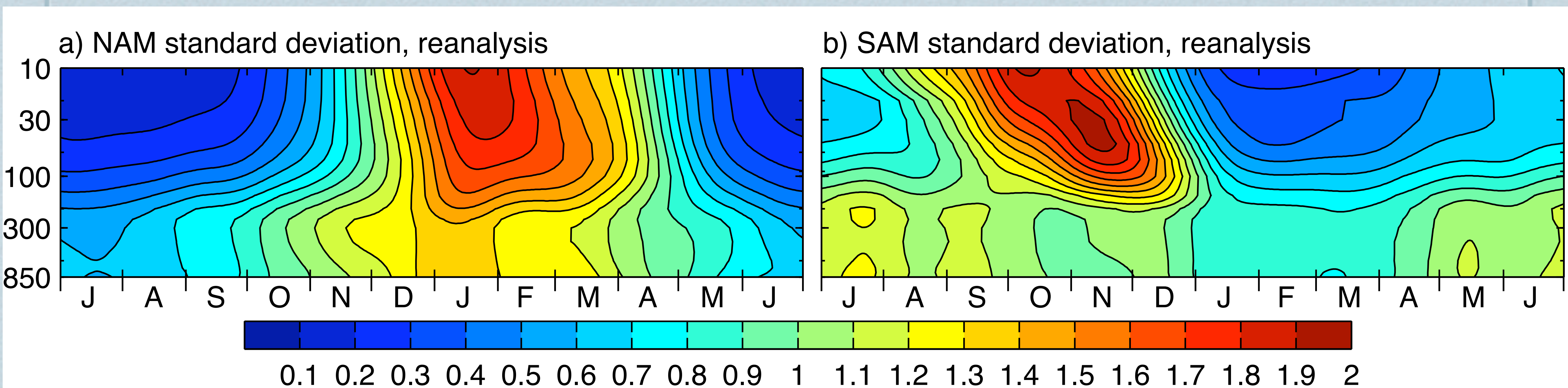
Sept. weather changes each week!

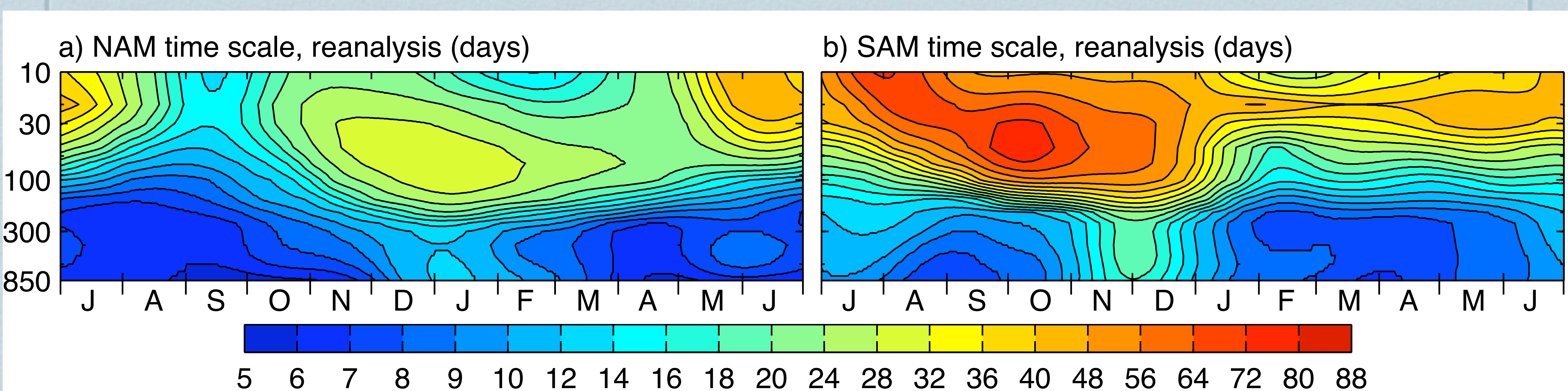


Jan. weather changes every **three** weeks!

Baldwin et al. 2003

Observed Annular Mode Amplitude and Time Scale





Baldwin et al. 2003, Gerber et al. 2010

Questions

1. What sets the time scales of internal variability?
2. What is the role of the stratosphere (if any) in tropospheric variability?
3. Why is internal variability important? Connection to climate change.

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Portola Plaza Theatre

(cast, in order of appearance)

- The barotropic vorticity equation on the sphere
  - stirred with random vorticity perturbations
- Dry dynamical core (primitive eqns on sphere, “self stirring”)
  - *Held and Suarez* (1994) forcing: troposphere climate
  - *Polvani and Kushner* (2002): add stratospheric polar vortex
- CMIP3 coupled atmosphere-ocean climate models, used in the IPCC Fourth Assessment Report
- Chemistry Climate Models (CCMs)
  - simulate interactive stratospheric ozone chemistry
  - well resolved stratosphere + comparable horizontal resolution to CMIP3, but forced with specified SSTs

The Simplest Model:
Barotropic Vorticity Dynamics on the Sphere

2D zonal momentum:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -\frac{\partial \phi}{\partial x} + F_u - D_u$$

forcing dissipation

take zonal mean, and note that eddy momentum flux divergence = the vorticity flux

$$\overline{v'\zeta'} = -\frac{\partial \overline{u'v'}}{\partial y}$$

$$\frac{\partial \overline{u}}{\partial t} = \overline{v'\zeta'} + \overline{F}_u - \overline{D}_u$$

(¯ is zonal mean, ′ deviation therefrom)

assume no direct momentum forcing, and Rayleigh friction

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

e.g. Held 2000, Vallis et al. 2004

The Simplest Model:
Barotropic Vorticity Dynamics on the Sphere

to understand $\overline{v'\zeta'}$
start with the linearized
barotropic vorticity eqn.

$$\frac{\partial \zeta'}{\partial t} + \overline{u}\frac{\partial \zeta'}{\partial x} + \gamma v = F'_\zeta - D'_\zeta$$

$$\gamma = \beta - \partial^2 \overline{u}/\partial y^2$$

is the meridional gradient in abs. vorticity

divide by ϒ, multiply
by ζ, take zonal mean
to get pseudo-
momentum eqn.

$$\frac{\partial M}{\partial t} - \boxed{\overline{v'\zeta'}} = -\frac{1}{\gamma}(\overline{\zeta' F'_\zeta} - \overline{\zeta' D'_\zeta})$$

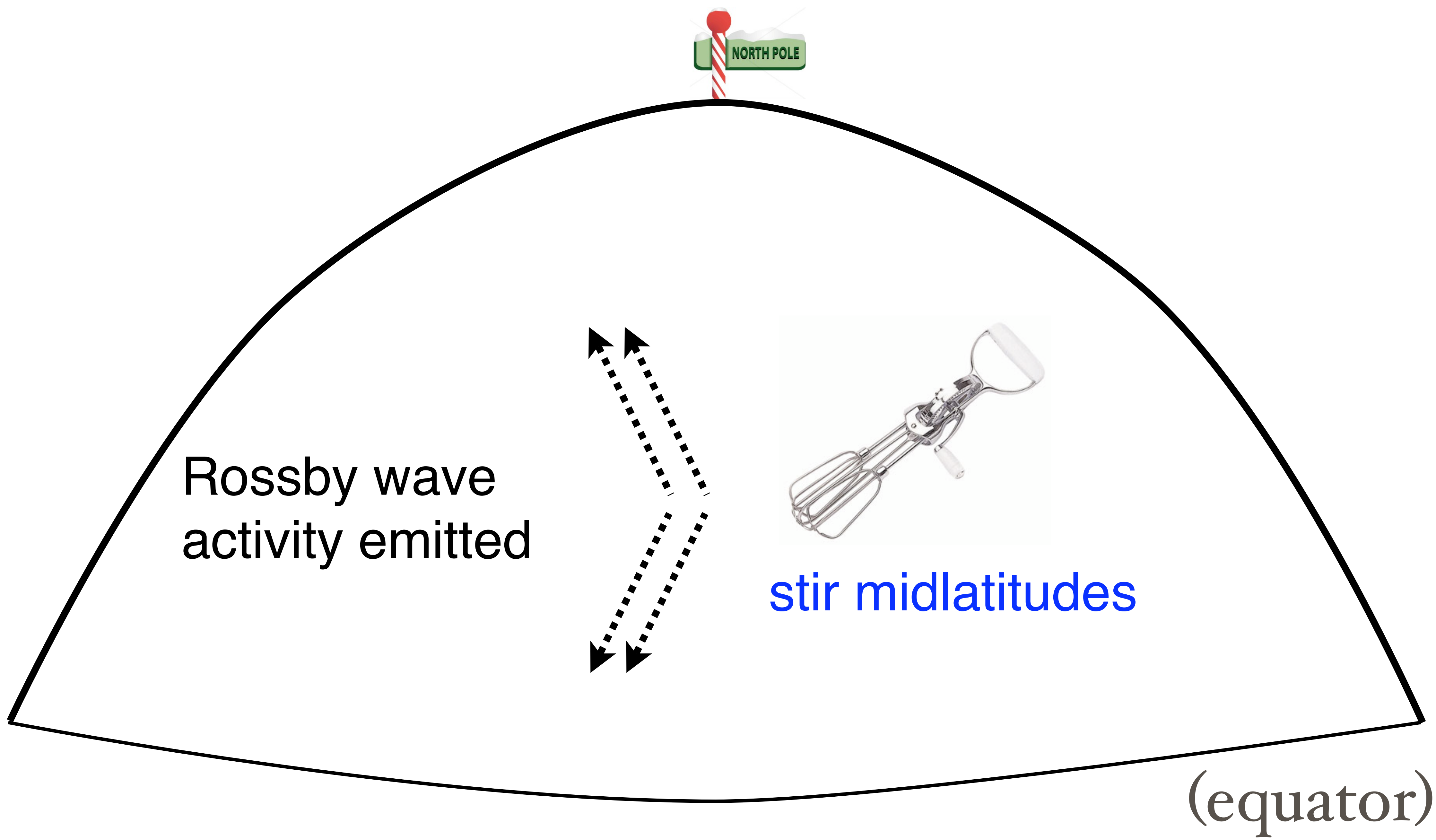
$$M = -\overline{\zeta'^{\,2}}/2\gamma$$

Lastly, combine w/ the momentum equation:

$$\frac{\partial \overline{u}}{\partial t} - \frac{\partial M}{\partial t} = -r\overline{u} + \frac{1}{\gamma}(\underbrace{\boxed{\overline{\zeta' F'_\zeta}}}_{\text{stirring}} - \underbrace{\boxed{\overline{\zeta' D'_\zeta}}}_{\text{damping}})$$

e.g. Held 2000, Vallis et al. 2004

A Physical Picture



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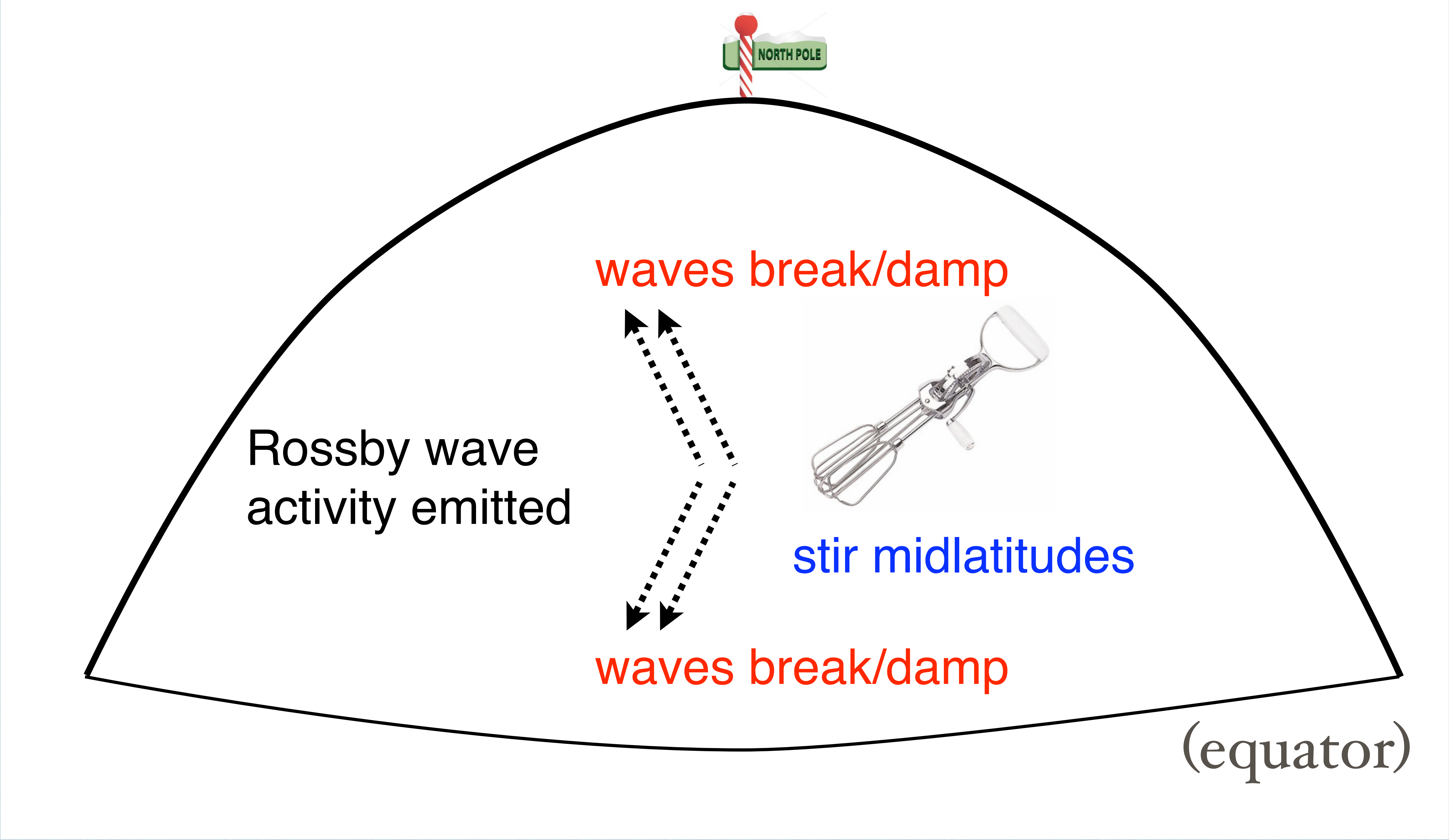

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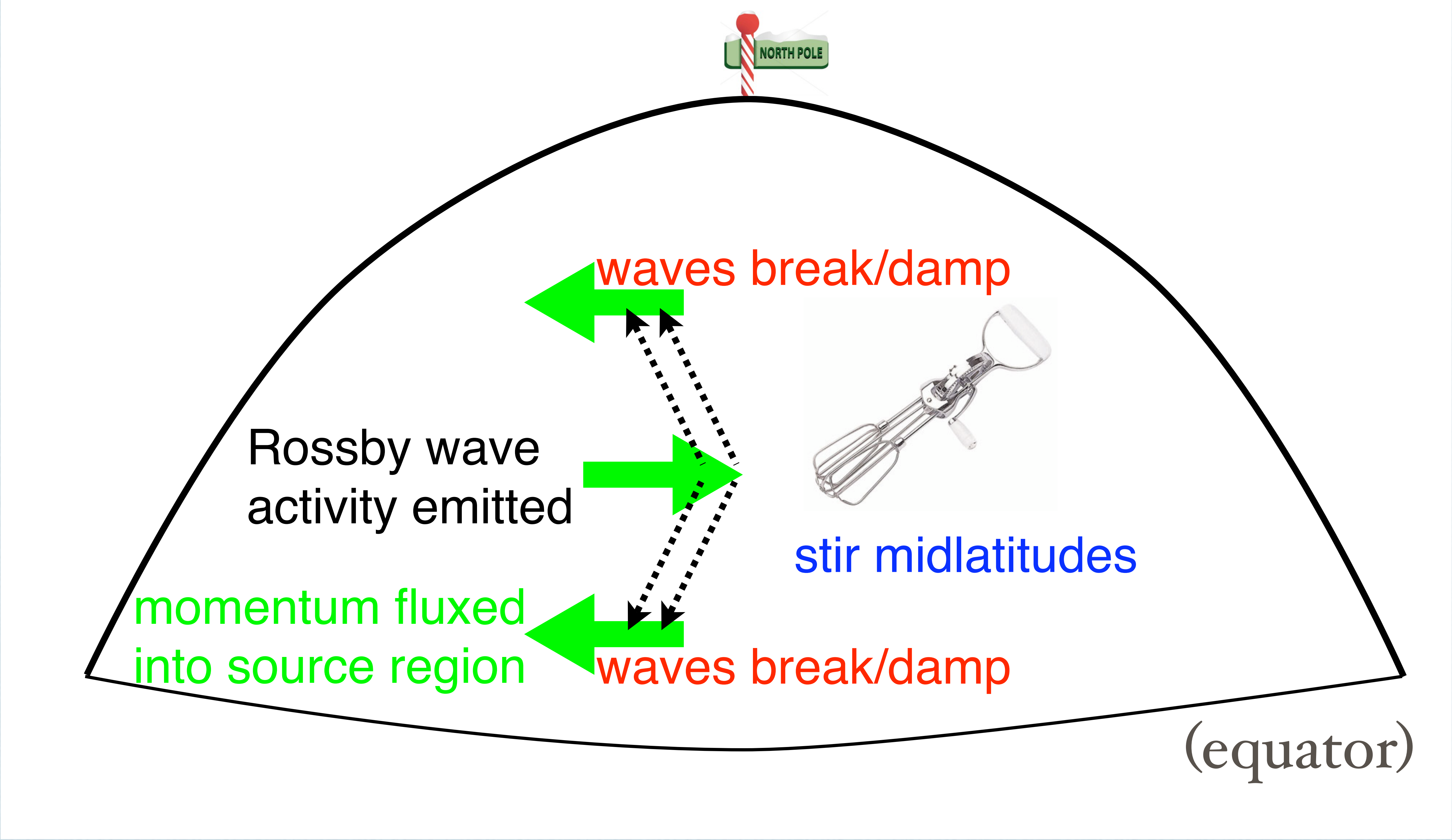
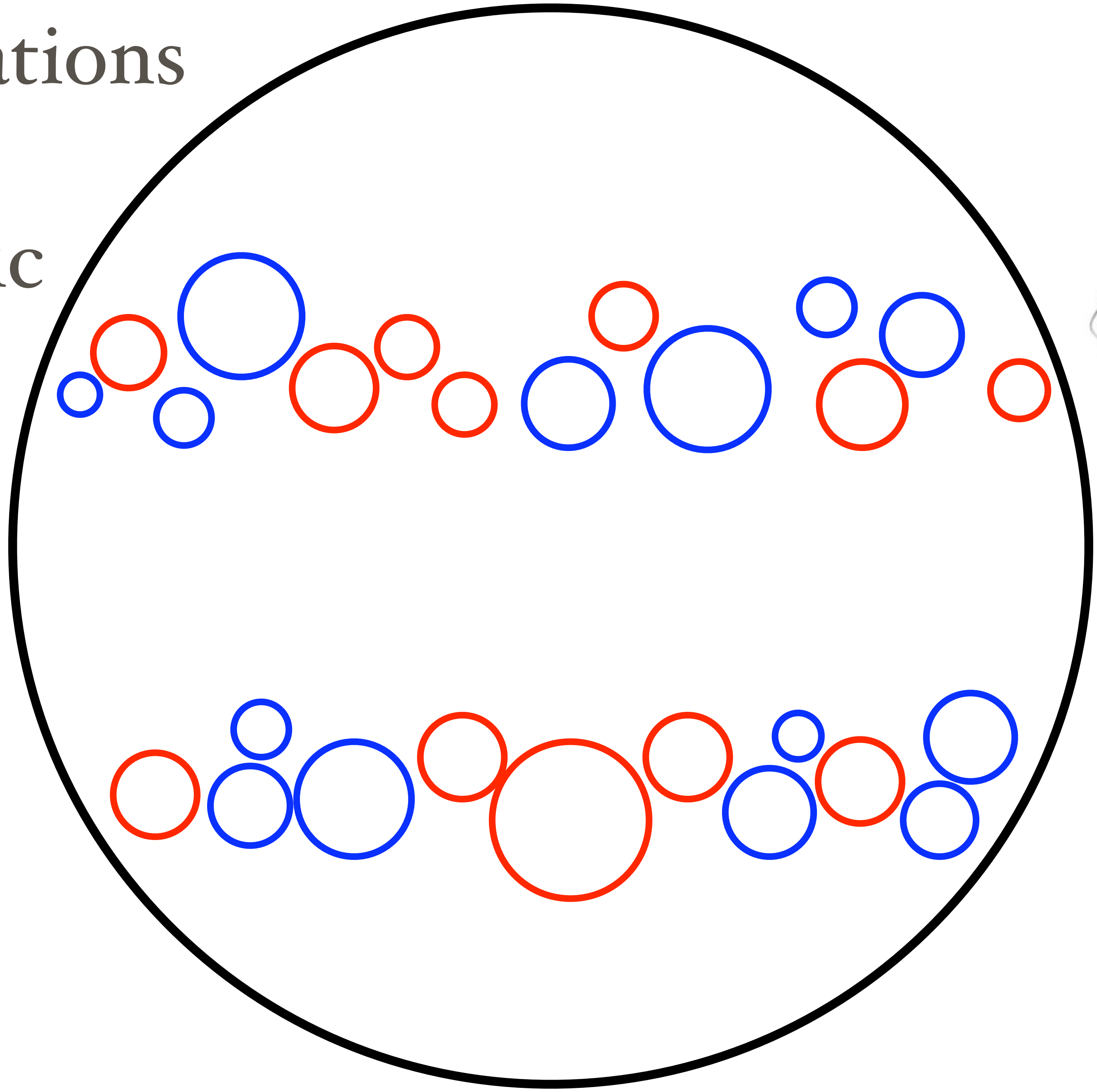
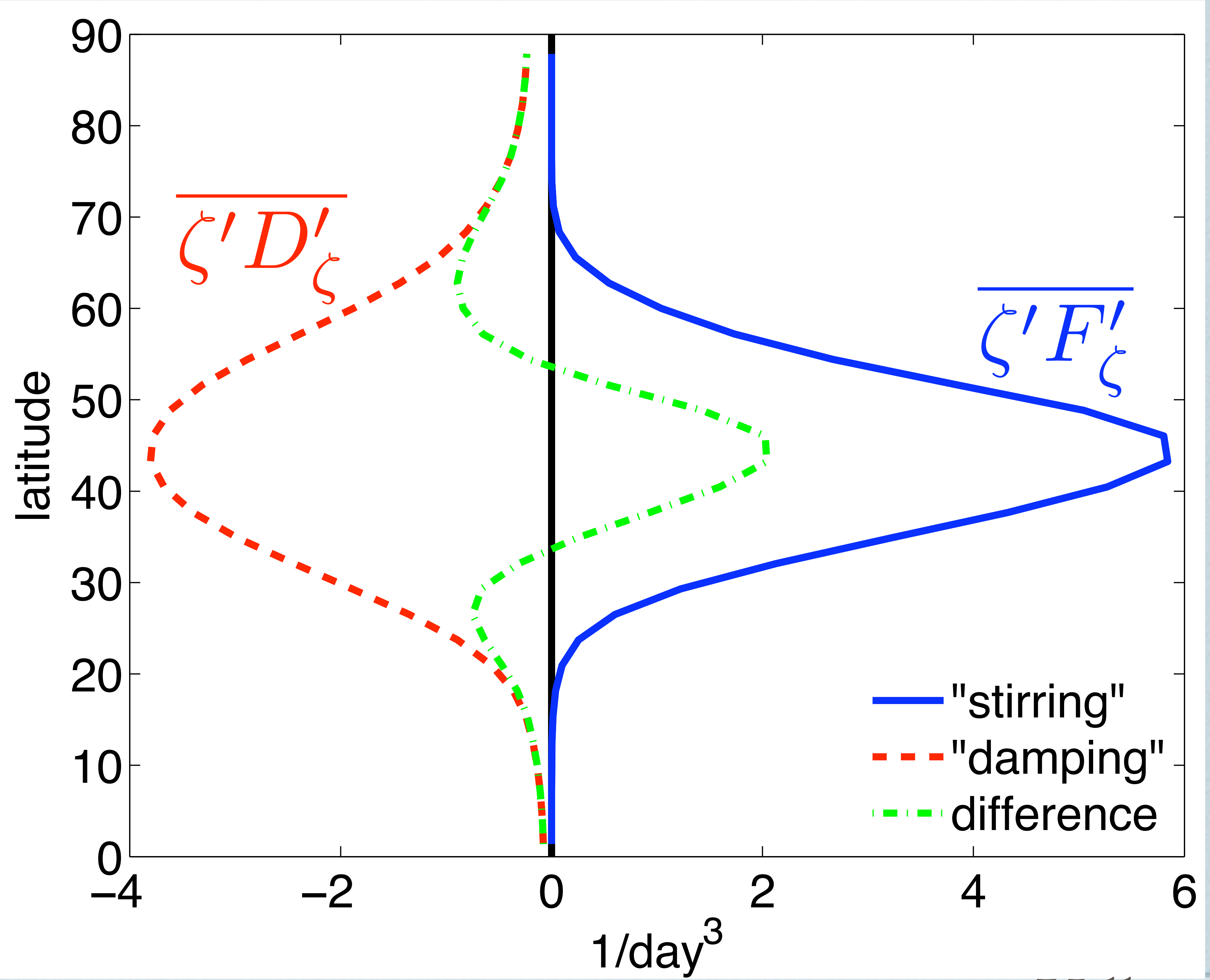


Numerical Experiments on the Sphere

random perturbations to the vorticity forced in synoptic wave numbers in midlatitude band; perturbations have no net vorticity

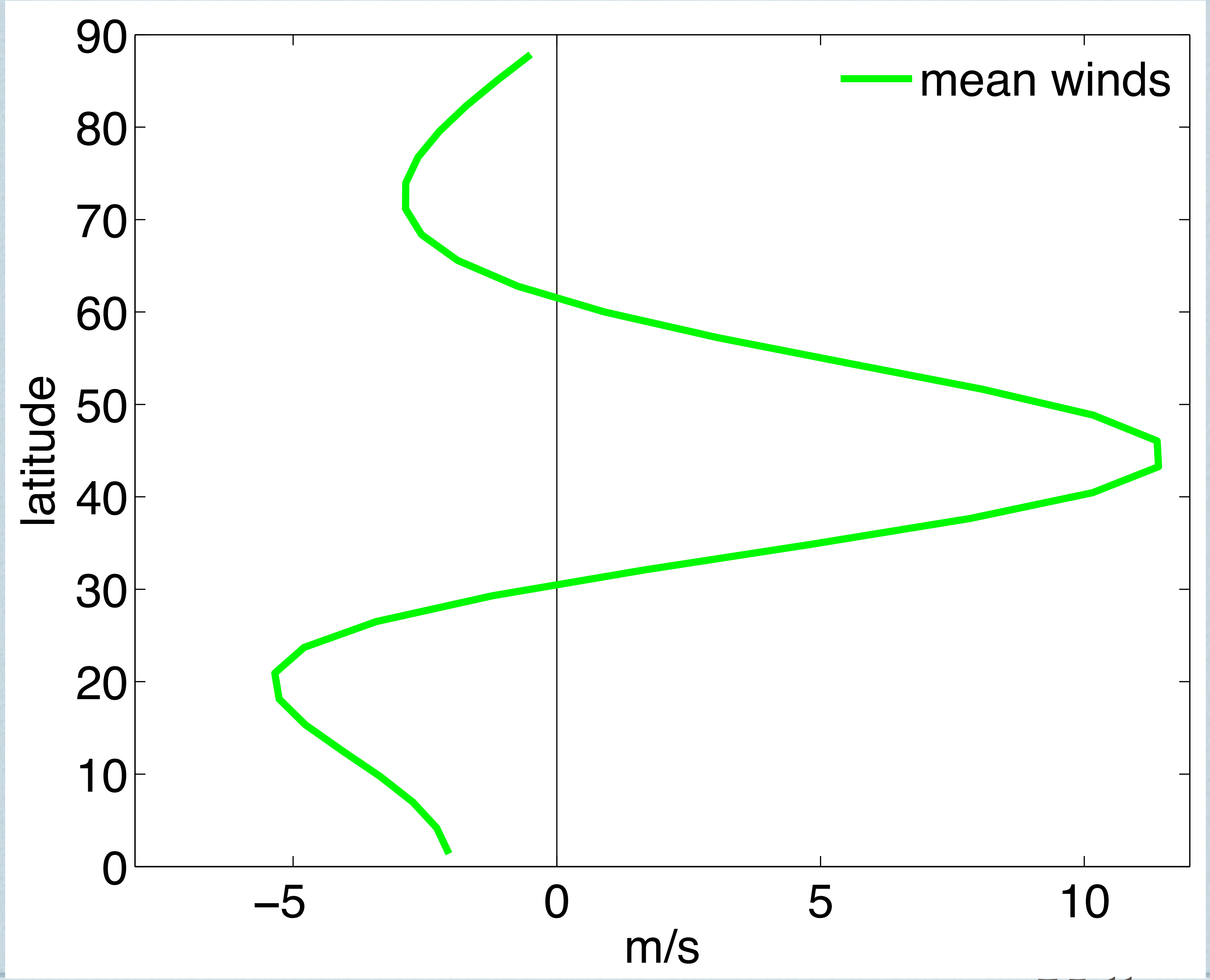


Numerical Simulations



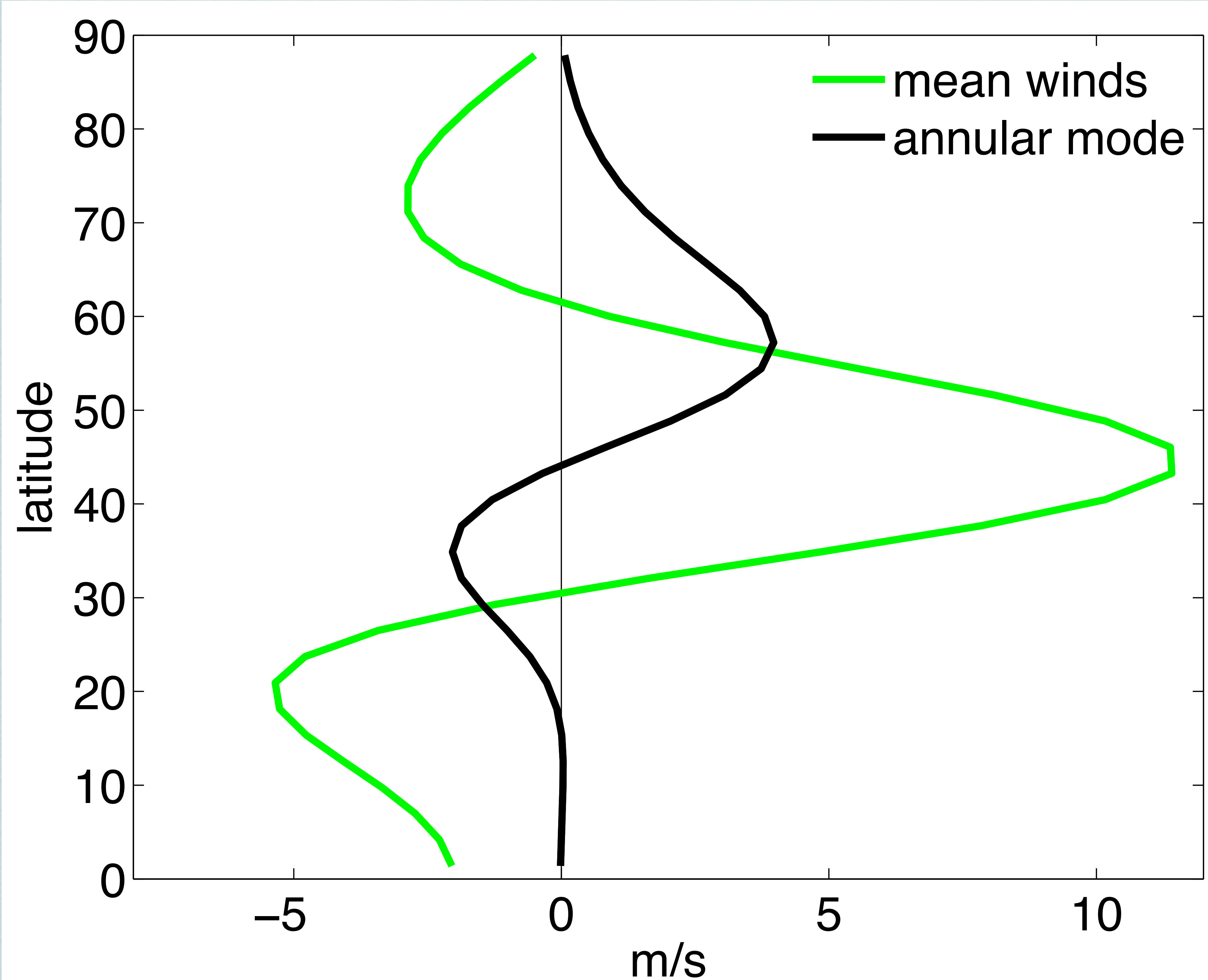
Vallis et al. 2004

Prototype Midlatitude Jet



Vallis et al. 2004

Variability in stirring ➔ Variability in jet (Annular Mode)



Vallis et al. 2004

Simple Model of Annular Mode Time Scales

variations in zonal mean driven by variations in vorticity fluxes

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

project ū anomalies onto AM, approx. forcing as white noise: looks like Ornstein-Uhlenbeck process (discrete analog AR-1)

$$\boxed{\frac{dx}{dt} = \dot{W}} - rx$$

Anomalies of zonal mean winds are the integral of the vorticity fluxes created by baroclinic eddies, hence will have redder spectrum of variability!

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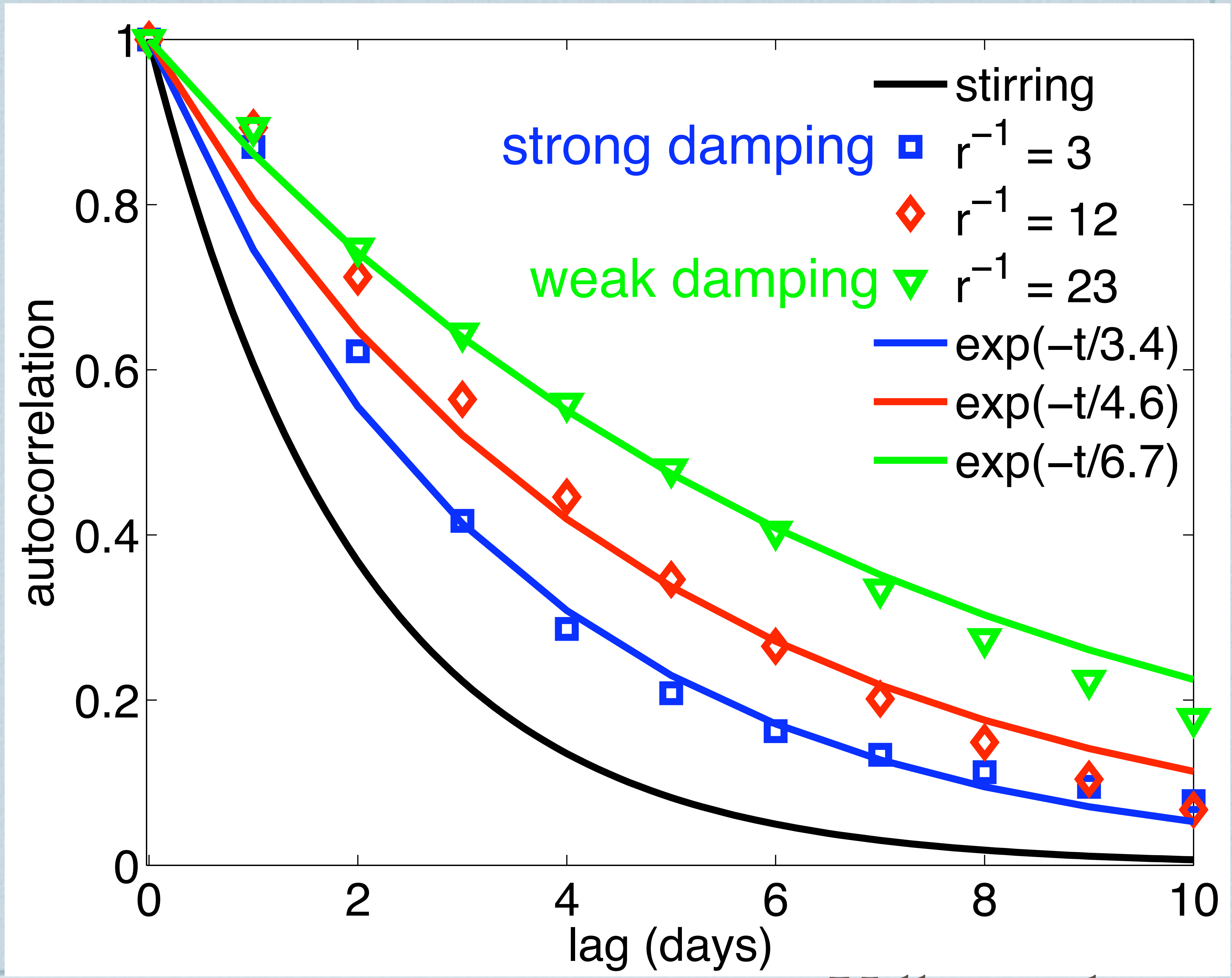
Anomalies of zonal mean winds are the integral of the vorticity fluxes created by baroclinic eddies, hence will have redder spectrum of variability!

Friction will bound variability on low frequencies.

Model Results: Exponential-ish Decay, like AR-1 Process

decrease the damping, increase the time scales

non-linear interactions limit time scales

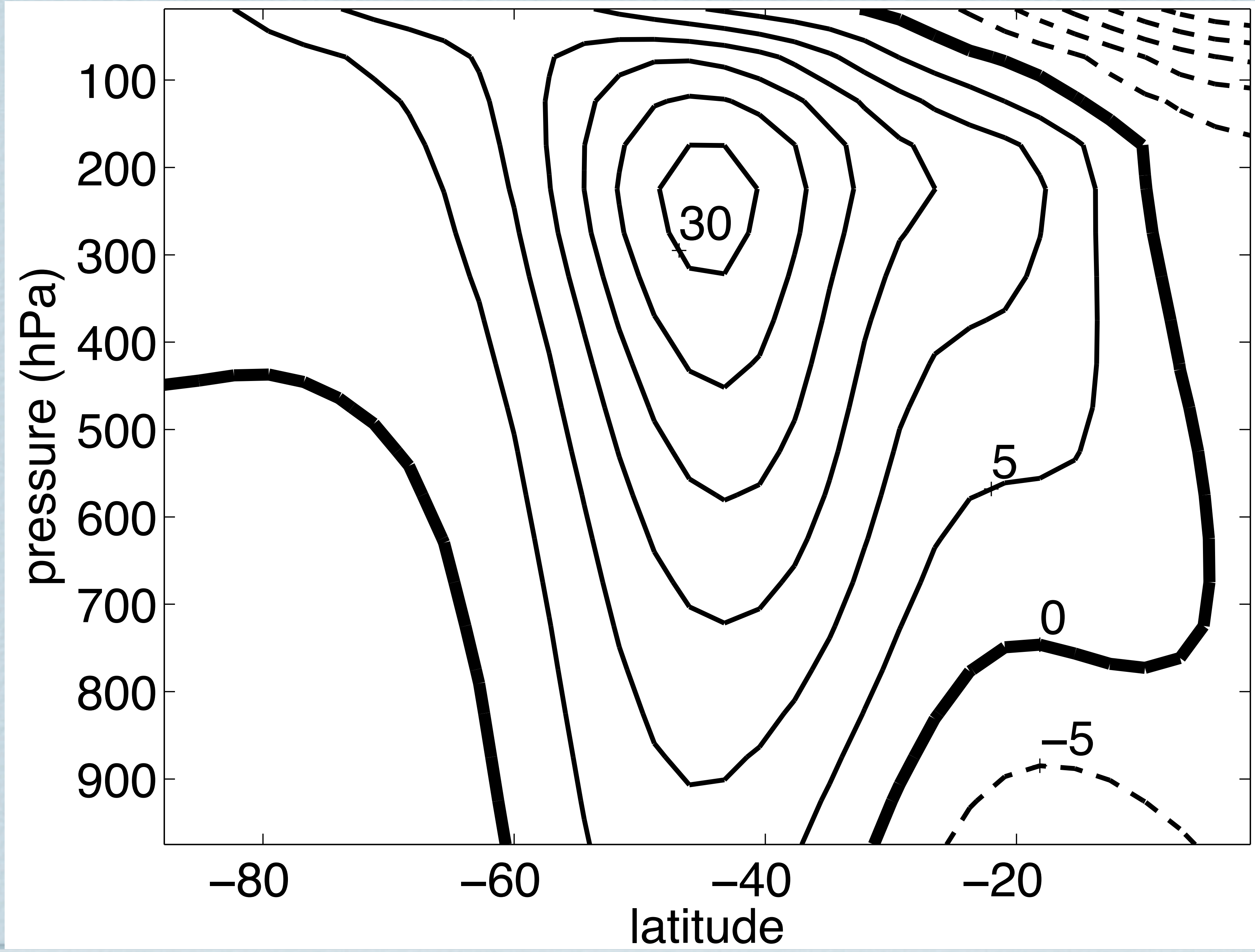


Vallis et al. 2004

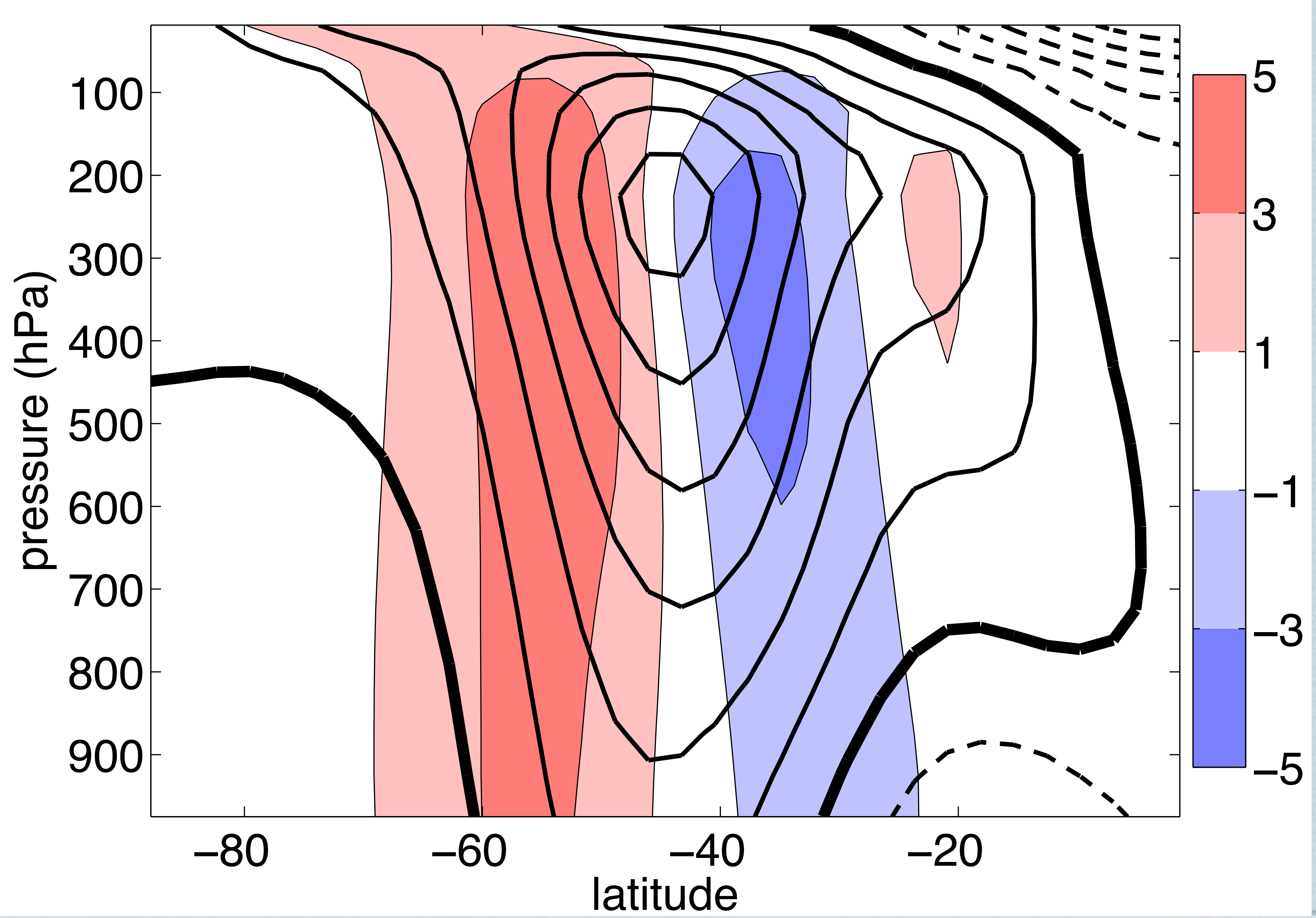
Interactive Stirring: Dynamical Core

- Vorticity "stirring" is generated by baroclinic instability, which is a function of jet structure. Potential for positive feedbacks! (Lorenz and Hartmann 2001, 2003)
- Dynamical core integrates 3-D primitive equations, captures baroclinic instability
- Forced by Held-Suarez simplified physics (Newtonian relaxation to radiative-convective equilibrium)

Held-Suarez Jet Structure



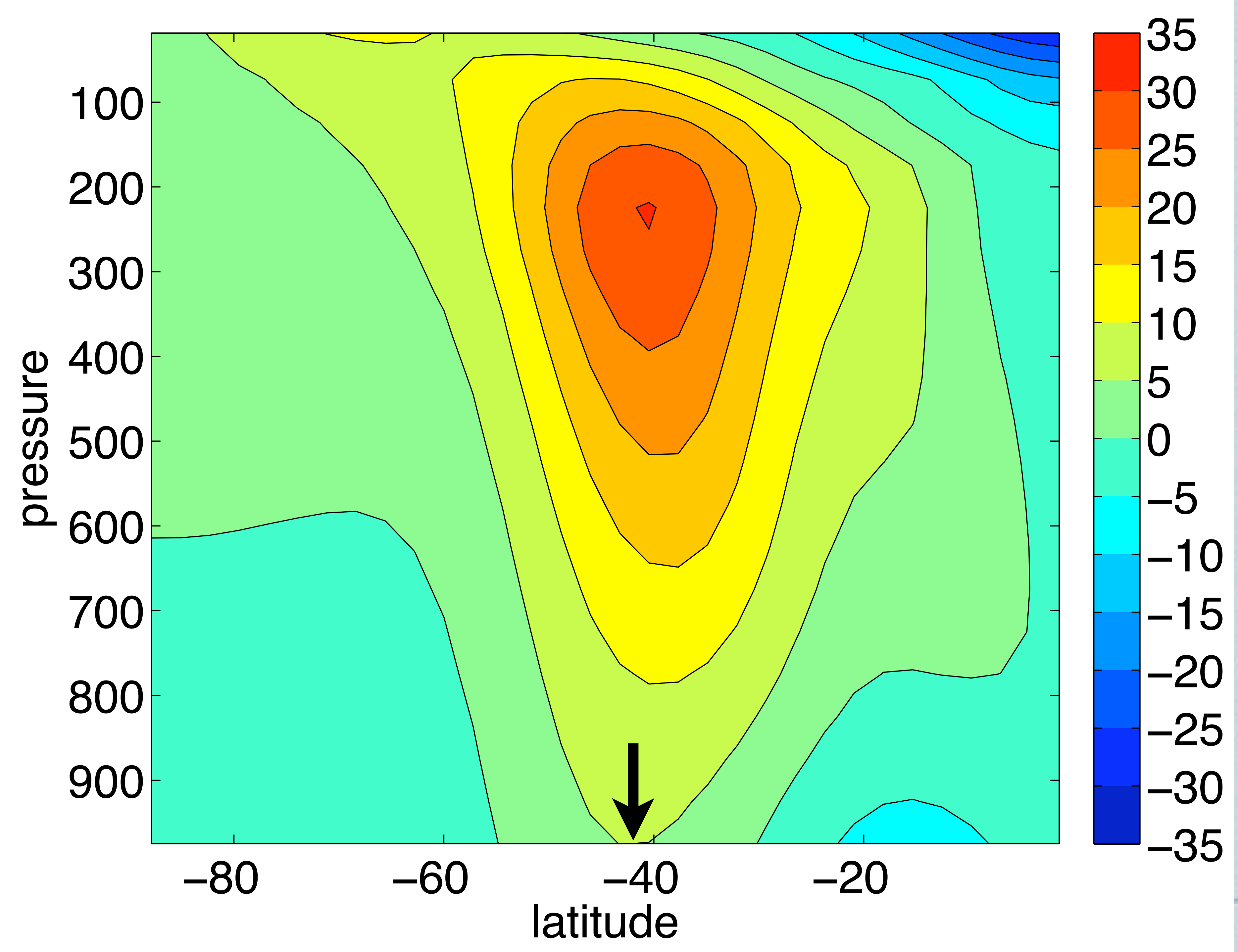
Held-Suarez Jet Structure and Annular Mode



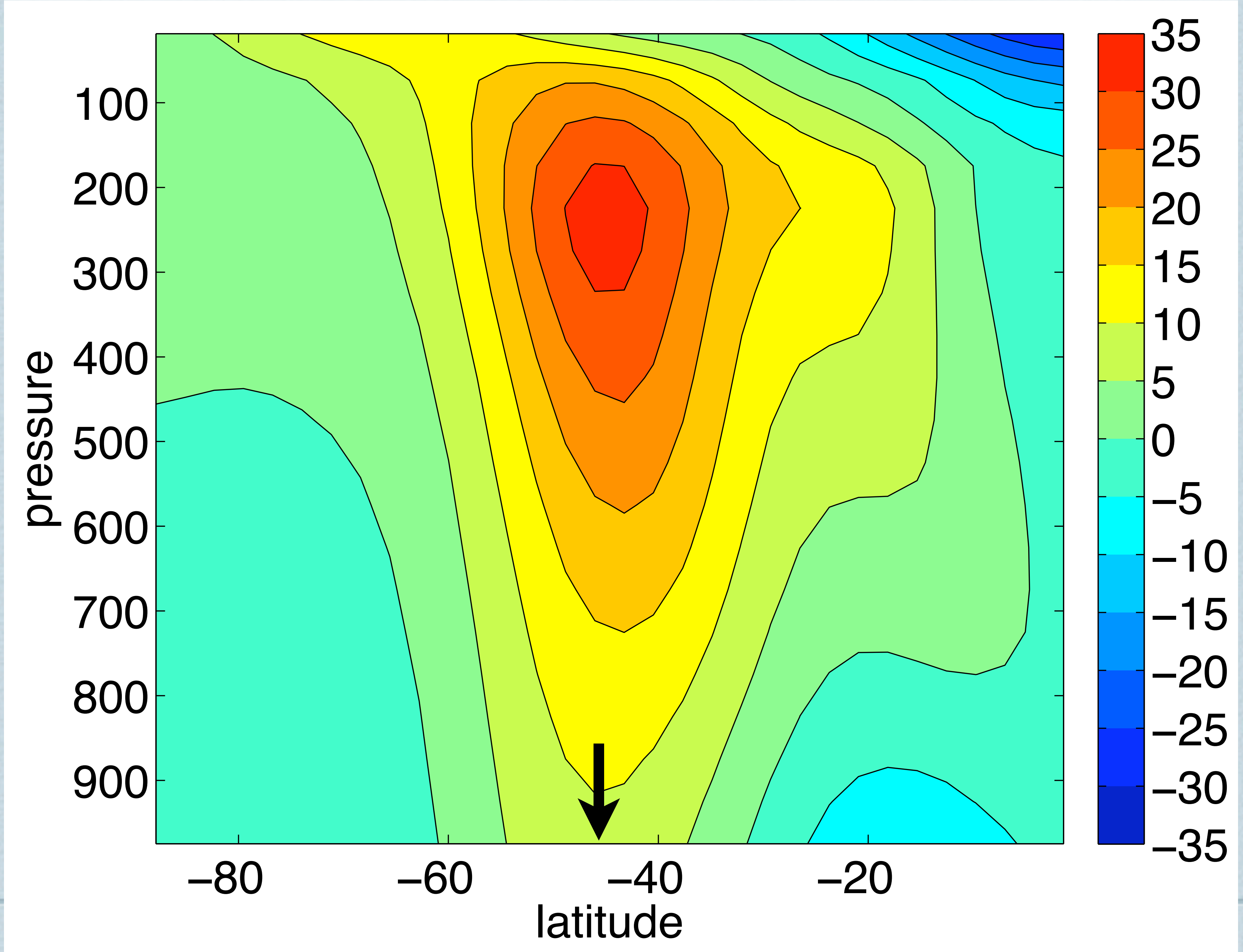
What determines time scale of Annular Mode in this system?

- First, systematically vary Held-Suarez forcing parameters
  - Thermal restoring time scale k_a^{-1}=40 days: $\frac{dT}{dt} = ... - k_a(T - T_{eq})$
  - Surface friction k_f^{-1}=1 day: $\frac{du}{dt} = ... - k_f \frac{p/p_s - 0.7}{0.3} u, p/p_s > 0.7$
  - baroclinic growth of eddies (heat fluxes) effect vertical momentum transport on synoptic time scale of 6-8 days; to modulate baroclinicity, vary equator-to-pole temperature gradient of equilibrium profile: ΔT_{eq}
- Second, investigate impact of zonal asymmetries (more appropriate for the NH)

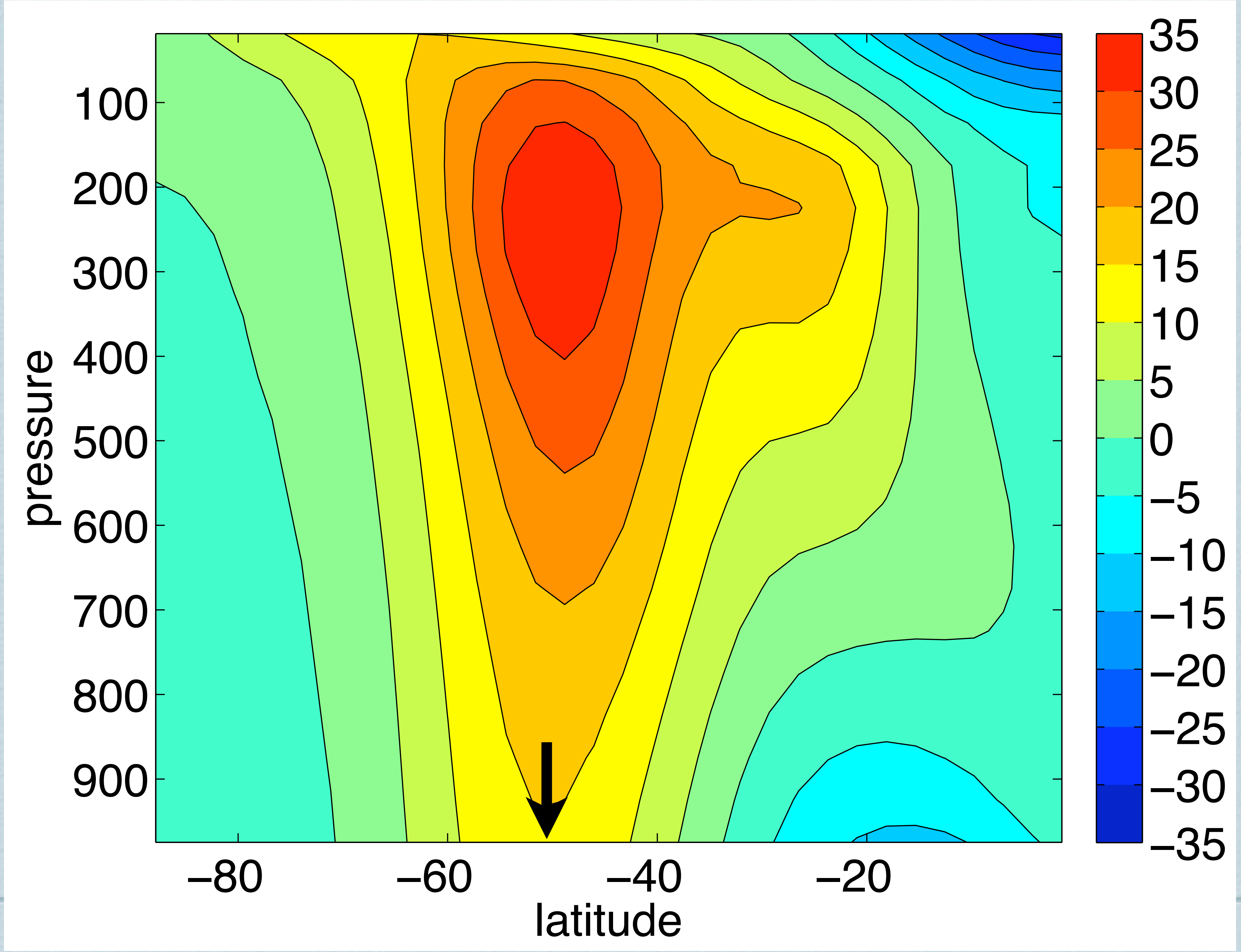
Vary Surface Friction
k_f = 4/3 day^{-1}



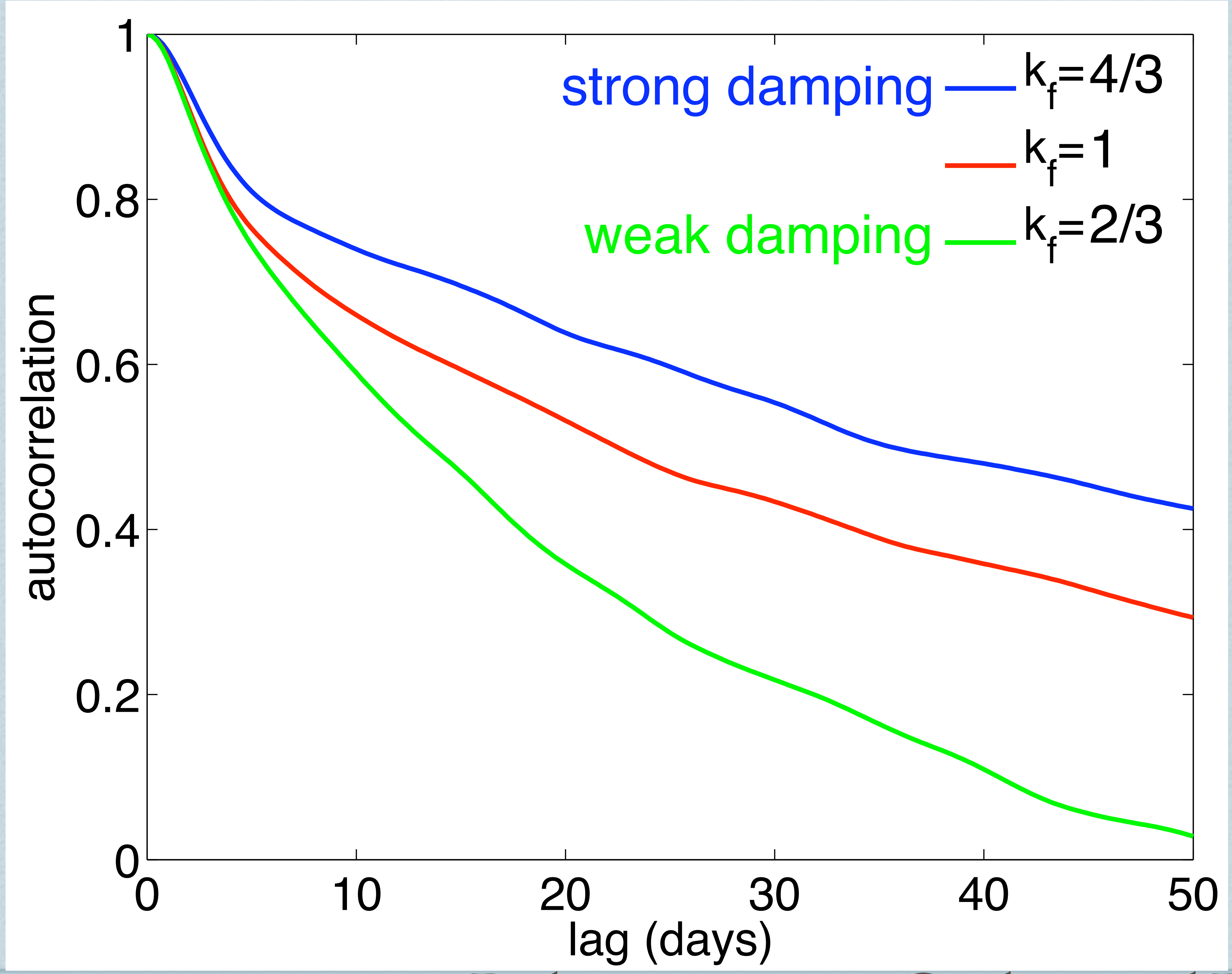
Vary Surface Friction
k_f = 1 day^{-1}



Vary Surface Friction
k_f = 2/3 day^{-1}

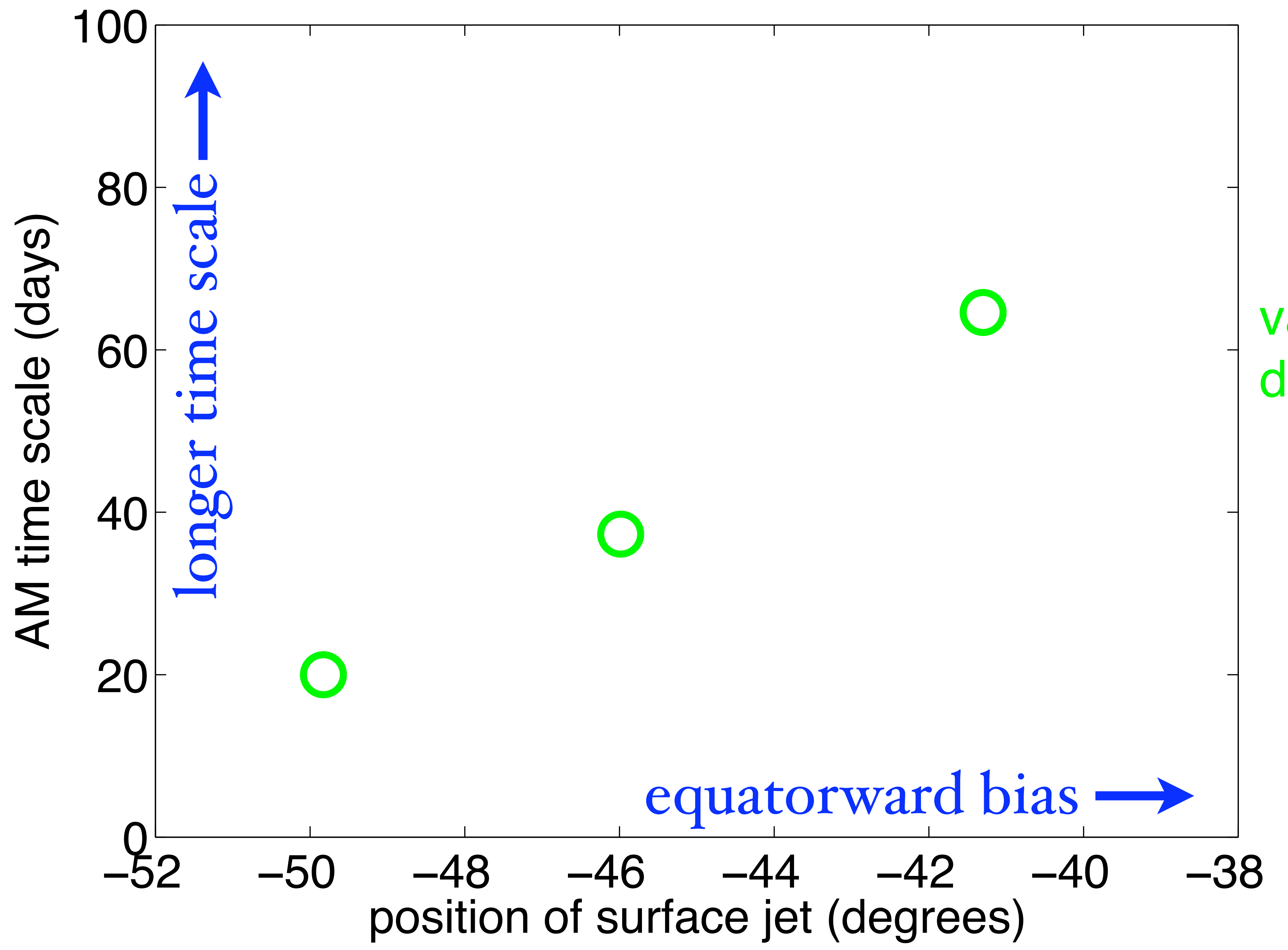


AM autocorrelation structure: stronger damping = greater persistence!



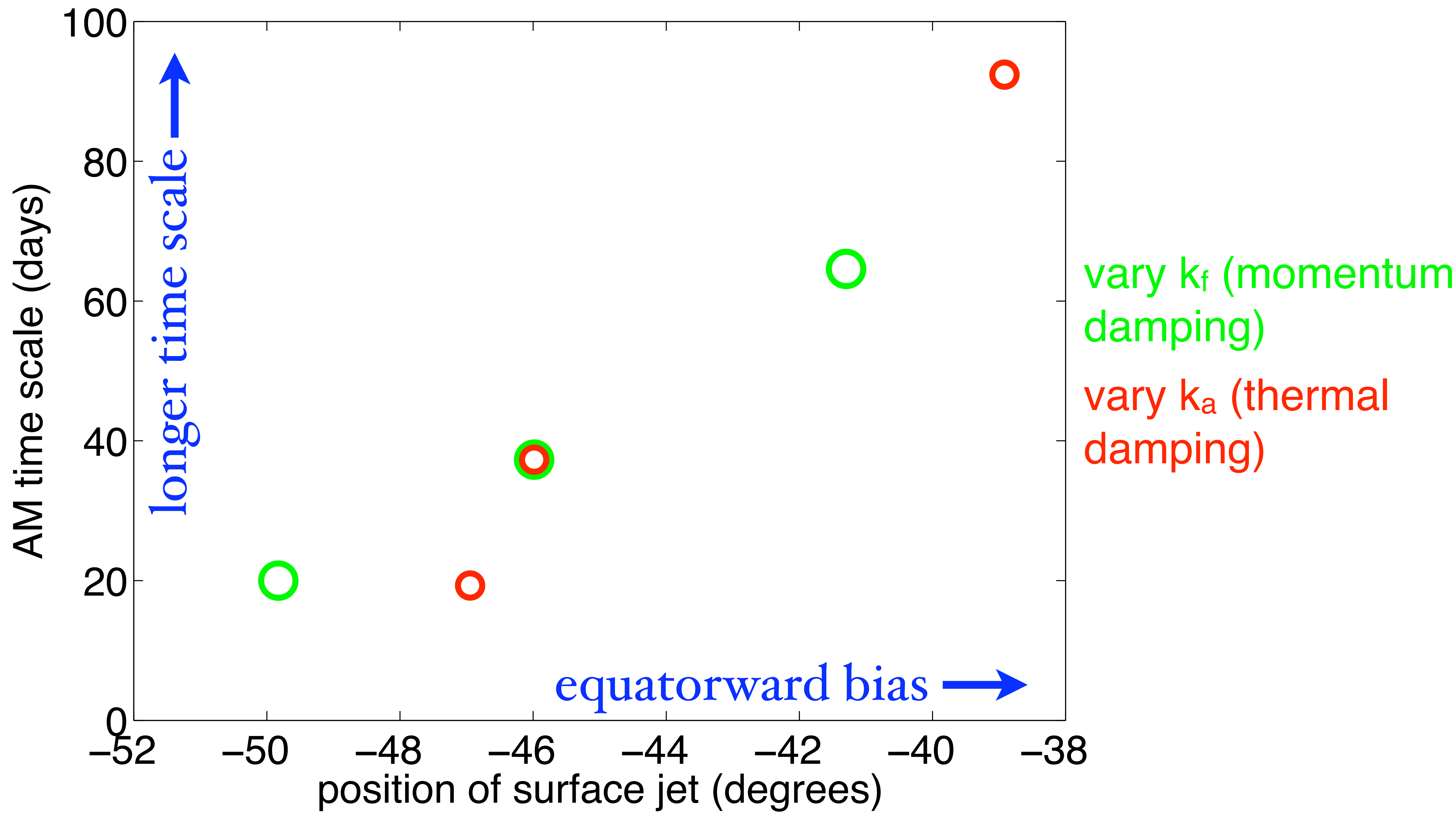
Robinson 1996, Gerber and Vallis 2007

Annular Mode Time Scale - Jet Latitude Connection



vary k_f (momentum damping)

Annular Mode Time Scale - Jet Latitude Connection



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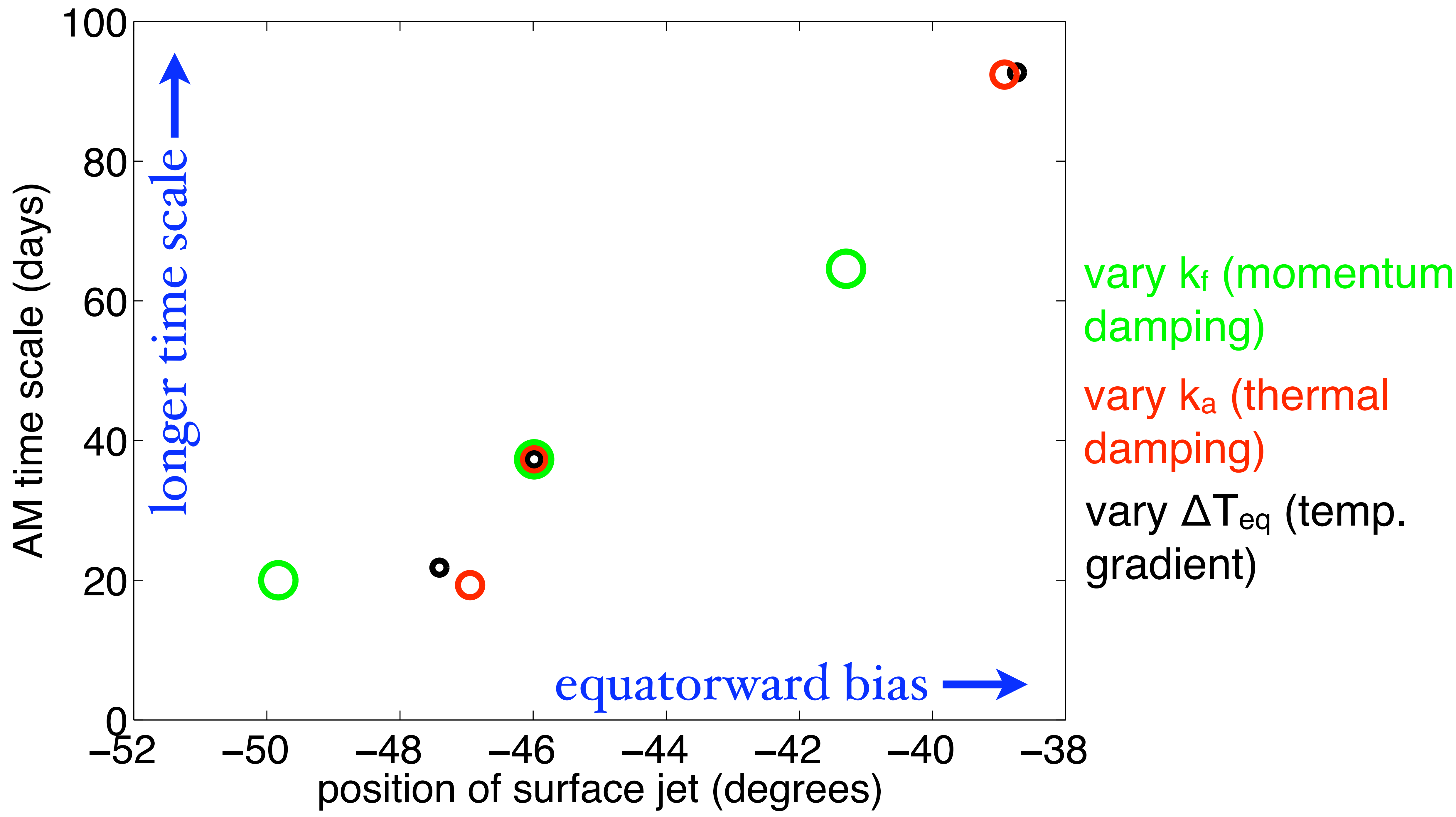


Summary of Parameter Impacts

equilibrium temperature gradient $\Delta T_{eq} \downarrow$

thermal damping $k_a \downarrow$

momentum damping $k_f \uparrow$

$\Rightarrow$

AM time scale $\uparrow$

jet moves equatorward

Implications:

1) AM time scale is distinct from the imposed time scales, rather a product of eddy-mean flow interactions

2) processes that set jet location also set AM time scale

Simple Model of Feedback
(after Lorenz and Hartmann 2001)

variation in annular mode index z(t)

$$\frac{dz}{dt} = \dot{W} - \frac{z}{\tau} + bz$$

stochastic "eddy" forcing

frictional damping

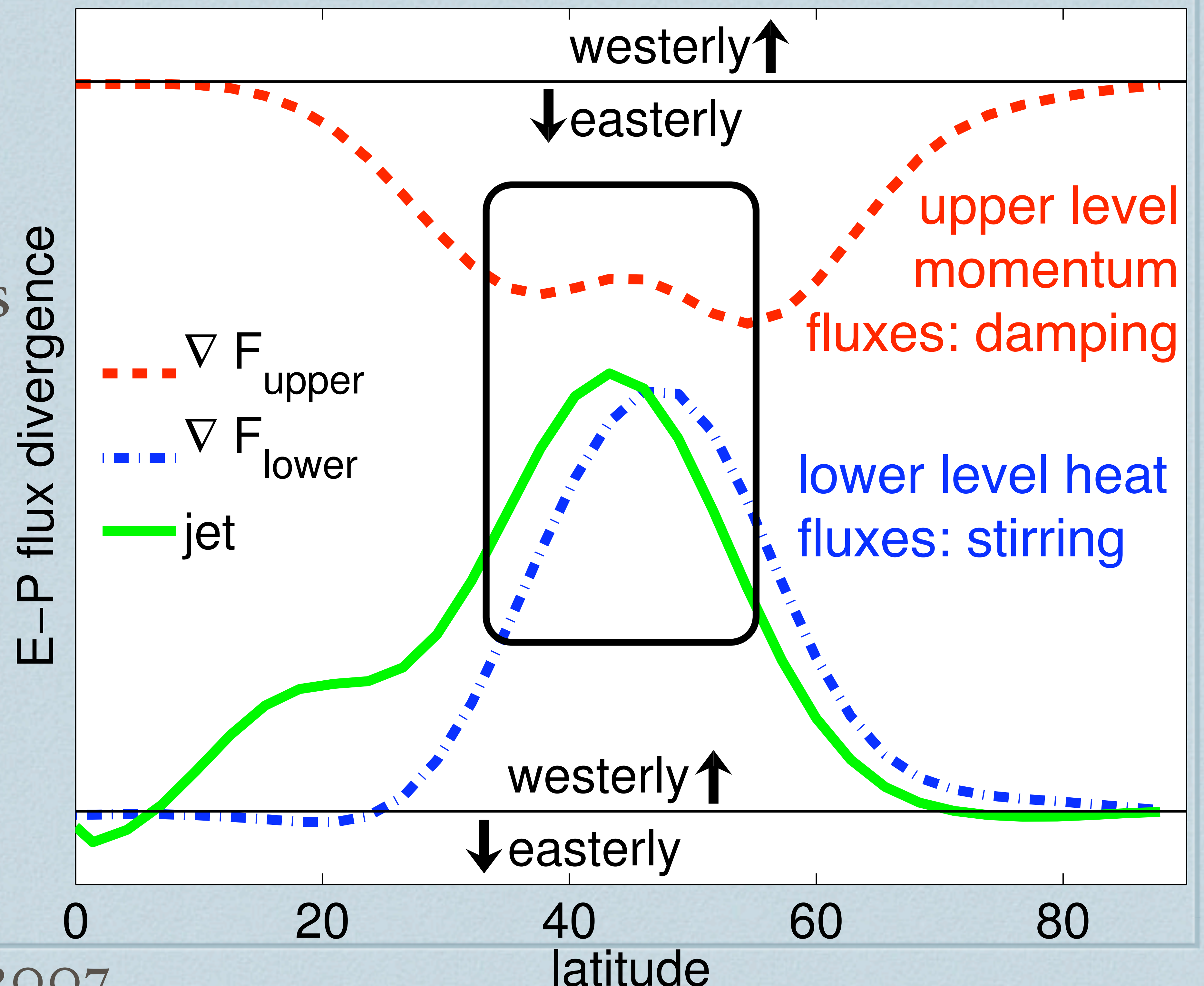
positive feedback btw jet and eddies

Net effect of feedback is new time scale τ_2

$$\frac{dz}{dt} = \dot{W} - \frac{z}{\tau_2}, \quad \tau_2 = (\tau^{-1} - b)^{-1}$$

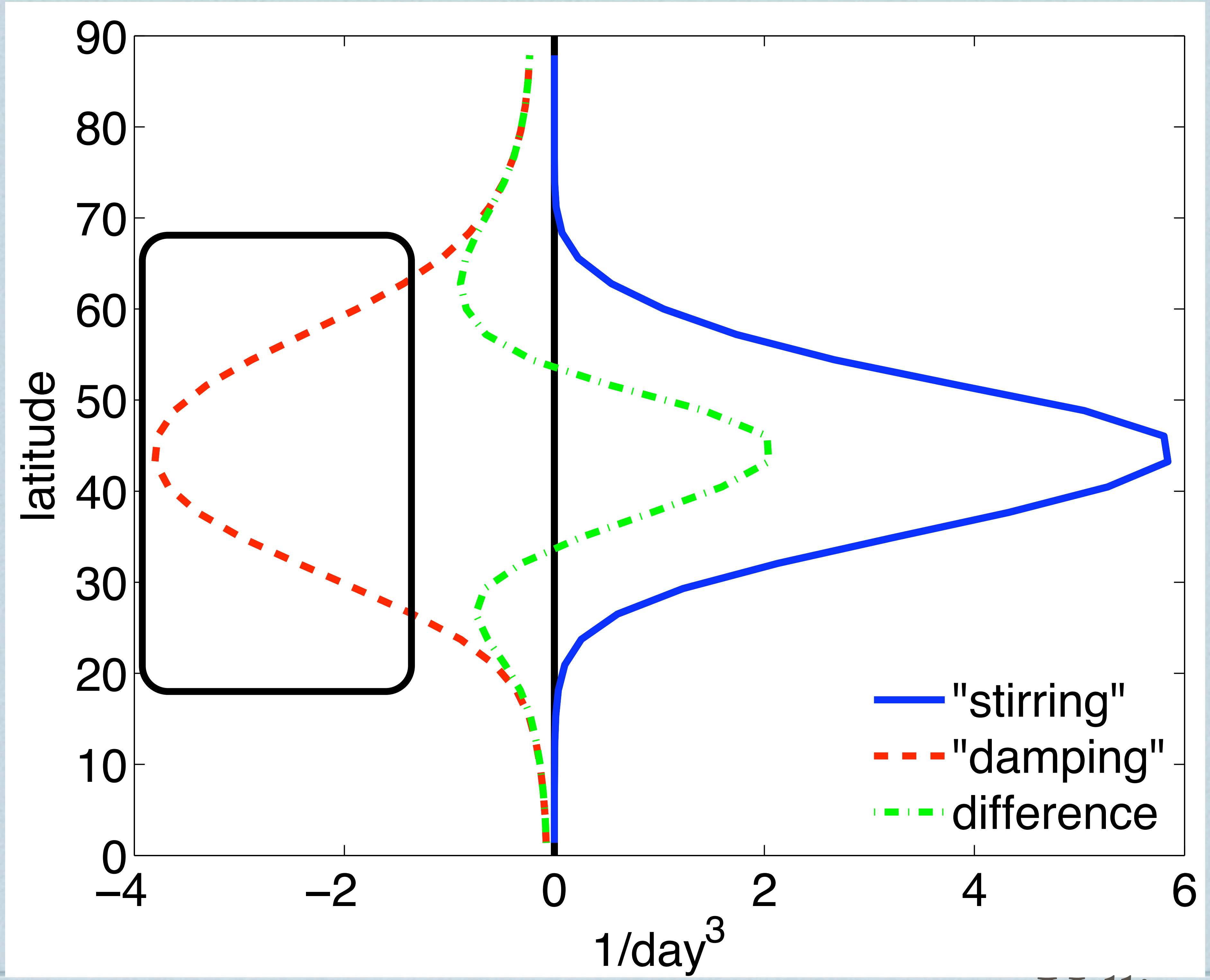
Schematic of the Feedback: "Self Maintaining jet" (Robinson 2006)

Key to feedback: upper level winds steer Rossby waves out of the jet core, thus maintaining the baroclinicity



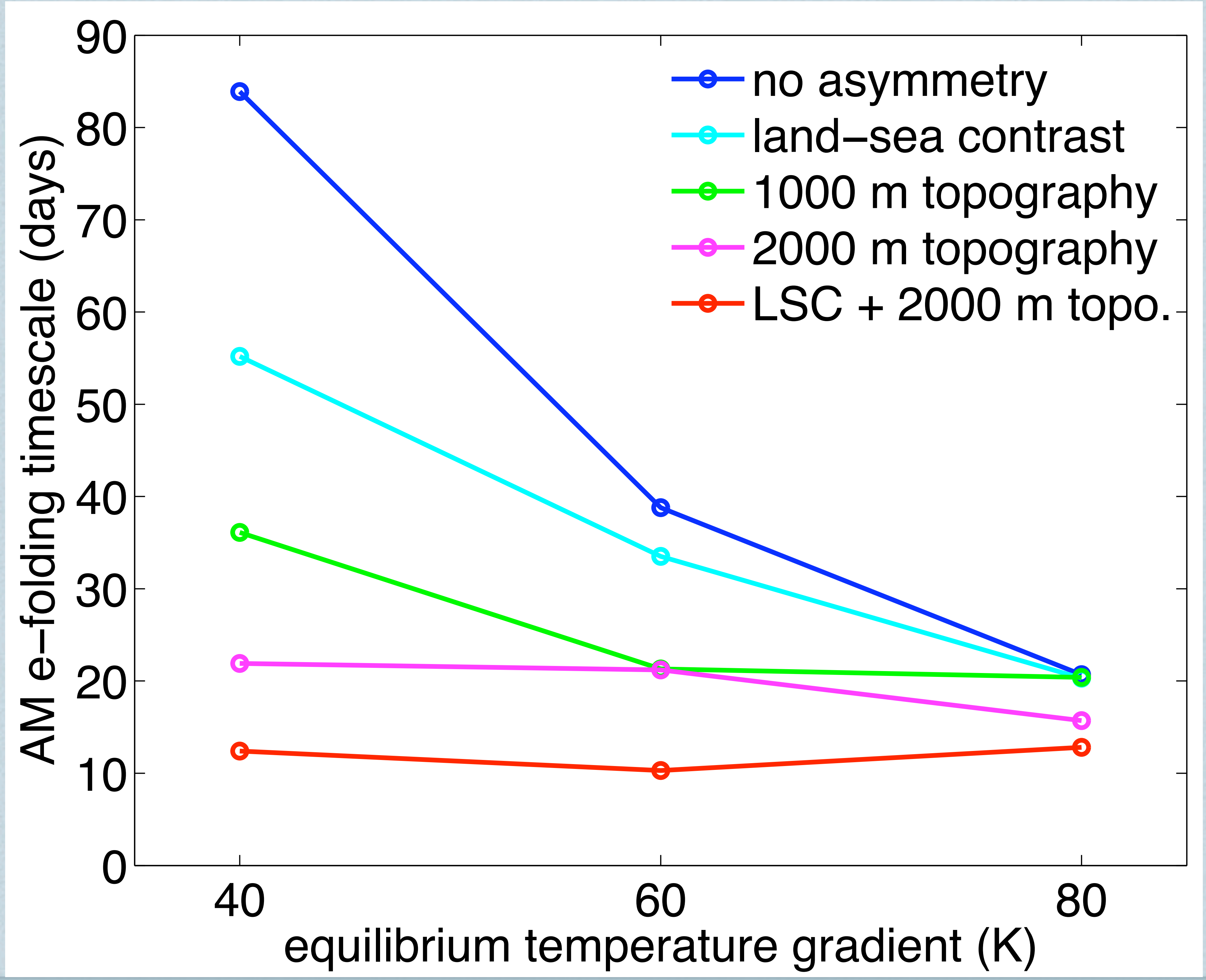
Gerber and Vallis 2007

Barotropic Vorticity Dynamics



Vallis et al. 2004

Zonal Asymmetries Eliminate Parameter Sensitivity (Destroy Feedbacks!)



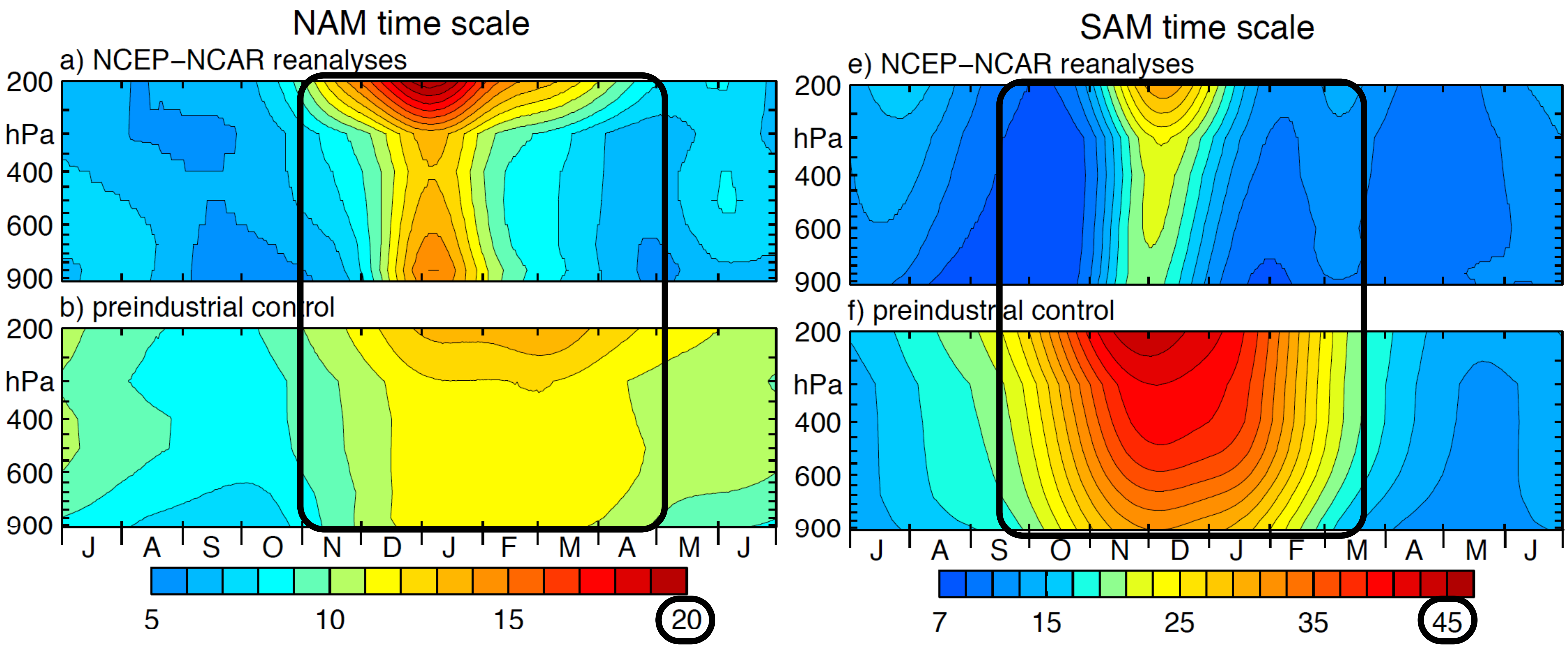
Gerber and Vallis 2007

How does this relate to the real atmosphere?

- Simple model time scales very sensitive to many things
- Zonal asymmetries (as found in “real” world) seem to take away these problems

Move to comprehensive climate models

IPCC AR4 Models: Ensemble Mean Performance

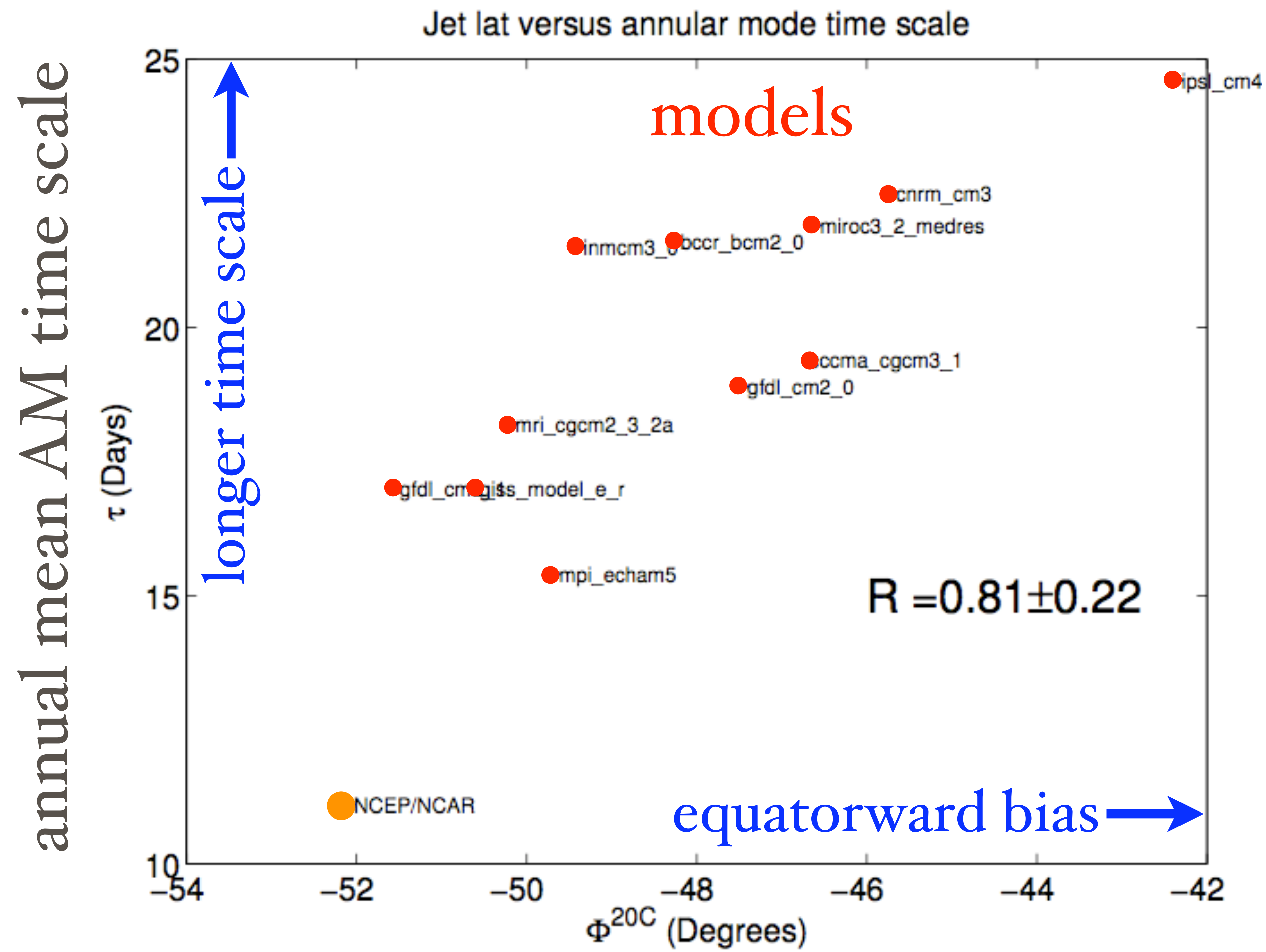


1) models have trouble with amplitude of SH time scales

2) models have trouble with sharpness of seasonal cycle

Gerber, Polvani, Ancukiewicz 2008

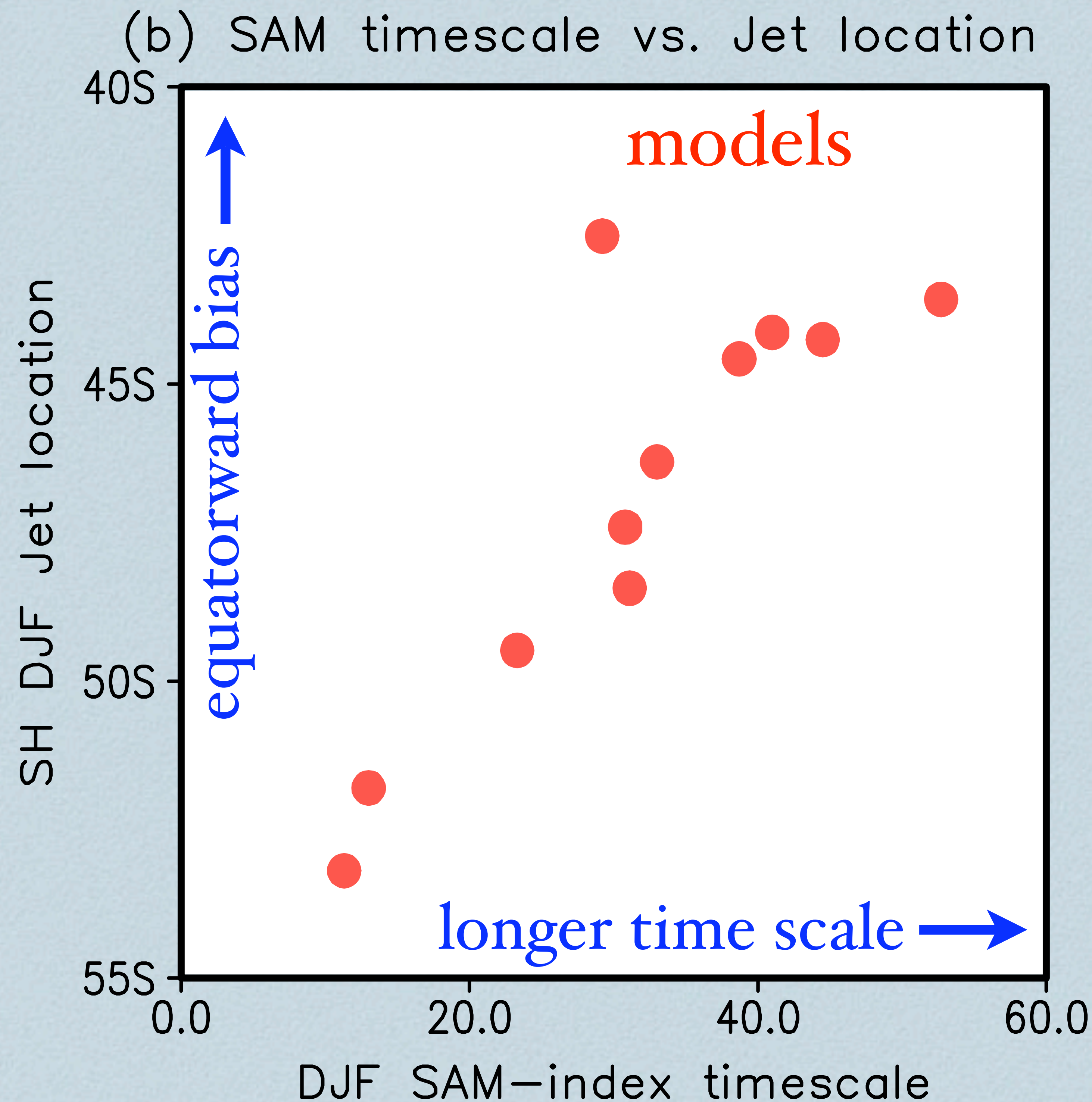
IPCC: Time scale - Jet lat. Connection



position of jet in 20th century control runs

Kidston and Gerber 2010

Chemistry Climate Models



(axes flipped)

Son et al. 2010

Why are SH time scales so hard to simulate?

- In idealized GCMs w/ little zonal asymmetry and full model integrations of SH, feedbacks can lead to long time scales and large biases in jet location. Very sensitive to resolution, forcing, numerics, ...
- Increased zonal asymmetries appear very effective at reducing time scales in models (and constraining the location of the jet)

How do Zonal Asymmetries Prevent Strong Feedbacks?

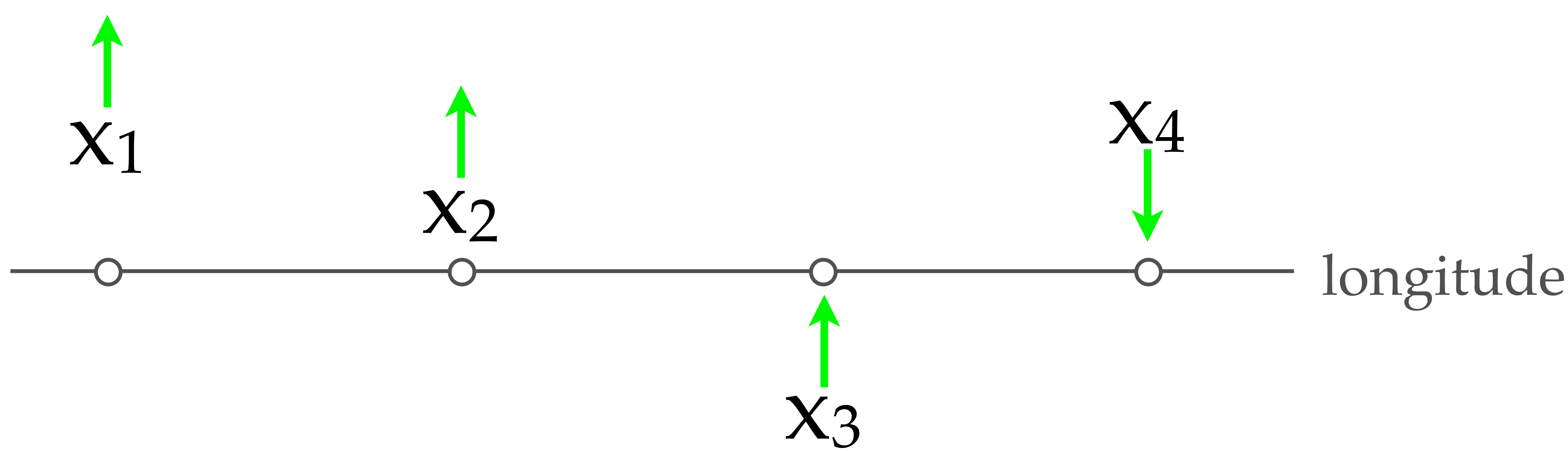
Let x_i, the state of the zonal flow at *i=1,...,n* representative longitudes, be determined by coupled stochastic oscillators. (Similar to Lorenz and Hartmann feedback, but spread in longitude.)

$$\frac{d}{dt}x_i = \dot{W}_i - \frac{x_i}{\tau} + b\,x_{i-1}$$

stochastic "eddy" forcing

linear damping

coupling with upstream flow



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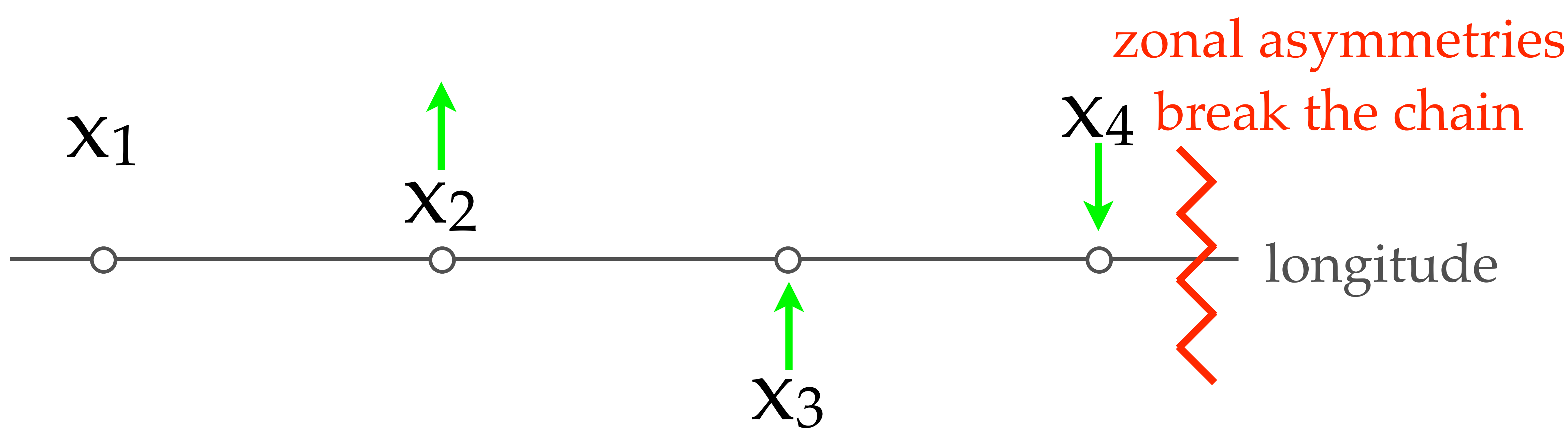


Time Scale of the Zonal Average

How does the short range feedback influence the "zonal average" signal?

$$z = \frac{1}{n}\sum_i x_i$$

In the zonally symmetric case, the spread of the interaction in longitude has no impact on the total persistence.

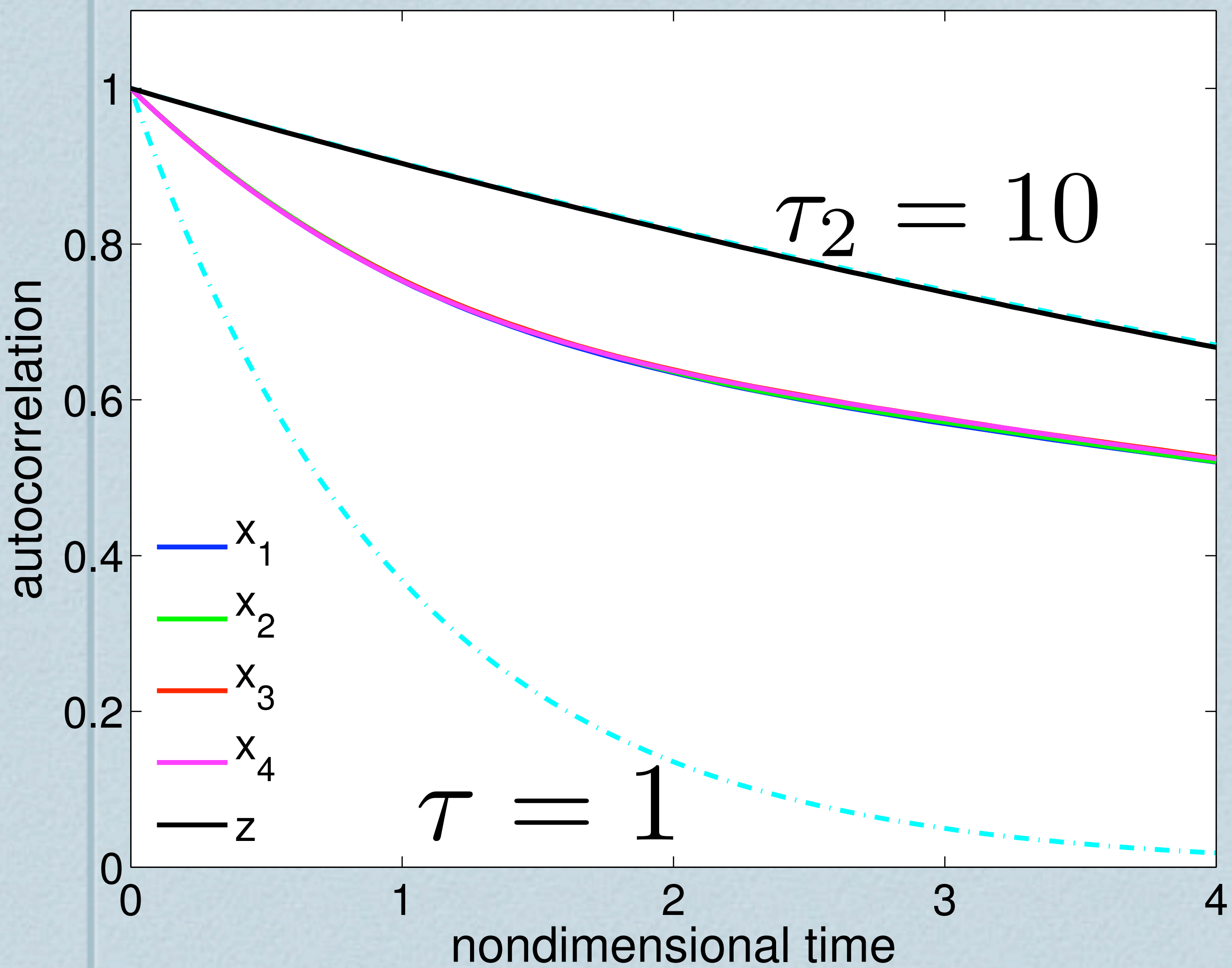
$$\frac{dz}{dt} = \frac{1}{\sqrt{n}}\dot{W} - \frac{z}{\tau} + b\,z$$
$$= \frac{1}{\sqrt{n}}\dot{W} - \frac{z}{\tau_2}$$

$$\tau_2 = (\tau^{-1} - b)^{-1}$$

What happens when the interaction is broken at one link? Simulations with n=4, $\tau = 1$, $\tau_2 = 10$.

Simulation Without Break
(verify the analytic result)

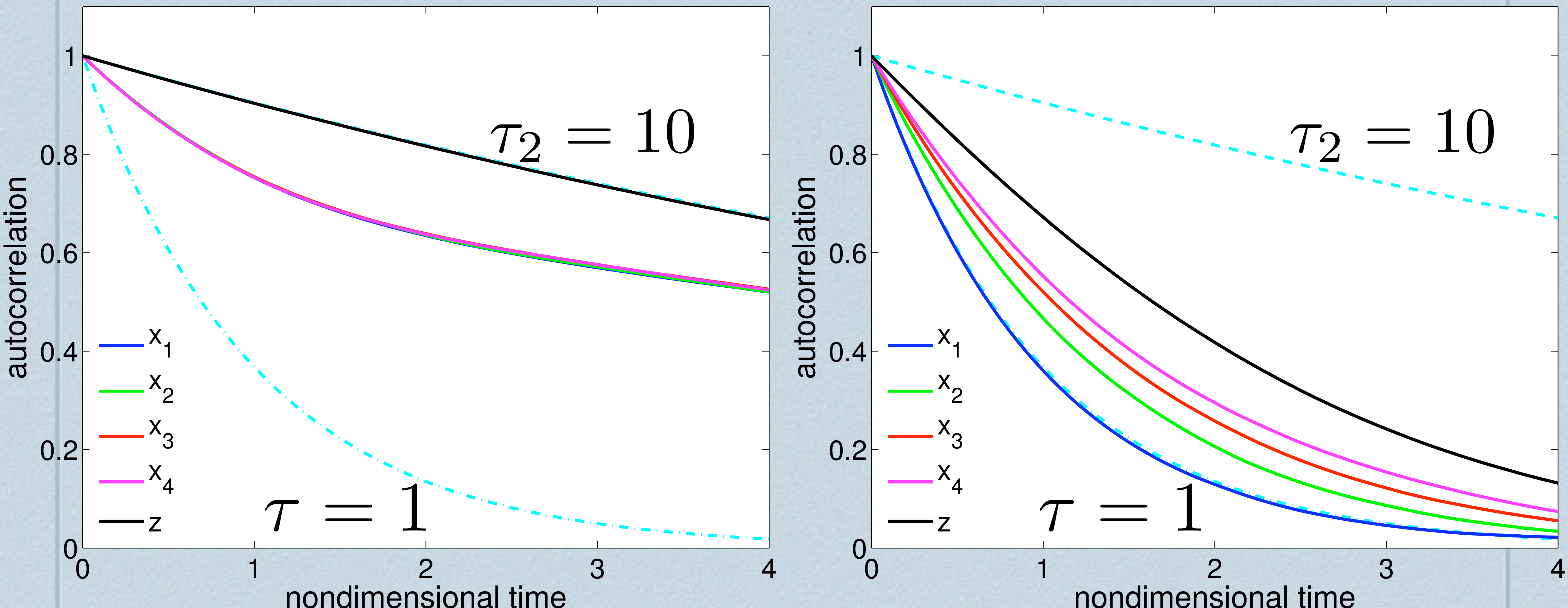
zonally symmetric model:
unbroken chain



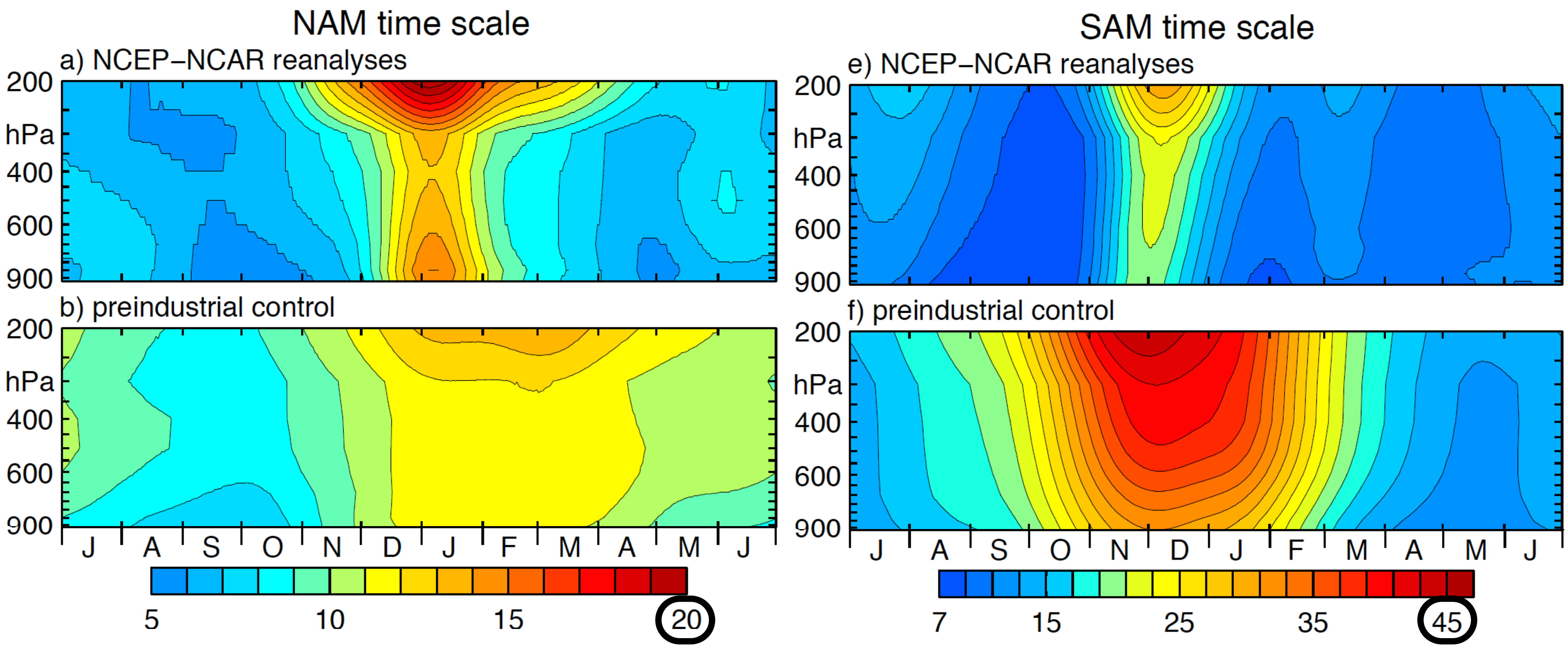
Break in Chain Kills Feedback

zonally symmetric model: unbroken chain

no interaction between x_4 and x_1: broken chain

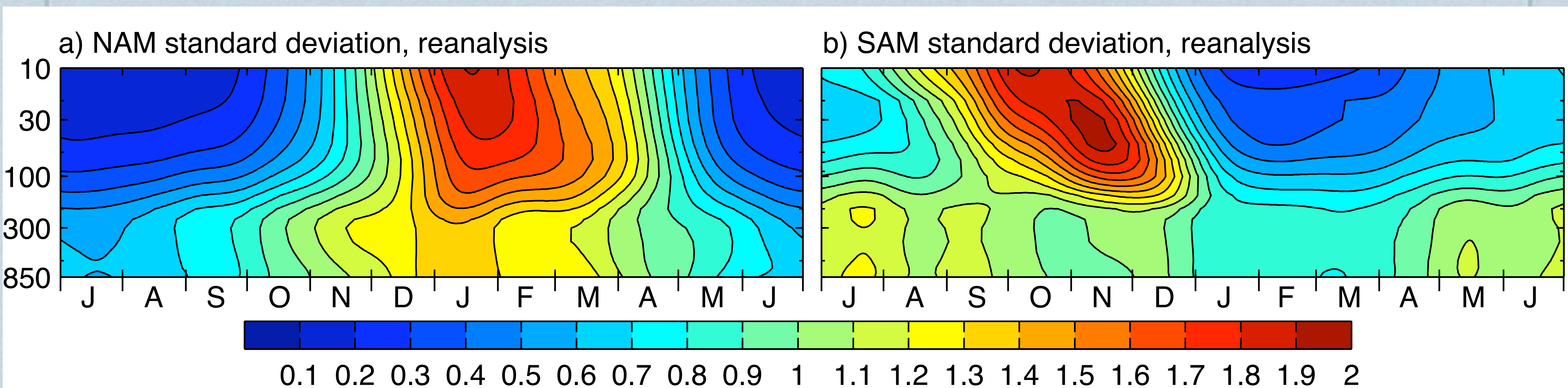


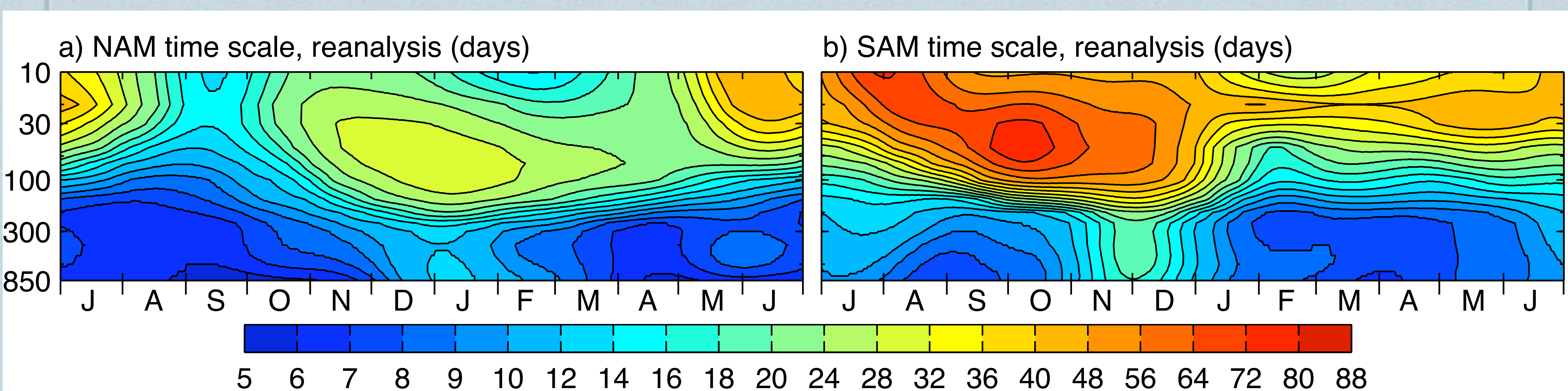
SH Much Harder to Simulate due to Potential for Positive Feedbacks



Gerber, Polvani, Ancukiewicz 2008

(2) Seasonal Cycle: Stratospheric Variability and Tropospheric Persistence

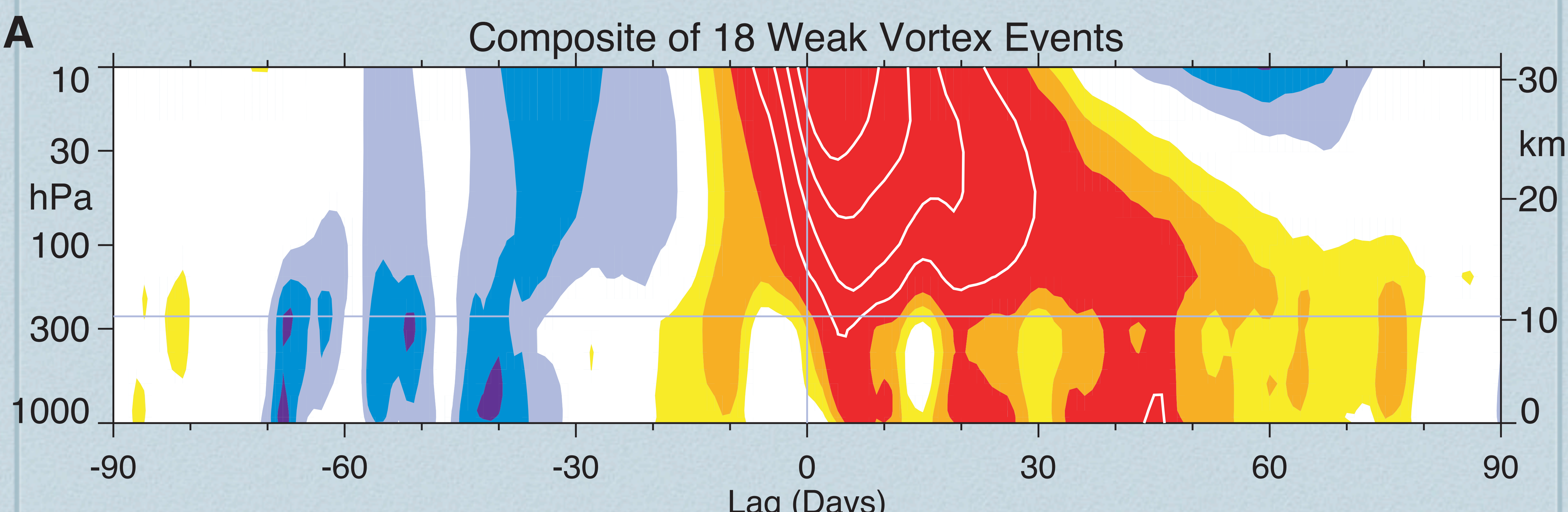




Baldwin et al. 2003, Gerber et al. 2010

Downward influence from Stratosphere

composite of AM index formed about instances
when the stratospheric vortex is very weak - negative AM
(Stratospheric Sudden Warmings)



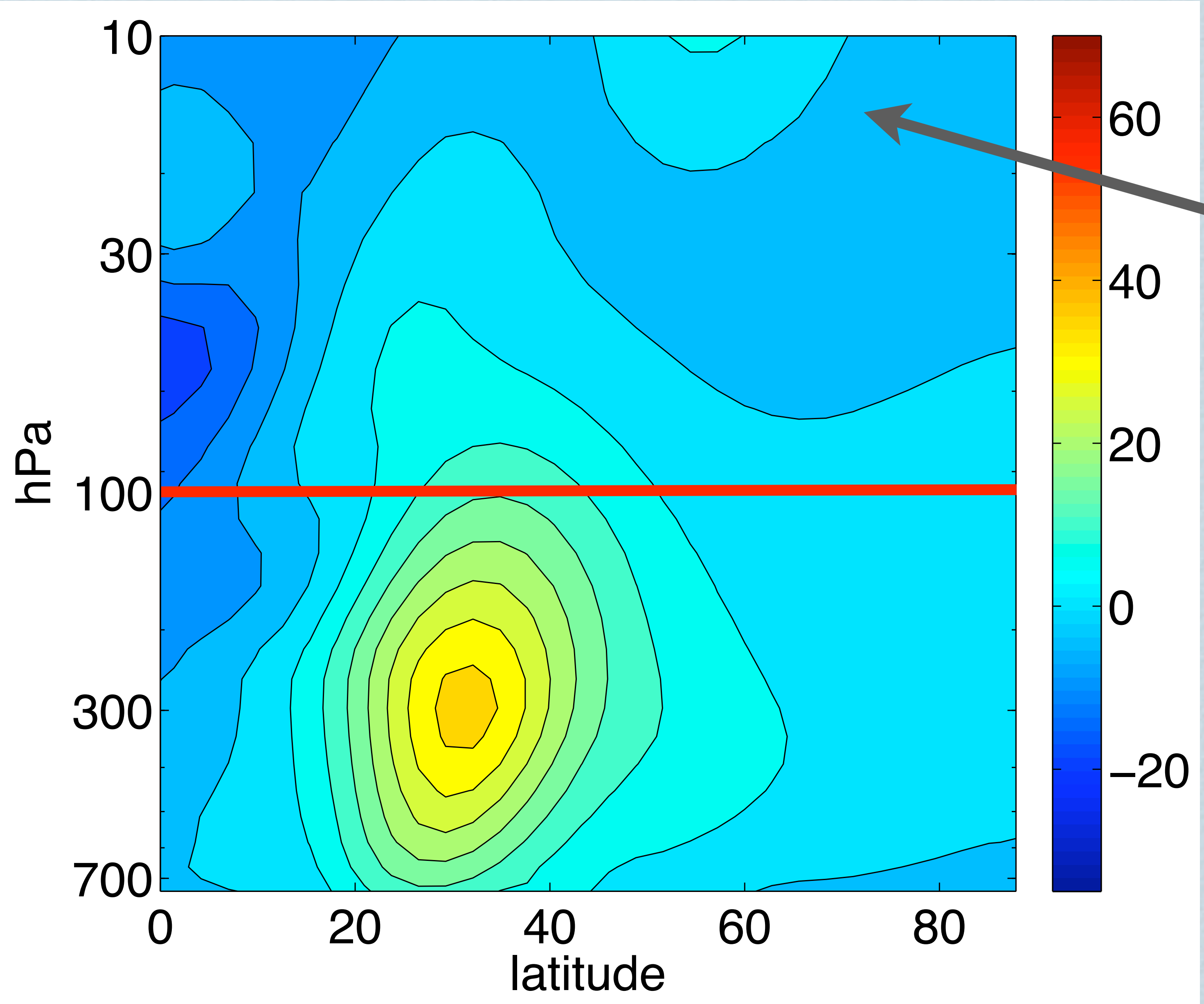
Baldwin and Dunkerton. 2002

Clean test: Vary only the Stratosphere

- Gerber and Polvani (2009) idealized GCM
  - forced by Polvani and Kushner 2002 forcing (Held Suarez troposphere + a stratospheric polar vortex)
  - includes simple wavenumber 2 topography (needed to produce stratospheric variability)
  - Experiment: compare time slice runs where only the stratospheric vortex is varied

Impact of Seasonal Variations of Stratosphere Alone

γ =0: no vortex (summer-ish)



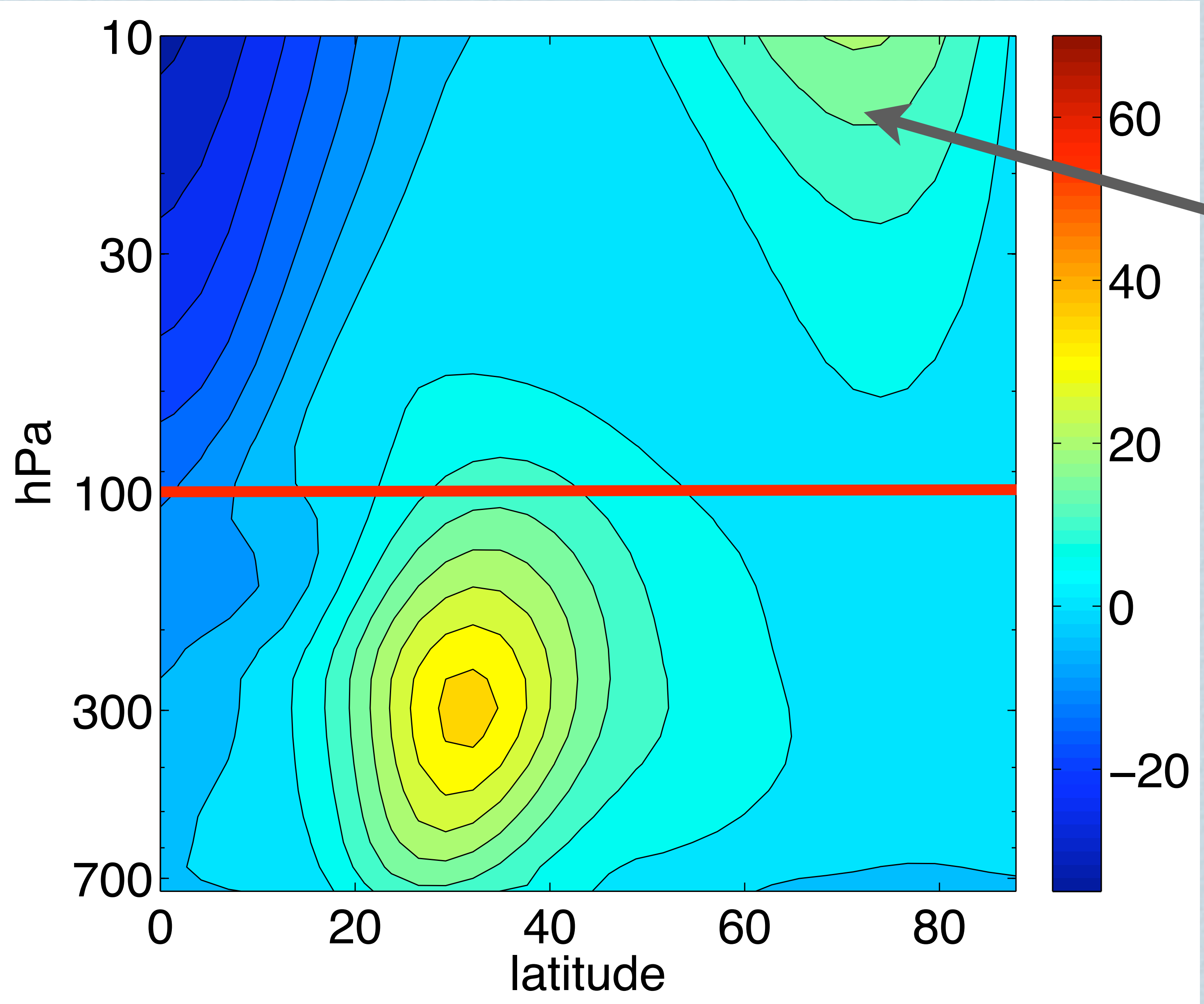
vary strength of polar vortex

tropospheric forcing unchanged

Gerber and Polvani 2009

Impact of Seasonal Variations of Stratosphere Alone

γ =2: weak vortex (fall)



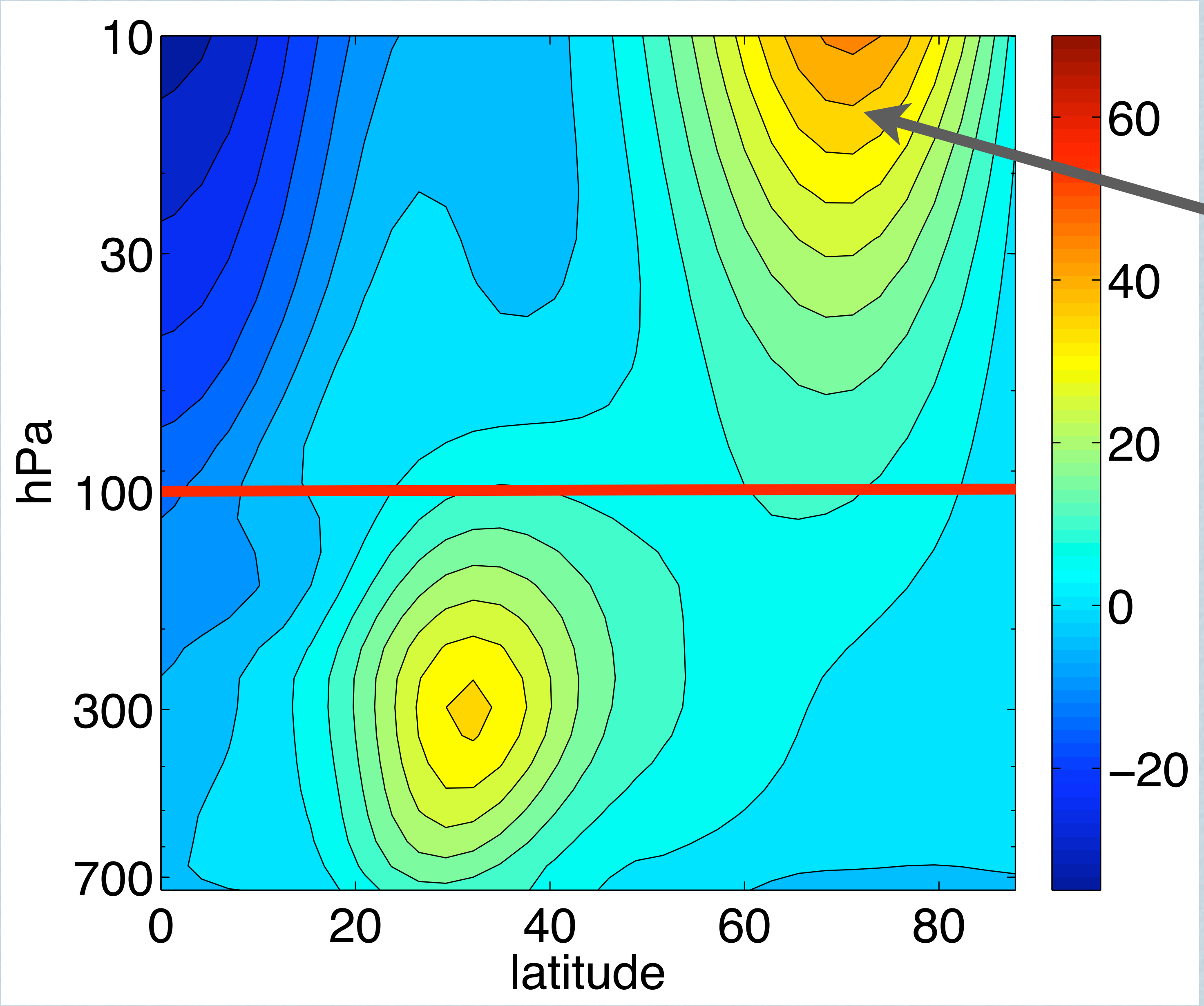
vary strength of polar vortex

tropospheric forcing unchanged

Gerber and Polvani 2009

Impact of Seasonal Variations of Stratosphere Alone

γ =4: medium vortex (early winter)



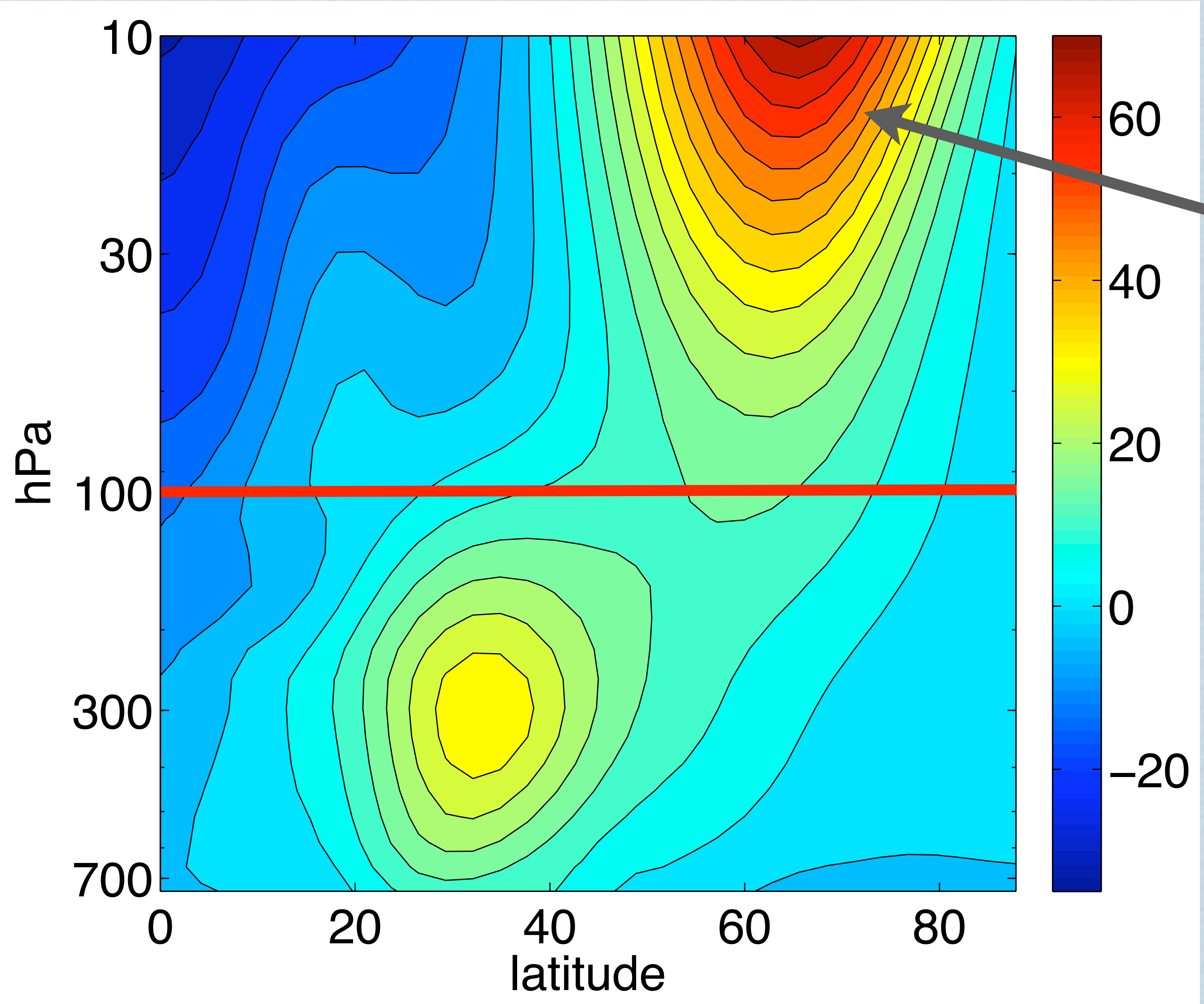
vary strength of polar vortex

tropospheric forcing unchanged

Gerber and Polvani 2009

Impact of Seasonal Variations of Stratosphere Alone

γ =6: strong vortex (deep winter)

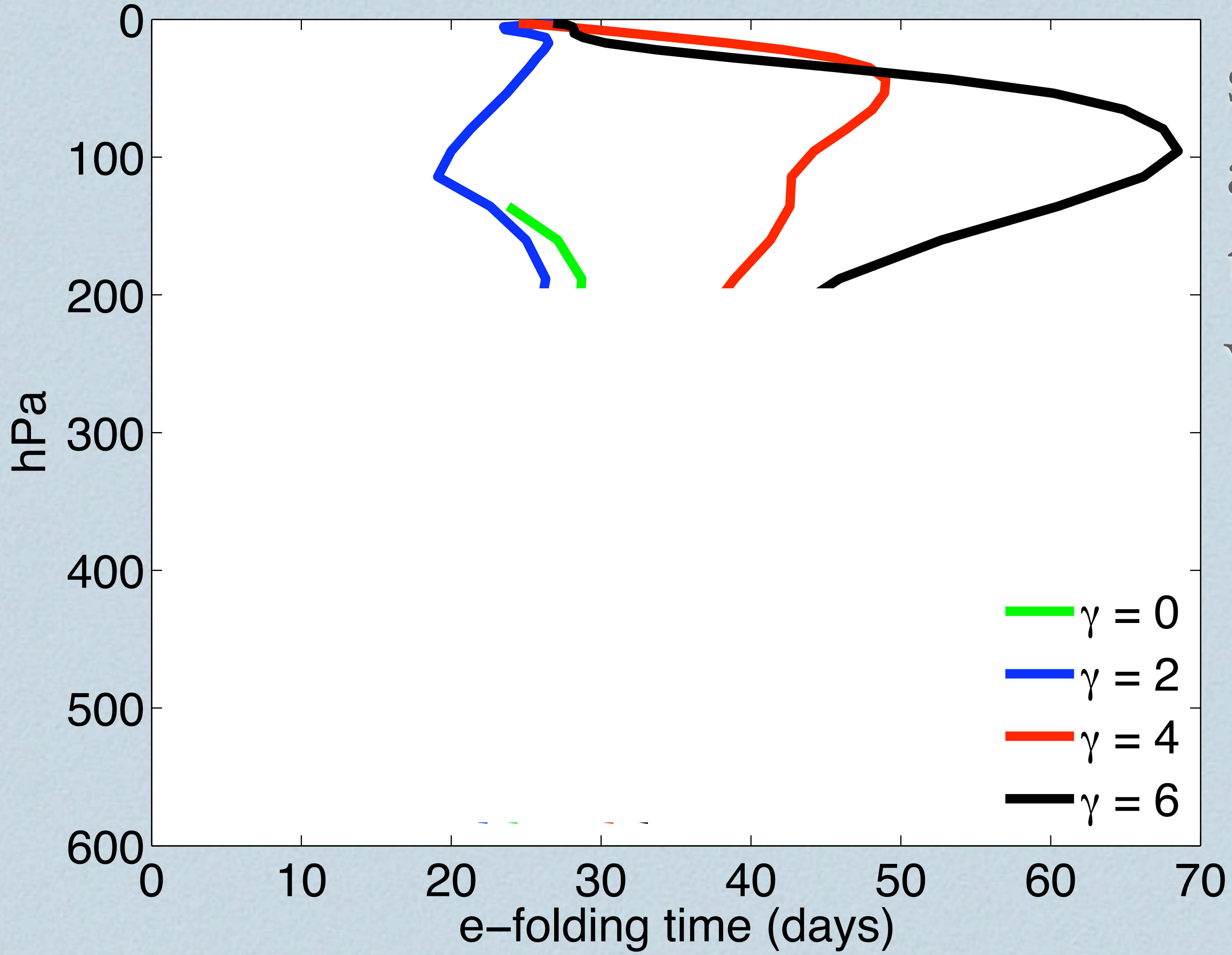


vary strength of polar vortex

tropospheric forcing unchanged

Gerber and Polvani 2009

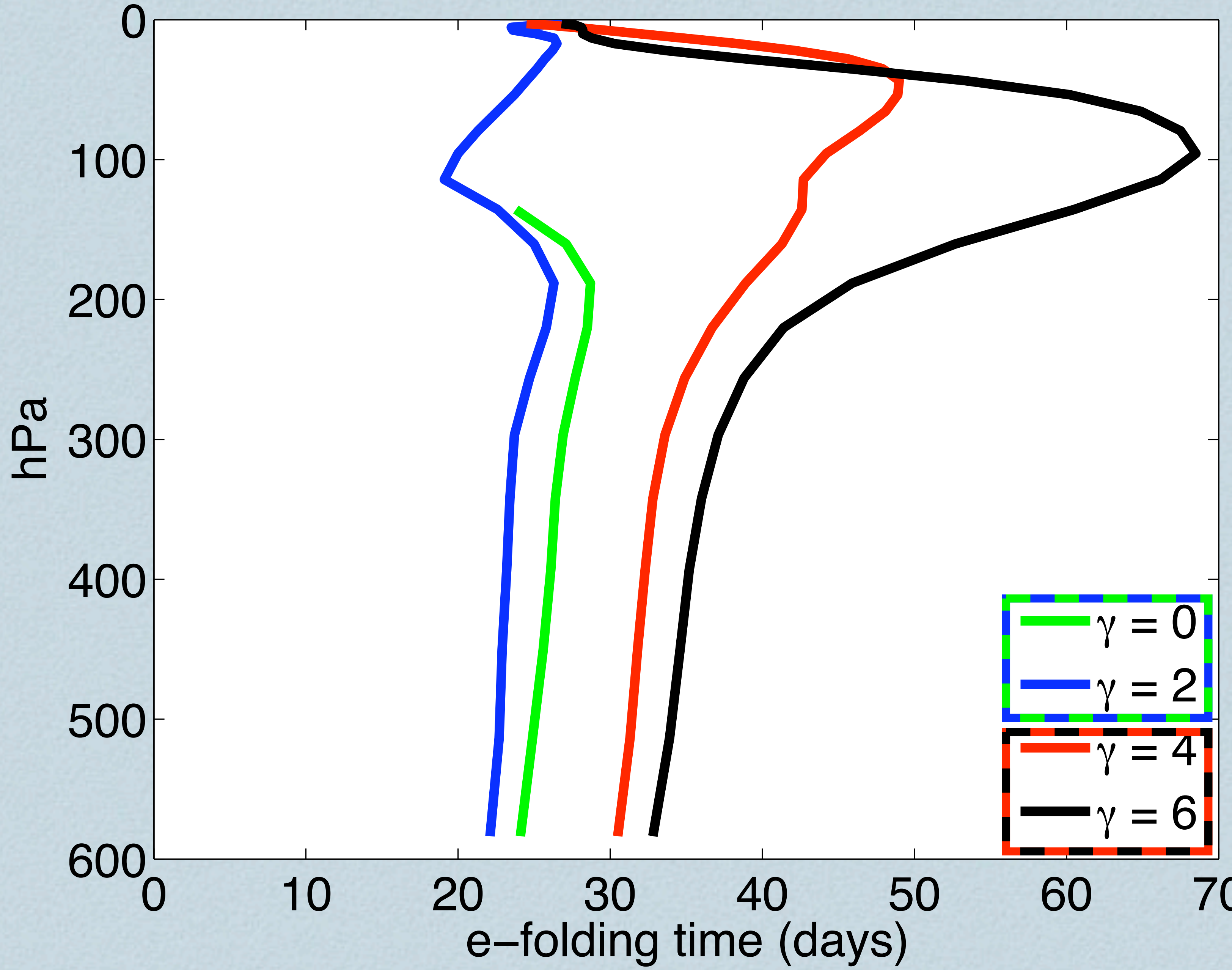
Stratosphere-Troposphere Coupling Enhances Tropospheric Persistence



stratosphere is active only when there are sufficient westerly winds

Gerber and Polvani 2009

Stratosphere-Troposphere Coupling Enhances Tropospheric Persistence



lower stratosphere provides extended memory to troposphere

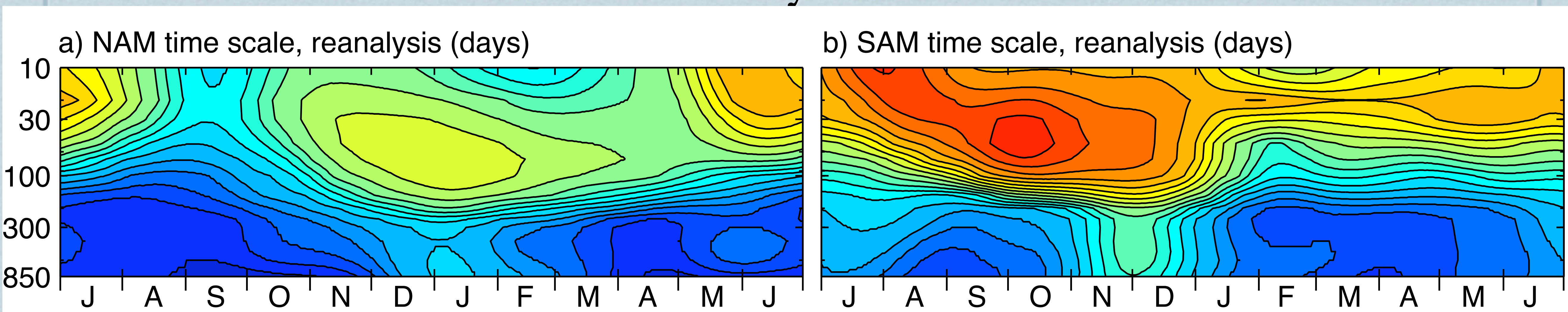
passive strat.

active strat.

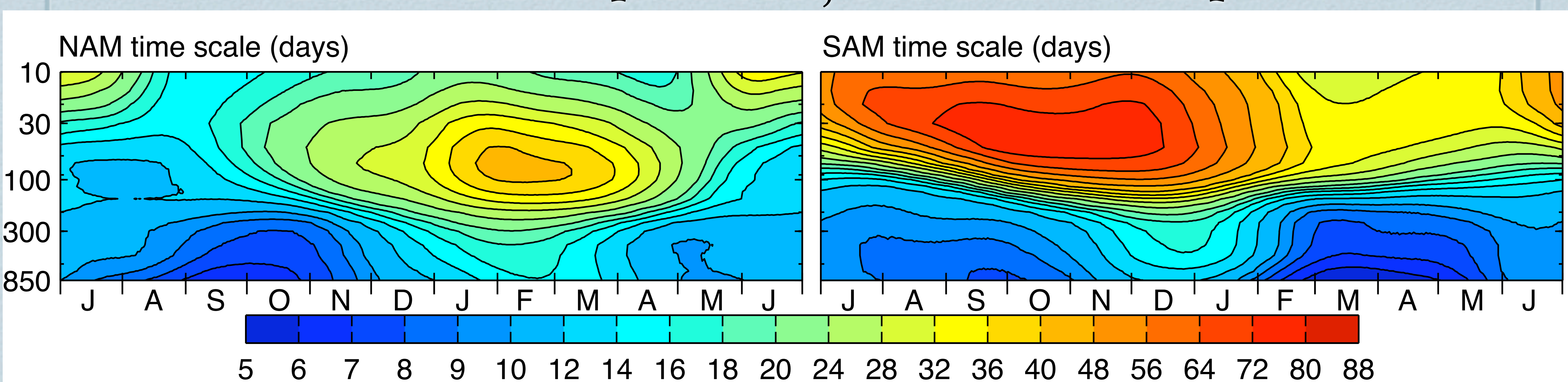
Gerber and Polvani 2009

(Some) Chemistry Climate Models capture tighter seasonal structure!

Reanalyses



GEOSCCM [Pawson, Stolarski et al.]



Gerber et al. 2010

(3) Internal Variability - Climate Response Connection

- Fluctuation-dissipation theory relates connects the response of a system to external forcing with the time scales of its internal, unforced variability
- Proper application requires knowledge of correlations between all modes of variability to compute the proper response operator (Gritsun and Branstator 2008, Majda et al. 2010)
- If climate modes are roughly uncorrelated with others, autocorrelation function may provide rough estimate (Leith 1975)

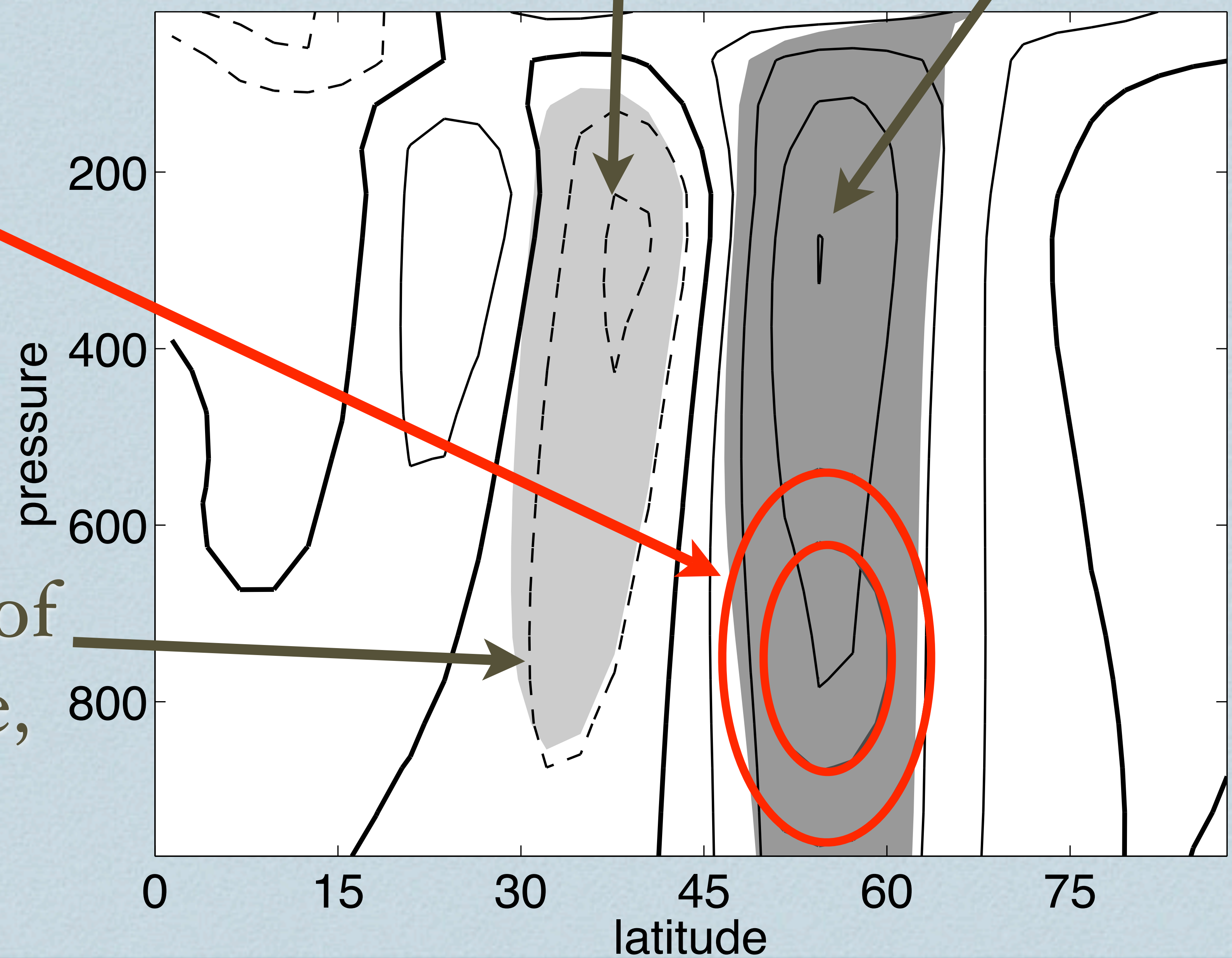
Experiment with Idealized GCM (Held-Suarez)

- Consider two models with very different AM time scales: 33 days versus 96 days
- Apply torque the projects well onto the AM pattern (Ring and Plumb 2008)
- Compare model response (shift in jet stream): F-D suggests that model with longer time scales will be more sensitive to the the torque.

Response of Annular mode to External Forcing (Torque)

shading: first EOF of u from control integration, negative and positive

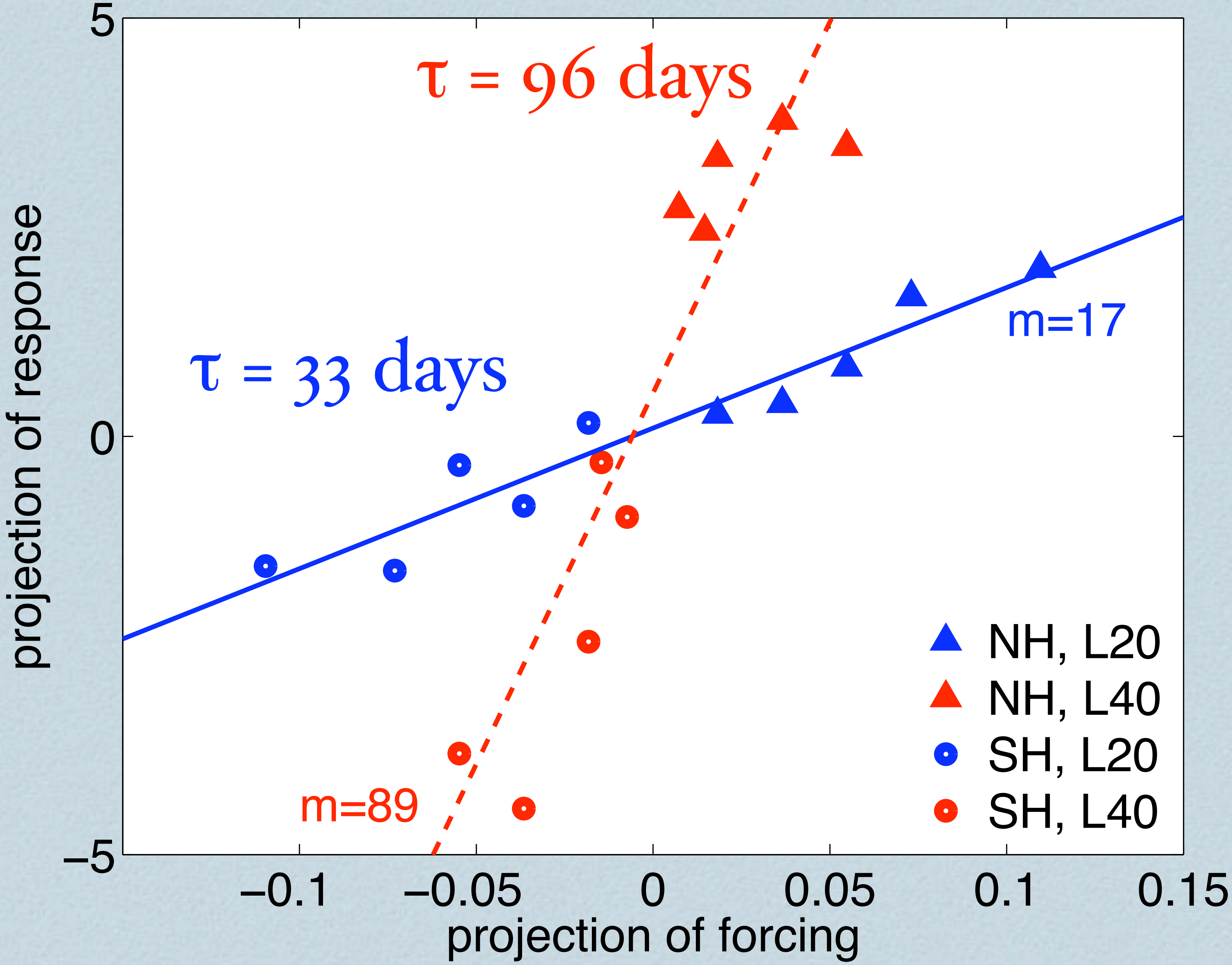
apply a torque that projects onto the EOF



contours: response of model to the torque, $\bar{u}_{forced} - \bar{u}_{control}$ (negative dashed)

after Ring and Plumb 2008

Model with longer time scale more sensitive to external

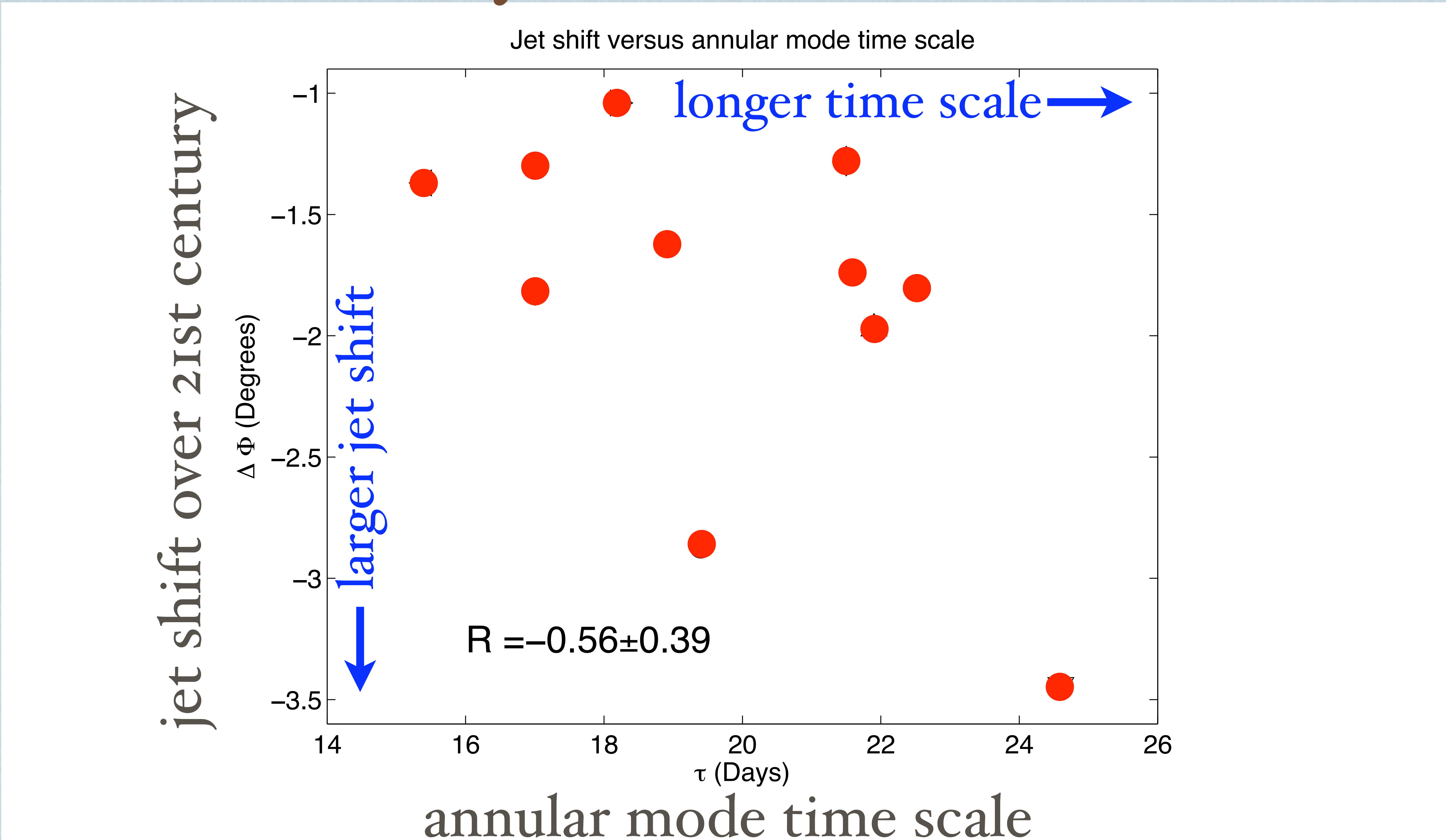


Gerber, Voronin, and Polvani 2008

Comprehensive GCMs

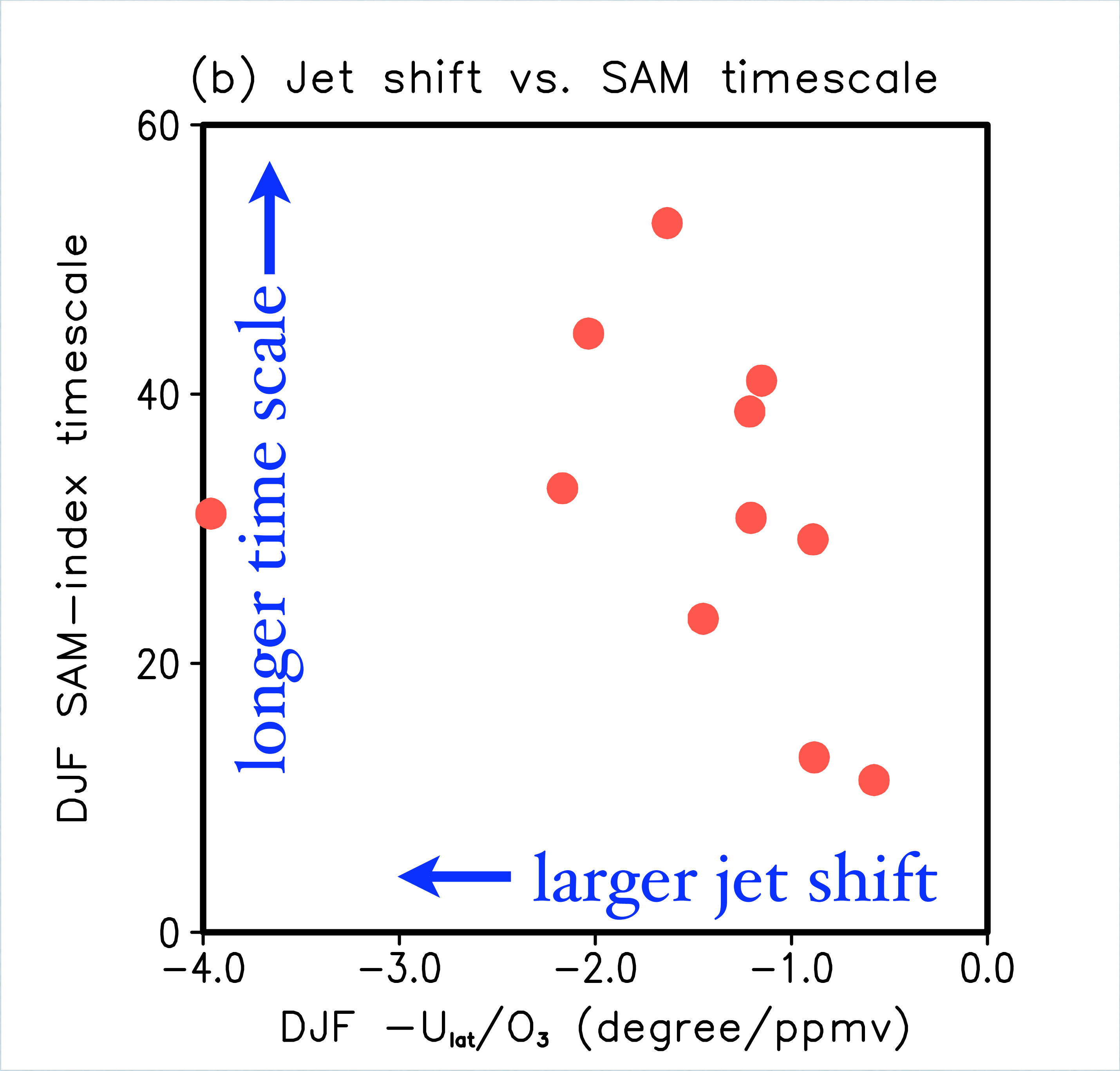
- IPCC model time scales vary by a factor of 2, CCM model time scales vary by factor of 4
- If projection of anthropogenic forcing in the A2 / REF-B2 scenarios models is roughly the same, one might expect models with longer time scales to exhibit a larger response.

IPCC Model Climate Response Sensitivity to AM Time Scale



Kidston and Gerber 2010

CCM Climate Response Sensitivity to AM Time Scale



(axes flipped)

Son et al. 2010

Conclusions

- Simplified models help us understand the key features of annular mode variability
  - zonal mean variability is integral of eddy forcing: hence increased power on lower frequencies
  - eddy-mean flow feedbacks create distinct time scale
- zonal asymmetries (e.g. topography) shorten time scales: variability in NH is less persistent than SH
- stratosphere increases persistence of tropospheric variability during active seasons (NH winter, SH spring)
- SH harder to simulate (stronger eddy-mean flow feedbacks)
  - biases in mean state: equatorward jet ⇔ long time scales
  - climate change: long time scales ⇔ enhanced response to anthropogenic forcing

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