Annular Modes and the Role of the Stratosphere

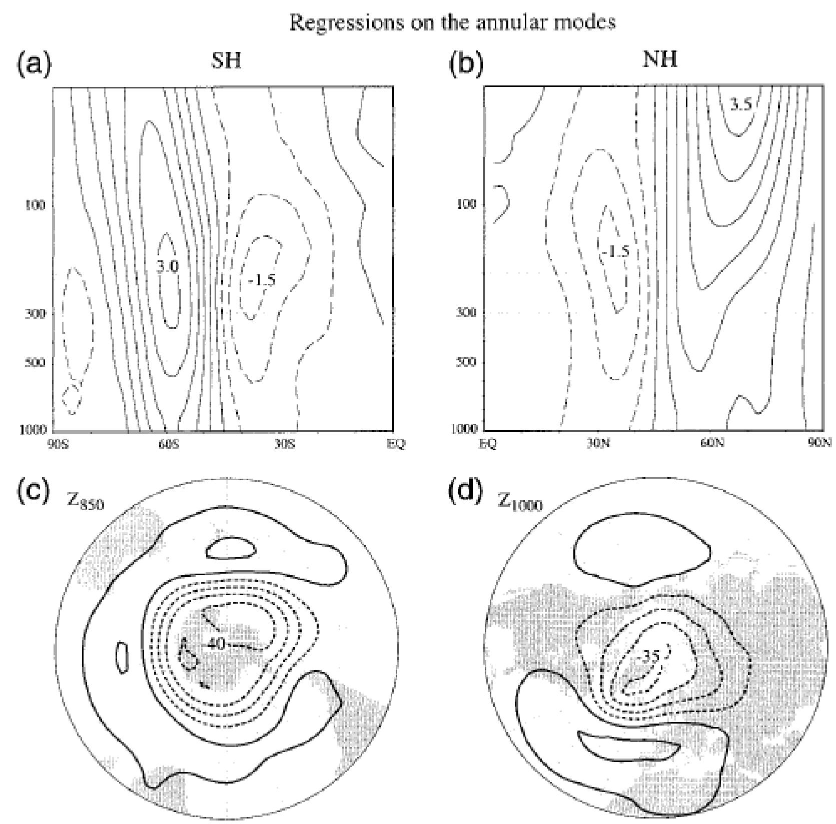
Alan Plumb

(+ Mike Ring, Cegeon Chan, Gang Chen & Daniela Domeisen)

M. I. T.

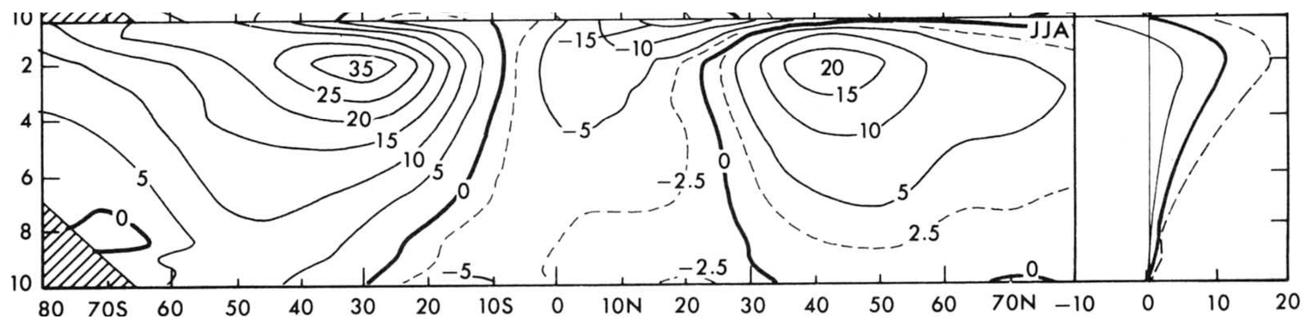
Annular Modes

- Leading patterns of variability in extratropics of each hemisphere (EOFs: leading eigenvectors of covariance matrix)
- Strongest in winter but visible year-round in troposphere; present in stratosphere during “active seasons”

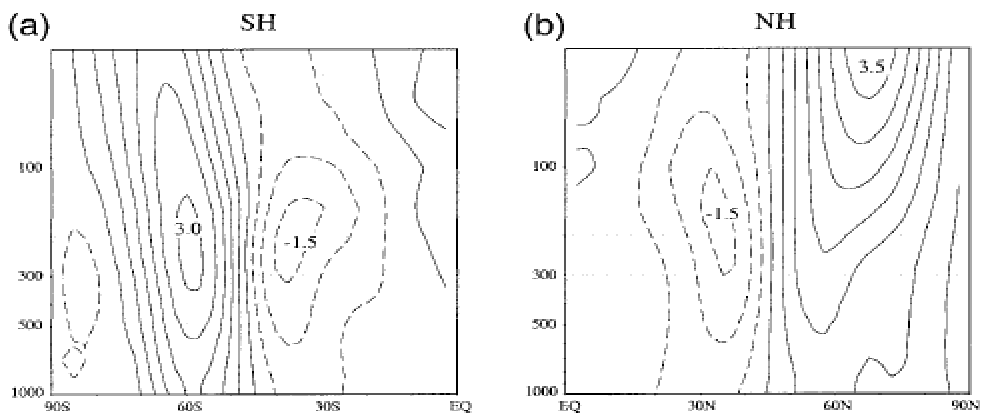


[Thompson and Wallace, 2000]

U, JJA



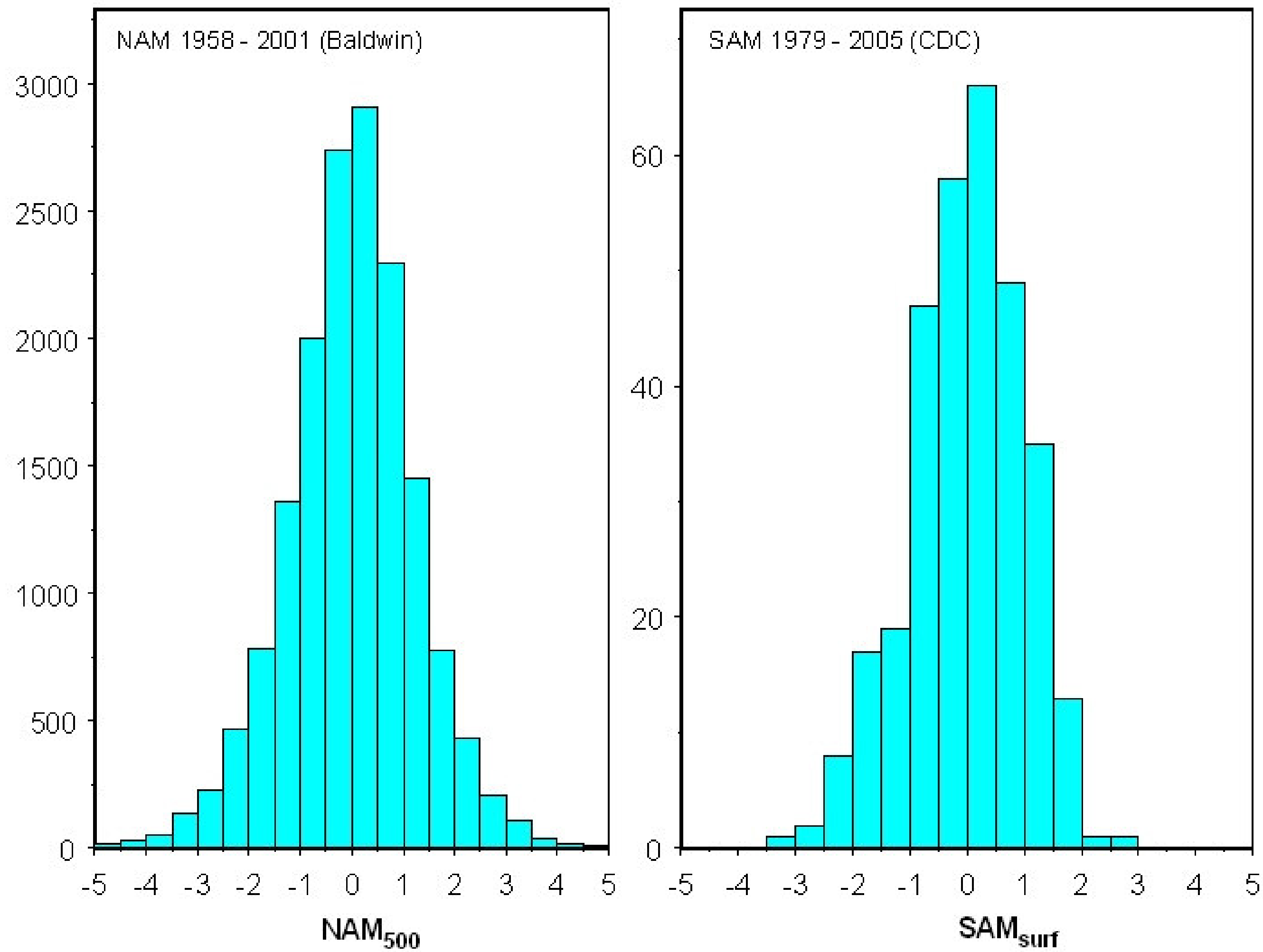
Regressions on the annular modes



$$\phi_{AM}(\lambda, \varphi, z, t) = P_{AM}(t)\, E_{AM}(\lambda, \varphi, t)$$

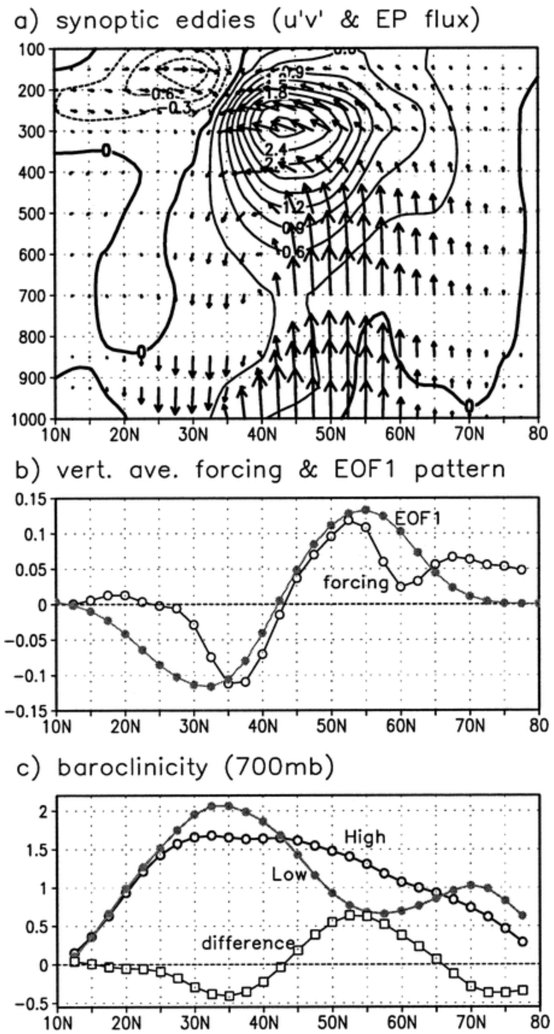
AM index   AM structure

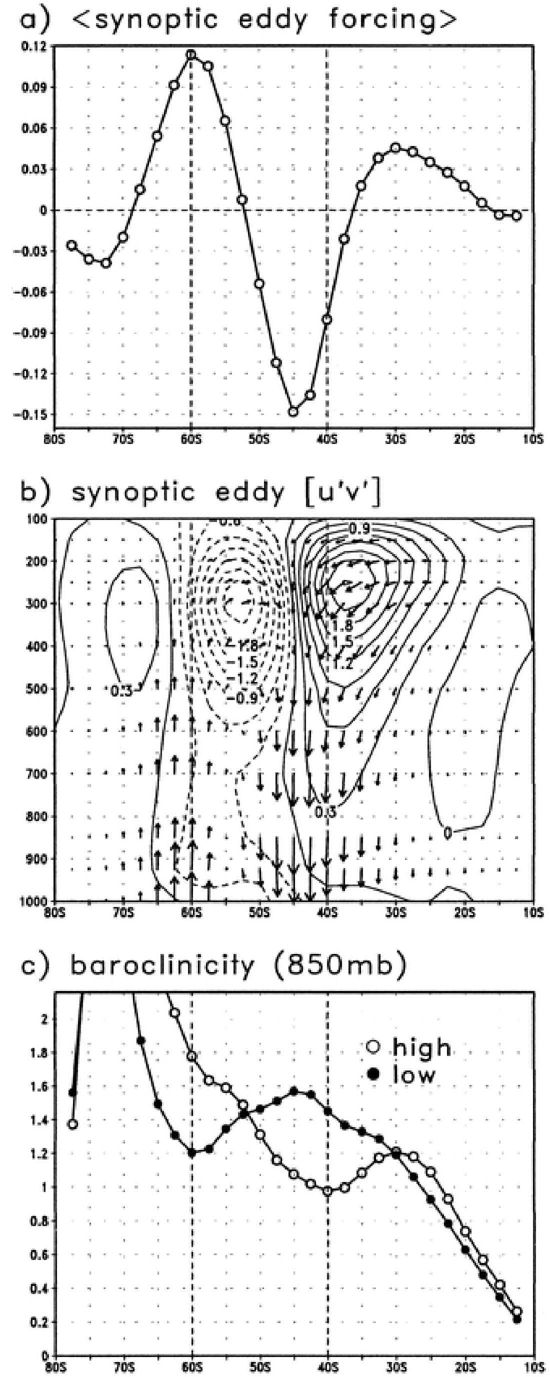
Northern/southern annular mode indices: distribution



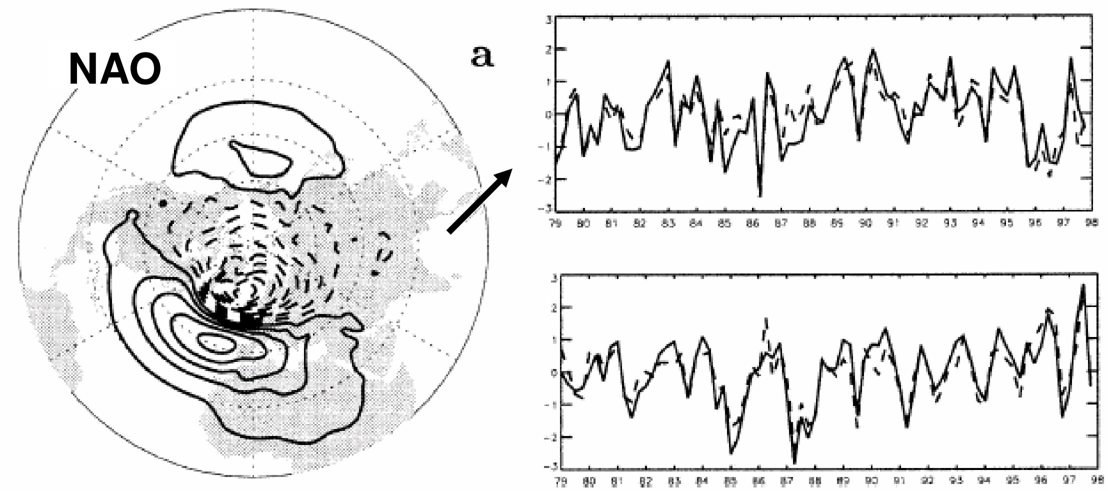
Eddy fluxes drive the mean flow changes

[Lorenz & Hartmann, *J. Atmos. Sci* (2001); *J. Clim* (2003)]





surface



500 K

FIG. 2. (a) First principal component of Atlantic sector mean sea level pressure, with contour interval 1 hPa (. . . , −0.5, 0.5, 1.5, . . .). It explains 48% of the variance over the Atlantic sector and 24% over the full hemisphere. The solid line in the graph is its standardized time series, the NAO index, and the dashed line is the NAO_t index. (b) First principal component of the potential vorticity at the θ = 500 K isentropic surface, with contour interval 1 PVU. It explains 34% of the variance. The solid line in the graph is its standardized time series, the PV500 index, and the dashed line is the $PV500_s$ index.

Impact of stratosphere during winter?

Ambaum & Hoskins (2002)

$\tau_{NAO} \sim$ *10 d.*

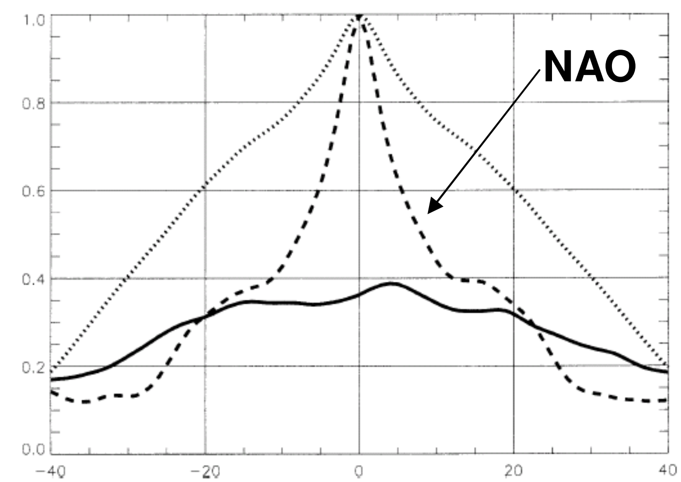
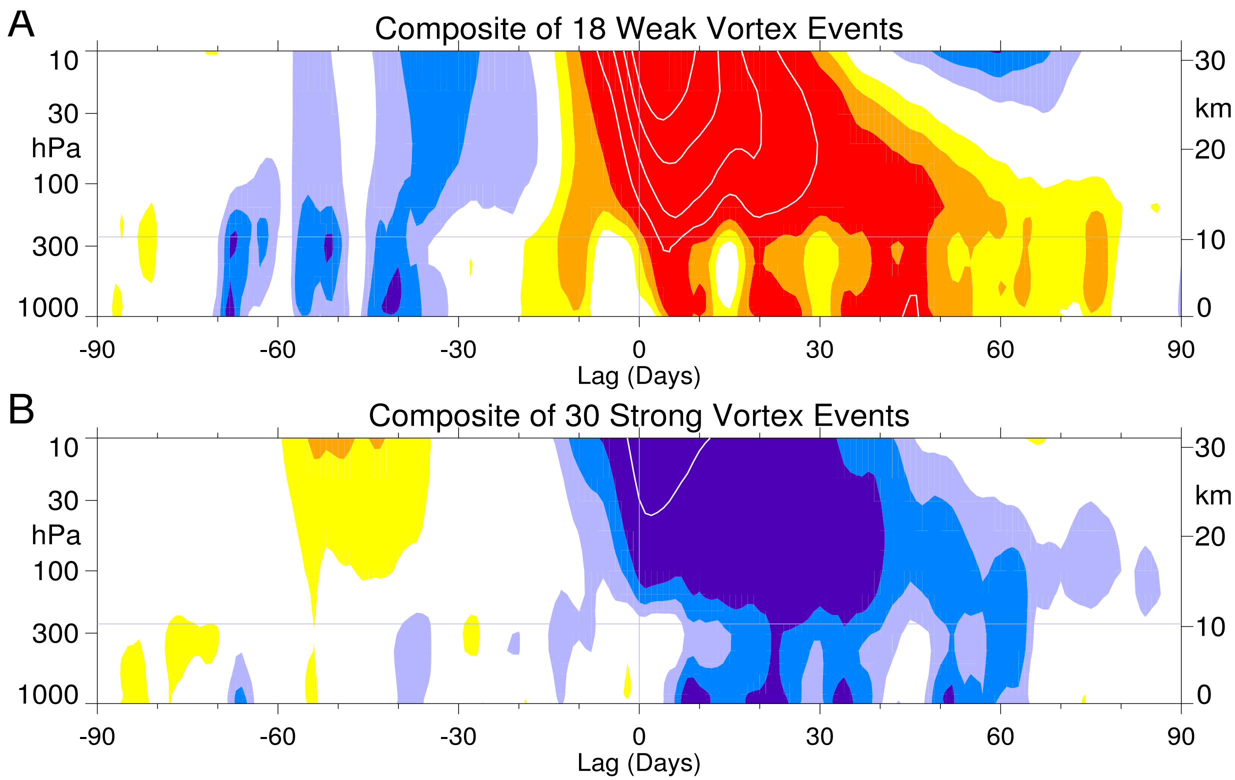


FIG. 7. (solid) Correlation between the daily NAO and PV500 indices as a function of the lag (in days). Positive lag means NAO leading PV500. (dashed) Lagged autocorrelation for the daily NAO index. (dotted) Lagged autocorrelation for the daily PV500 index.

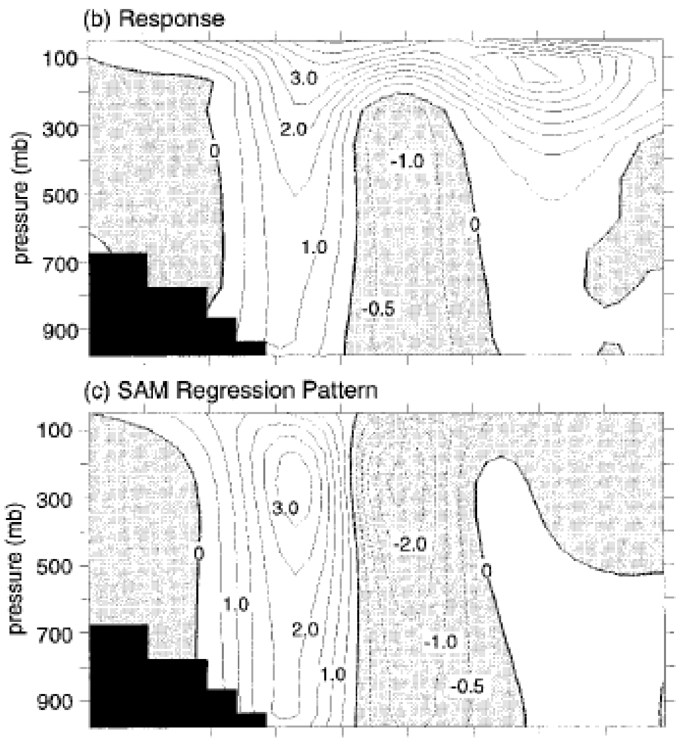
Projection onto annular mode index at each height:

Composites with respect to 10 hPa



[Baldwin & Dunkerton, *Science,* 2001]

Climate forcings and annular modes



GCM response to global warming [Kushner et al., 2001]

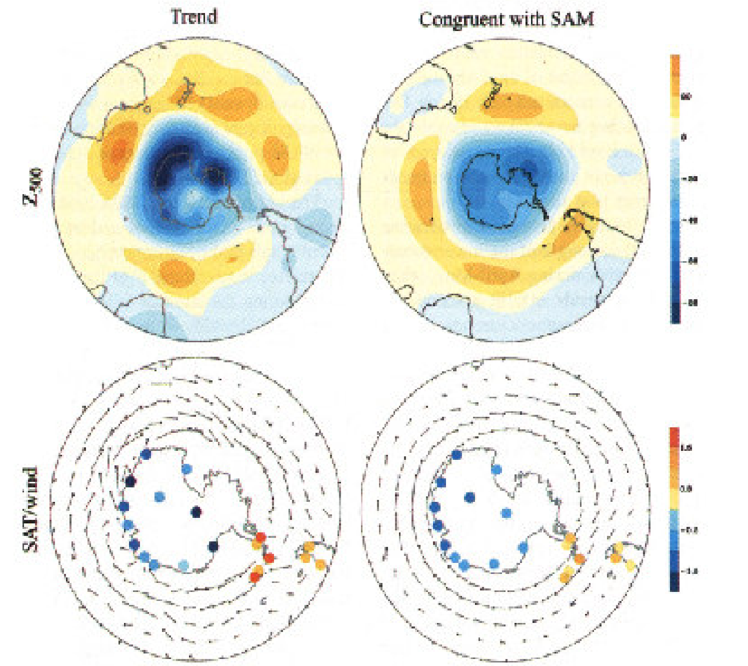
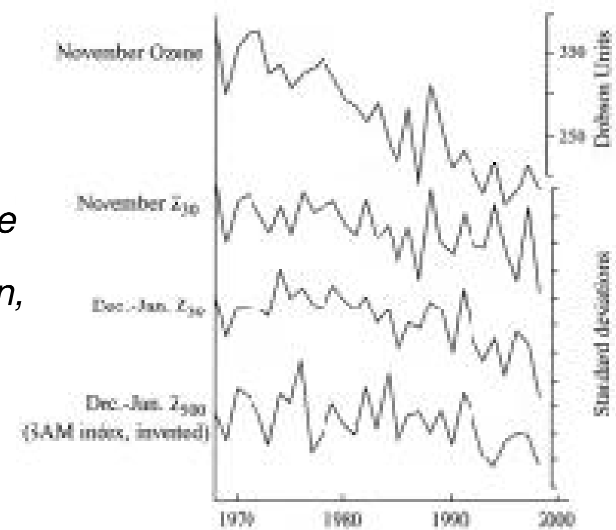
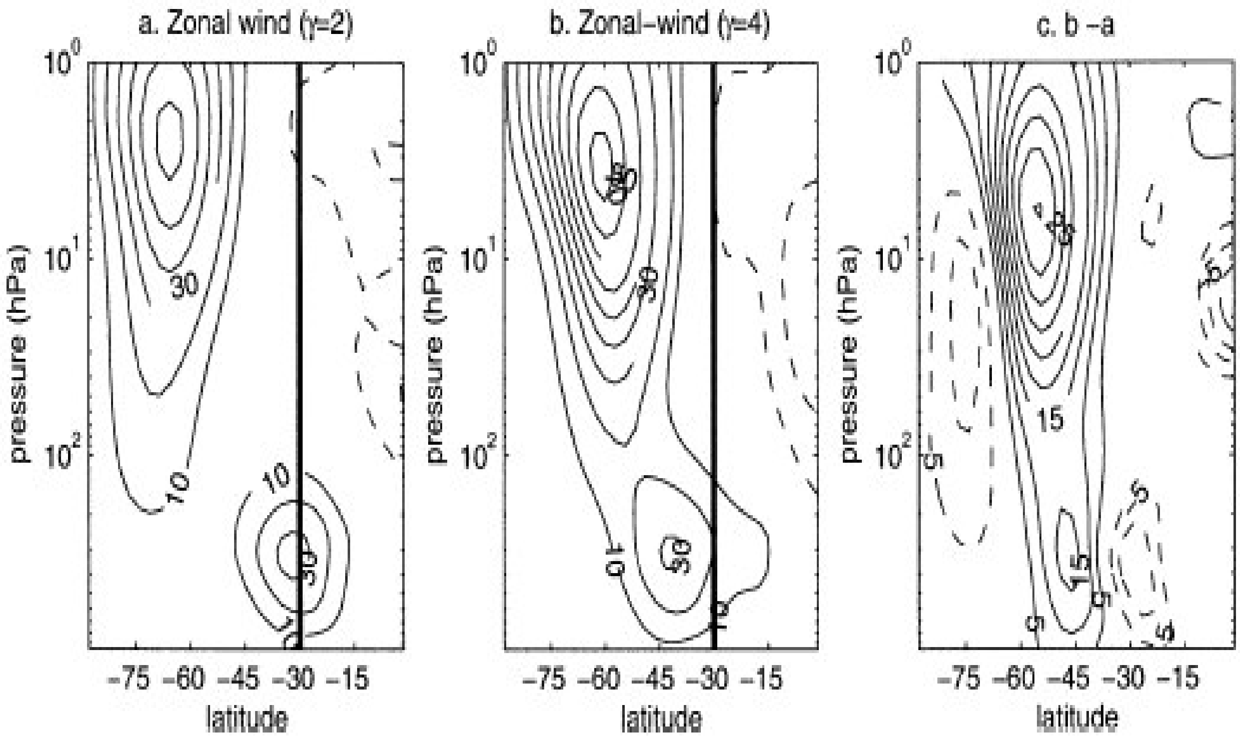


Fig. 3. December-May trends (**left**) and the contribution of the SAM to the trends (**right**). Top, 22-year (1979–2000) linear trends in 500-hPa geopotential height. Bottom: 32-year (1969–2000) linear trends in surface temperature and 22-year (1979–2000) linear trends in 925-hPa winds. Shading is drawn at 10 m per 30 years for 500-hPa height and at increments of 0.5 K per 30 years



Tropospheric response to ozone depletion [Thompson & Solomon, 2002]

Response to altered stratospheric radiative state
[Kushner & Polvani, *J Clim*, 2004]



The fluctuation-dissipation theorem

$$\frac{\partial \mathbf{X}}{\partial t} + \mathcal{L}(\mathbf{X}) + \mathcal{N}(\mathbf{X}) = \mathbf{F}$$

Linearize about climatological state:

$$\frac{\partial \mathbf{x}}{\partial t} + \mathbf{A}\mathbf{x} = \mathbf{f}\,.$$

Steady forcing:

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{f}\,.$$

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→ but we don't know what **A** is: so how do we find out?

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With no external forcing:

Unknown **A**, stochastic $\mathbf{f} = \epsilon(\mathbf{r},t)$

$$\mathbf{A} = \mathbf{V}\mathbf{\Lambda}\mathbf{W}^T \quad ;$$

$$\mathbf{V}\mathbf{W}^T = \mathbf{I} = \mathbf{W}^T\mathbf{V}$$

$$\frac{\partial}{\partial t}\mathbf{W}^T\mathbf{x} + \mathbf{\Lambda}\mathbf{W}^T\mathbf{x} = \mathbf{W}^T\boldsymbol{\epsilon}$$

$$\mathbf{C}_\tau = \left\langle \mathbf{x}(\mathbf{t}+\boldsymbol{\tau})\mathbf{x}^T(t) \right\rangle$$

$$\mathbf{G}_\tau = \mathbf{C}_\tau \mathbf{C}_0^{-1}$$

$$\rightarrow \qquad \mathbf{G}_t = \mathbf{V}\mathbf{\Gamma}_\tau \mathbf{W}^T \quad ,$$

$$\mathbf{\Gamma}_\tau = \exp(-\mathbf{\Lambda}\tau) \; .$$

The vectors **V** are the *principal oscillation patterns* (POPs)

[*e.g.*, Penland 2002]

The fluctuation-dissipation theorem; principal oscillation patterns (POPs)

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Linearize about climatological state:

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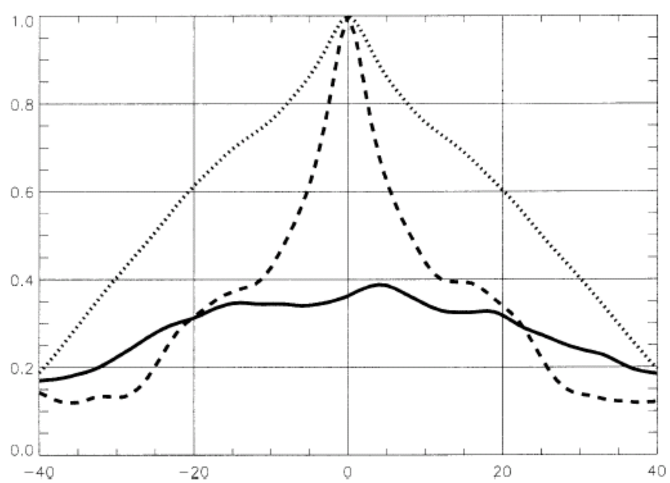

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Baldwin and Dunkerton, Science (2001)

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$$\mathbf{A} = \mathbf{V}\Lambda\mathbf{W}^T \quad ;$$

$$\mathbf{V}\mathbf{W}^T = \mathbf{I} = \mathbf{W}^T\mathbf{V}$$

$$\frac{\partial}{\partial t}\mathbf{W}^T\mathbf{x} + \Lambda\mathbf{W}^T\mathbf{x} = \mathbf{W}^T\epsilon$$

$$\mathbf{C}_\tau = \left\langle \mathbf{x}(\mathbf{t}+\boldsymbol{\tau})\mathbf{x}^T(t)\right\rangle$$

$$\mathbf{G}_\tau = \mathbf{C}_\tau\mathbf{C}_0^{-1}$$

$$\bar{\mathbf{C}}_\tau = \langle \mathbf{W}^T\mathbf{x}(t+\tau)\mathbf{x}(t)\mathbf{W}\rangle$$

$$\bar{\mathbf{C}}_\tau = \exp(-\Lambda\tau)\bar{\mathbf{C}}_0$$

→ Lag covariance of each principal component decays exponentially with decorrelation time $\tau = \Lambda^{-1}$

The fluctuation-dissipation theorem; principal oscillation patterns (POPs)

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Steady response to steady forcing:

$$\mathbf{A} = \mathbf{V}\mathbf{\Lambda}\mathbf{W}^T$$

$$\mathbf{\Lambda}\mathbf{W}^T\mathbf{x} = \mathbf{W}^T f$$

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$$\rightarrow \quad y_n = \tau_n g_n$$

y_n: Response of PC; τ_n: decorrelation time; g_n: projection of forcing

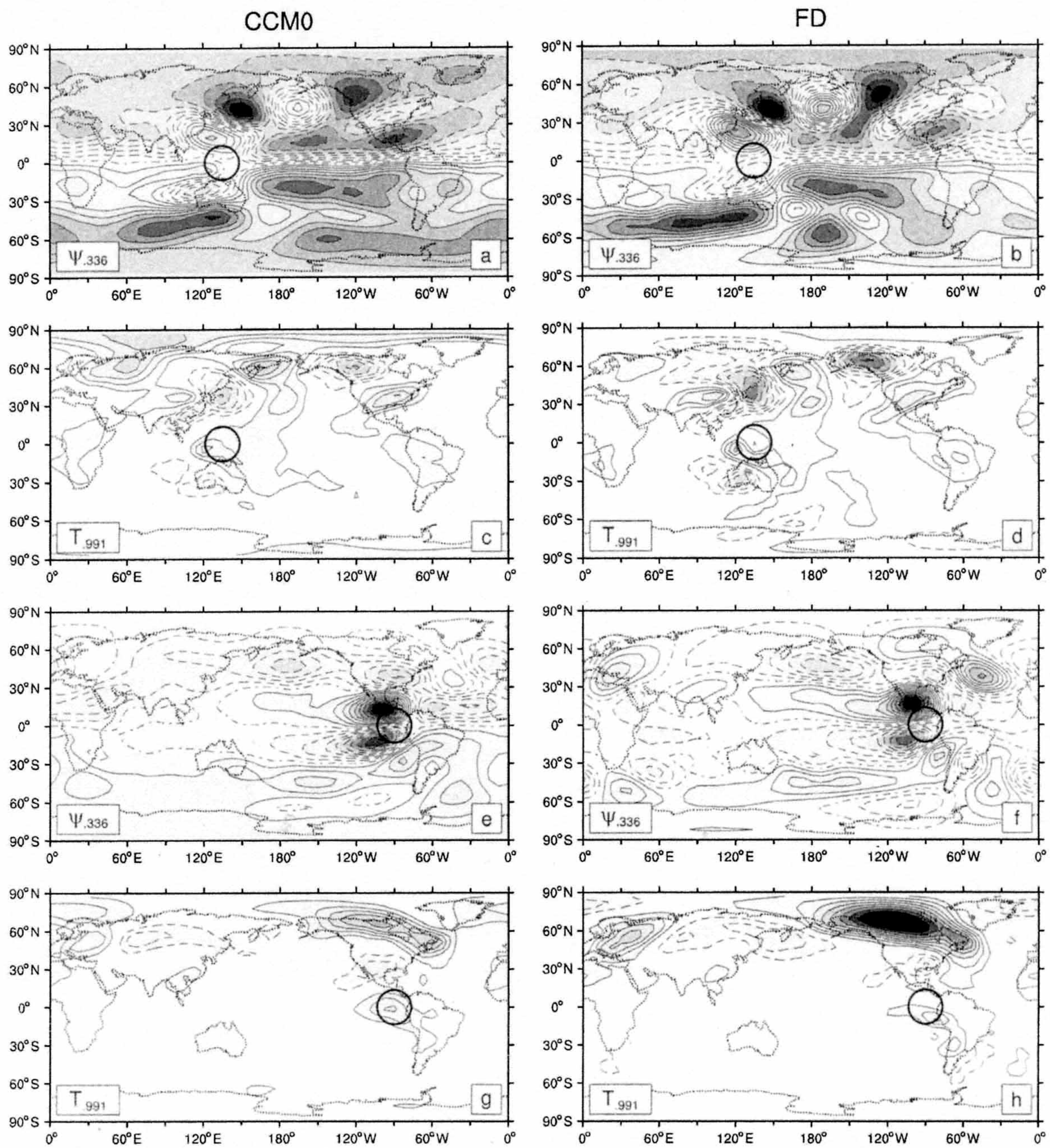


FIG. 3. Time-averaged anomalous response of (left) AGCM and (right) FDT operator to sinusoidal 2.5°C day^{-1} forcing at (top four) (0°, 135°E) and (bottom four) (0°, 90°W). Fields shown are $\psi_{0.336}$ and $T_{0.991}$ as indicated. Contour intervals are 5×10^5 m^2 s^{-1} for streamfunction and 0.2°C for temperature.

Application to forced barotropic model [Gritsun & Branstator *J. Atmos. Sci.,* 2007]

Model Setup

- GFDL dry dynamical core; no geography
- T30 resolution
- Linear radiation and friction schemes

$$\frac{\partial \mathbf{u}}{\partial t} + \ \ldots\ldots\ldots\ldots = \mathbf{F} - \gamma \mathbf{u} + \boldsymbol{\nu} \nabla^6 \mathbf{u}$$

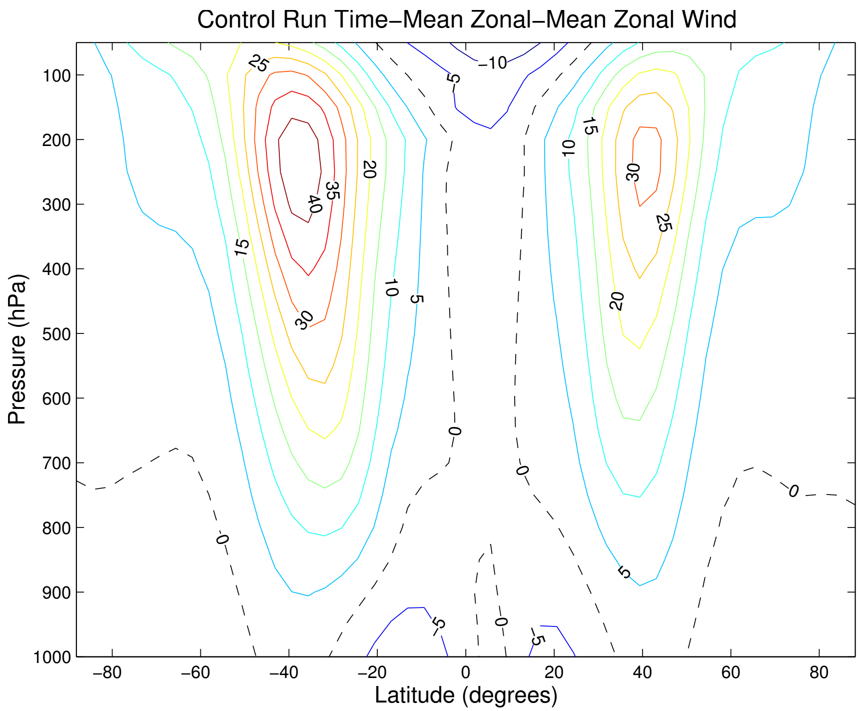
$$\frac{\partial T}{\partial t} + \ldots\ldots\ldots\ldots = \alpha (T_e - T)$$

- Held-Suarez-like reference temperature profile but modified for perpetual solstitial conditions
- Friction twice the value used by Held and Suarez (1994) to reduce decorrelation times

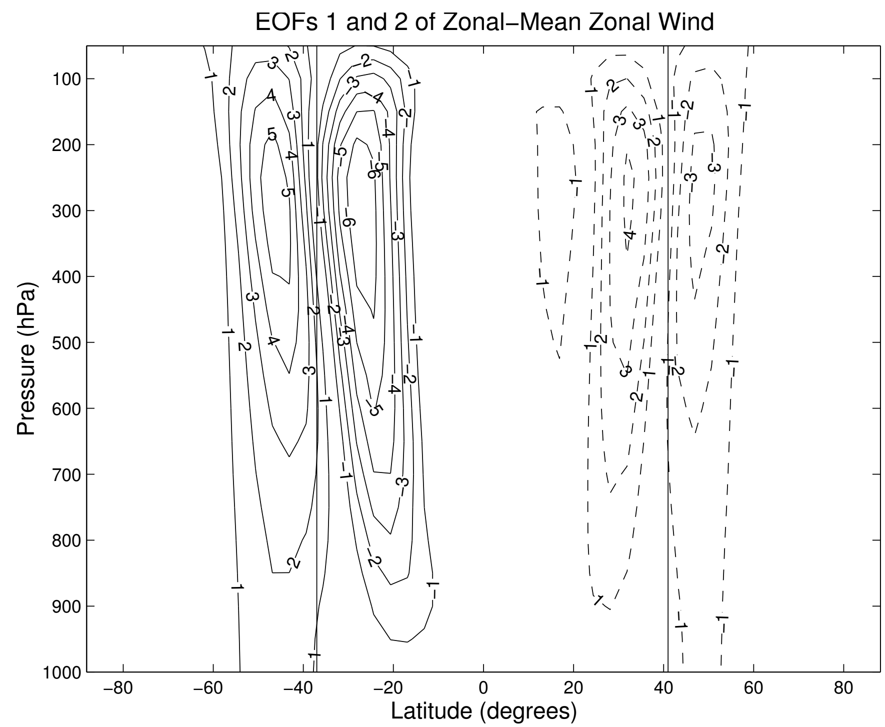
Troposphere "dynamical core" model with Held-Suarez-like forcing *(Ring & Plumb 2007)*

Mean and variability of control run

mean zonal wind

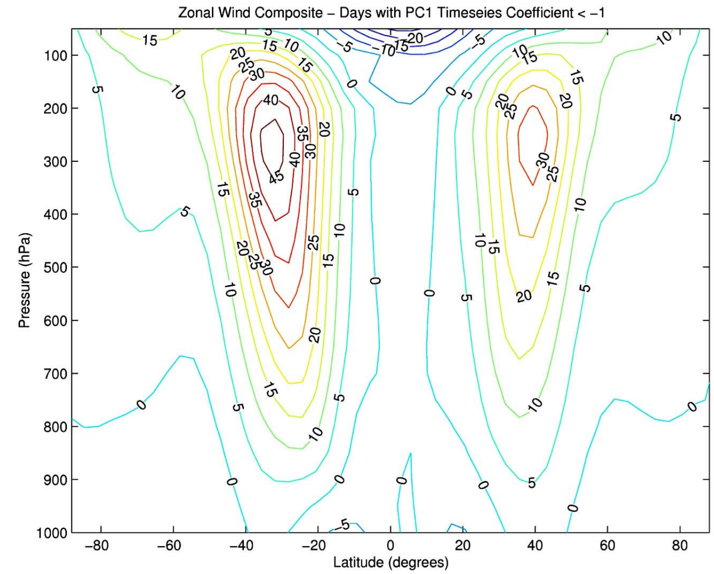


first 2 EOFs of mean u

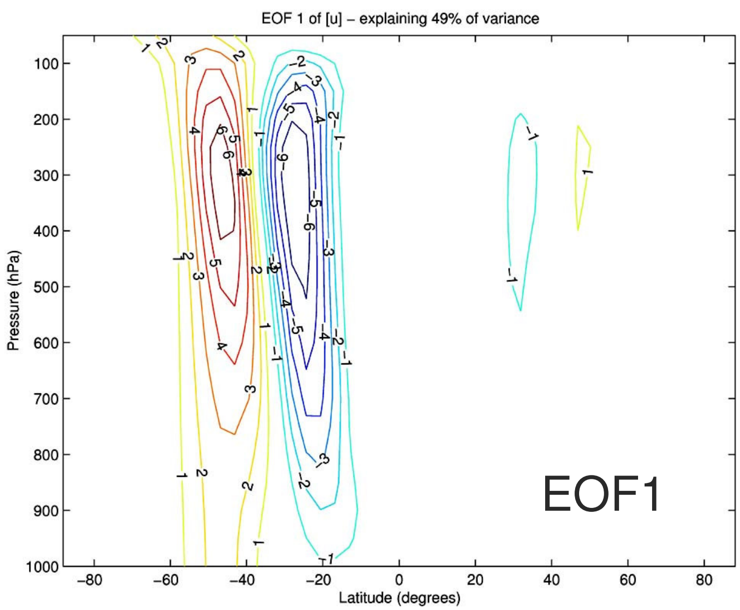


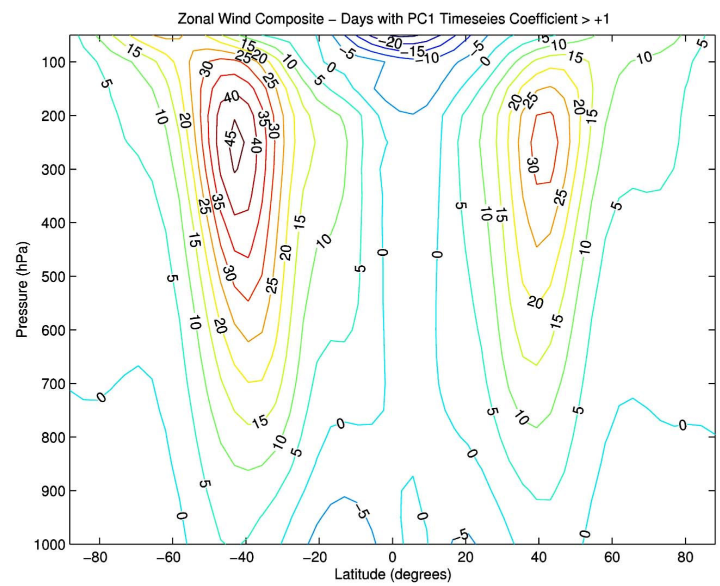
Behavior of a simplified GCM (no longitudinal variations in external conditions)

*(*Ring & Plumb, *J Atmos Sci*, 2007*)*

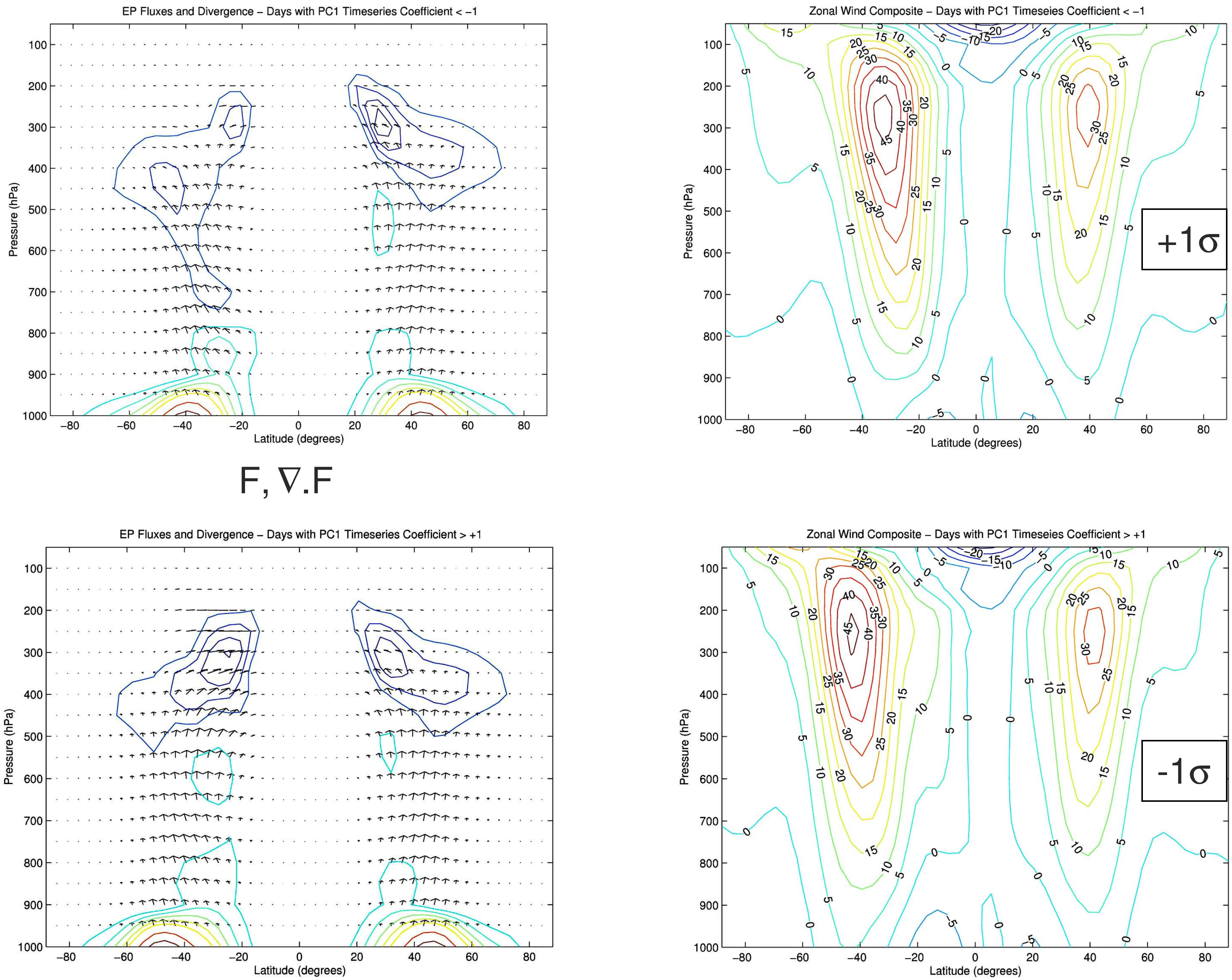


+1σ



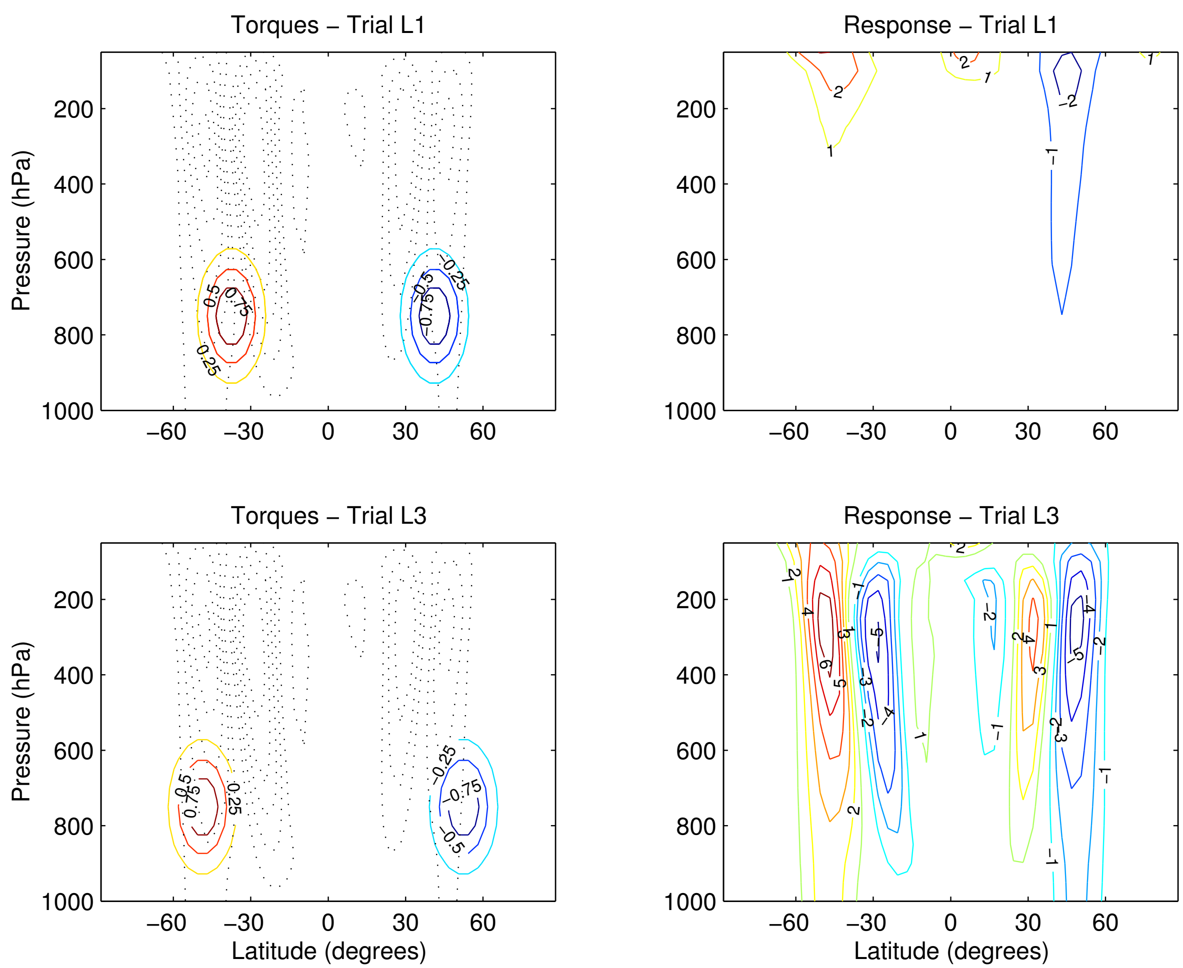


-1σ



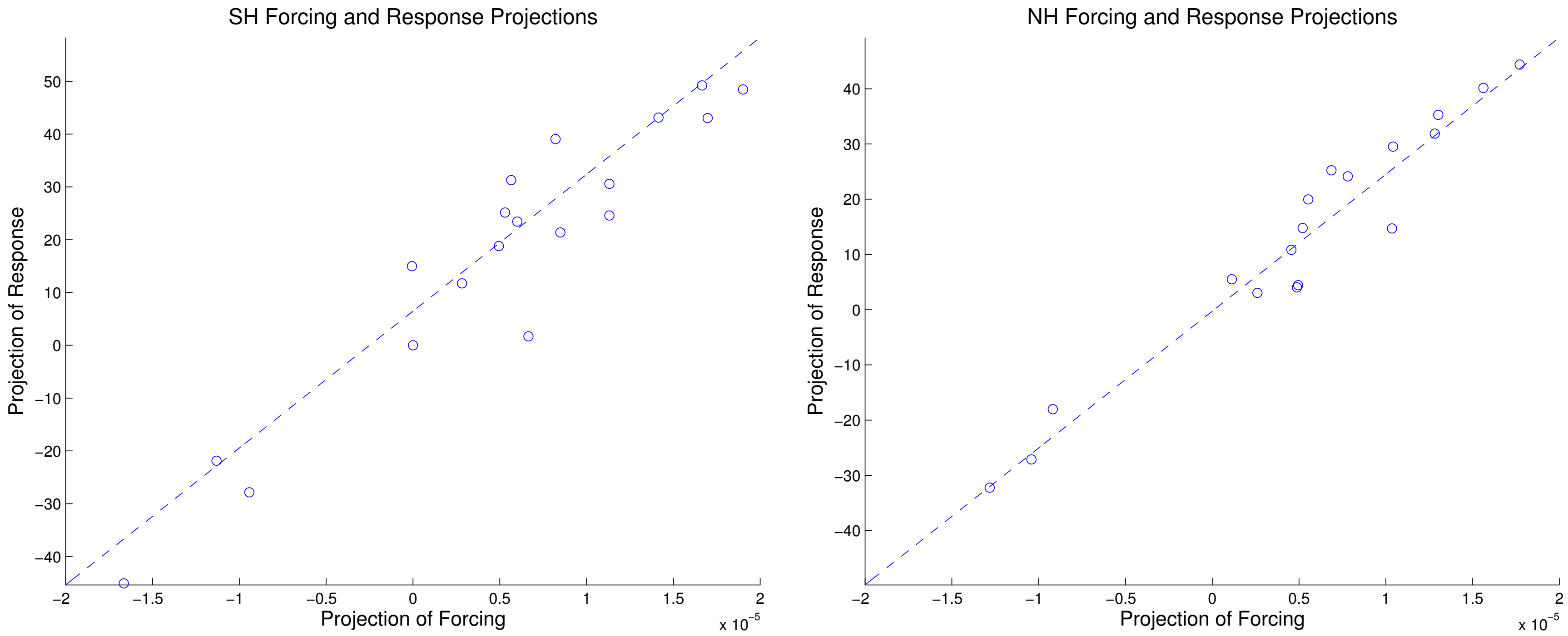
(Ring & Plumb, *J Atmos Sci*, 2007)

Responses to Mechanical Forcings



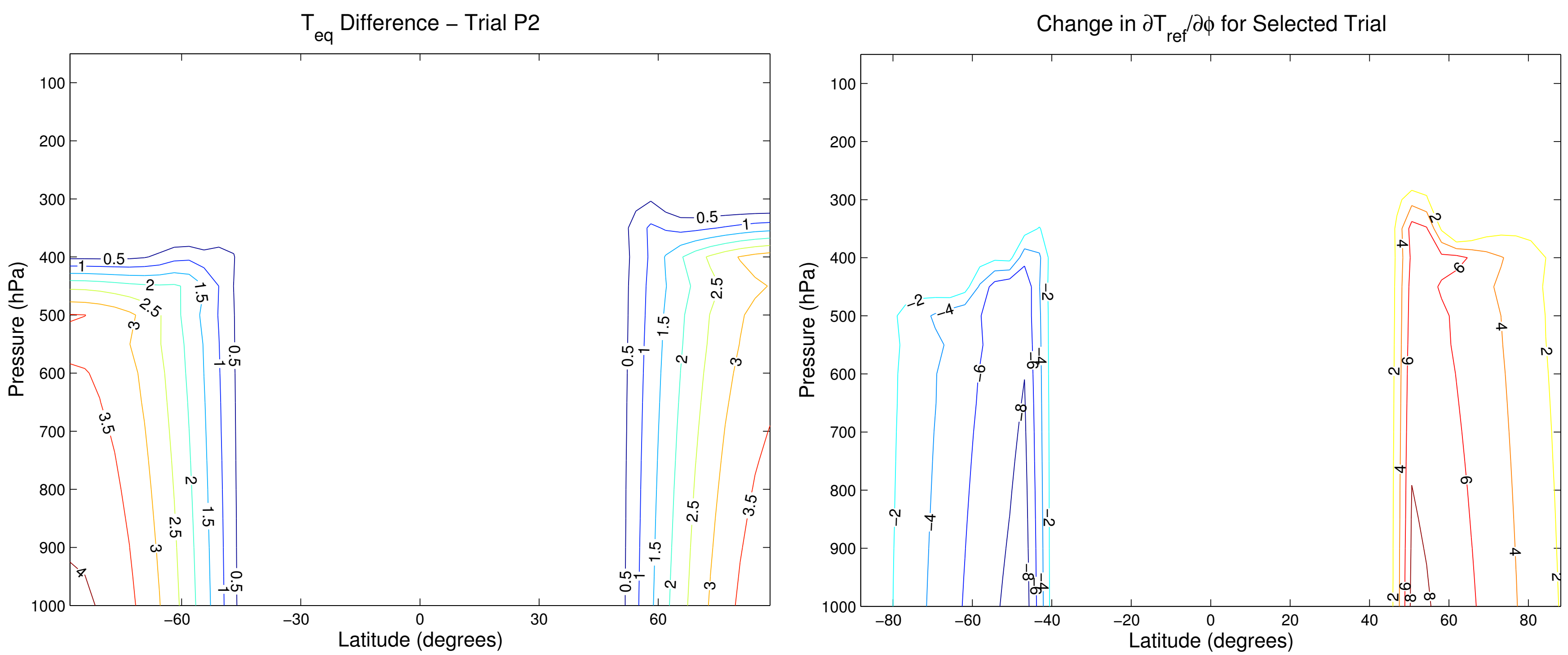
Ring and Plumb (2007)

Hypothesis: response in each EOF U_n is proportional to projection of forcing onto U_n



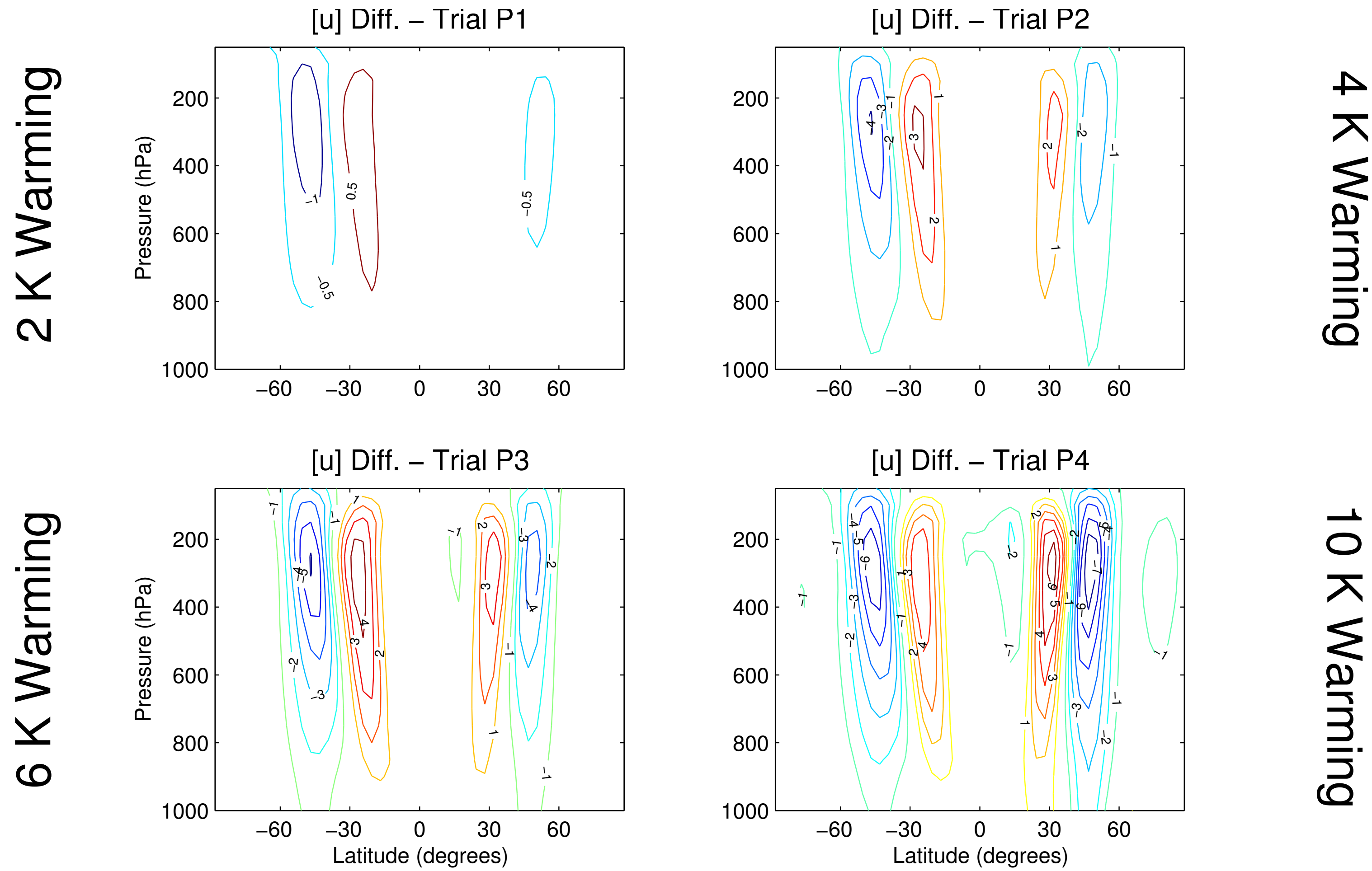
Ring and Plumb (2007)

Reference Temperature Changes Confined to Poleward of Jet

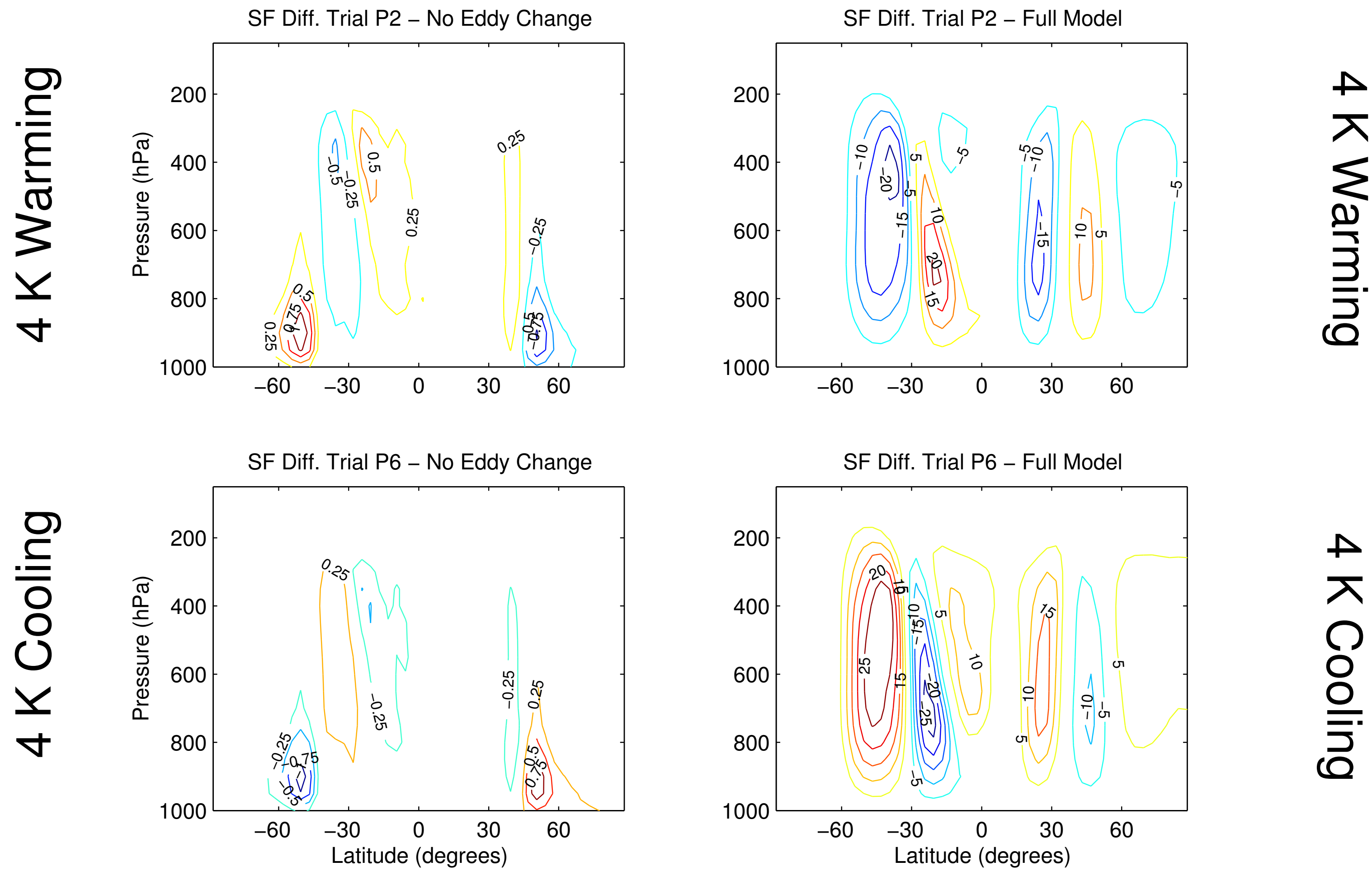


Ring and Plumb (2007)

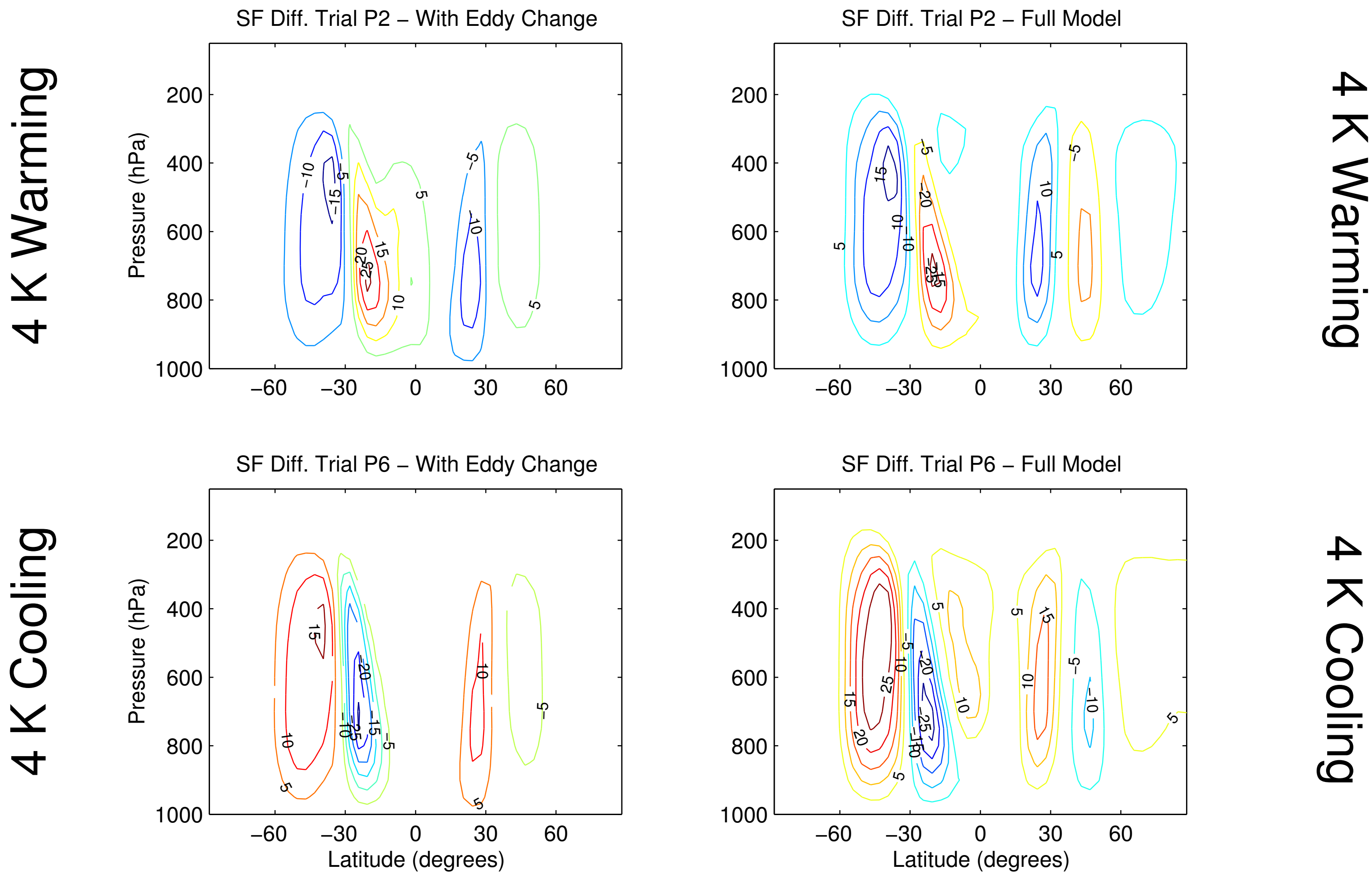
Wind Changes Resulting From Poleward Side T_{ref} Changes



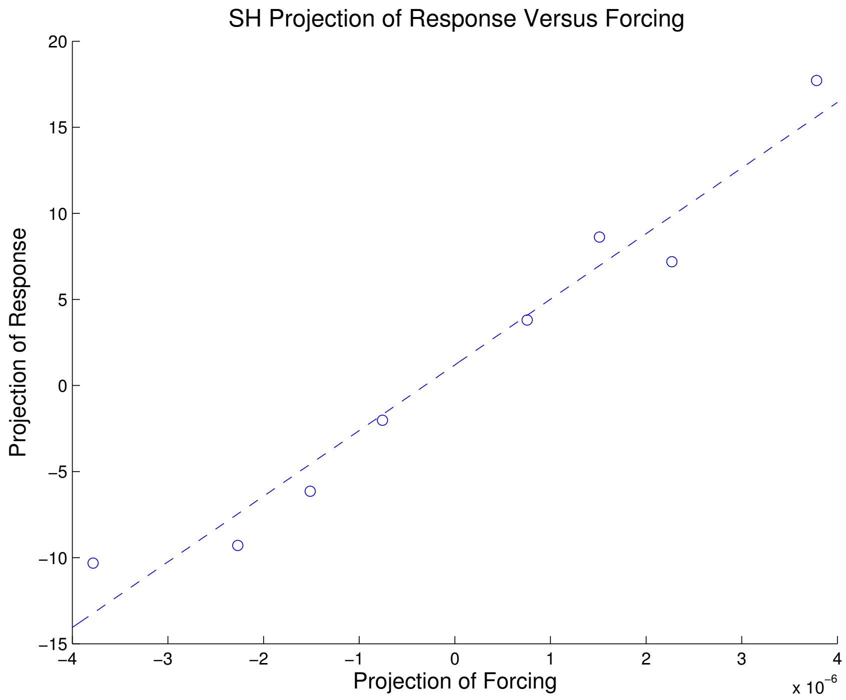
Direct Response to Forcing

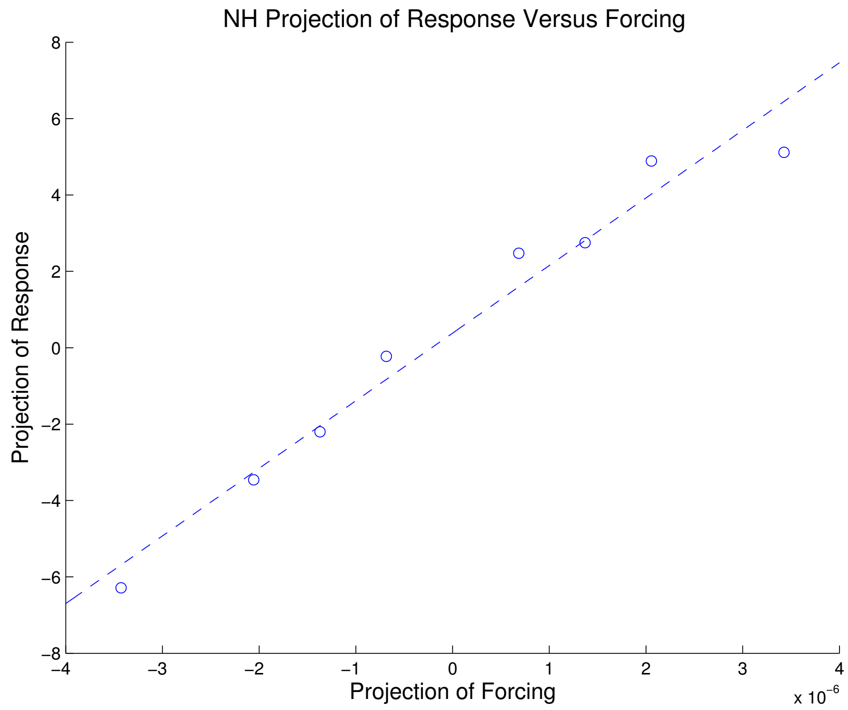


Response to Forcing Including Eddy Flux Changes



Responses to Poleward Side Thermal Forcings





Ring and Plumb (2007)

The fluctuation-dissipation theorem; principal oscillation patterns (POPs)

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$$\boldsymbol{\Lambda}\underbrace{\mathbf{W}^T\mathbf{x}}_{\downarrow} = \underbrace{\mathbf{W}^T f}_{\downarrow}$$

$$\rightarrow \qquad y_n = \tau_n g_n$$

Governing eqs of system

Linearize about unforced time-mean state [U,V,Ω,Θ](φ,p)

Anomalies [u,v,ω,T, $\mathbf{F}_u$,$\mathbf{F}_T$](φ,p,t)

$$u_t + (\mathbf{V} \cdot \nabla)u + (\mathbf{v} \cdot \nabla)U - fv = -\nabla \cdot \mathbf{F}_u - \lambda u + h$$

$$T_t + (\mathbf{V} \cdot \nabla)T - \tfrac{\kappa}{p}\Omega T + (\mathbf{v} \cdot \boldsymbol{\nabla})\Theta - \tfrac{\kappa}{p}\omega\Theta = -\nabla \cdot \mathbf{F}_T - \alpha T + q$$

Assume anomalous eddy fluxes depend linearly on anomalous *u* (and neglect time lags) + stochastic term:

$$\nabla \cdot \mathbf{F}_u = \mathrm{E}_u u + \epsilon_u \ ; \ \ \nabla \cdot \mathbf{F}_T = \mathrm{E}_T u + \epsilon_T$$

$$\longrightarrow \quad \boxed{\mathbf{x}_t + \mathrm{C}\mathbf{x} = \mathbf{g} + \boldsymbol{\epsilon}}$$

Governing eqs of system

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Nonlinear balance:

$$ap^{-1}R\cos^2\varphi\ T_\varphi = 2\sin\varphi\ [u(U + \Omega a\cos\varphi)]_p$$

Neglect advection of static stability anomalies

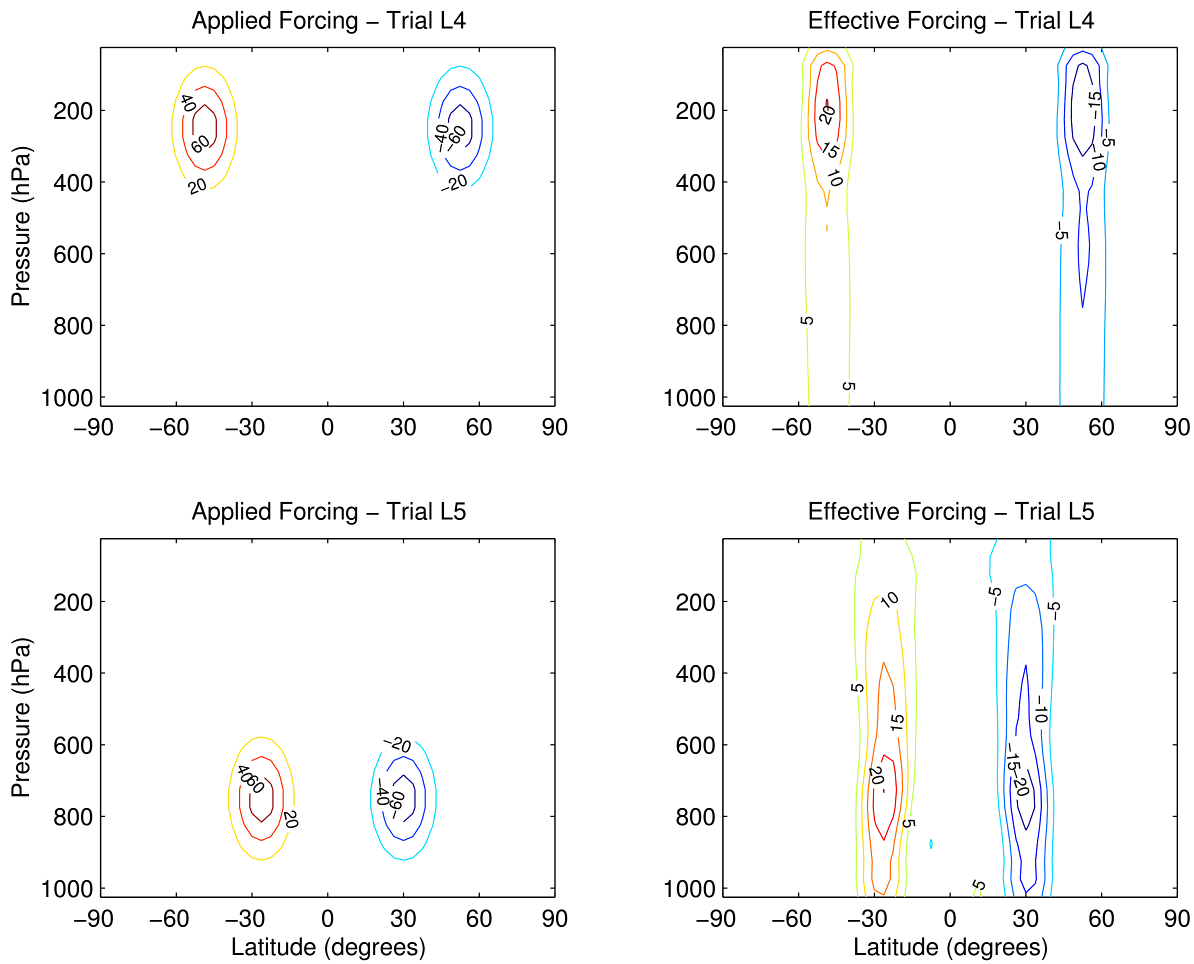
$$\longrightarrow \quad \boxed{u_t + \mathrm{A}u = f + \epsilon}$$

where

$$f = h - \mathrm{HL}^{-1}\left(\frac{1}{a}\frac{\partial q}{\partial\varphi} - \frac{2\sin\varphi}{a^3\cos^3\varphi}\frac{p}{R}\frac{\partial}{\partial p}(hM)\right)$$

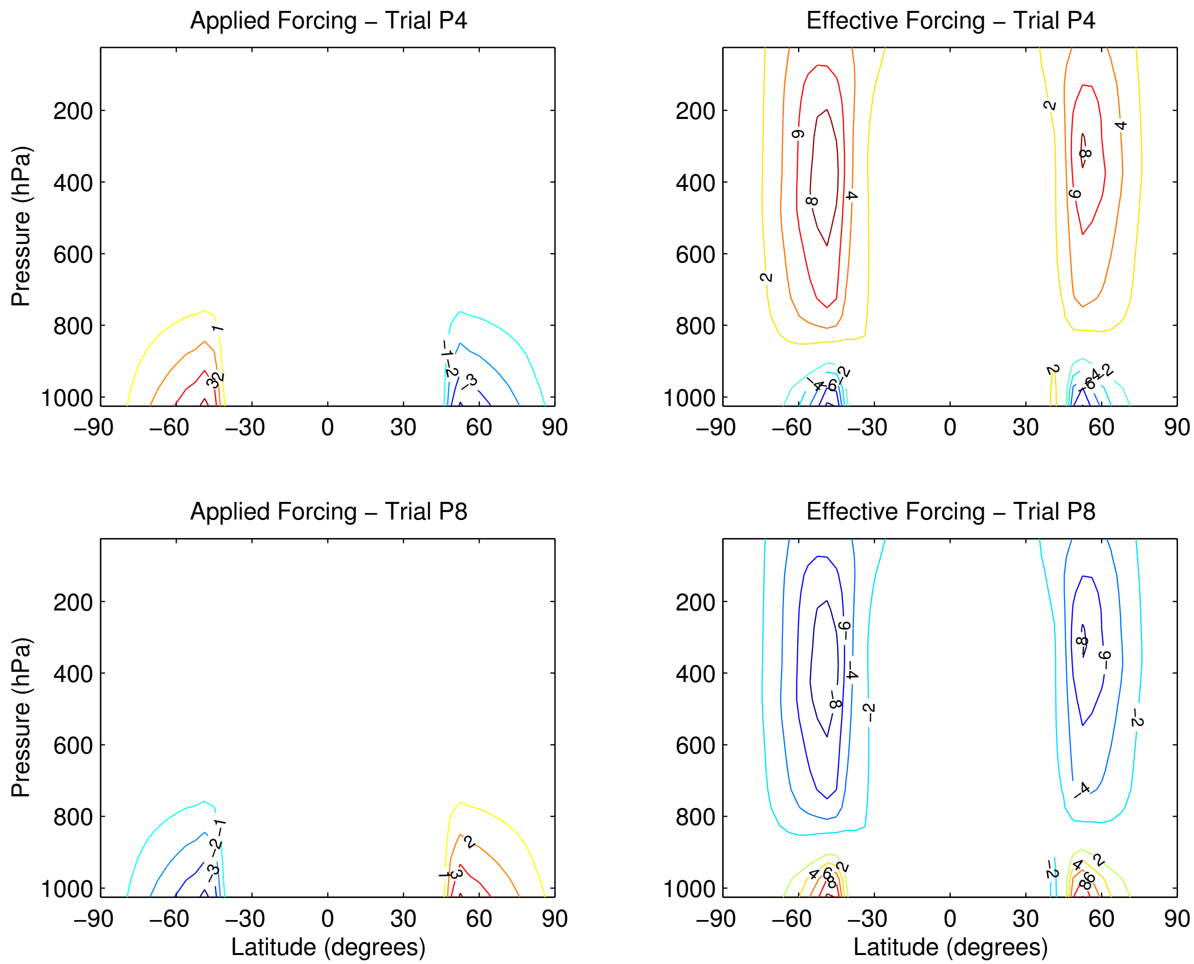
= *Kuo-Eliassen response*

Effective Torques: Mechanical Forcing



Ring and Plumb (2007)

Effective Torques: Thermal Forcing



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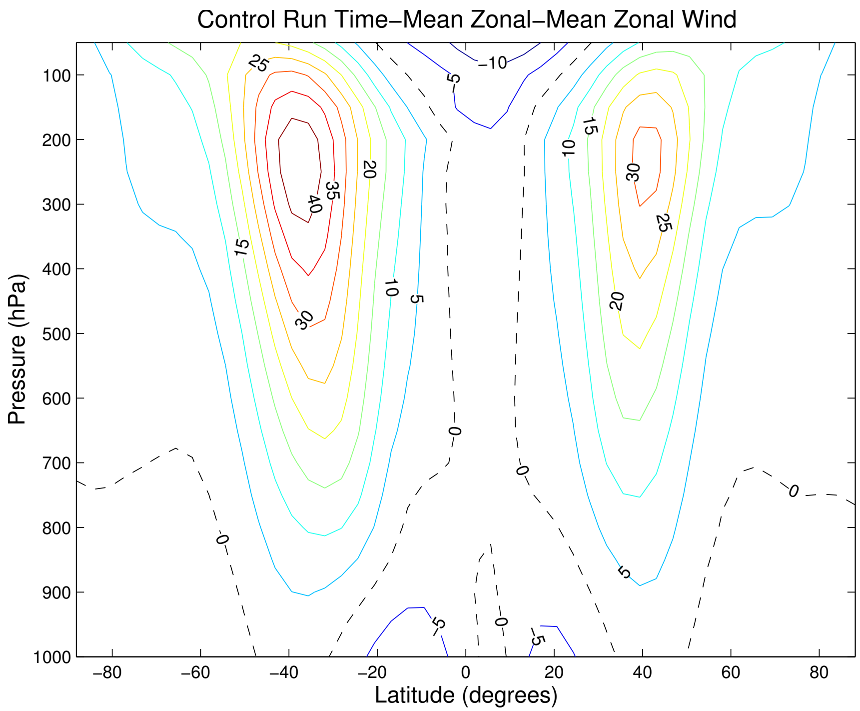
Troposphere "dynamical core" model with Held-Suarez-like forcing *(Ring & Plumb 2007)*

Mean and variability of control run

mean zonal wind



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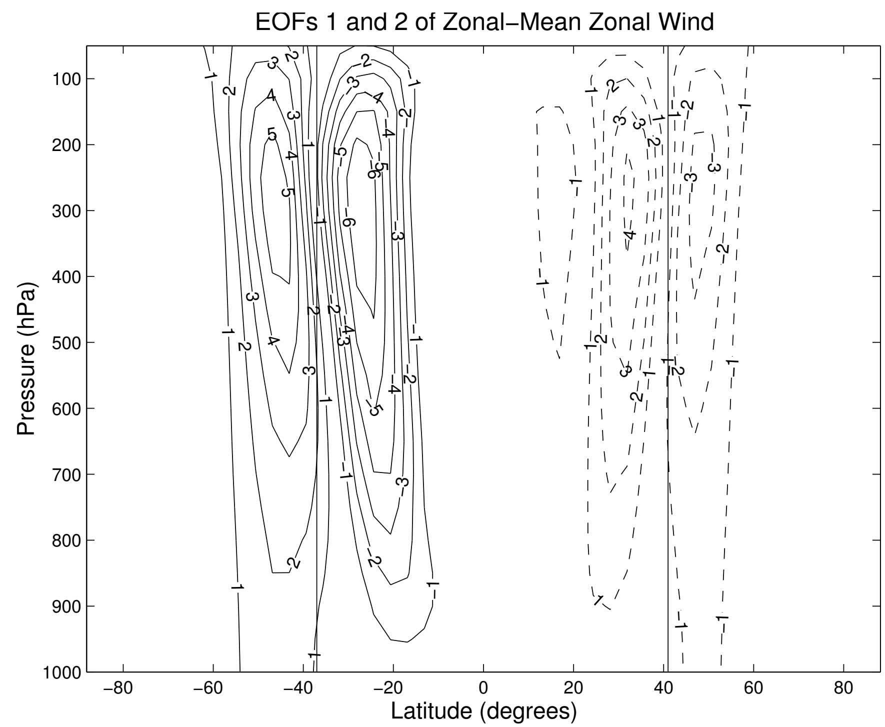
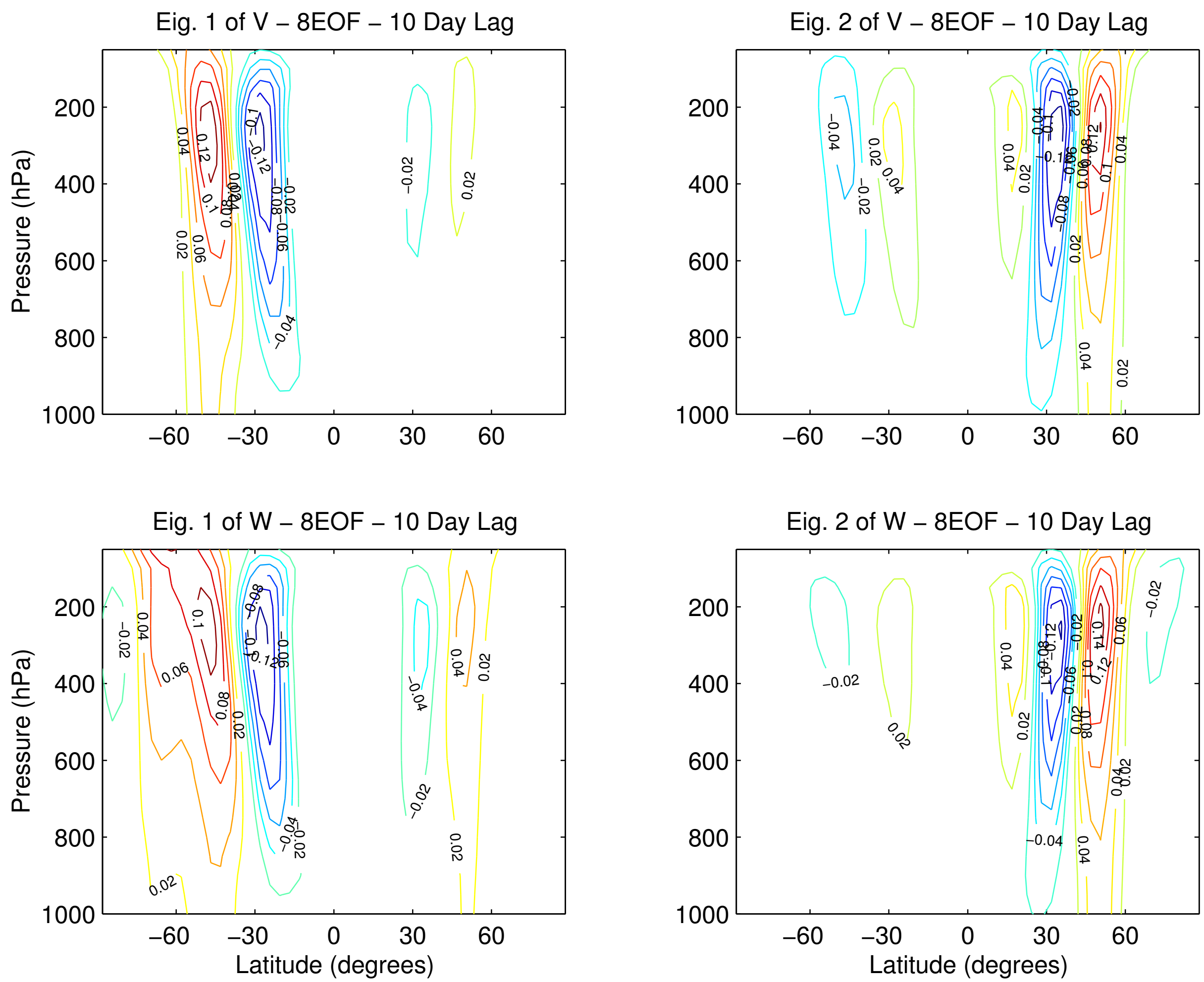


POP Spatial Patterns

8 EOFs retained – 10 day lag



Ring and Plumb (2007)

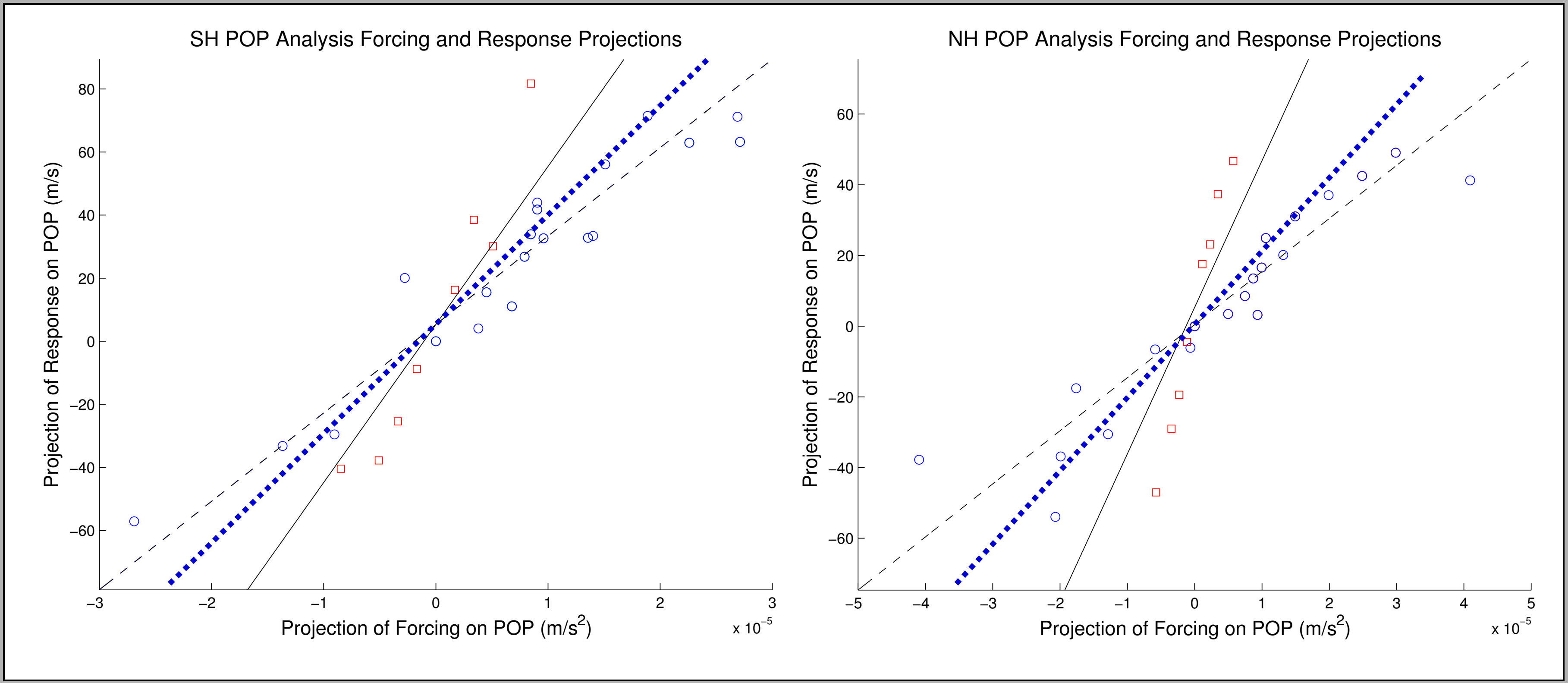
Response Versus Effective Torques:
(Ring & Plumb 2008)

$$x_n = \lambda_n^{-1} g_n = \tau_n g_n$$

decorrelation time of unforced mode

proj. of response onto mode

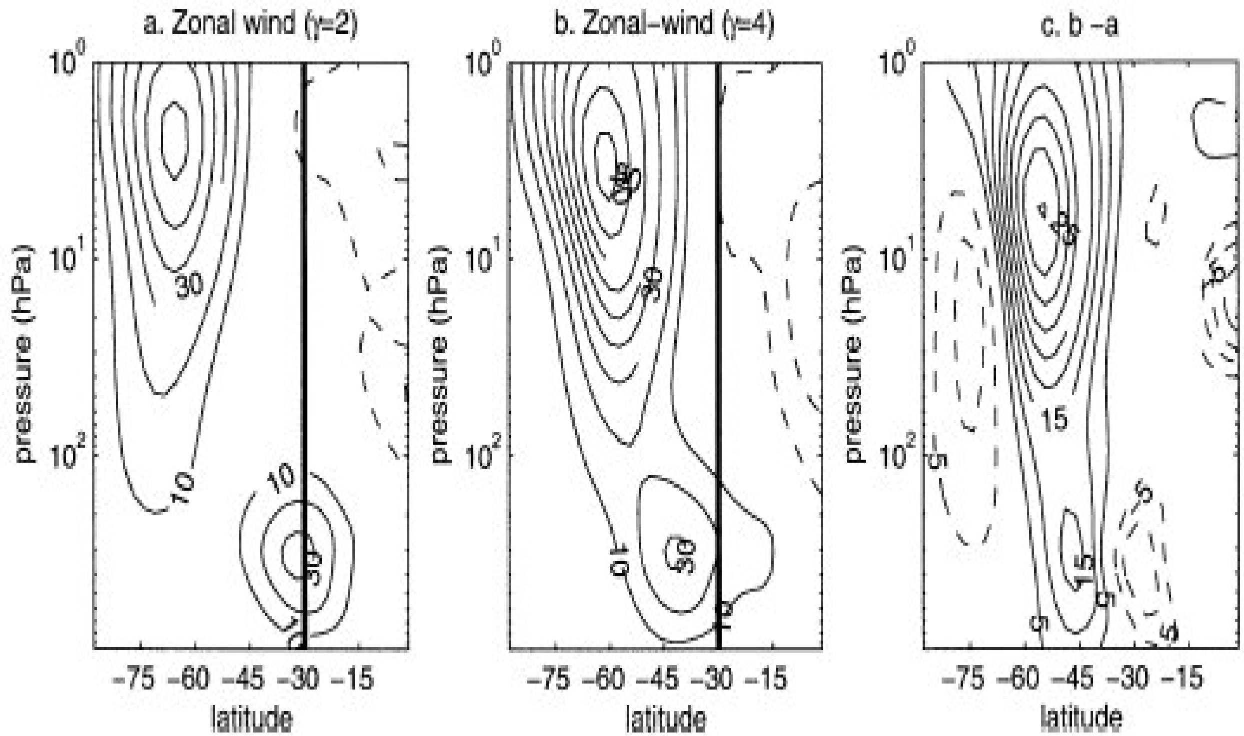
proj. of forcing onto mode



circles indicate mechanically forced trials; squares thermally forced trials

Response to altered stratospheric radiative state

[Kushner & Polvani 2004]



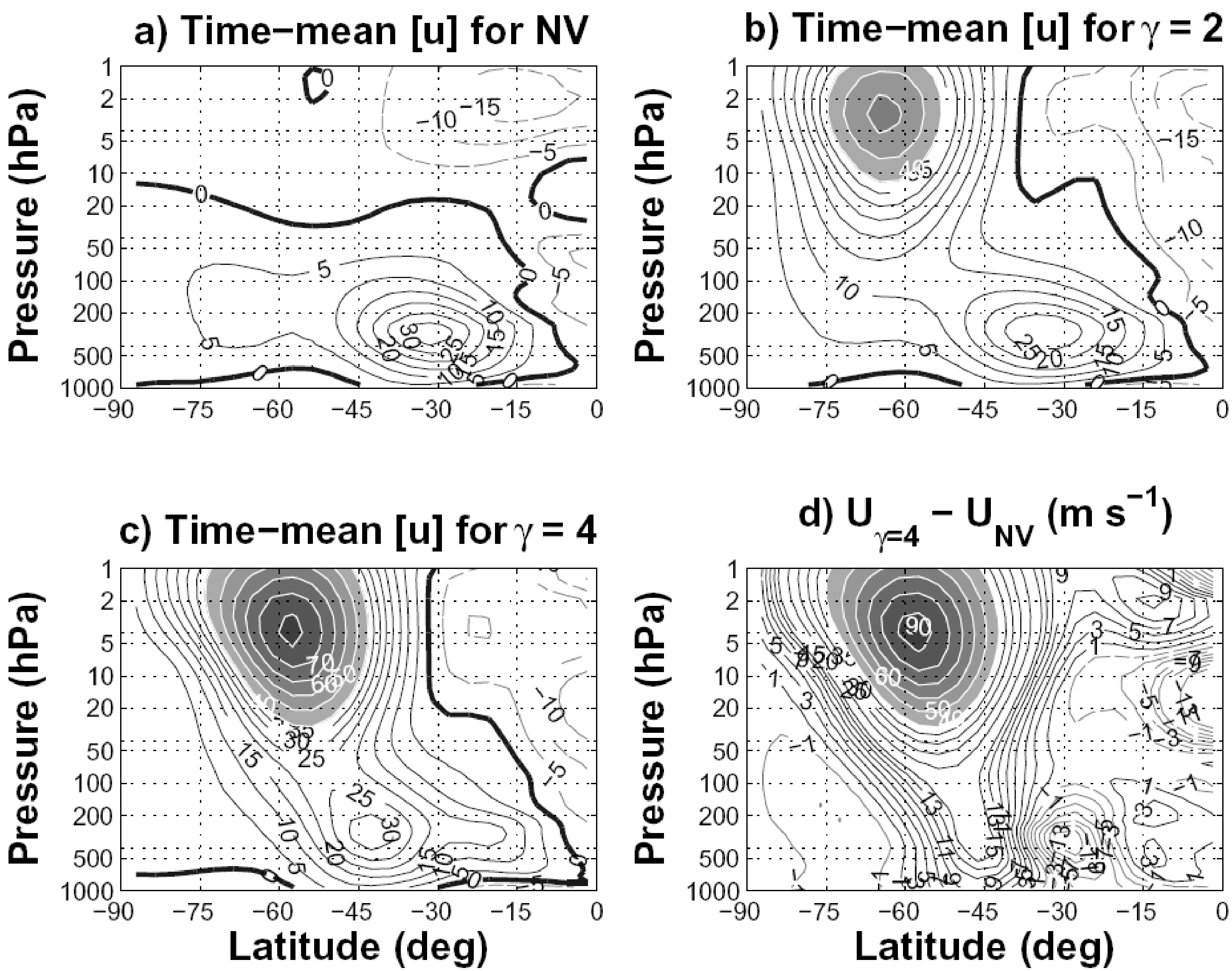


Figure 2: (a)-(c) Climatological zonally-averaged zonal winds for experiment 1a-1c. (d) Difference between (c) and (a).

Chan & Plumb (2009)

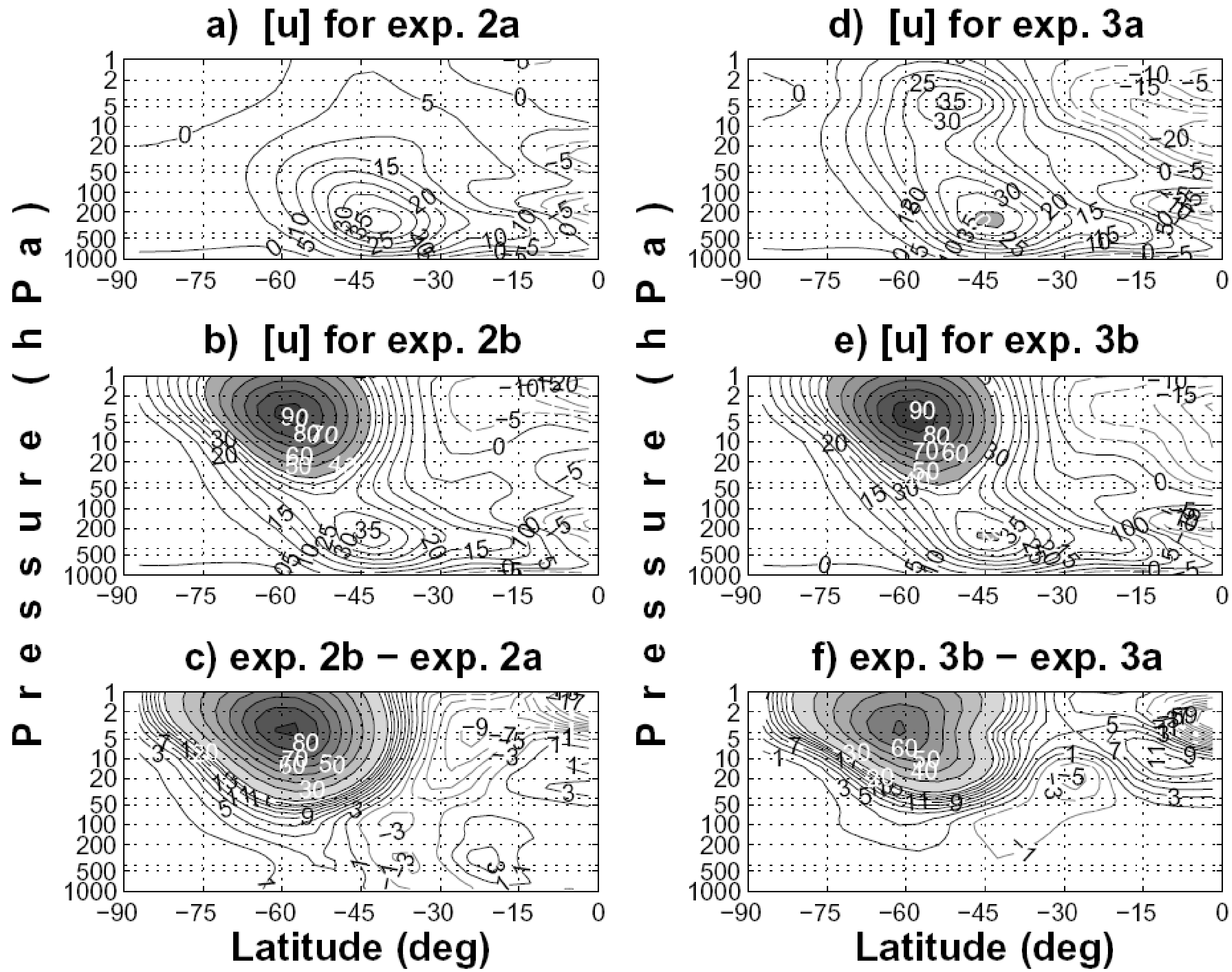
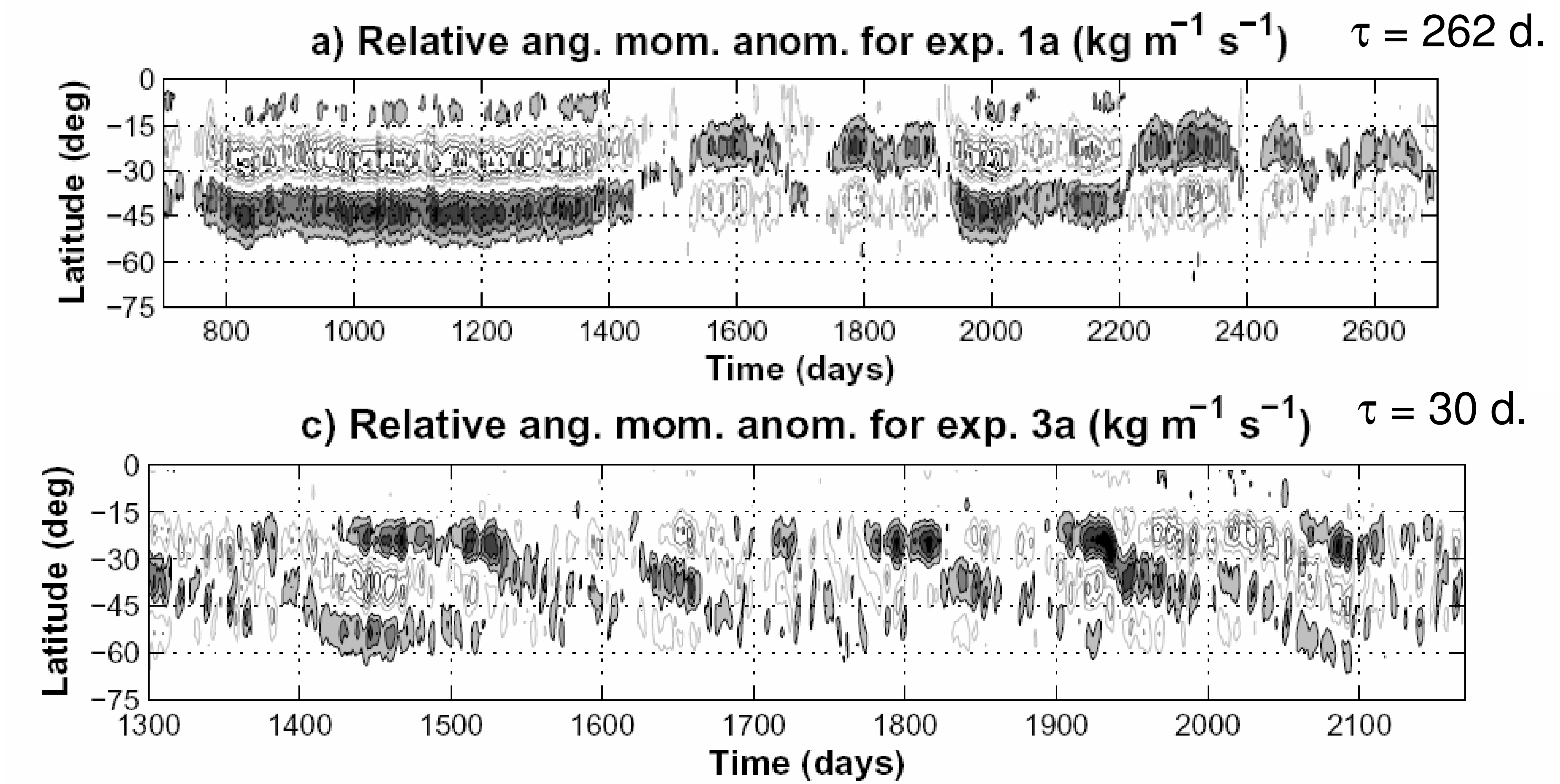


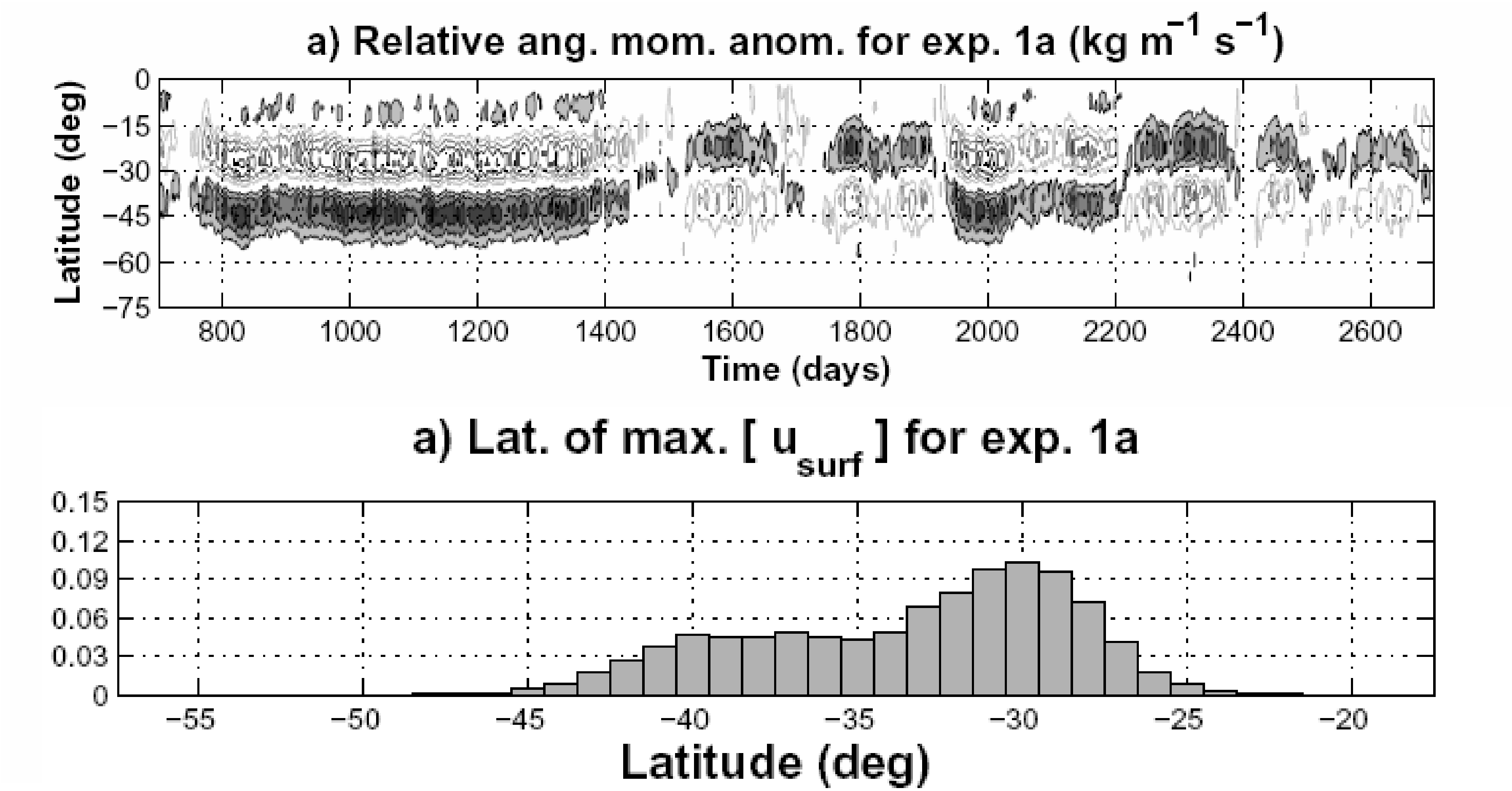
Figure 4: (a) Climatological zonally-averaged zonal winds for exp. 2a. (b) As in (a) but for exp. 2b. (c) Difference between (b) and (a). (d) As in (a) but for exp. 3a. (e) As in (a) but for exp. 3b. (f) Difference between (e) and (d). Contours are labelled every 5 ms^{-1} for (a), (b), (d) and (e), with shading for values greater than 40 ms^{-1}. For (c) and (f), contours are labelled every 2 ms^{-1} for values less than 20 ms^{-1} and are shaded and labelled every 10 ms^{-1}. Negative values are gray and dashed.

Chan & Plumb (2009)



Chan & Plumb (2009)

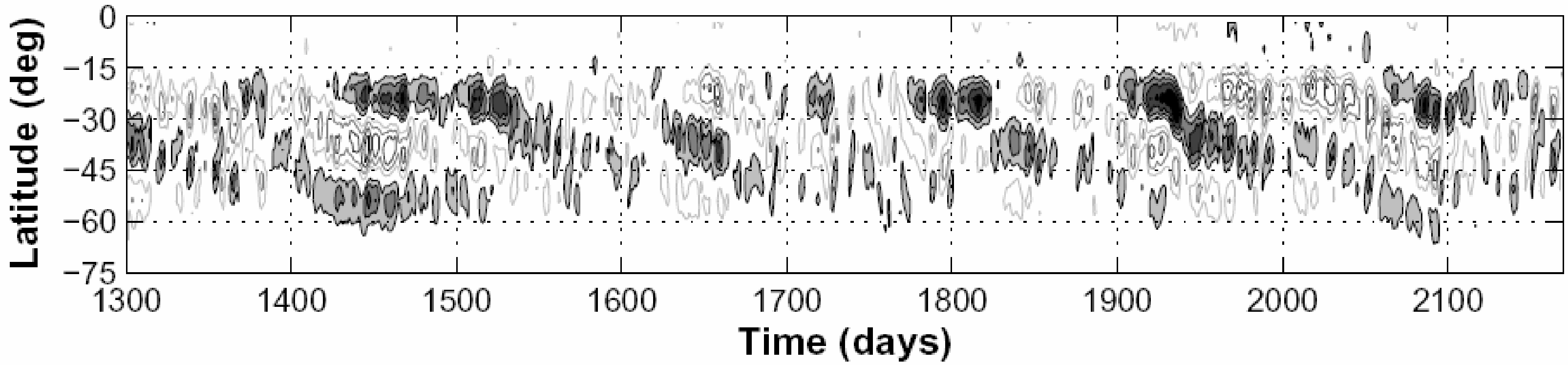
τ = 262 d.



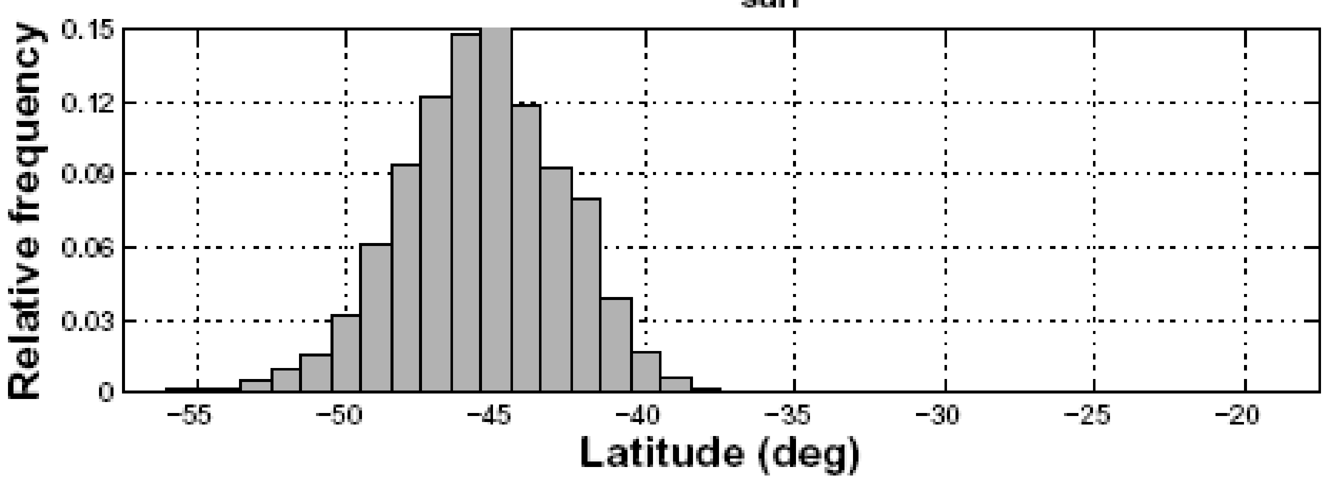
Chan & Plumb (2009)

τ = 30 d.

c) Relative ang. mom. anom. for exp. 3a (kg m^{-1} s^{-1})



b) Lat. of max. [u_{surf}] for exp. 3a



Chan & Plumb (2009)

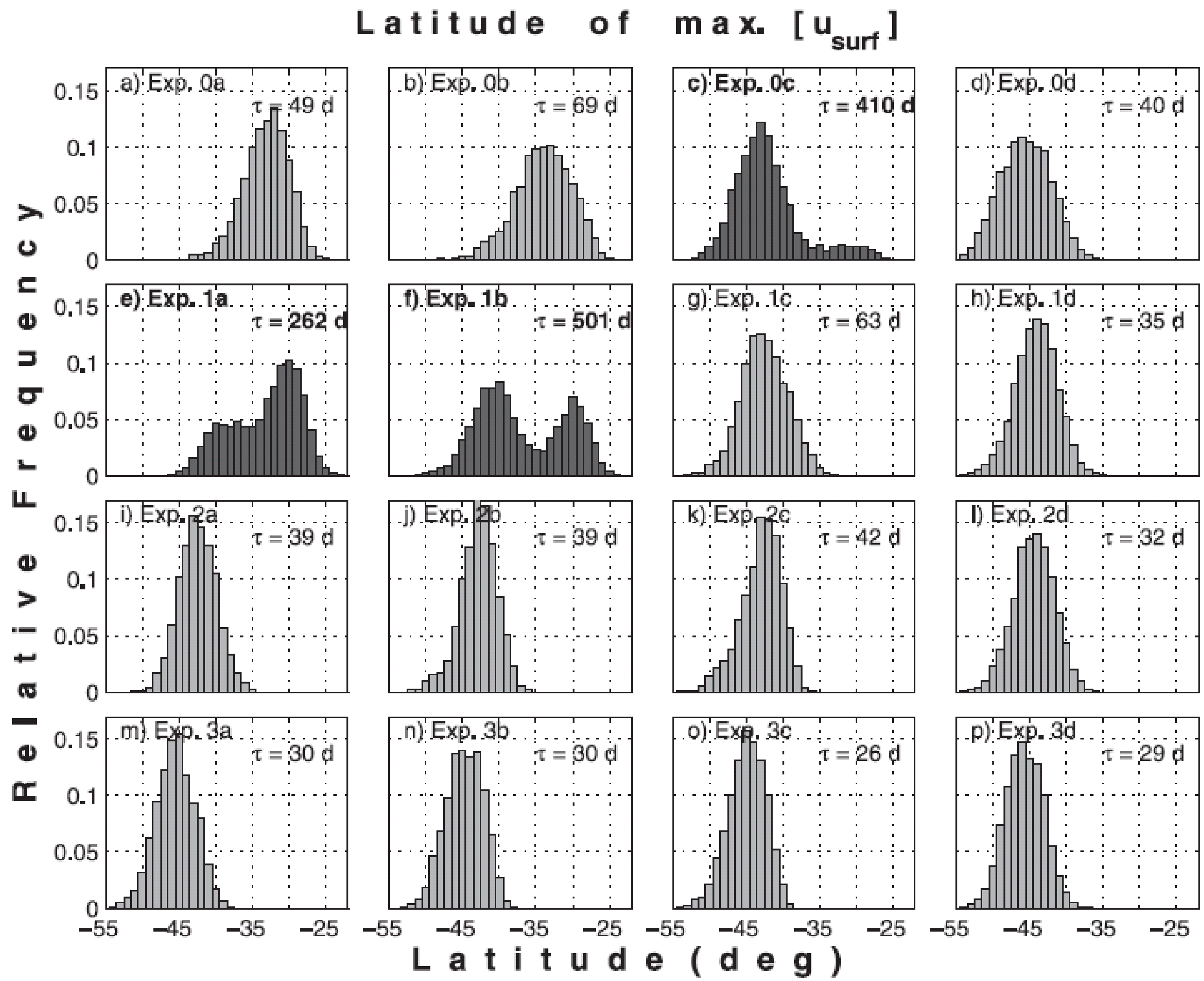
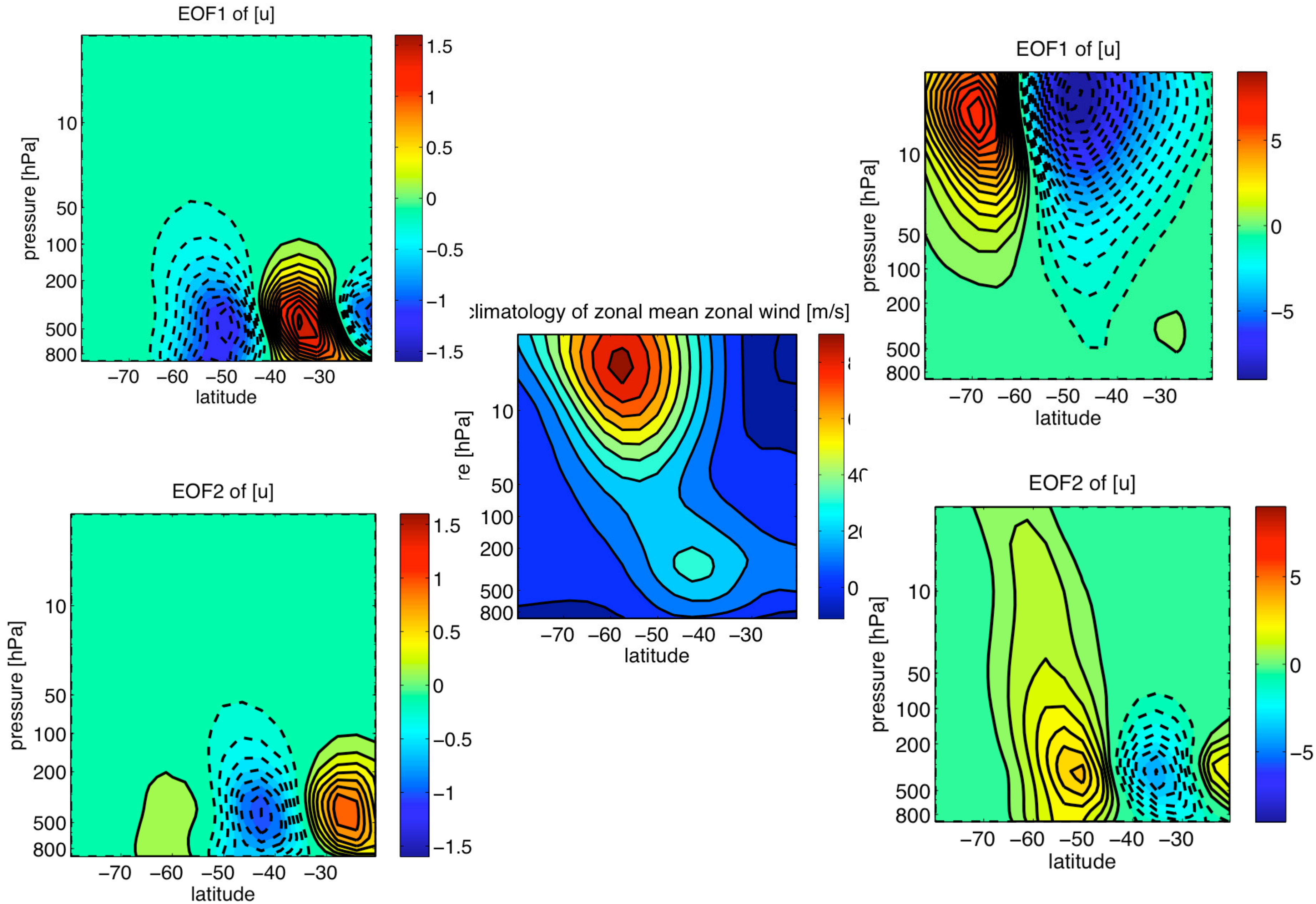


FIG. 3. A relative histogram of the latitudinal location of the maximum daily averaged near-surface zonally averaged zonal winds for all model runs listed in Table 1. Histograms in bold are model runs for which the decorrelation time for the leading principal component is greater than 200 days. Within each column, the same stratospheric equilibrium temperature profile is used, with polar vortex intensities (γ) increasing to the right. Within each row, the same tropospheric equilibrium temperature profile is used, with the magnitude of the equator to pole temperature difference increasing downward.

Chan & Plumb (2009)

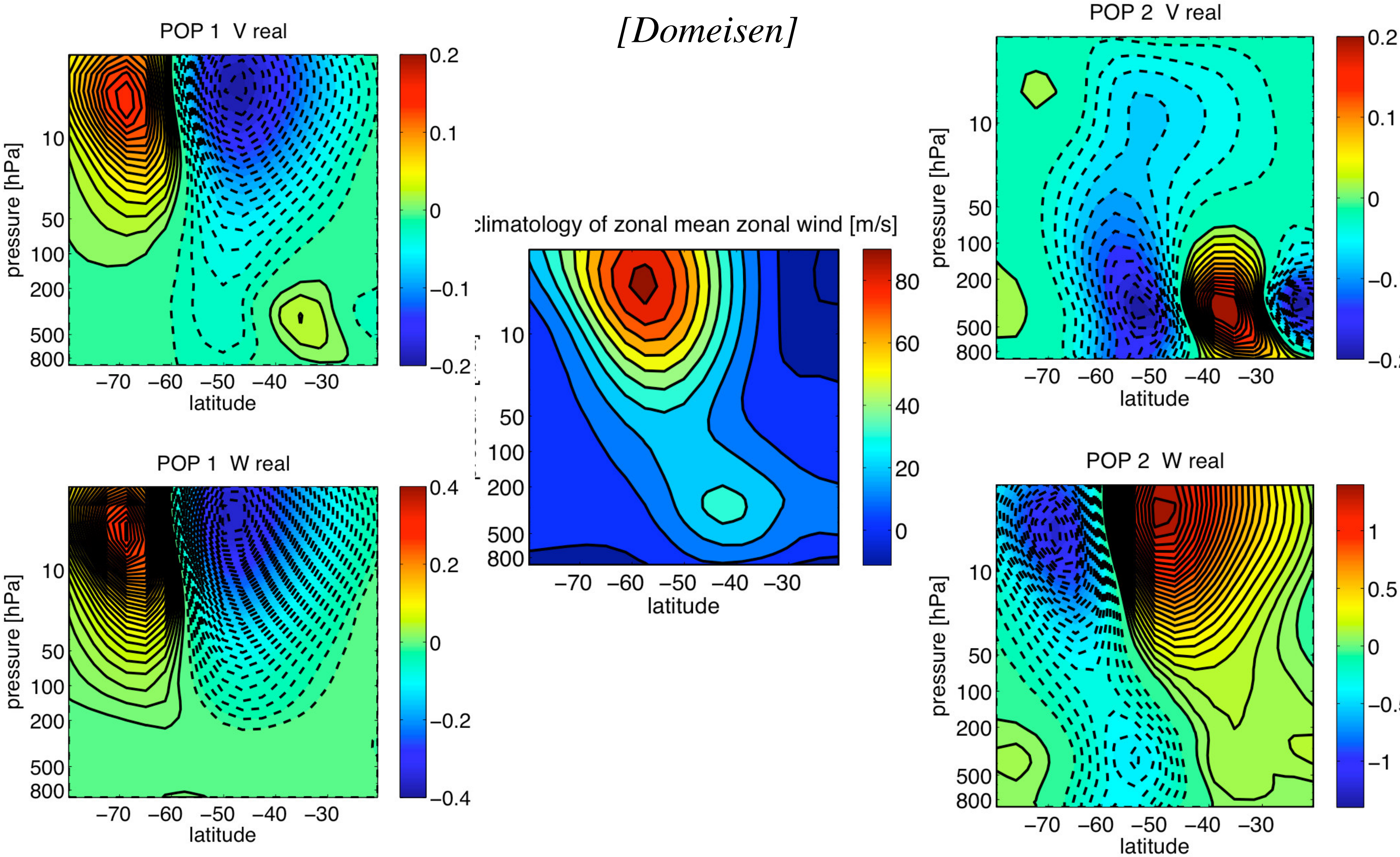


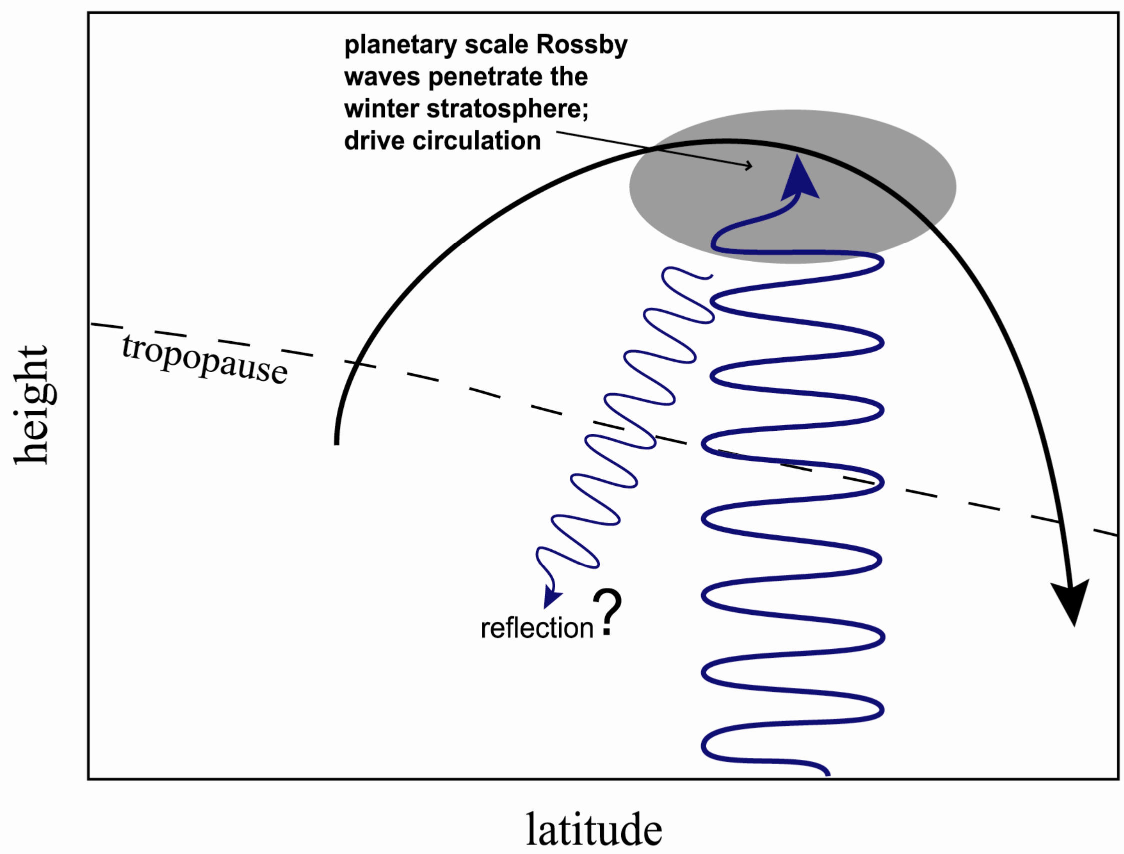
pressure-weighted

not pressure-weighted

POPs

[Domeisen]





Anderson et al.

Conclusions

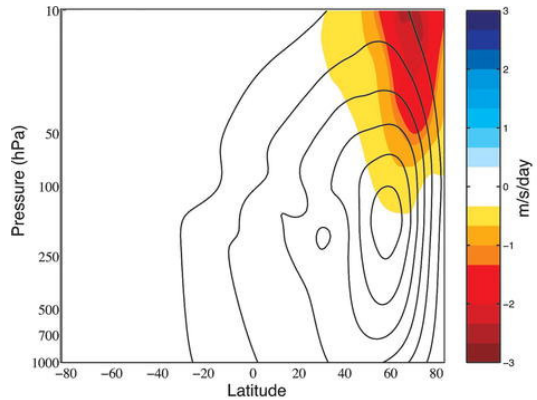
$$x_n = \lambda_n^{-1} g_n = \tau_n g_n$$

- FDT works *reasonably* well as a predictor of system response
- Response depends on projected *effective* forcing **and** on autocorrelation time τ of "natural" fluctuations
- Model simulations need to have good EOFs (or POPs) **and** their autocorrelation times
- POP analysis suggests distinct stratospheric and tropospheric modes
- Hard to determine robust adjoint POPs for stratosphere-troposphere model to do accurate prediction from FDT
- Response to tropical forcing does not fit the pattern – strong Hadley circulation response

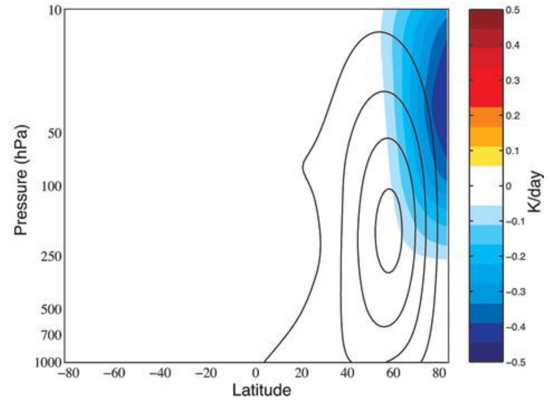
Kuo-Eliassen response
to observed forcing

[Thompson et al., *J Atmos* Sci, 2006]

Δ (div **F***)*

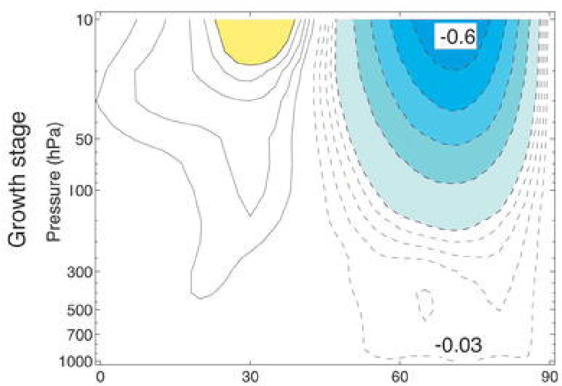


ΔQ

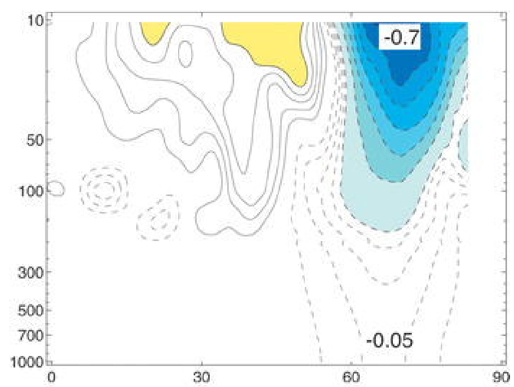


X

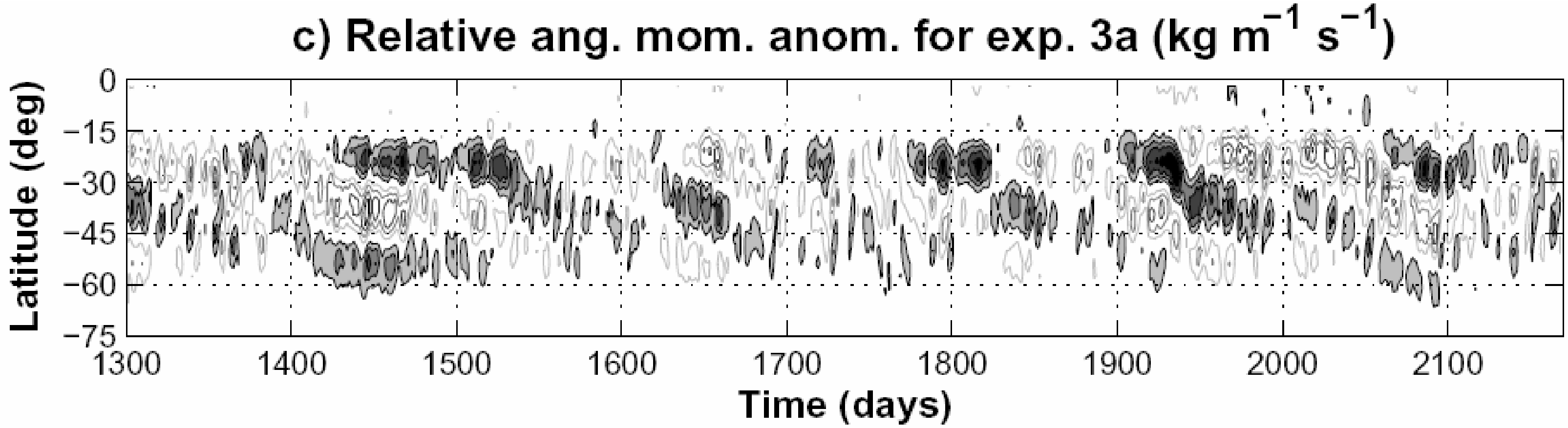
observed

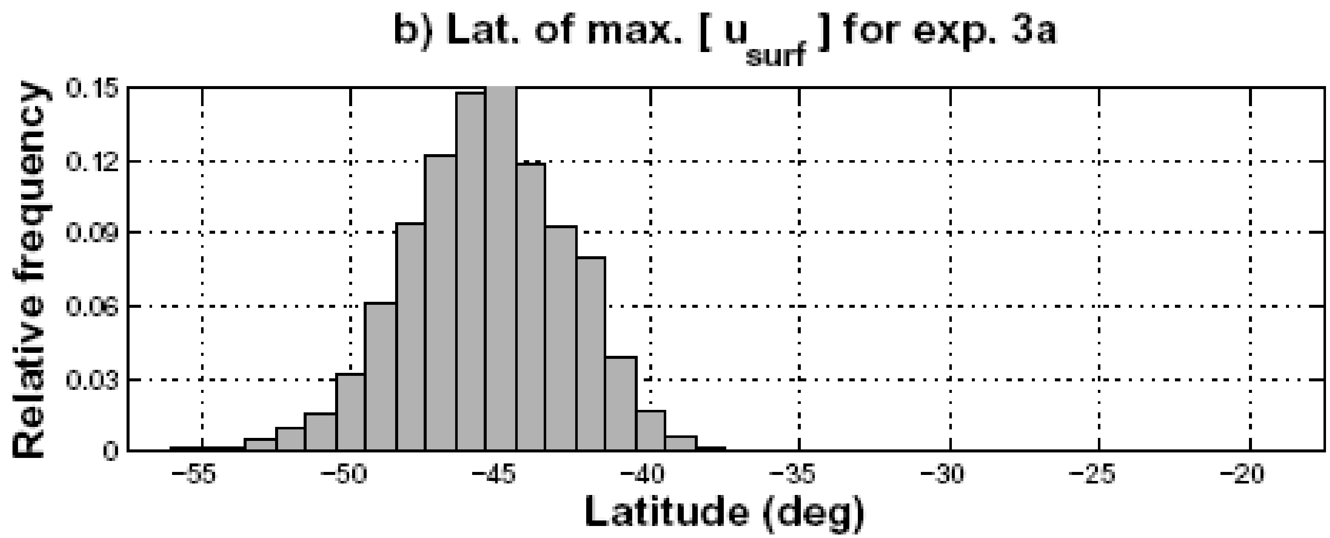


calculated



u_t





Chan & Plumb (2009)

$$\frac{\partial z}{\partial t} = \tilde{m} - D^{-1}z$$

$$\tilde{m} = m + Bz$$

$$\rightarrow \frac{\partial z}{\partial t} = m - \tau^{-1}z$$

$$\tau^{-1} = D^{-1} - B$$

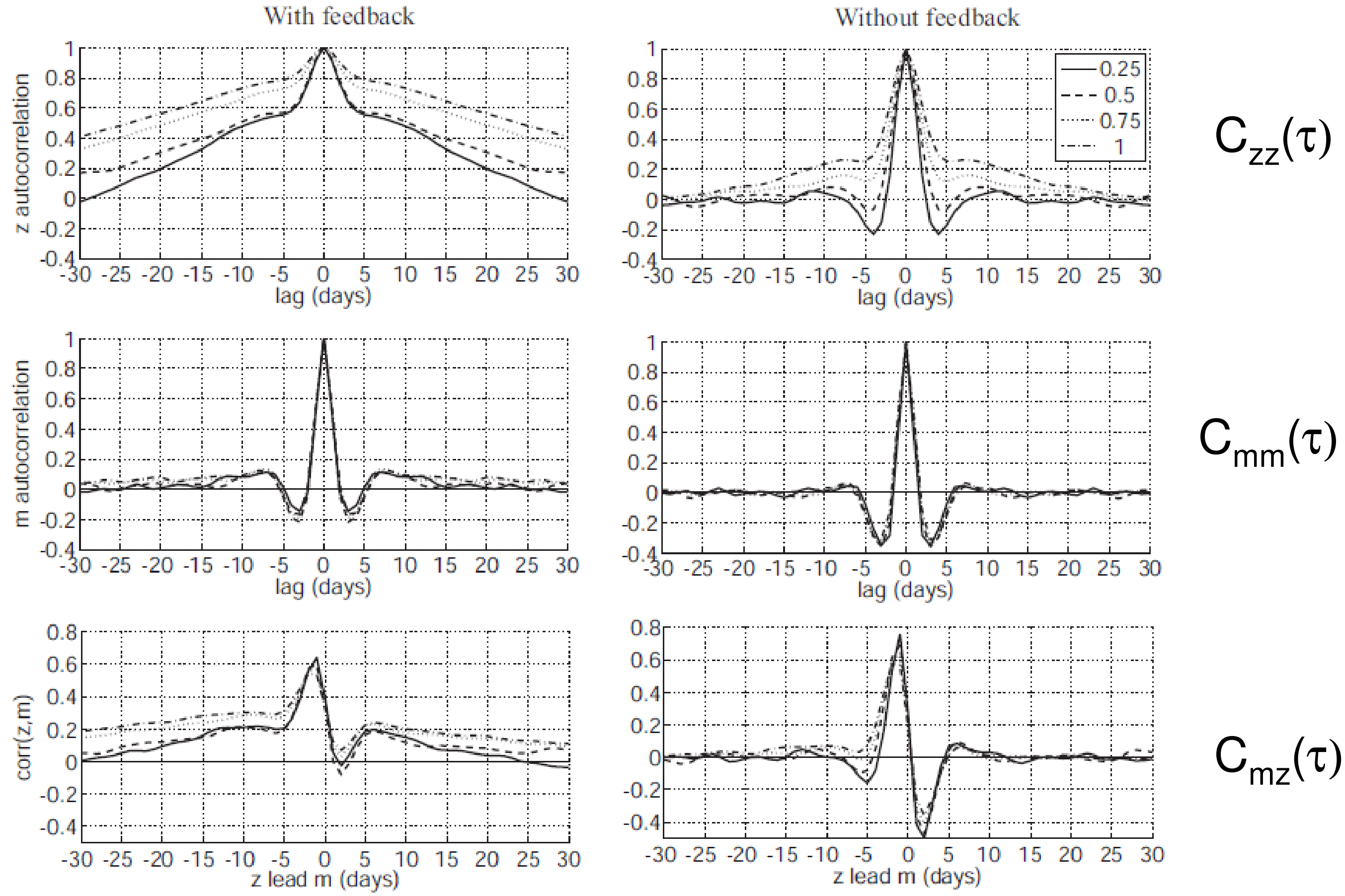


FIG. 5. The autocorrelation functions of (top) the zonal index and (middle) eddy forcing, and (bottom) their cross-correlations for different surface frictional damping time scales. The left column shows the correlations for z and m, and the right column shows the correlations for $\tilde{z}$ and $\tilde{m}$ where the feedback is eliminated. *(Chen & Plumb, 2009)*

$$\frac{\partial z}{\partial t} = m - \tau^{-1} z$$

$$\tau^{-1} = D^{-1} - B$$

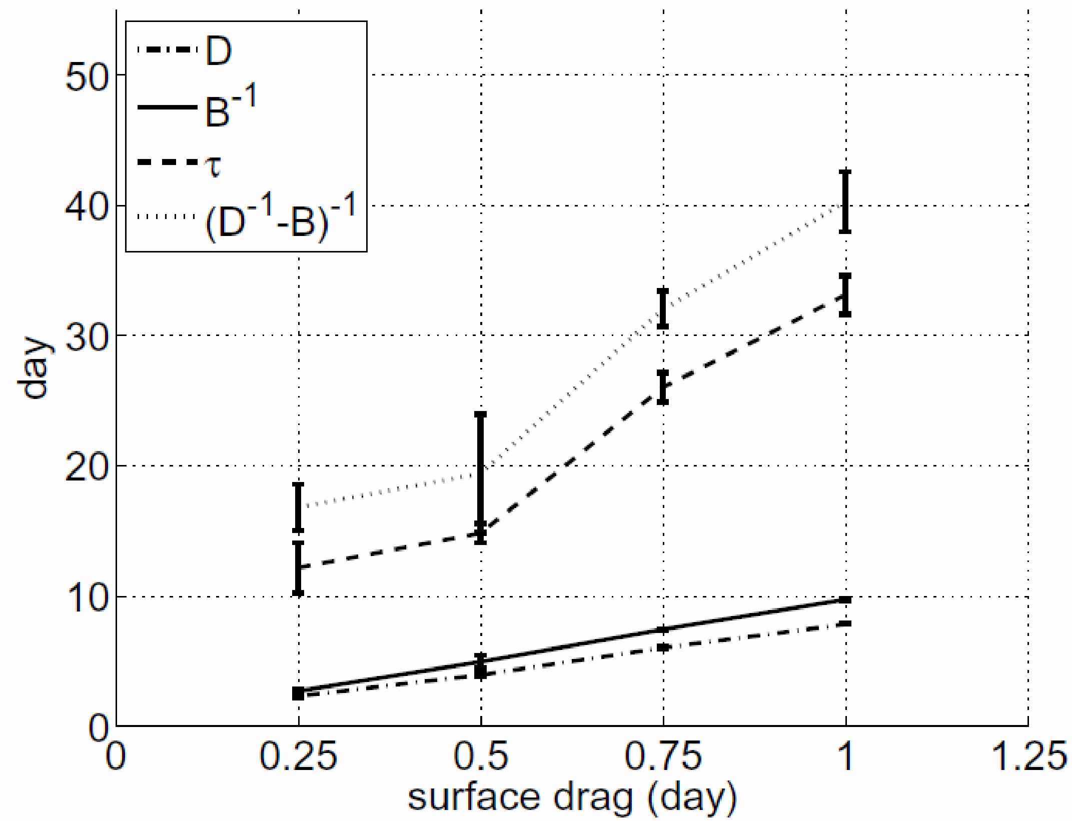


FIG. 7. The time scale of the zonal index damping D, eddy feedback B^{-1}, and the zonal index decorrelation τ as a function of surface friction. The error bars denote the difference of the two hemispheres. Note that the inverse of the eddy feedback is plotted.

Chan & Plumb (2009)

$$\frac{\partial z}{\partial t} = m - \tau^{-1} z$$

$$C_{zz}(\Delta t) = \int_{-\infty}^{0} \int_{-\infty}^{0} C_{mm}(\Delta t + r - s)\ \exp\left(\frac{r+s}{\tau}\right) ds\, dr$$

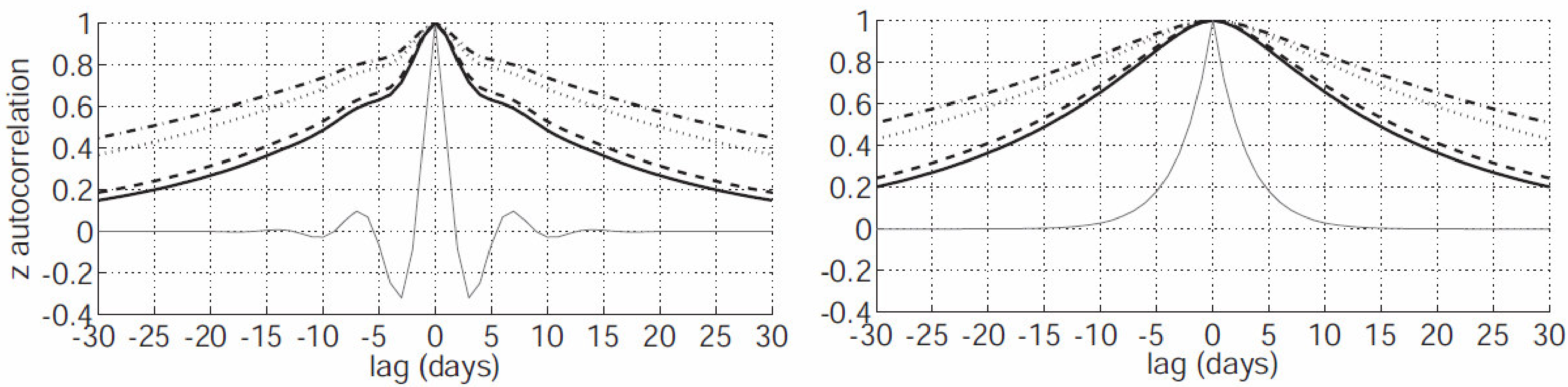


FIG. 6. The autocorrelation function of the zonal index for different surface frictional damping time scales, but the autocorrelation of $\tilde{m}$ is assumed of the form of Eq. (10), and is shown in the gray solid line. We use the best fit to the model result on the left, and remove the sinusoidal part and keep the same eddy decorrelation time scale on the right. The lines are symbolized in the same way as in Fig. 5. *(Chen & Plumb, 2009)*

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