Propagating annular modes

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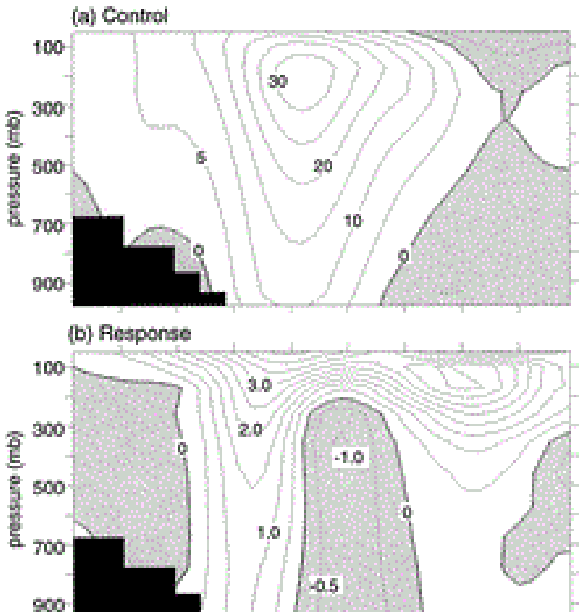
Fluctuation-dissipation theorem

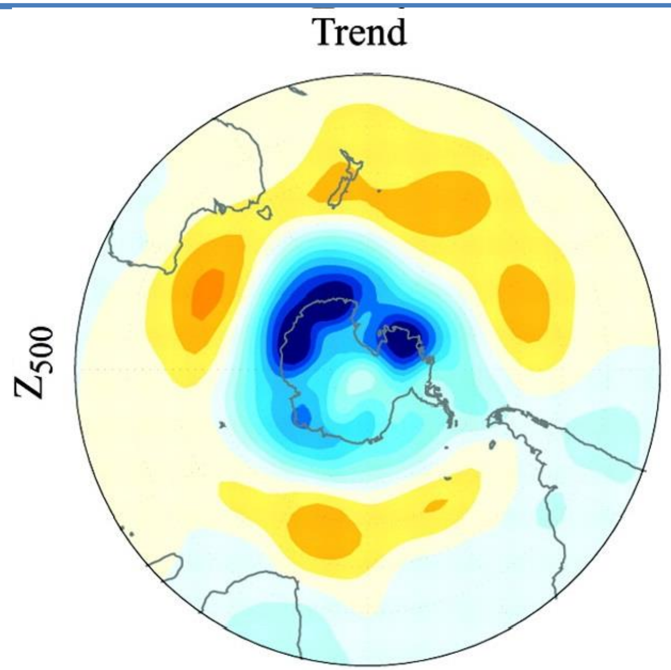
Relates the perturbed response of a dynamical system
to its unperturbed variability

Response = τ (mode timescale) × projection of the forcing on the mode

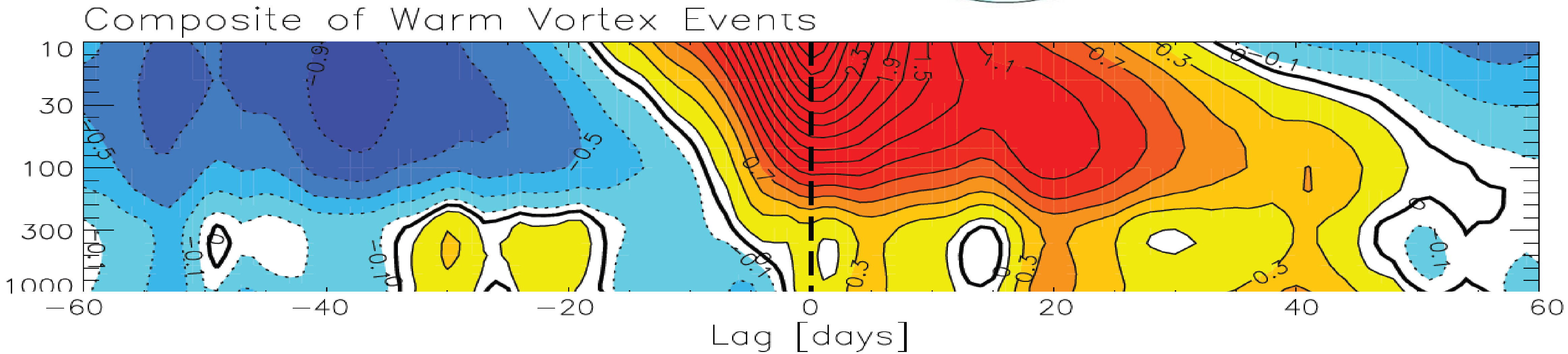
Dynamical climate responses and the fluctuation-dissipation theorem



GHG
Kushner et al. 2001



Ozone hole
Thompson and Solomon 2002



Kushner (2010)

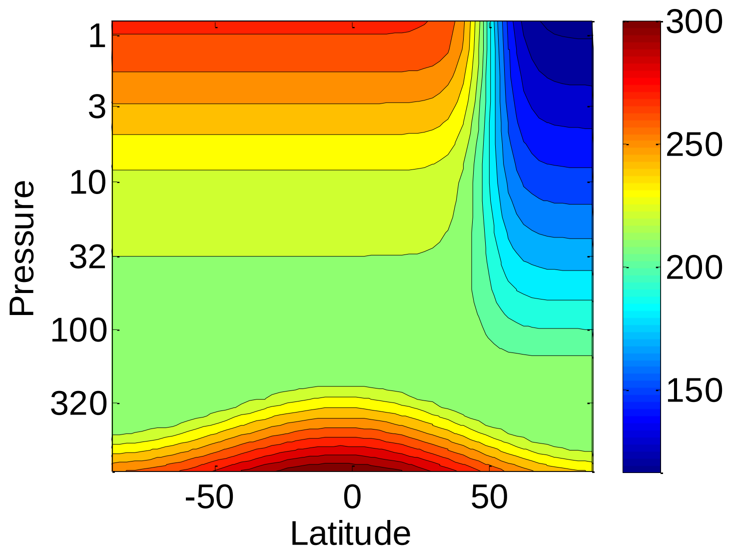
Model setup

- Dry, hydrostatic, global primitive equation model (based on Polvani and Kushner, 2002), T42, 40 levels

- Replaces radiation and convection schemes with relaxation to a zonally symmetric T_{eq}, that is similar to Held Suarez in the troposphere

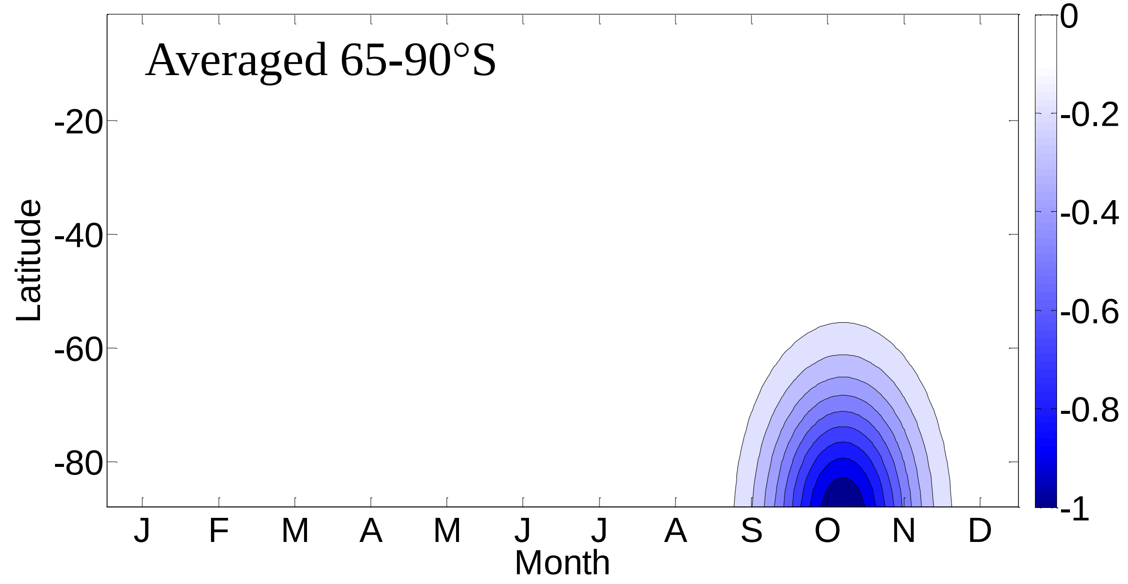
- In the stratosphere (above 200 hPa), equilibrium temperature set to U. S. Standard atmosphere, except over the winter pole, where a cold anomaly provides a representation of the polar vortex

- Simple seasonal cycle in equilibrium temperature that is **confined to the stratosphere**



T_{eq} at NH winter solstice

Polar stratospheric cooling

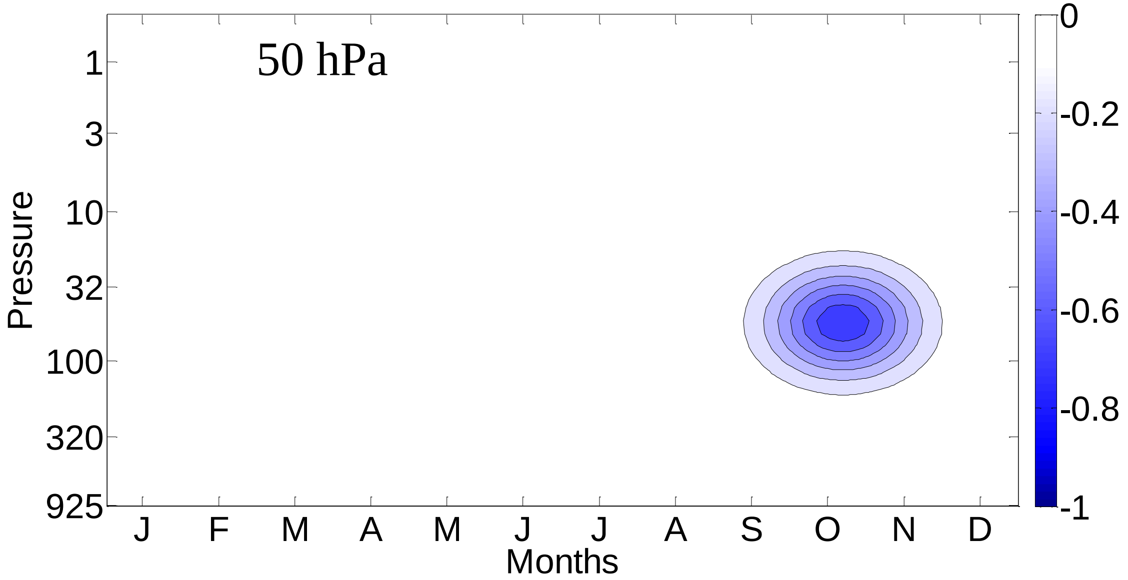


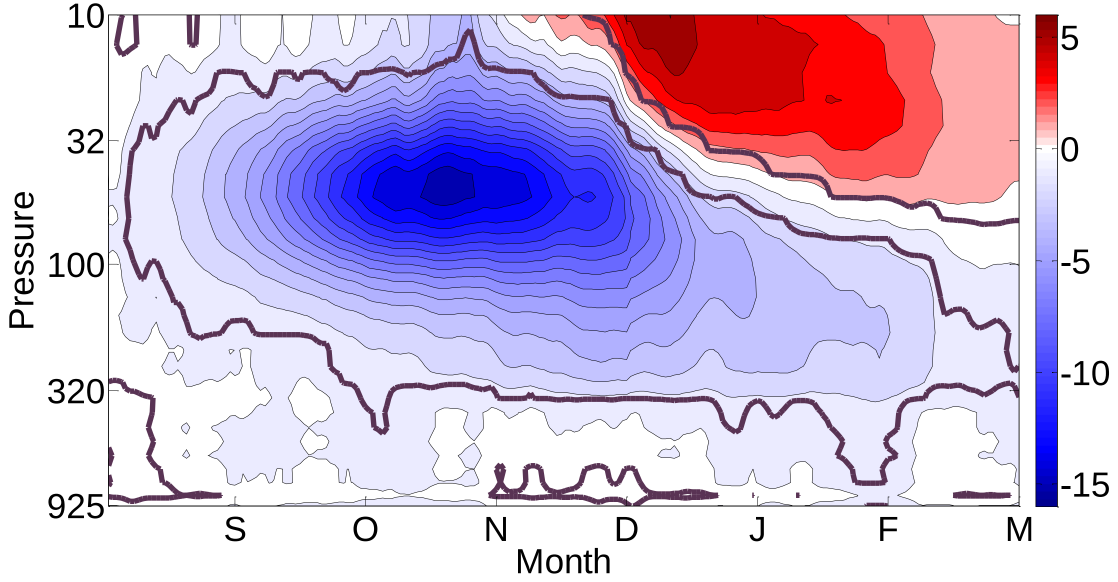
$$Q(\phi,\sigma,t) = q_0 \exp\left[-\left\{\frac{(\phi-\phi_0)^2}{2\sigma_\phi^2} + \frac{(-7000\ln\sigma + 7000\ln\sigma_0)^2}{2\sigma_\sigma^2} + \frac{(t-t_0)^2}{2\sigma_t^2}\right\}\right]$$

Similar to Butler et al. 2010 and Sun et al. 2014, but with

$q_0 = -0.5K/day$ $\phi_0 = -\pi/2$ $\sigma_\phi = 0.28$ $\sigma_0 = 0.05$

$\sigma_\sigma = 4000$ $\sigma_t = 20$ t_0= *October 20* (We'll vary this)

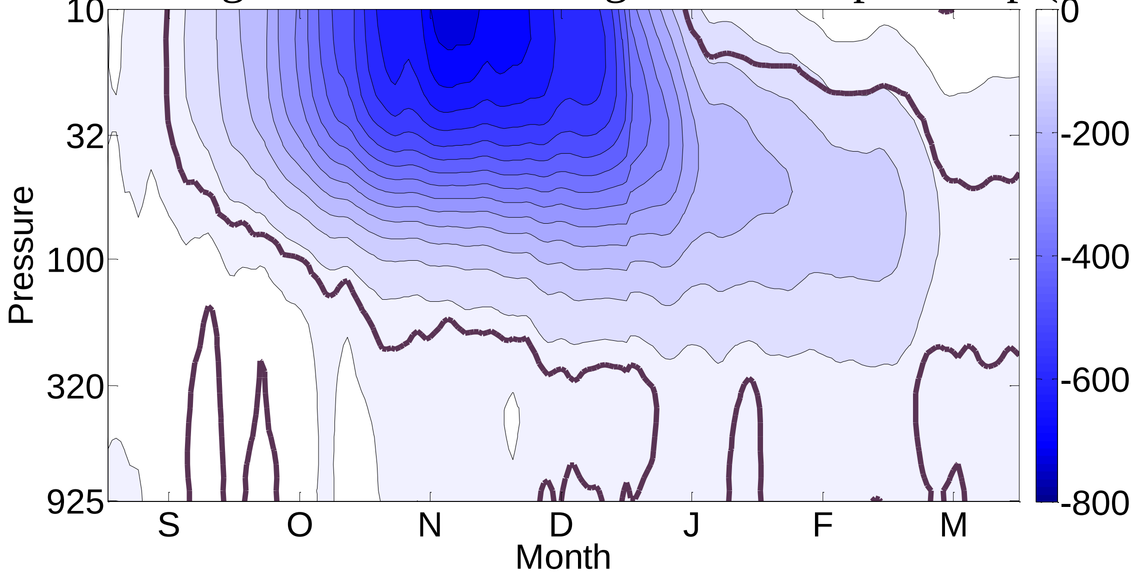




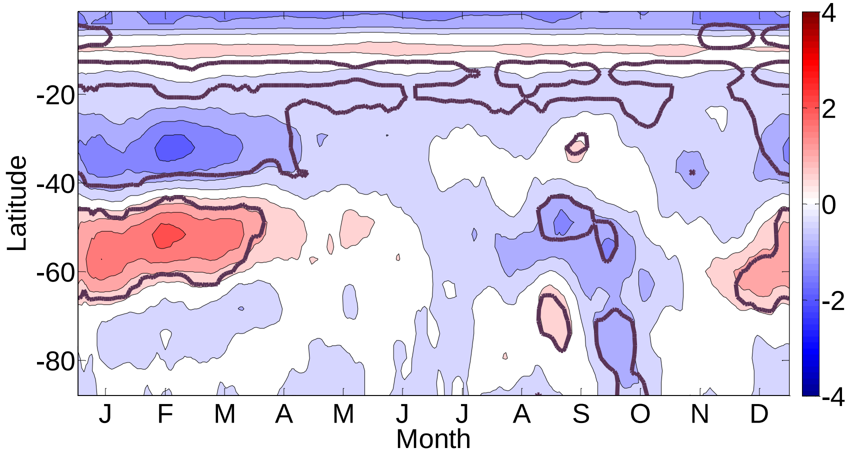
Temperature difference averaged over the polar cap (65-90°S)

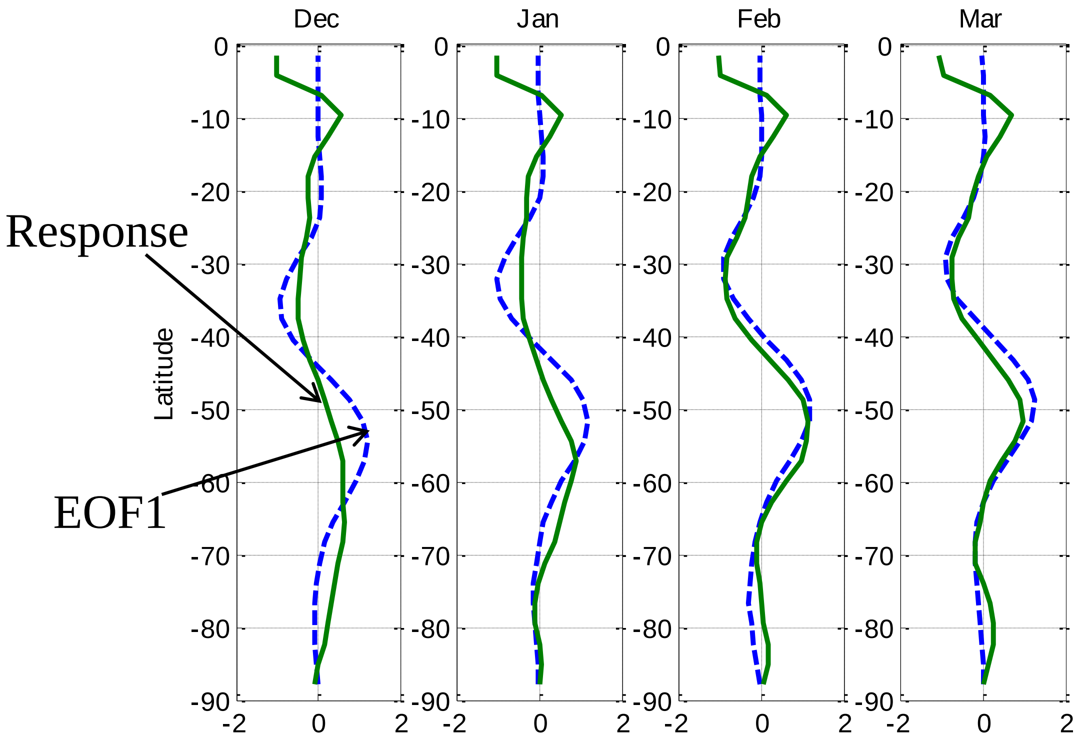
Tropospheric circulation changes

Geopotential height difference averaged over the polar cap (65-90°S)



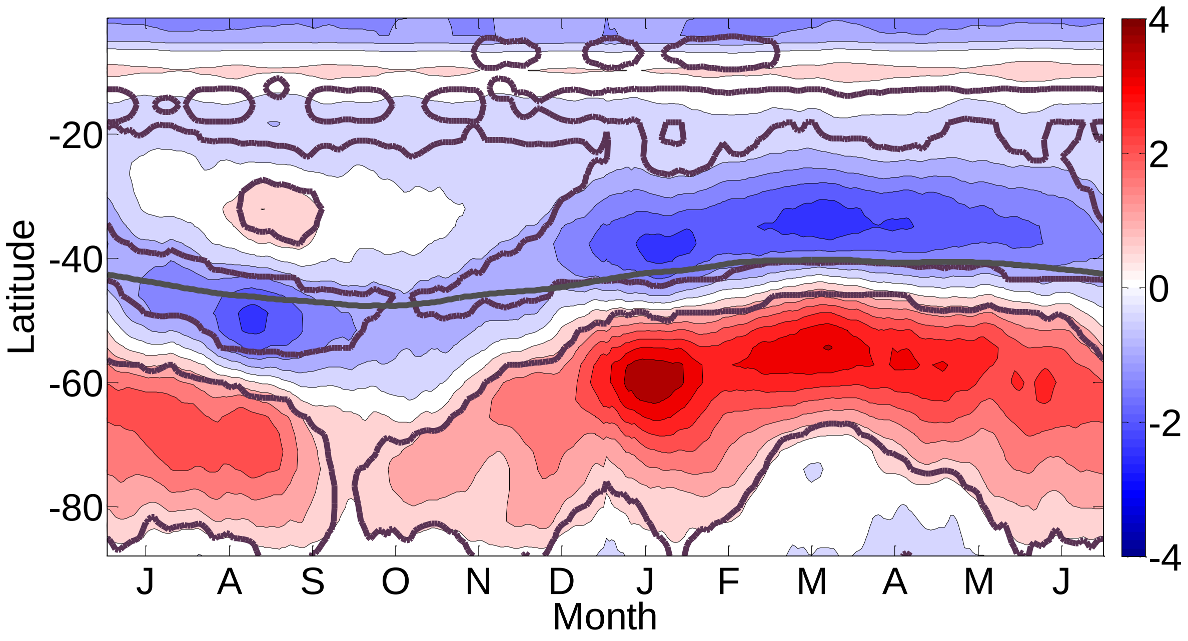
850 hPa [u] response

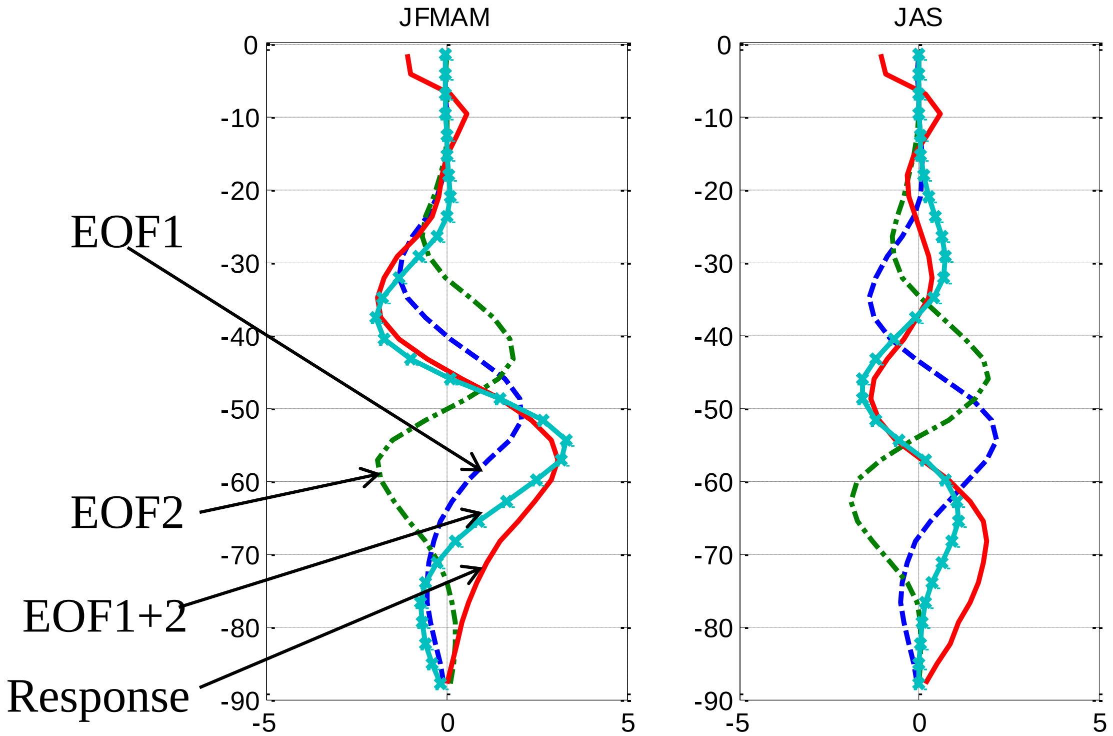




850 hPa [u] response doesn't always match the first annular mode!

Surface responses to all year cooling – involves 2 EOFs

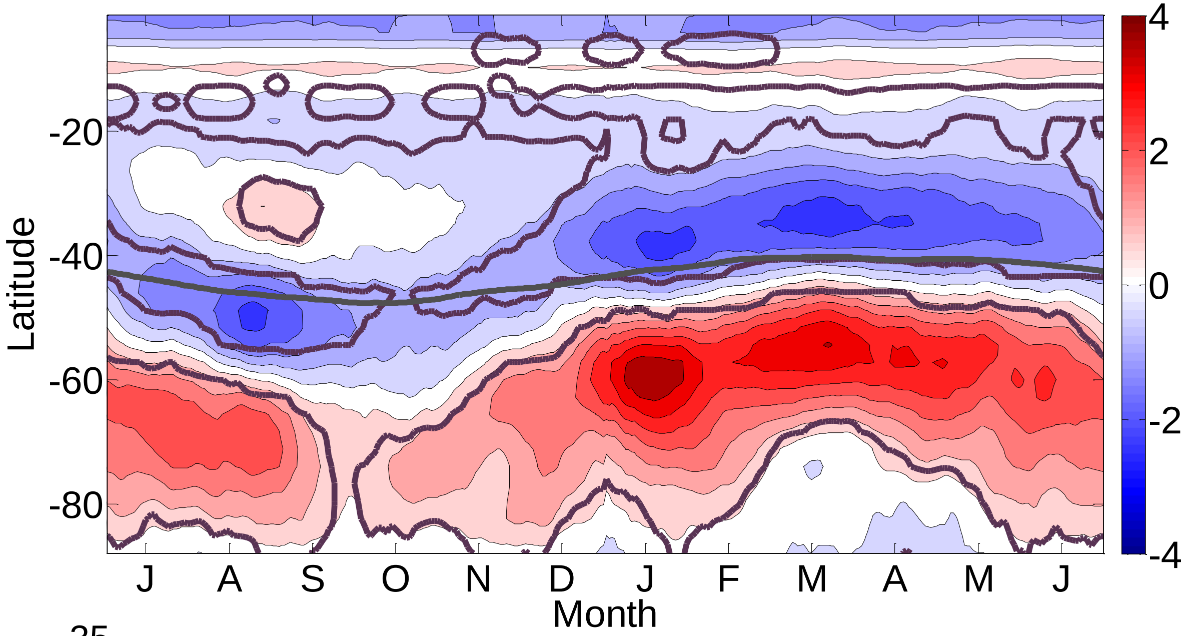


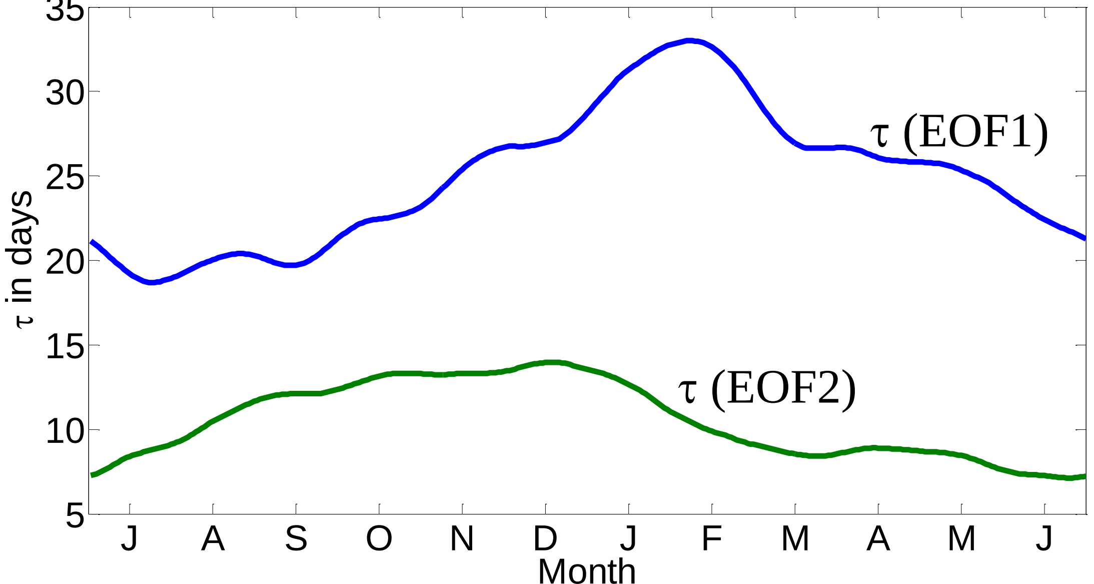


- Large dipole response early in the year
- Minimum, poleward shifted response in SON

Almost all the response explained by sum of contributions from 2 EOFs

Seasonal cycle of annular mode timescales

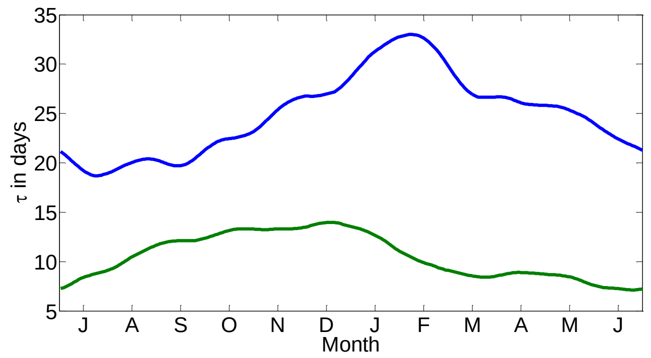




- Seasonality in tropospheric τ (in the control run) induced by lower stratospheric seasonality
- If the projection of the forcing on the modes does not change through the year, the response in mode 2, relative to 1 would change by a factor of 2 over the year

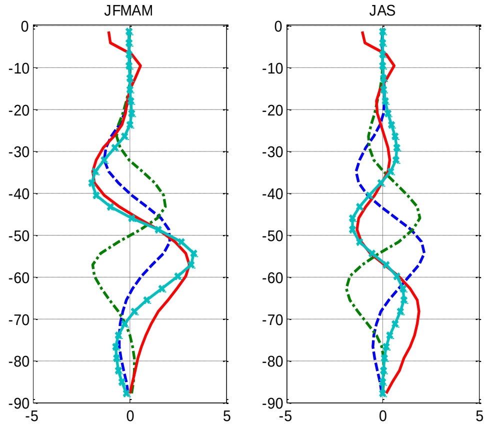
Summary – tropospheric response to ozone depletion

- Stratospheric seasonal cycle leads to seasonal changes in the persistence of the tropospheric mid-latitude jet and storm tracks



- The response of the atmosphere to external forcing cannot be described by a single “annular mode”!

  (cf. Black and McDaniel 2007a,b)



Sheshadri and Plumb 2016a

Two leading EOFs actually one propagating mode?

- **P**rincipal **O**scillation **P**atterns (POPs) are the true modes

e.g. Von Storch (1988), Penland (1989)

$$G_\tau = C_\tau C_0^{-1}$$

$$G_\tau = V\Gamma_\tau W^T$$

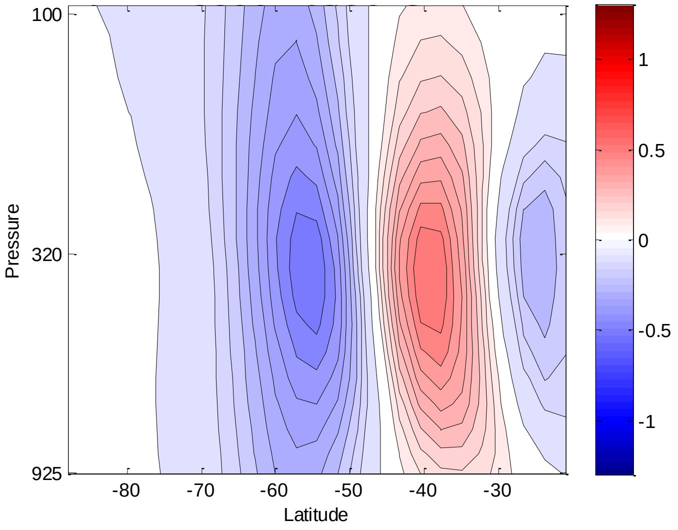
they contain dynamical information, and can be used to extract both **spatial patterns** and **timescales.** If EOFs were all independent, POPs would look like EOFs.

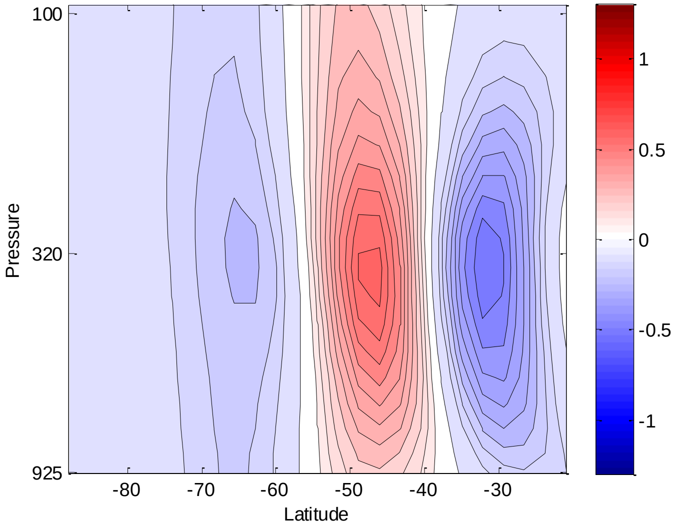
- Let's simplify the problem, and look at a perpetual winter situation

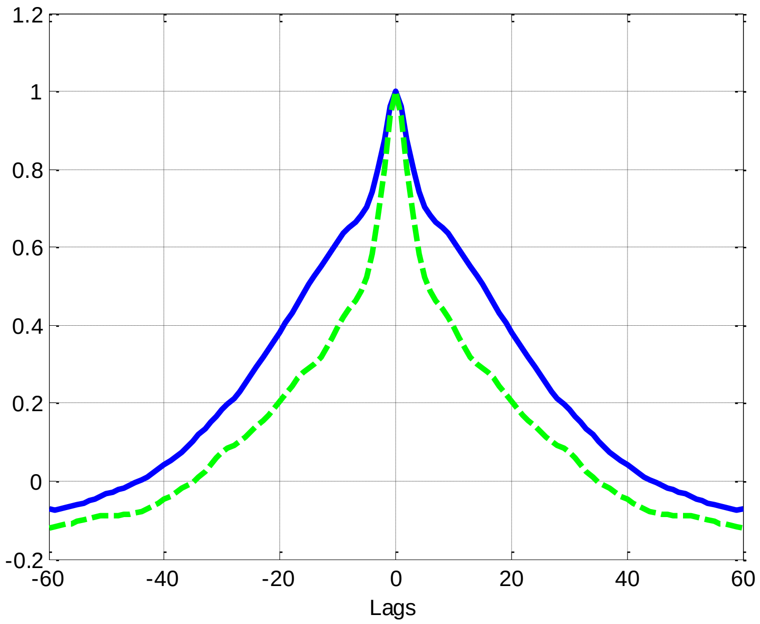
Are the model's **two leading EOFs** actually **one mode** describing **systematic latitudinal migrations** of the jet?

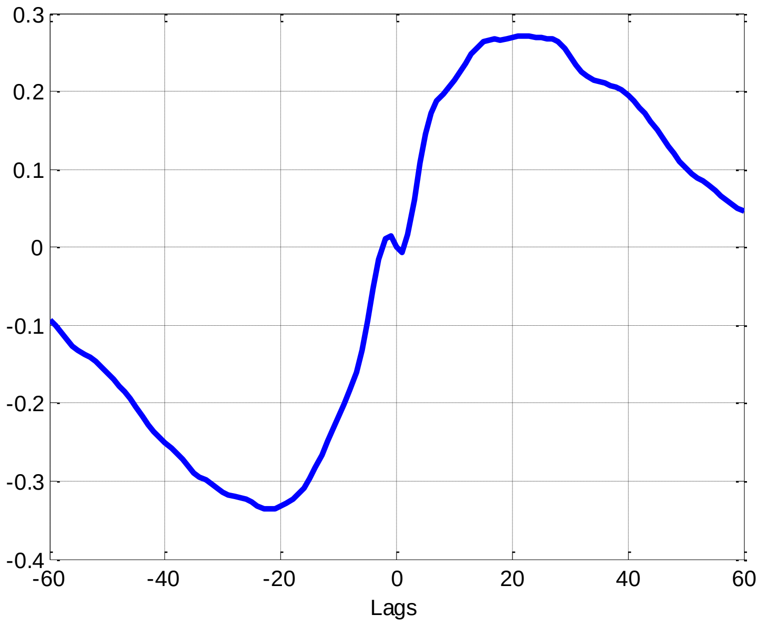
PCs of two leading EOFs show lagged cross-correlation

2 leading EOFs explain 40% and 29% of variance, with τ = 19 and 13 days



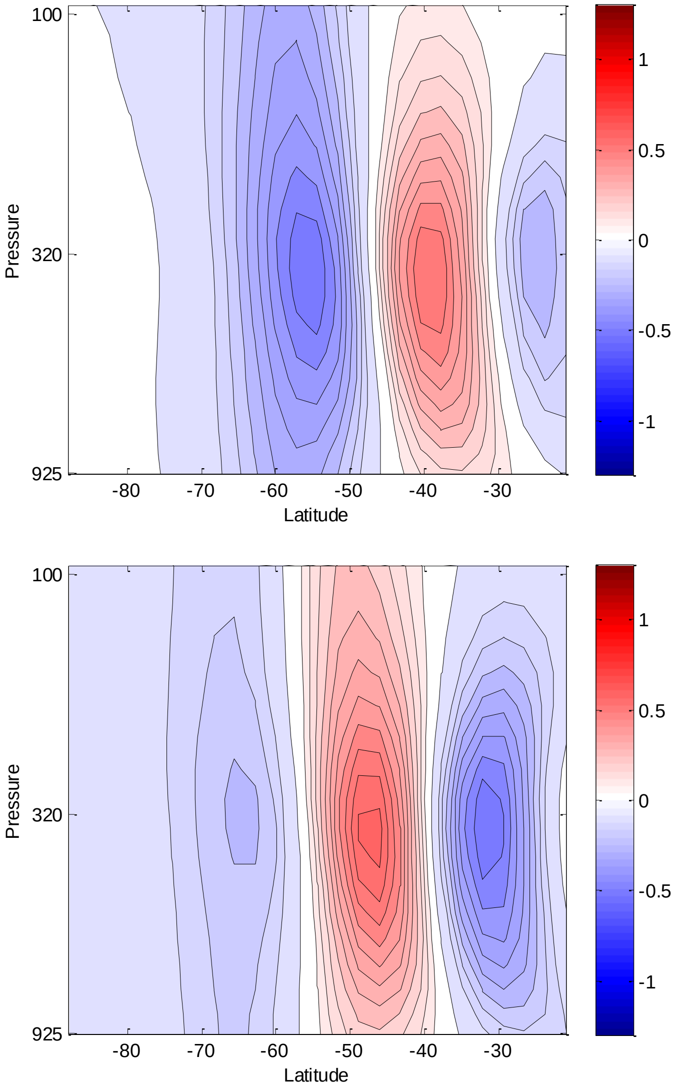




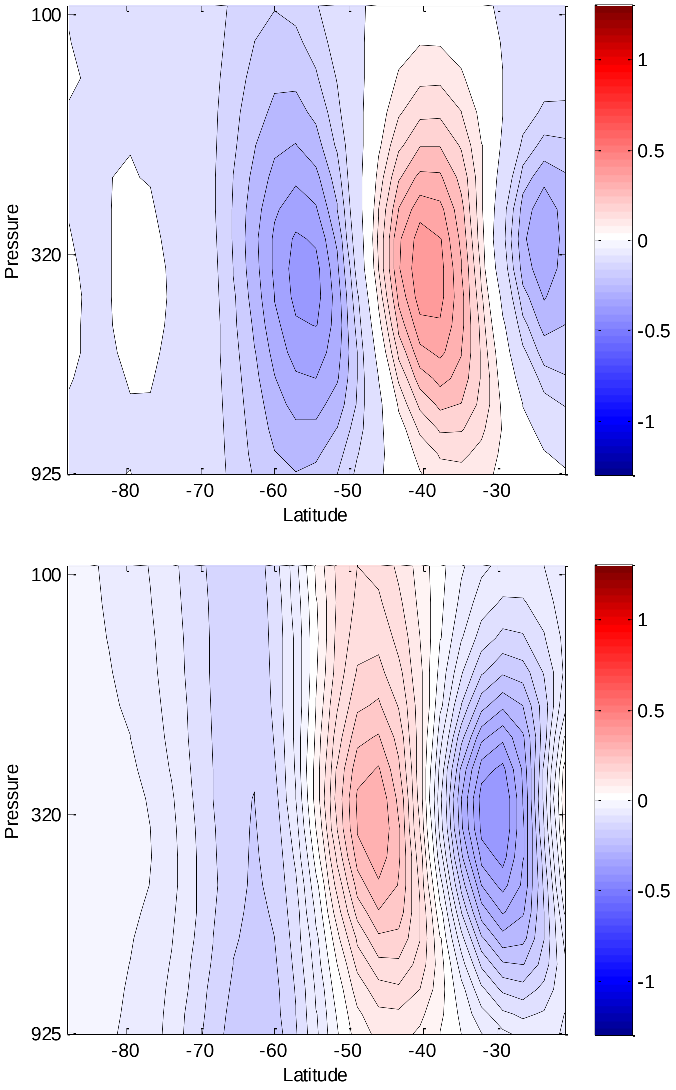


Complex conjugate eigenvalues/eigenvectors imply propagation

2 leading EOFs explain 40% and 29% of variance, with τ = 19 and 13 days

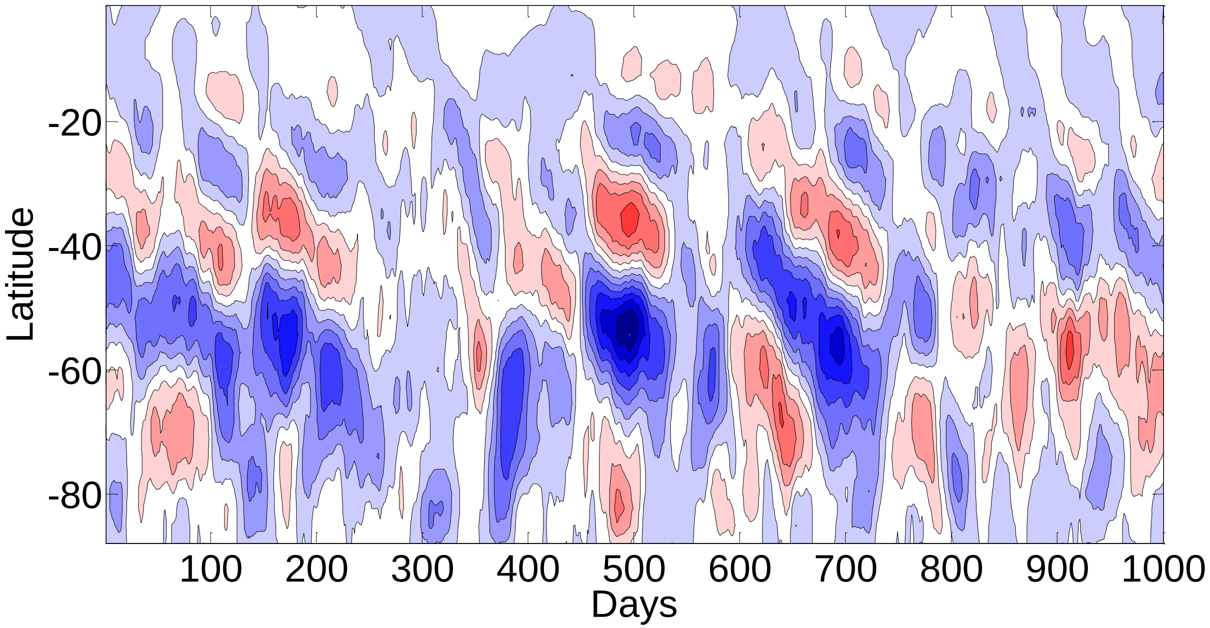


POP, (Re/Im) Γ=0.3574±0.4818i

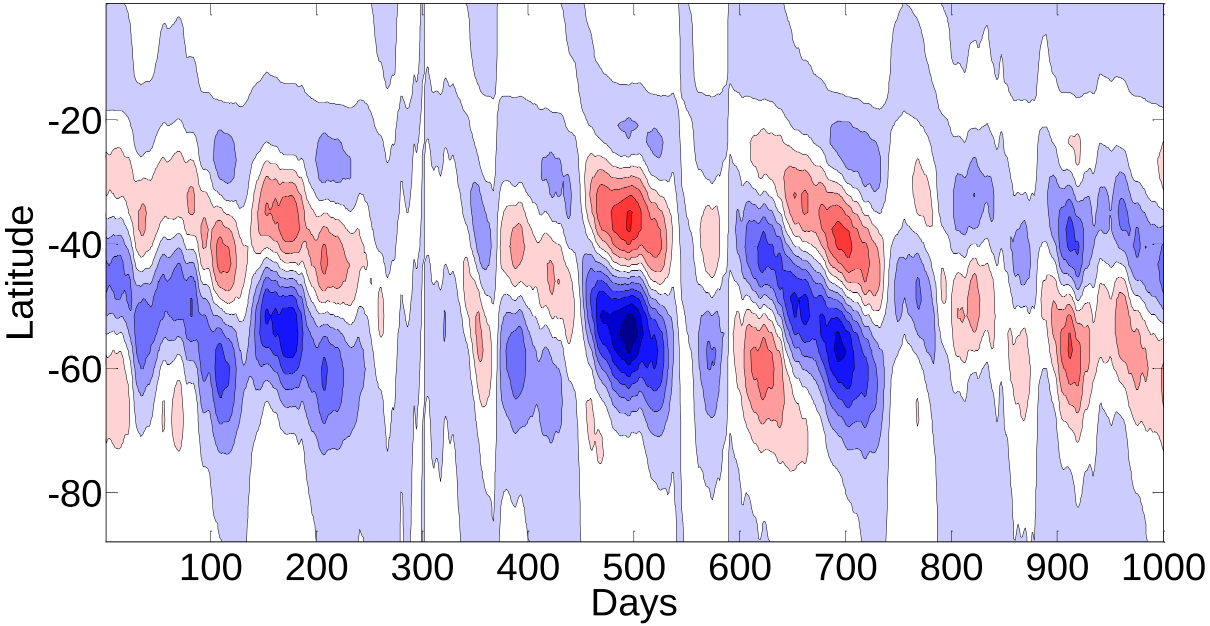


Gives a decay time of 39 days, and a period of 134.8 days (recovers the lag at which cross-correlation maximizes)

Poleward propagation of wind anomalies



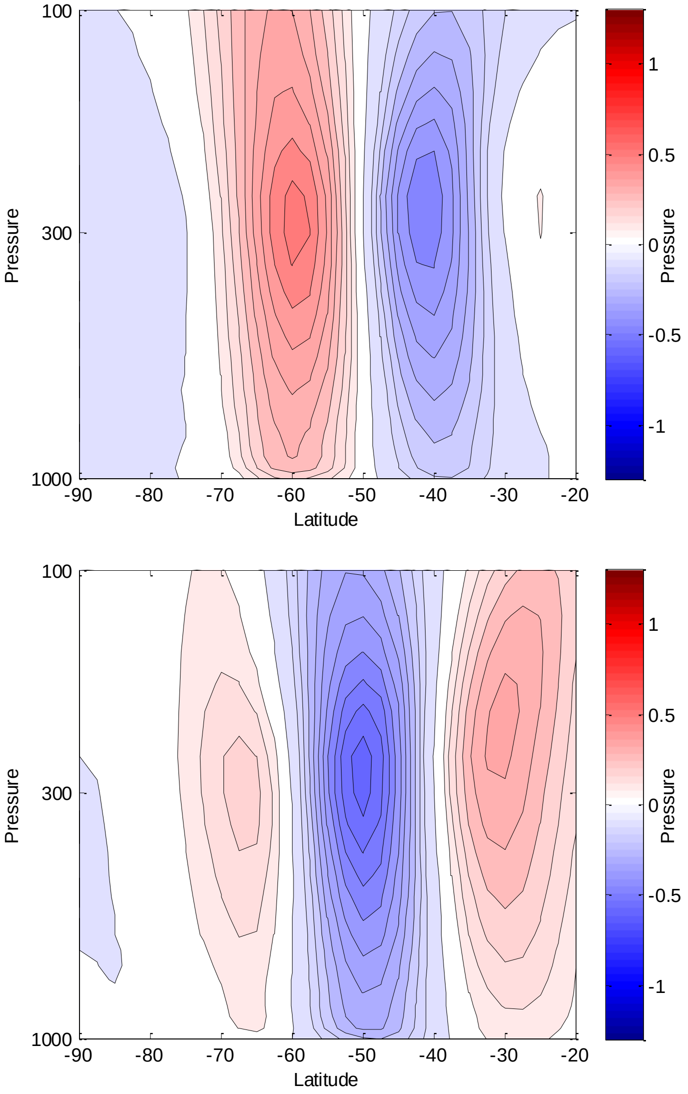
[u] anomalies integrated through the troposphere show consistent poleward propagation.. (cf. Feldstein 1998)



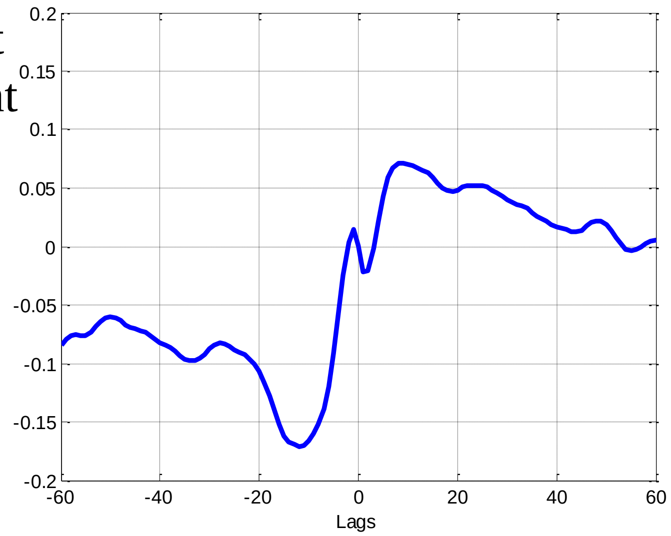
and are well captured by the first 2 EOFs

ERA-I consistent with this picture

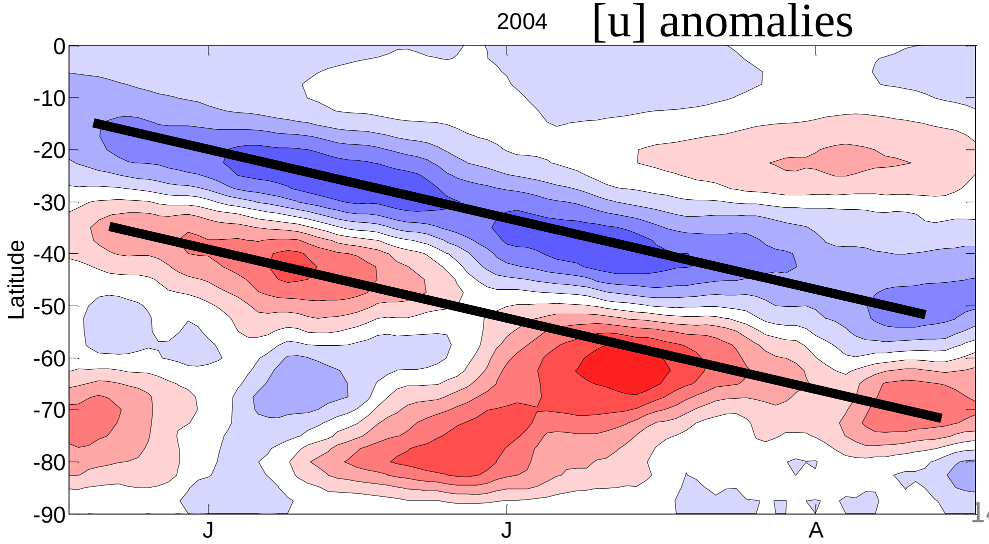
2 leading EOFs explain 37% and 19% of variance, with τ = 11 and 8 days



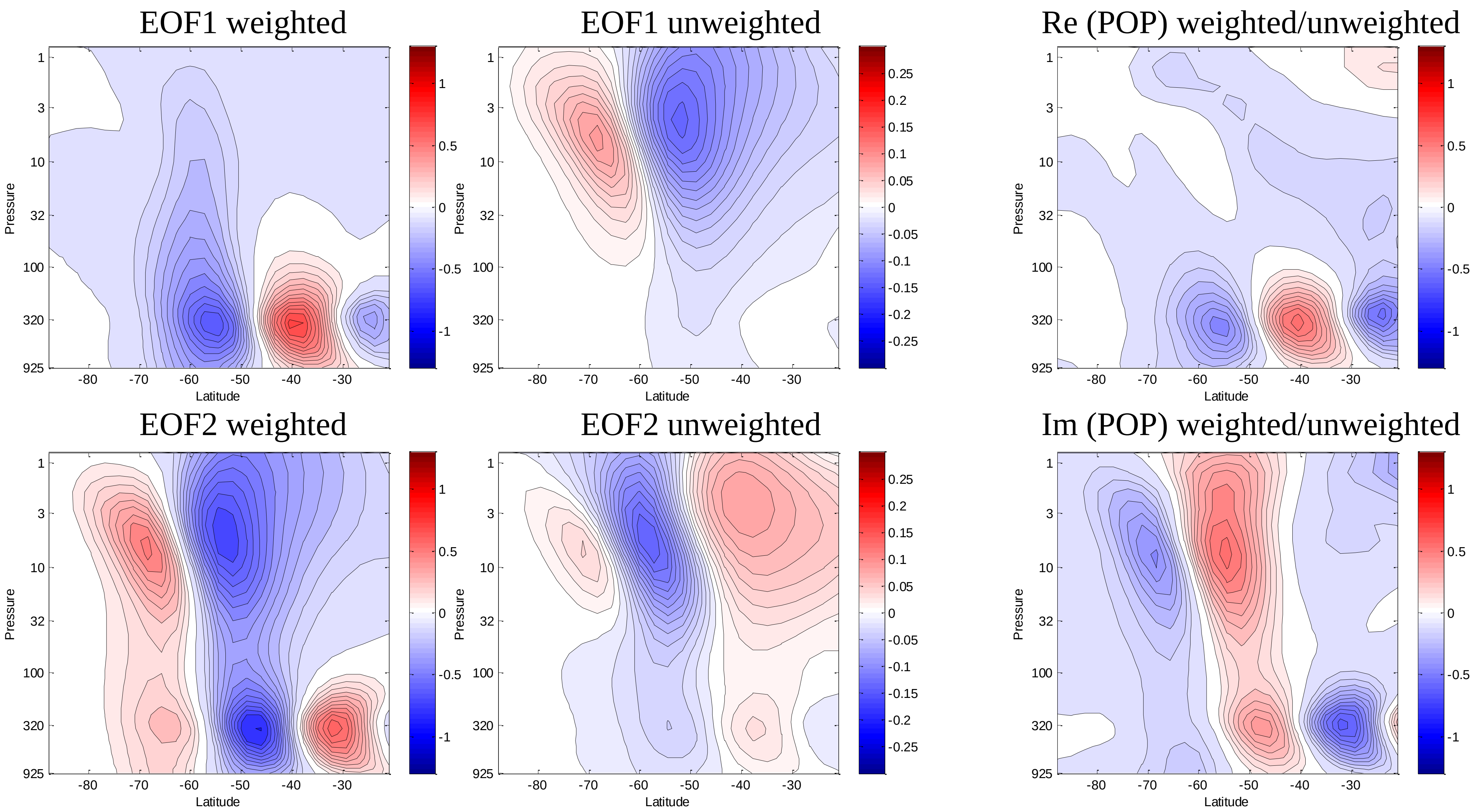
PCs are not independent



Poleward propagation of [u] anomalies

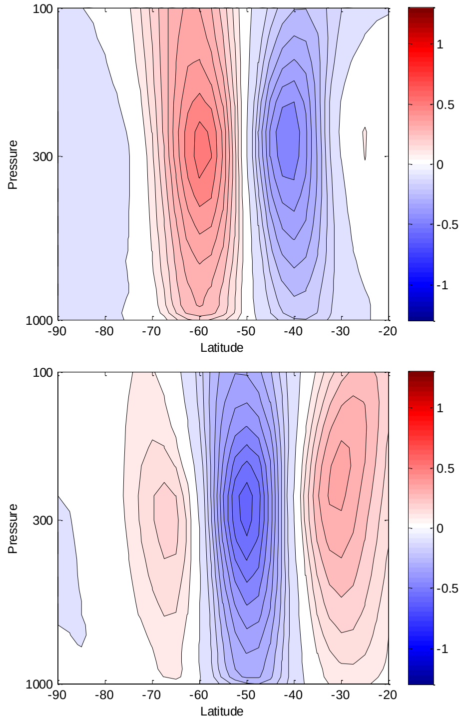


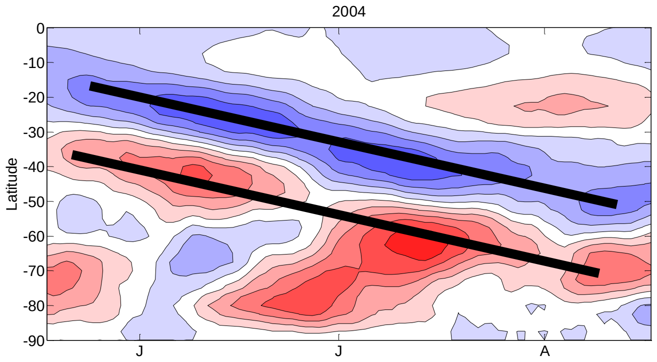
POPs are independent of pressure weighting



Summary – propagating annular modes

- 2 leading EOFs form one coupled, propagating mode, describing systematic latitudinal jet migration





- Models need to get POPs **and** their timescales correct

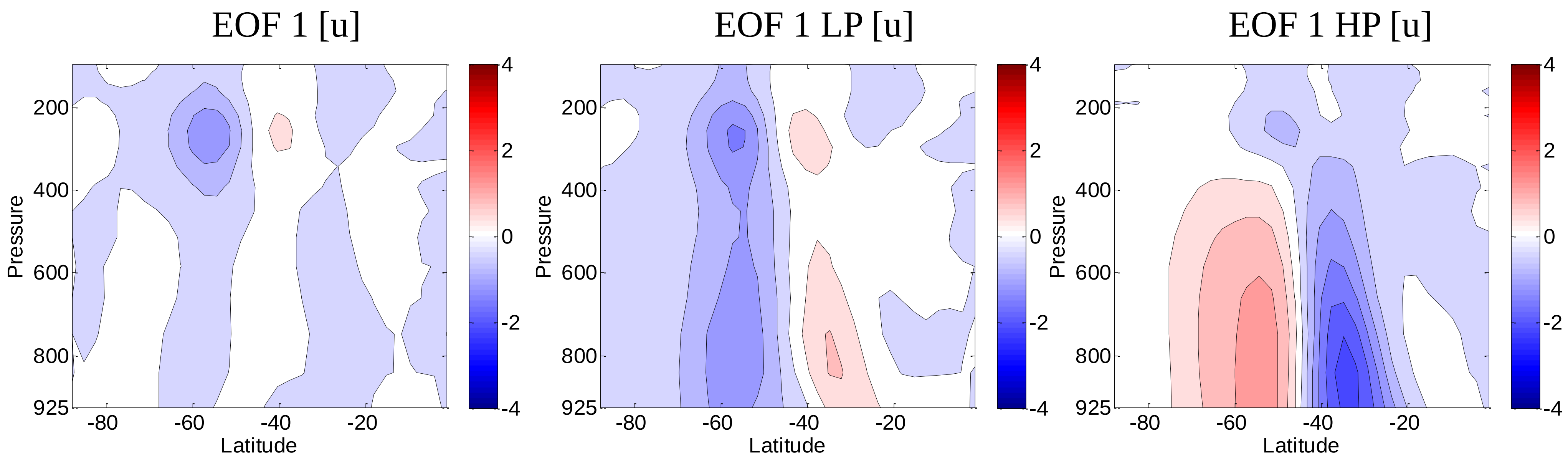
- Future work…how does external forcing project onto this mode?

More details in a paper in preparation, to be submitted soon

My website: http://www.columbia.edu/~as4915 For future questions, please email aditi_s@ldeo.columbia.edu

Frequency-dependent barotropic/baroclinic modes

Regressions of heat flux on..
(cf. Thompson and Woodworth, Thompson and Barnes)



Sheshadri and Plumb 2016b (in review at J. Atmos. Sci.)