Internal variability of zonal flow in the two-layer model and in observations

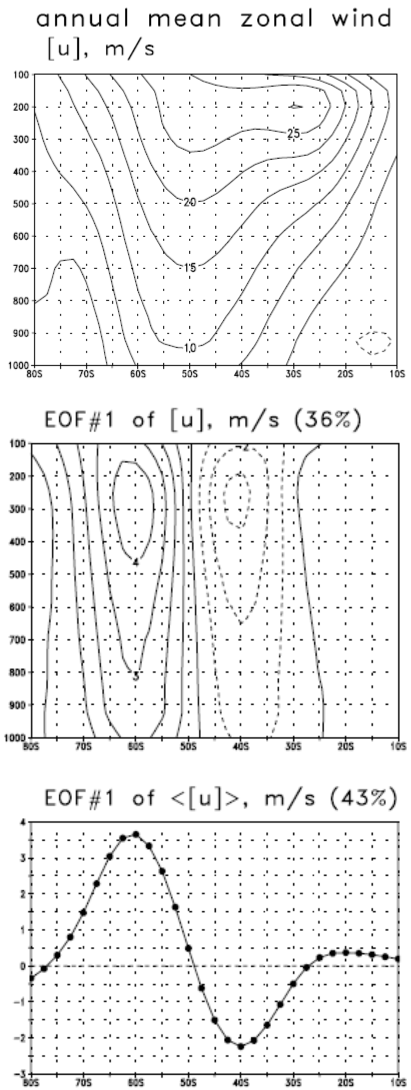
Pablo Zurita Gotor

Javier Blanco-Fuentes

Universidad Complutense, Madrid, Spain

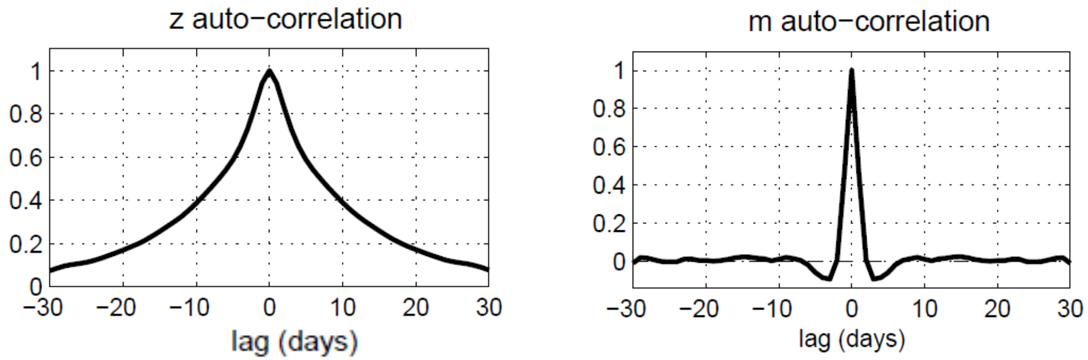
Hierarchical modeling of Climate. Trieste, 7/18/11

Extratropical zonal wind variability

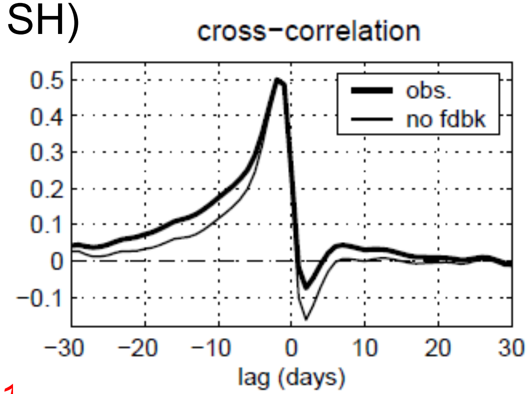


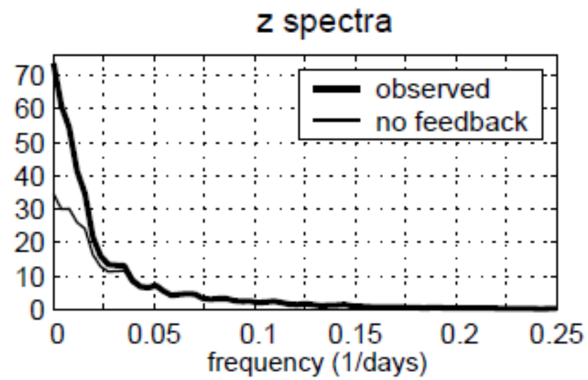
- Leading mode of variability: equivalent barotropic latitudinal shift.
- Forced by the eddy momentum flux, but much more persistent

$$\frac{\partial z}{\partial t} = m - Fric \qquad z = \left(\int \bar{U} dz\right) \cdot EOF \qquad m = -\left(\int \frac{\partial}{\partial y} \overline{u'v'} dz\right) \cdot EOF$$



- Eddy feedback modestly increases persistence (8.9 to 13 days in SH)





Lorenz and Hartmann (2001)

Motivation

A baroclinic mechanism for eddy feedback (Robinson 2000; Lorenz & Hartmann 2001)

Eddy momentum forcing displaces barotropic jet → Friction forces baroclinicity at the shifted latitude → Enhanced eddy generation/barotropic acceleleration there

Maintenance of baroclinic anomalies? Relation to barotropic variability?

CLIMATOLOGICAL BAROCLINICITY

- Generated by differential heating
- Damped by transient eddy heat flux
- Eddy momentum flux (Ferrel cell) smaller but not negligible.

FINITE TIME SCALES?

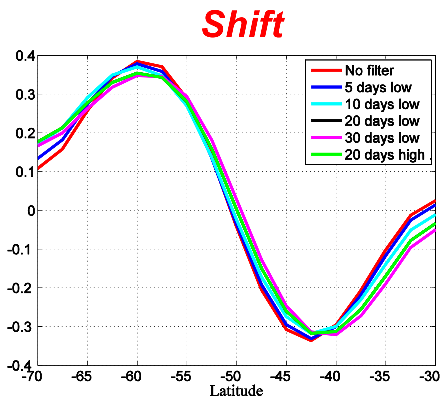
Two possible scenarios (time-scale dependent?)

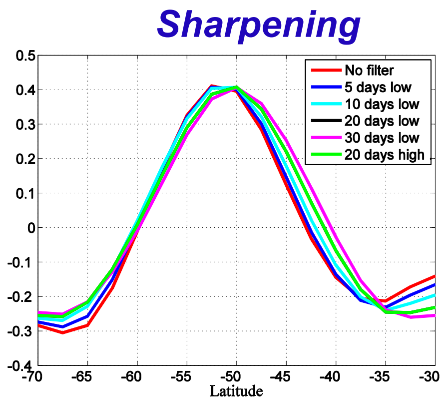
- Episodic eddy development (erase/restore cycles of baroclinicity) → pulsing variability
- Baroclinicity generated by eddy momentum fluxes → shifting variability

We study the ***dynamics of baroclinic variability*** in observations and in the two-layer model

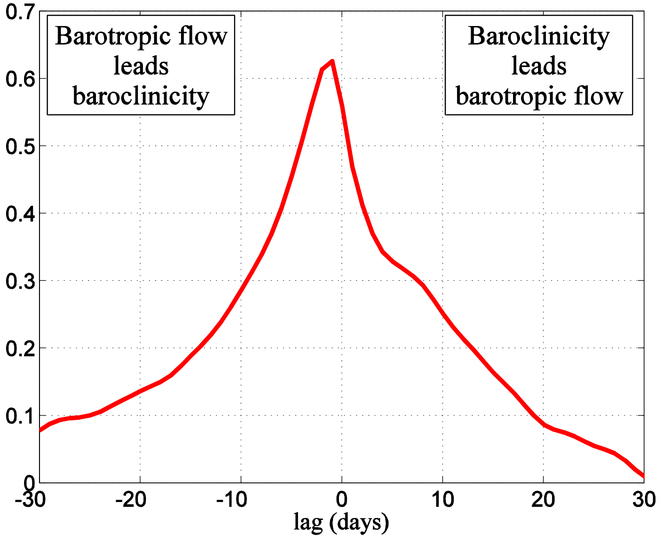
Variability of baroclinic flow

Leading EOF for zonal-mean meridional temperature gradient at 600 hPa (SH deseasonalized data)



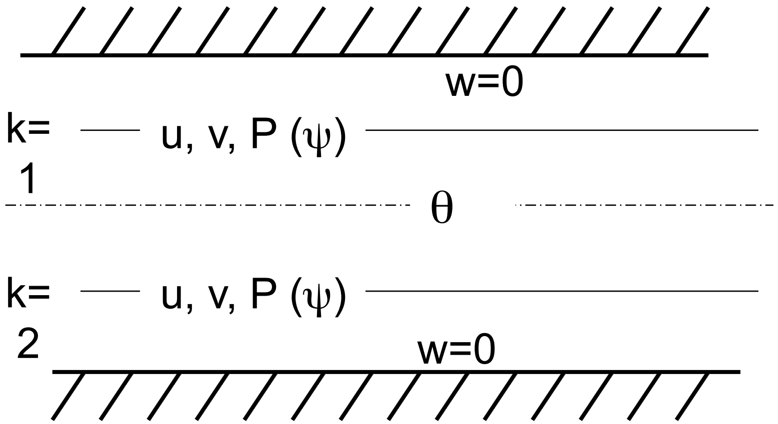


	Shift	*Sharpening*
No filter	35,1 %	25,6 %
5 days ‘low’	38,3 %	26,4 %
10 days ‘low’	42,8 %	25,7 %
20 days ‘low’	47,0 %	24,6 %
30 days ‘low’	50,0 %	22,8 %
20 days ‘high’	28,2 %	27,0 %



- Highly correlated with barotropic variability
- Maximum correlation when barotropic flow leads

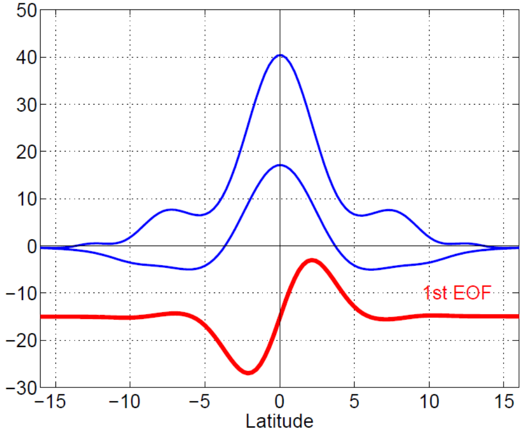
Two-layer QG model



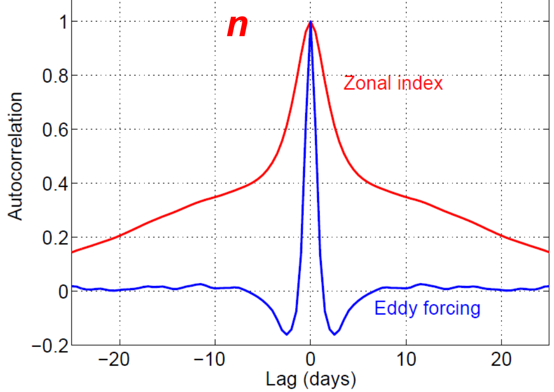
- QG formulation (fixed static stability)
- Bounded by rigid lid on top and bottom.
- Only two levels/modes.
- Beta channel.
- Newtonian forcing, Rayleigh friction

- Cheap to obtain long time series (50,000 days here) → clearer signal
- Minimal barotropic/baroclinic decomposition → cleaner, less ambiguity

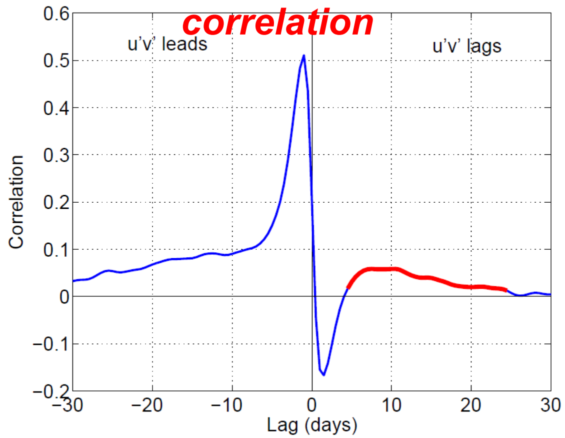
Mean zonal wind and 1st EOF



m, z autocorrelation

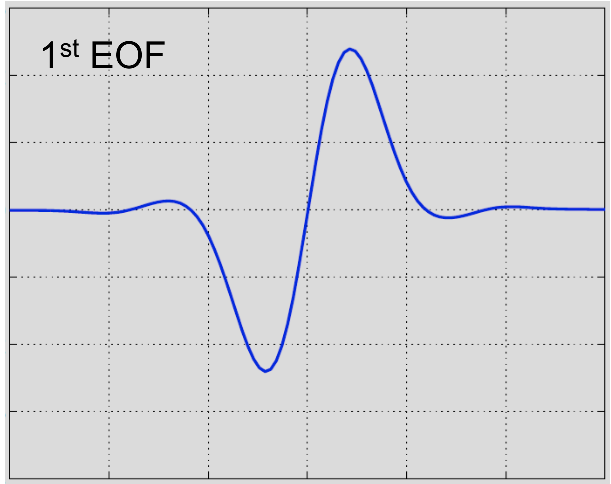


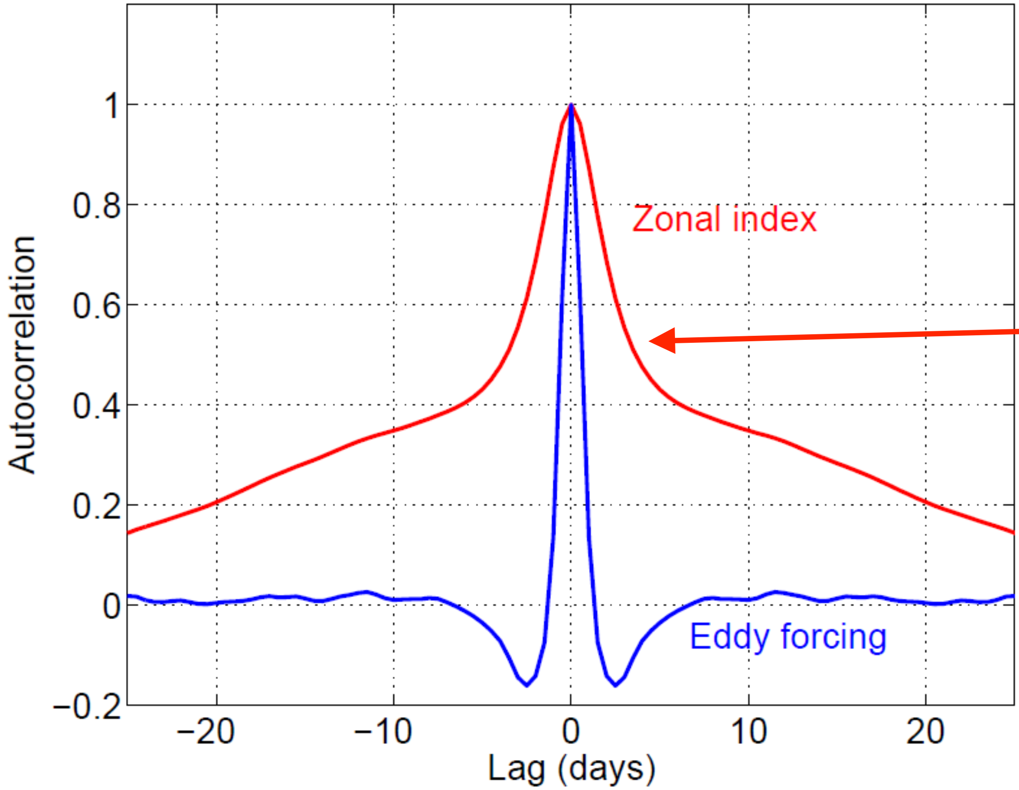
<m, z> lagged correlation



Impact of eddy forcing memory

$$z = \left(\int \bar{U} dz\right) \cdot EOF \qquad m = -\left(\int \frac{\partial}{\partial y} \overline{u'v'} dz\right) \cdot EOF$$

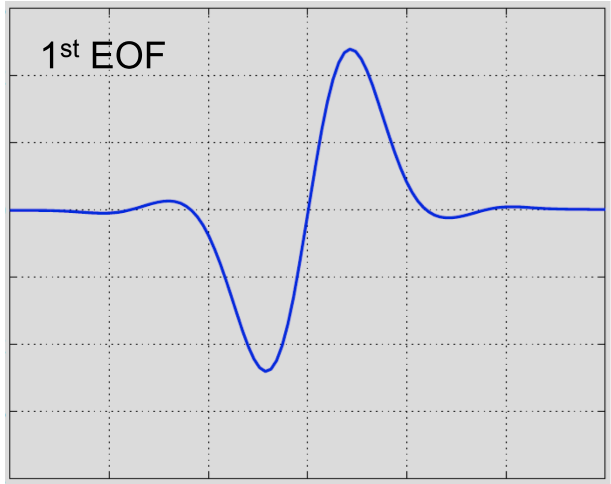


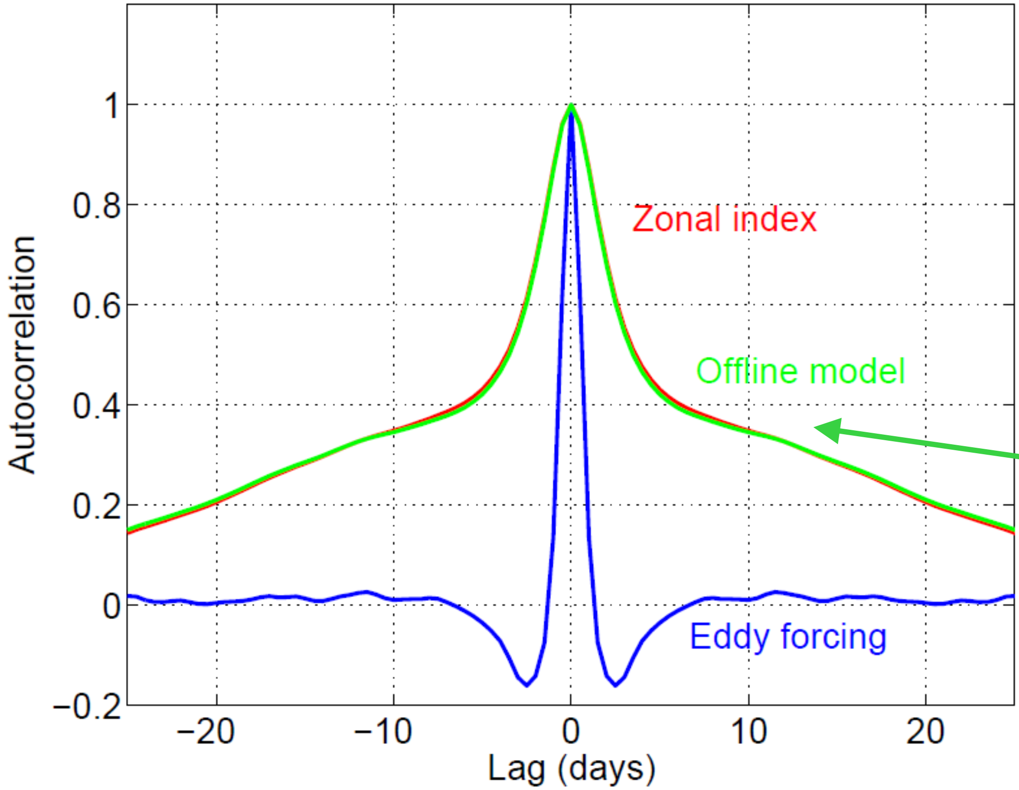


$$\frac{\partial z}{\partial t} = m - Friction$$

Impact of eddy forcing memory

$$z = \left(\int \bar{U} dz\right) \cdot EOF \qquad m = -\left(\int \frac{\partial}{\partial y} \overline{u'v'} dz\right) \cdot EOF$$



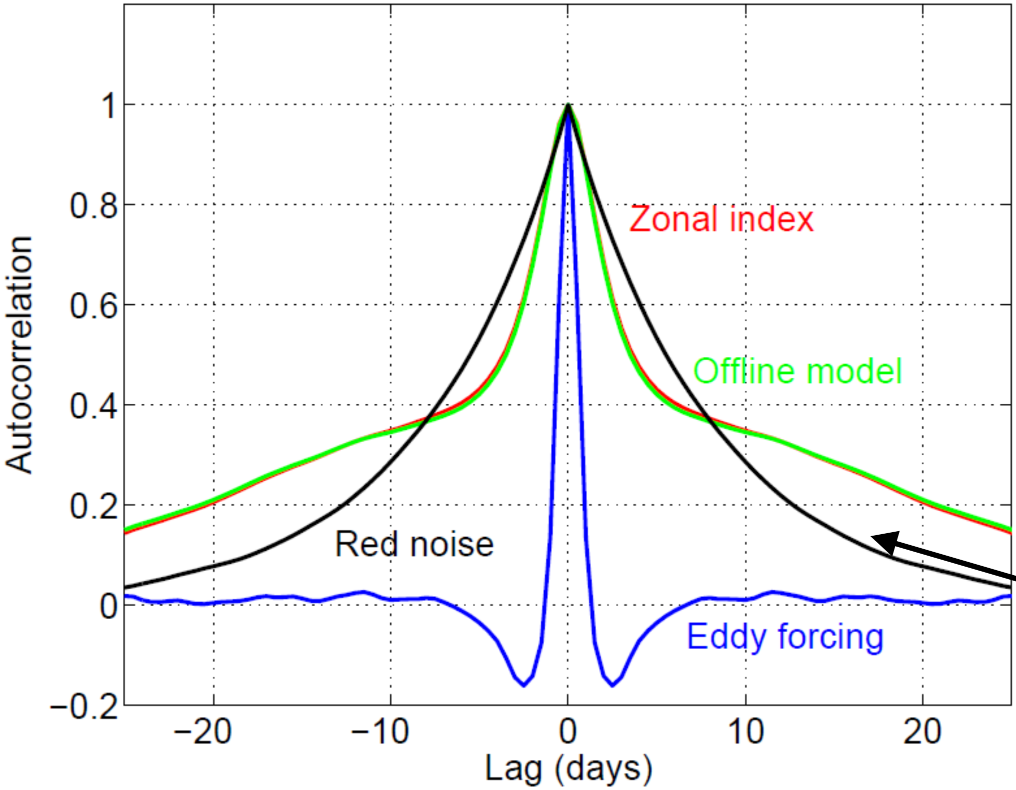


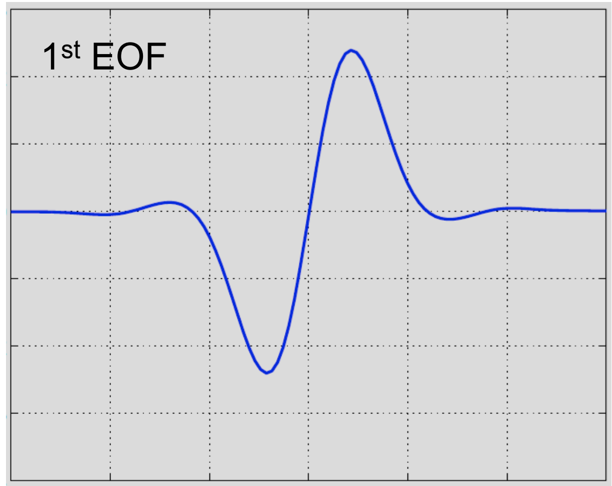
$$\frac{\partial z}{\partial t} = m - Friction$$

$$\frac{\partial z}{\partial t} = m - \frac{z}{2.8\tau_F}$$

Impact of eddy forcing memory

$$z = \left(\int \bar{U} dz\right) \cdot EOF \qquad m = -\left(\int \frac{\partial}{\partial y} \overline{u'v'} dz\right) \cdot EOF$$





$$\frac{\partial z}{\partial t} = m - Friction$$

$$\frac{\partial z}{\partial t} = m - \frac{z}{2.8\tau_F}$$

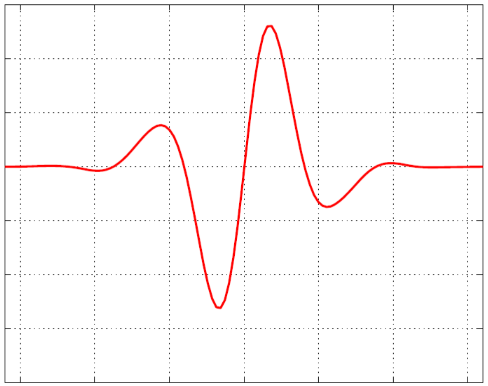
$$\frac{\partial \mathbf{z}}{\partial t} = w - \frac{\mathbf{z}}{2.8\tau_F}$$

Eddy forcing memory decreases / increases persistence at short / long time lags

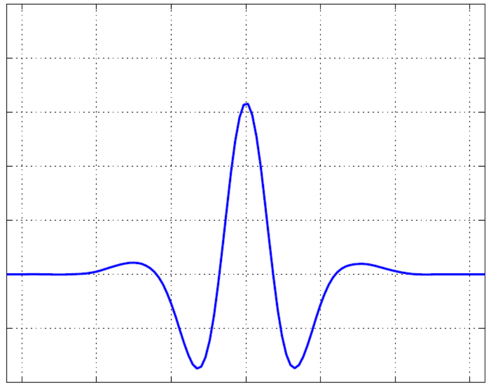
Baroclinic variability in two-layer model

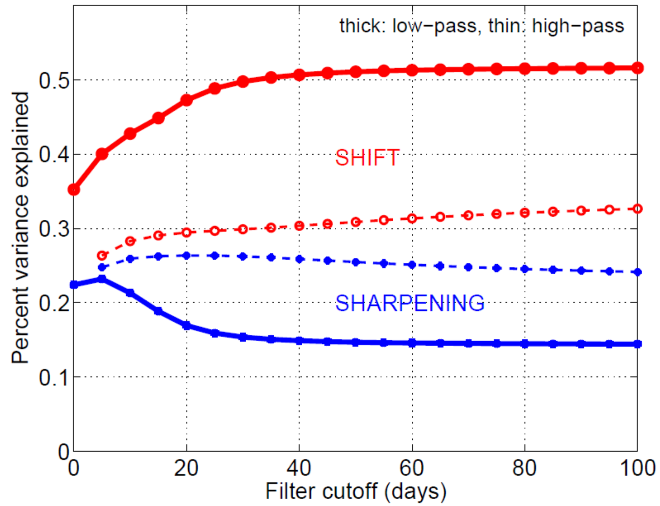
Leading mode of variability for baroclinicity is also a shift at all time scales.

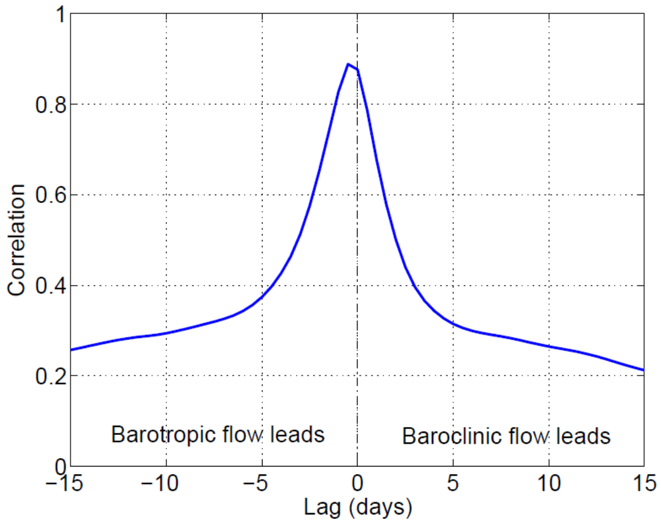
Shift



Sharpening



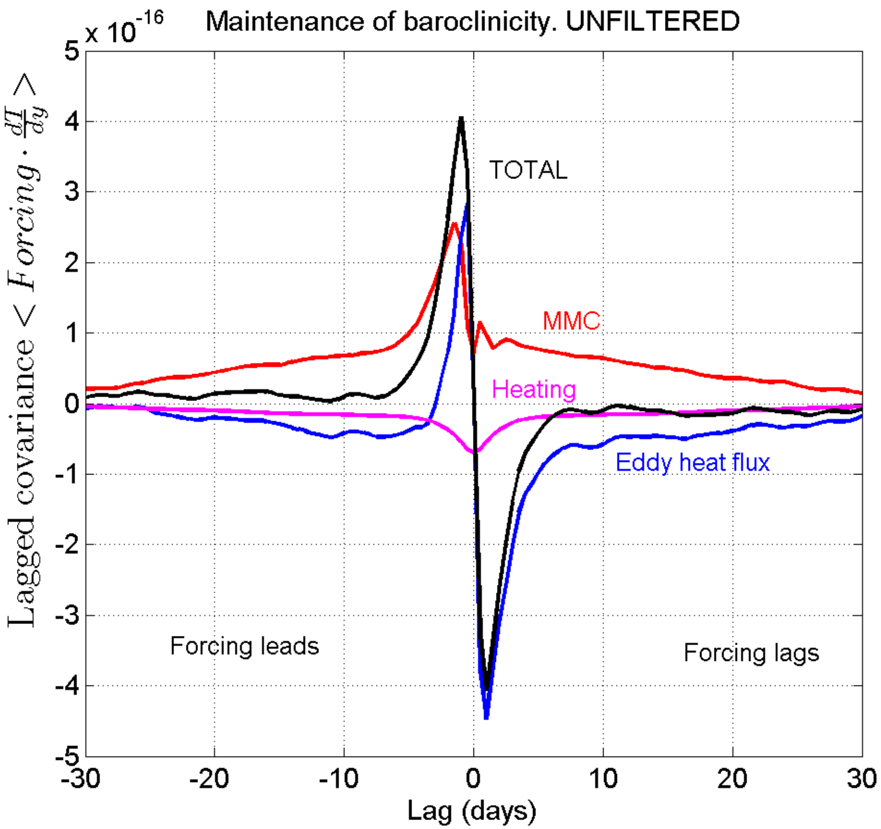




- Strongly correlated with barotropic variability
- Maximum correlation when barotropic flow leads

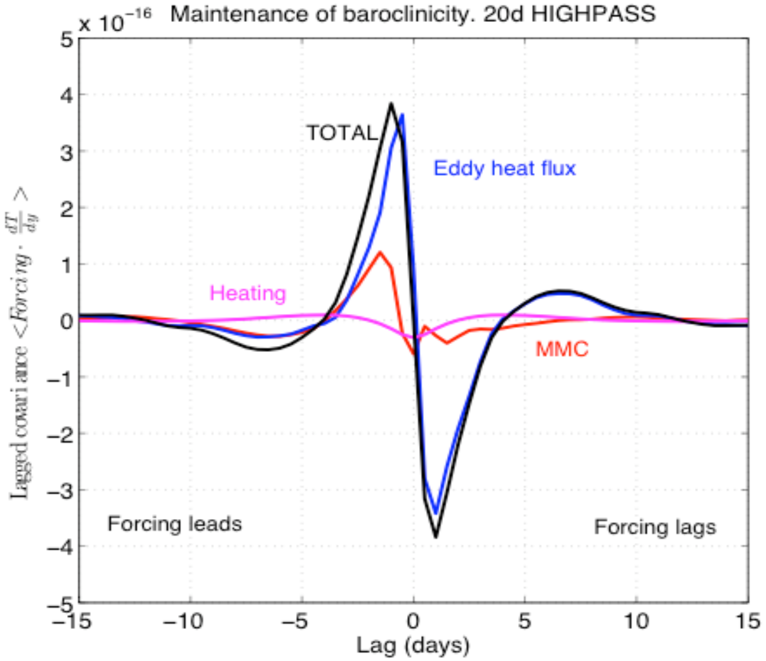
Life cycles of baroclinic anomalies

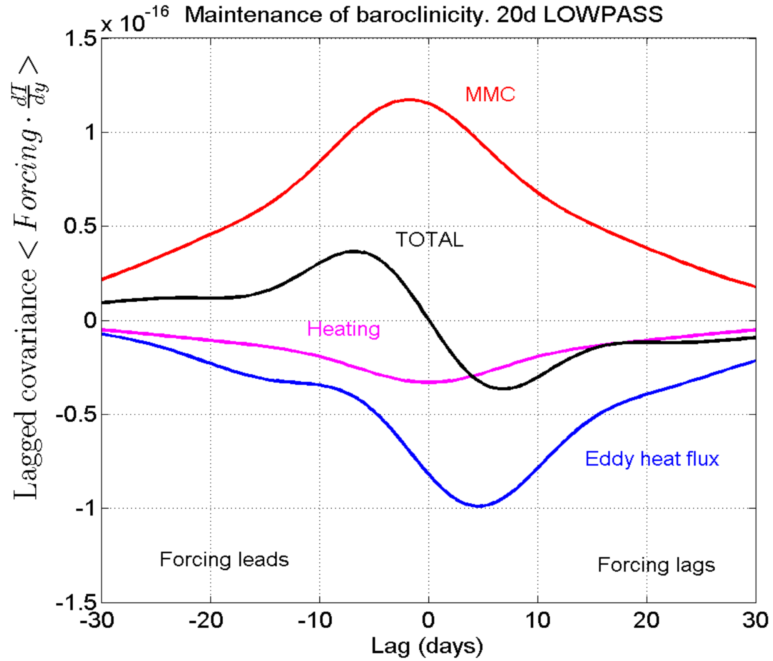
$$\frac{\partial Bar}{\partial t} = F\{\overline{v'\theta'}\} + F\{MMC\} + F\{Heat\}$$ (projected on leading EOF)



Life cycles of baroclinic anomalies

$$\frac{\partial Bar}{\partial t} = F\{\overline{v'\theta'}\} + F\{MMC\} + F\{Heat\}$$ (projected on leading EOF)



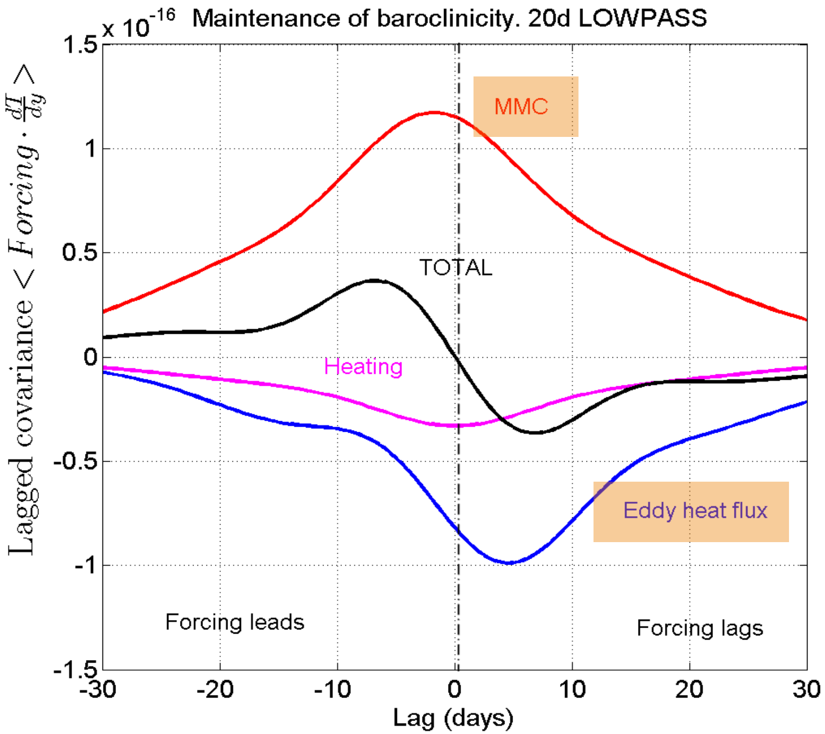


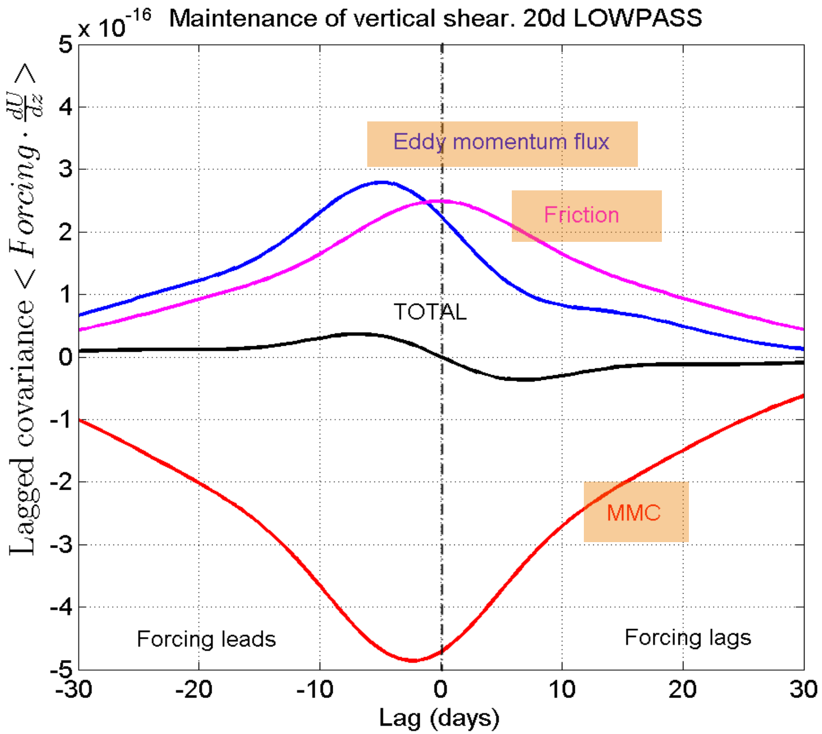
- High frequency: tendency dominated by transient eddy heat flux
- ***Low frequency: baroclinicity forced by MMC, damped by transient eddy heat flux ("diffusive")***

We can get a more complete picture performing a similar analysis for the vertical shear.

$$\frac{\partial Bar}{\partial t} = F\{\overline{v'\theta'}\} + F\{MMC\} + F\{Heat\}$$

$$\frac{\partial Shear}{\partial t} = F\{\overline{u'v'}\} + F\{MMC\} + F\{Fric\}$$



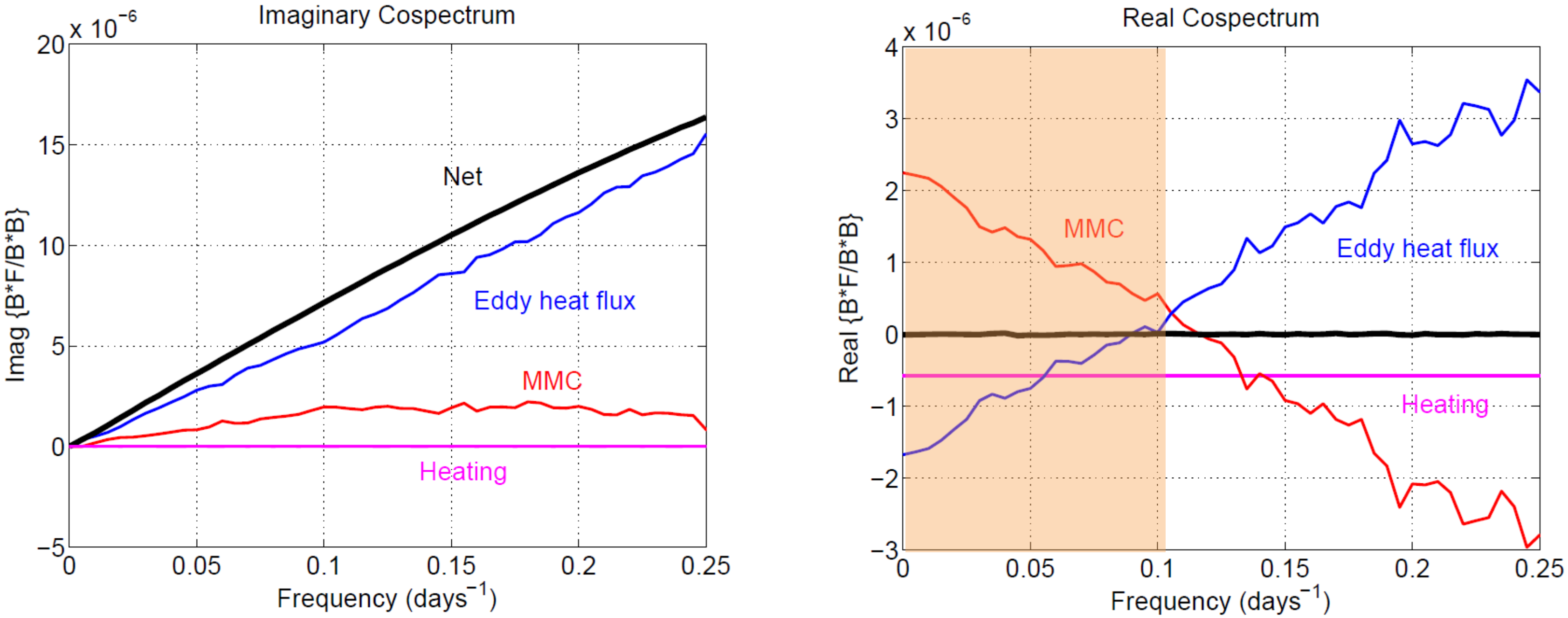


1. Eddy momentum flux forces anomalous shear.
2. Friction strengthens/extends shear anomaly.
3. MMC damps vertical shear anomaly.
4. MMC creates anomalous baroclinicity.
5. Eddy heat flux damps baroclinic anomaly.

Complex cospectrum

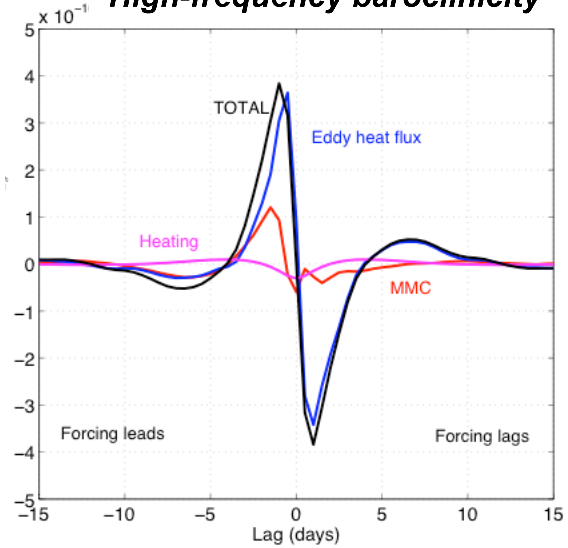
Take Fourier transform of $\frac{\partial B}{\partial t} = F\{v'\theta'\} + F\{MMC\} + F\{Heat\}$

$$i\omega\tilde{B} = \tilde{F}\{v'\theta'\} + \tilde{F}\{MMC\} + \tilde{F}\{Heat\} \longrightarrow i\omega = \sum \frac{\tilde{F}_k \tilde{B}^*}{\tilde{B}^* \tilde{B}}$$

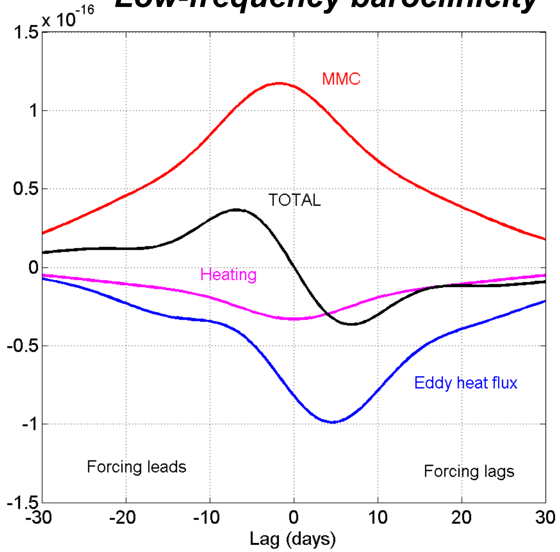


Comparison with observations

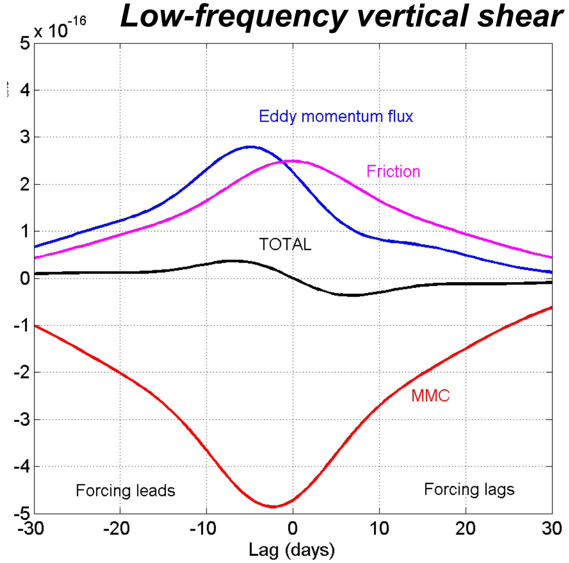
High-frequency baroclinicity

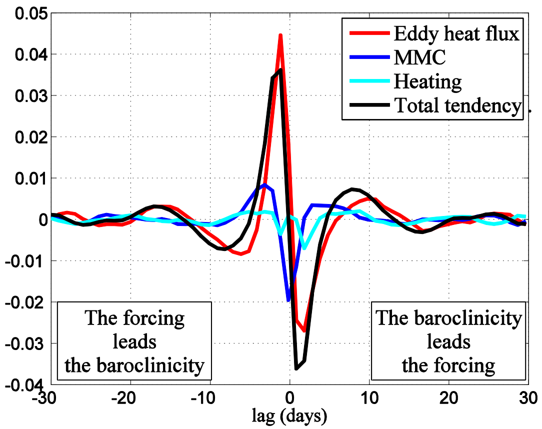


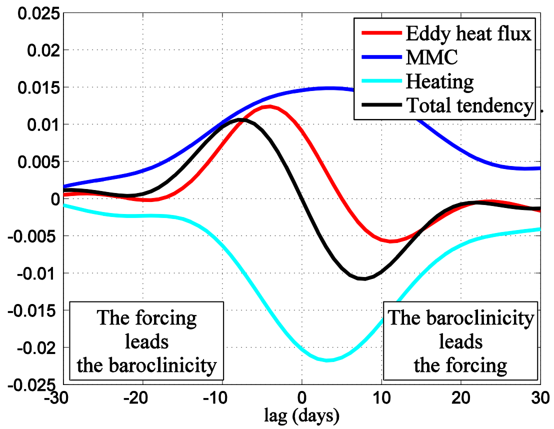
Low-frequency baroclinicity

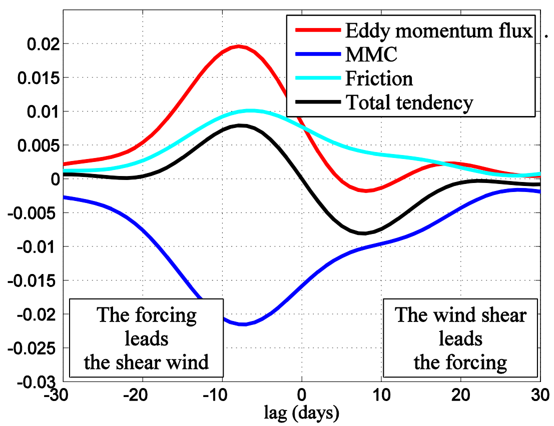


Low-frequency vertical shear



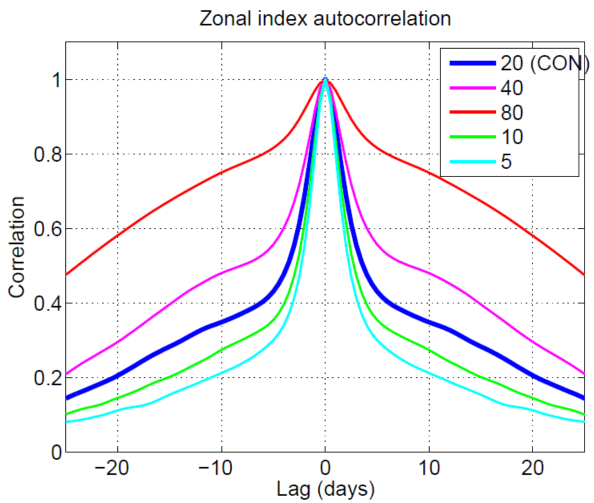


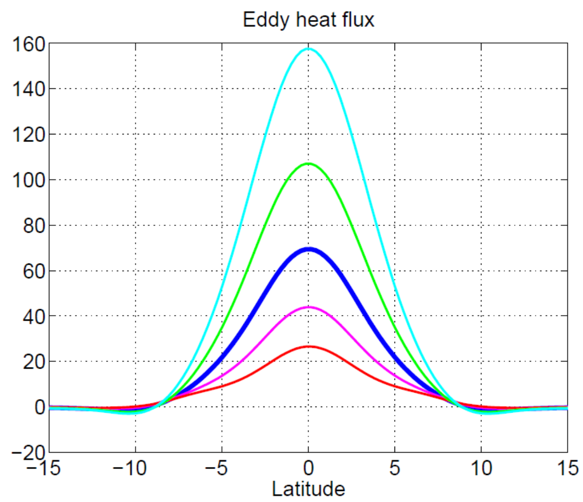




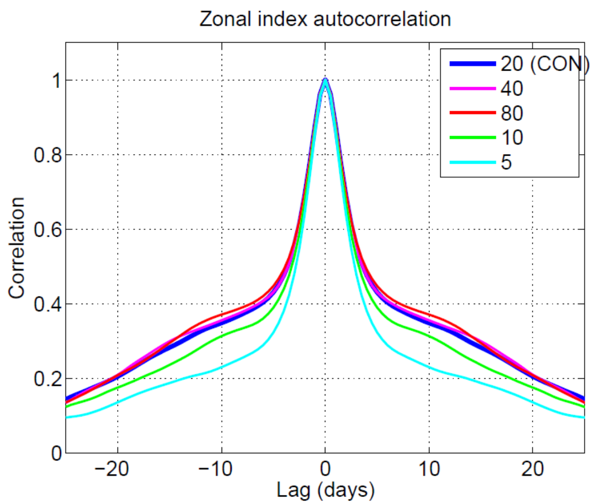
- Results qualitatively similar except for the role of eddy heat flux, no longer diffusive.
- Diabatic heating is now the main damping term. Anchored to SST? Moist processes?

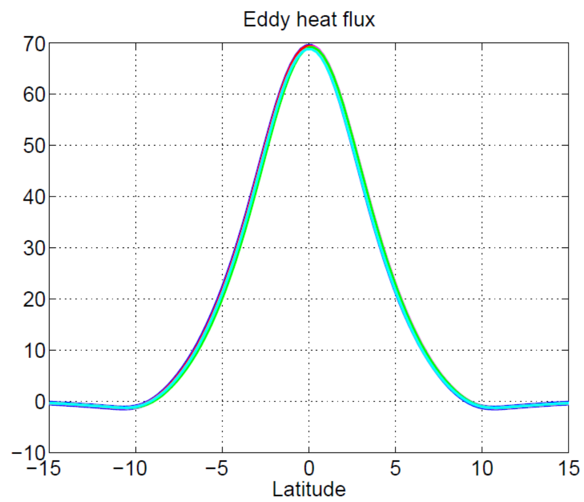
Sensitivity to diabatic timescale





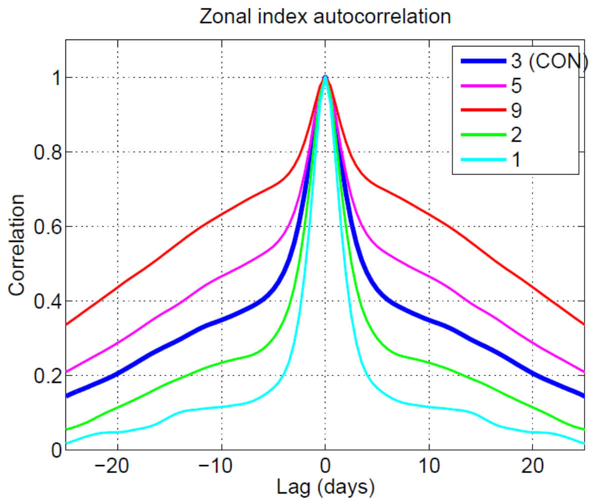
Persistence is sensitive to the diabatic time scale, but so is the mean state and hence the eddies.

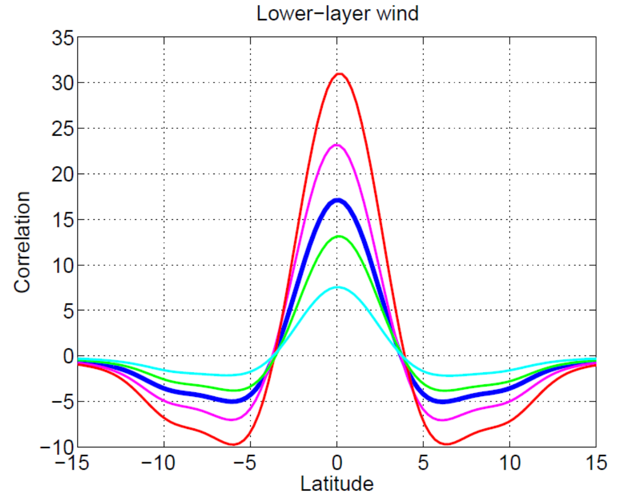




Adding a constant heating term to keep the mean state fixed, much of the sensitivity disappears

Sensitivity to frictional timescale

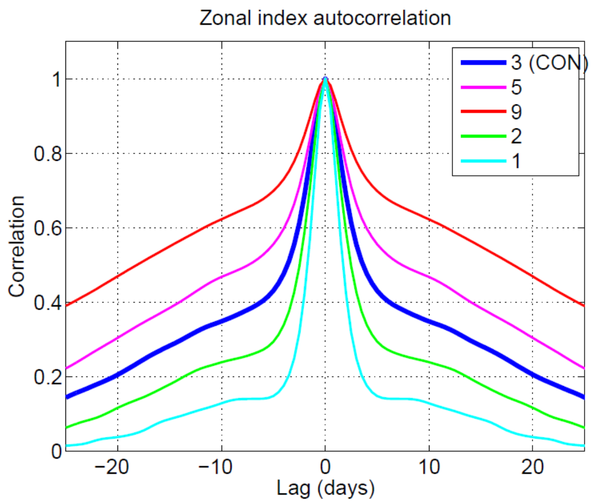


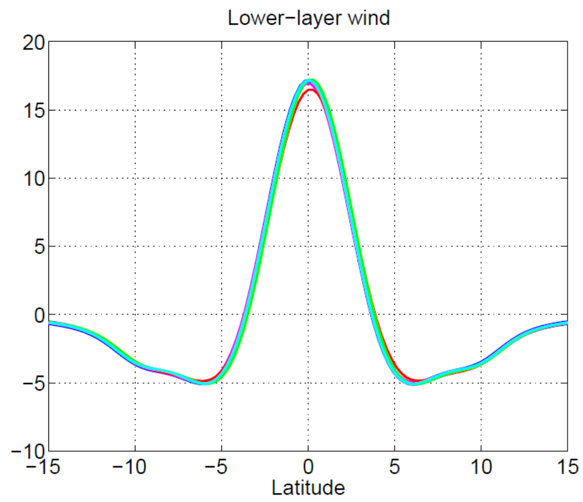


Persistence is sensitive to the frictional time scale, but so is the mean state (barotropic governor)

We can keep the mean state fixed if we vary friction ***on the direction of the first EOF alone***

$$\bar{U}_{EOF} = (\bar{U}_1 \cdot \overrightarrow{EOF})\overrightarrow{EOF} \qquad \bar{U}_{RES} = \bar{U}_1 - \bar{U}_{EOF} \qquad Fric = -\frac{\bar{U}_{EOF}}{\tau_{EOF}} - \frac{\bar{U}_{RES}}{\tau}$$





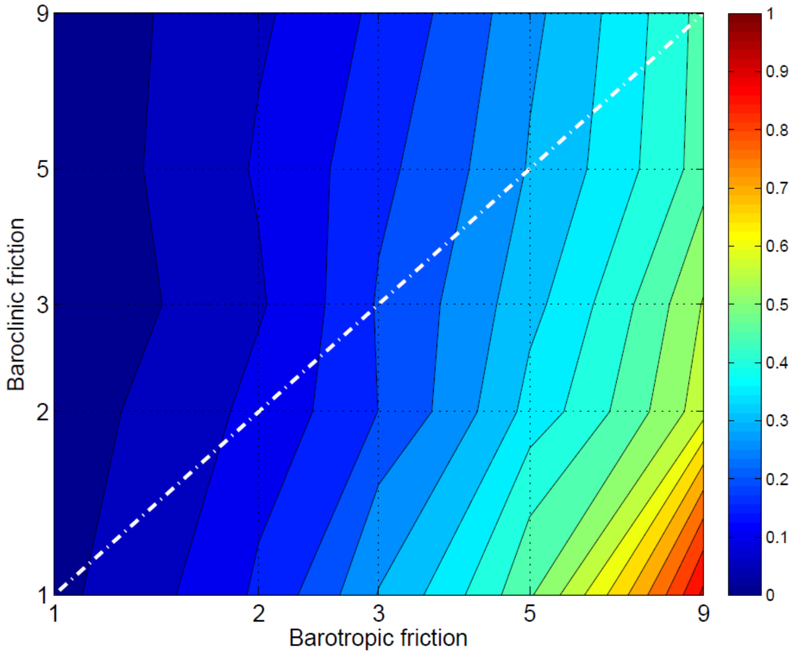
Although the mean state is now fixed as friction changes, ***zonal index persistence increases with decreasing friction***

Barotropic versus baroclinic friction

We can alter the barotropic /baroclinic friction splitting the frictional torque across both layers

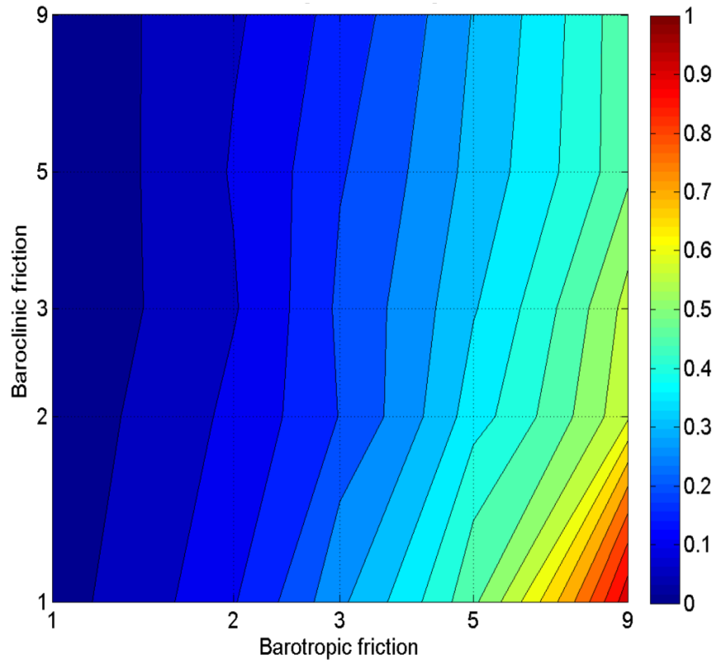
lower layer $F_1 = -\left(\frac{1}{2\tau_{BT}} + \frac{1}{2\tau_{BC}}\right)\bar{U}_1$ upper layer $F_2 = -\left(\frac{1}{2\tau_{BT}} - \frac{1}{2\tau_{BC}}\right)\bar{U}_1$

20-day memory. Full model



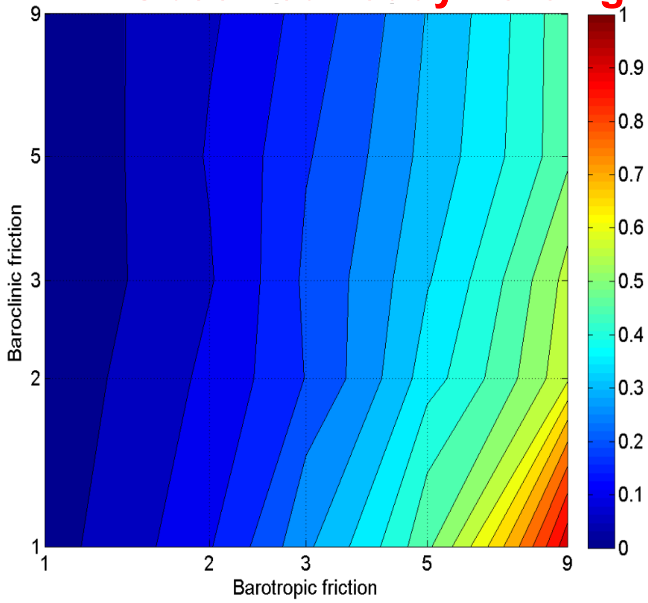
$$\frac{\partial z}{\partial t} = m - Friction$$

20-day memory. Offline model



$$\frac{\partial z}{\partial t} = m - \frac{z}{2.8\tau_F}$$

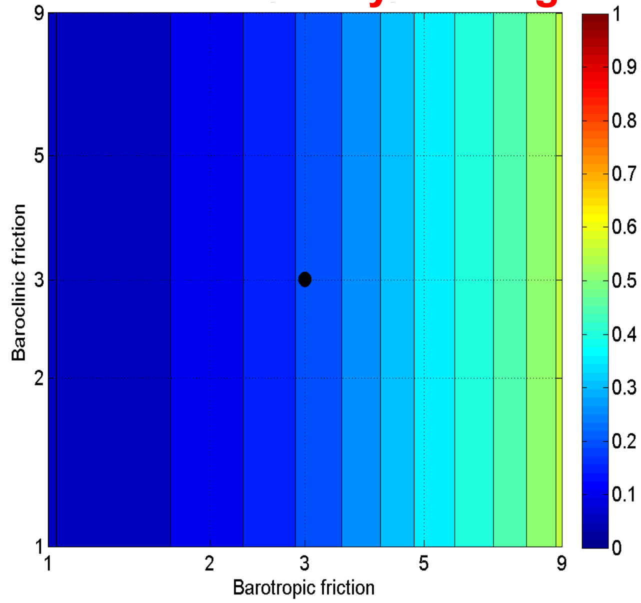
“Observed” eddy forcing



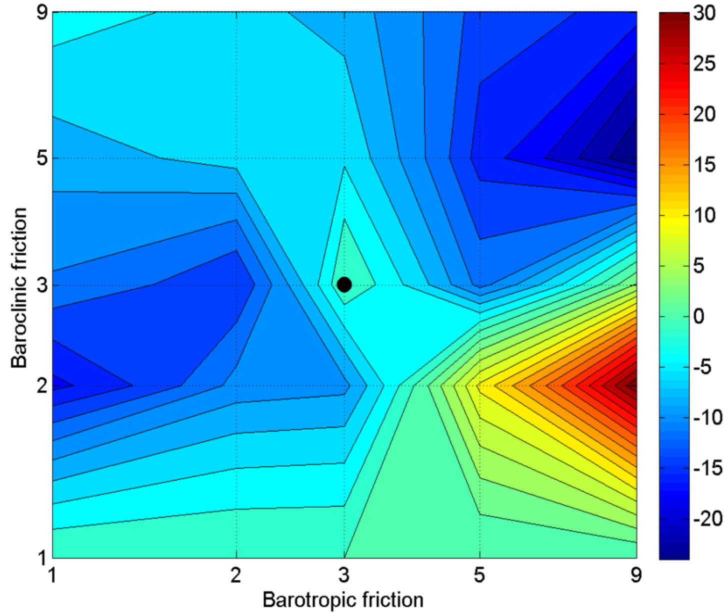
Offline model

$$\frac{\partial z}{\partial t} = m - \frac{z}{2.8\tau_F}$$

Control eddy forcing



Percent difference



Changing baroclinic friction impacts the eddy forcing memory, leading to zonal index persistence changes of ±30% when the timescale is changed by a factor of 3

Conclusions

1. The zonal index variability consists of a meridional shift of the zonal wind driven by the eddy momentum flux. Because the eddy forcing has memory this variability has enhanced persistence at long lags relative to a red noise process.

2. The leading mode of variability for zonal-mean baroclinicity is a meridional shift at all time scales. This variability is strongly correlated with that of the barotropic component (zonal index) and the correlation is maximized when the latter leads.

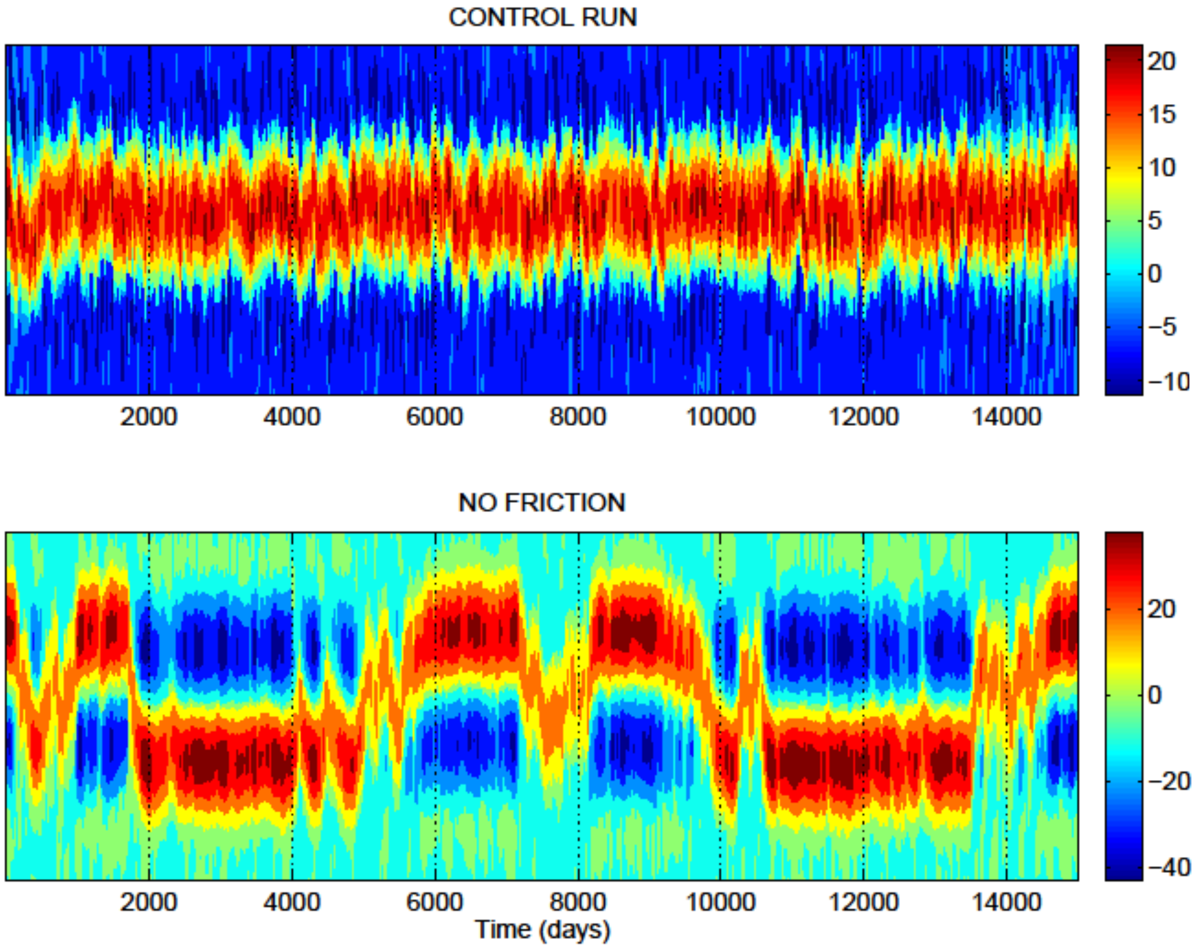
3. In the low frequency, zonal-mean baroclinic anomalies are forced by the mean meridional circulation and damped by a "diffusive" eddy heat flux (two-layer model) or diabatically (observations). The MMC is forced by the eddy momentum flux and friction.

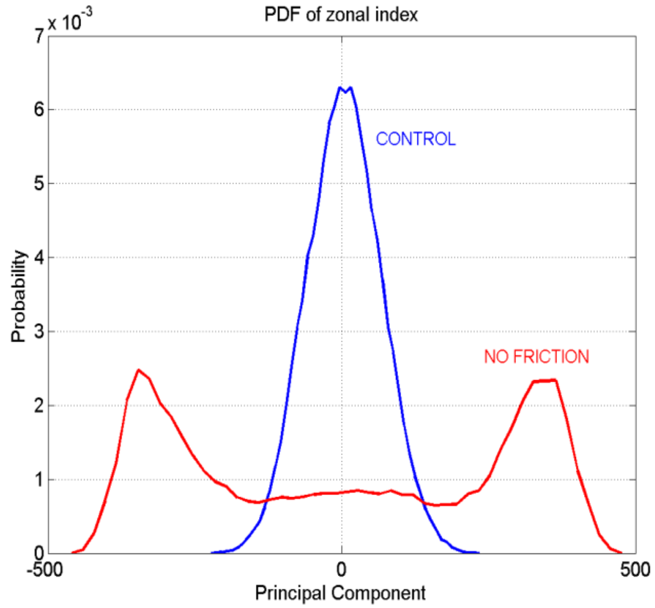
4. In the two-layer model zonal-index persistence is insensitive to the diabatic time scale and decreases with increasing friction. The baroclinic component of friction enhances persistence but the barotropic component dominates.

5. The ultra-simple two-layer model can produce quite reasonable extratropical variability, which makes it a wonderful tool for studying this problem.

Sensitivity to EOF friction

What happens if we remove friction altogether? Extremely persistent variability (bimodal)





$$\frac{\partial z}{\partial t} = m - Friction$$