2D turbulence and zonal jets

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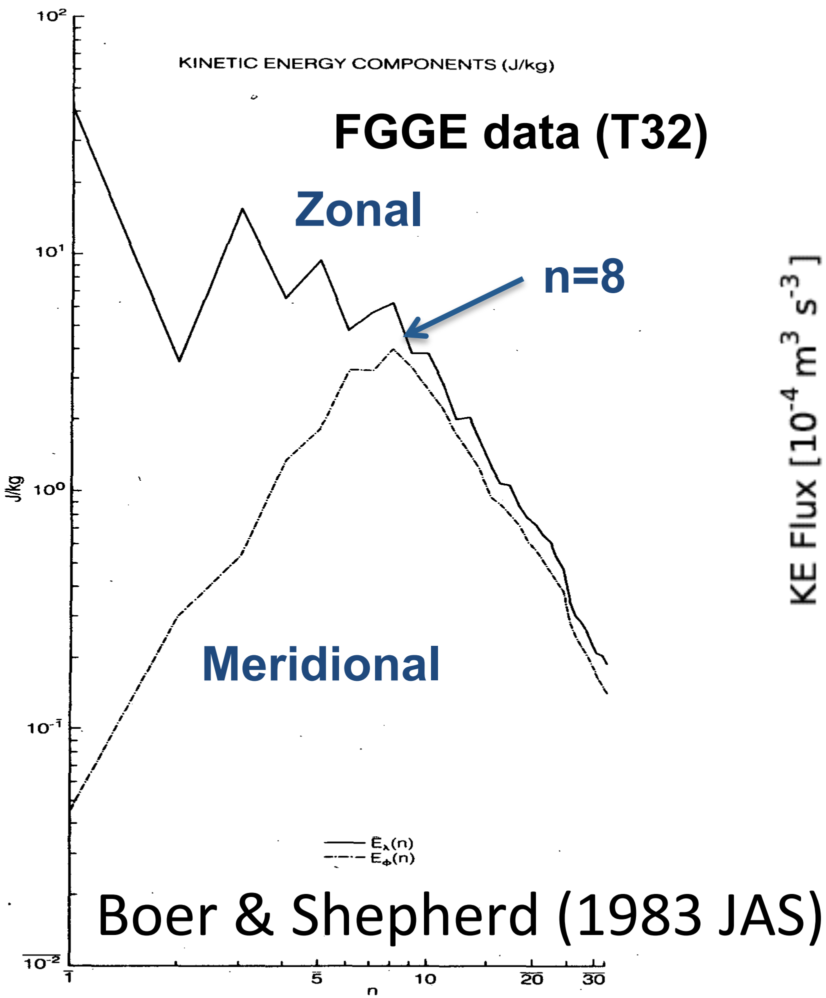
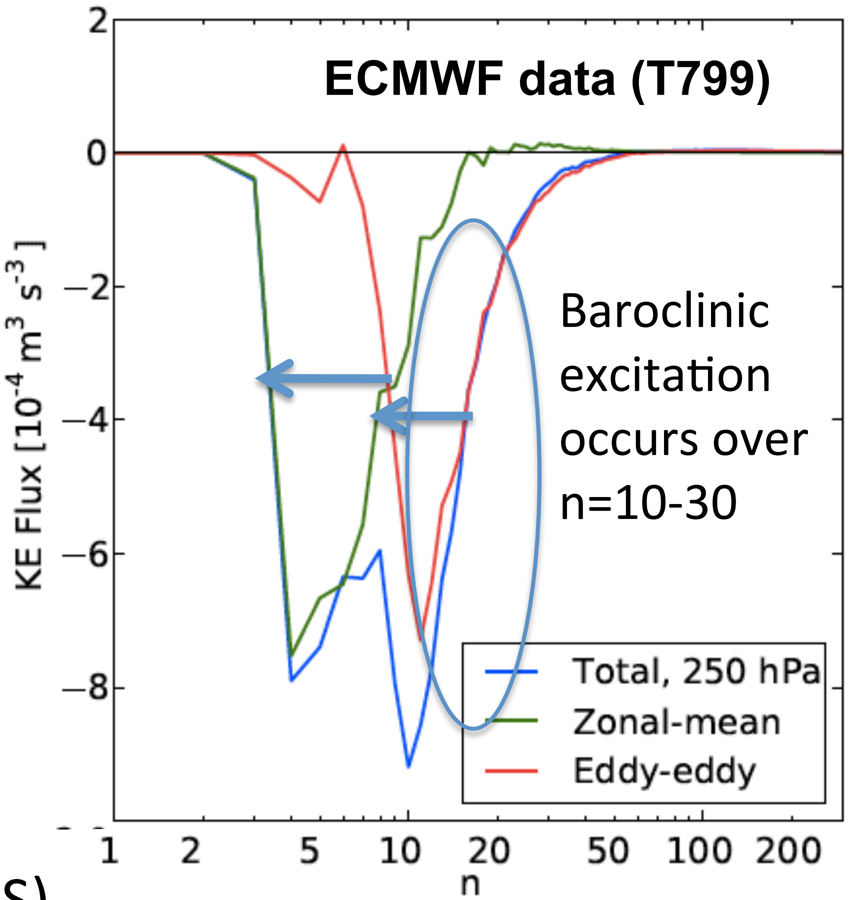
- Atmospheric observations show an upscale "cascade" of kinetic energy in the upper troposphere, but **the transfer into the largest (zonal) scales mainly occurs through eddy-mean flow, not eddy-eddy, interactions** (Shepherd 1987 JAS)



Boer & Shepherd (1983 JAS)



Burgess, Erler & Shepherd (2013 JAS)

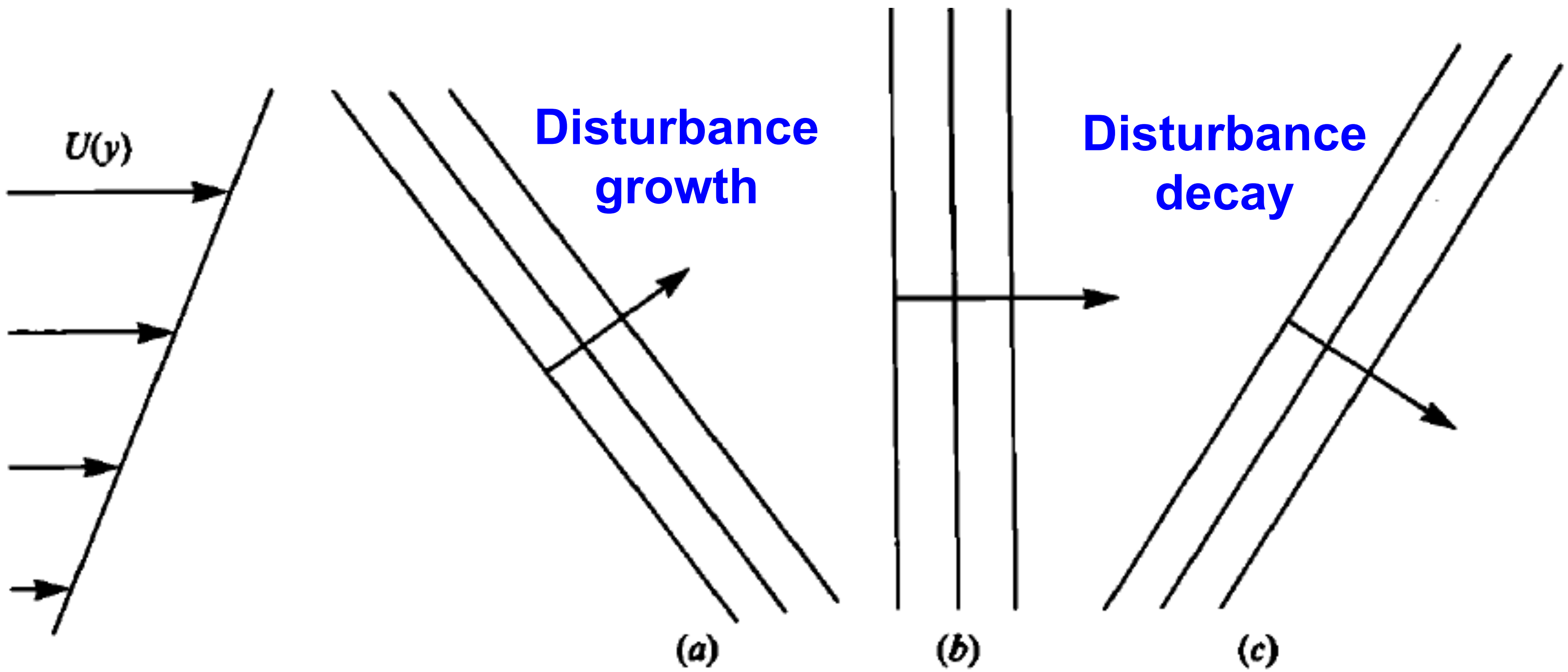
Moreover even the turbulent cascade is limited

- Schneider & Walker (2006 JAS) argue that the limited transient upscale energy cascade is no accident
  - Atmosphere adjusts towards weak nonlinearity (i.e. most-unstable scale equals energy-containing scale)
- A more extensive upscale energy cascade is found in the ocean (Scott & Wang 2005 JPO; Schlosser & Eden 2007 GRL)

Why is the mixed (stationary-transient, or zonal-eddy) component of the atmospheric energy flux upscale?

- The textbook arguments for an upscale energy cascade have lots of loopholes (see Holloway 2010 J. Turb.)
  - Moreover they are not relevant to this situation, which involves spectrally non-local wavenumber triads

- In general, some disturbances will extract energy from a large-scale flow (downscale energy flux; the "Orr effect"), and some will give energy up (upscale energy flux)



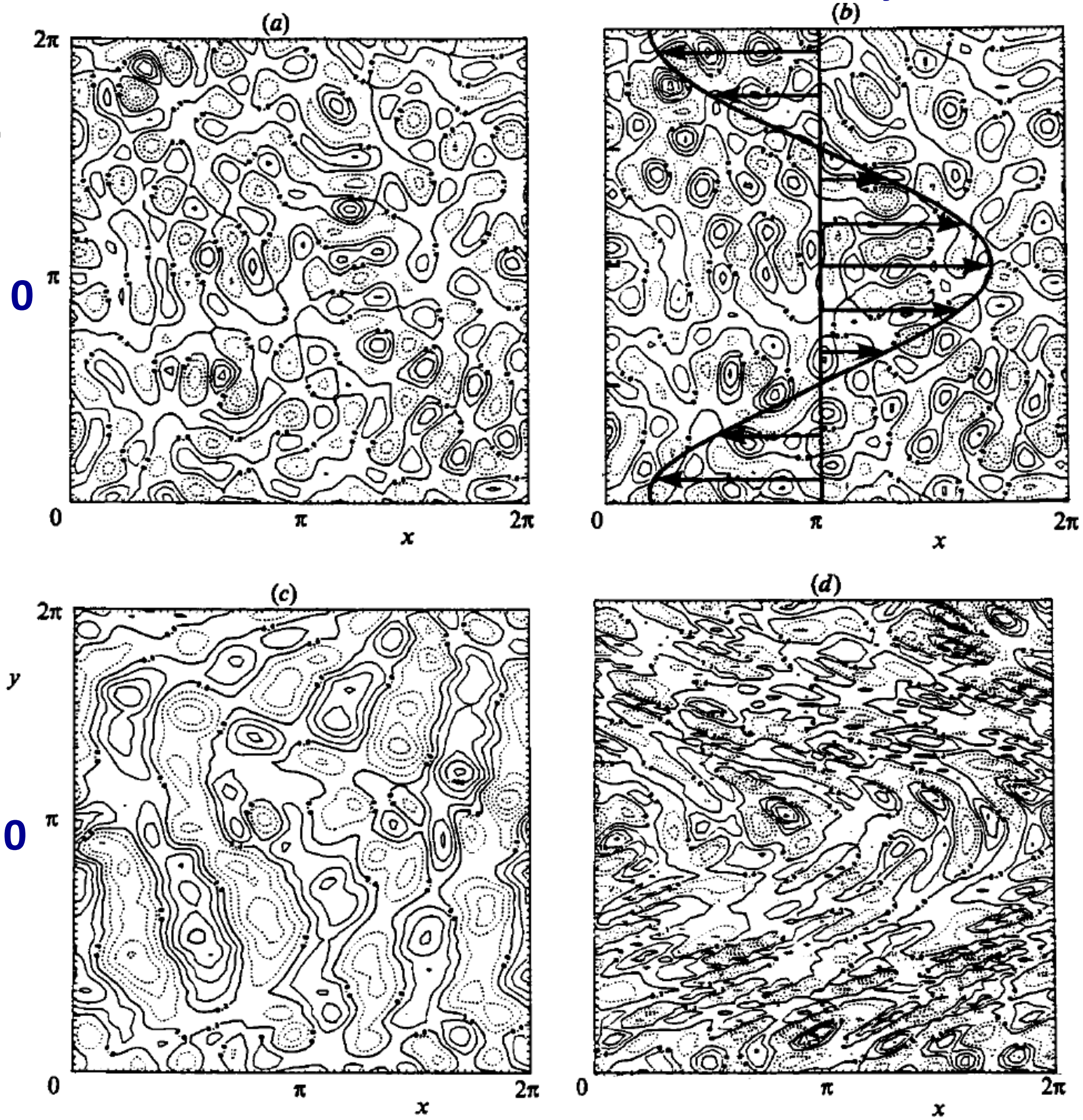
Shepherd (1987 JFM)

Streamfunction

Vorticity

$t = 0$

$t > 0$



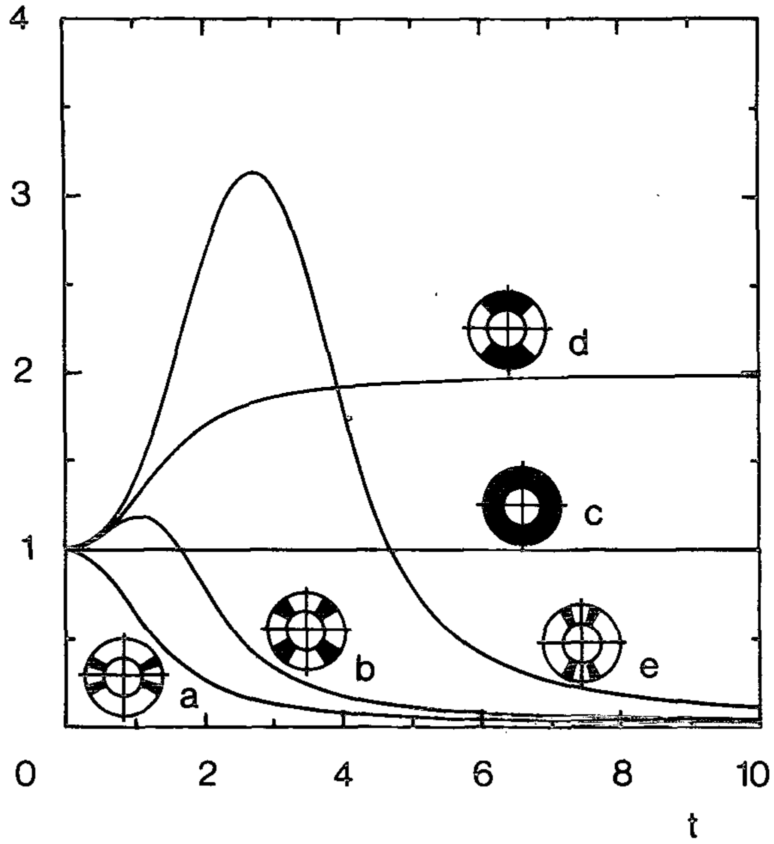
- Linear evolution of initially isotropic distribution of eddies in a shear flow
- Vorticity shows sheared out eddies (large k_y)
- Streamfunction shows amplified eddies ($k_y \approx 0$)

Shepherd (1987 JFM)

- The "Orr effect" (Thomson (Lord Kelvin) 1887; Orr 1907); including β doesn't change anything

$$\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\nabla^2\psi - U_{yy}\psi_x = 0, \qquad U = Sy$$

$$\zeta(x, y, t) = \mathrm{Re}[\exp i[kx + (l - Skt)y + \phi]]$$

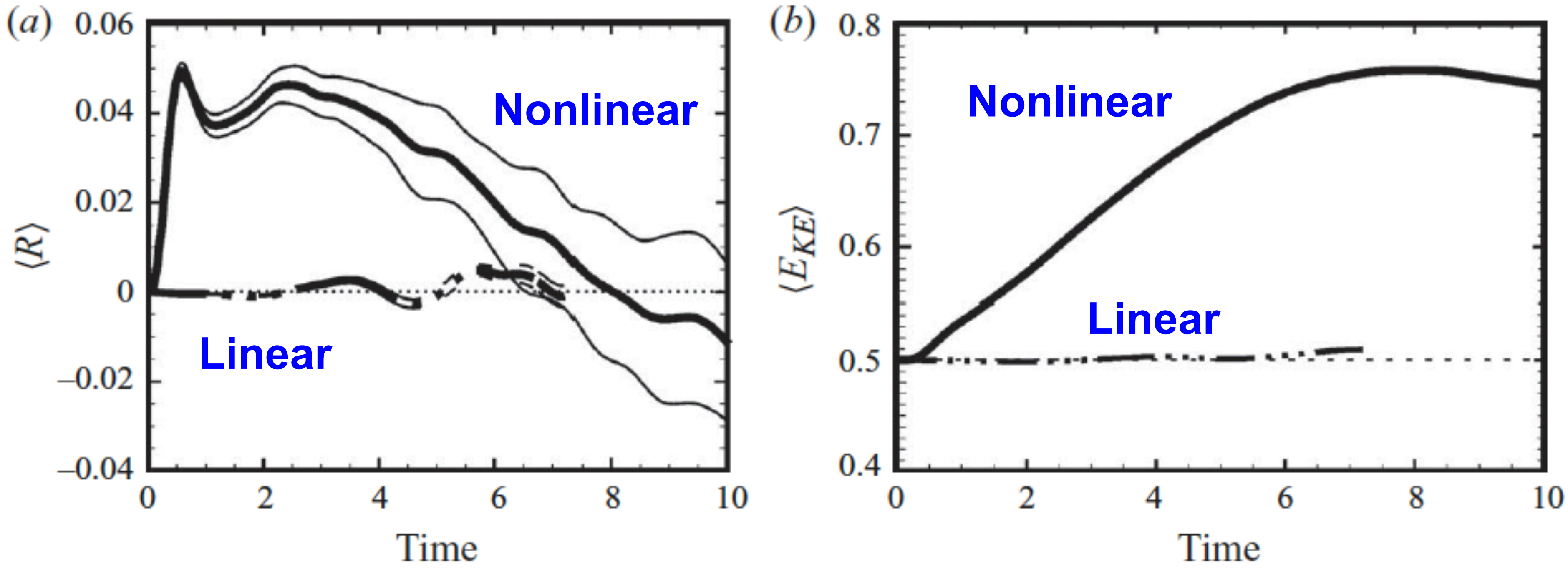


$$E(k, l, t) = \frac{\frac{1}{2}|\zeta|^2}{k^2 + (l - Skt)^2} = \frac{k^2 + l^2}{k^2 + (l - Skt)^2} E(k, l, 0).$$

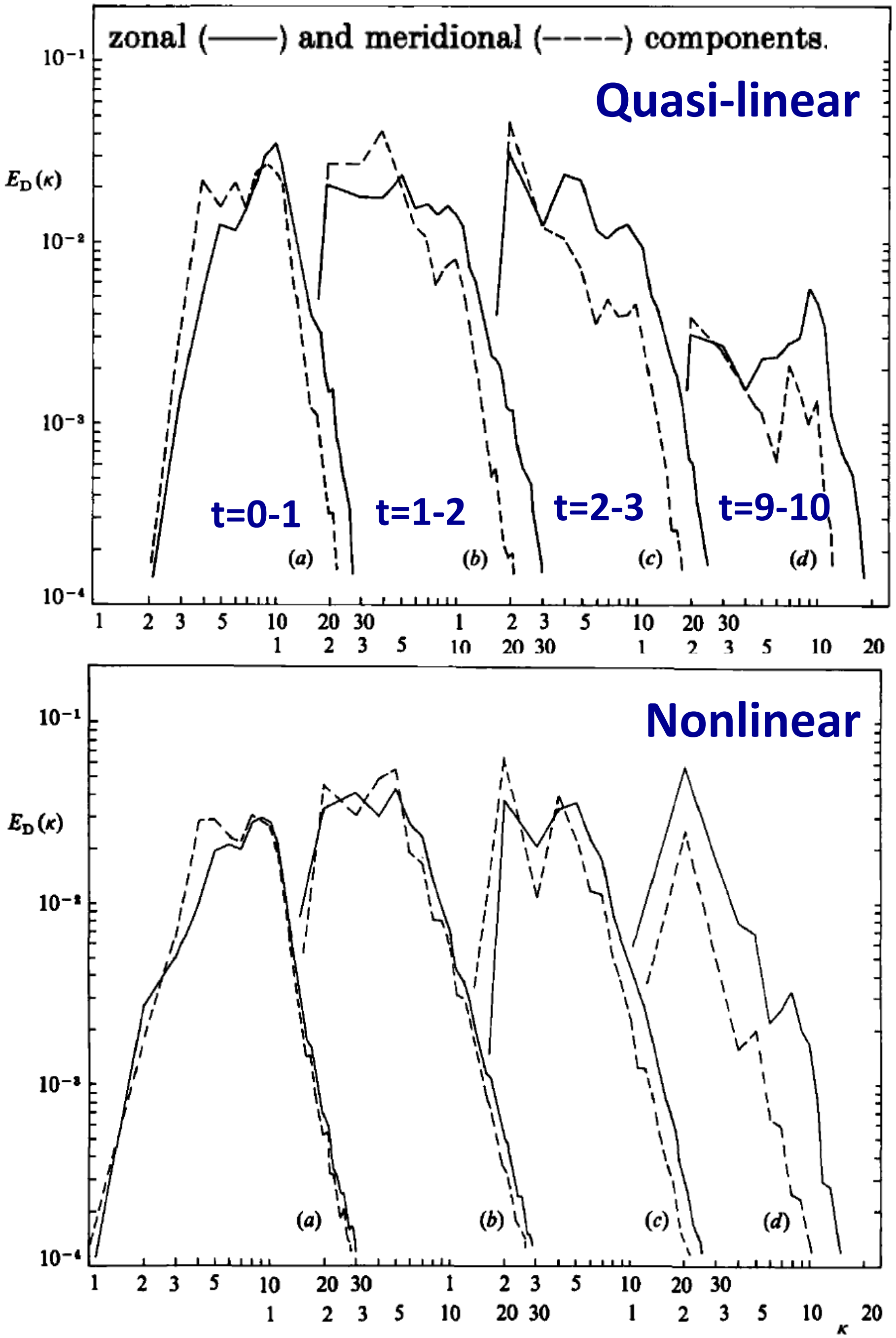
For any finite l, disturbances will eventually decay

Shepherd (1985 JAS)

- An *initially random* collection of disturbances evolving linearly in the presence of pure strain (Kraichnan 1976 JAS) or pure shear (Shepherd 1985 JAS) will exactly conserve its energy, implying *zero net energy exchange* with the background flow
- Nonlinearity leads to net disturbance *growth*



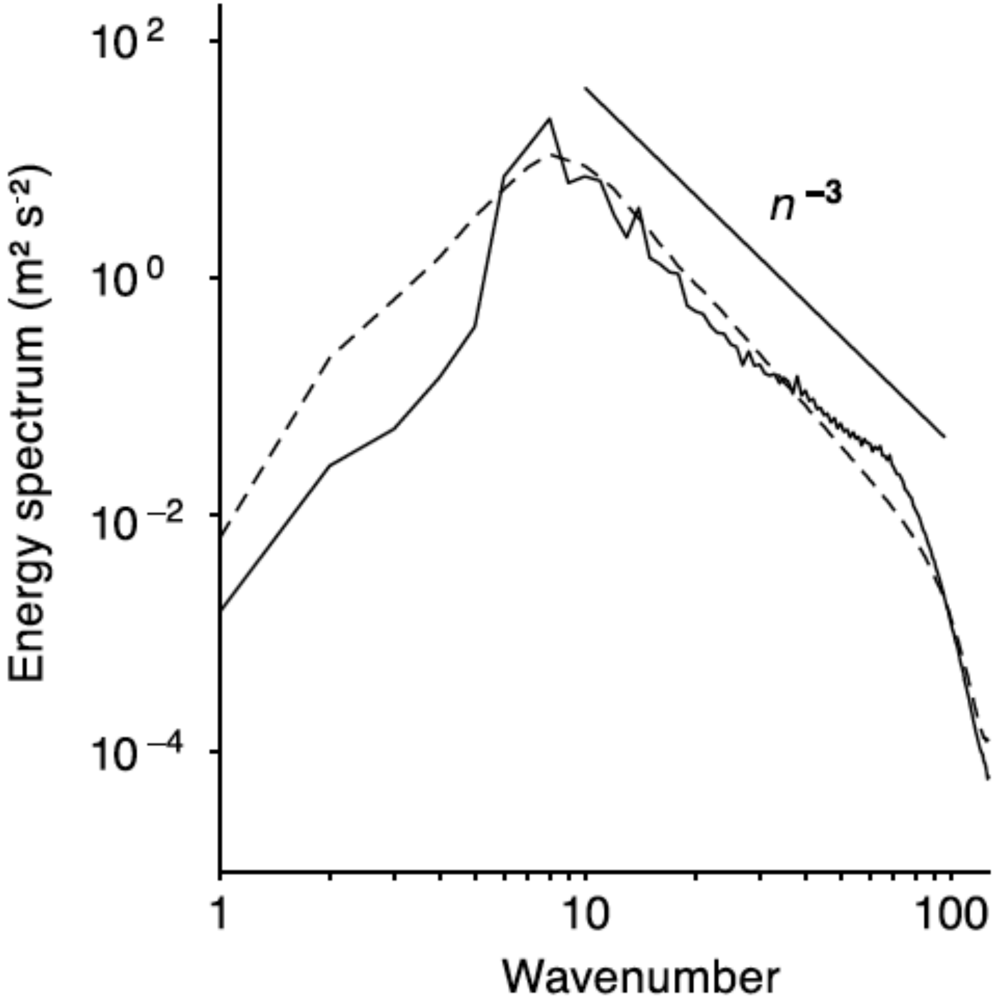
Case of shear flow, by Cummins & Holloway (2010 JFM)



- Energy spectra of decaying 2D turbulence in a sinusoidal zonal jet
- In quasi-linear simulation, eddies decay rapidly, and are anisotropic
- In nonlinear simulation, eddies do not decay at large scales, as they are isotropized
- Wave-wave interactions render the upscale cascade irreversible, thus reduce the eddy forcing of the mean flow via eddy straining

Shepherd (1987 JFM)

- An n^{-3} spectrum (for eddy KE) is also found (though less cleanly) in an idealized GCM with wave-wave interactions suppressed: there is still a downscale enstrophy cascade



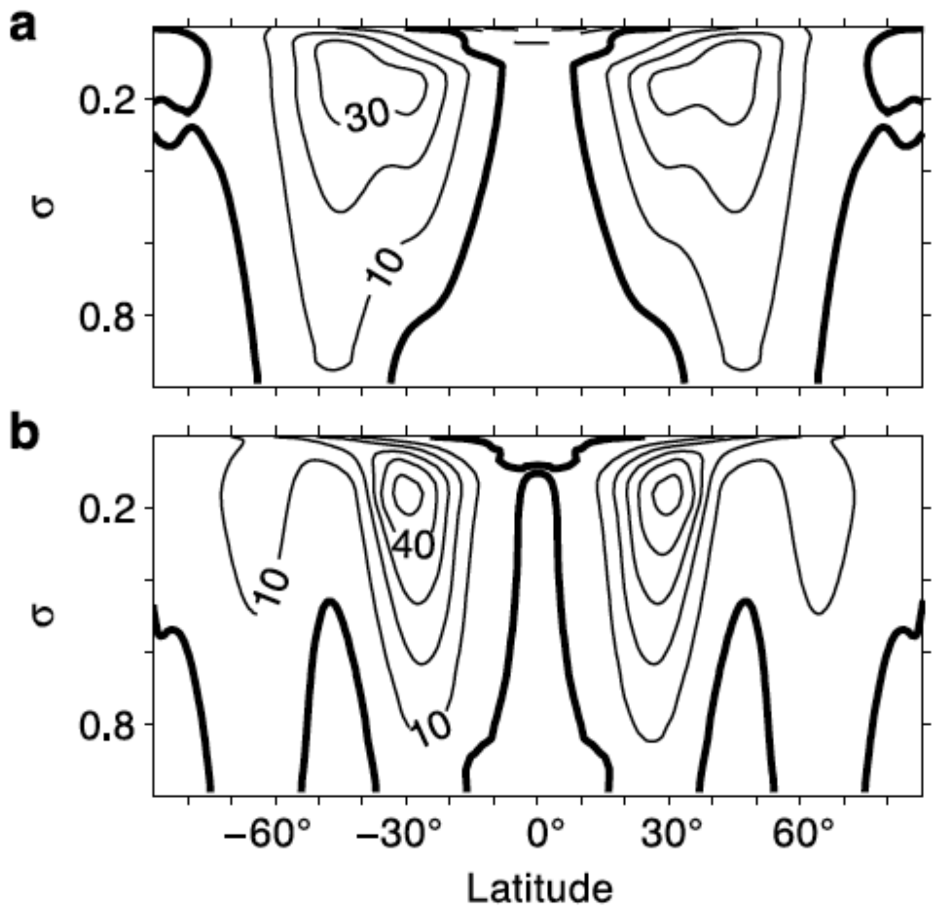
Eddy KE

Dashed: Nonlinear simulation

Solid: Wave-wave interactions suppressed (scaled)

O'Gorman & Schneider (2007 GRL)

- However, the wave-wave interactions strongly affect the wave-mean interactions, and reduce the forcing of the jet (Shepherd 1987 JAS; Huang & Robinson 1998 JAS)



Zonal mean zonal wind

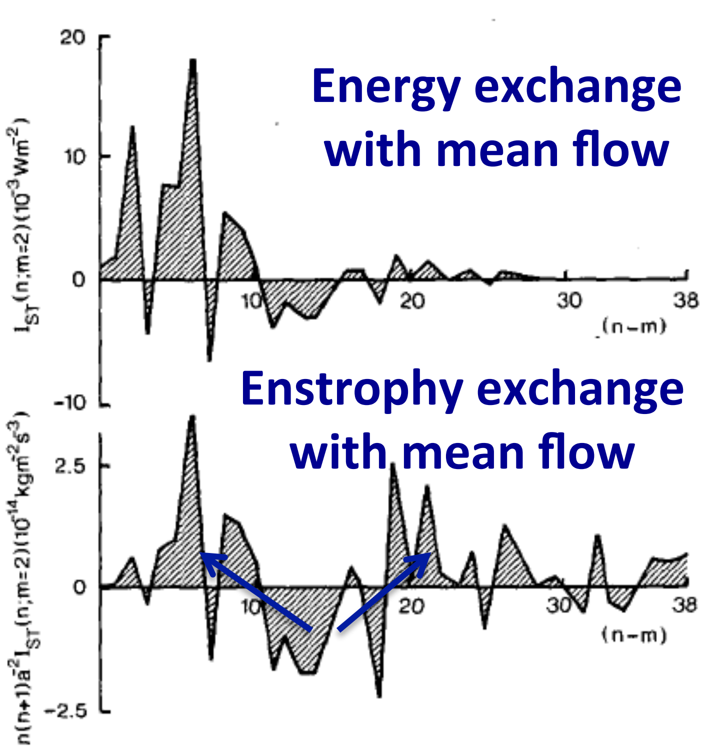
Nonlinear simulation

Wave-wave interactions suppressed (jets too strong)

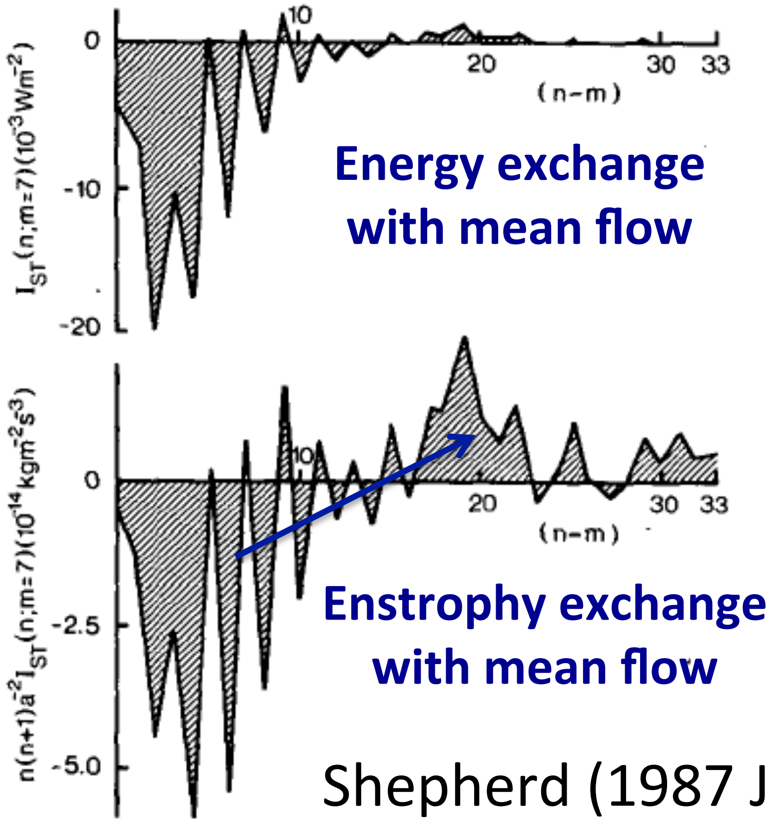
O'Gorman & Schneider (2007 GRL)

- In the real atmosphere, the transient planetary waves extract energy from the zonal mean flow, while the synoptic-scale waves give energy up to the mean flow
  - cf. Lorenz & Hartmann (2001 JAS)

m=2: eddies gain energy from mean flow

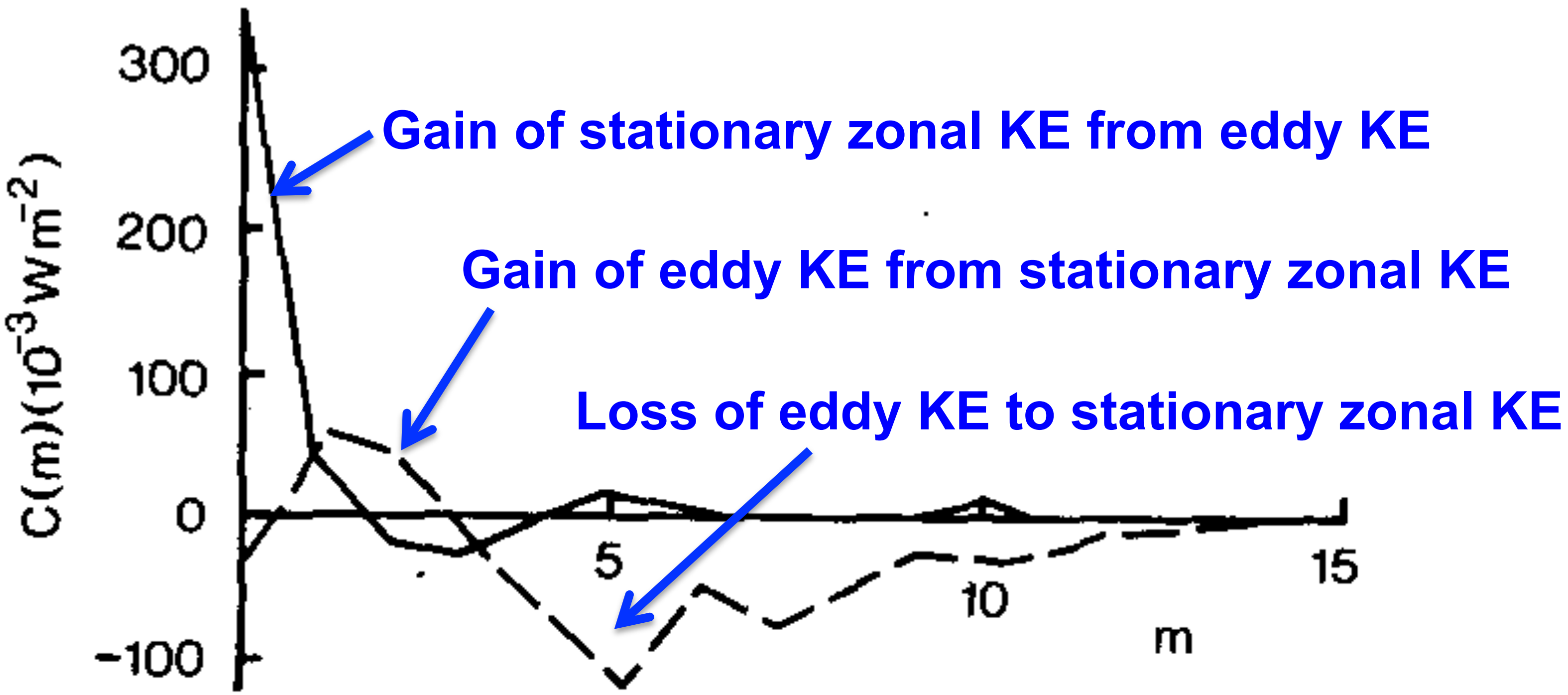


m=7: eddies lose energy to mean flow



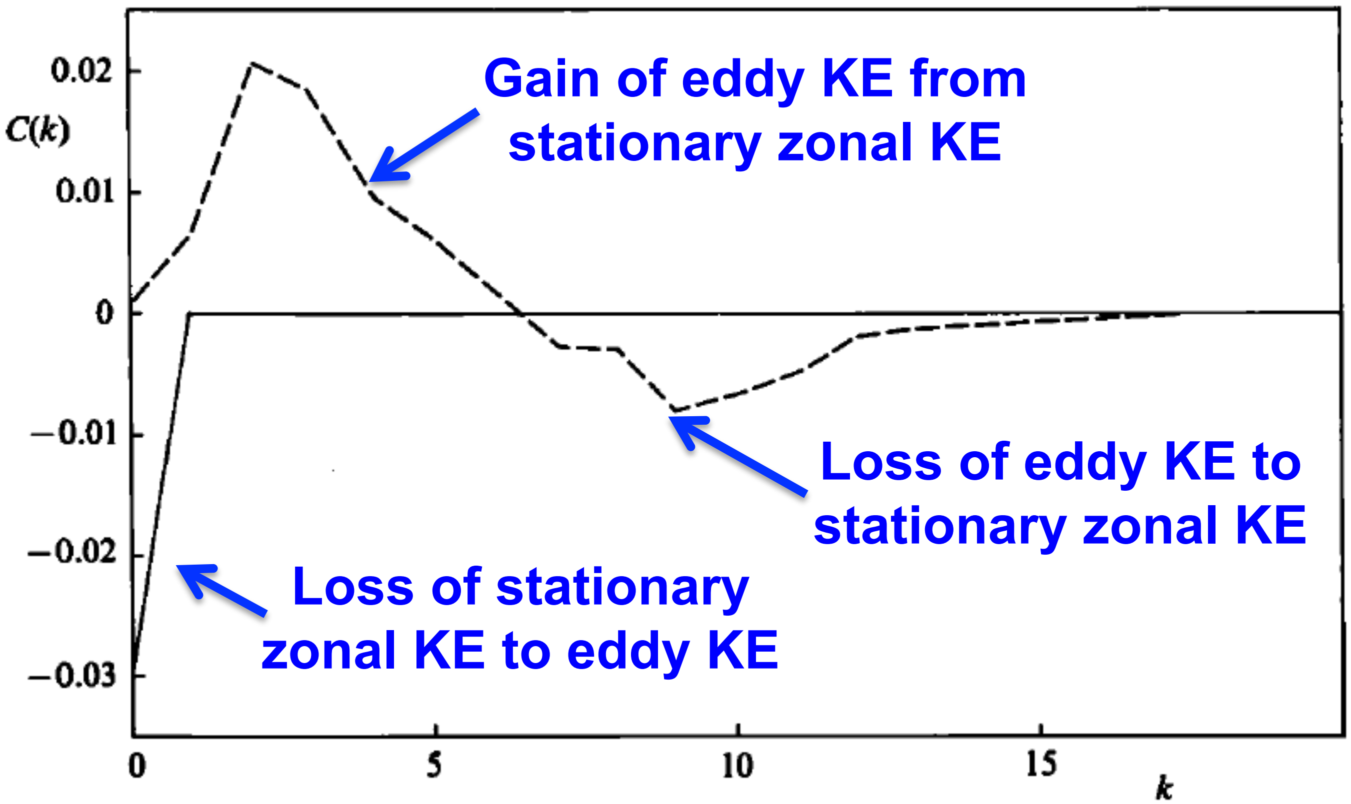
Shepherd (1987 JAS)

- The synoptic-wave contribution dominates; this is what gives the net upscale energy transfer



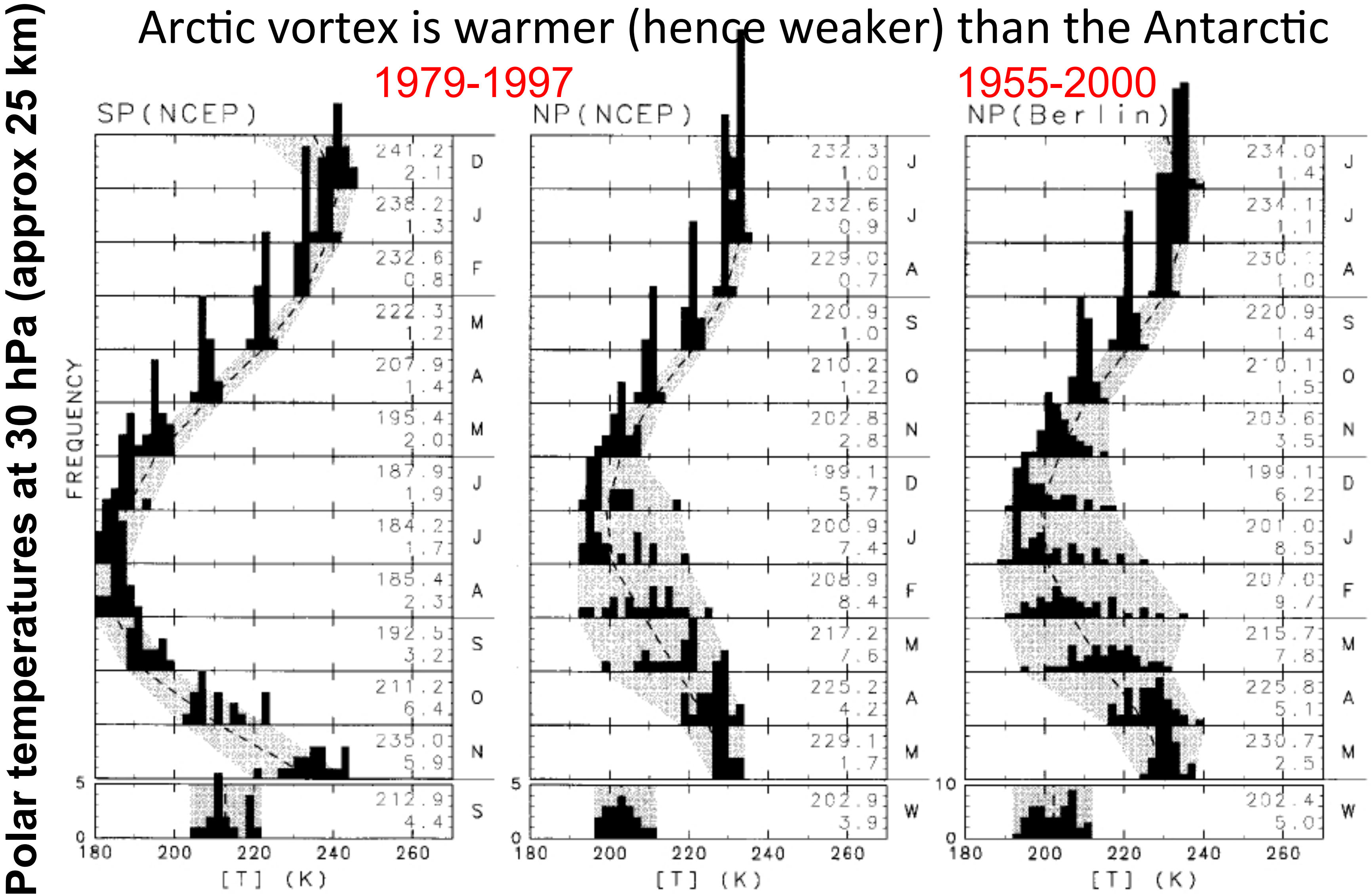
FGGE analysis in Shepherd (1987 JAS)

- But if the jets are not eddy-driven, then it's not clear that the eddies have to maintain them
- In numerical simulations with an imposed jet and random forcing, the sign of the eddy-mean energy transfer depends on the parameter regime



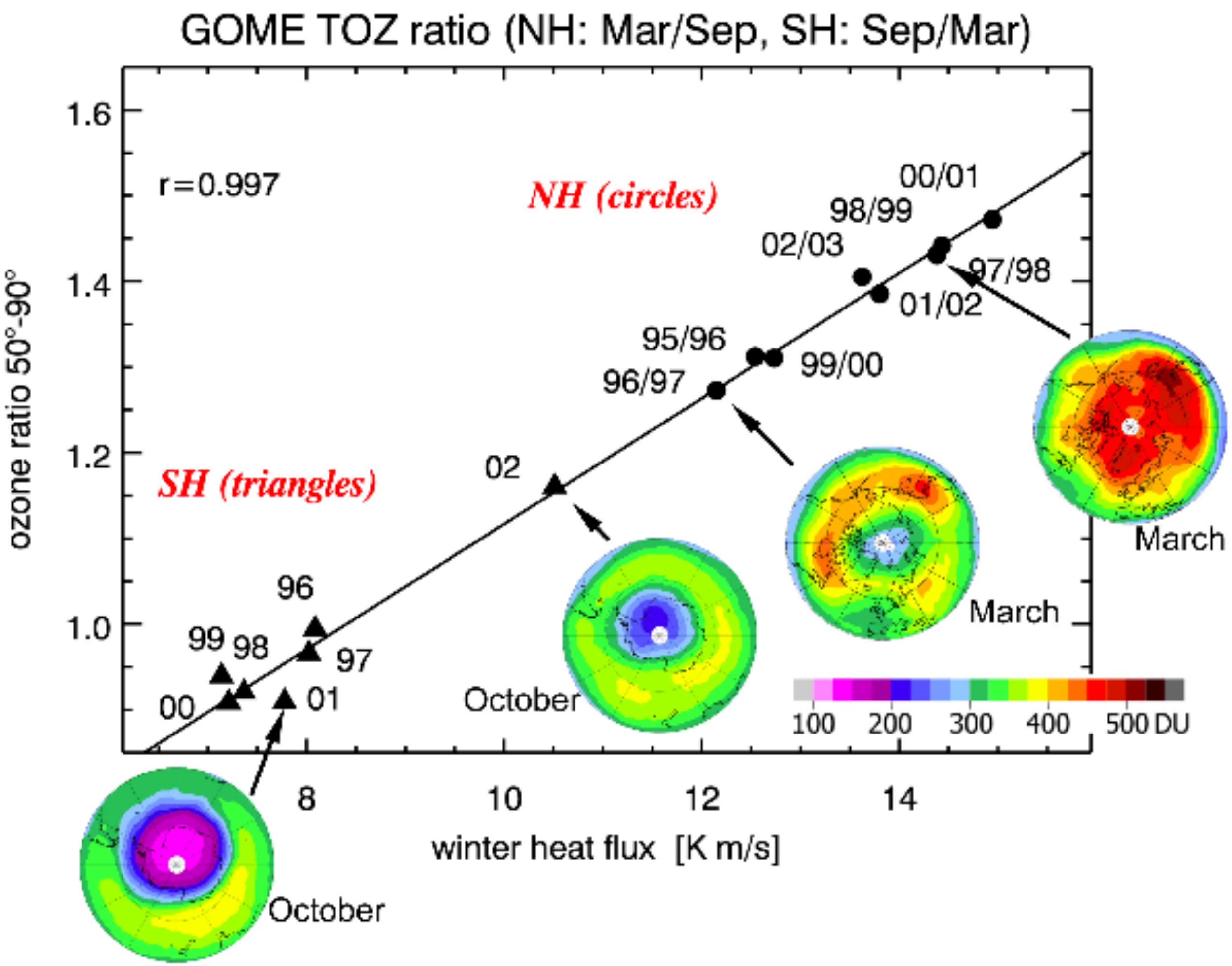
Barotropic numerical simulations in Shepherd (1987 JFM)

- The stratospheric polar vortex is *weakened* by eddy forcing
- Planetary Rossby waves stronger in NH than in SH, so the Arctic vortex is warmer (hence weaker) than the Antarctic



Yoden, Taguchi & Naito (2002 JMSJ)

- Variations in the upward wave forcing ("winter heat flux", proportional to vertical EP flux) are associated with variations in polar downwelling, hence in polar vortex strength and in polar ozone abundance



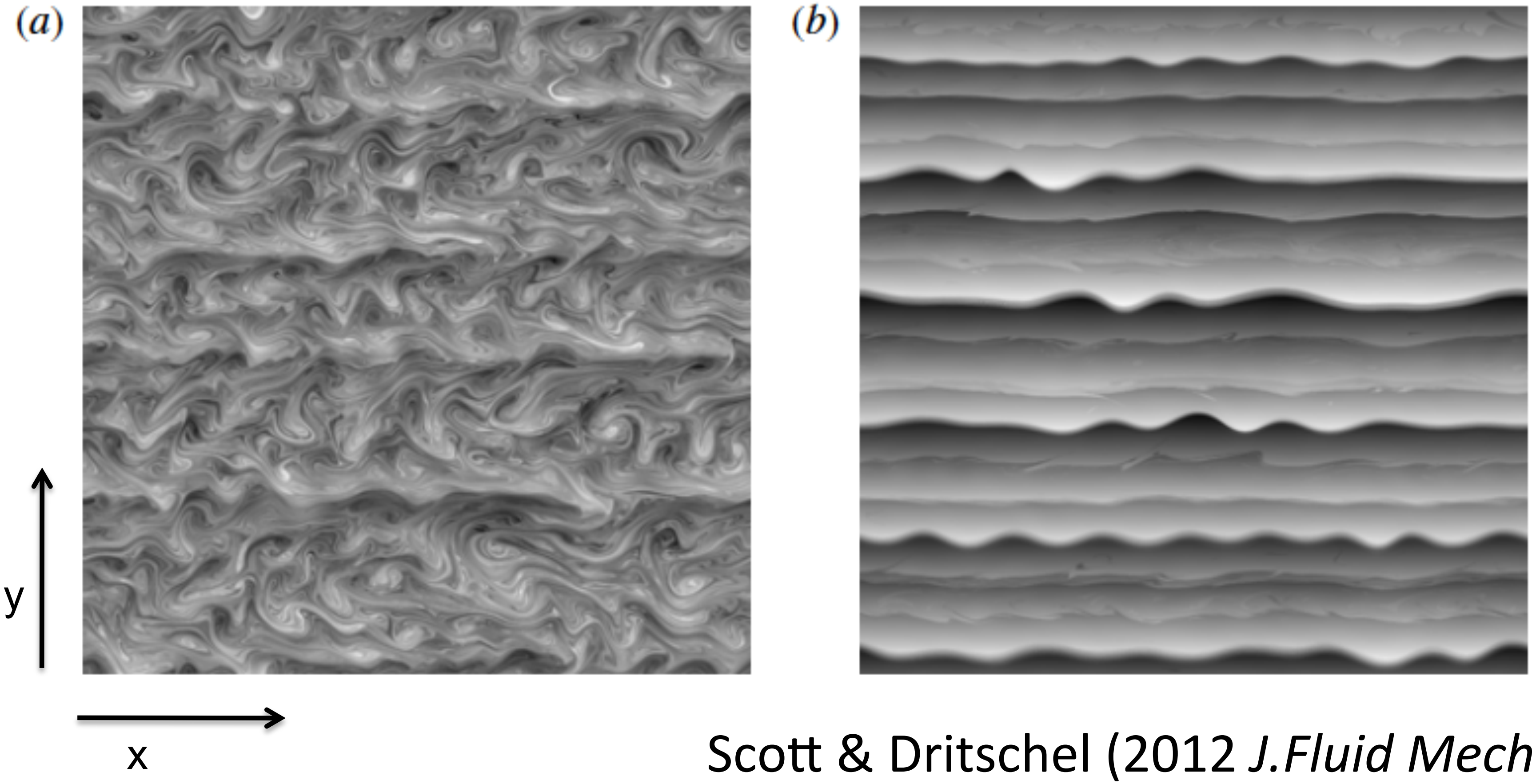
A weaker vortex permits more ozone transport and less chemical ozone loss, thus has a larger summertime photochemical decay of ozone

Adapted from Weber et al. (2003 GRL)

- **β-plane turbulence:** spontaneous generation of zonal jets

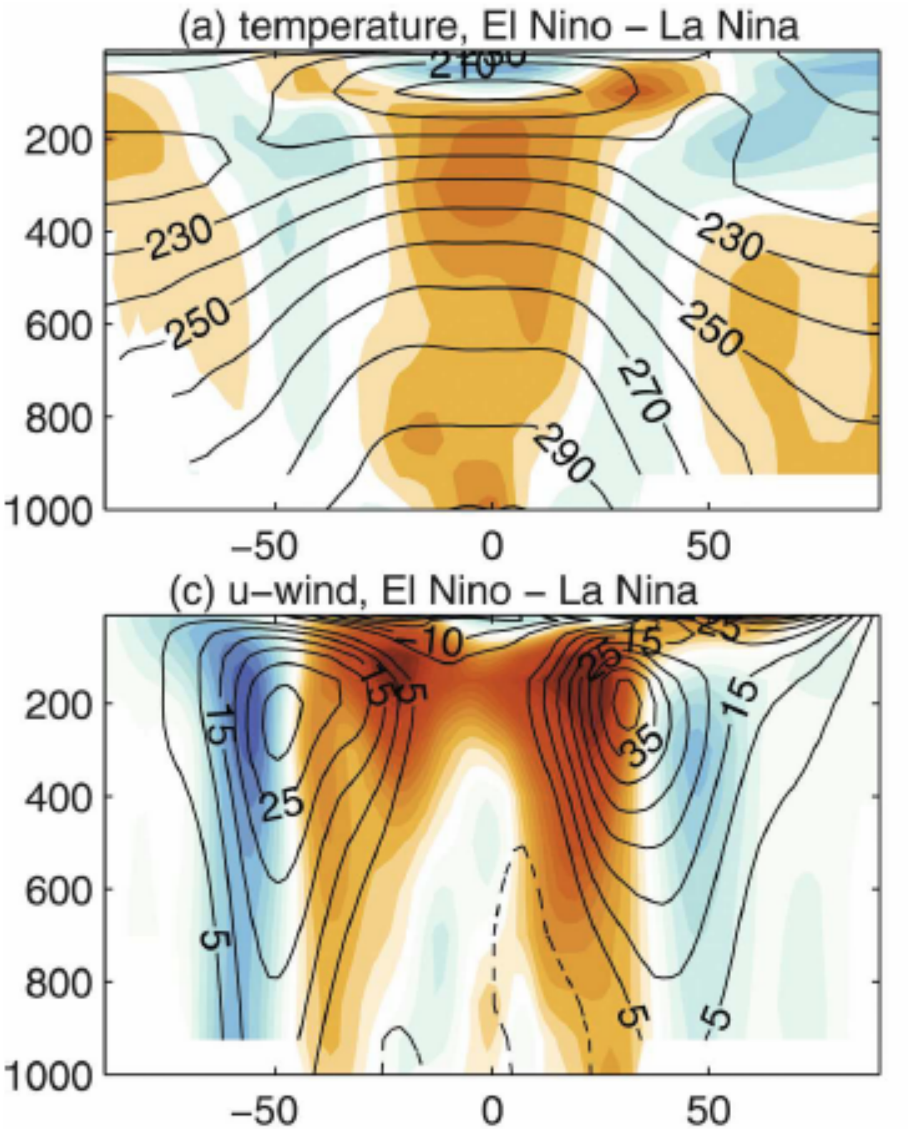
  Figures show plan views of instantaneous PV anomaly $q - \beta y$

  When there is enough dynamic range between the energy injection scale and the Rhines scale $L_R = (\beta U)^{1/2}$, the turbulence is nearly suppressed and a PV 'staircase' is formed (right)



Scott & Dritschel (2012 *J.Fluid Mech.*)

- Observations show a **zonally symmetric midlatitude tropospheric response to ENSO** (here for DJF)

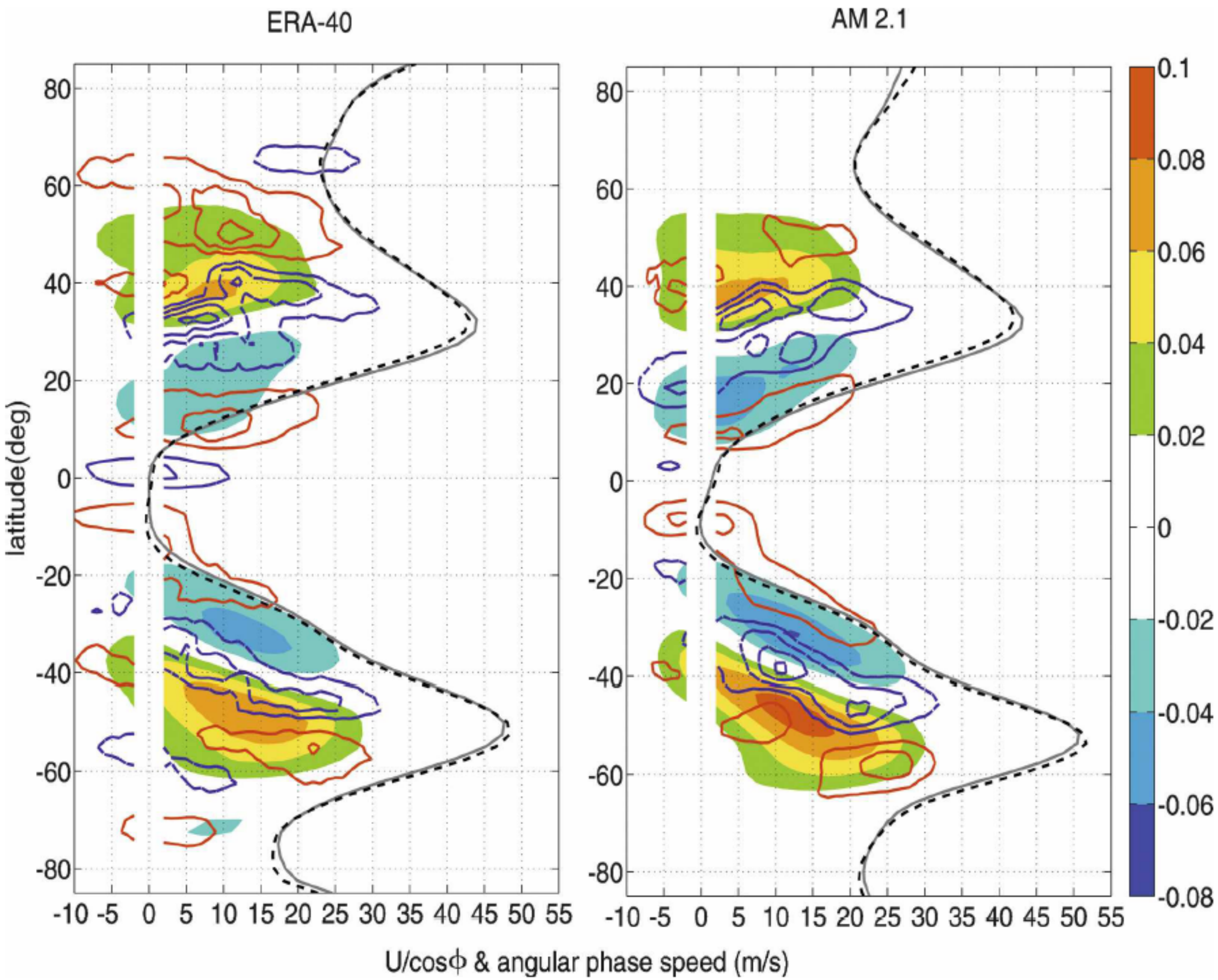


Midlatitude jet shifts equatorward in response to El Niño, poleward in response to La Niña

Driven by meridional shift in eddy momentum flux

Lu, Chen & Frierson (2008 J Clim)

- Argued to be a response to meridional shift in critical layers induced by zonal wind changes (after Robinson 2002 GRL)



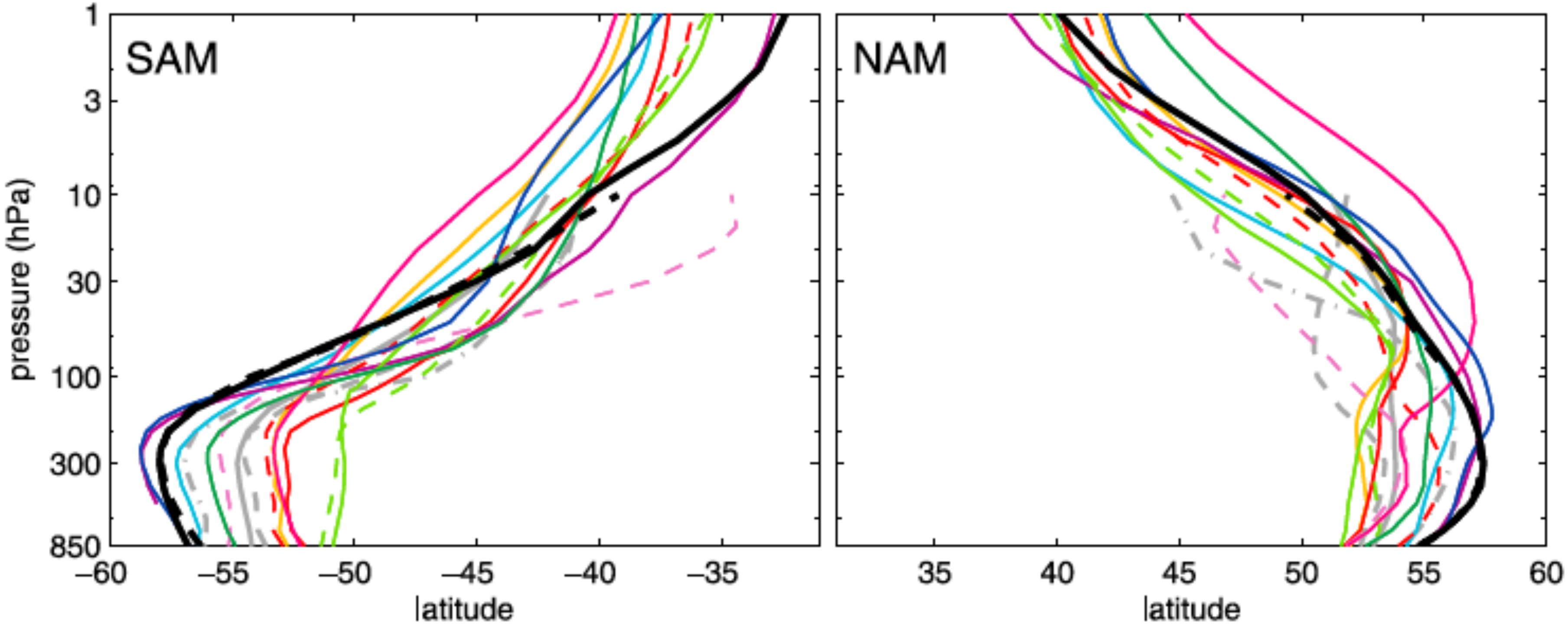
250 hPa, DJFM

Response of momentum flux convergence to La Niña

Climo shaded, perturbation contoured (also dashed line for zonal wind)

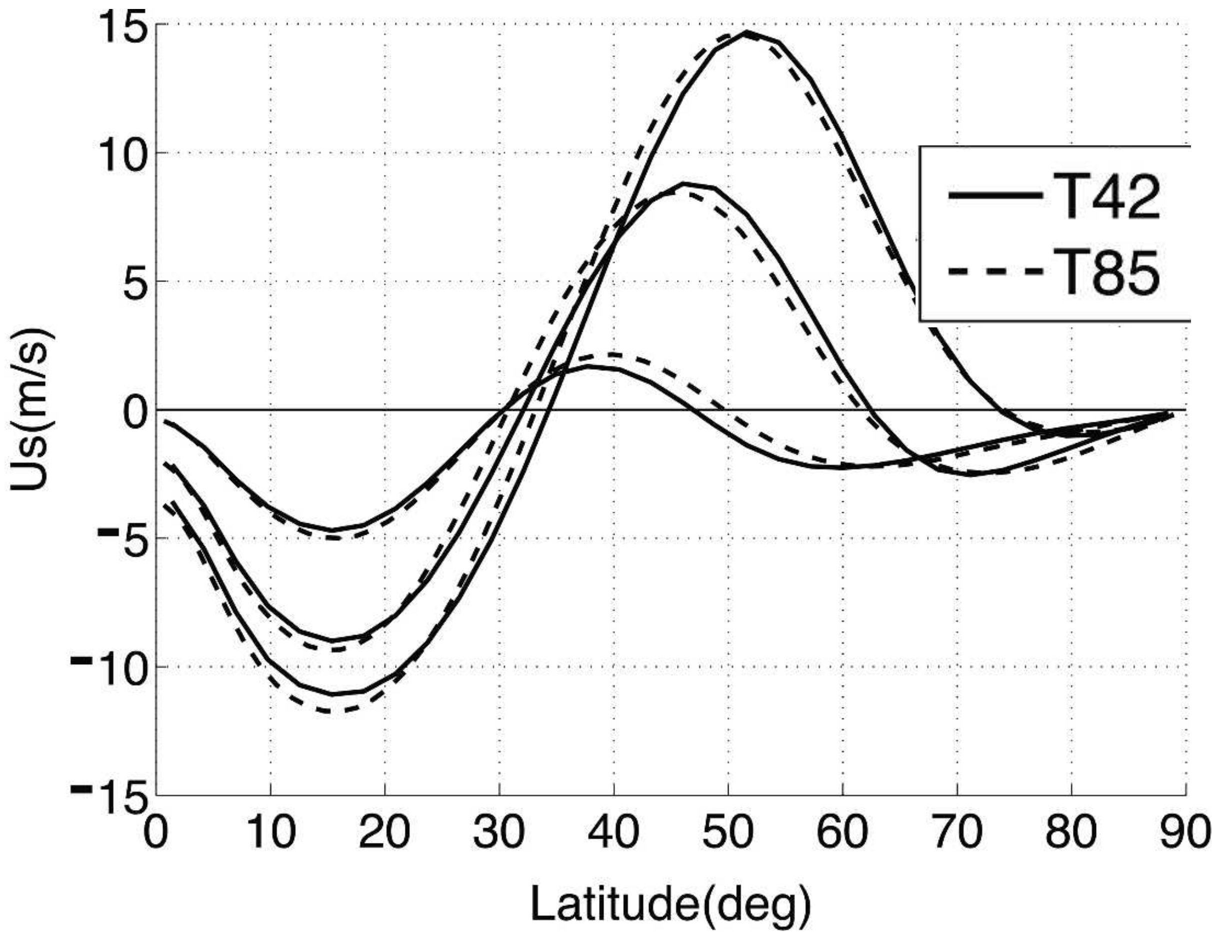
Chen, Liu & Frierson (2008 J. Clim.)

- Models tend to locate the tropospheric eddy-driven jet too far equatorward, in both hemispheres (black are obs)
  – Reflected here in the location of the node of annular-mode variability
  – Biases are similar when observed SSTs are imposed, implying the errors arise from atmospheric processes



Gerber et al. (2010 JGR)

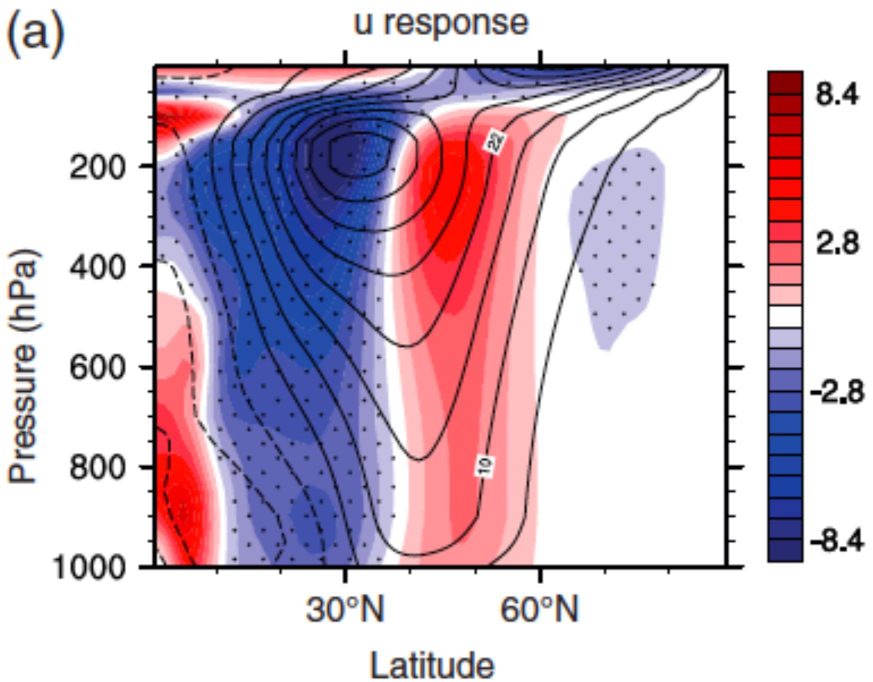
- In idealized AGCMs, surface jet strength and latitude are highly sensitive to surface drag, via feedback on baroclinic eddies

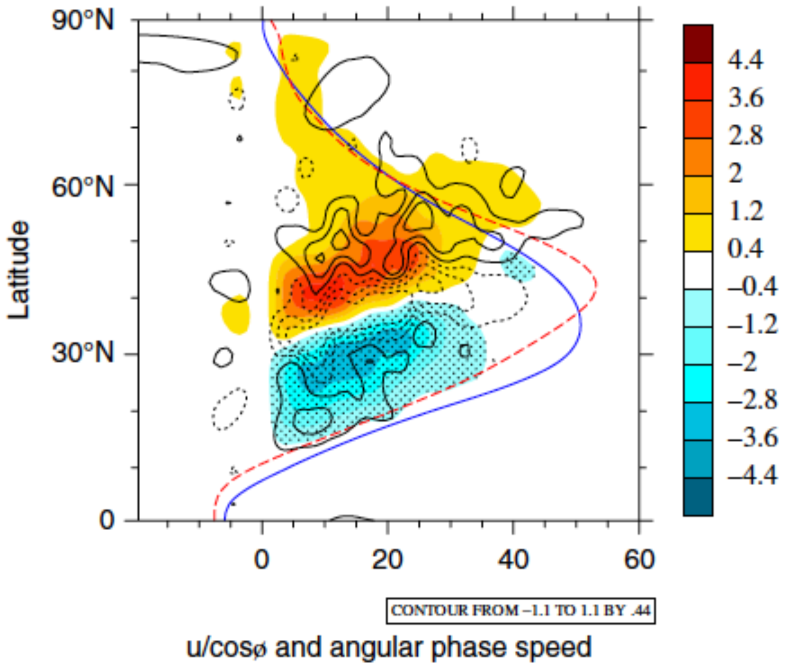


The three different curves are for damping timescales of 0.5, 1.0 and 1.5 days

Chen, Held & Robinson (2007 JAS)

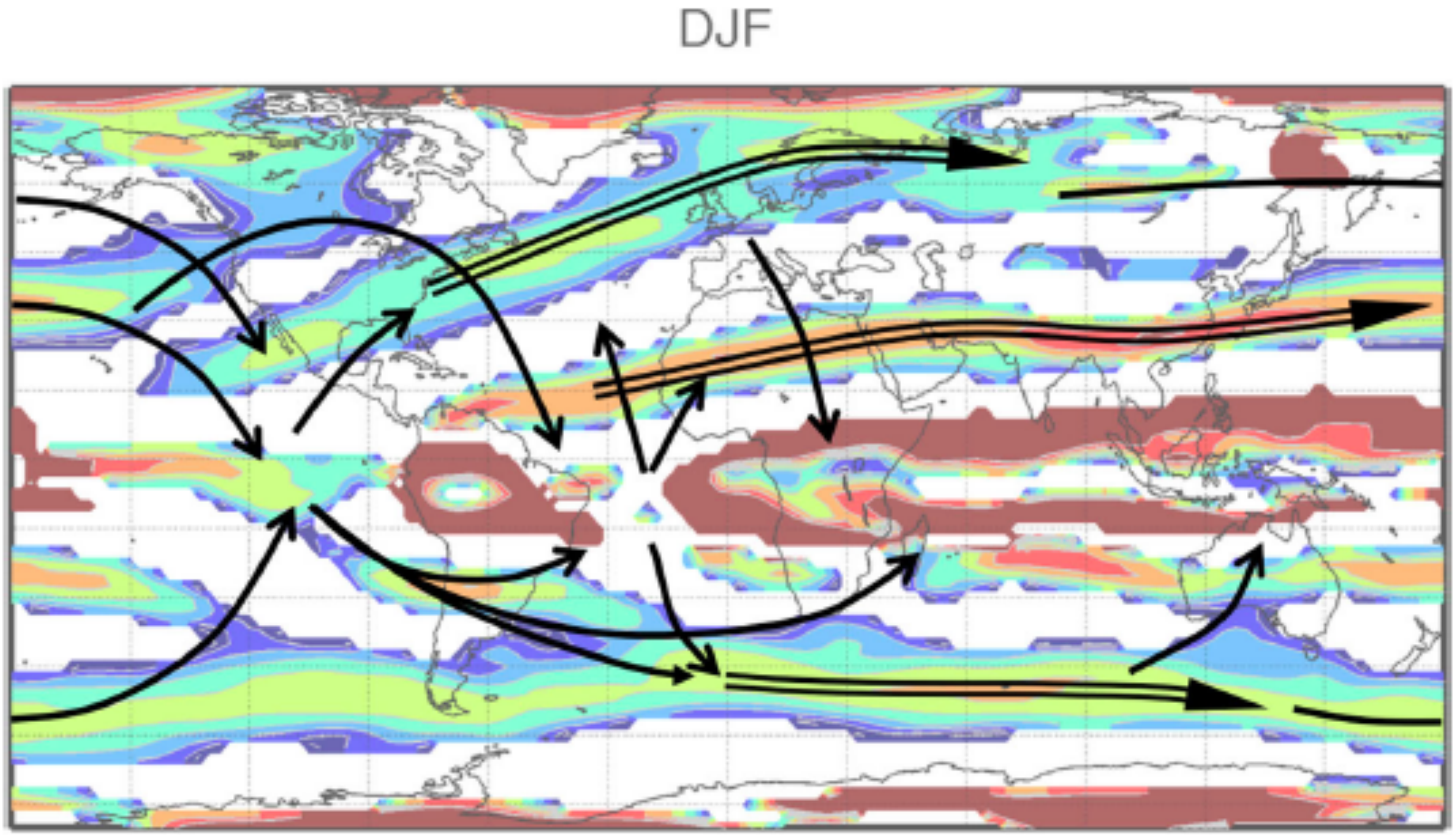
- The NCAR CAM in aquaplanet configuration shows a poleward jet shift in response to reduction in momentum roughness length at small wind speeds (where observational constraints are weak), **which originates from the tropics** (also big change in the ITCZ)
  - Similar response seen in AMIP mode
  - Mechanism for extratropical influence seems similar to that seen by Chen, Lu & Frierson (2008 J. Clim.) for ENSO





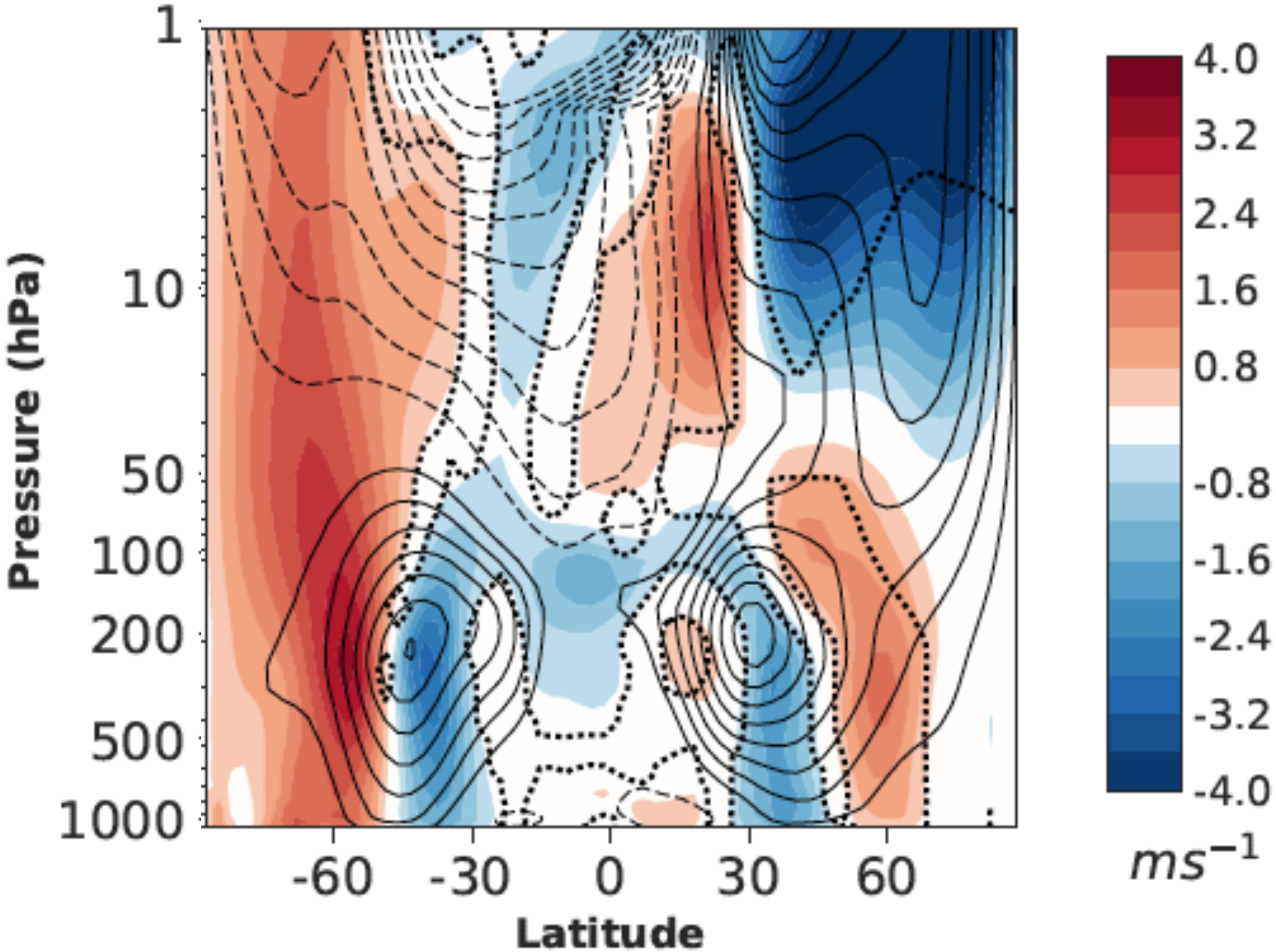
Polichtchouk & Shepherd (2016 QJRMS)

- The longitudinally varying jet provides waveguides (double arrows) and preferred pathways (single arrows) for stationary Rossby wave propagation



Hoskins & Woollings (2016), after Hoskins & Ambrizzi (1993 JAS)

- The midlatitude jet is **sensitive to orographic drag**
- Increased low-level blocking shifts jets poleward
  - Driven by stationary momentum fluxes in NH, and by transient momentum fluxes in SH

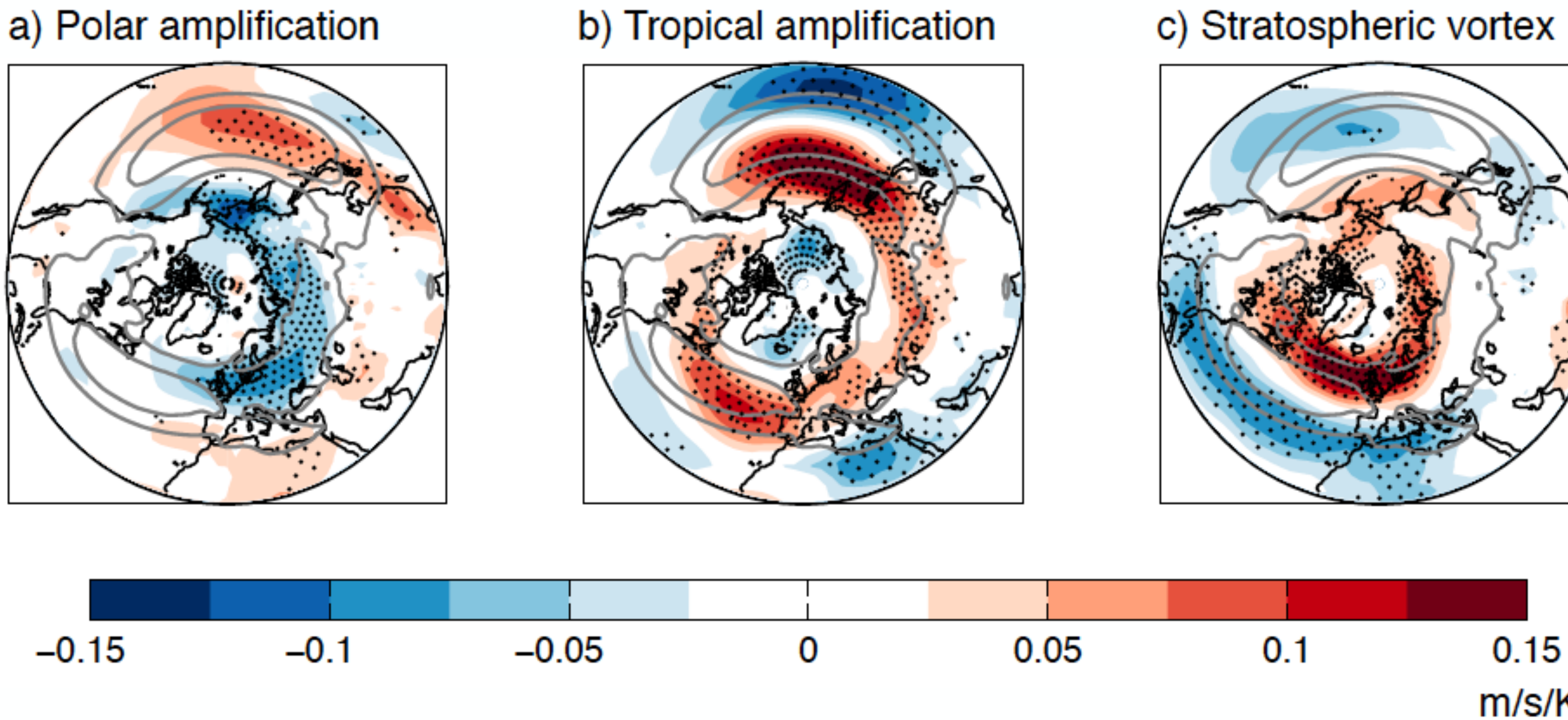


DJF zonal wind

Contours are climo, colours are response to drag

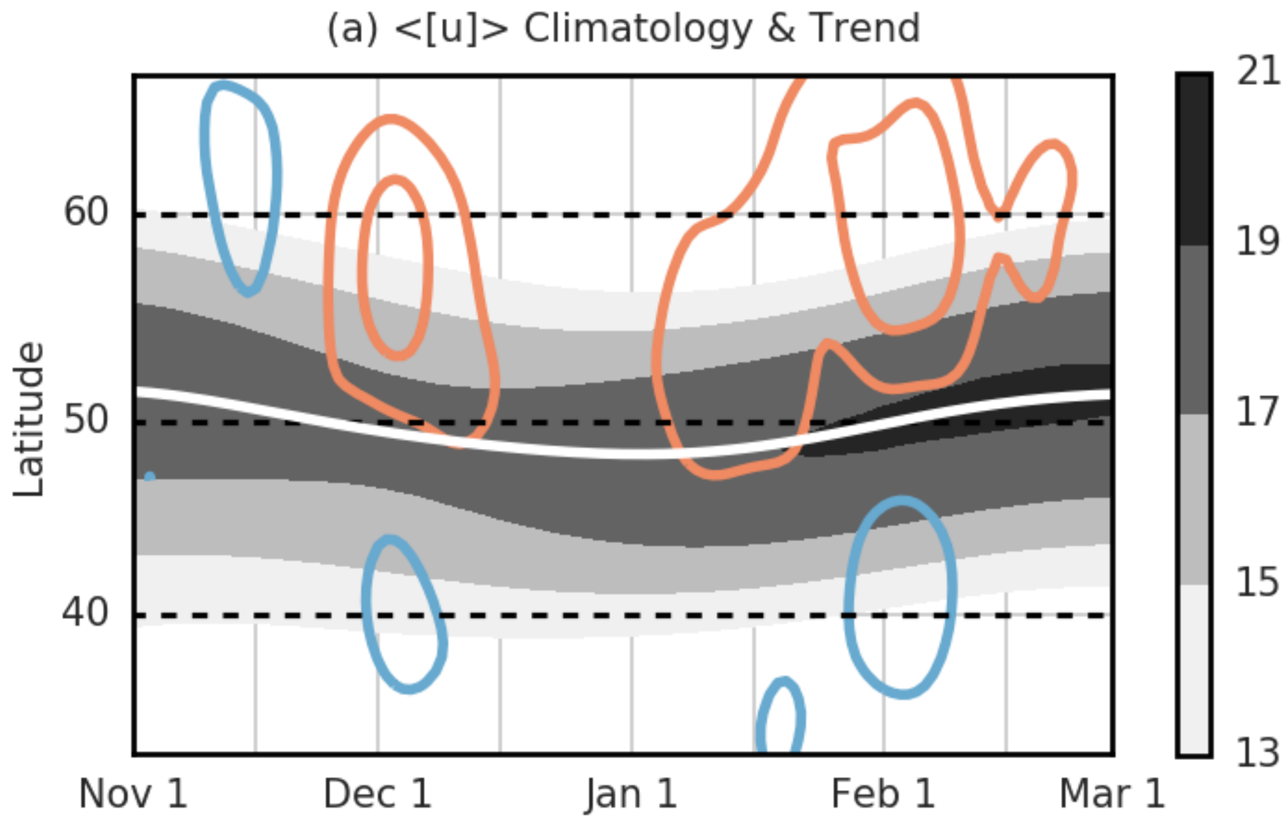
van Niekerk, Scinocca & Shepherd (2017 JAS)

- Response of NH midlatitude circulation to climate change involves a "tug of war" between different regional drivers
  - Helps explain the **non-robustness of the circulation response**
- Sensitivity of the U850 wind response to 1σ uncertainty in the regional drivers of climate change (cf. Manzini et al. 2014 JGR)



Zappa & Shepherd (2017 J. Clim.)

- The only observed circulation change that has been attributed to anthropogenic forcing is the poleward shift of the summertime SH eddy-driven jet (SAM)
- Can be alternatively interpreted as a delay of the seasonal equatorward transition, induced by delayed vortex breakdown



Contours show climatology of tropospheric *u* from 1979-2016, contours the long-term change, C.I. 0.6 m/s/decade

Byrne, Shepherd, Woollings & Plumb (2017 J. Clim.)

- First-order explanation of **zonal-mean jet variations** is provided by the vertically averaged zonal momentum equation

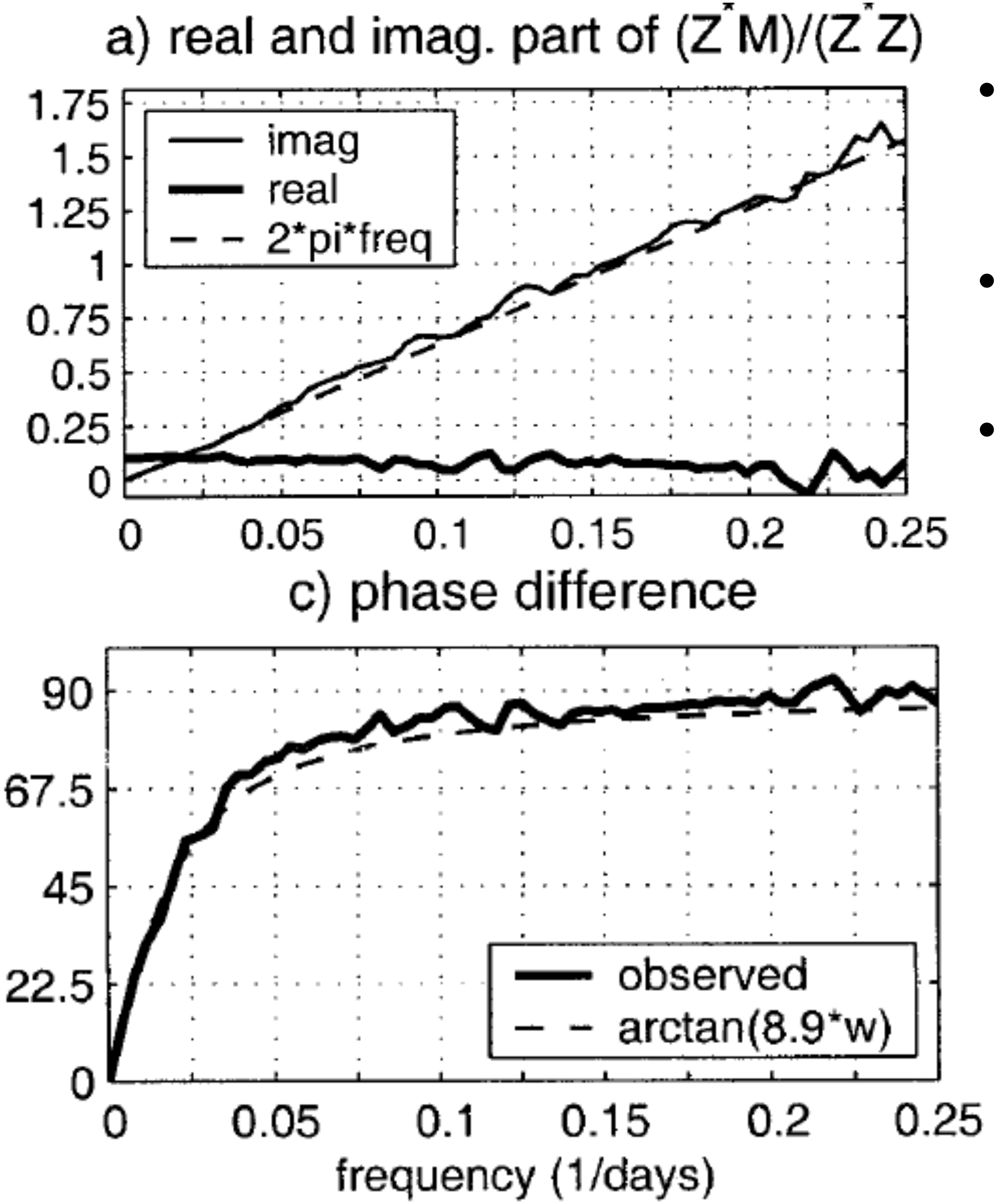
$$\frac{\partial < [u] >}{\partial t} = -\frac{1}{\cos^2\phi}\frac{\partial(< [u'v'] > \cos^2\phi)}{a\partial\phi} - F$$

- *F* represents surface torques; Coriolis term vanishes under the vertical average (under QG scaling)
- Variability can be represented by the simple anomaly model

$$\frac{\mathrm{d}z}{\mathrm{d}t} = m - \frac{z}{\tau}$$

(Lorenz & Hartmann 2001)

- Eddy forcing *m* (white noise; weather) drives low-frequency variability in *z* (red noise; climate): Hasselmann (1976)

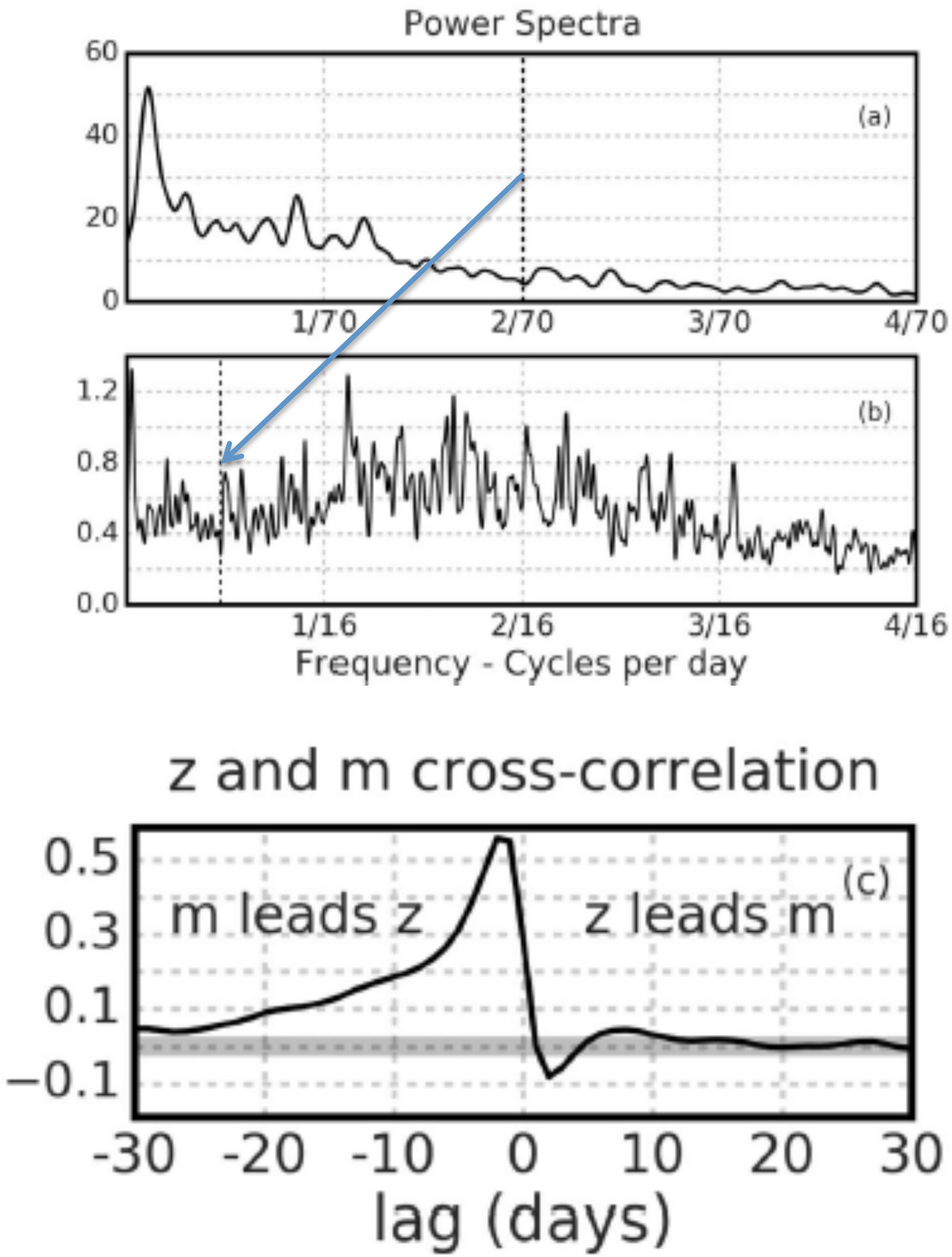


- Simple model implies

$$M = (\tau^{-1} + i\omega)Z$$

- SH observations fit this relationship quite well
- *M* and *Z* are in phase at low frequencies, and 90° out of phase at high frequencies (periods shorter than about 20 days)

Lorenz & Hartmann (2001 JAS)

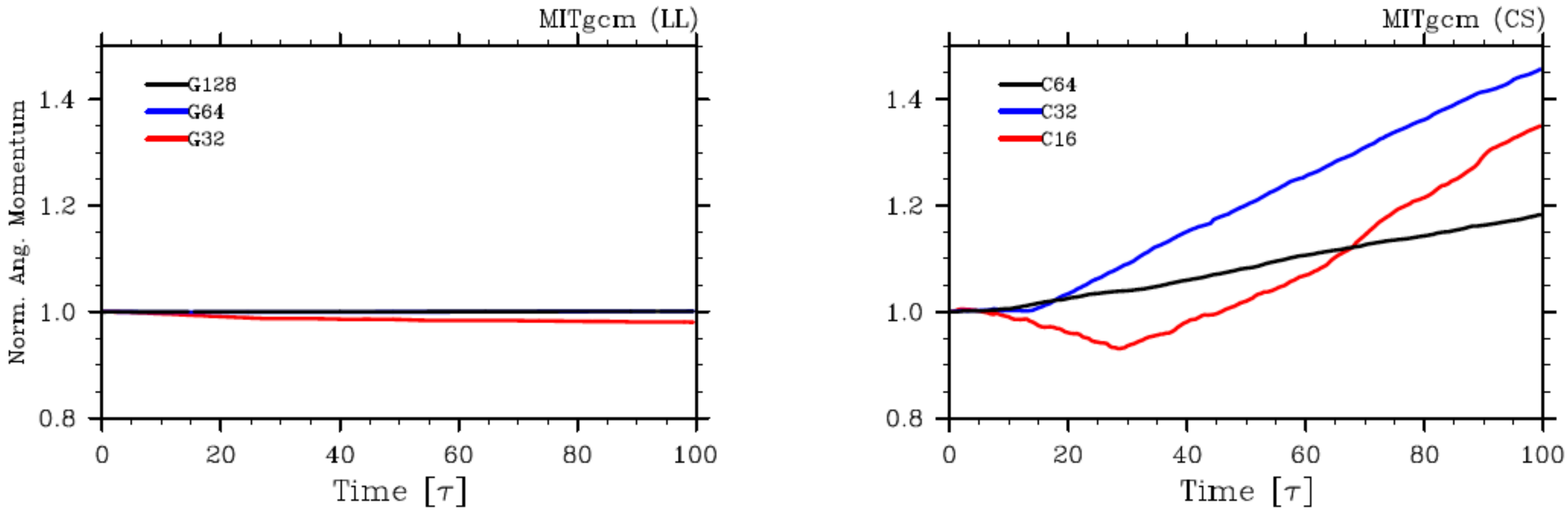


- SH observations show there is a distinct peak at 2 years which spoils the assumed timescale separation
- The cross-correlation at positive lags has been interpreted as an eddy feedback, but this is controversial!

Byrne, Shepherd, Woollings & Plumb (2016 GRL), after Lorenz & Hartmann (2001)

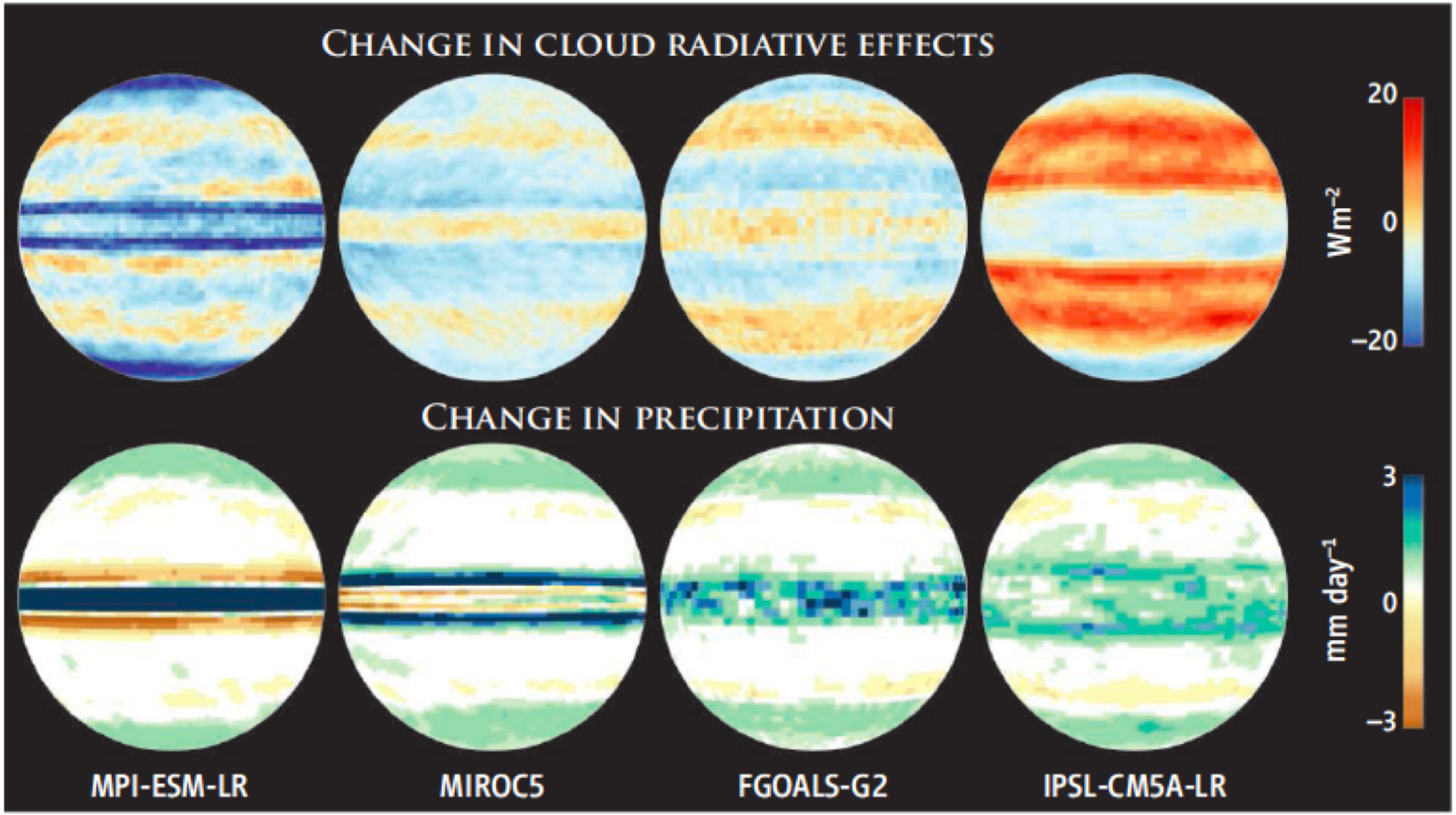
A cautionary note for modelling

- Evolution of angular momentum in idealized set-up for hot extrasolar planets (tidally locked)
- Cubed sphere violates angular momentum conservation
- There is a tendency towards grids that break rotational symmetry



Polichtchouk et al. (2014 Icarus)

- Response to 4°C warming in aquaplanet with prescribed SSTs
  - More generally, see ‘Aquaplanet Experiment’ (Blackburn & Hoskins 2013, special issue of J. Meteor. Soc. Japan)



Stevens & Bony (2013 Science)

Phenomenology of Earth's atmosphere

- Hadley circulation, midlatitude baroclinicity
- Baroclinically driven eddies
- Eddy momentum forcing of zonal jets

Balanced and unbalanced dynamics

- Vortical dynamics, IG waves
- Slow manifold

Hamiltonian GFD

- Pseudomomentum of β-plane eddies (finite-amplitude Rossby waves)

2D and shallow-water turbulence

- Upscale energy cascade
- Downscale enstrophy cascade
- Gage-Nastrom spectrum

Wave, mean-flow interaction

- Non-acceleration theorem
- Rossby-wave source drives westerlies
- Wave-turbulence jigsaw puzzle

2D turbulence and zonal jets

- Eddy-driven jets
- Eddy-damped jets
- Complexities of Earth's atmosphere