Macroturbulence in the General Circulation of the Atmosphere

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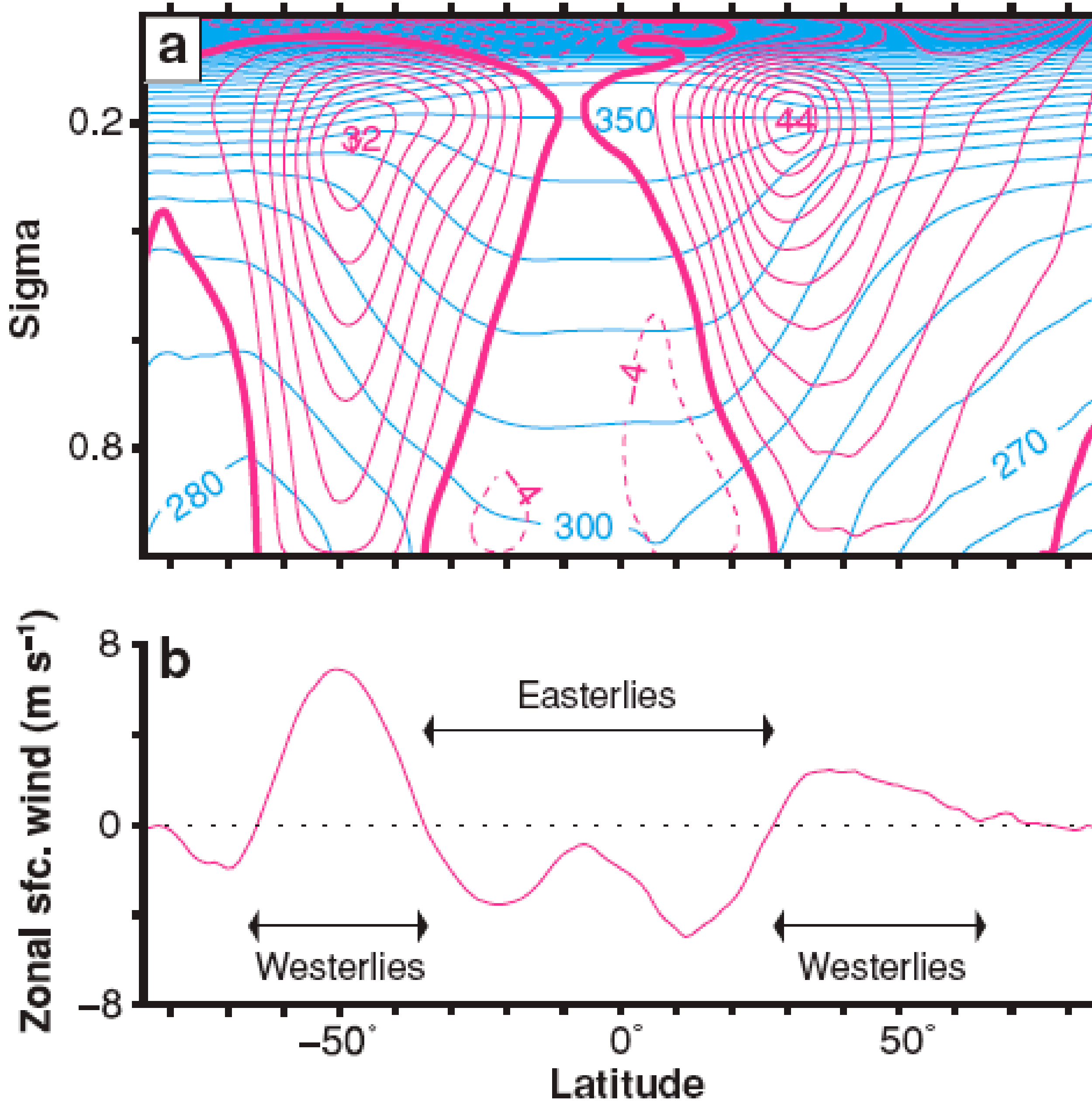
(with Chris Walker, Simona Bordoni, Paul O'Gorman, Xavier Levine, Tim Merlis)

January zonal wind and potential temperature



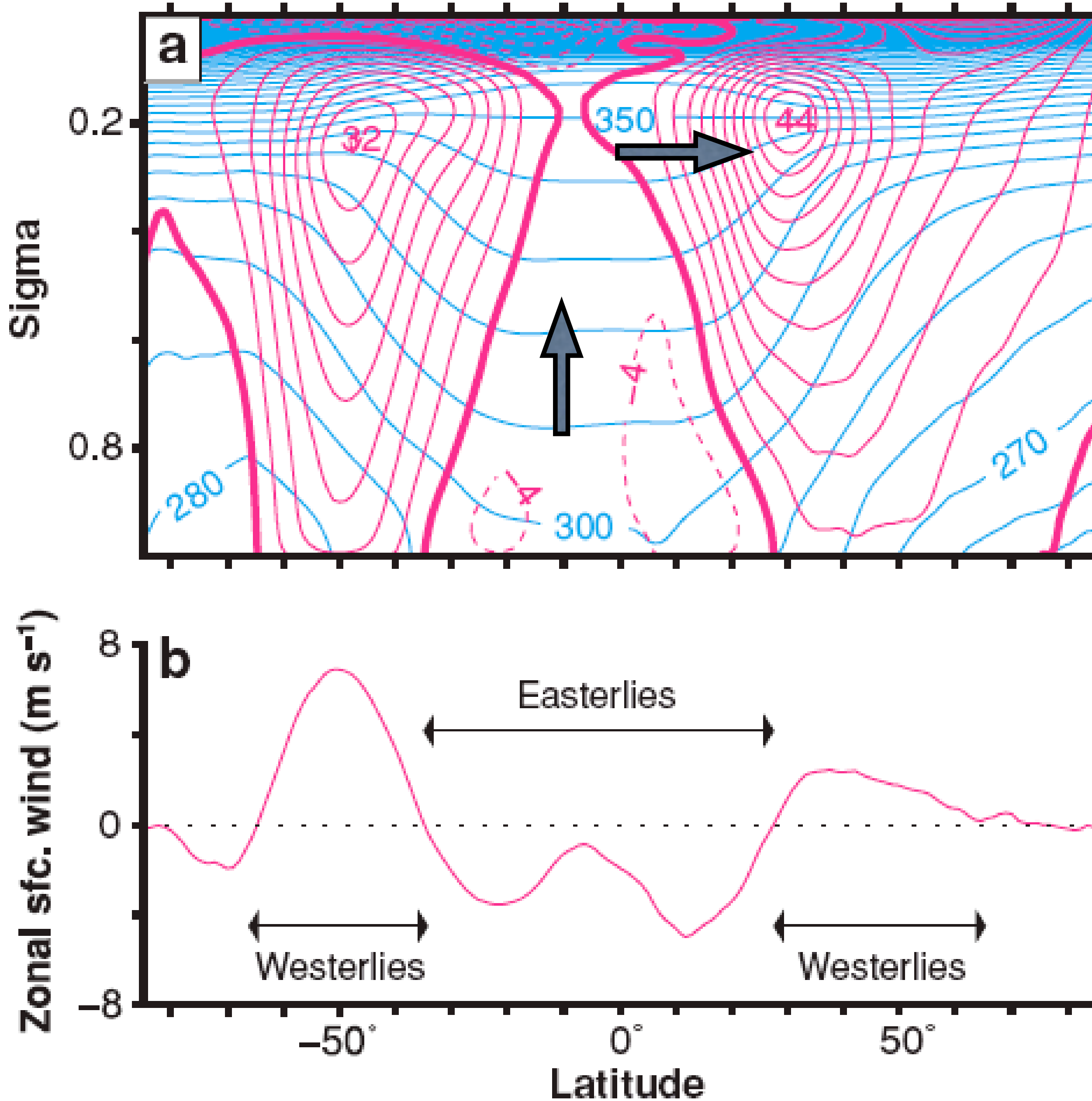
(Schneider 2006)

VI. *Concerning* the Caufe *of the* General Trade-Winds: *By* Geo. Hadley, *Efq;* *F. R. S.*

I Think the Caufes of the General Trade-Winds have not been fully explained by any of thofe who have wrote on that Subject, for want of more particularly and diftinctly confidering the Share the diurnal Motion of the Earth has in the Production of them: For although this has been mention'd by

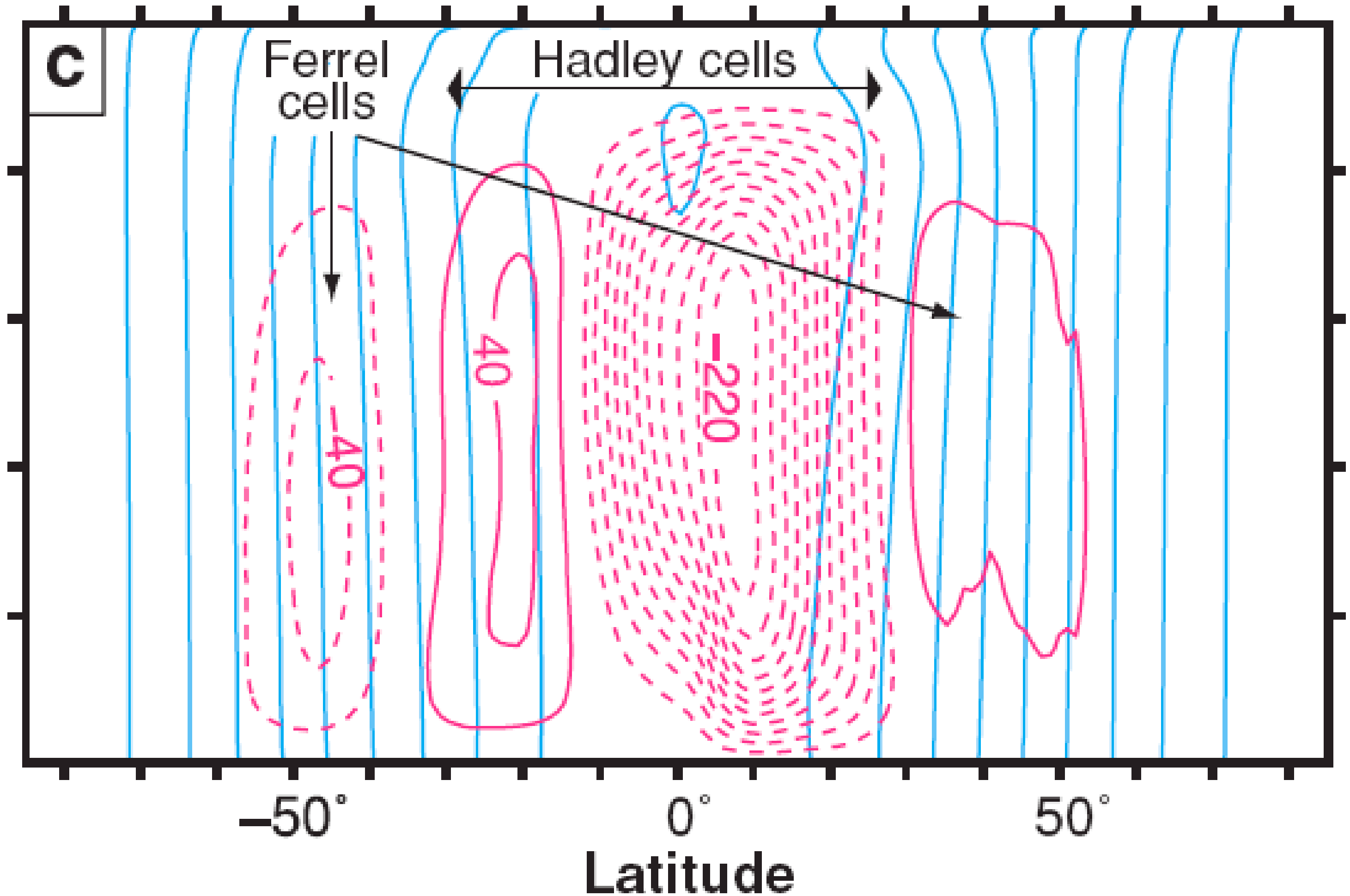
(Hadley 1735)

January zonal wind and potential temperature



Angular momentum advection in upper branch of circulation

January streamfunction and angular momentum



(Schneider 2006)

The ideal Hadley circulation...

- Conserves angular momentum *m* in upper branch

$$\bar{v}\partial_y \bar{m} \approx 0$$

Since $\partial_y \bar{m} \propto f + \bar{\zeta}$, this implies

$$(f + \bar{\zeta})\bar{v} = f(1 - \mathrm{Ro})\bar{v} \approx 0$$

with *local Rossby number* $\mathrm{Ro} = -\bar{\zeta}/f \to 1$

- Is energetically closed (no heat export)

- Responds *directly* to variations in thermal driving

- Result: $\phi_h \sim (H_t' \Delta_h')^{1/2}, \qquad \Psi_{\max} \sim (H_t' \Delta_h')^{5/2}$

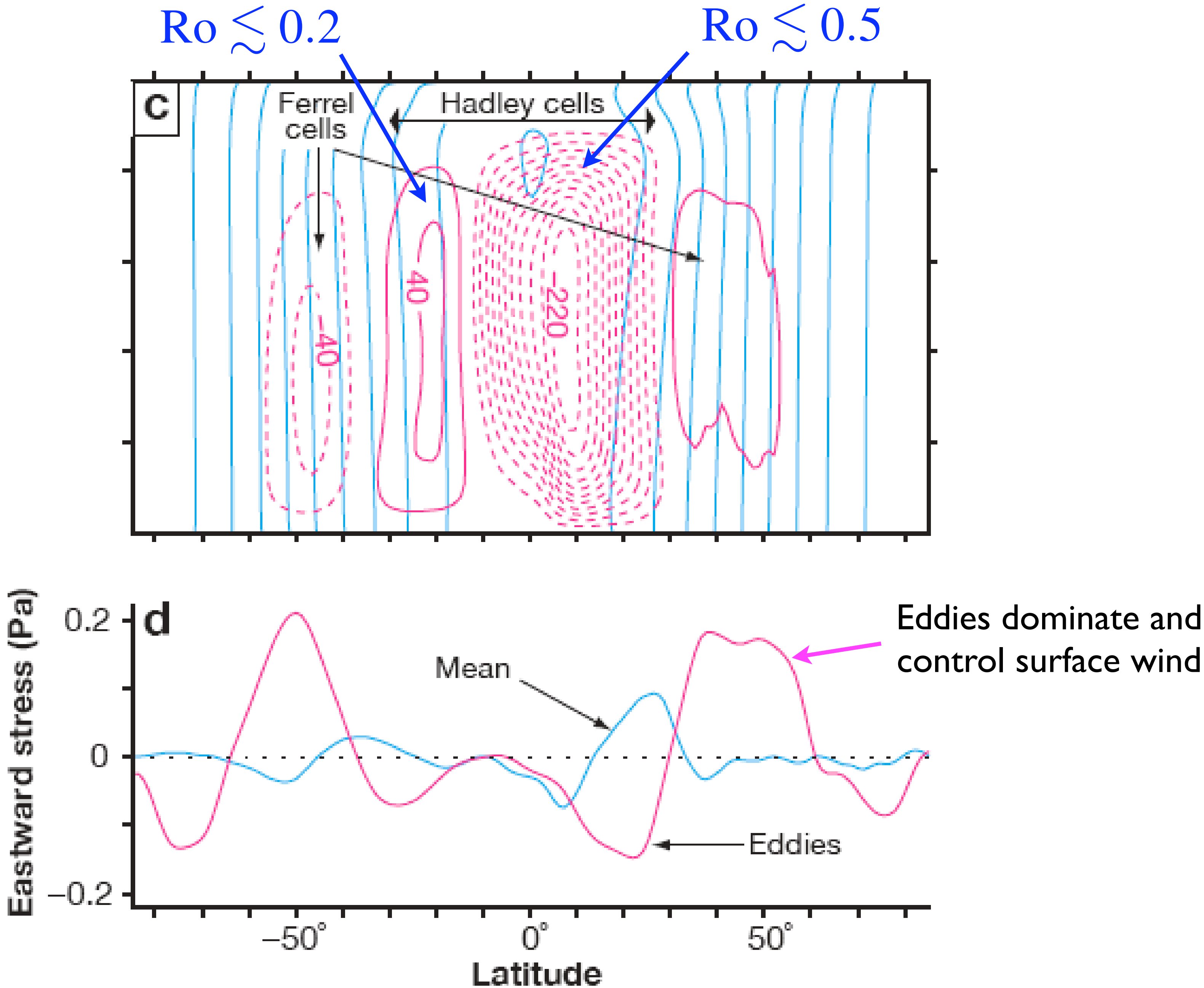
(Schneider 1977; Schneider & Lindzen 1976, 1977; Held & Hou 1980)

Ideal Hadley circulation theory...

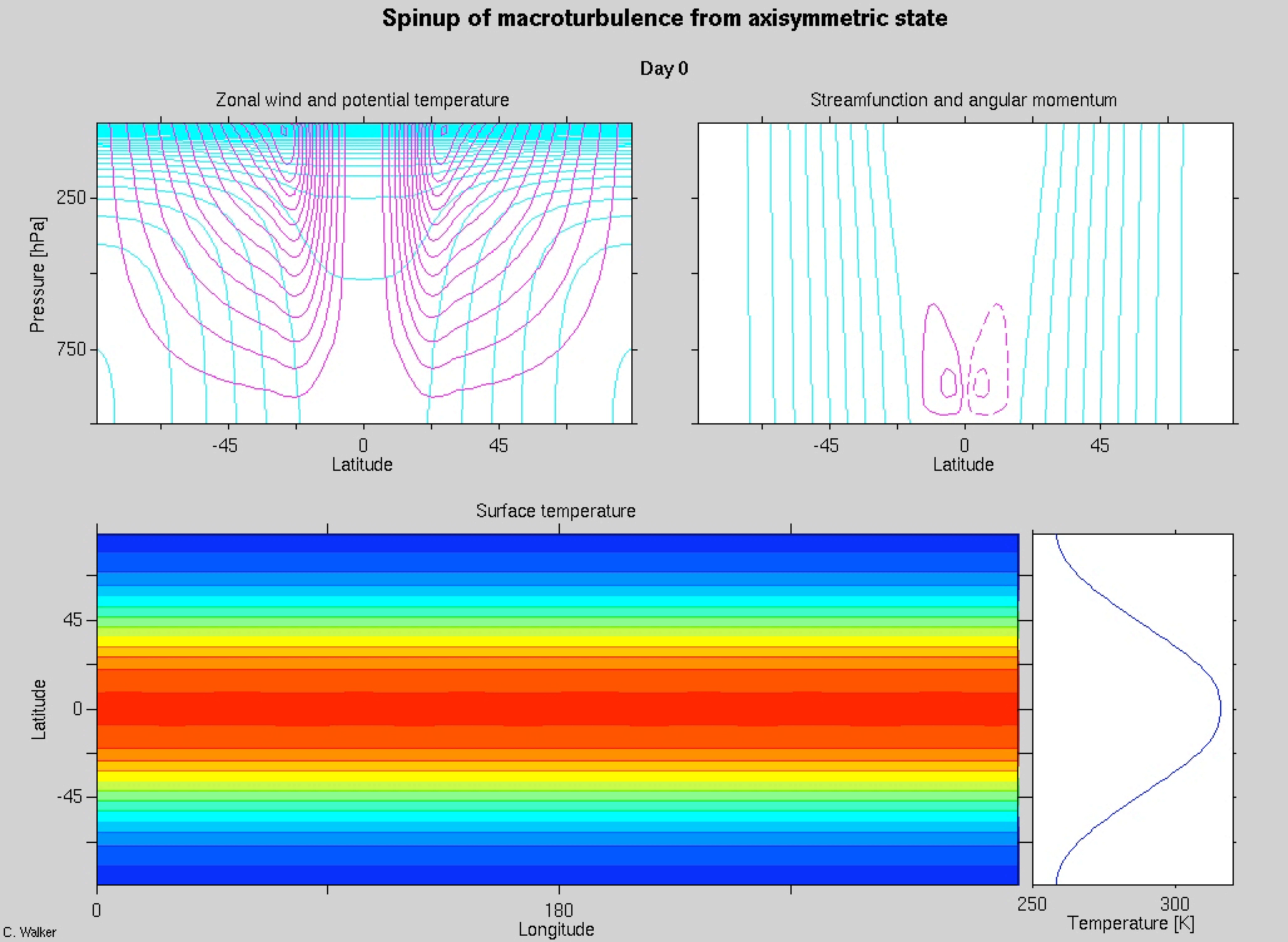
- Is intuitively appealing (direct reponse to thermal driving)
- Appears to account for extent of circulation in Earth's atmosphere

But does it account for variations in Hadley circulation as climate varies?

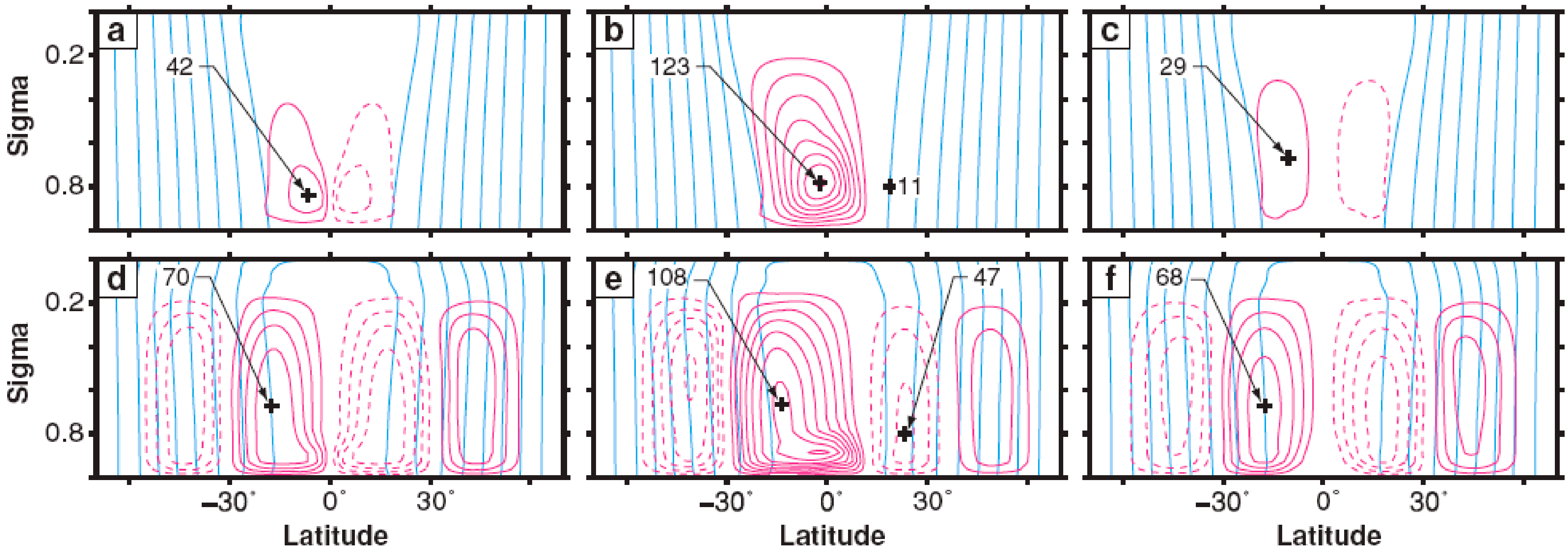
January streamfunction and angular momentum



(Schneider 2006)


Spinup of macroturbulence from axisymmetric state
Day 0
Zonal wind and potential temperature
Pressure [hPa]
250
750
-45
0
45
Latitude
Streamfunction and angular momentum
-45
0
45
Latitude
Surface temperature
Latitude
45
0
-45
0
180
Longitude
250
300
Temperature [K]
C. Walker

‘Seasonal’ variations in axisymmetric (top) and eddy-resolving (bottom) simulations

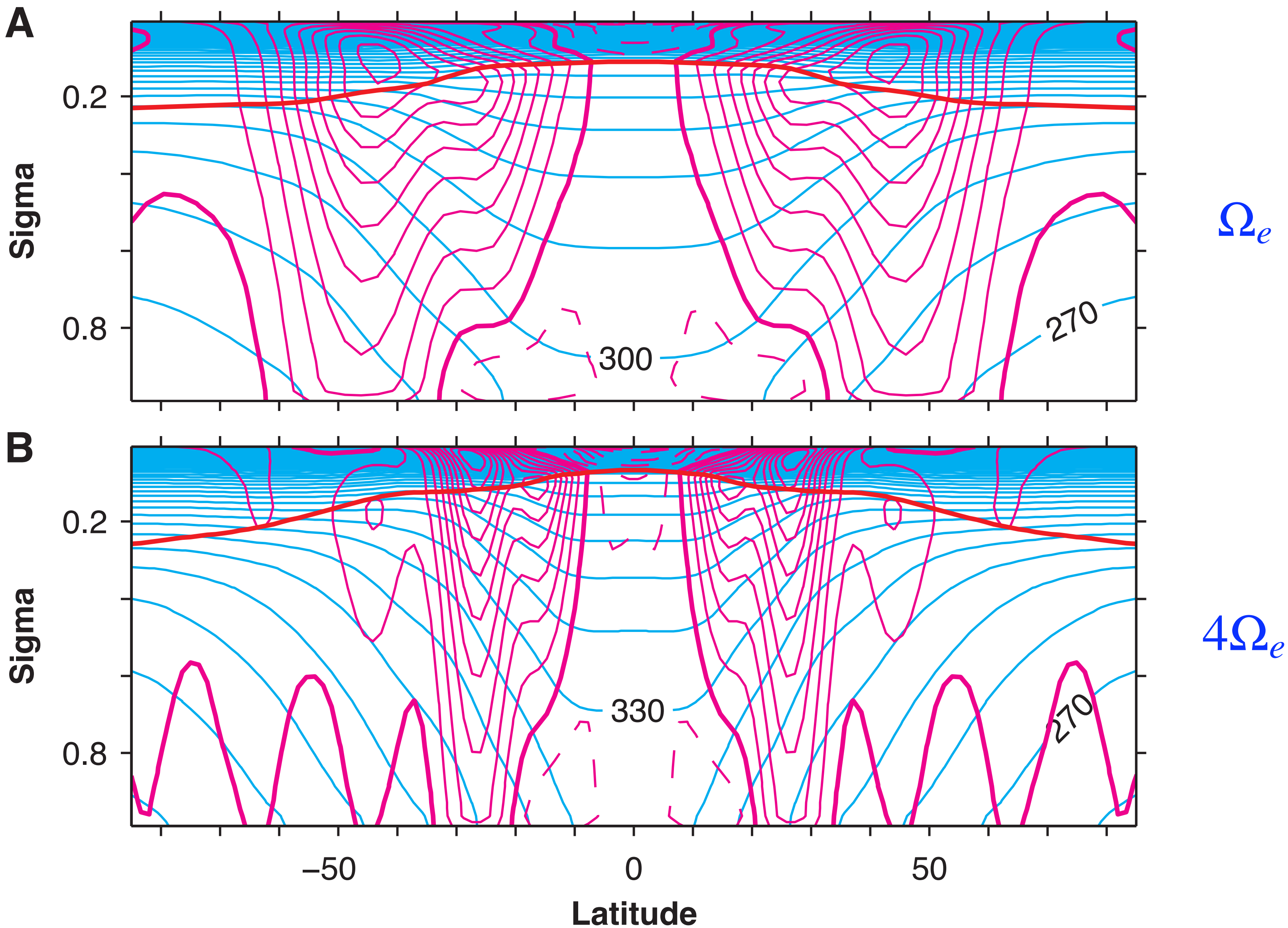


$\phi_0 = 0$ $\phi_0 = 6^\circ$ $\frac{1}{2}[\Psi(\phi_0) + \Psi(-\phi_0)]$

Hadley circulation not strongly nonlinear (cf. Dima & Wallace 2003)

(Walker & Schneider 2005; Schneider 2006)

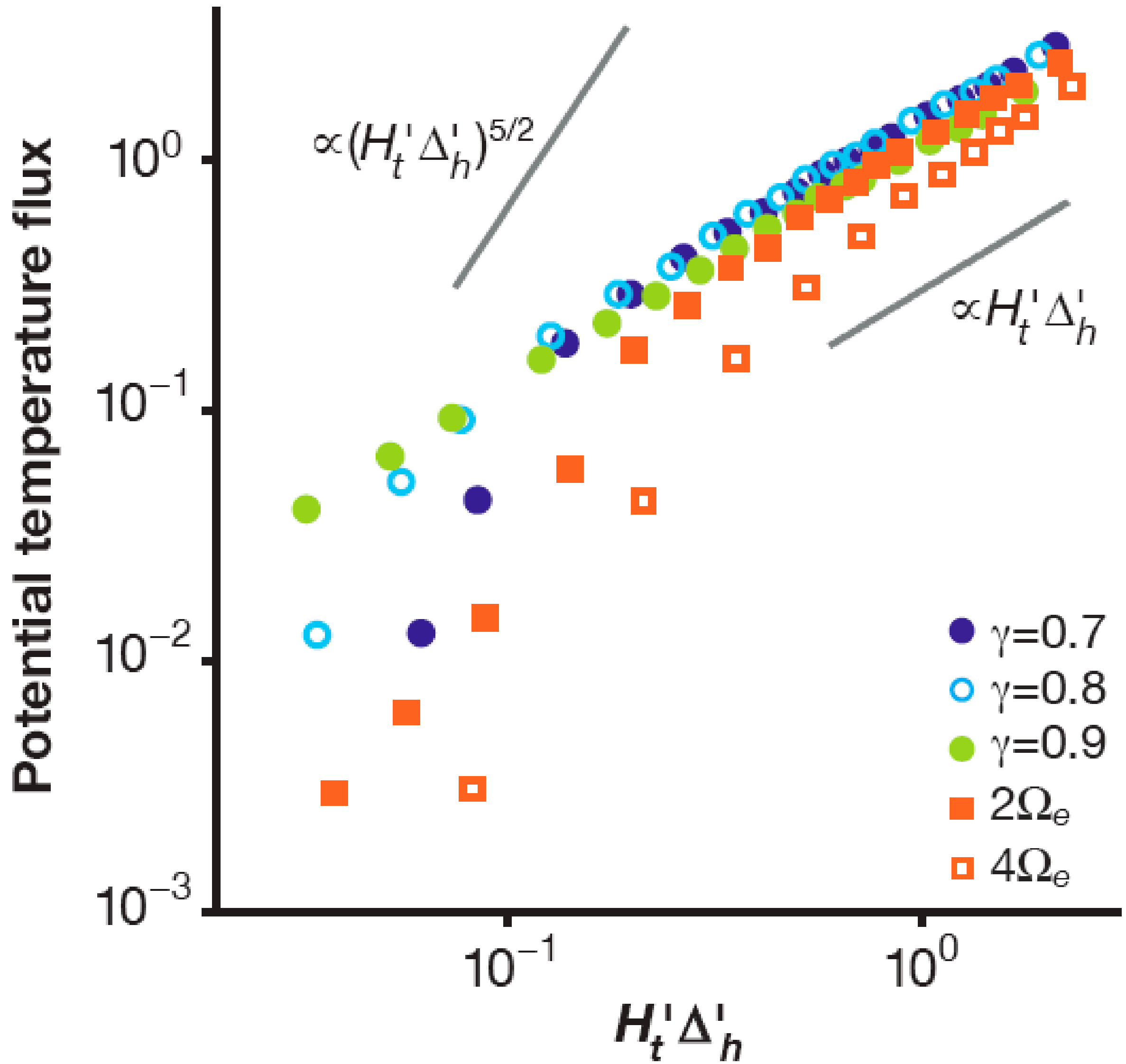
Theory development with idealized dry GCM



Zonal wind (magenta) and potential temperature (blue)

(Schneider and Walker 2006)

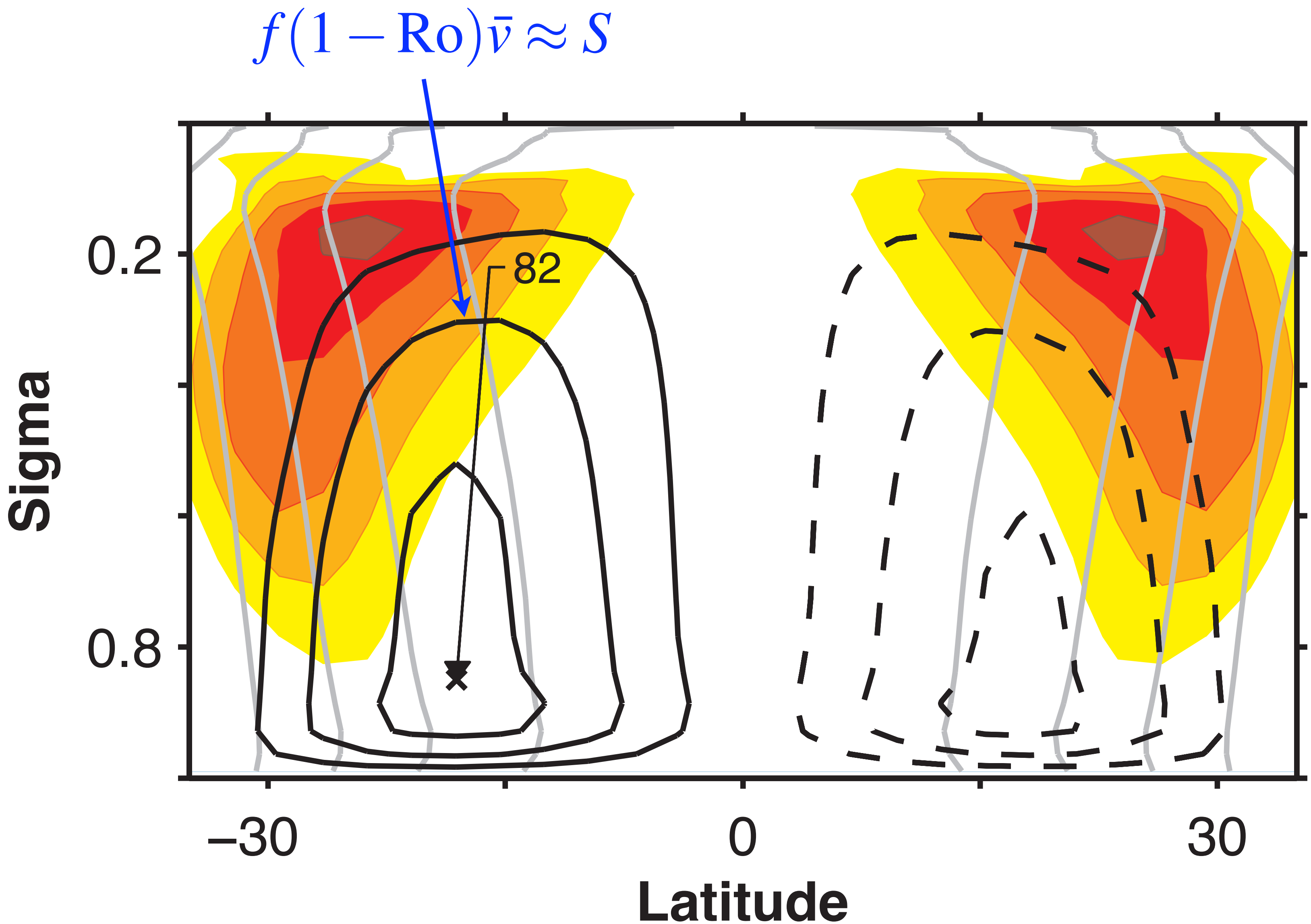
Hadley circulation strength in idealized GCM



Convective lapse rate $\gamma\Gamma_d = \gamma(g/c_p)$

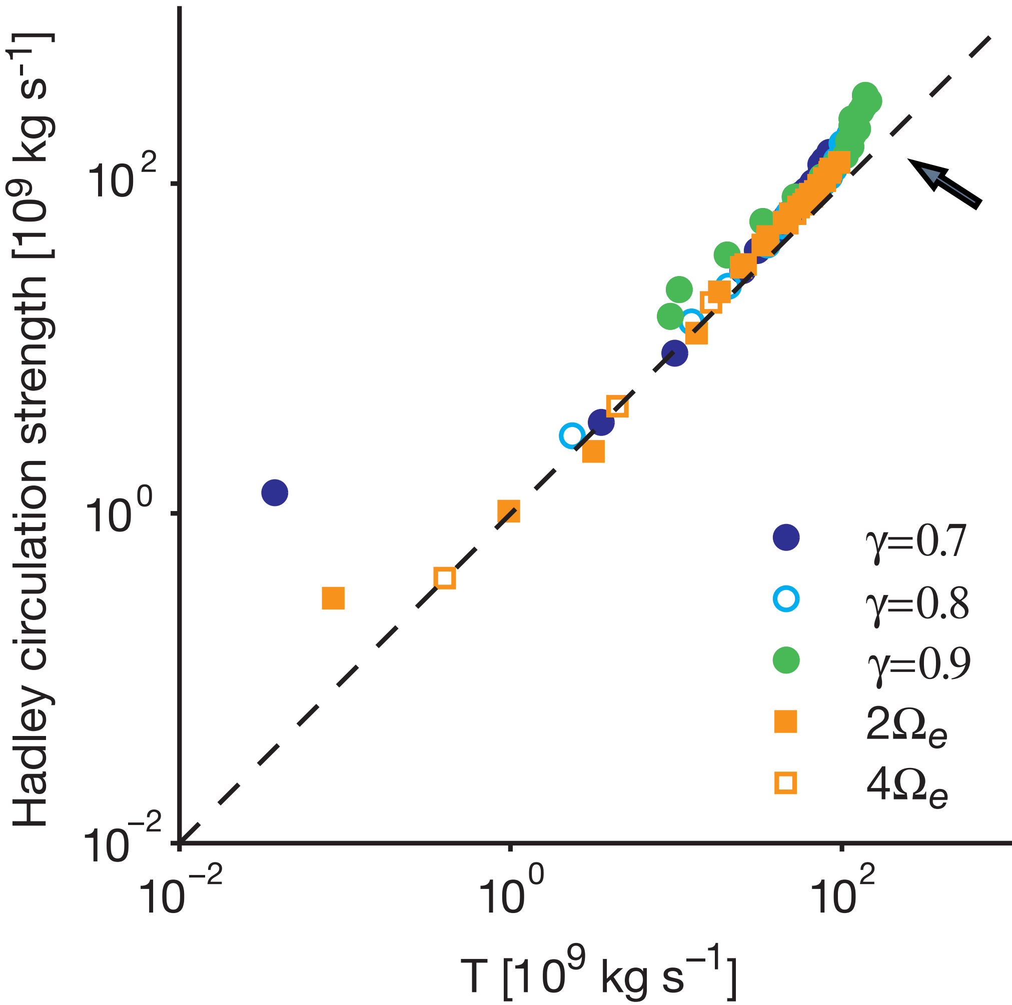
(Walker & Schneider 2006; Schneider 2006)

Eddy momentum flux divergence and streamfunction



Streamfunction (black), angular momentum (gray), and eddy momentum flux divergence S (colors)

Hadley circulation and eddy momentum fluxes

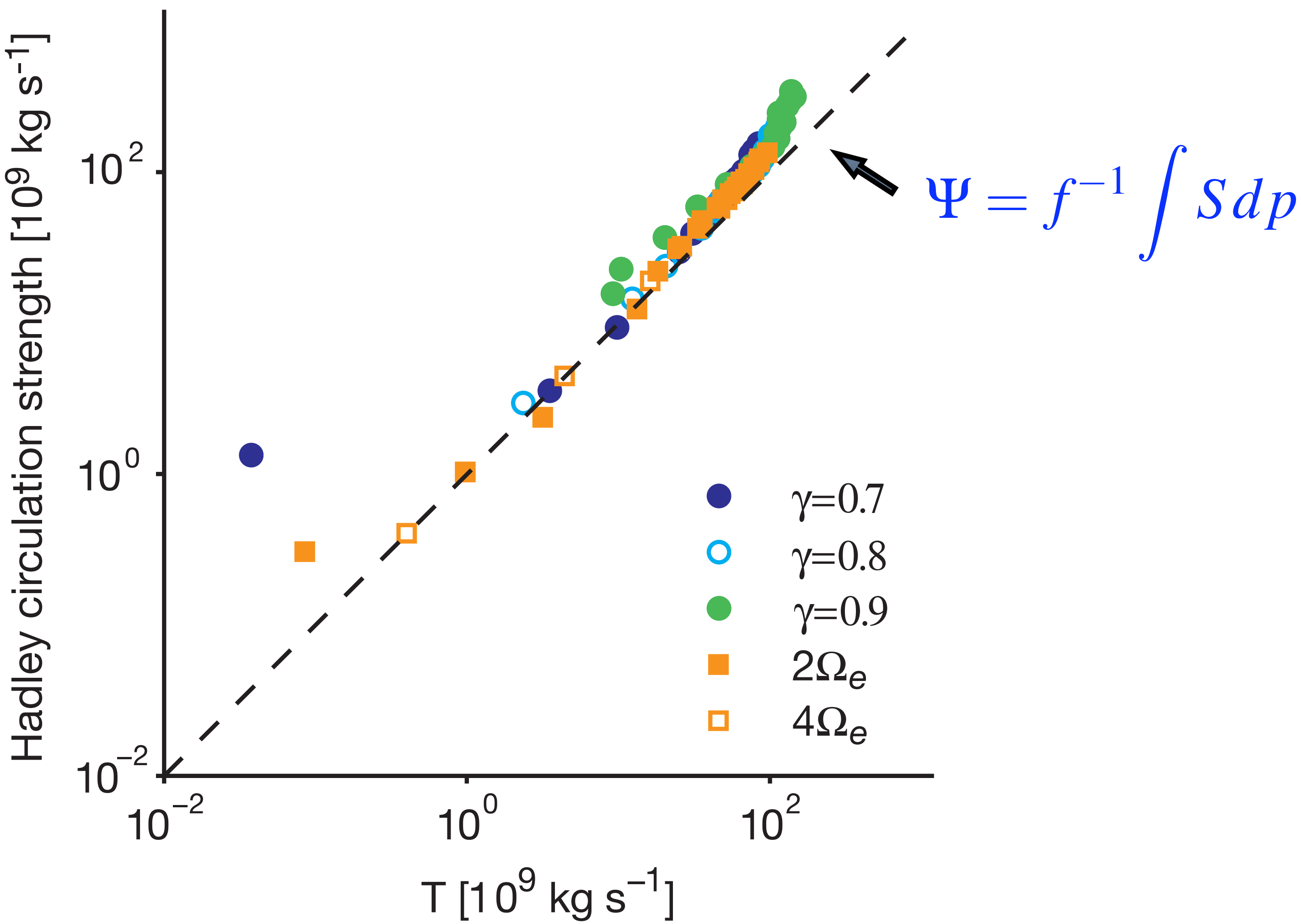


$$\Psi = f^{-1} \int S \, dp$$

Momentum balance: $\Psi_{\max} \approx \int \frac{S}{f(1-\mathrm{Ro})} dp$

(Walker & Schneider 2006)

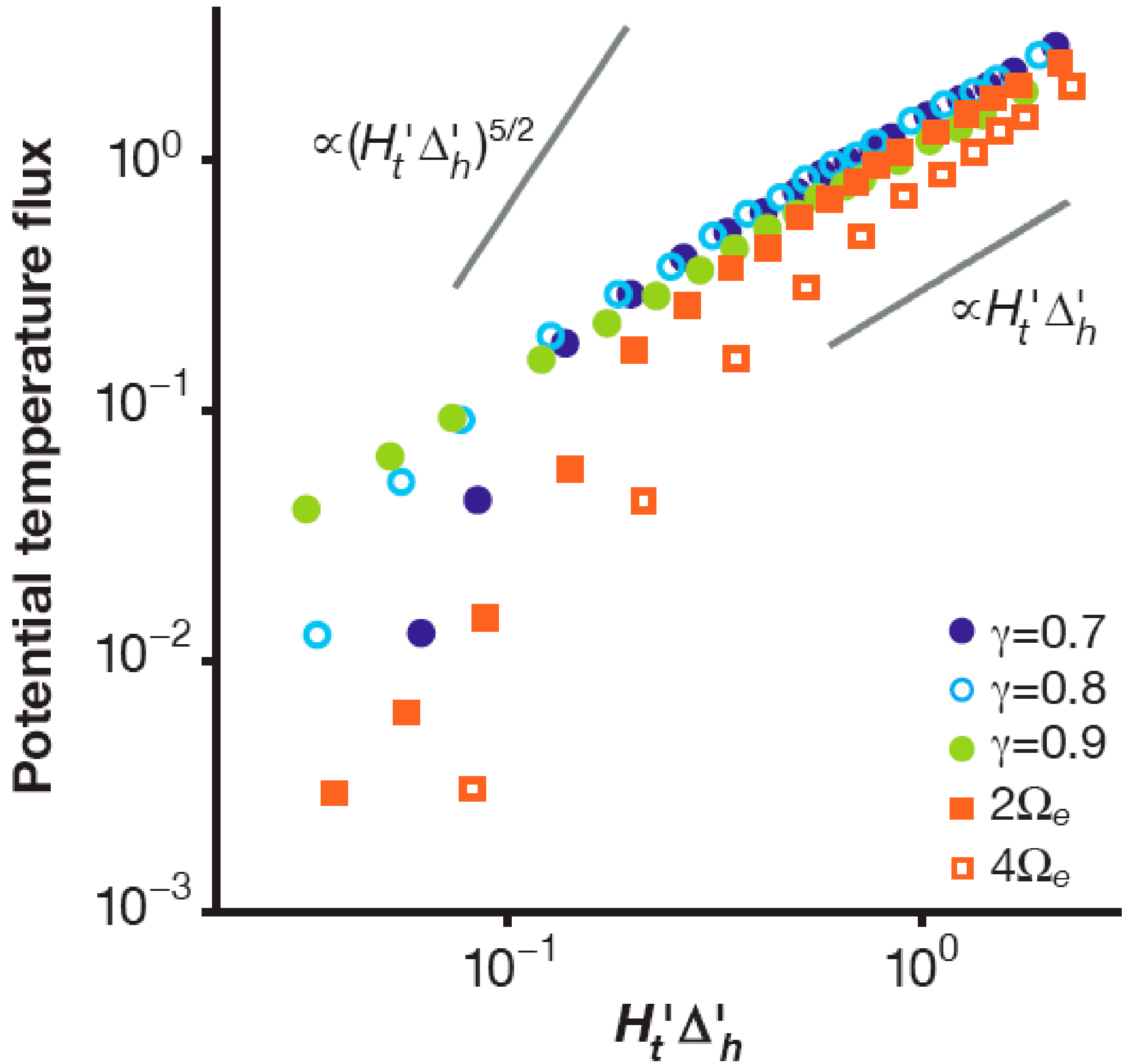
Hadley circulation and eddy momentum fluxes



Eddies influence (and can control) Hadley cell

(Walker & Schneider 2006)

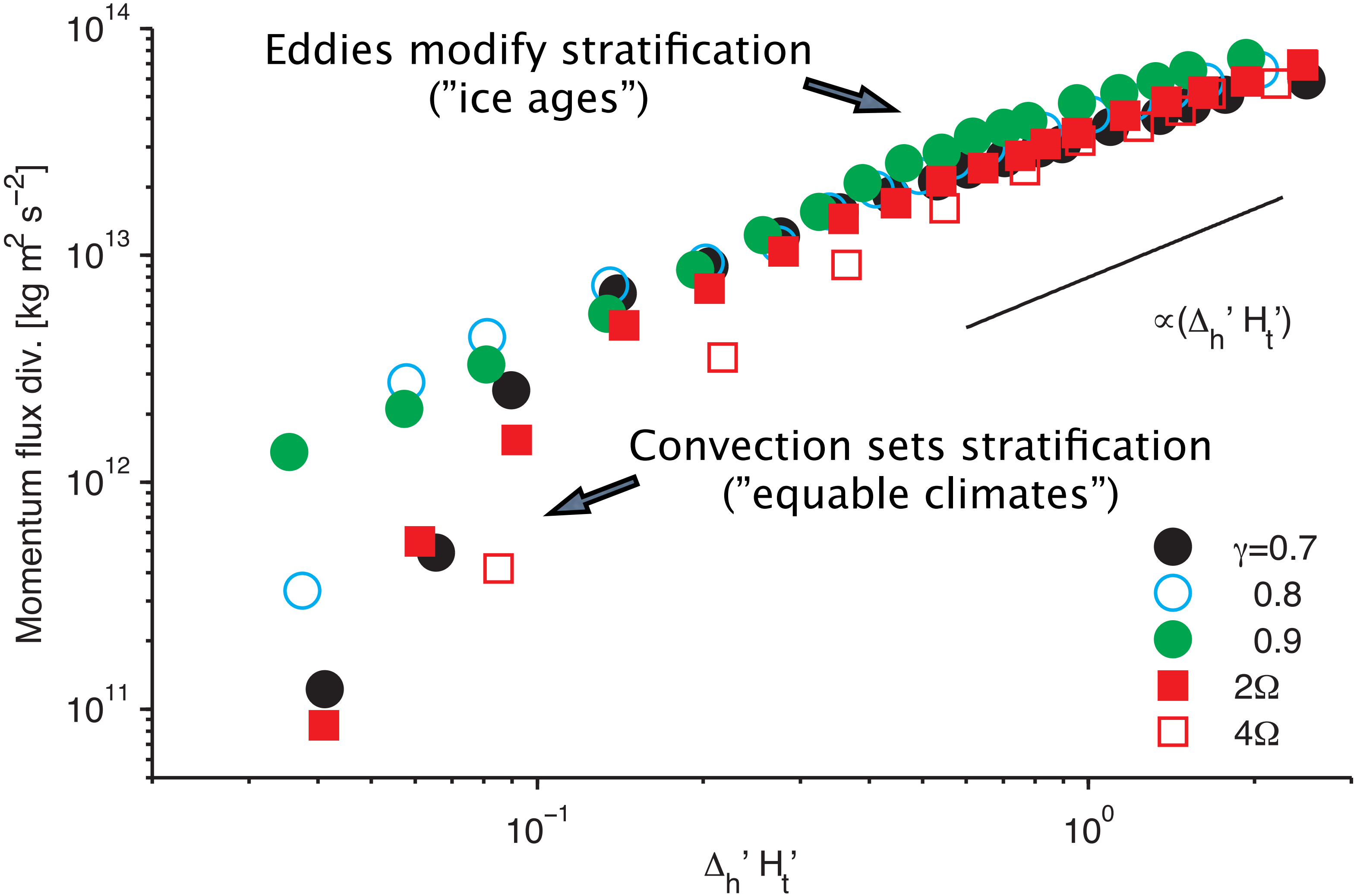
Hadley circulation strength in idealized GCM



Regime transition in eddy scaling

(Walker & Schneider 2006; Schneider 2006; Schneider & Walker 2008)

Eddy momentum flux divergence



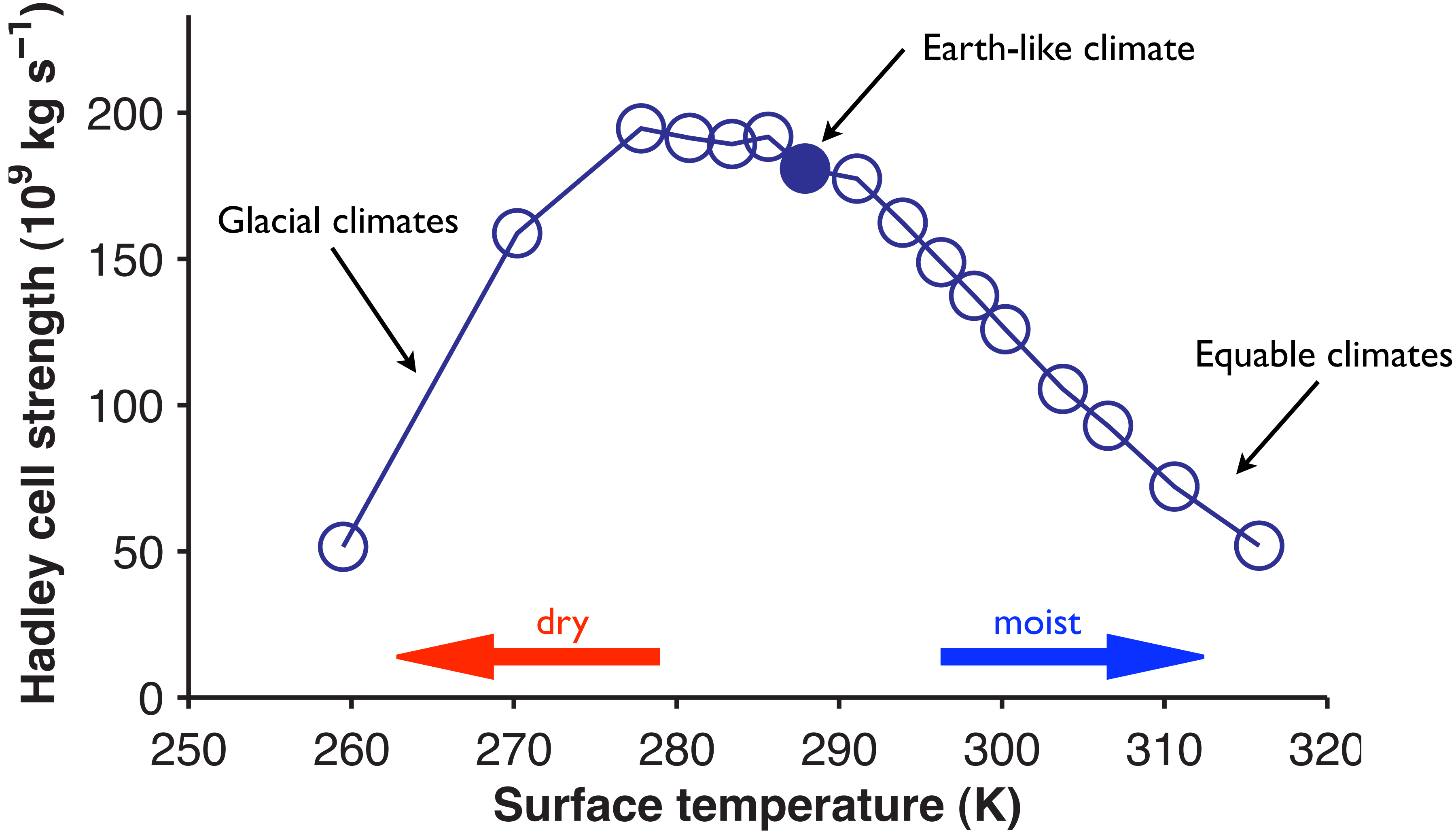
Earth-like Hadley circulations...

- In the annual mean or during equinox are close to limit $\mathrm{Ro} \rightarrow 0$

- Do not respond directly to variations in thermal driving but respond via changes in eddy fluxes

We need to rethink Hadley circulation response, for example, to ENSO and global warming

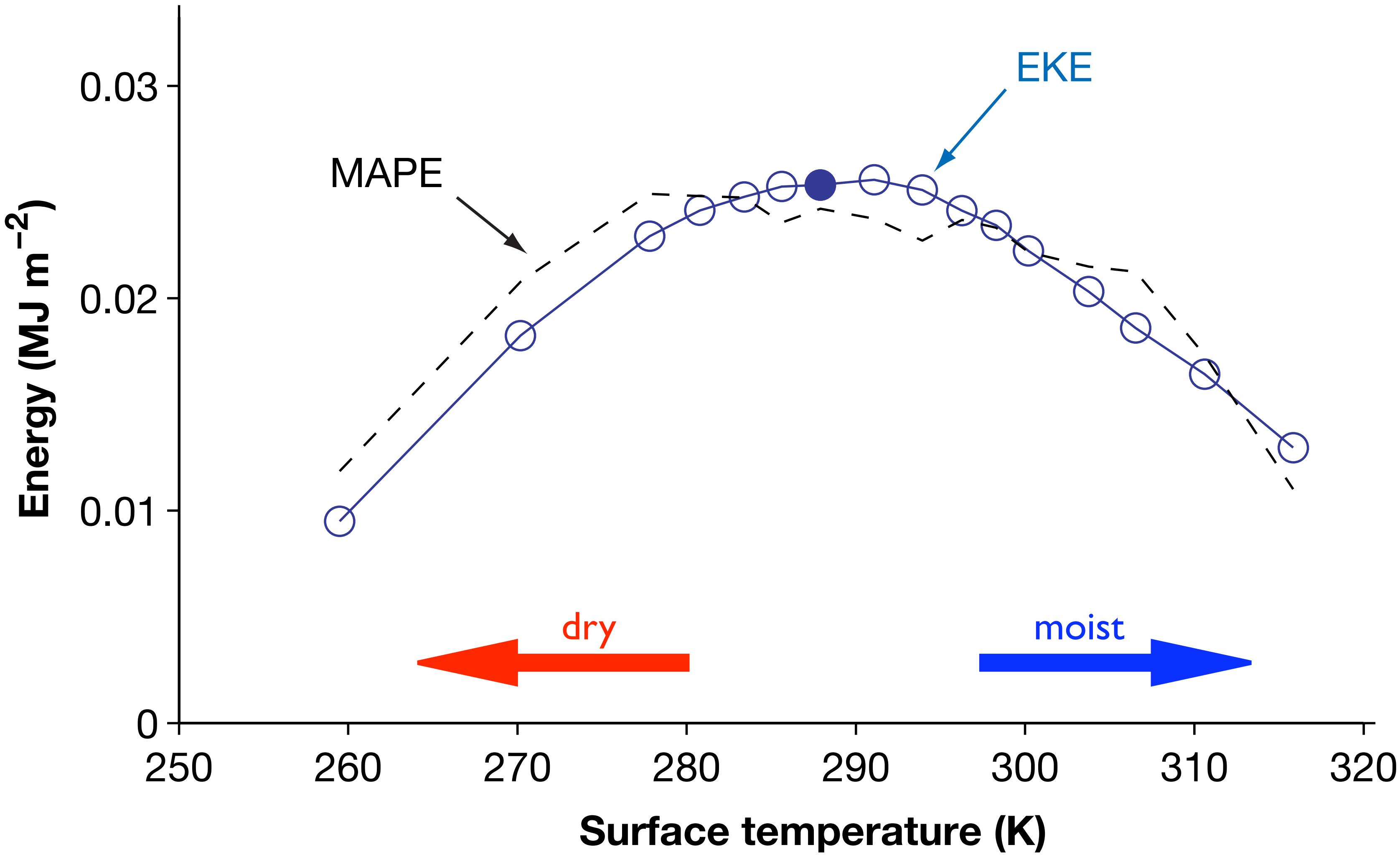
Hadley circulation strength in moist GCM



Variations in optical thickness of longwave absorber

(Levine & Schneider, in prep.)

Eddies mediate Hadley circulation response



Eddy momentum flux scales with EKE, which is maximal near reference climate and scales with MAPE

(O'Gorman & Schneider 2008; Schneider & Walker 2008, in press)

Equinox/annual mean Hadley circulation

Strength typically controlled by eddy momentum fluxes in the subtropics:

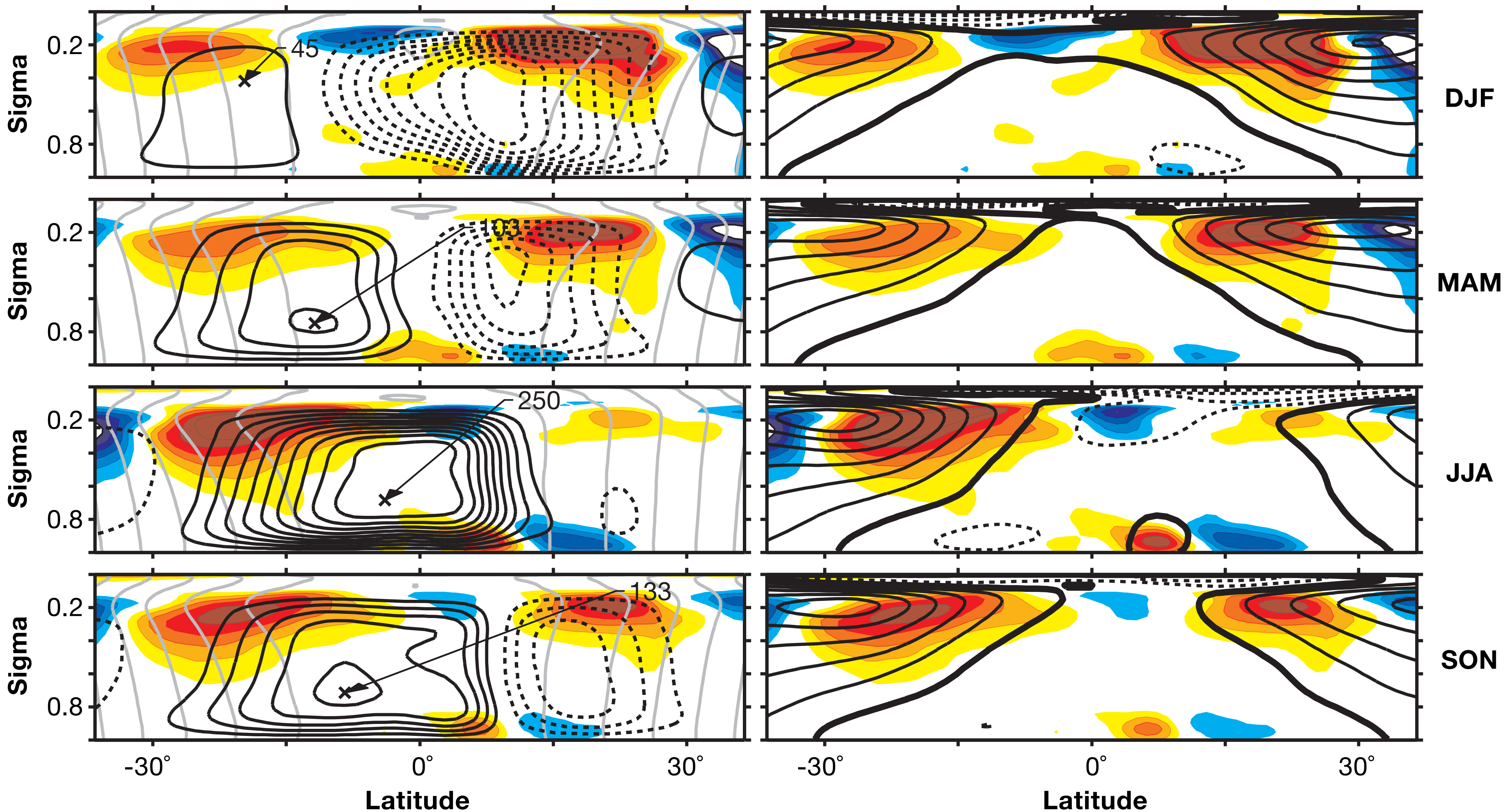
- Eddy scaling imprinted on it
- Weaker in much warmer *and* in much colder climates
- Consistent with IPCC simulations (e.g., Lu et al. 2007)

Width typically controlled by baroclinic instability:

- Accounts for global warming response (widening because of increased static stability in subtropics)

What about seasonal cycle?

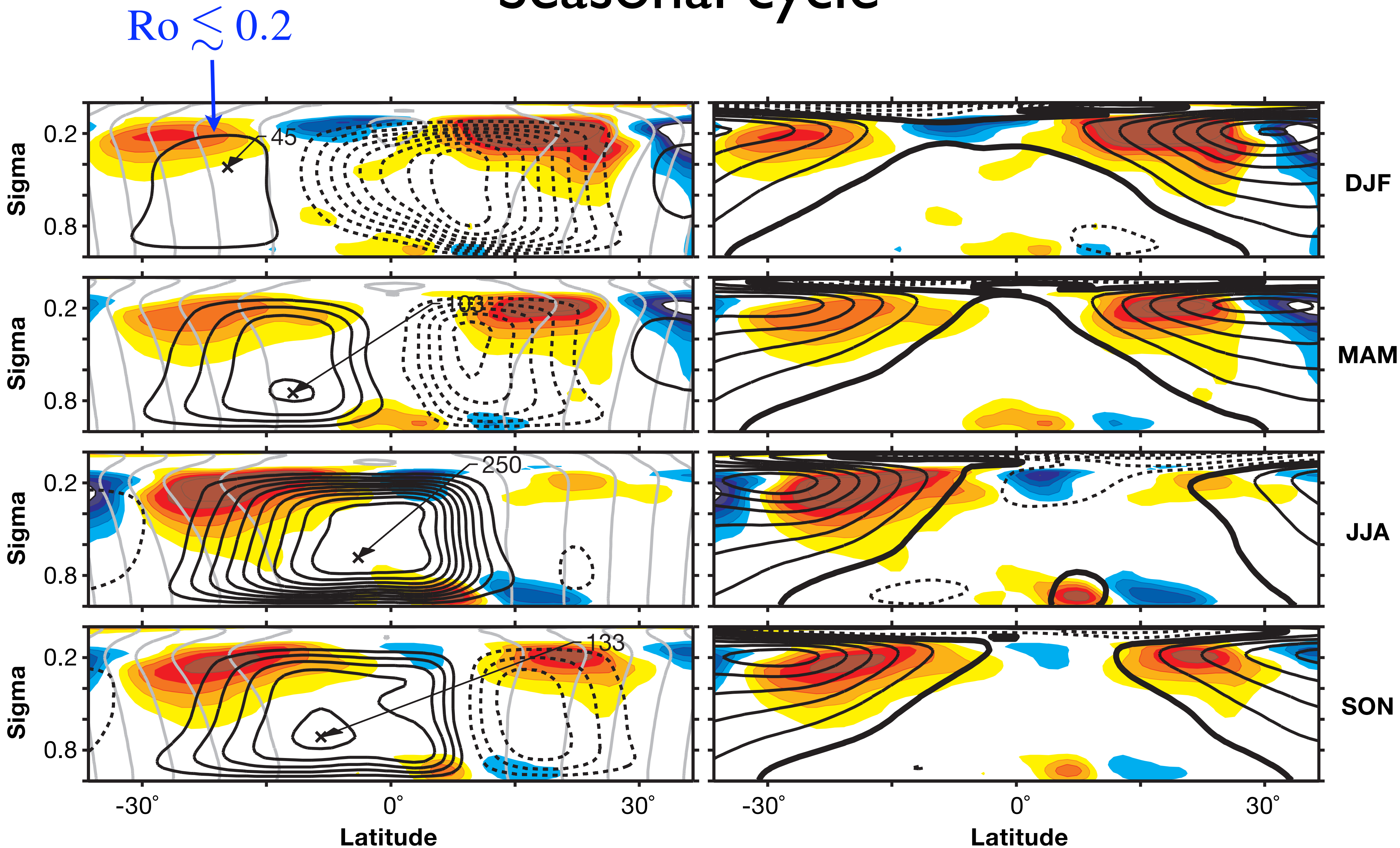
Seasonal cycle



$\Psi, \quad \mathrm{div}\,\overline{u'v'}$ $\qquad$ $\bar{u}, \quad \mathrm{div}\,\overline{u'v'}$

(*Data source:* ERA-40)

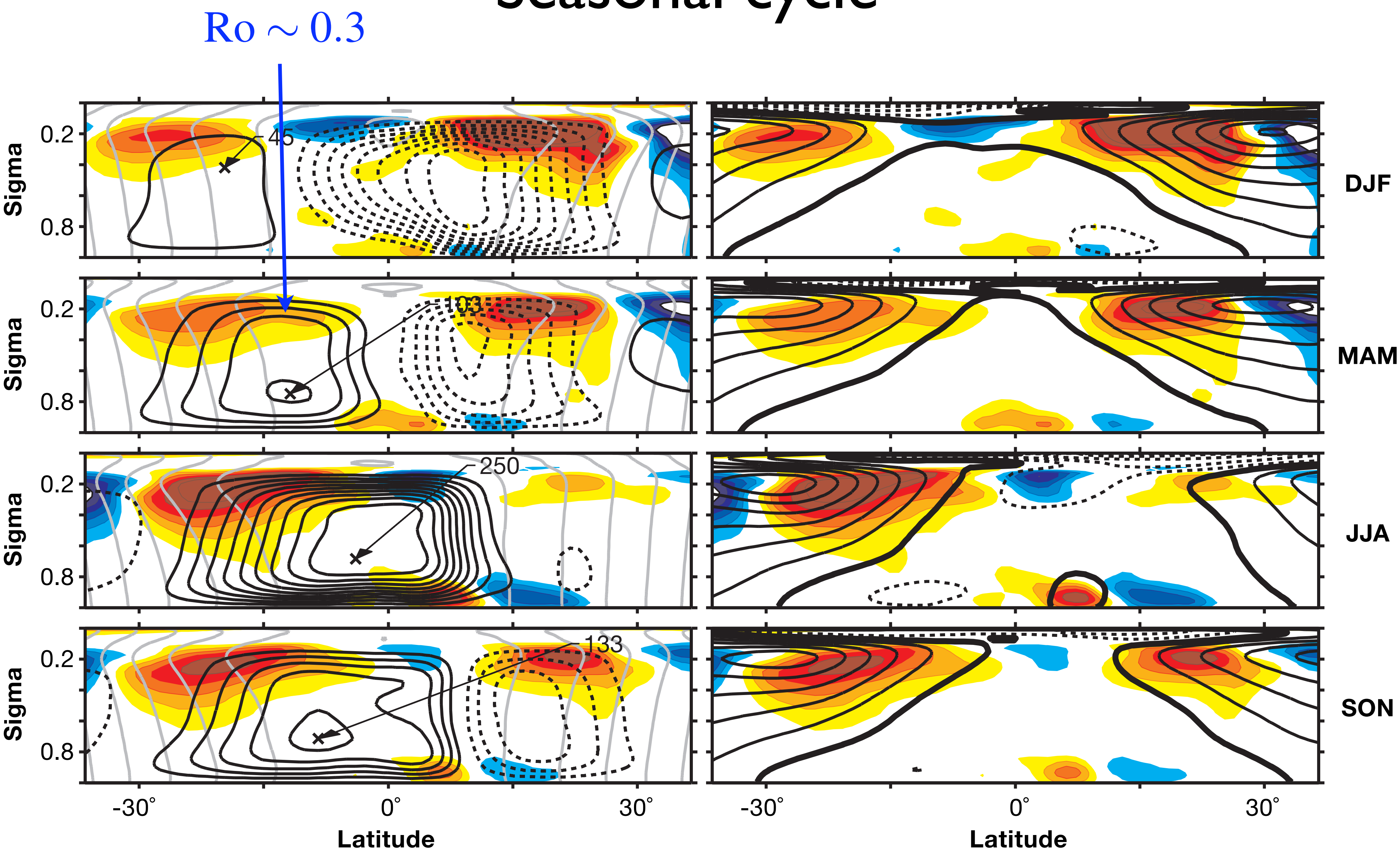
Seasonal cycle



$\Psi, \quad \mathrm{div}\,\overline{u'v'}$ $\quad\quad$ $\bar{u}, \quad \mathrm{div}\,\overline{u'v'}$

(*Data source:* ERA-40)

Seasonal cycle

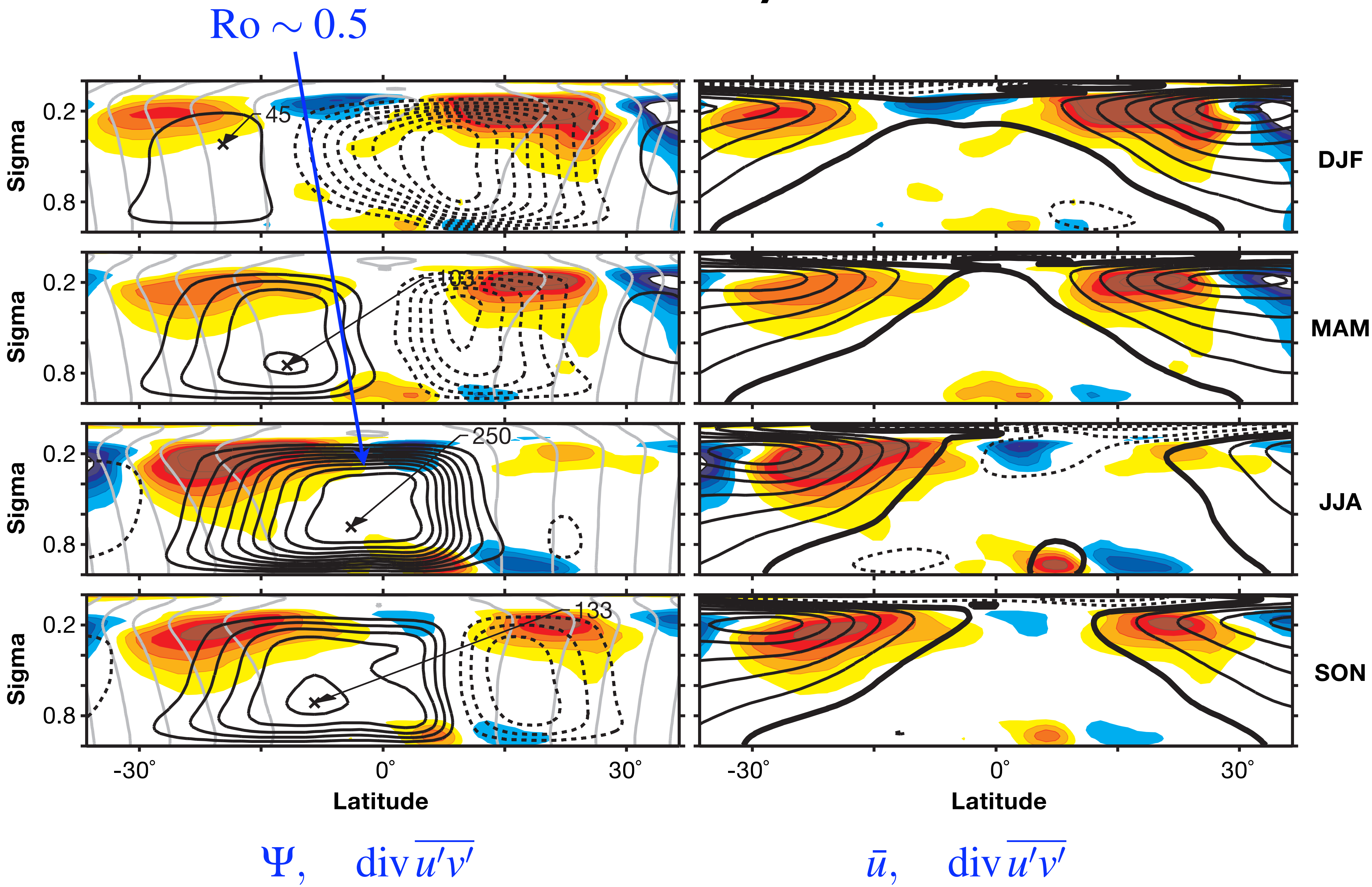


$\Psi, \quad \mathrm{div}\,\overline{u'v'}$

$\bar{u}, \quad \mathrm{div}\,\overline{u'v'}$

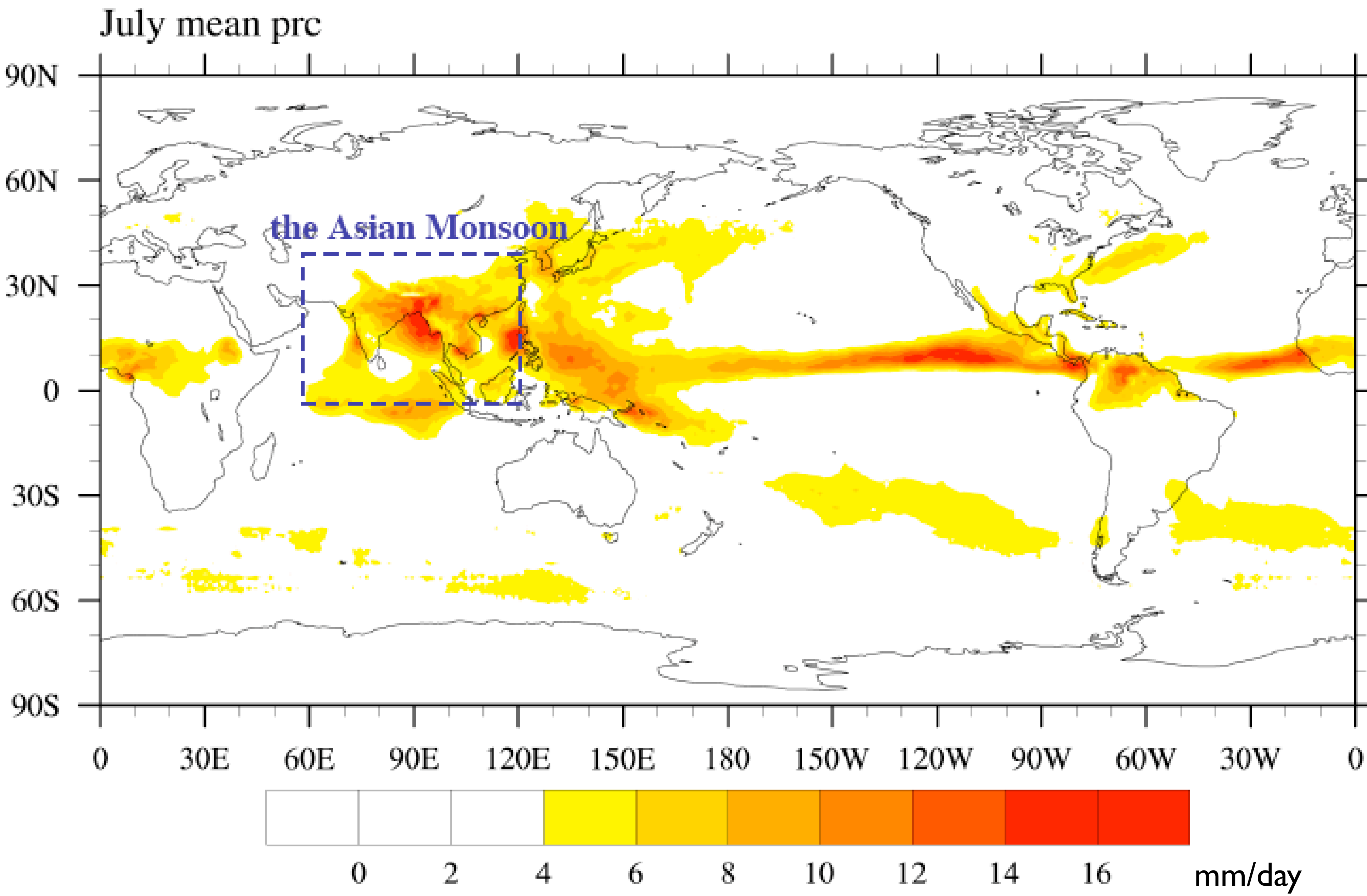
(*Data source:* ERA-40)

Seasonal cycle



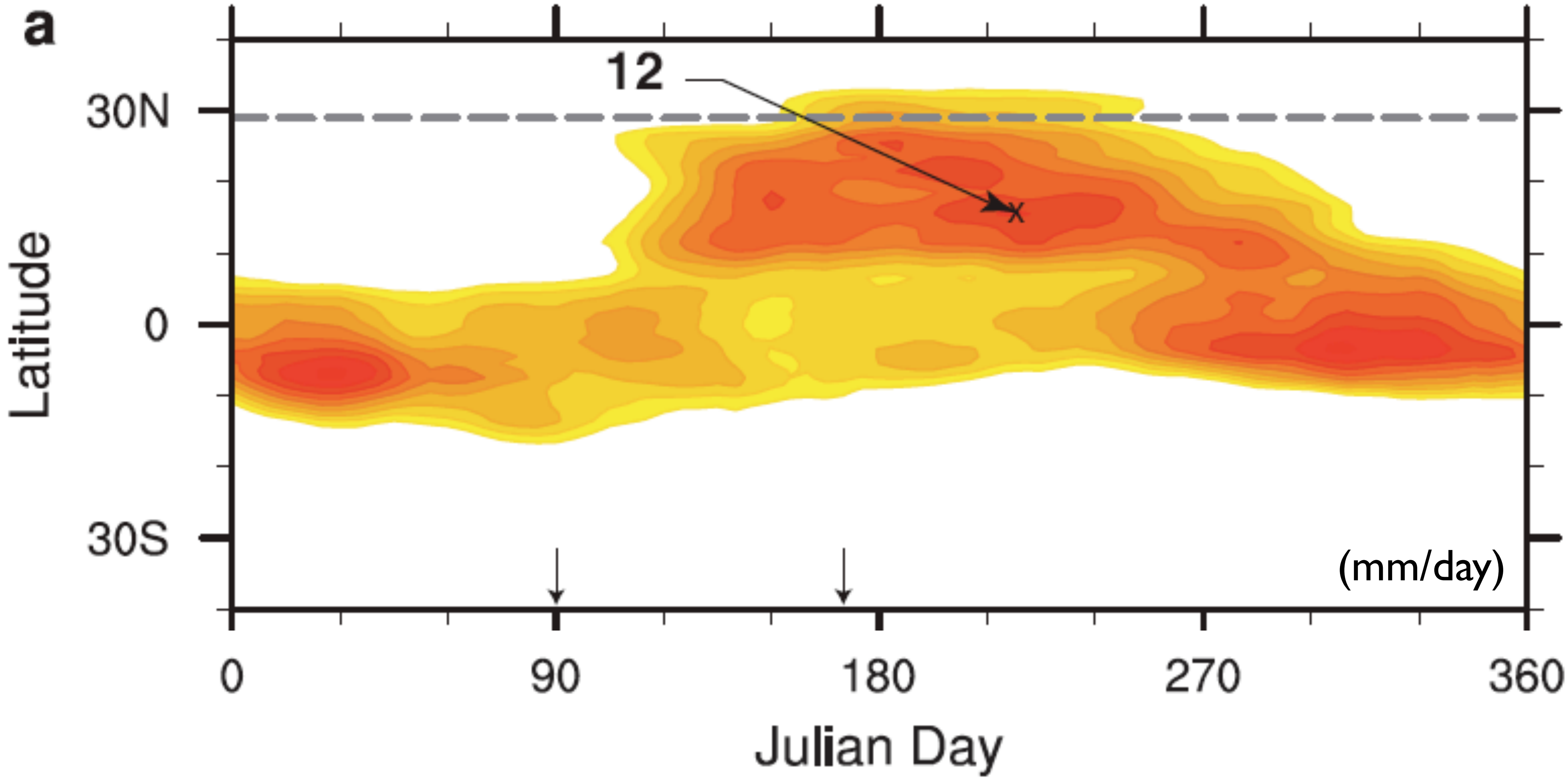
(*Data source:* ERA-40)

Northern Hemisphere summer monsoon



(*Data source:* GPCP 1DD; Bordoni 2007)

Abrupt transitions: precipitation 70E-100E



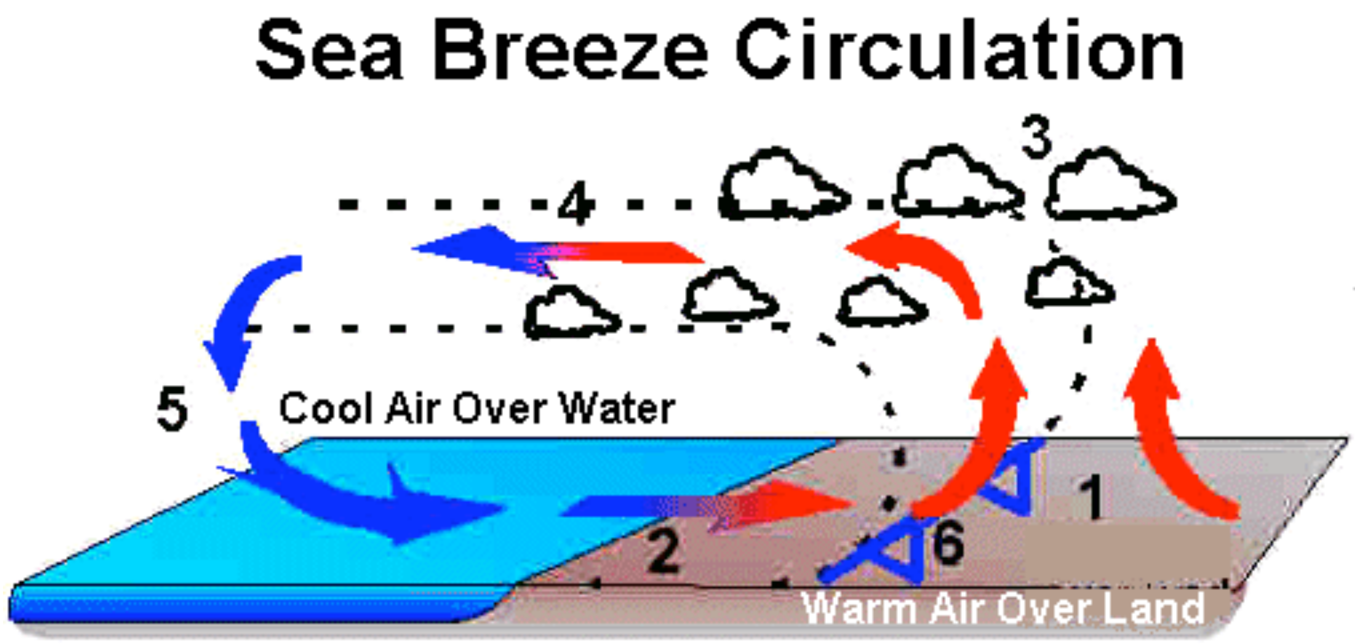
(*Data source:* GPCP 1DD; Bordoni & Schneider 2007, submitted)

An Historical Account of the Trade Winds, *and* Monsoons, *observable in the Seas between and near the* Tropicks, *with an attempt to assign the Phisical cause of the said Winds, by* E. Halley.

riations of the Winds, from the former general Rule: for if a Country lying near the Sun, prove to be flat, sandy, low Land, such as the Desarts of *Lybia* are usually reported to be, the heat occasioned by the reflection of the Suns Beams, and the retention there of in the Sand, is incredible to those that have not felt it; whereby the Air being exceedingly rarified, it is necessary that this cooler and more dense Air should run thitherwards to restore the *Æquilibrium*: This I take to be the cause, why near the Coast of *Guinea* the Wind al-

(Halley 1686)

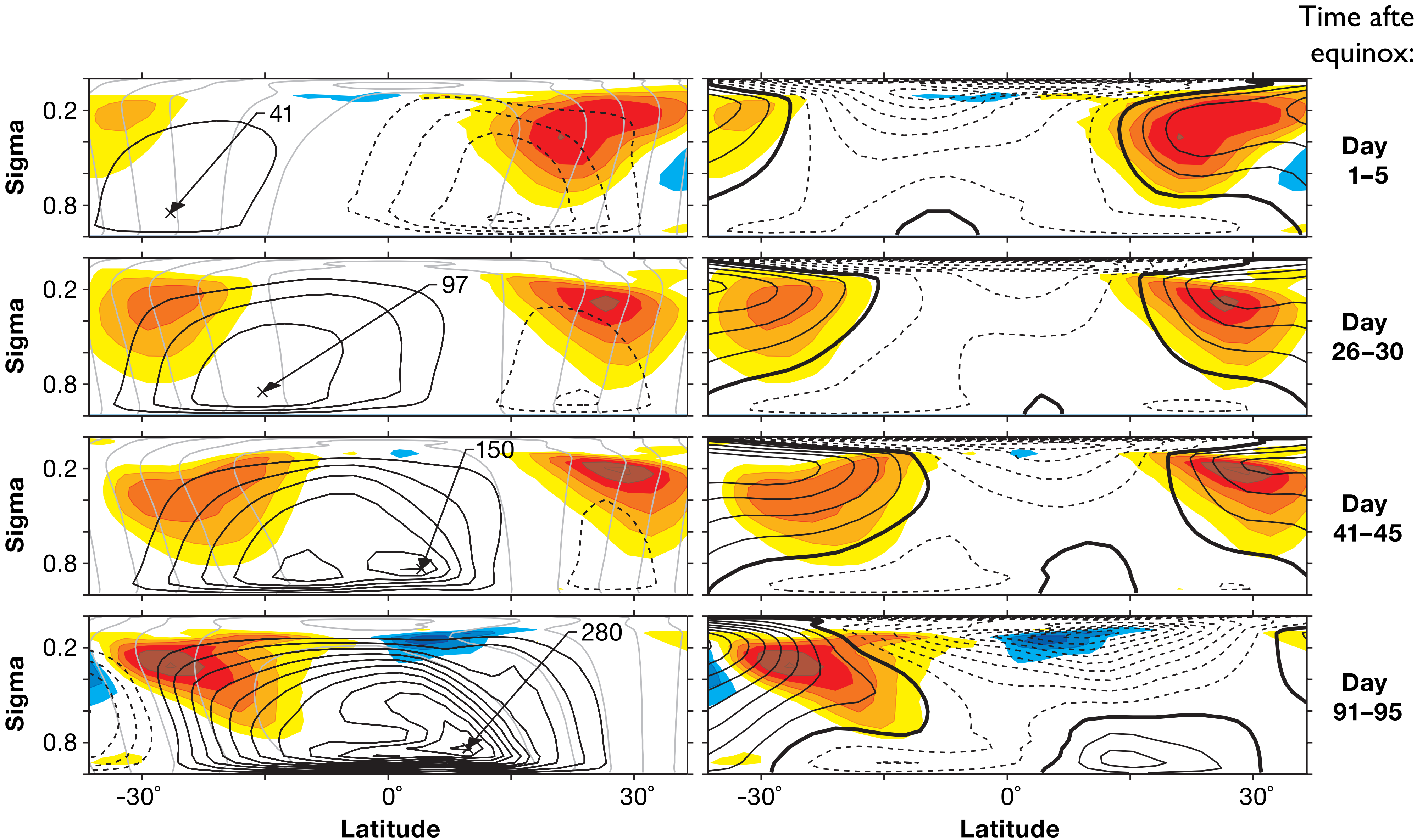
The classic picture of monsoons



- But why are transitions abrupt?
- Is land-sea contrast necessary?

Monsoons in a dry GCM with homogeneous boundary

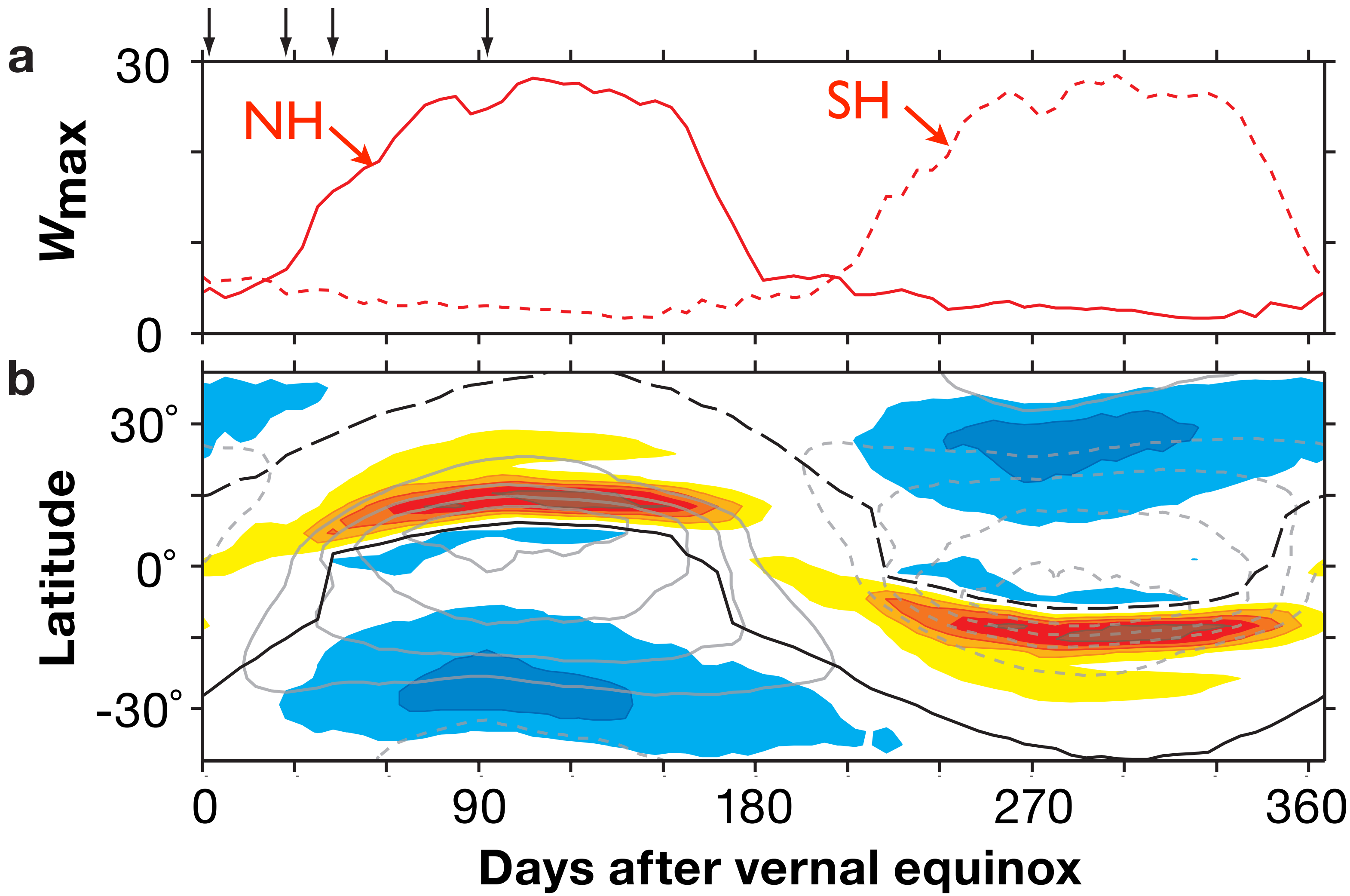
Seasonal cycle in dry GCM



$\Psi, \quad \mathrm{div}\,\overline{u'v'}$ $\qquad$ $\bar{u}, \quad \mathrm{div}\,\overline{u'v'}$

(Schneider & Bordoni, 2008)

Abrupt monsoon transitions in dry GCM



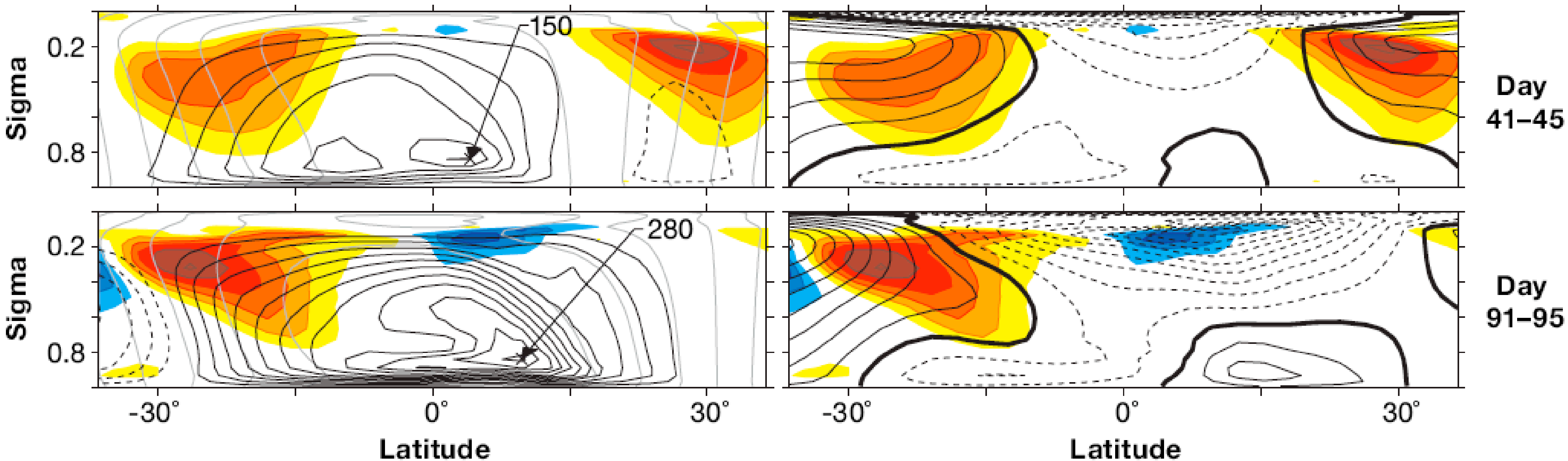
Maximum lower-level upward mass flux (10^4 kg m^{-1} s^{-1})

Lower-level upward mass flux (colors)

Lower-level streamfunction (gray contours)

(Schneider & Bordoni, 2008)

Abrupt transition owing to eddy-mean flow feedbacks



Upper-level easterlies shield eddies

Positive eddy-mean flow feedback

(Schneider & Bordoni, 2008)

Positive feedbacks in monsoon transition

Eddy-mean flow:

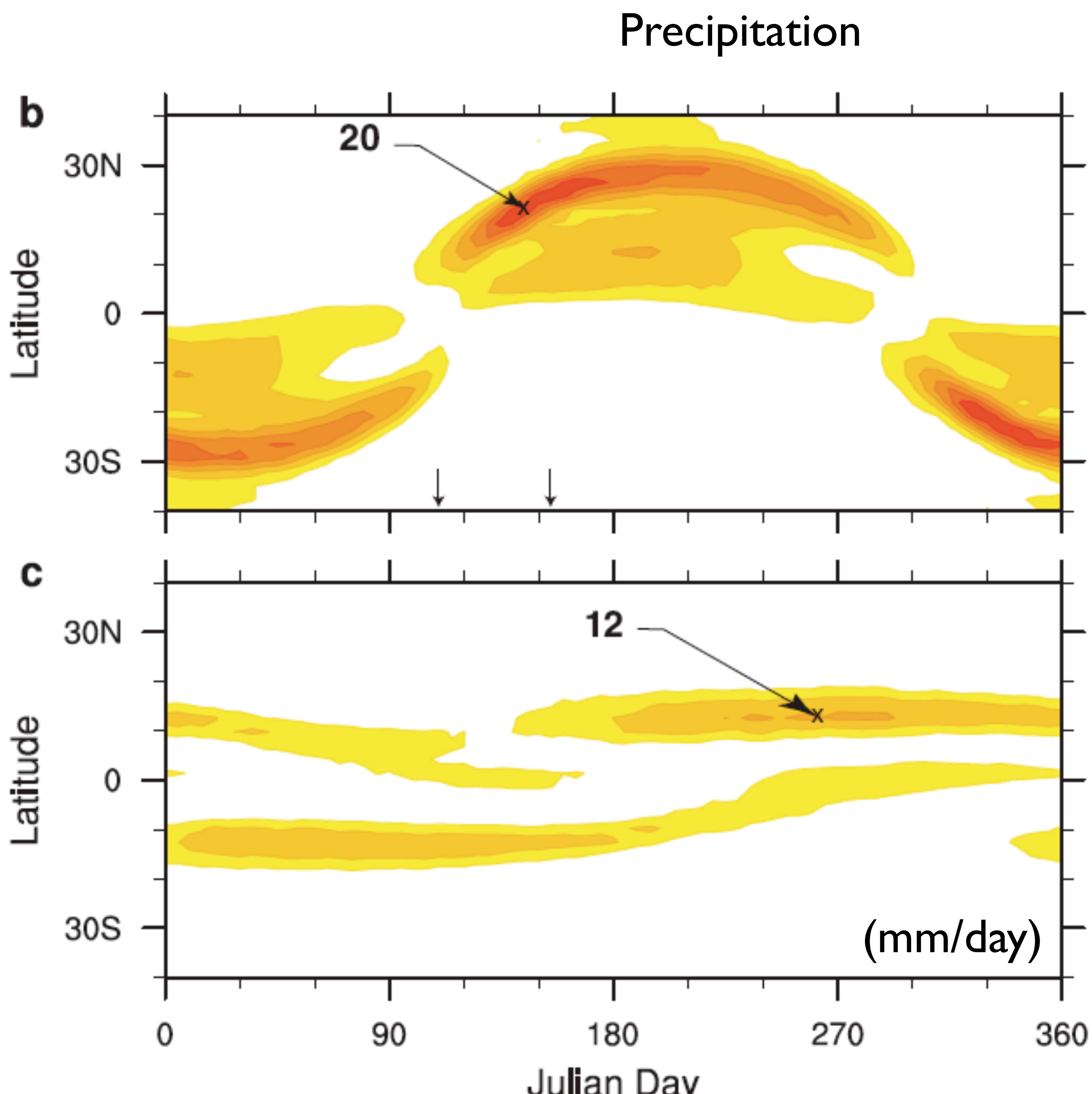
- Cold advection strengthens temperature gradients, leading to strengthened upper-level easterlies
- Upper-level easterlies shield winter cell from eddies, leading to strengthening of cell

Mean flow:

- Cold advection leads to larger radiative heating maximum and pushes boundary between winter and summer cell poleward, leading to strengthening of winter cell

Transition when AM-conserving stronger than eddy-driven flow

Same dynamics act in moist aquaplanet GCM...



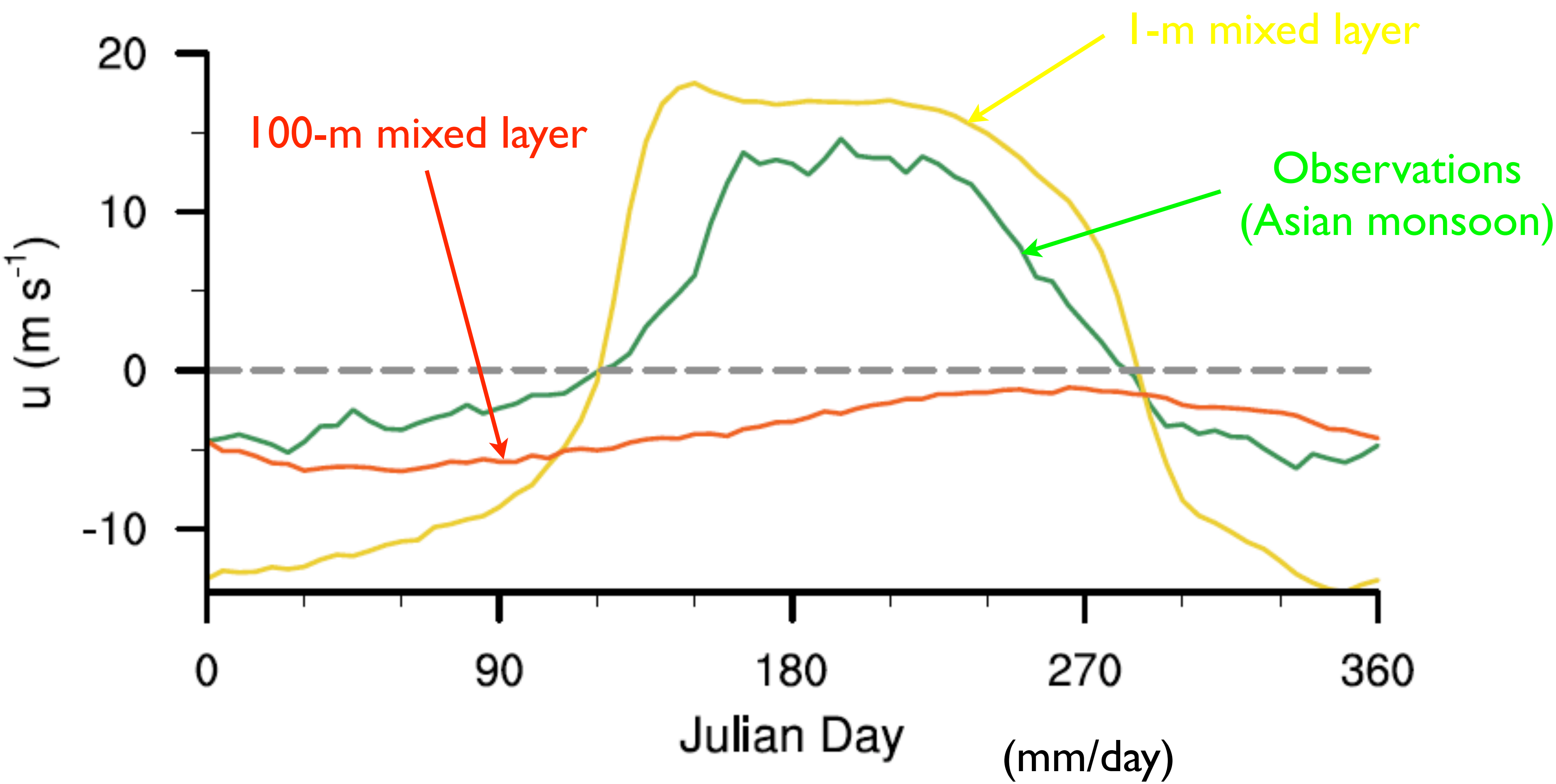
1-m mixed layer ocean

100-m mixed layer ocean

(Bordoni & Schneider, 2007, submitted)

Same dynamics act in moist aquaplanet GCM...

Near-surface zonal wind at 15N

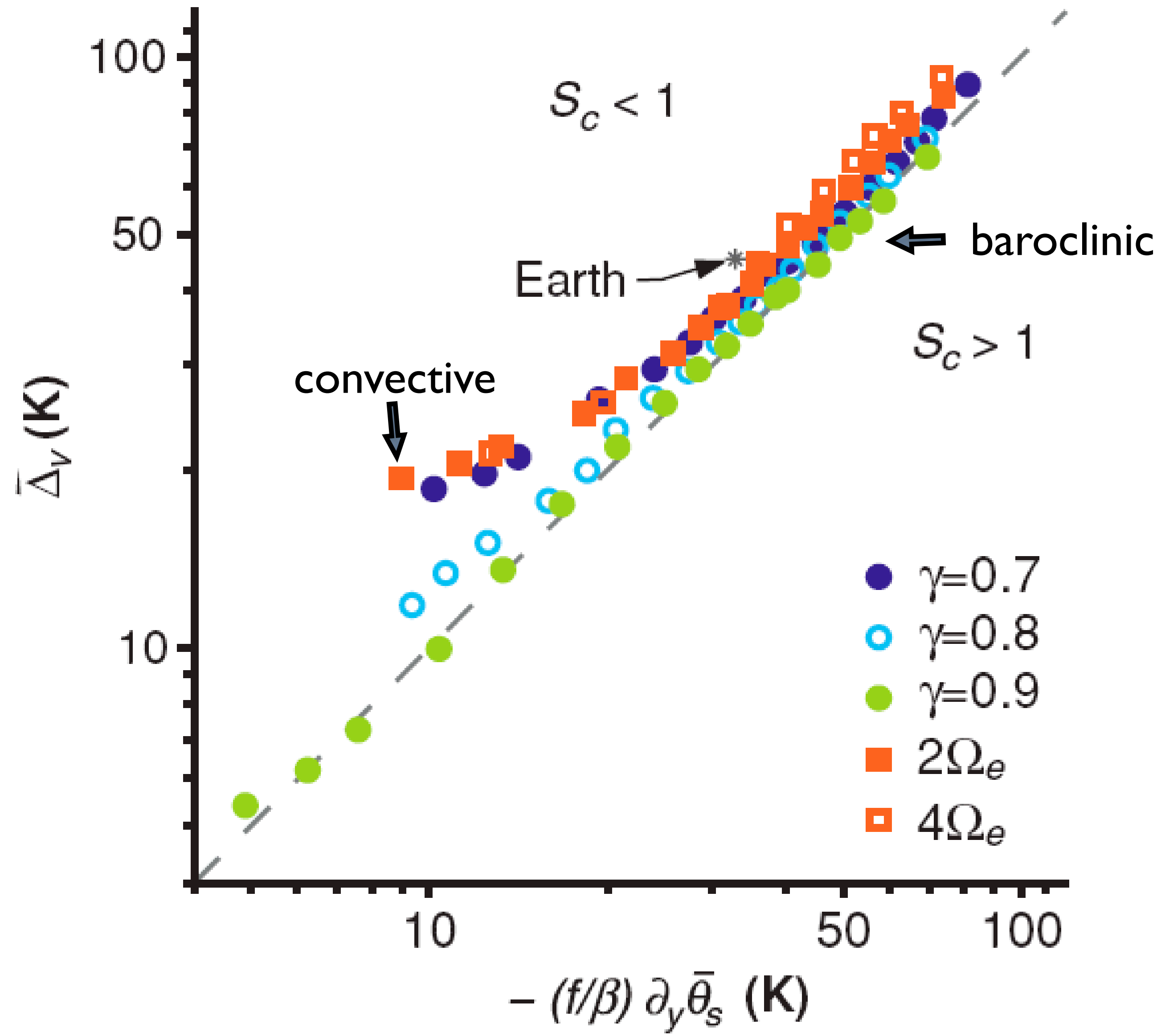


(Bordoni & Schneider, 2007, submitted)

Macroturbulence

- Dominates transport of heat, momentum, mass, water vapor, tracers in extratropics (well known)
- Influences (controls?) Hadley cell strength and extent
- Scaling theory essential for scaling theory of extratropical *and* tropical climate

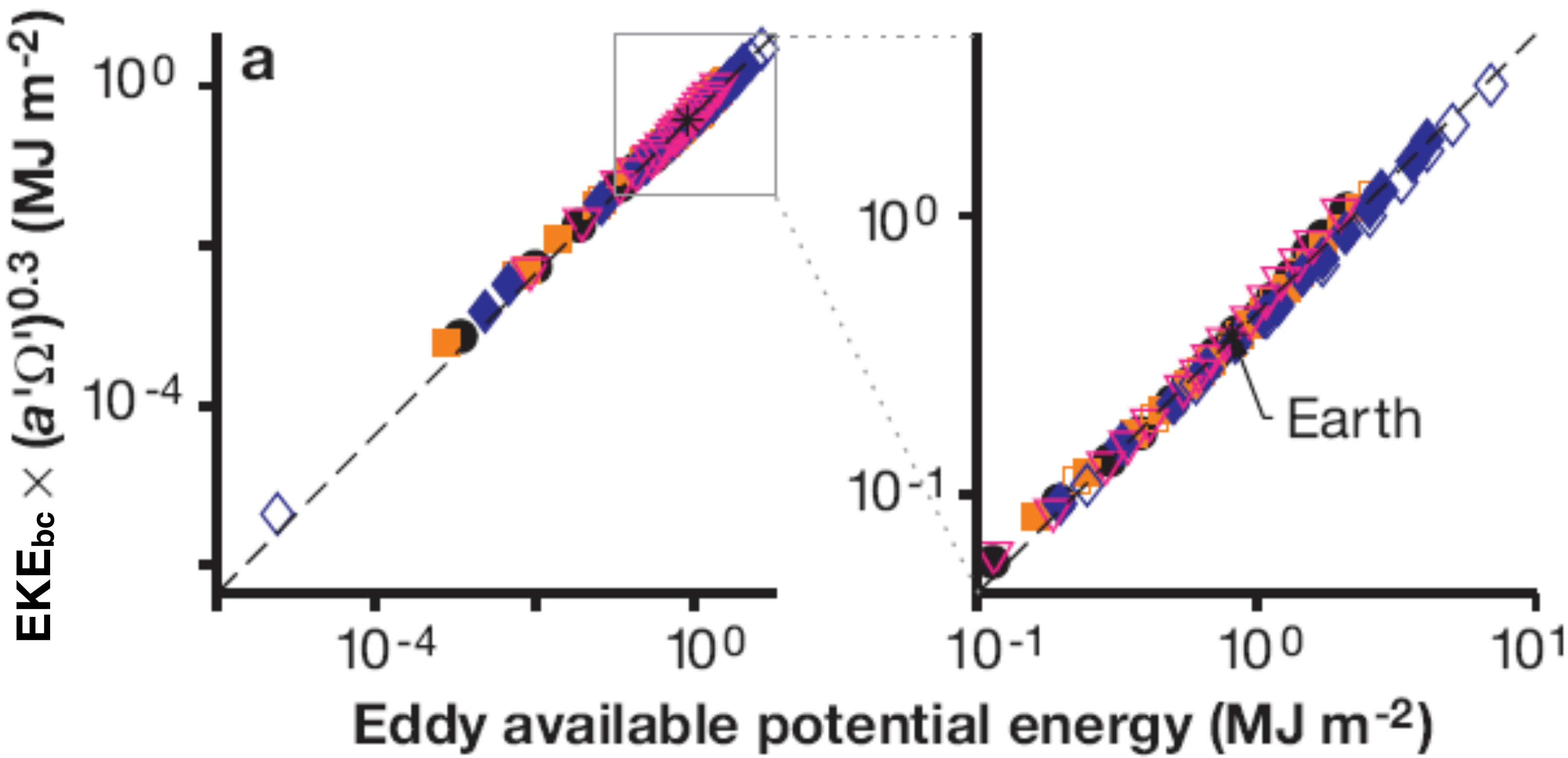
Macroturbulence effect on stratification



Small parameter $1\text{-}S_c$

(Schneider & Walker 2006)

Implication: weak eddy-eddy interactions



Scaling laws for large-scale averages follow

(Schneider & Walker 2008, in press)

Summary

- Hadley cell during equinox, summer, and in annual mean controlled by eddy fluxes; response to climate change mediated by eddy fluxes

- Hadley cell undergoes regime transition over seasonal cycle, with zonal momentum balance shifting from eddy to mean-flow dominance

- Abruptness of regime transition owing to eddy-mean flow and mean-flow feedbacks

- Monsoons can be understood as regional manifestation of this regime transition

Summary (cont.)

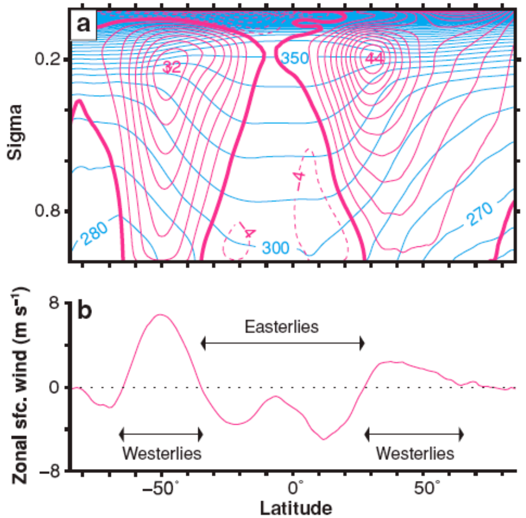
- Macroturbulence (in dry atmosphere) organizes itself to critical states of weak nonlinear eddy-eddy interactions

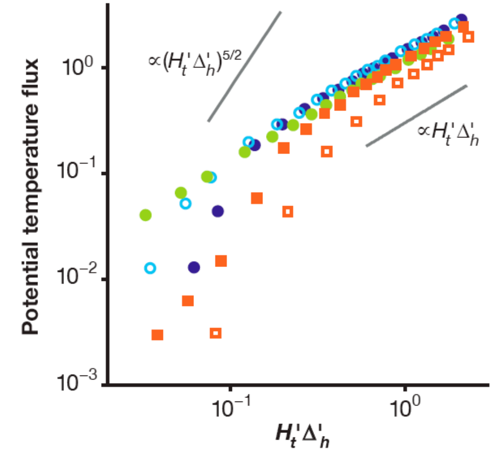
- Weakness of eddy-eddy interactions can be used to infer length scales of eddies and scaling laws for eddy energies, heat fluxes, momentum fluxes, etc.

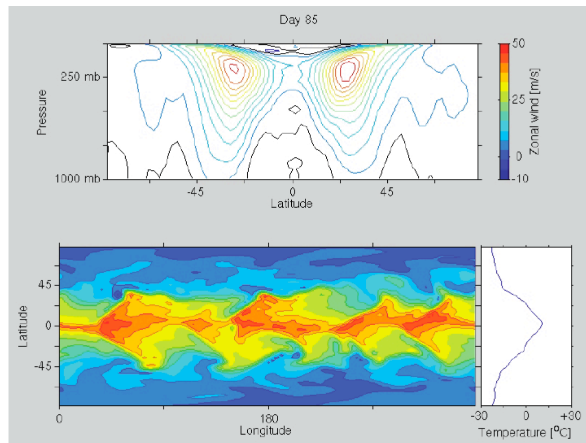
- Closures based on truncated expansions (e.g., cumulant expansions) can be fruitful for atmospheric macroturbulence

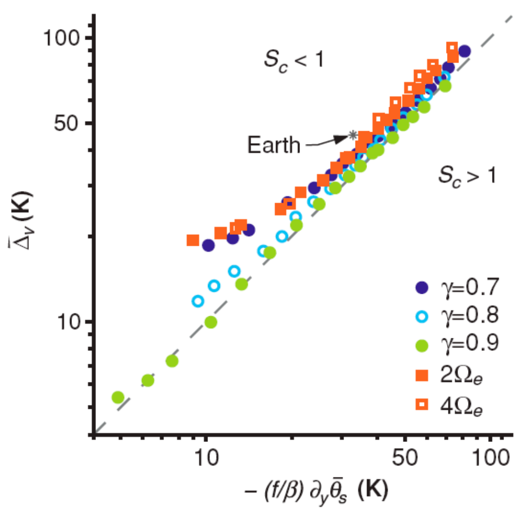
Open questions

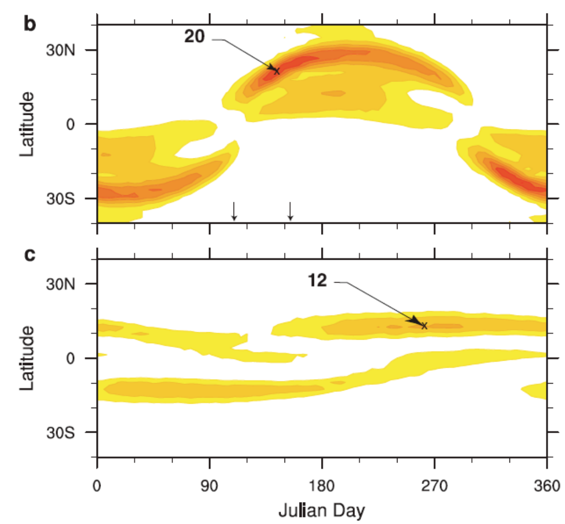
- What is meridional and vertical structure of eddy fluxes, given mean state of (a dry) atmosphere?
- How does the subtropical and extratropical static stability in a moist atmosphere depend on mean state of the atmosphere?
- More generally, what is role of moist processes in maintaining static stability, also in tropics?
- How do moist processes affect dynamics of baroclinic eddies (scaling laws)?


a
0.2
Sigma
0.8
32
350
44
-4
280
300
270
b
8
0
−8
Zonal sfc. wind (m s⁻¹)
Easterlies
Westerlies
Westerlies
−50°
0°
50°
Latitude


Potential temperature flux
$\propto (H_t' \Delta_h')^{5/2}$
$\propto H_t' \Delta_h'$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0
$H_t' \Delta_h'$


Day 85
250 mb
Pressure
1000 mb
-45
0
45
Latitude
50
25
0
-10
Zonal wind [m/s]
45
0
-45
Latitude
0
180
Longitude
-30
0
+30
Temperature [°C]


100
50
10
$\bar{\Delta}_v$ (K)
$S_c < 1$
Earth
$S_c > 1$
γ=0.7
γ=0.8
γ=0.9
$2\Omega_e$
$4\Omega_e$
10
50
100
$-(f/\beta)\,\partial_y \bar{\theta}_s$ (K)


b
30N
0
30S
Latitude
20
c
30N
0
30S
Latitude
12
0
90
180
270
360
Julian Day