Water Vapor and the Dynamics of Climate Changes

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(based on *Rev. Geophys.* article with Xavier Levine and Paul O'Gorman)

Water vapor dynamics in warming climate

Facts

- Saturation vapor pressure increases with temperature at ~7%/K
- Relative humidity *near the surface* stays roughly constant
- Precipitable water q increases at ~7%/K with sfc. temperature
- Precipitation P increases more slowly, at ~2–3 %/K
- Water vapor cycling rate P/q decreases

Common conjectures

- Tropical circulations (particularly Walker circulation) slow down
- Hadley circulation widens
- Extratropical storms become more energetic
- Precipitation extremes increase more rapidly than mean

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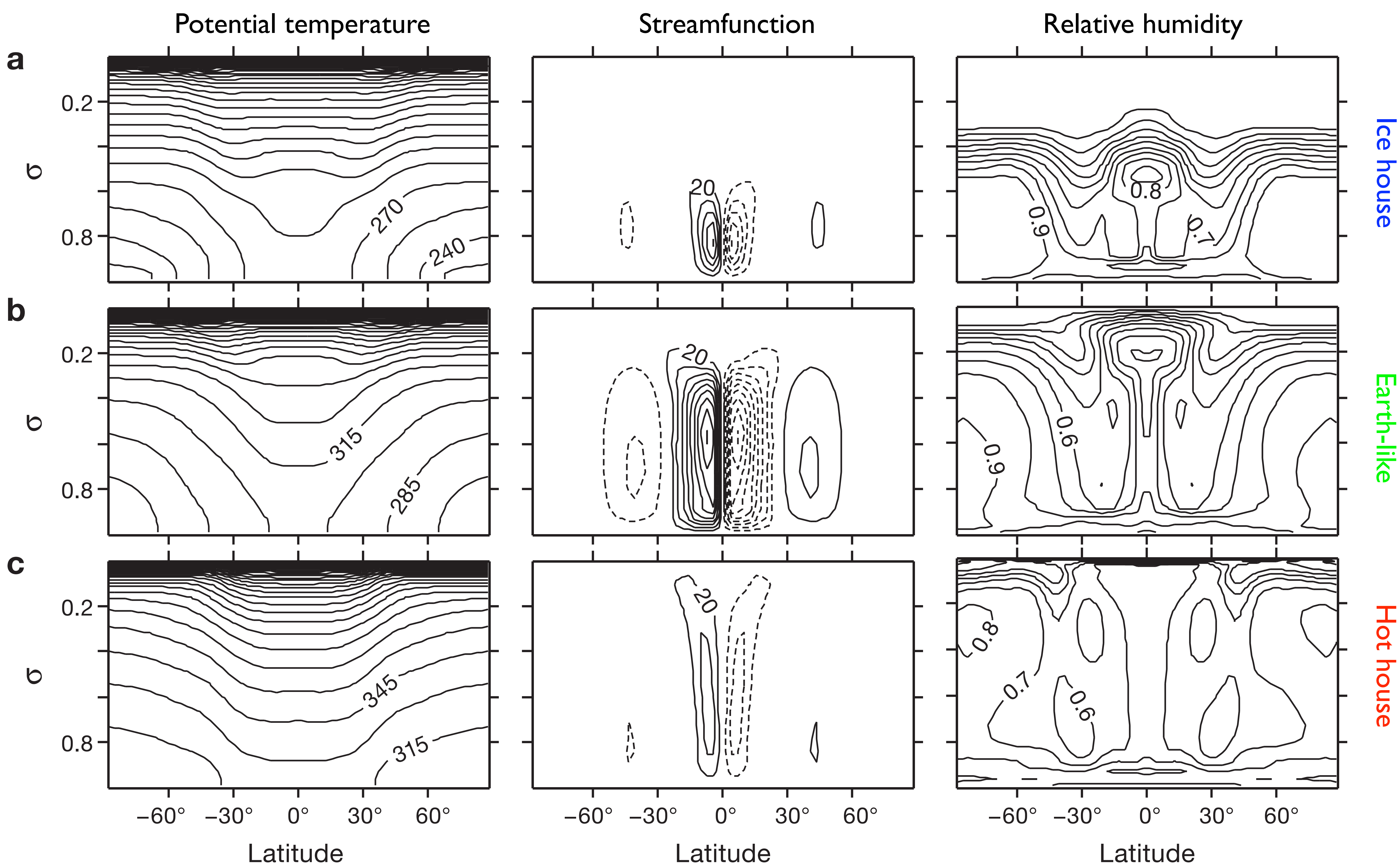
Simulations with idealized moist GCM

- Aquaplanet: uniform, water-covered surface; no ocean dynamics
- Built on GFDL FMS [similar to Frierson et al. (2006)]
- Only vapor-liquid phase transition considered (no ice)
- Radiative transfer of semi-gray atmosphere
- Climate varied by varying "greenhouse gas concentrations": scaling of optical thickness of longwave absorber (by factor 12)

Allows very large climate variations: Global-mean surface temperatures between 259 K and 316 K (!)

(O'Gorman & Schneider 2008)

A wide range of climates...



(O'Gorman & Schneider 2008)

Saturation vapor pressure

Clausius-Clapeyron relation between temperature *T* and saturation vapor pressure e_s

$$\frac{\delta e_s}{e_s} = \frac{L}{RT^2}\delta T$$

For warming Earth, this implies increase in saturation vapor pressure of 7%/K, or 21% for 3K warming.

(Boer 1993; Wentz & Schabel 2000; Trenberth 2003)

Near-surface relative humidity

Evaporation (over ocean) is proportional to

$$E \sim e_s - e = e_s(1 - \mathrm{RH})$$

so $\delta E \sim \delta e_s(1 - \mathrm{RH}) - e_s\delta(\mathrm{RH})$ or

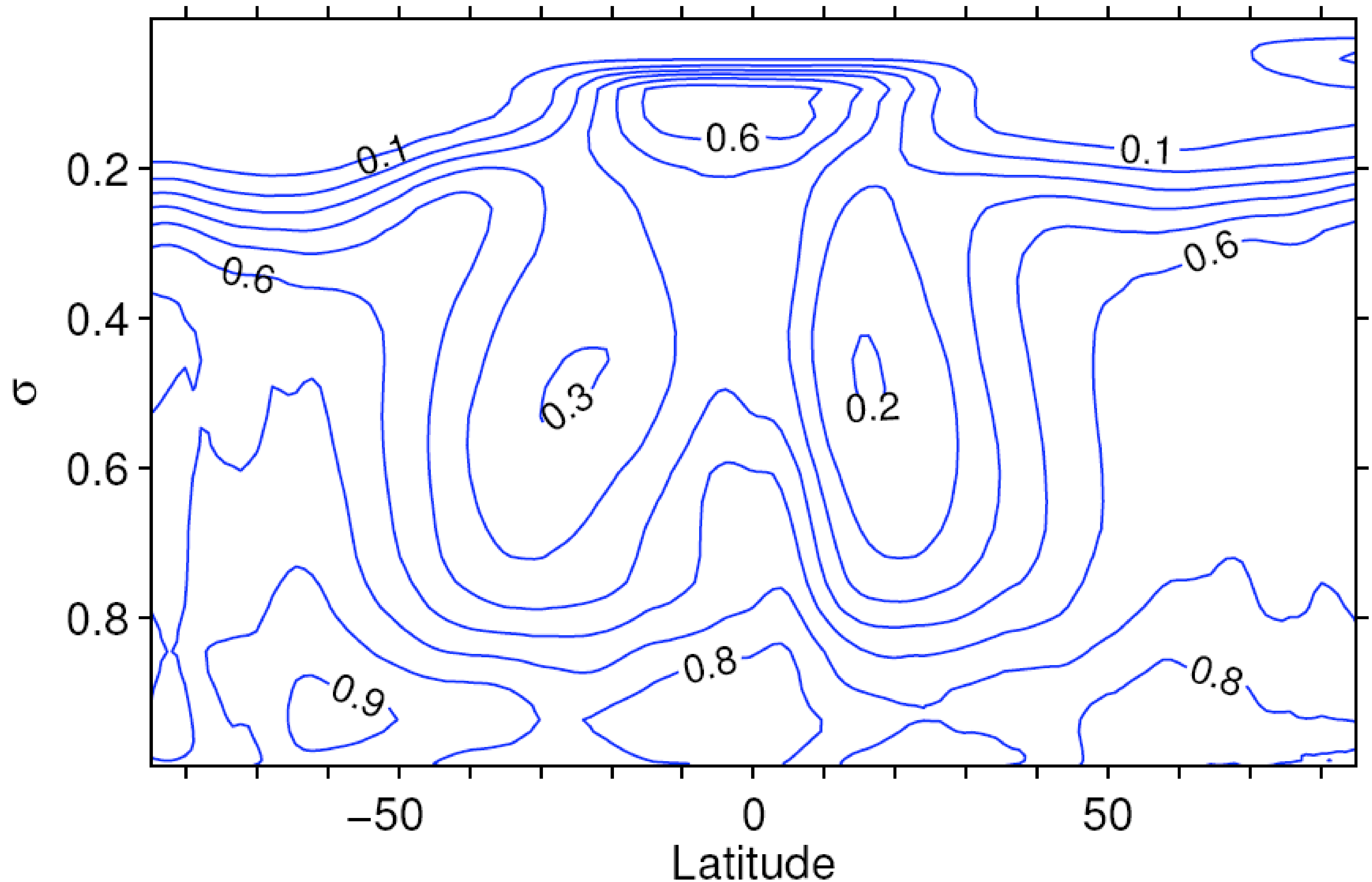
$$\delta(\mathrm{RH}) = (1 - \mathrm{RH})\left(\frac{\delta e_s}{e_s} - \frac{\delta E}{E}\right)$$

RH~85% near surface, $E \cong 80$ W/m^2, climate sensitivity ~0.8 K/(W m^2), so $\delta E/E \sim O(1\%/\mathrm{K}) \Rightarrow \delta(\mathrm{RH}) \sim O(1\%/\mathrm{K})$

Near-surface RH changes strongly energetically constrained

(Boer 1993; Held & Soden 2000)

Relative humidity (annual mean)



Data source: ERA-40

Near-surface relative humidity

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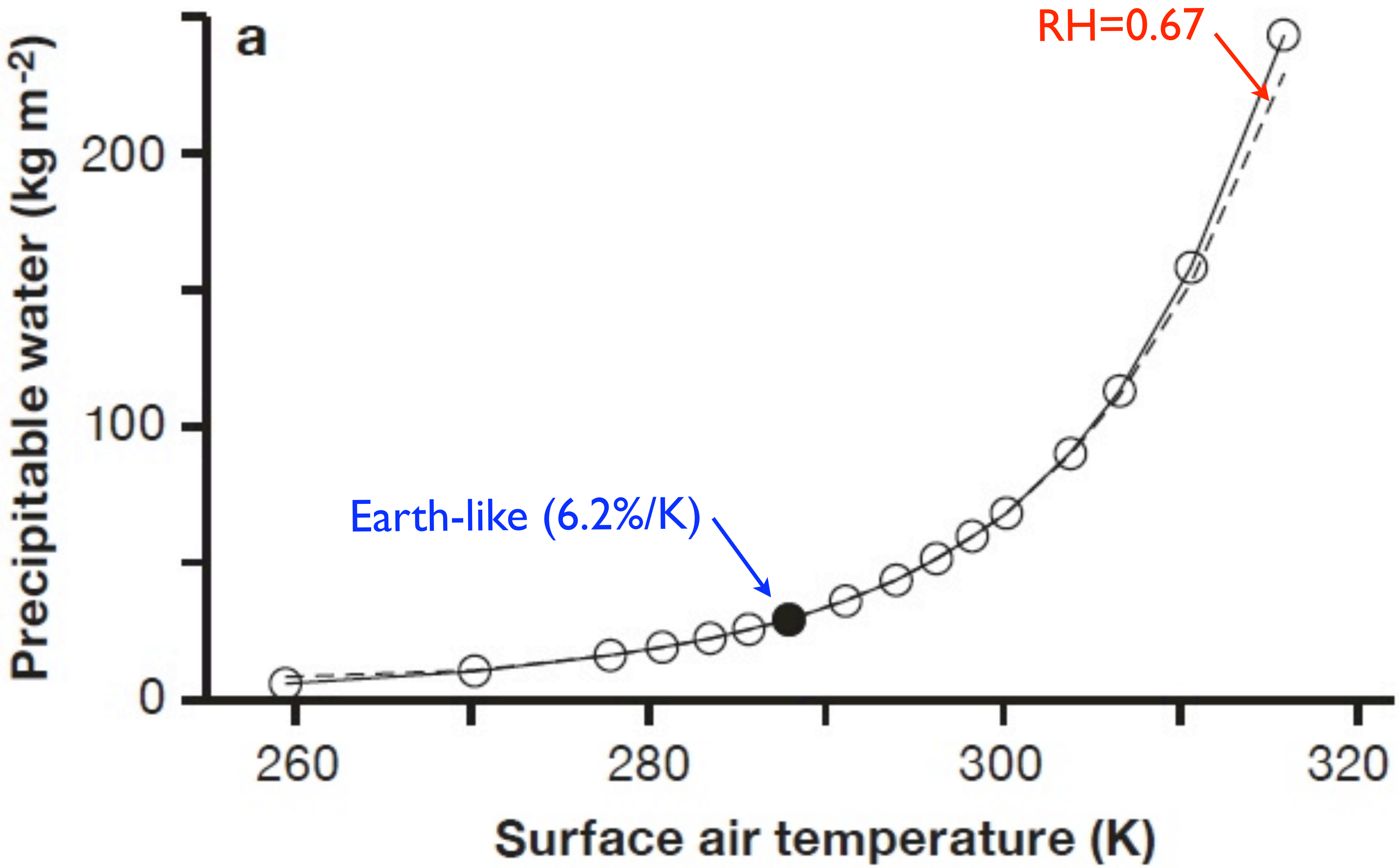
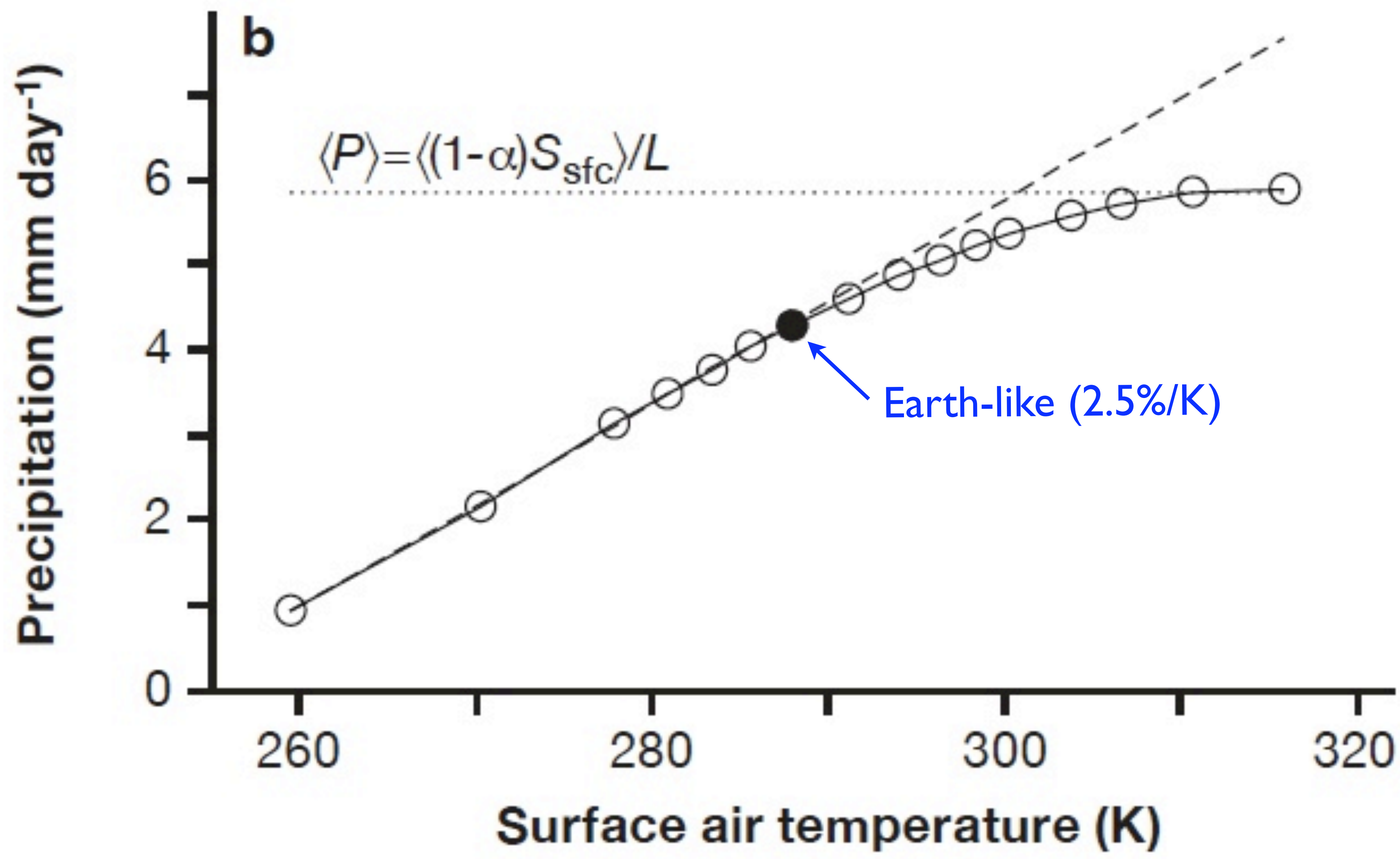
Precipitable water in idealized GCM



Most water vapor near surface
(Free-tropospheric RH does change)

(O'Gorman & Schneider 2008)

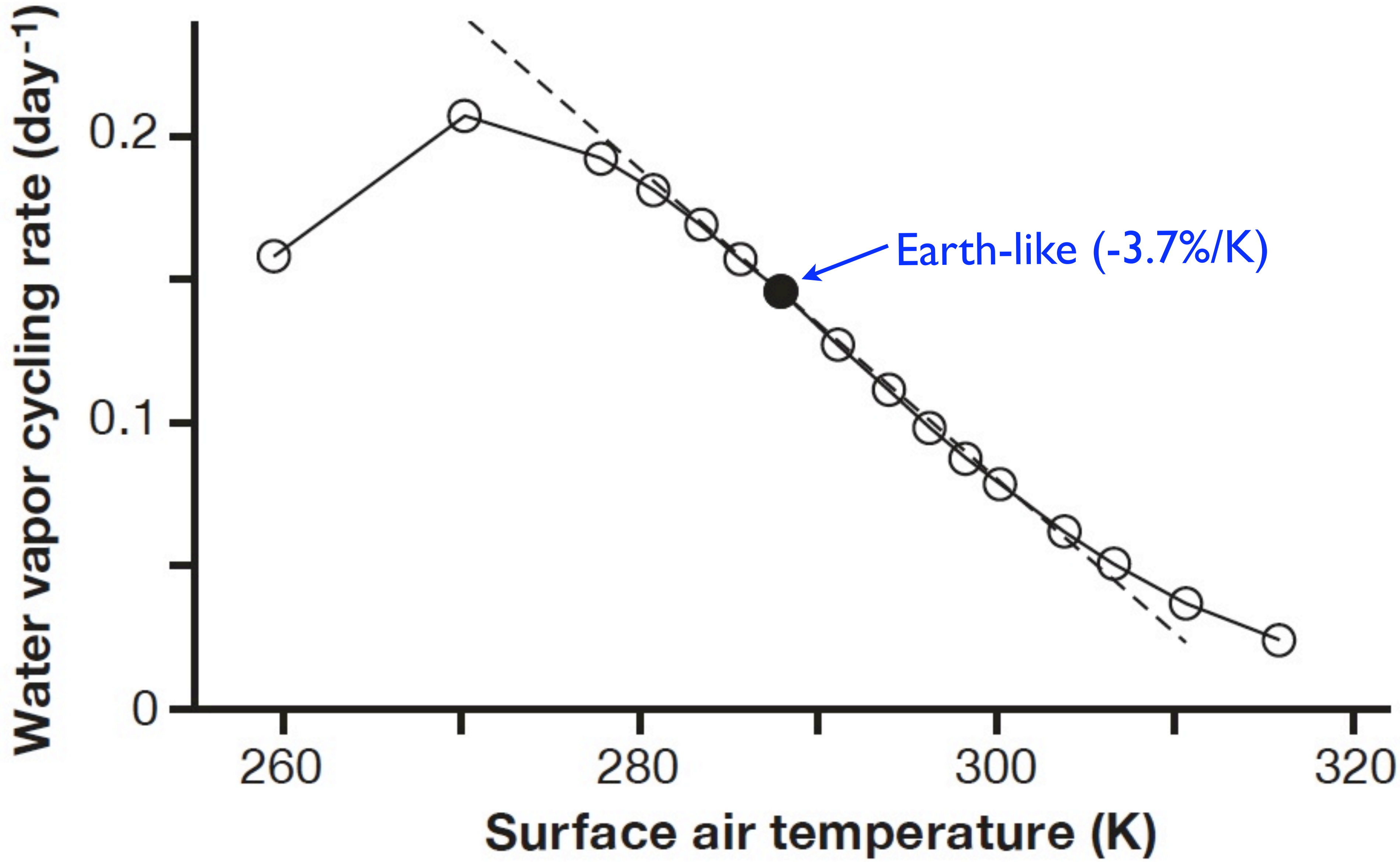
Precipitation in idealized GCM



Asymptotes to energetic bound

(O'Gorman & Schneider 2008)

Water vapor cycling rate



Generally decreases (except in cold climates)

(O'Gorman & Schneider 2008; Schneider et al. 2009)

Tropical convective mass flux

Moisture (or thermodynamic) balance in saturated updrafts

$$-\omega^{\uparrow}\partial_p q^* \approx c,$$

where

$$\omega^{\uparrow} = \begin{cases} \omega & \text{if } \omega < 0 \\ 0 & \text{if } \omega \geq 0 \end{cases}$$

Mass-weighted vertical integral $\{\cdot\}$

$$-\{\omega^{\uparrow}\partial_p q^*\} \approx P,$$

(avg'd over convective system)

(cf. Iribarne & Godson 1981; Schneider et al. 2009)

Scaling of convective mass flux

General scaling behavior

$$-\frac{\omega^{\uparrow}}{g} \sim \frac{P}{\Delta q^*}, \quad \Delta q^* = q_s^* - q^*$$

Case A

$$\Delta q^* \sim \partial_p q^* |_{\theta_e^*} \Delta p \sim S^* \Delta p$$

Mass flux scales with inverse static stability (Betts & Harshvardhan 1987)

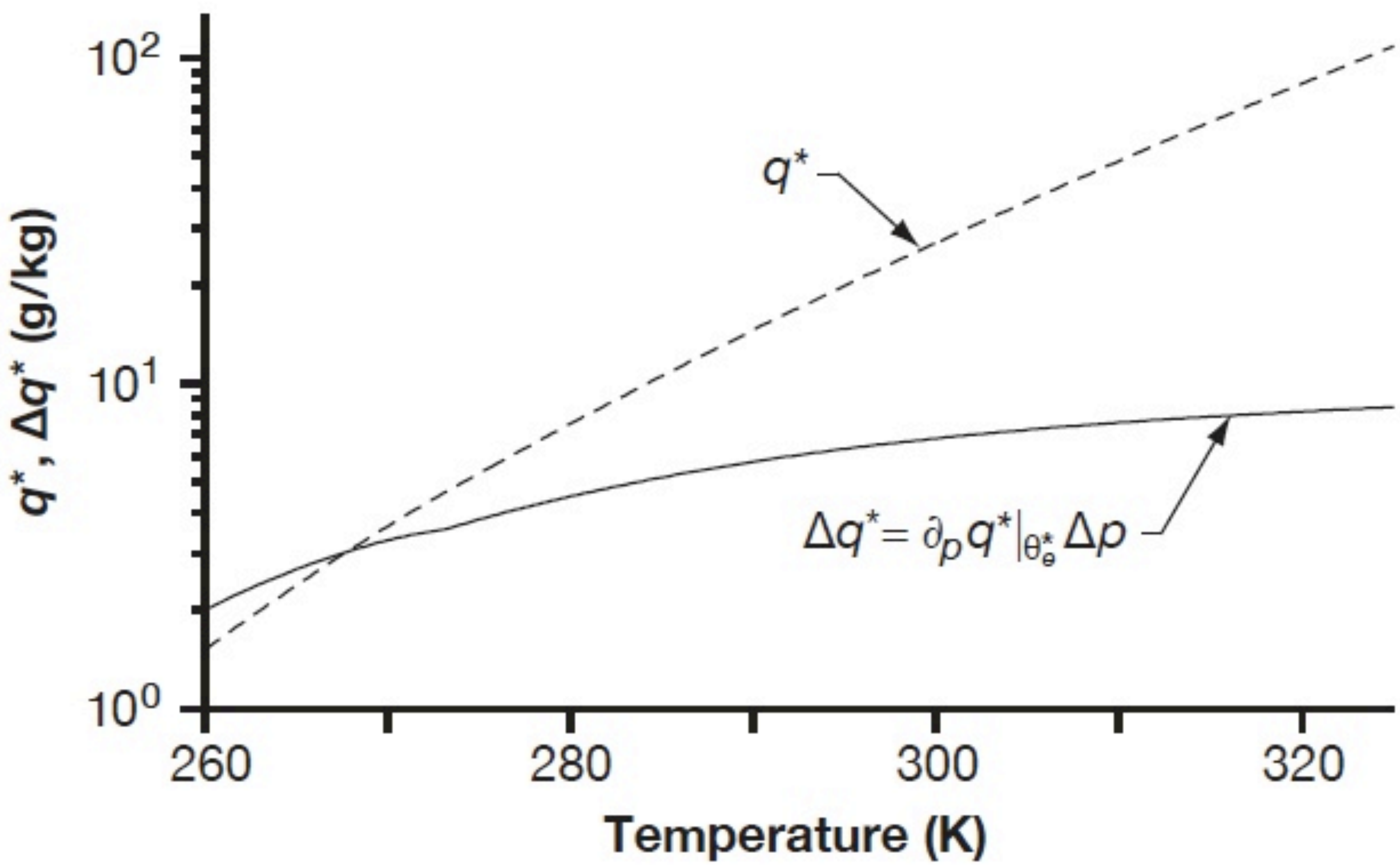
Case B

$$\Delta q^* \sim q_s^* - q^* \sim q_s^*$$

Mass flux scales with cycling rate (Betts 1998; Held & Soden 2006)

(Schneider et al. 2009)

Scaling estimates are very different...

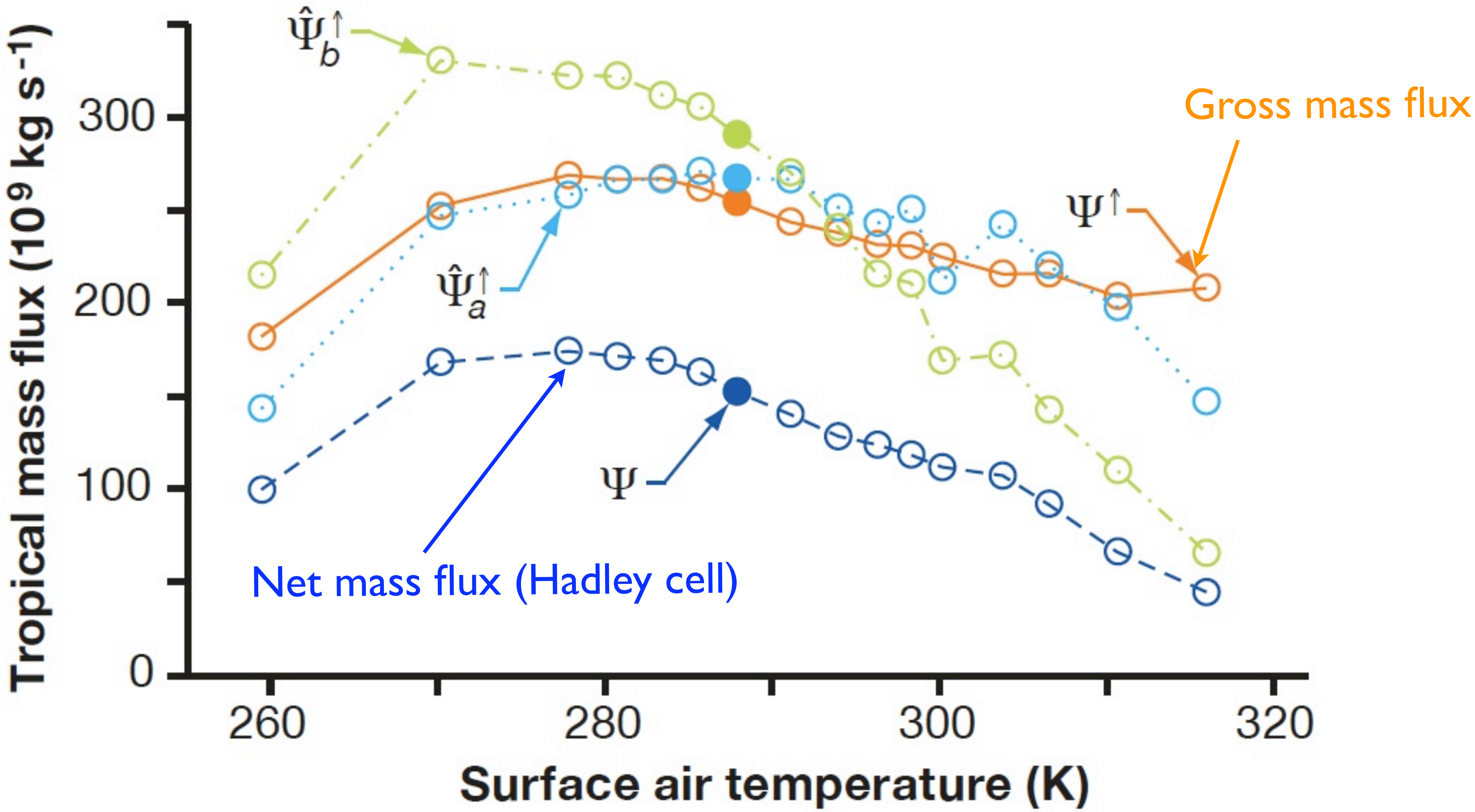


At 290 K, Δq increases at 2.0%/K, q at 6.4%/K

With $\delta P/P$~2.5%/K, mass flux increases under *A*, decreases under *B!*

(Schneider et al. 2009)

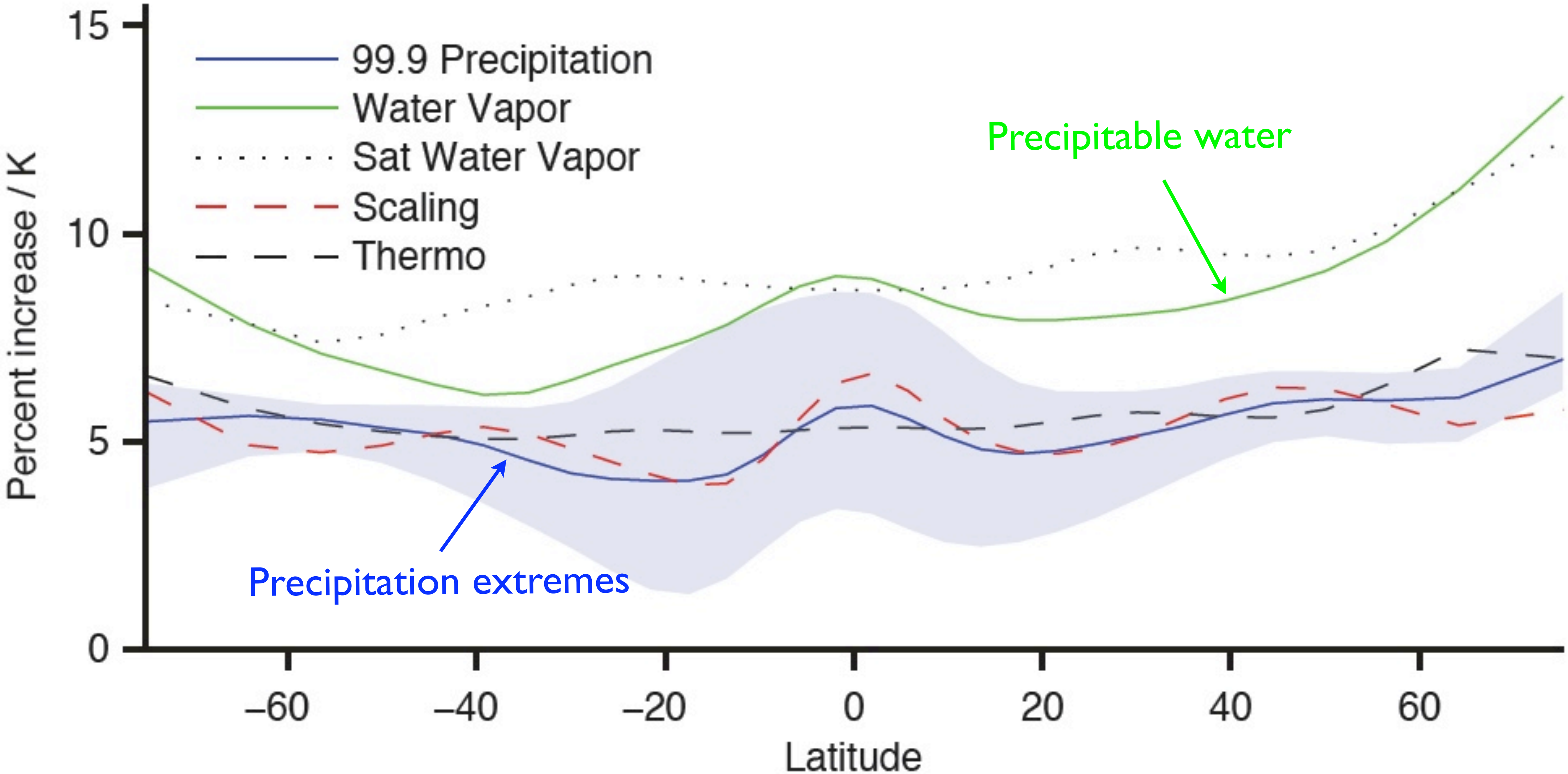
Tropical mass flux in idealized GCM



Convective mass flux scales inversely with static stability, not with cycling rate; non-monotonic function of surface temperature

(Schneider et al. 2009)

Precipitation extremes scale similarly...



Based on IPCC 21st-century global warming simulations

(O'Gorman and Schneider 2009)

So the convective *(gross) upward mass flux (zonally asymmetric) is thermally driven and depends on moist-adiabatic static stability. It may increase or decrease as the climate warms.*

What does that imply about the net upward mass flux (Hadley circulation)?

A Hadley circulation is thermally driven, if ...

- it 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

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

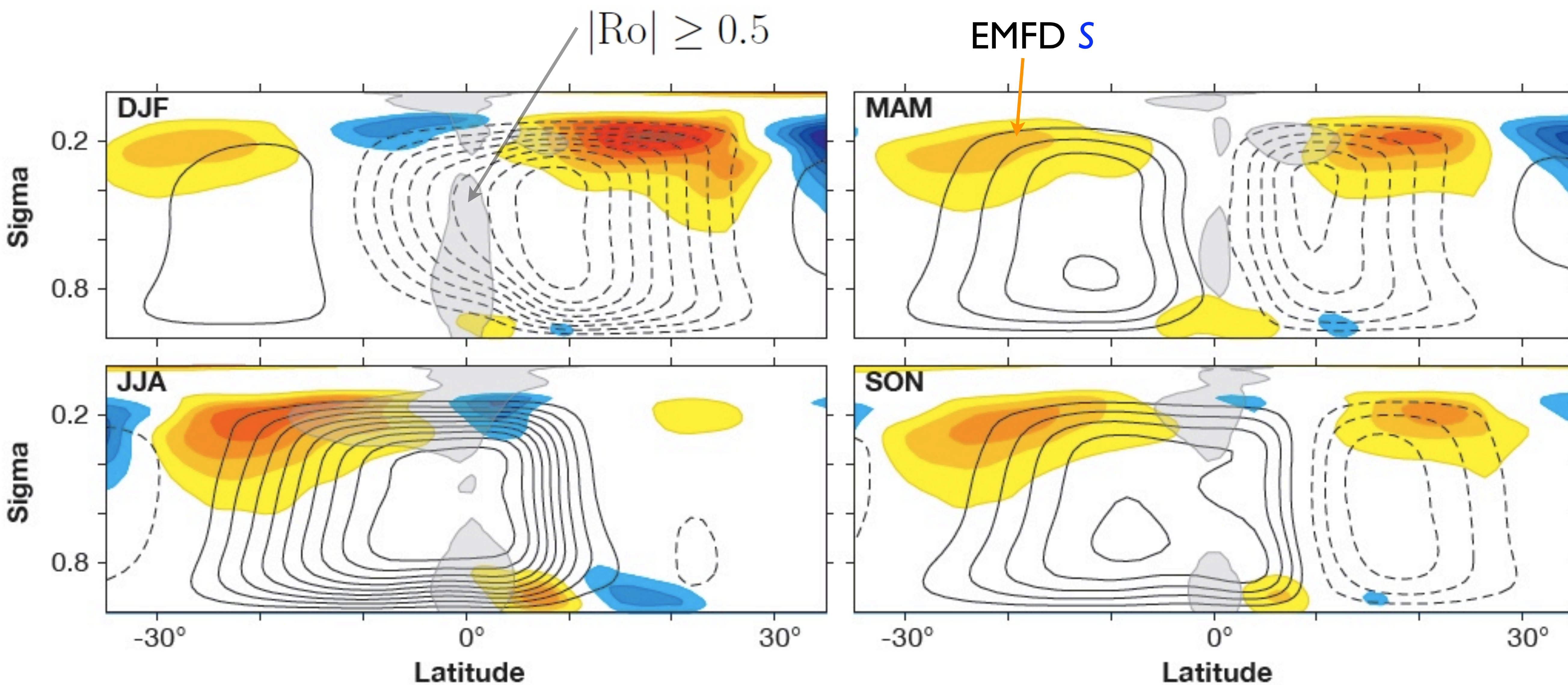
with *local Rossby number* $\mathrm{Ro} = -\bar{\zeta}/f \to 1$

- it is energetically closed (no heat export)

Classic theory is intuitively appealing, but is it adequate?

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

Hadley cells and eddy momentum flux divergence



Angular (or zonal) momentum balance:

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

Eddy driven if Ro<<1

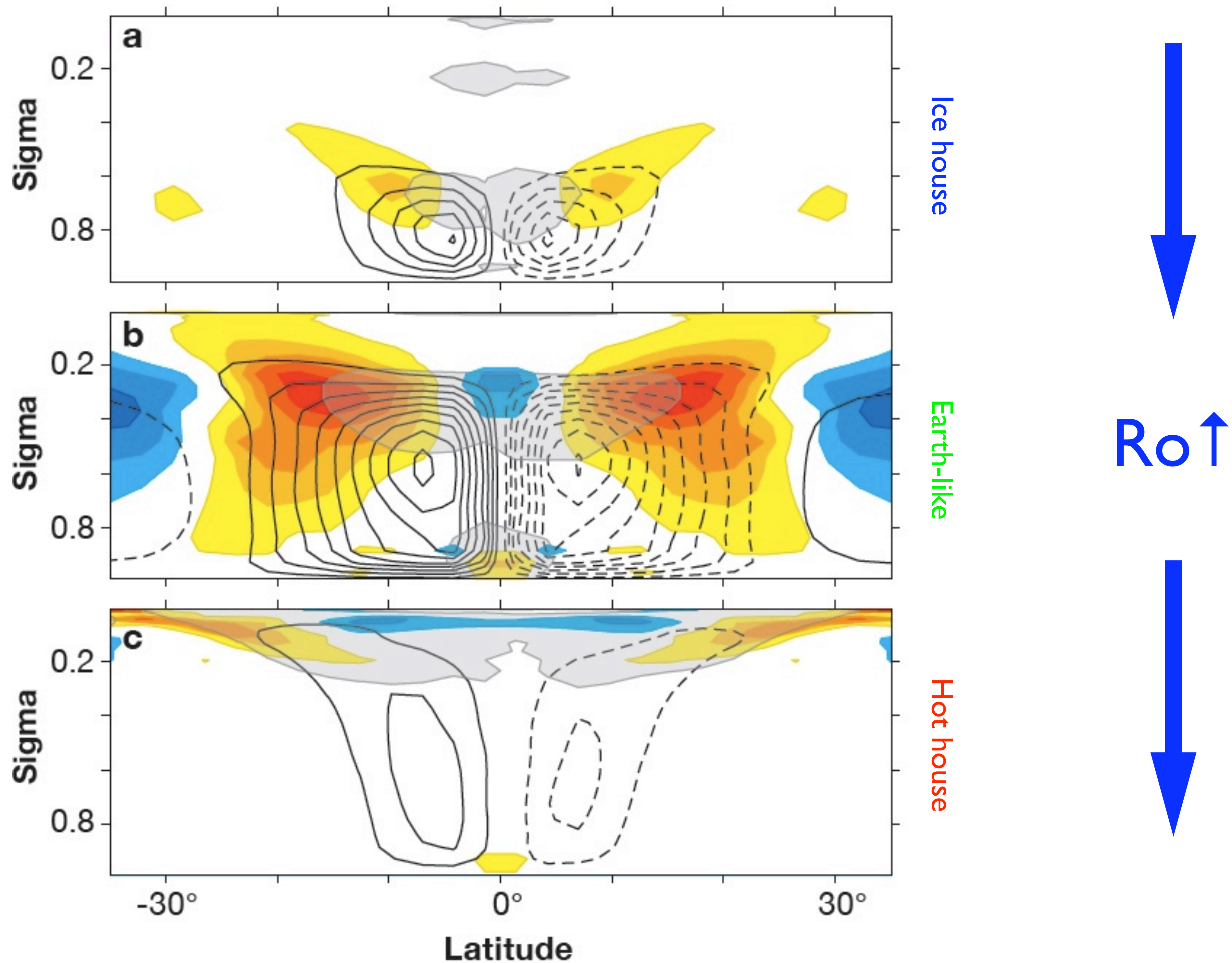
(Schneider 2006; Schneider et al. 2009; data source: ERA-40)

Earth-like Hadley circulations...

- In the annual mean or during equinox are close to limit $\mathrm{Ro} \to 0$
- Do not respond directly to variations in thermal driving but respond via changes in eddy momentum fluxes

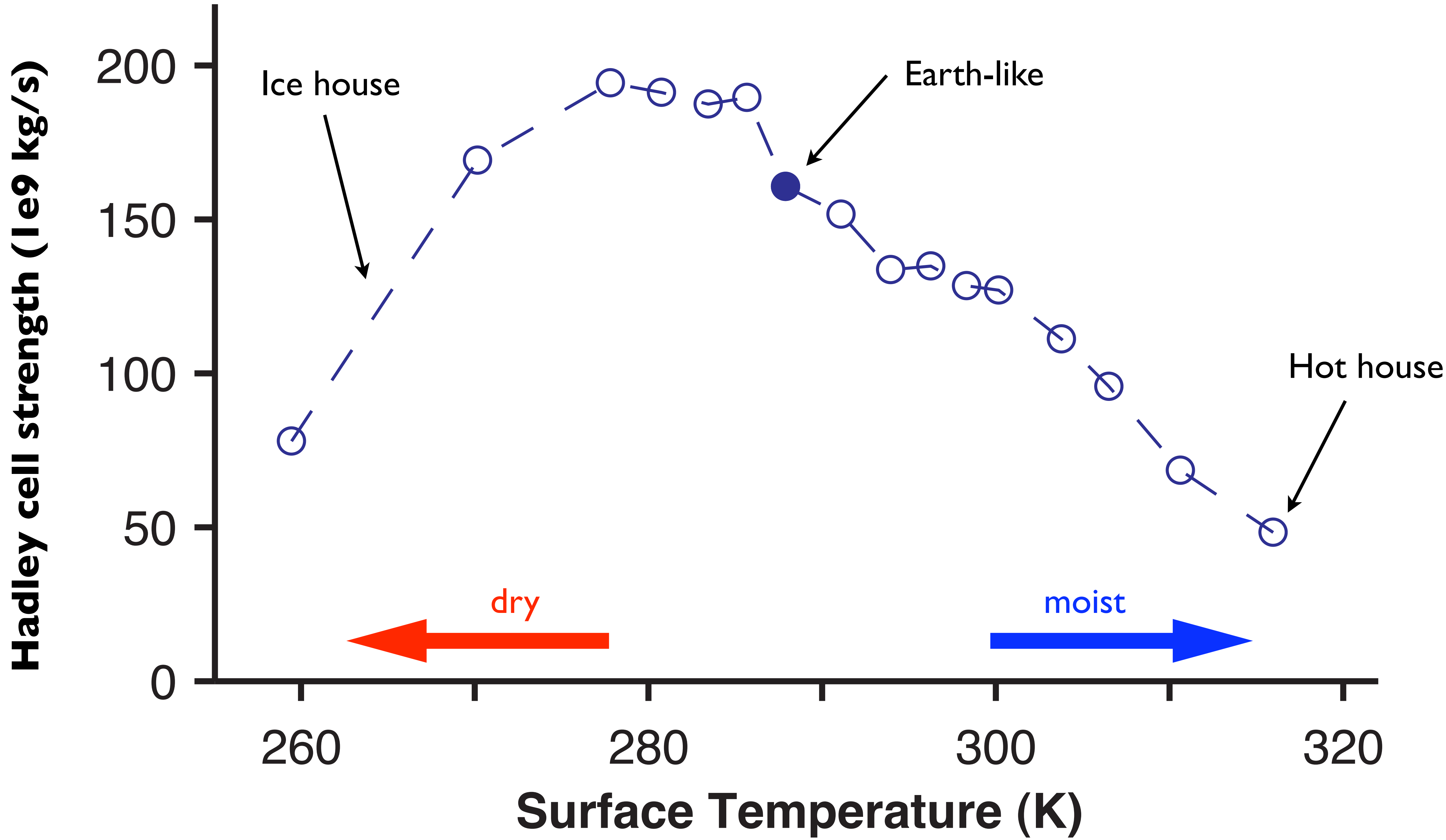
We need to rethink Hadley circulation response, for example, to ENSO and global warming

Hadley cell strength in idealized GCM



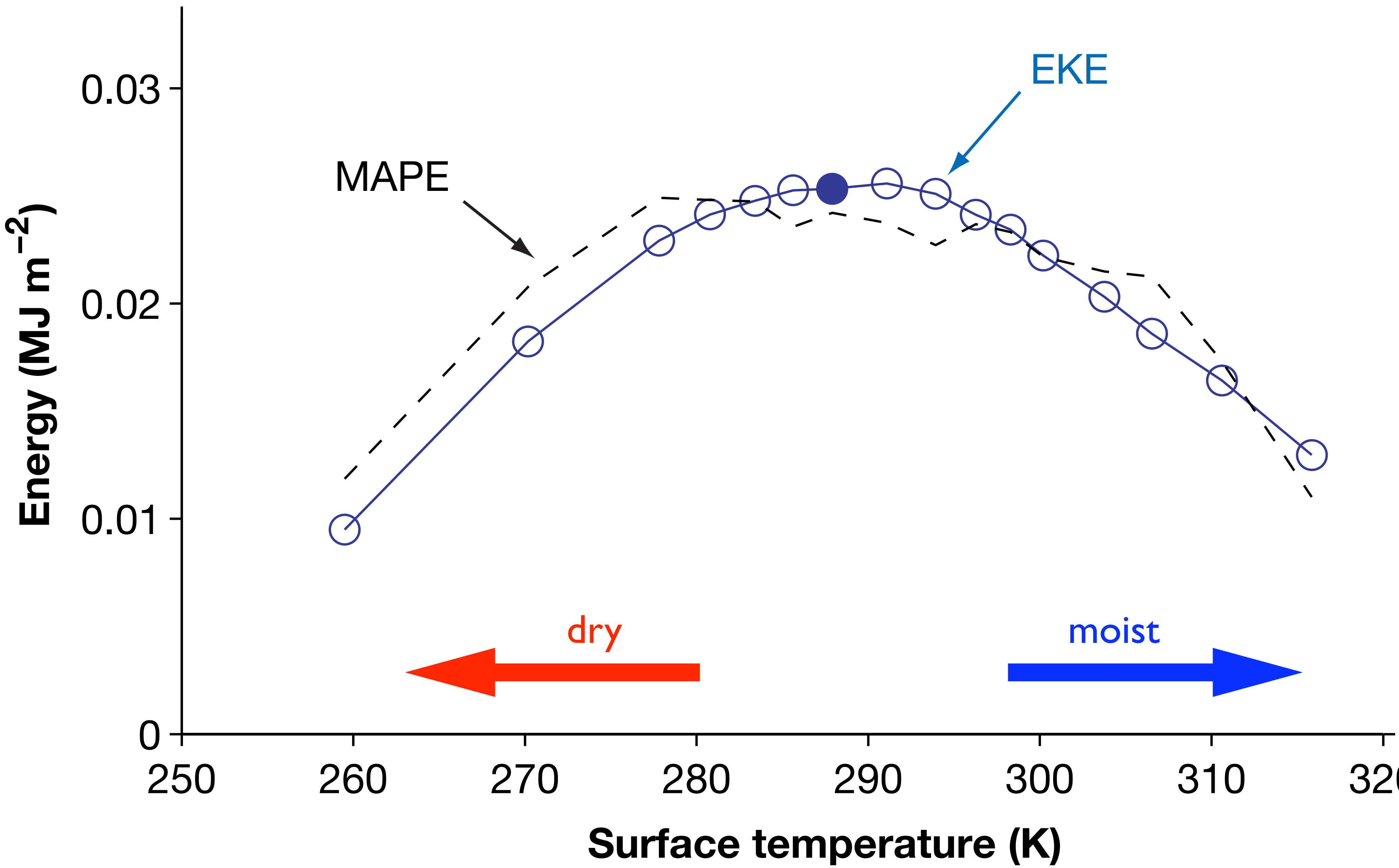
(Schneider et al. 2009)

Hadley cell strength



Non-monotonic function of surface temperature

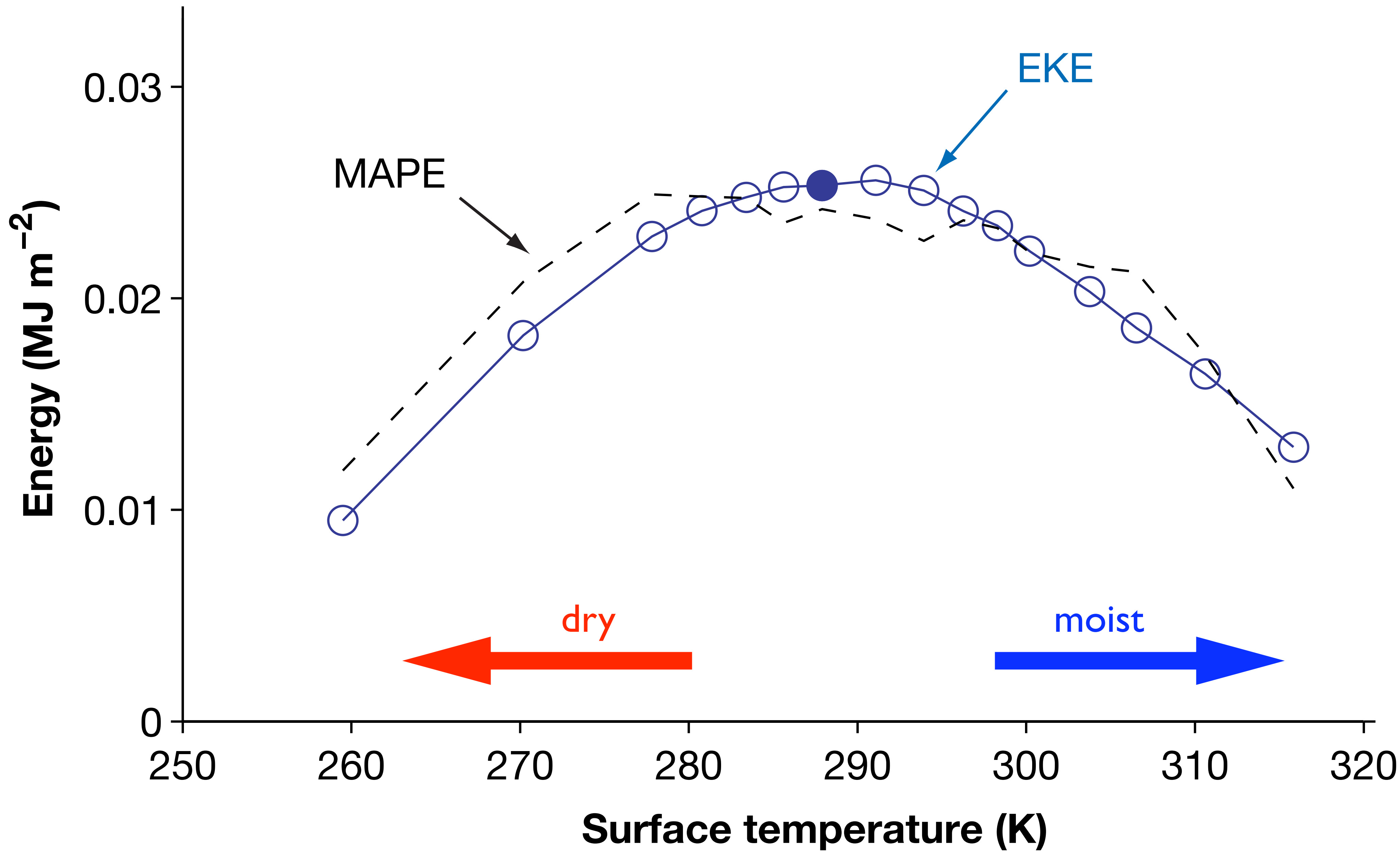
Eddies mediate Hadley circulation response



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

(O'Gorman & Schneider 2008; Schneider & Walker 2008)

Eddies mediate Hadley circulation response

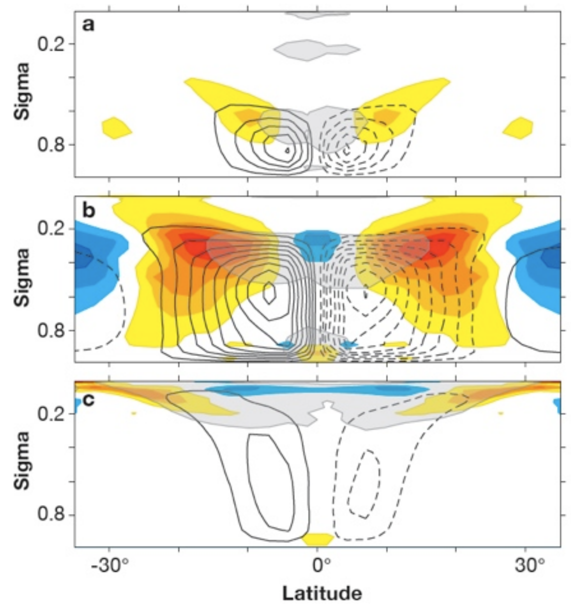


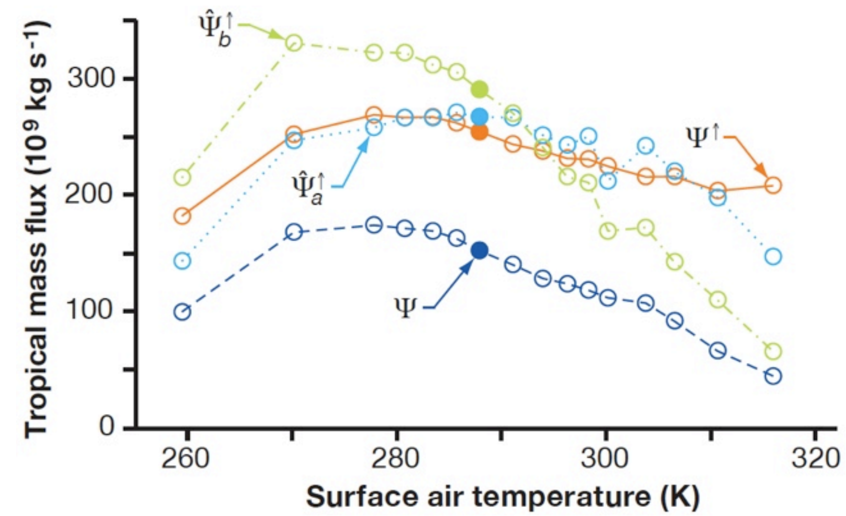
Non-monotonic function of surface temperature (e.g., LGM less stormy?)

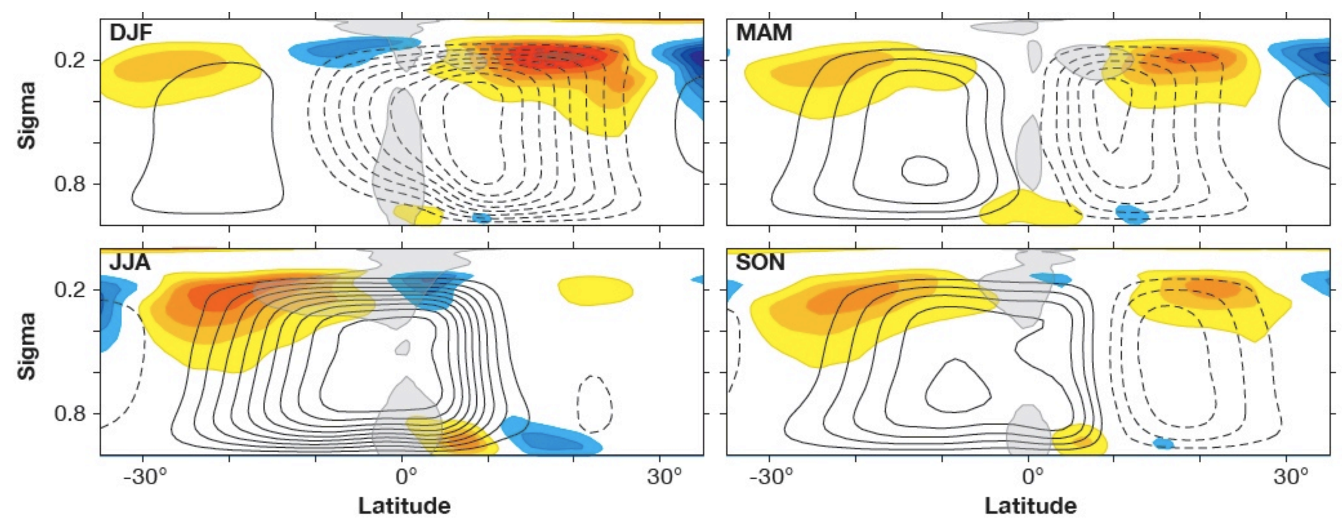
(O'Gorman & Schneider 2008; Schneider & Walker 2008)

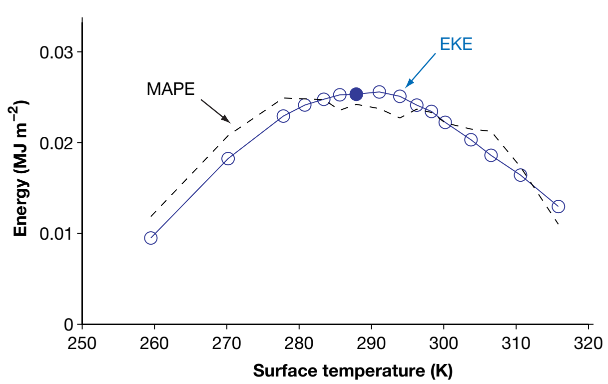
Conclusions

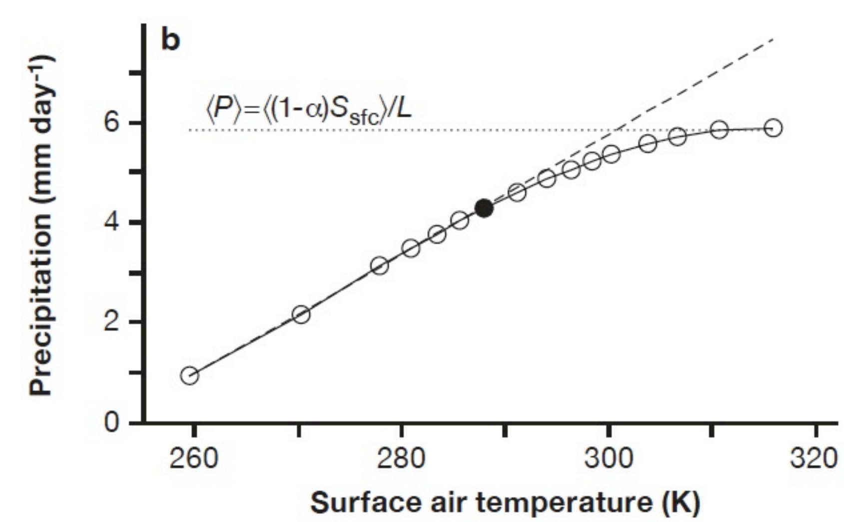
- Precipitable water increases rapidly with temperature, precipitation less rapidly, water vapor cycling rate generally decreases, but...
- Gross upward mass flux in tropics may depend on static stability (increases slowly with temperature).
- Hadley cell during equinox, summer, and in annual mean controlled by eddy fluxes.
- Eddy scaling (non-monotonic) imprinted on Hadley cell response to climate change.
- Hadley cell and extratropical storms weaker in warmer *and* in (much) colder climates.


a
b
c
Sigma
0.2
0.8
-30°
0°
30°
Latitude


Tropical mass flux (10^9 kg s^{-1})
Surface air temperature (K)
0
100
200
300
260
280
300
320
$\hat{\Psi}_b^{\uparrow}$
$\hat{\Psi}_a^{\uparrow}$
$\Psi^{\uparrow}$
Ψ


DJF
MAM
JJA
SON
Sigma
0.2
0.8
-30°
0°
30°
Latitude


Energy (MJ m^{-2})
0
0.01
0.02
0.03
MAPE
EKE
250
260
270
280
290
300
310
320
Surface temperature (K)


b
Precipitation (mm day^{-1})
$\langle P \rangle = \langle (1-\alpha) S_{sfc} \rangle / L$
0
2
4
6
260
280
300
320
Surface air temperature (K)