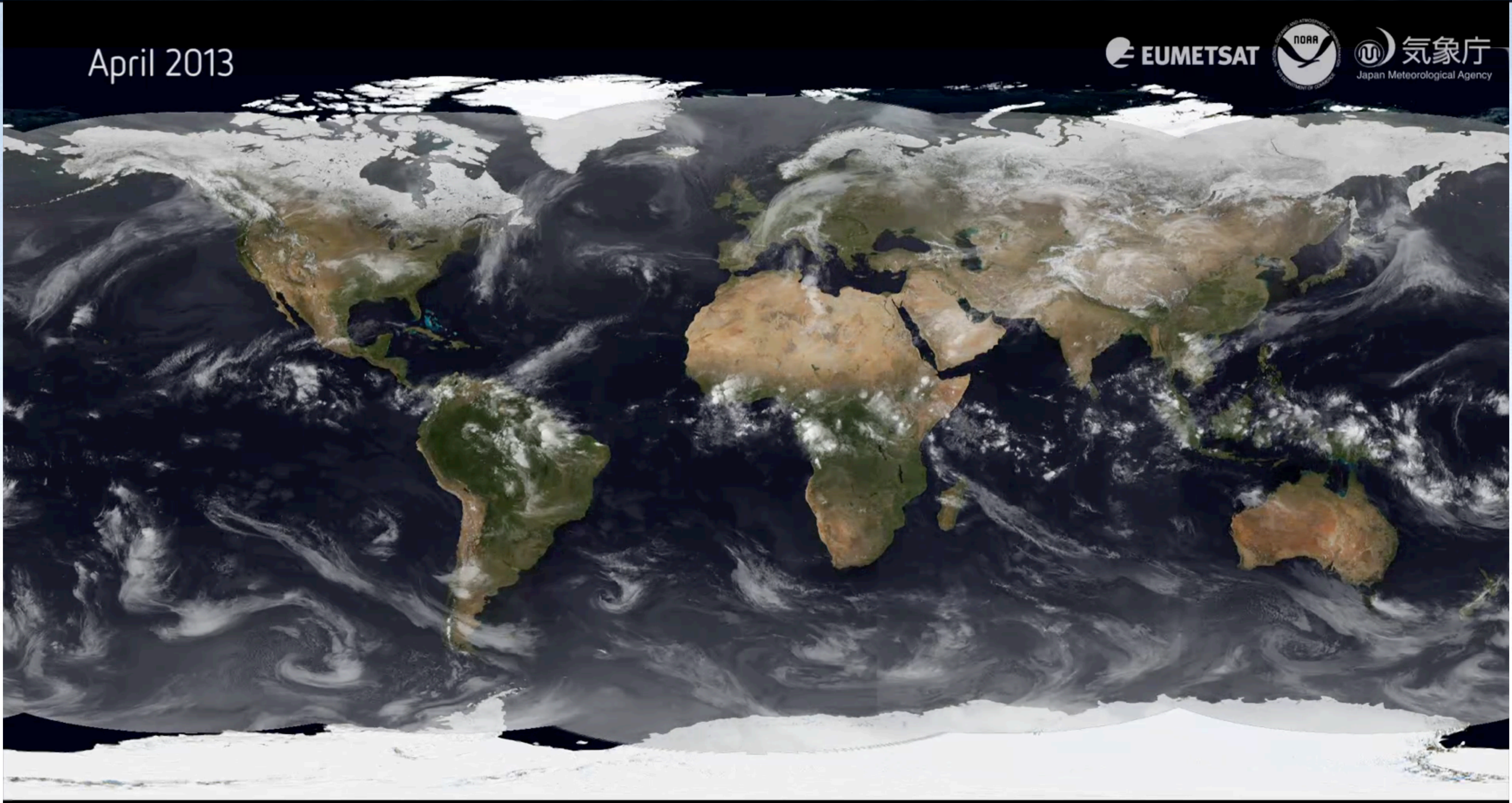
# Global Connections Among Atmospheric Circulations:

## From the ITCZ to the Storm Tracks

Tapio Schneider

(with Ori Adam, Tobias Bischoff, Xavier Levine, Cheikh Mbengue, Jennifer Walker)

# Infrared Brightness 2013




Mark Higgins, EUMETSAT, http://www.youtube.com/watch?v=m2Gy8V0Dv78

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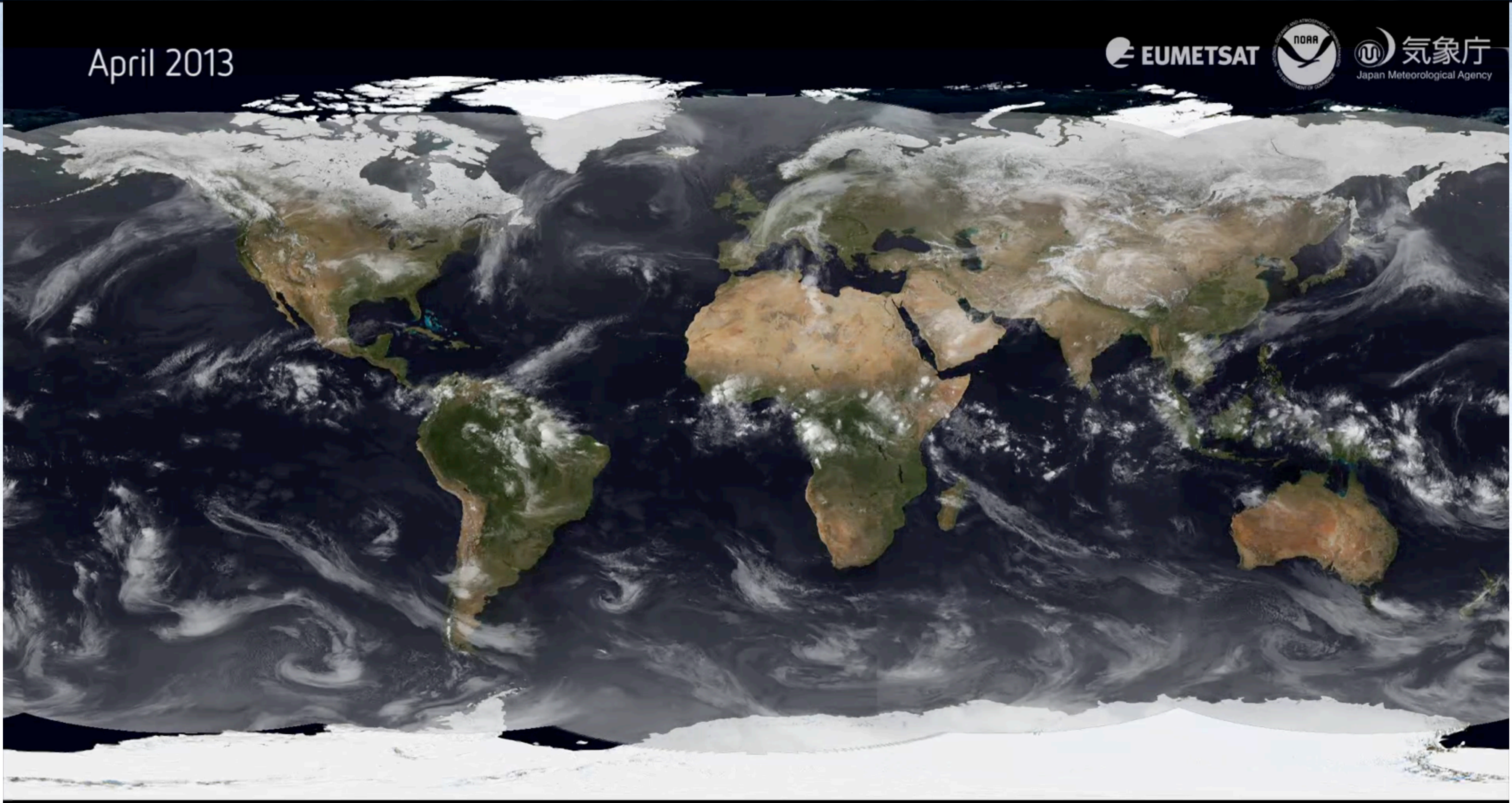


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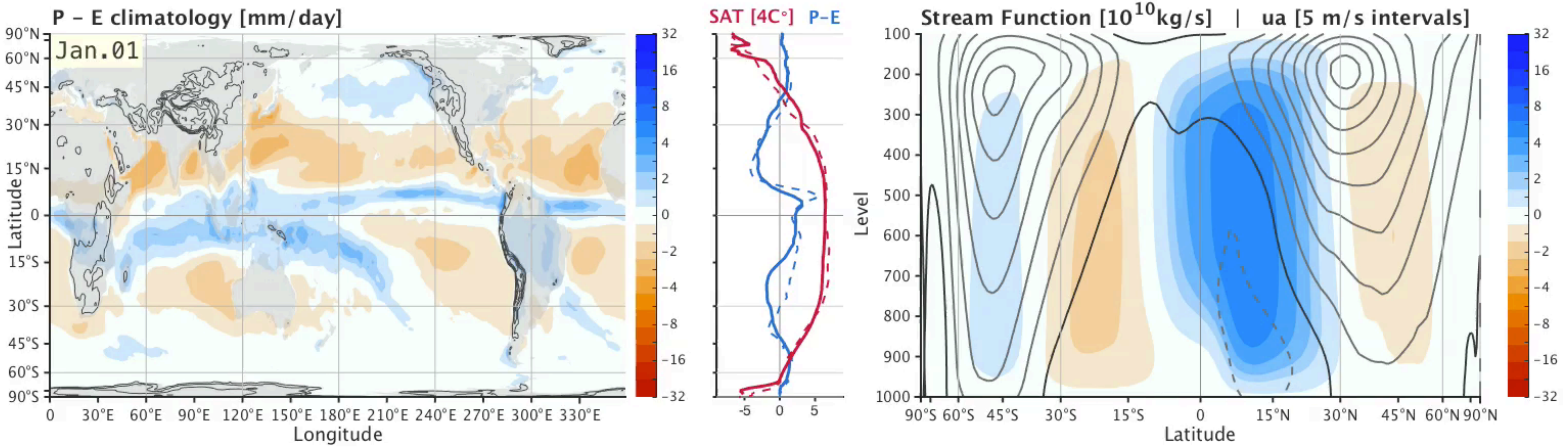
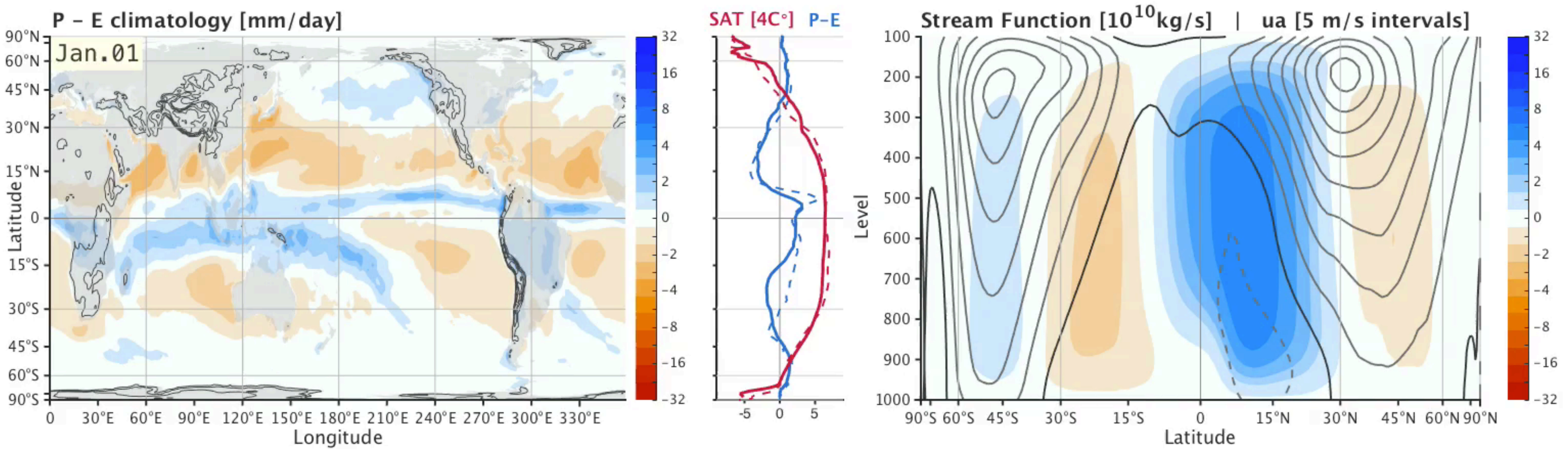
# Annual Cycle of *P-E*, Streamfunction, Zonal Wind



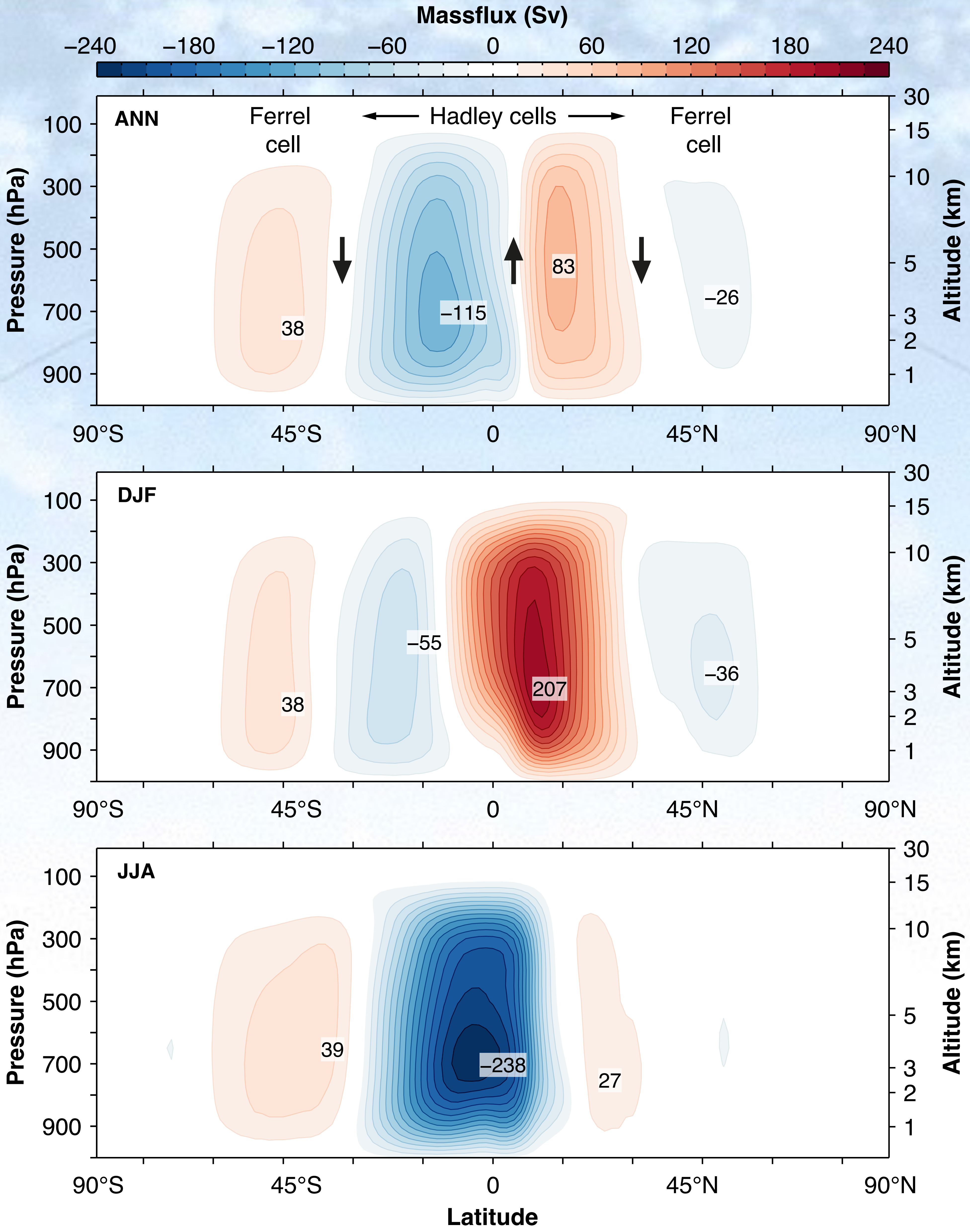

*Data source:* ERA-Interim; animation courtesy Ori Adam

# Annual Cycle of *P-E*, *S*treamfunction, Zonal Wind




*Data source:* ERA-Interim; animation courtesy Ori Adam

# Streamfunction Climatology

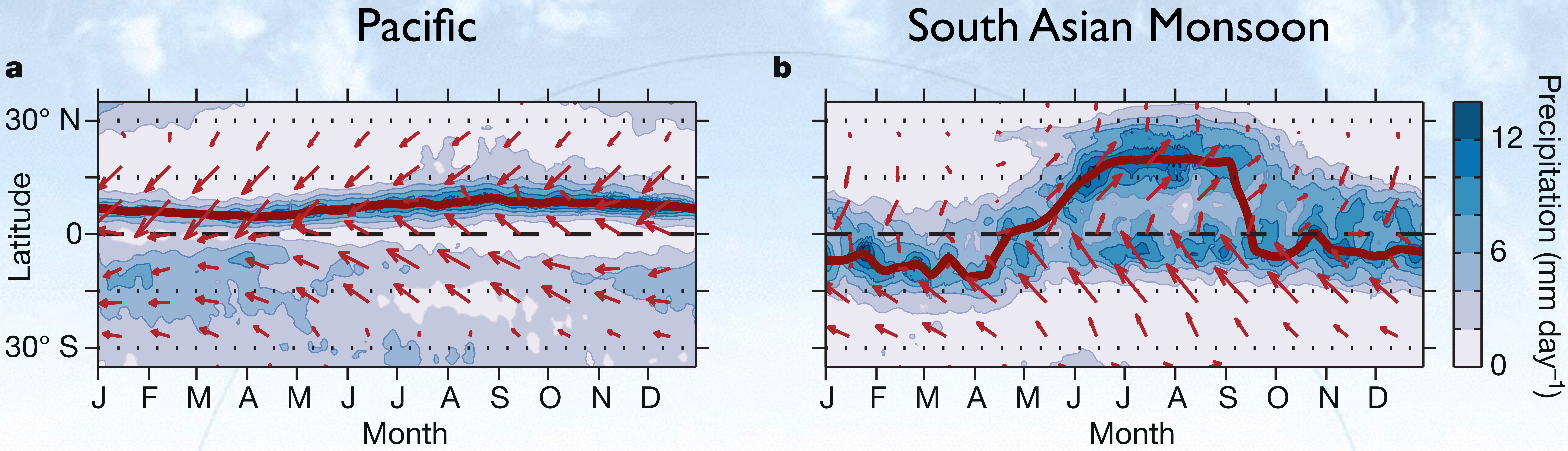



*Data source:* ERA-Interim

# First Observations

- ITCZ moves a lot seasonally (~25°)
- Subsiding branches of Hadley cells not so much (~2°)
- Storm tracks not much either

# Seasonal ITCZ Migrations




Surface wind (arrows) and precip (colors)

Schneider et al., *Nature*, 2014. *Data sources:* TRMM/TMPA, ERA-Interim

# Seasonal ITCZ Migrations

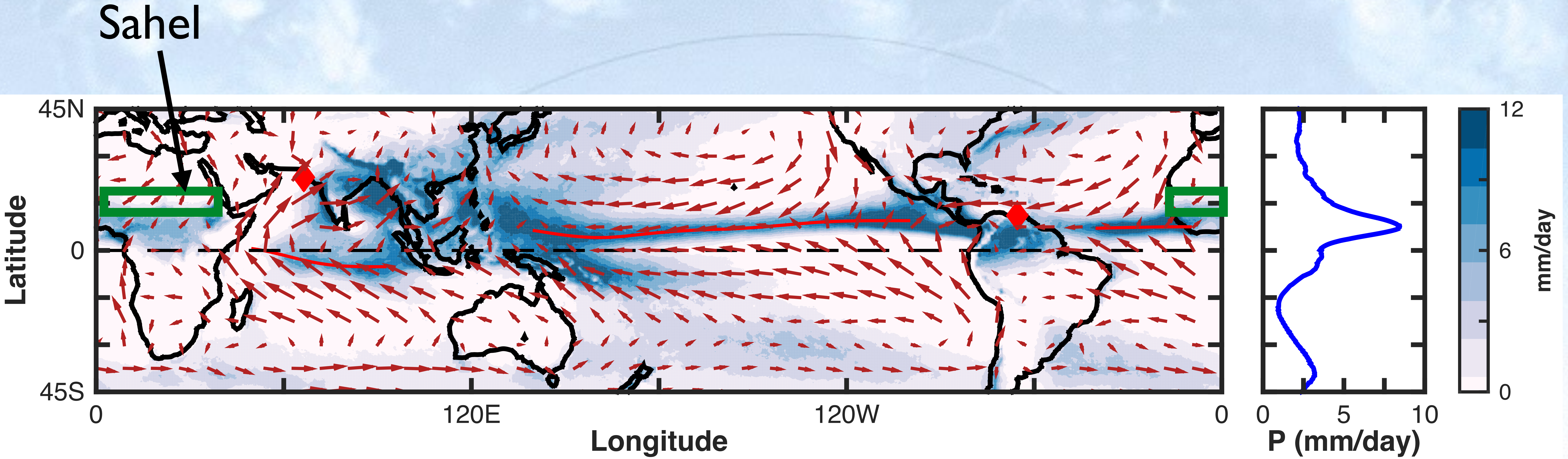
- ITCZ moves seasonally toward warming (summer) hemisphere
- Migration has lower amplitude and is gradual over most oceans
- Migration has higher amplitude and is abrupt in SA monsoon

*ITCZ generally migrates toward differentially warming hemisphere*

*Also true on longer timescales (not true for subsiding branches of HC!)*

See review by Chiang & Friedmann, *Ann. Rev. Geophys.* 2012

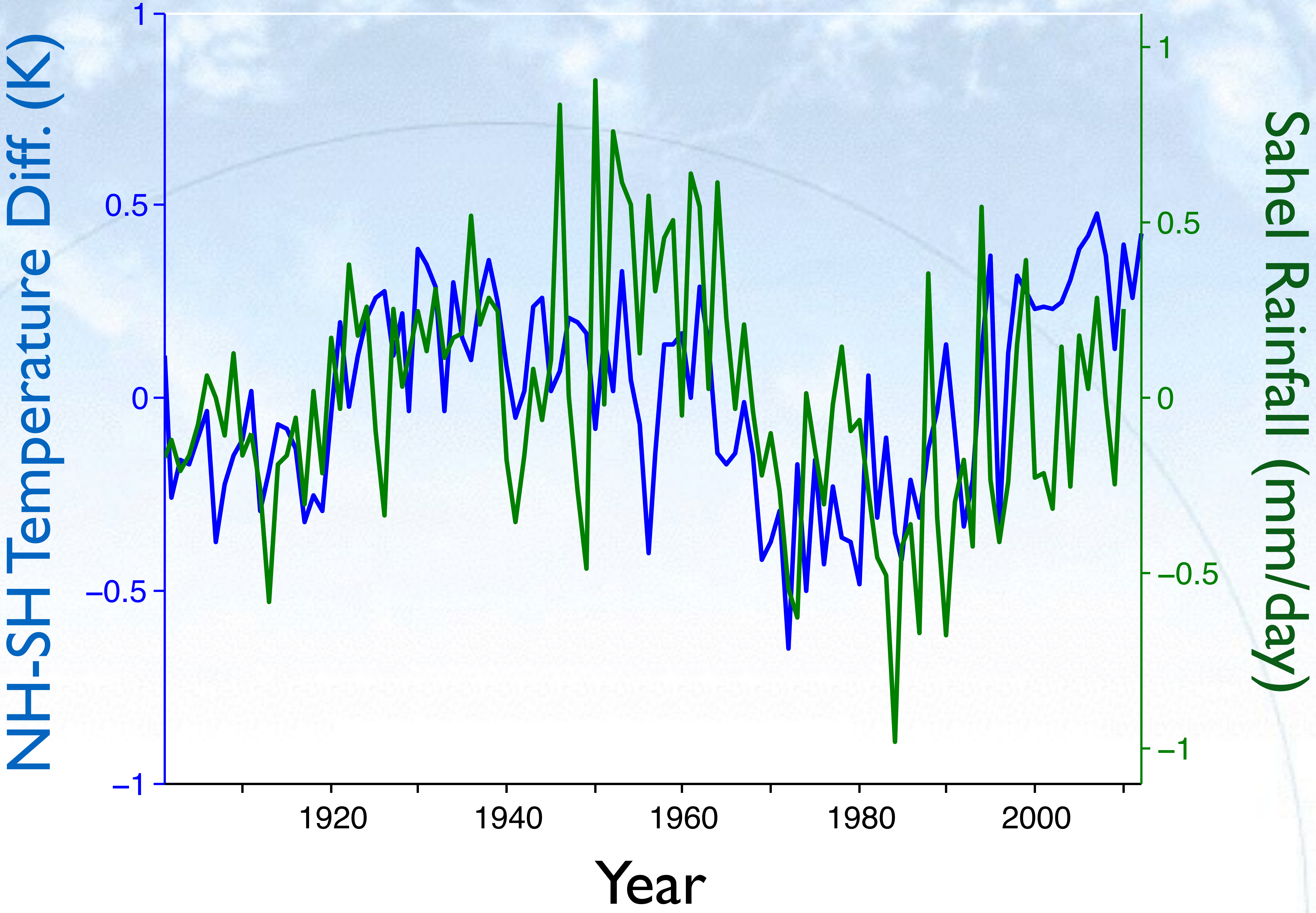
# Precipitation (JJA)




*Data source:* ERA-Interim

# African Sahel (Decadal Variations)

(*Image:* Wikipedia)

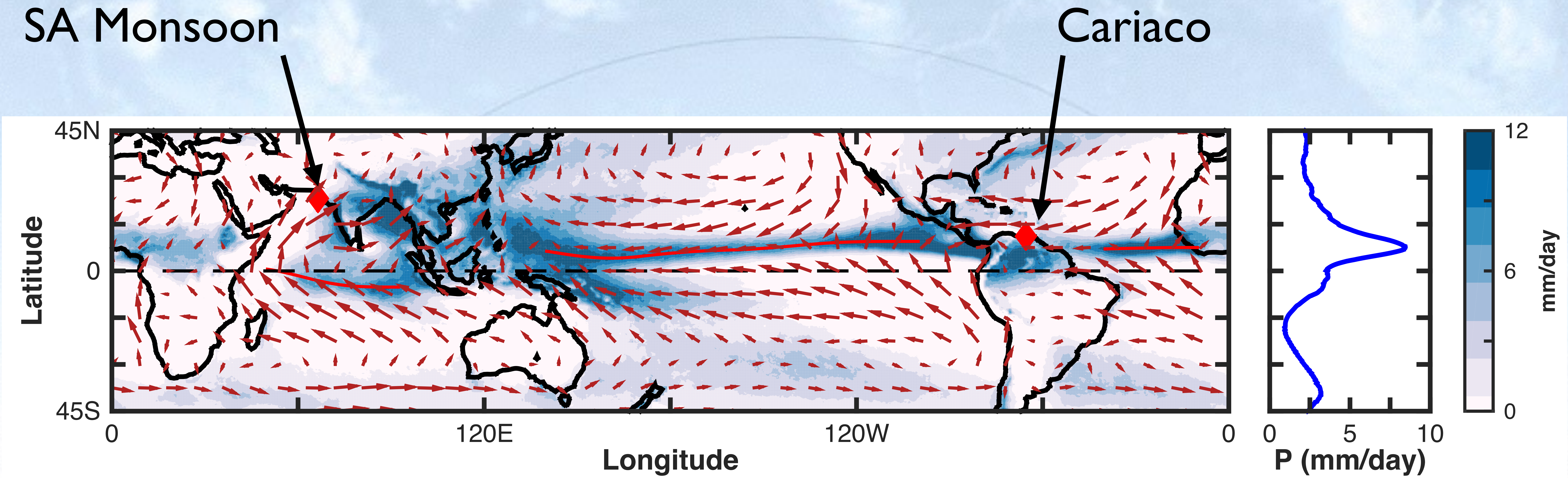



Schneider et al., *Nature*, 2014; harking back to Folland et al. 1986; Giannini et al. 2003; Held et al. 2005

# Sahel Rainfall

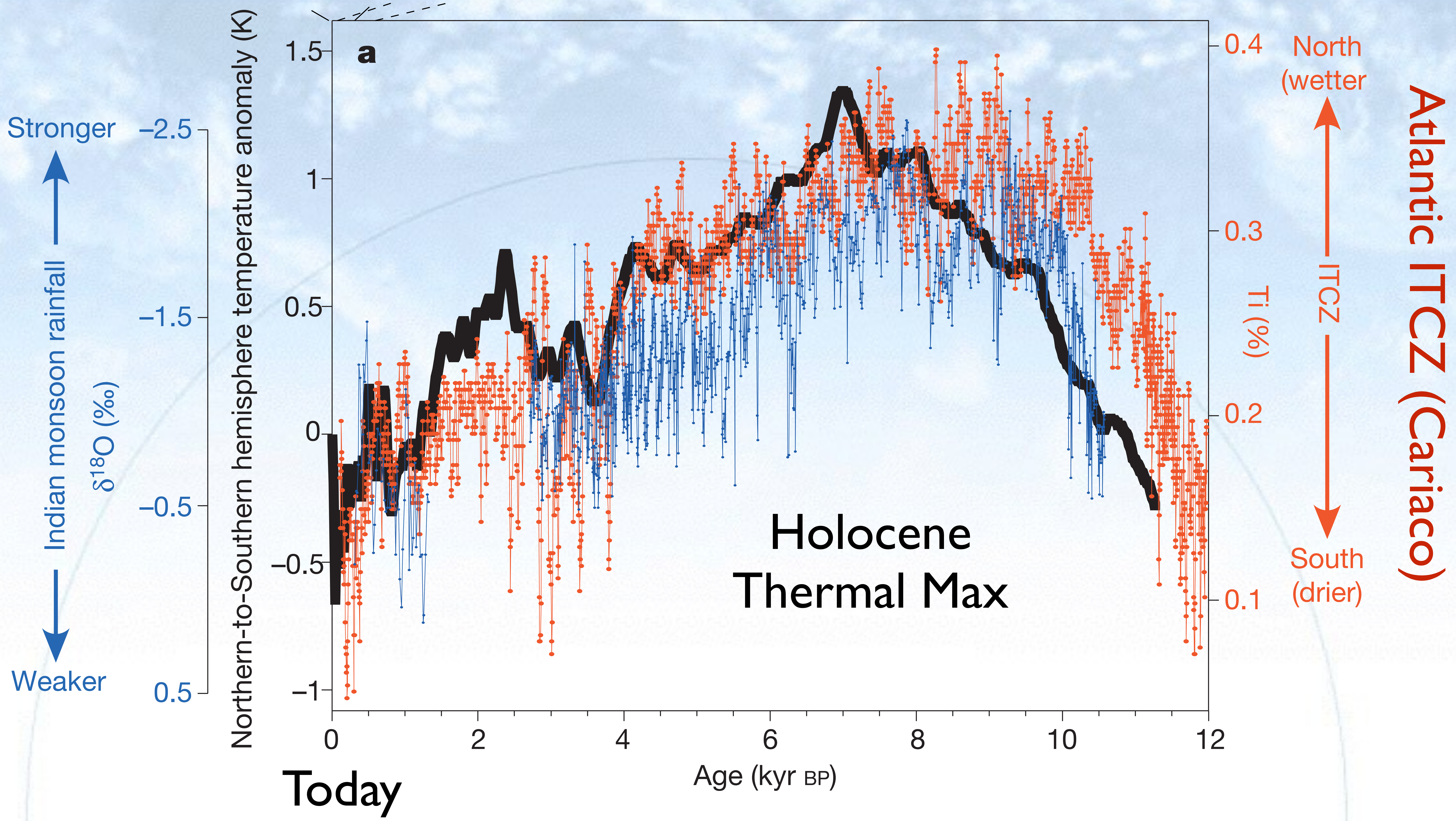
- Correlates with extratropical NH-SH temperature difference
- Variations linked to continental ITCZ migrations
- ITCZ migrations driven by variations in NH-SH temperature contrasts (caused by AMOC variations, aerosols, etc.)
- Same is true on timescales of 1000's of years: e.g., African Humid Period

# Precipitation (JJA)




*Data sources:* TRMM/TMPA, ERA-Interim

# Asian Monsoon and Atlantic ITCZ Over Holocene




Schneider et al., *Nature*, 2014; data from Haug et al. 2001; Fleitmann et al. 2003, Marcott et al. 2013

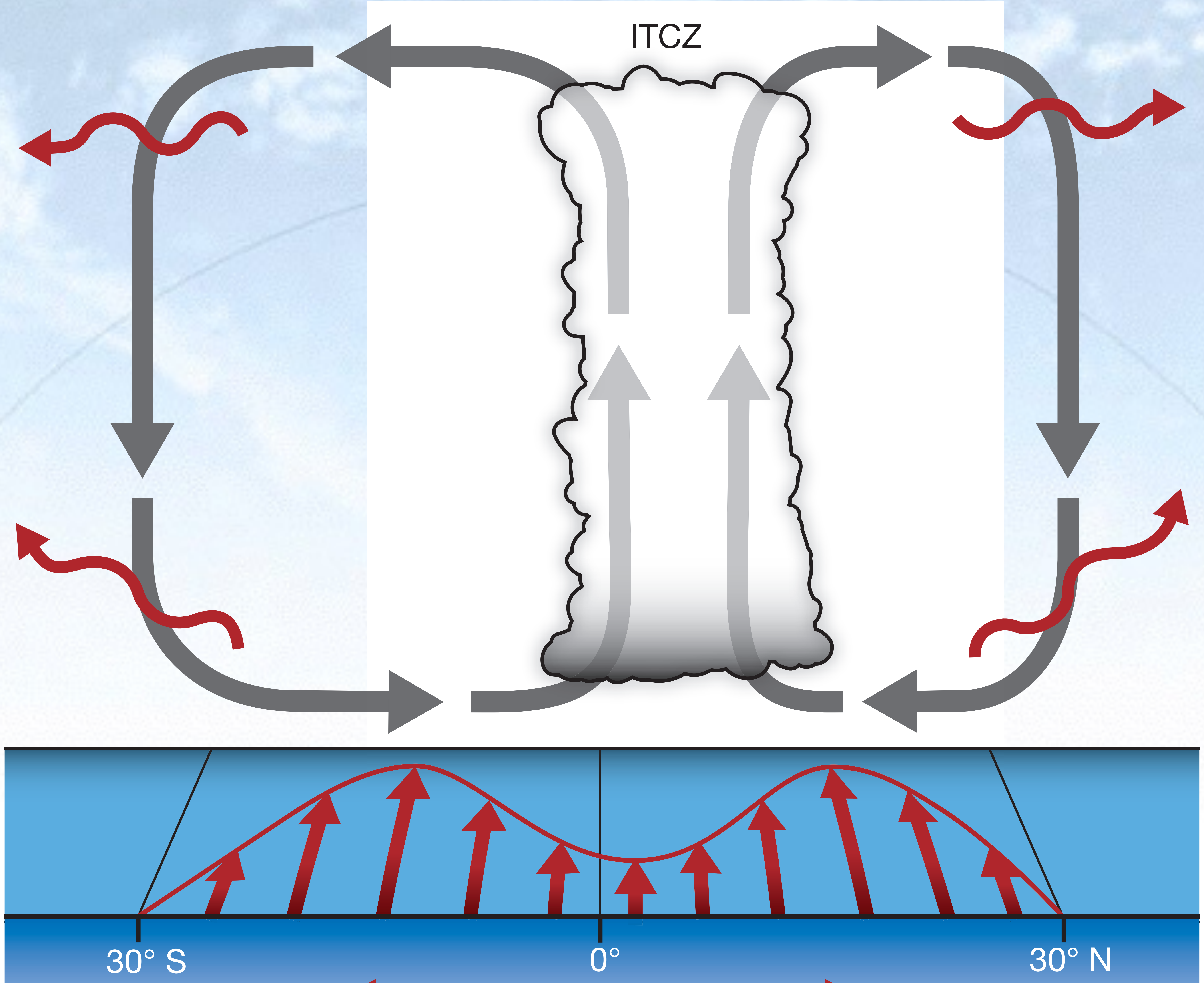
# ITCZ Migrations

- Generally toward warming hemisphere, on timescales from seasons to millennia

- Variations in monsoon strength also at least in part driven by ITCZ migrations (stronger monsoons when ITCZ farther north, Walker et al. 2015)

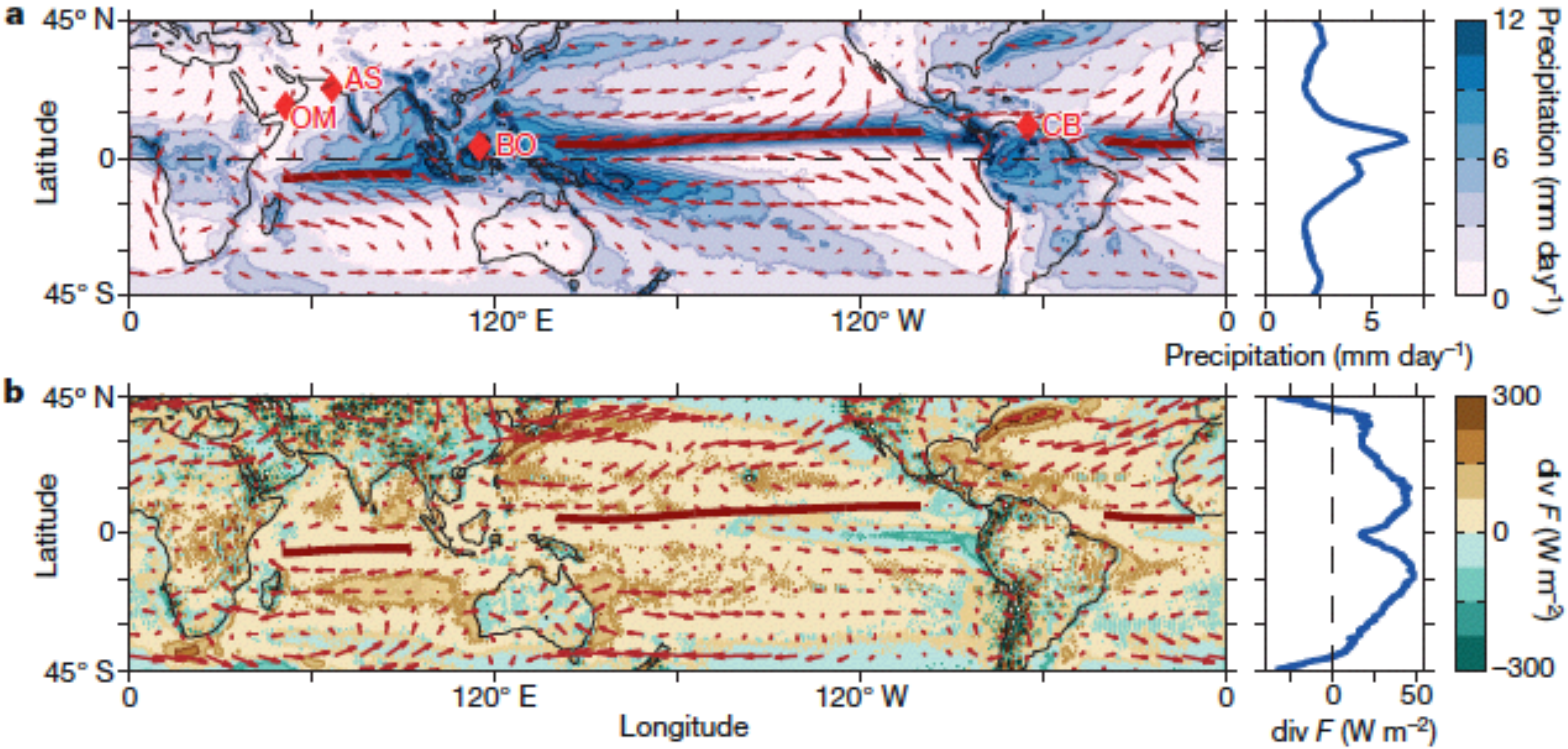
*What controls where ITCZ is located?*

# Energy Transport Generally Away From ITCZ



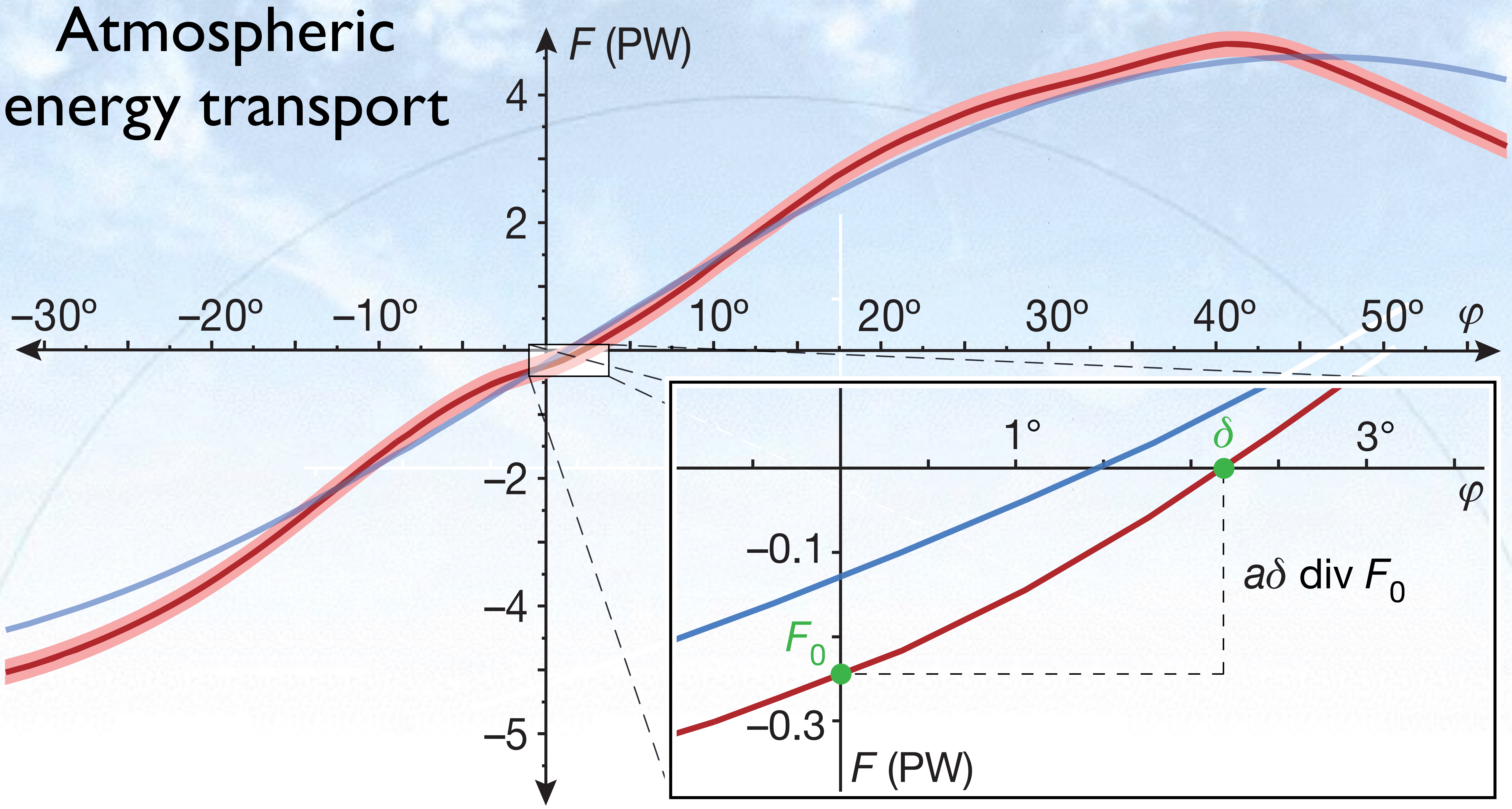

Schneider et al., *Nature*, 2014; based on ideas in Broccoli et al. 2006, Kang et al. 2009

# ITCZ and Atmospheric Energy Transport




Schneider et al., *Nature*, 2014

# ITCZ and "Energy Transport Equator"




Bischoff & Schneider, *J. Climate* 2014, Schneider et al., *Nature*, 2014; ideas from Kang et al. 2009

# Determine Energy Flux Equator

Atmospheric energy balance

$$\operatorname{div} F = S - L - O$$

connects flux divergence (LHS) to net energy input (RHS). Expand:

$$0 = F_\delta \approx F_0 + (\operatorname{div} F_0) a\delta$$

Latitude of energy flux equator:

$$\delta \approx -\frac{1}{a} \frac{F_0}{S_0 - L_0 - O_0}$$

Bischoff & Schneider, *J. Climate* 2014

# Latitude of Energy Flux Equator

$$\delta \approx -\frac{1}{a}\frac{F_0}{S_0 - L_0 - O_0}$$

Depends to first order on:

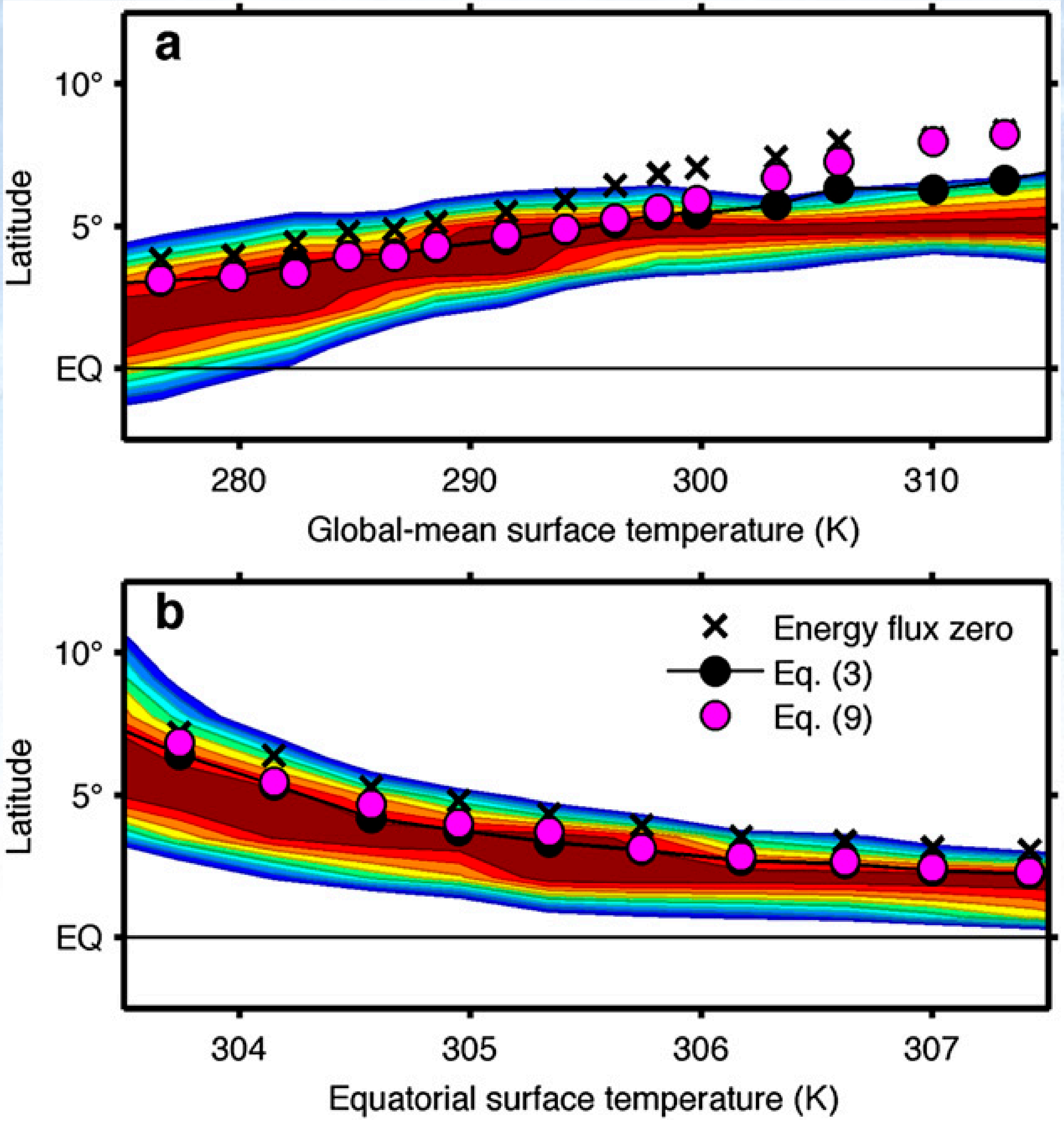
1. Cross-equatorial energy flux $F_0$: ~0.3 PW
2. Net equatorial energy input $S_0 - L_0 - O_0$: ~15 W m$^{-2}$ (*small residual!*)

$F_0$ dependence pointed out by Broccoli et al. 2006, Kang et al. 2009, and others.

Energy input dependence not previously examined.

Bischoff & Schneider, *J. Climate* 2014

# Test in Aquaplanet GCM

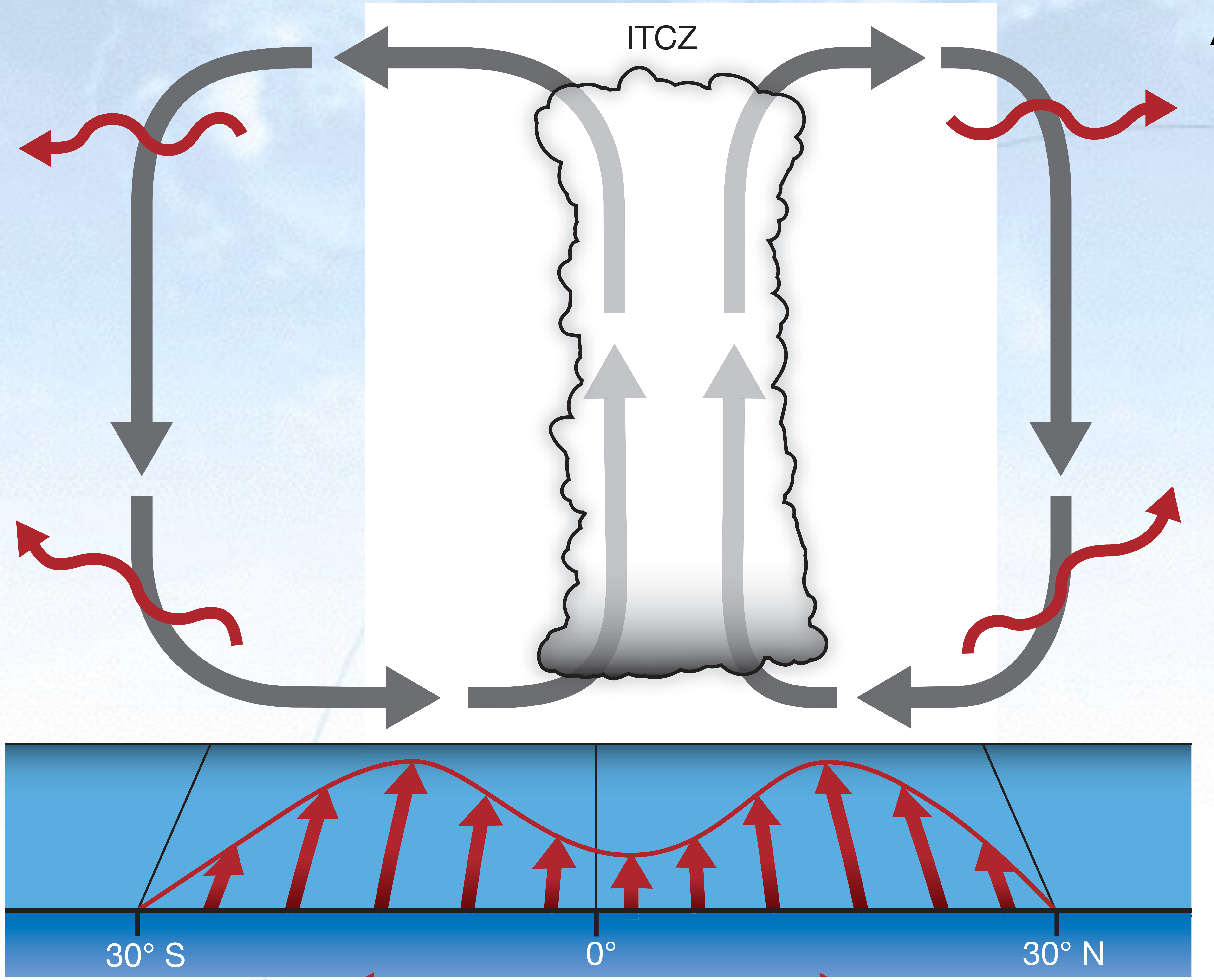



Global warming

Tropical warming ("ENSO")

Bischoff & Schneider, *J. Climate* 2014

# ITCZ Sensitive to Energy Export out of Tropics




Asymmetric eddy energy export
(~4 PW at 30°N/S)

$$F_0 = \{\langle\overline{v'h'}\rangle\}_S^N - \left\{\int_0^y (S - L - O)\, dy\right\}_S^N$$

Asymmetric
tropical energy input

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

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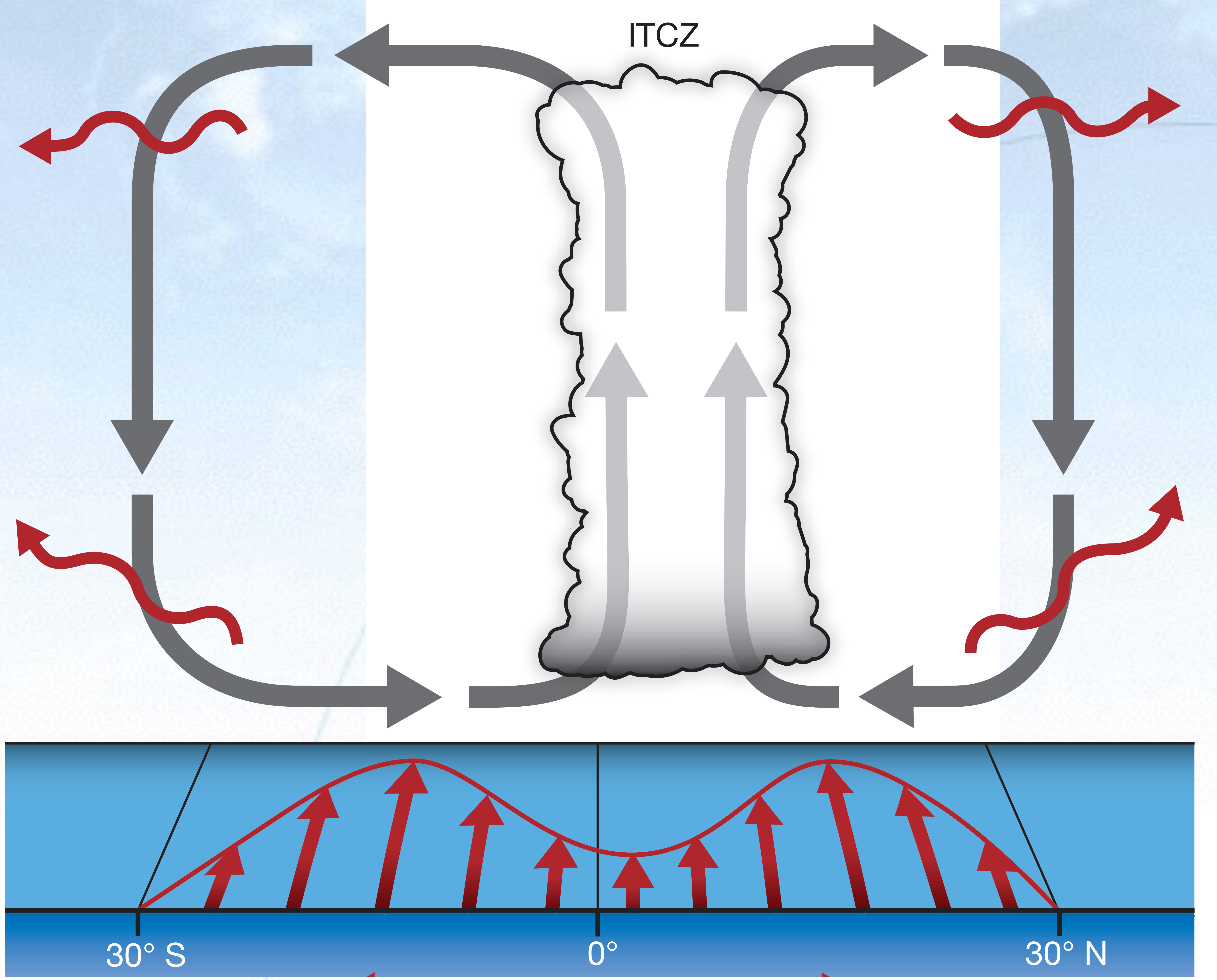


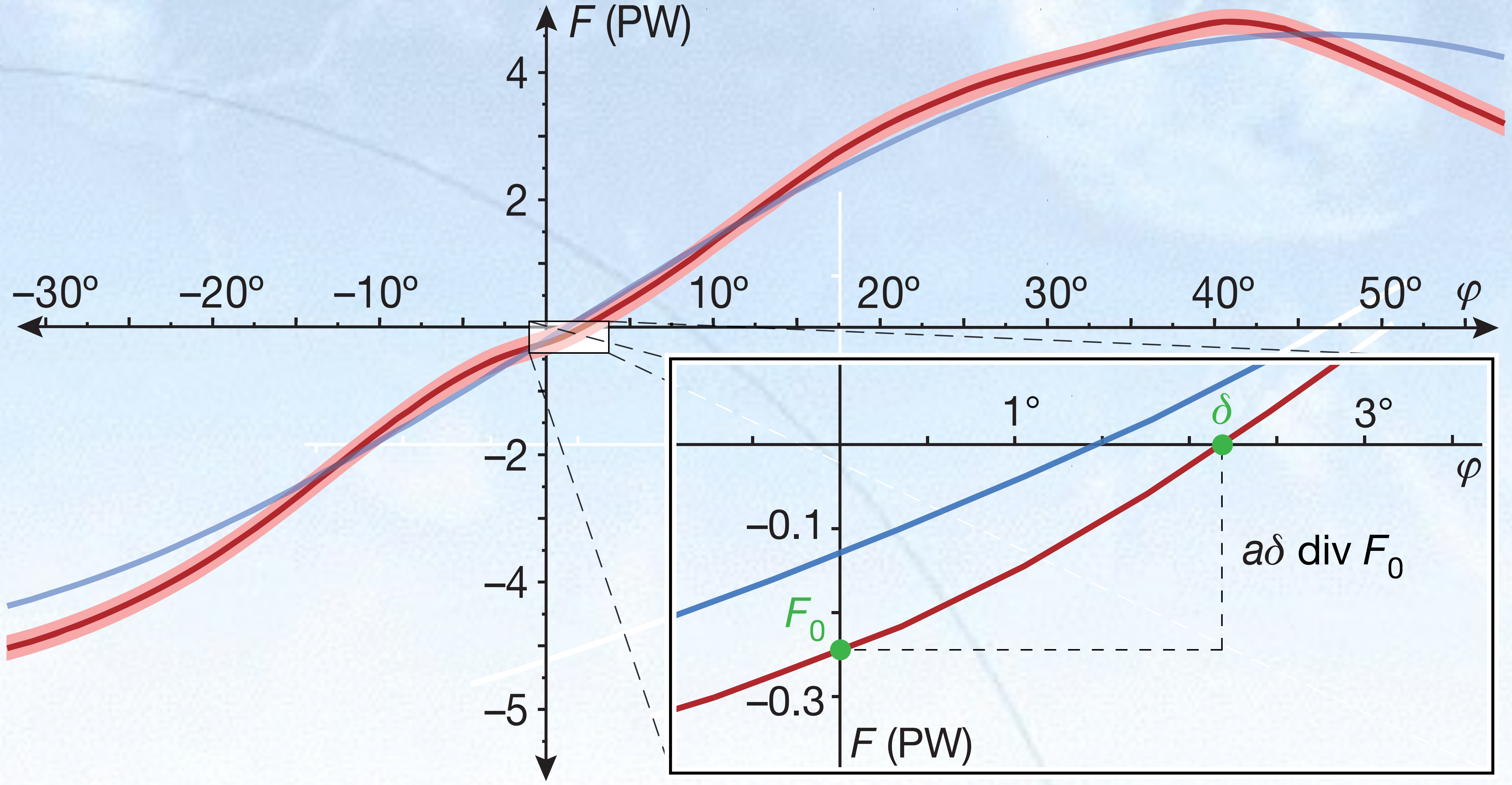


Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

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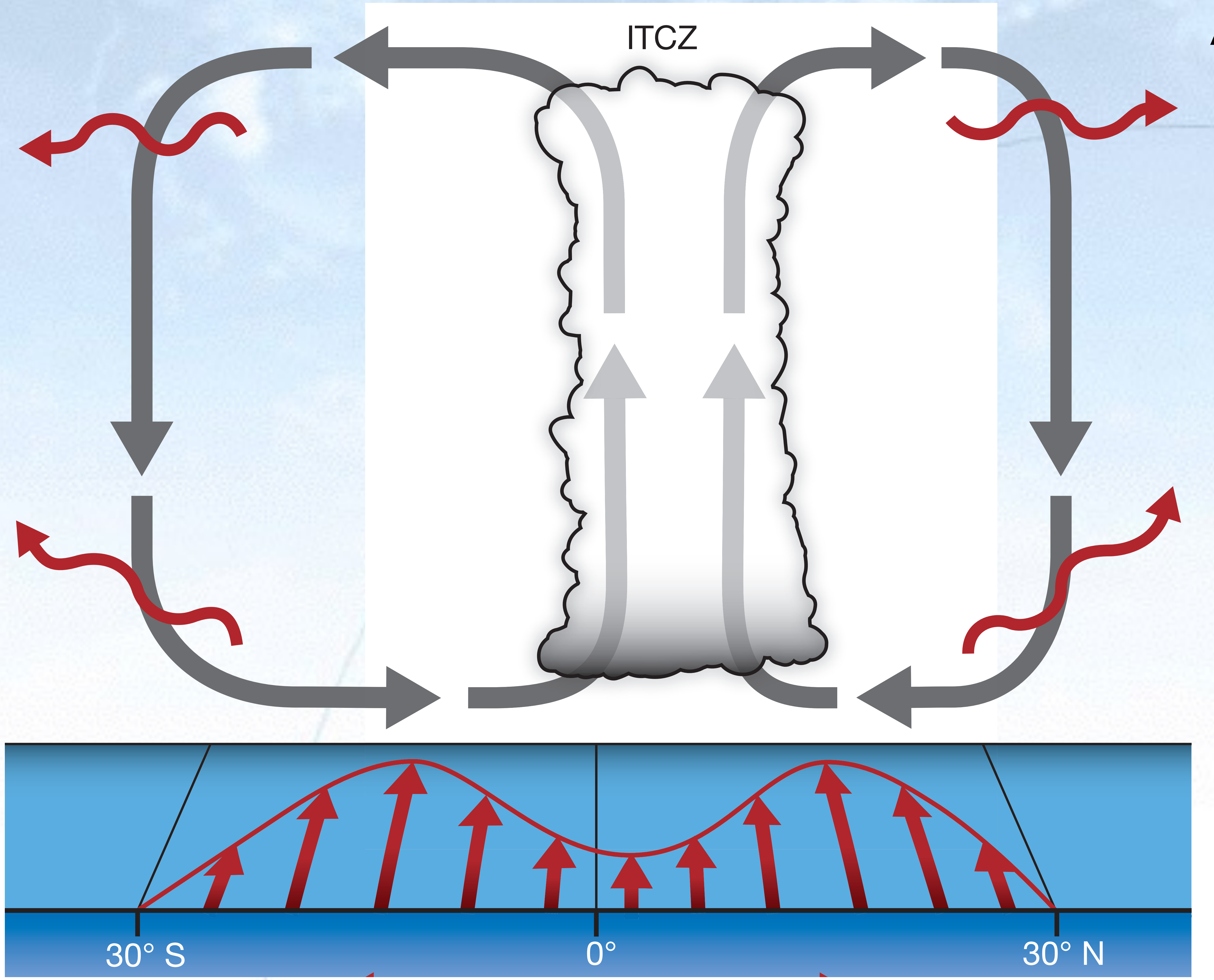


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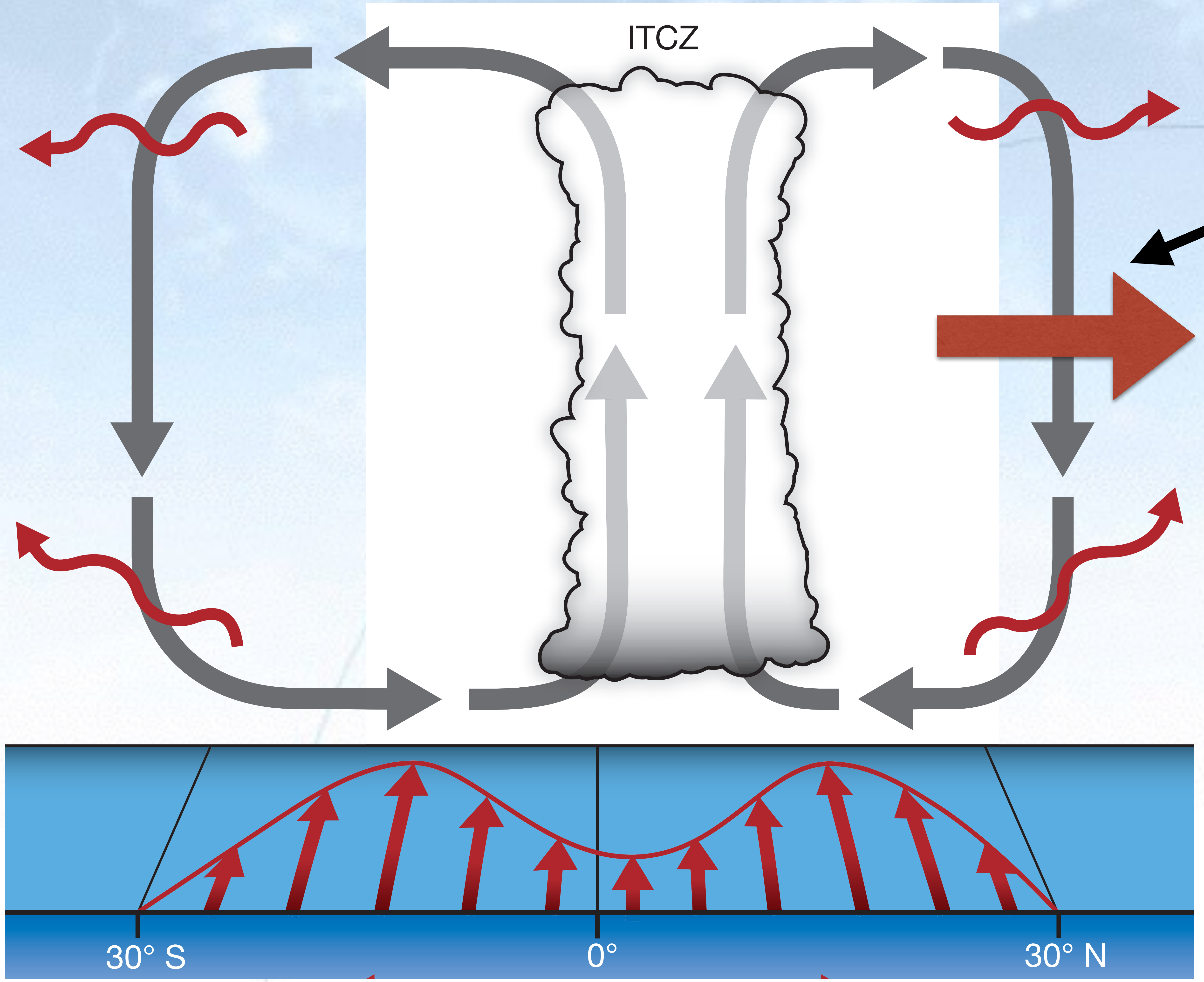
# Perturbation to Energy Export at 30°N




Increased at 30°N

$$\Delta F_0 = \{\langle \Delta \overline{v'h'} \rangle\}_S^N - \left\{ \int_0^y (\Delta S - \Delta L - \Delta O)\, dy \right\}_S^N$$

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

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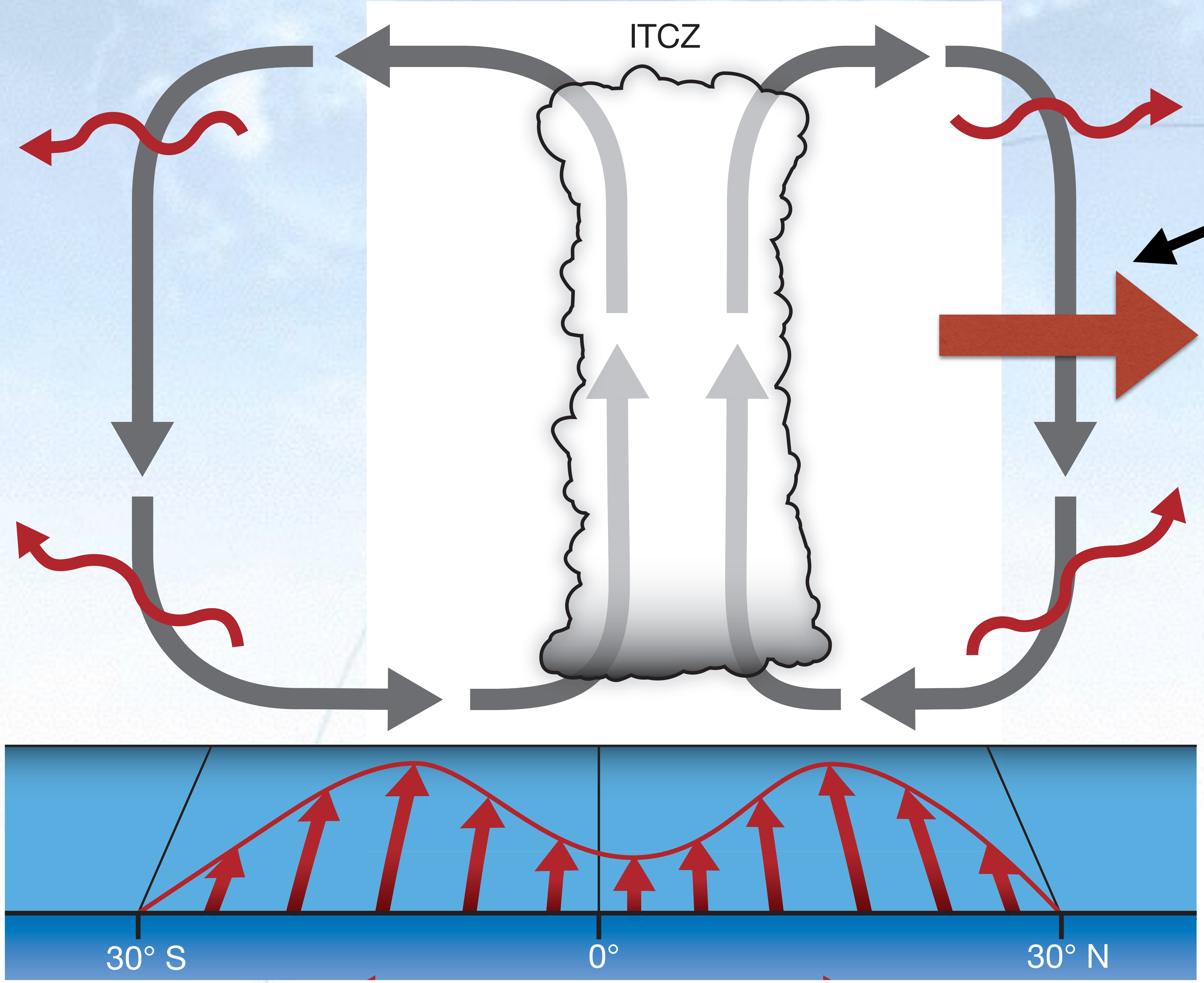


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Thermal response
(+ cloud feedback)

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

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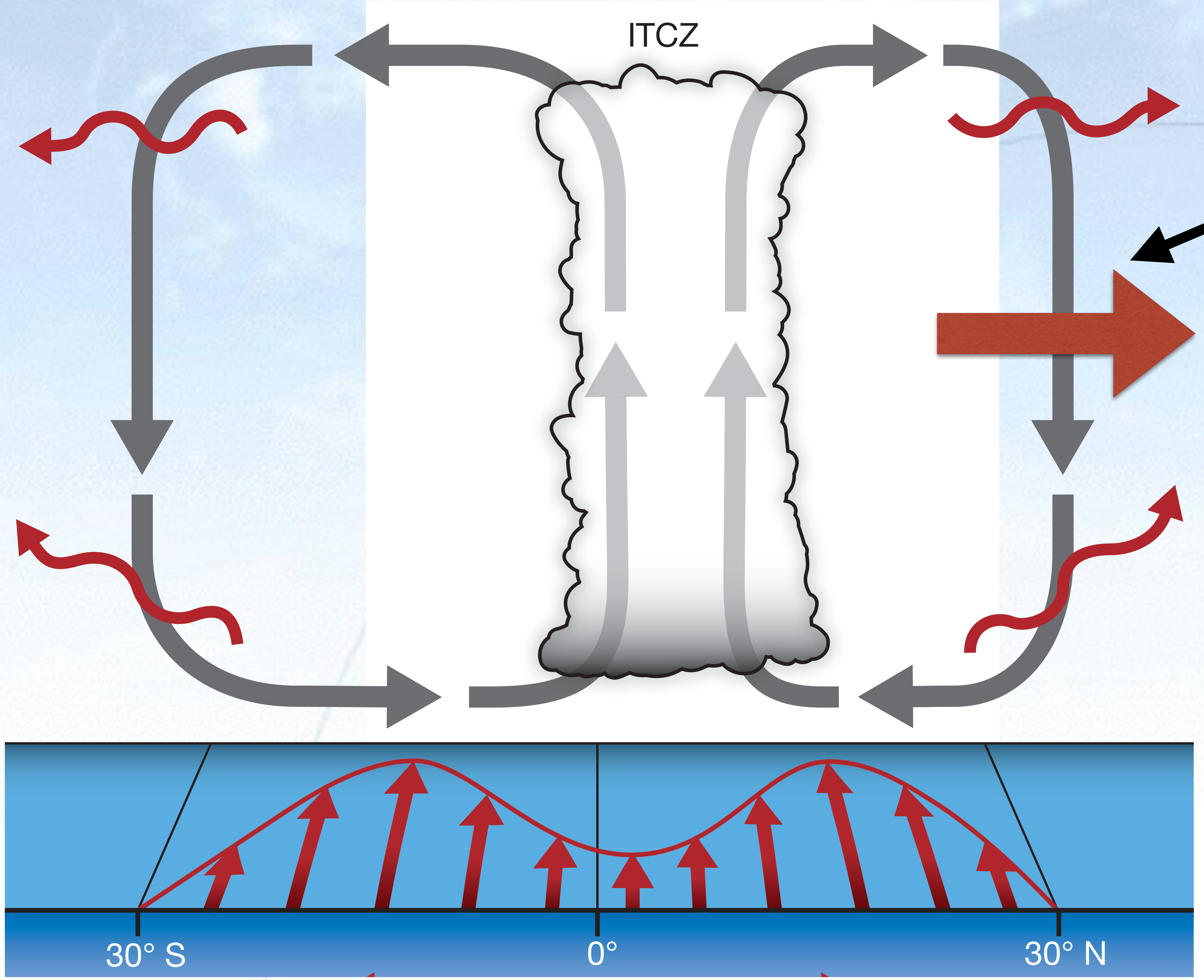


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Cloud feedbacks
(*S-L* net likely weak)

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

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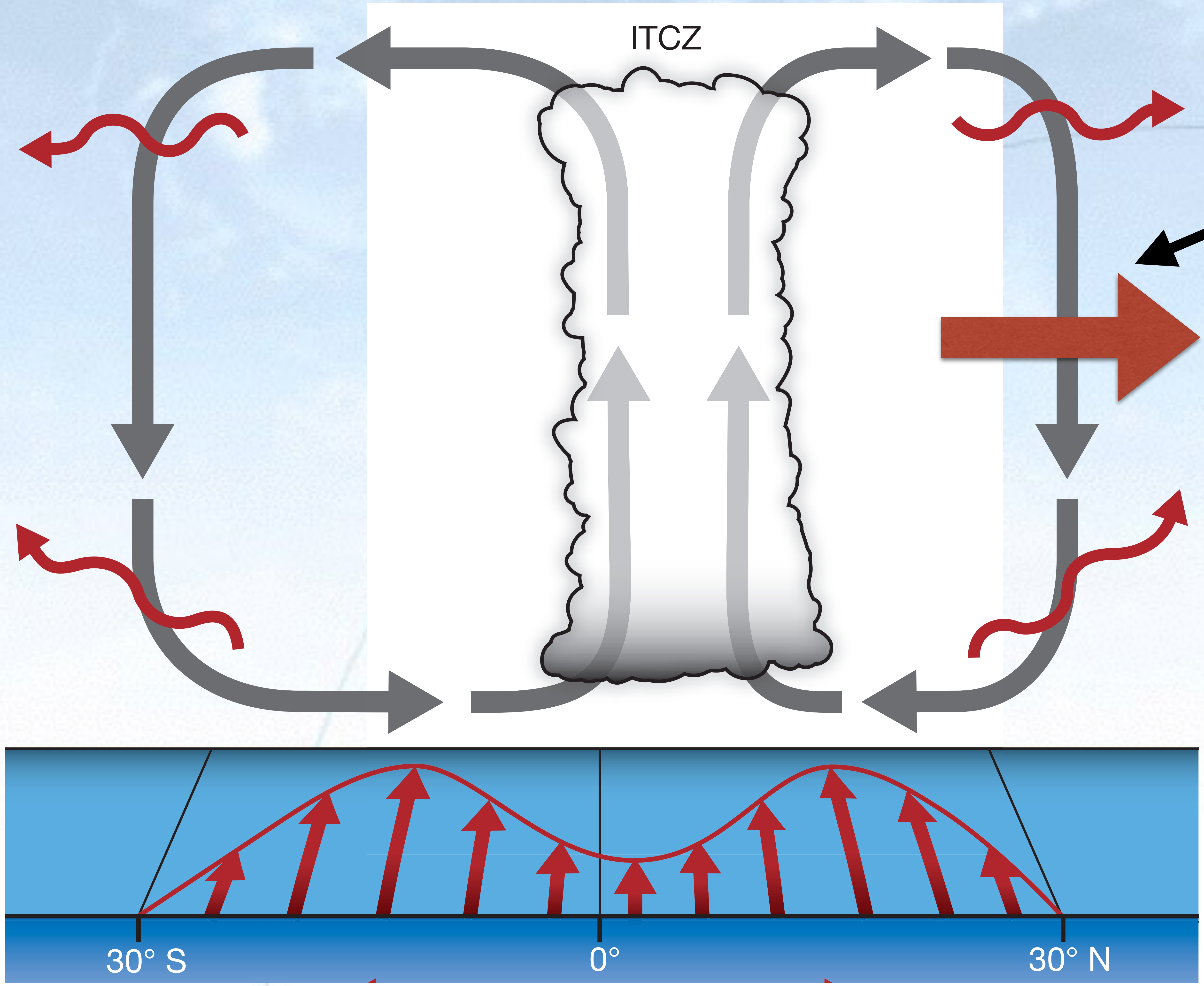


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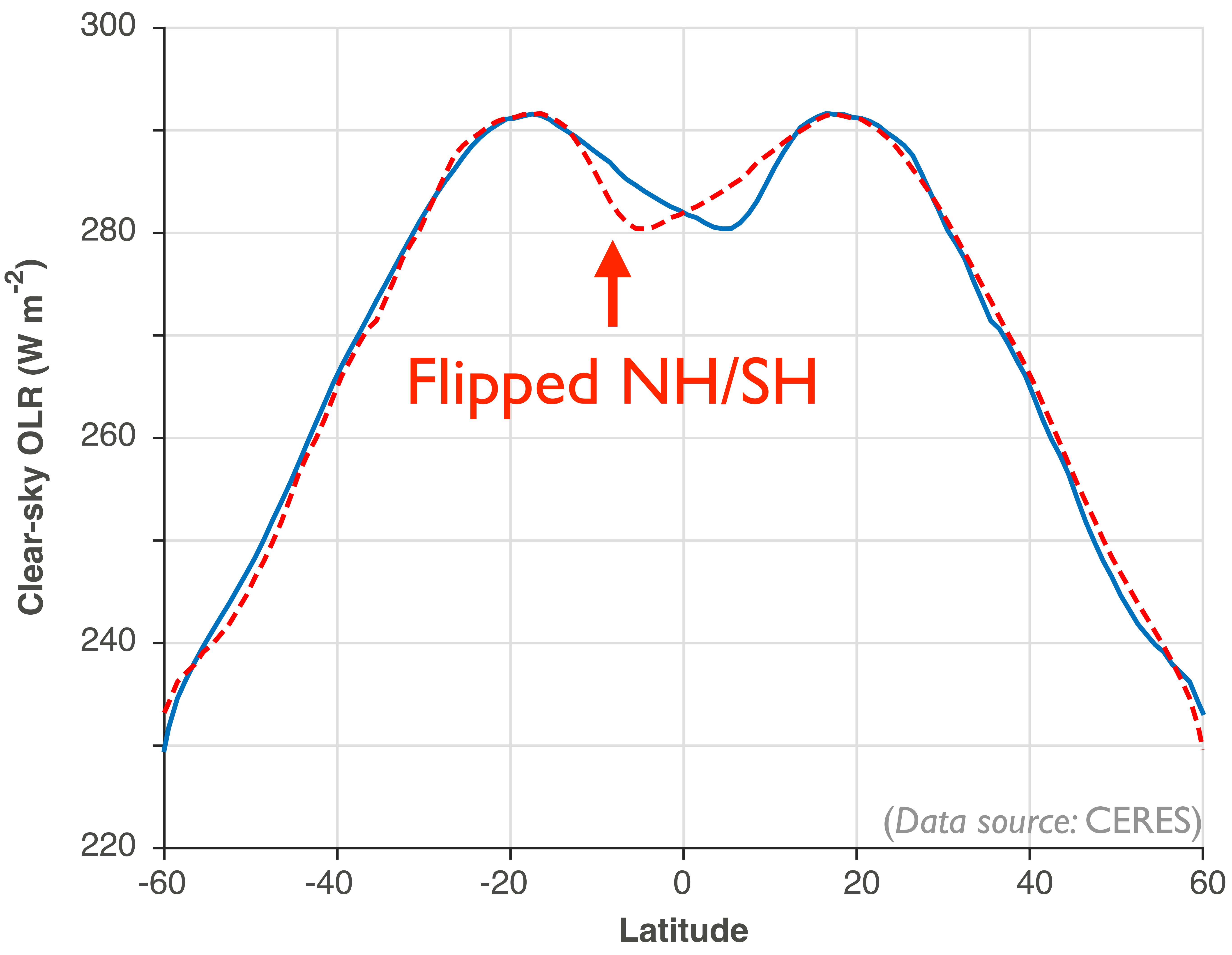
$$\Delta F_0 = \{\langle \Delta \overline{v'h'} \rangle\}_S^N - \left\{ \int_0^y (\Delta S - \Delta L - \Delta O)\, dy \right\}_S^N$$

Ocean feedbacks (damping)

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

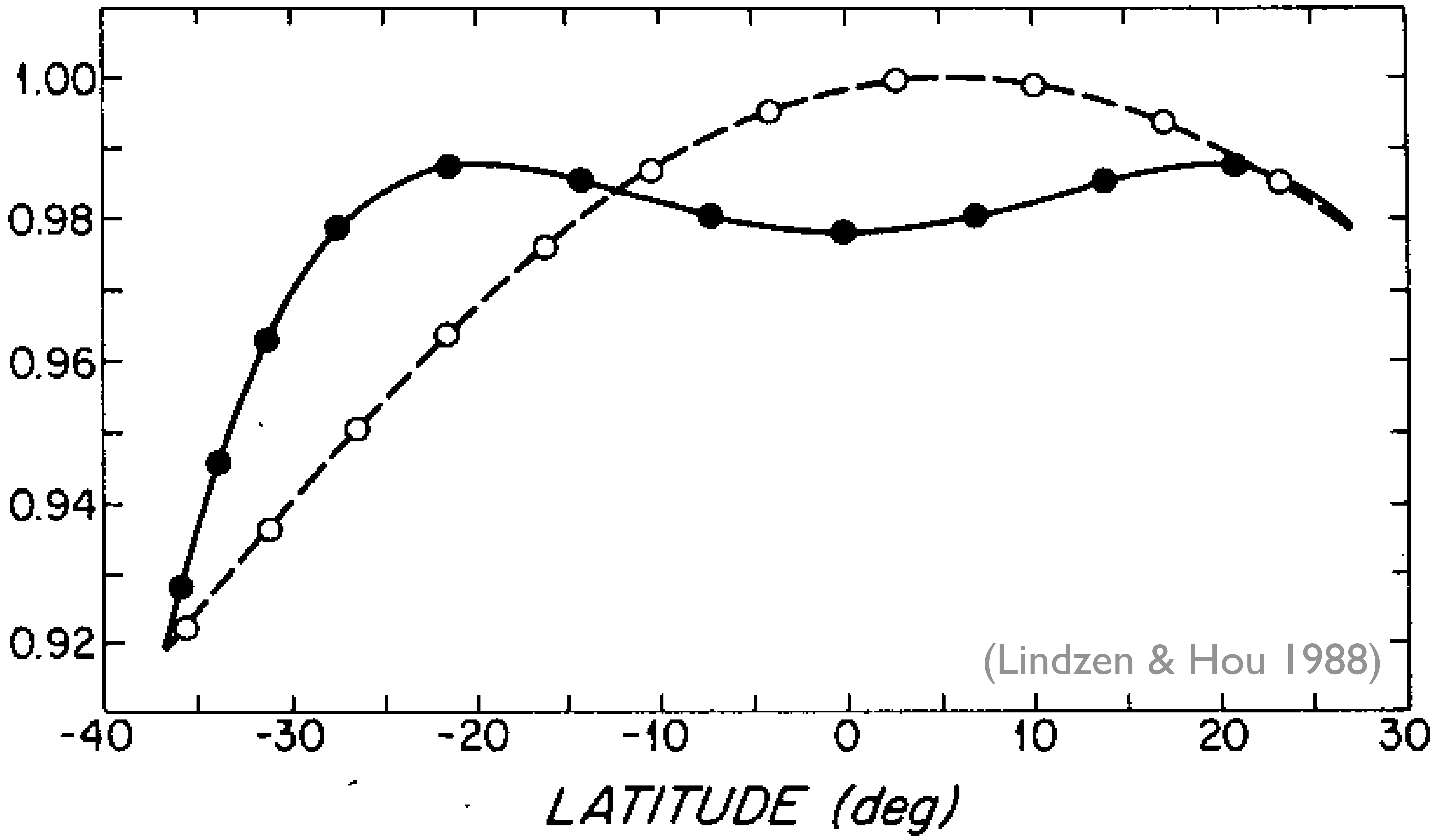
# Longwave Response




- Clear-sky OLR fairly symmetric about equator
- Dynamically constrained in tropics
- OLR response to extratropical perturbation approximately symmetric (up to cloud feedbacks)

# Longwave Response

Tropical temperatures for ideal solstitial Hadley cell

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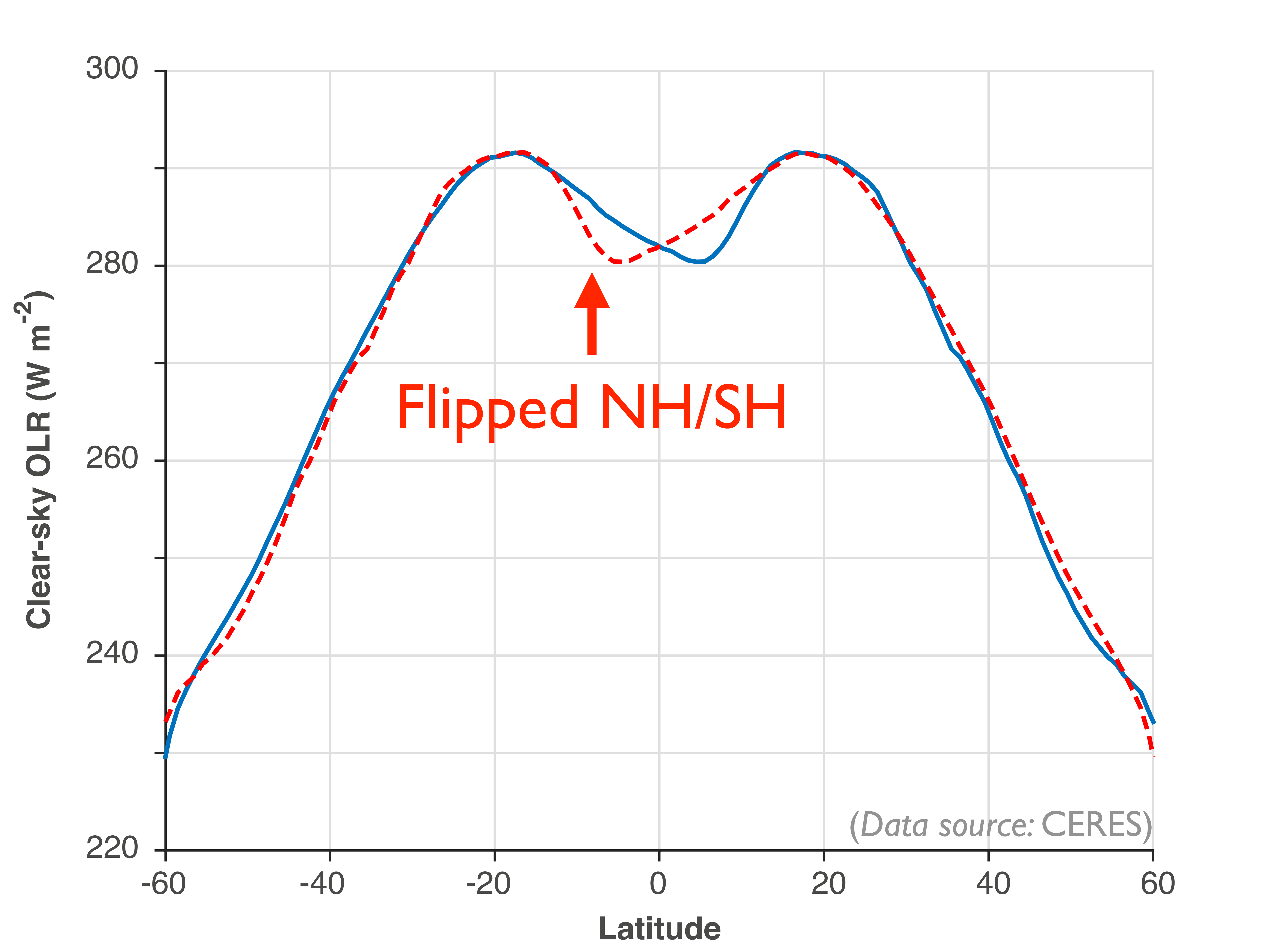
# Longwave Response

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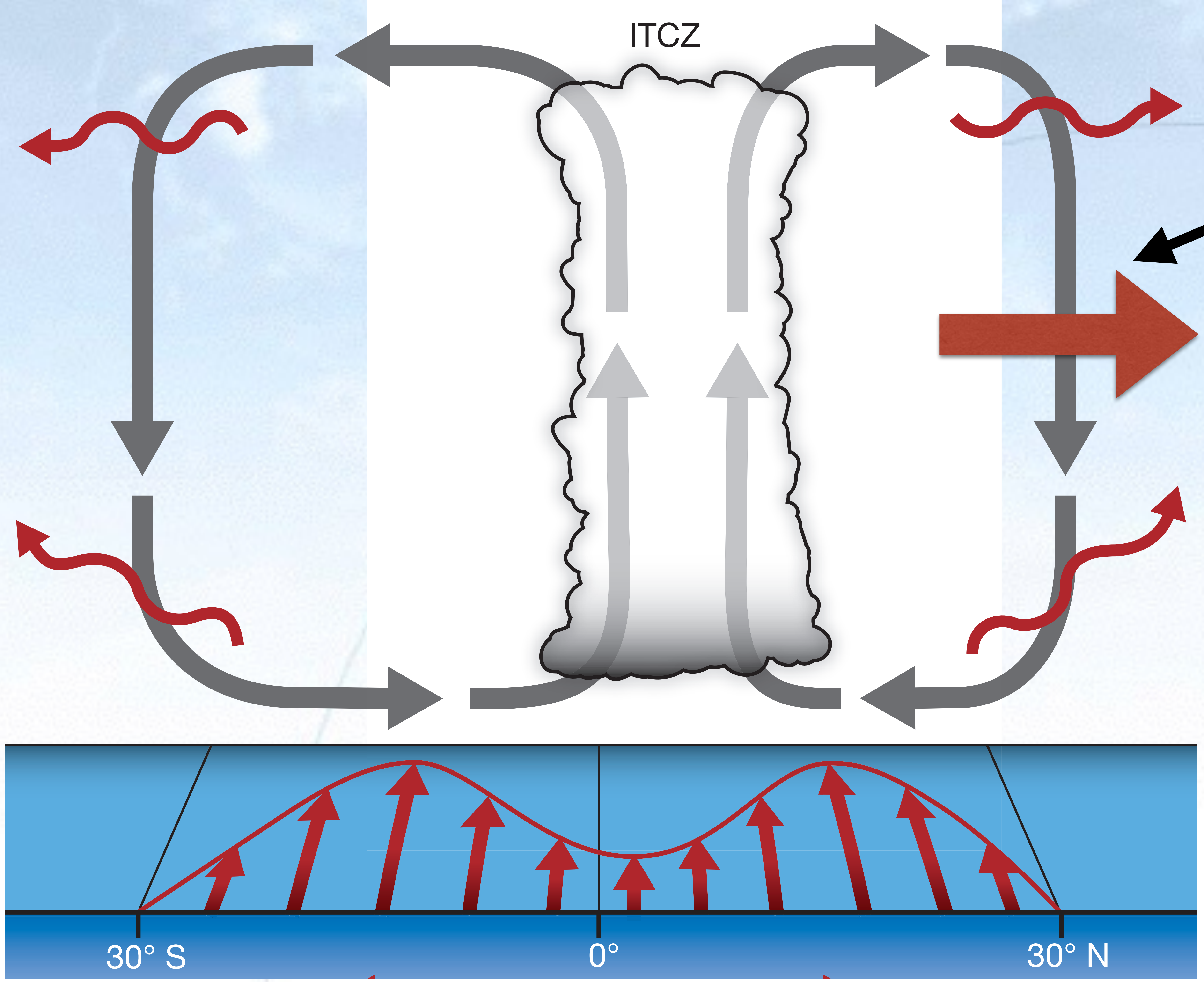



Increased at 30°N

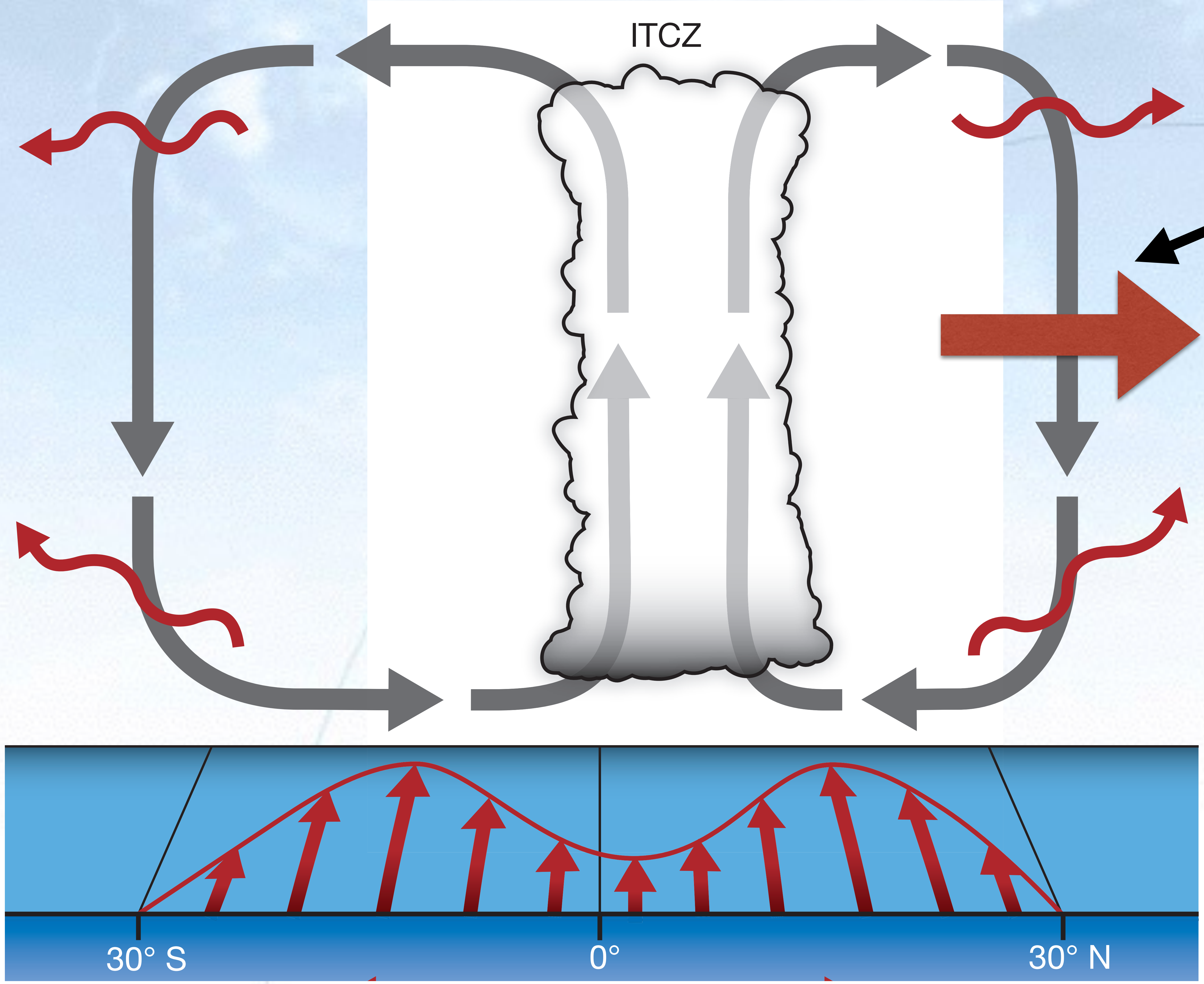
$$\Delta F_0 = \{\langle \Delta \overline{v'h'} \rangle\}_S^N - \left\{ \int_0^y (\Delta S - \Delta L - \Delta O)\, dy \right\}_S^N$$

Thermal response

Symmetric
(up to cloud feedbacks)

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

# Perturbation to Energy Export at 30°N



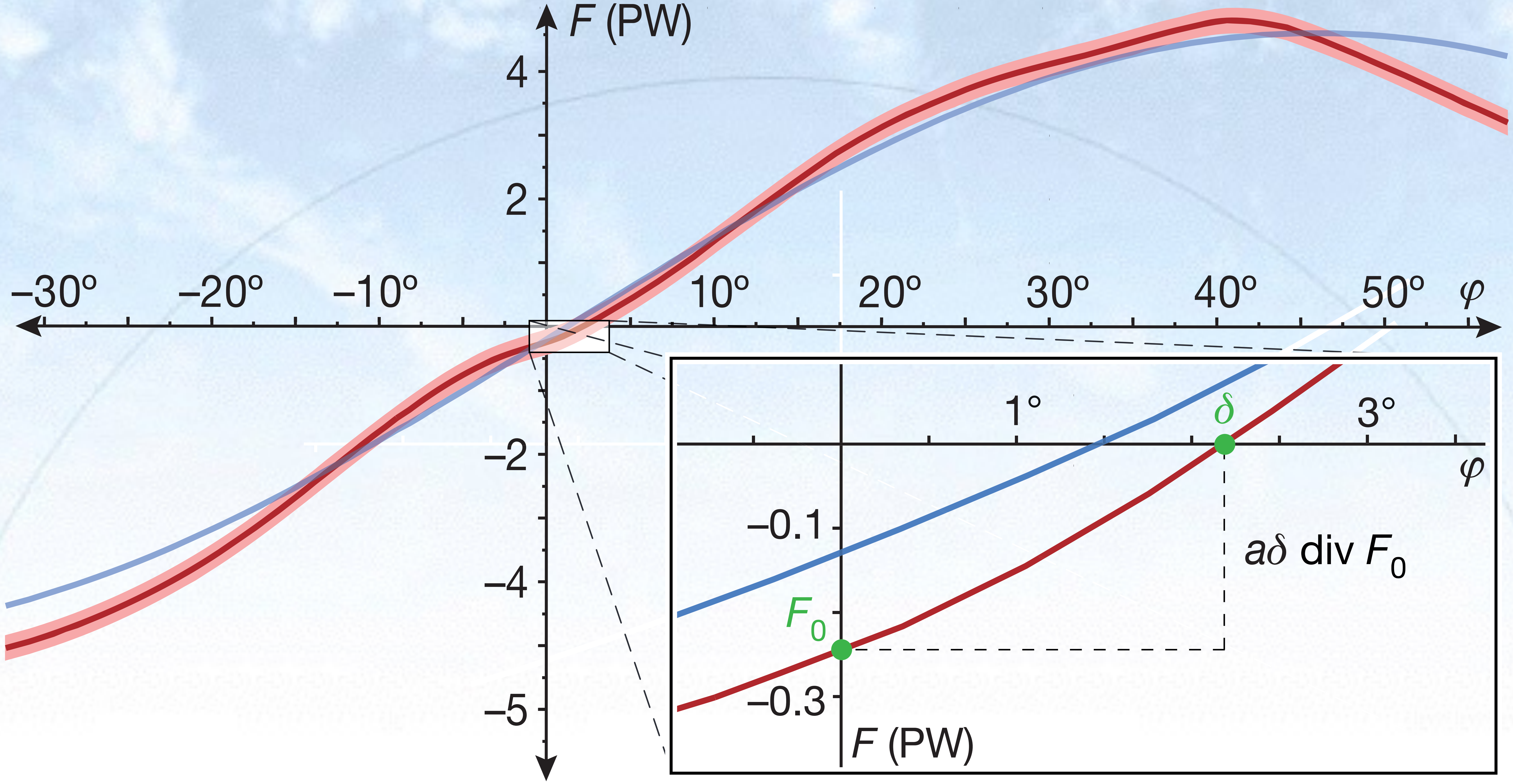

Increased at 30°N

$$\Delta F_0 = \{\langle \Delta \overline{v'h'} \rangle\}_S^N - \left\{ \int_0^y (\Delta S - \Delta L - \Delta O)\, dy \right\}_S^N$$

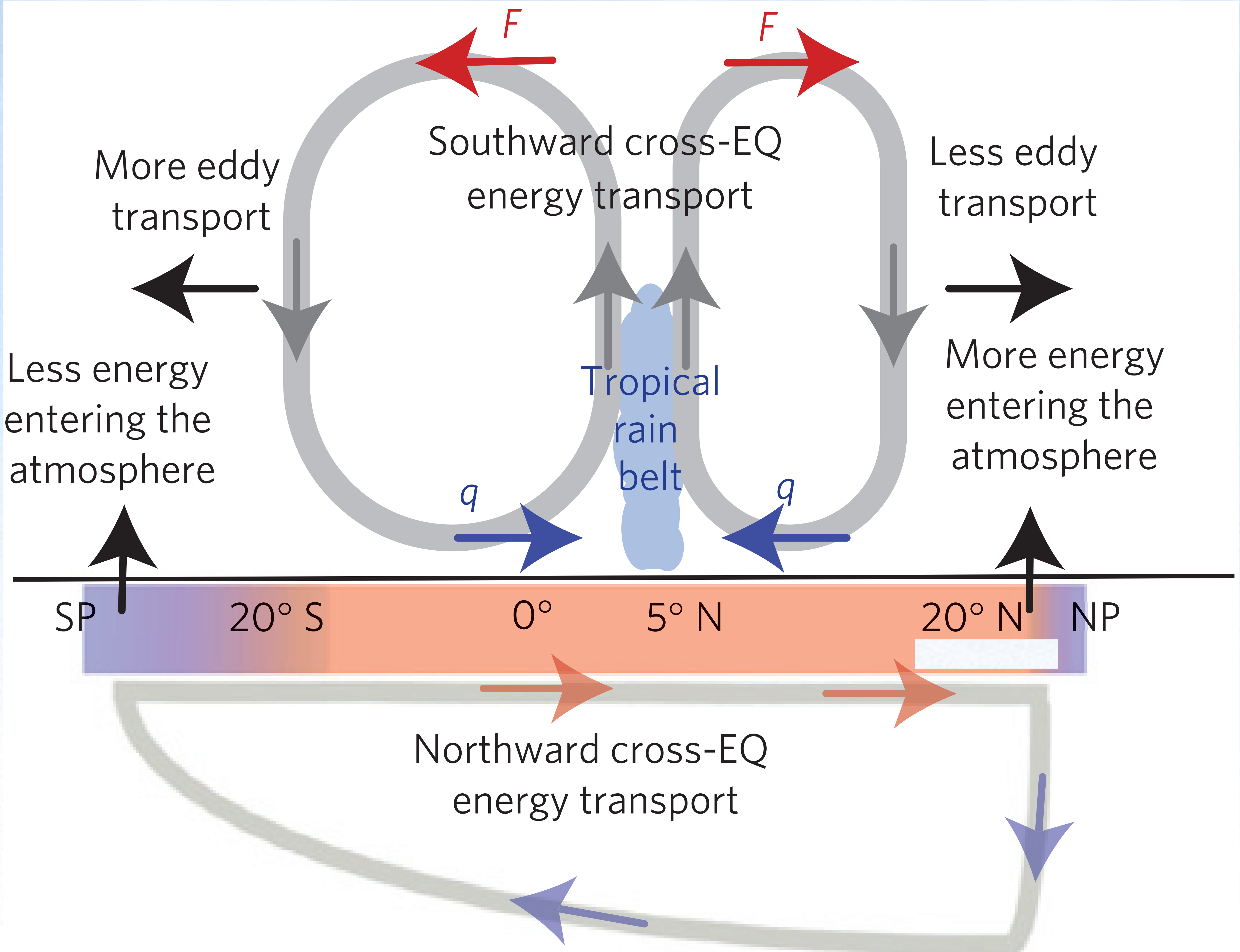
*Hemispherically asymmetric energy flux perturbation at edge of tropics generally drives cross-equatorial energy flux; hence ITCZ shift*

Bischoff & Schneider, *J. Climate*, 2014; Schneider et al. 2014, *Nature*, 2014

# Result is Southward ITCZ Migration



# Such ITCZ Shifts Seen in Observations and Simulations

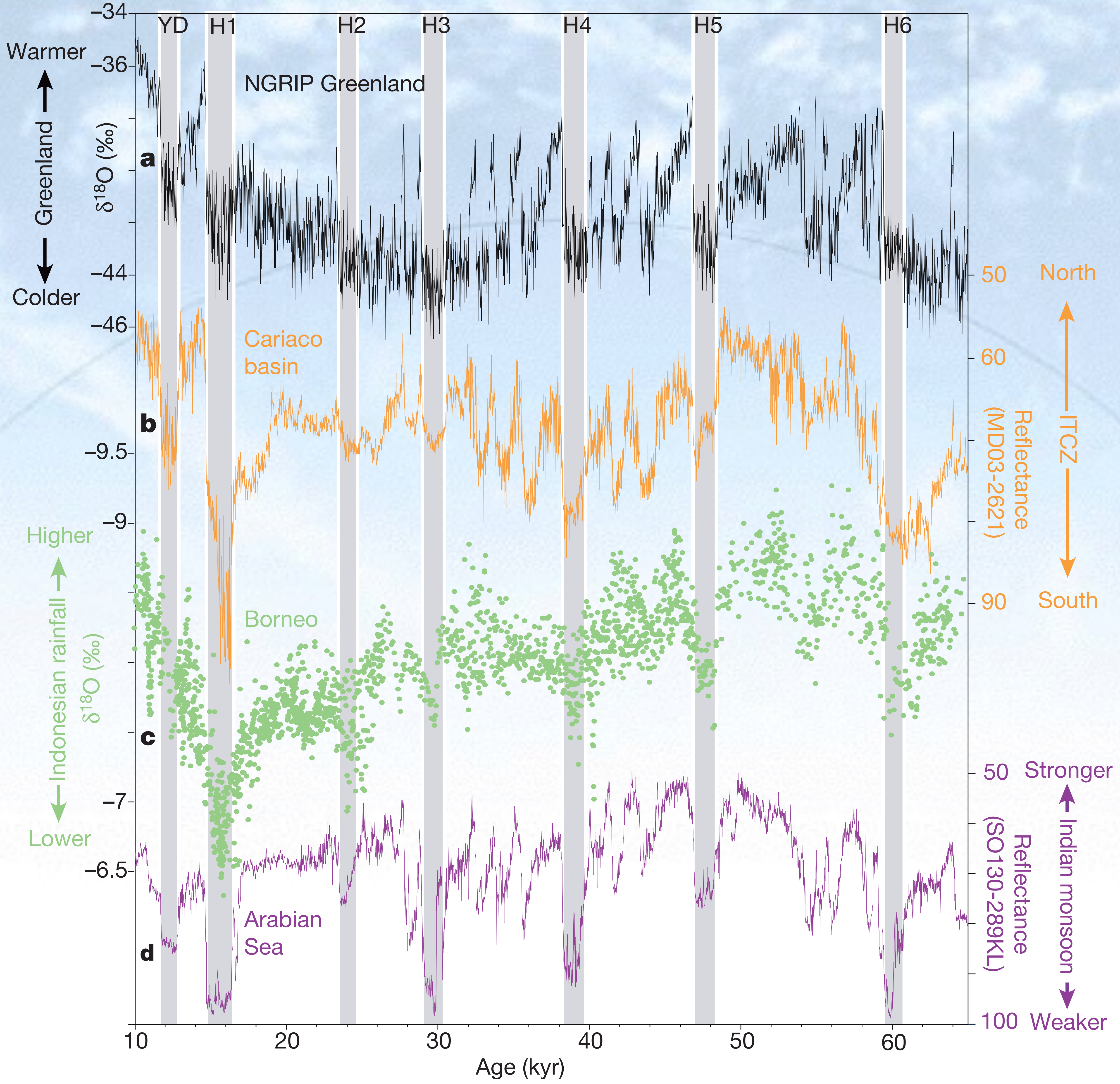



(Frierson et al. 2013)

- Accounts for mean ITCZ in NH because NH warmer (Marshall et al. 2013, Frierson et al. 2013)
- Accounts for southward ITCZ shift when NH cools (e.g., Heinrich events) with energy flux closure
- May account for some monsoon variations

(Many papers on this: Chiang & Bitz 2005; Broccoli et al. 2006; Kang et al. 2009; **Chiang & Friedman 2012 [review]**; Donohoe et al. 2013)

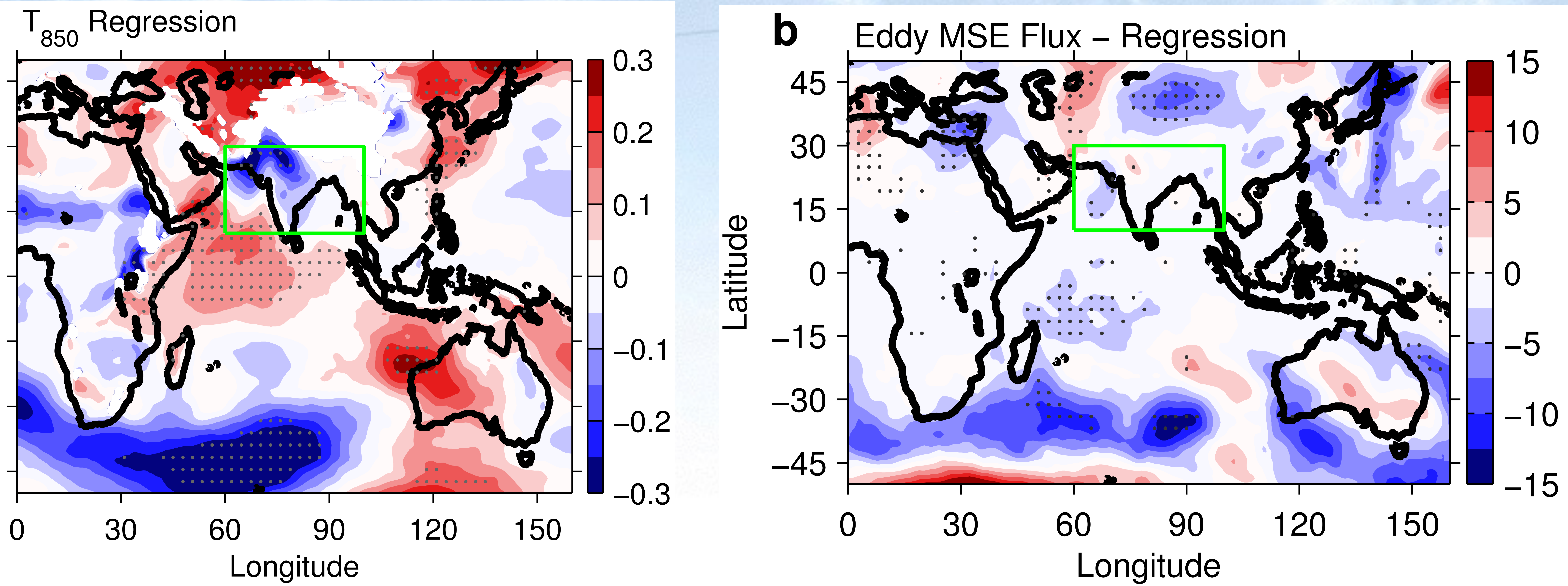
# For Example: Last Ice Age




Schneider et al. *Nature*, 2014; based on data from Bond et al. 1993; Deplazes et al. 2013; Carolin et al. 2013; Fleitmann et al. 2007

# For Example: Interannual Monsoon Variations

Regressions on Moisture Flux Convergence in SA Monsoon Region




Walker, Bordoni & Schneider, *J. Climate*, in press

# What We Think We Understand About The ITCZ

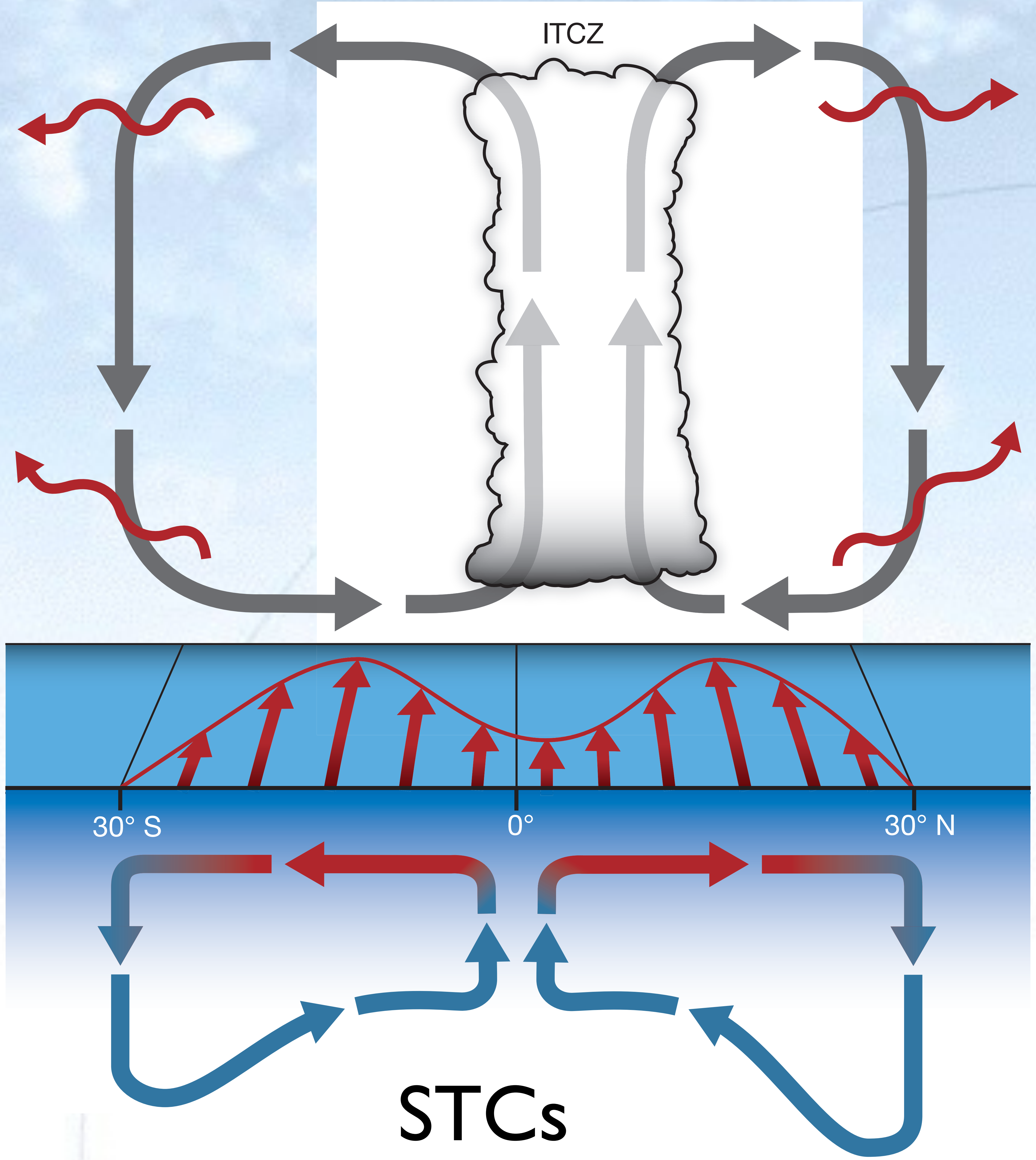
- Position depends on equatorial net energy input $S_0 - L_0 - O_0$ and cross-equatorial energy flux $F_0$

- Position linked to extratropical eddy energy fluxes through $F_0$ because tropical temperatures are "stiff" with respect to perturbations (need to stay nearly symmetric)

- Sensitive to small energetic perturbations because $S_0 - L_0 - O_0 \approx 15$ W m$^{-2}$ is small residual of large terms (~100 W m$^{-2}$), and so is $F_0 \approx 0.3$ PW (residual of ~4 PW energy exports into N and S extratropics)

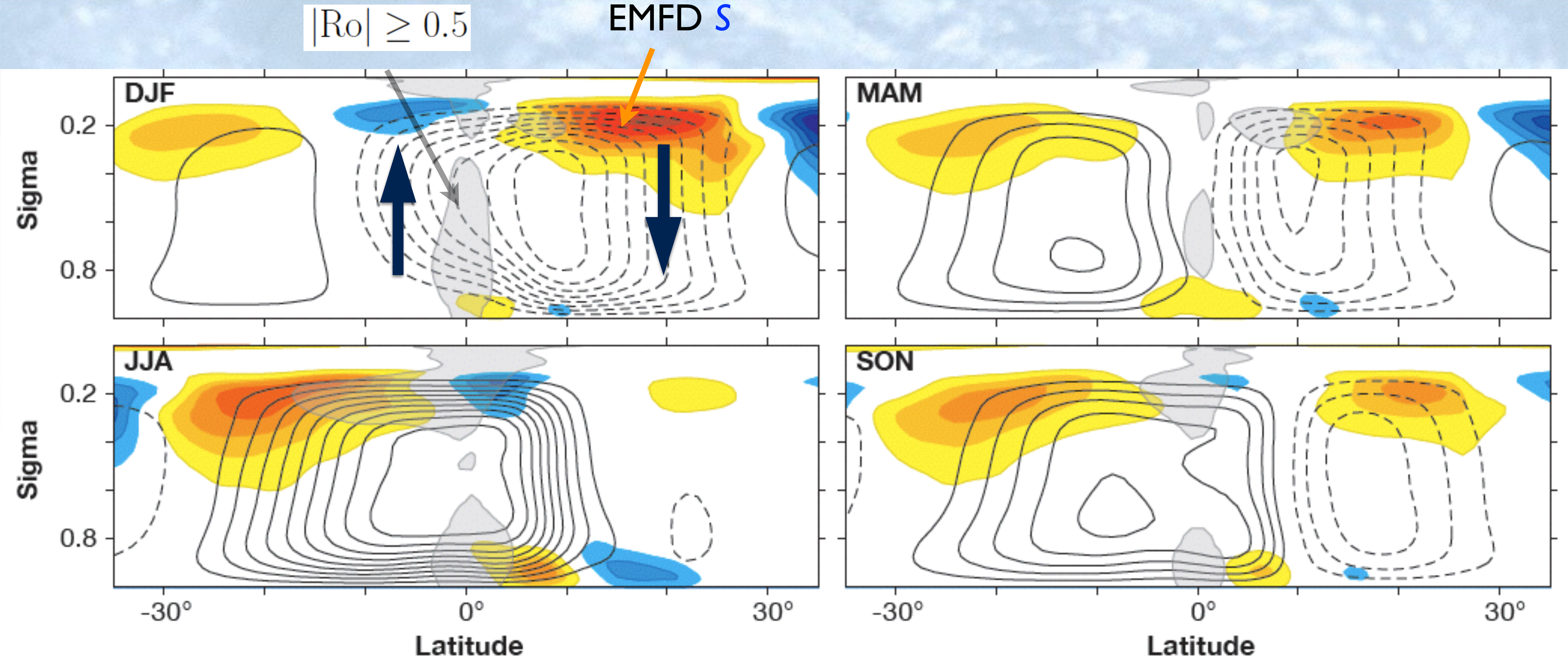
*There's more (Toby this afternoon)!*

# Open Questions




- How does angular momentum balance (Hadley circulation) enter? (E.g., controls $S_0 - L_0 - O_0$)
- Ocean feedbacks? Likely damping because of Ekman transport in subtropical cells.
- Cloud feedbacks? Sign unclear (e.g., Voigt et al. 2014).

# Why Does Subsiding Branch Move So Little?



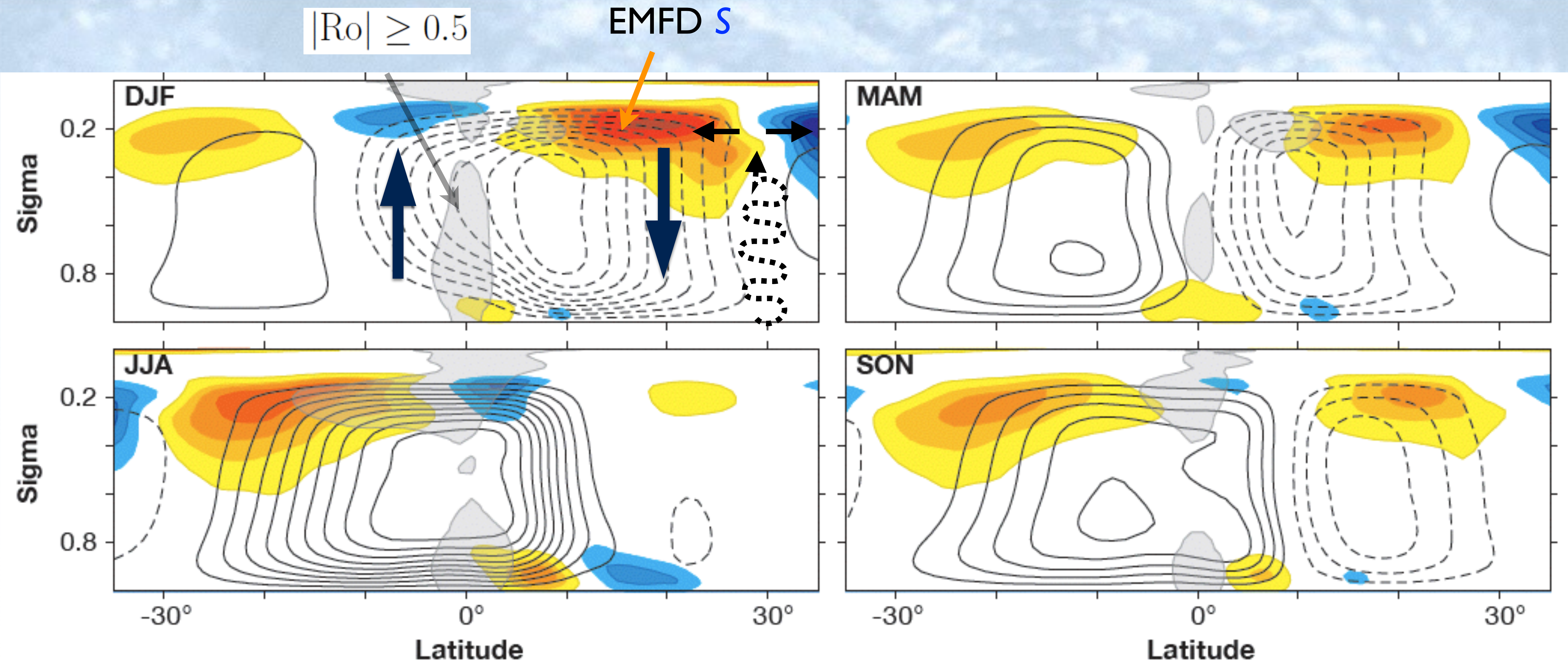

Angular (or zonal) momentum balance:

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

Eddy driven if Ro≪1

Schneider, *Ann. Rev. Geophys.*, 2006; Schneider, O'Gorman & Levine *Rev. Geophys.*, 2010

# Why Does Subsiding Branch Move So Little?




Angular (or zonal) momentum balance:

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

Eddy driven if $\mathrm{Ro} \ll 1$

Schneider, *Ann. Rev. Geophys.*, 2006; Schneider, O'Gorman & Levine *Rev. Geophys.*, 2010

# Termination of Hadley Cells

- HC terminates where EMFD in upper troposphere changes sign
- This is where baroclinic wave activity flux becomes deep enough to reach UT (Korty & Schneider 2008)
- Measure of depth of baroclinic wave activity flux

$$S_c = -\frac{f}{\beta}\frac{\partial_y \bar{\theta}_s}{\Delta_v} \sim \frac{\bar{p}_s - \bar{p}_e}{\bar{p}_s - \bar{p}_t} \lesssim 1$$

with effective bulk stability $\Delta_v$

Held 1978; Schneider and Walker 2006; O'Gorman 2011; Levine & Schneider, submitted

# Why Is HC Width So Insensitive?

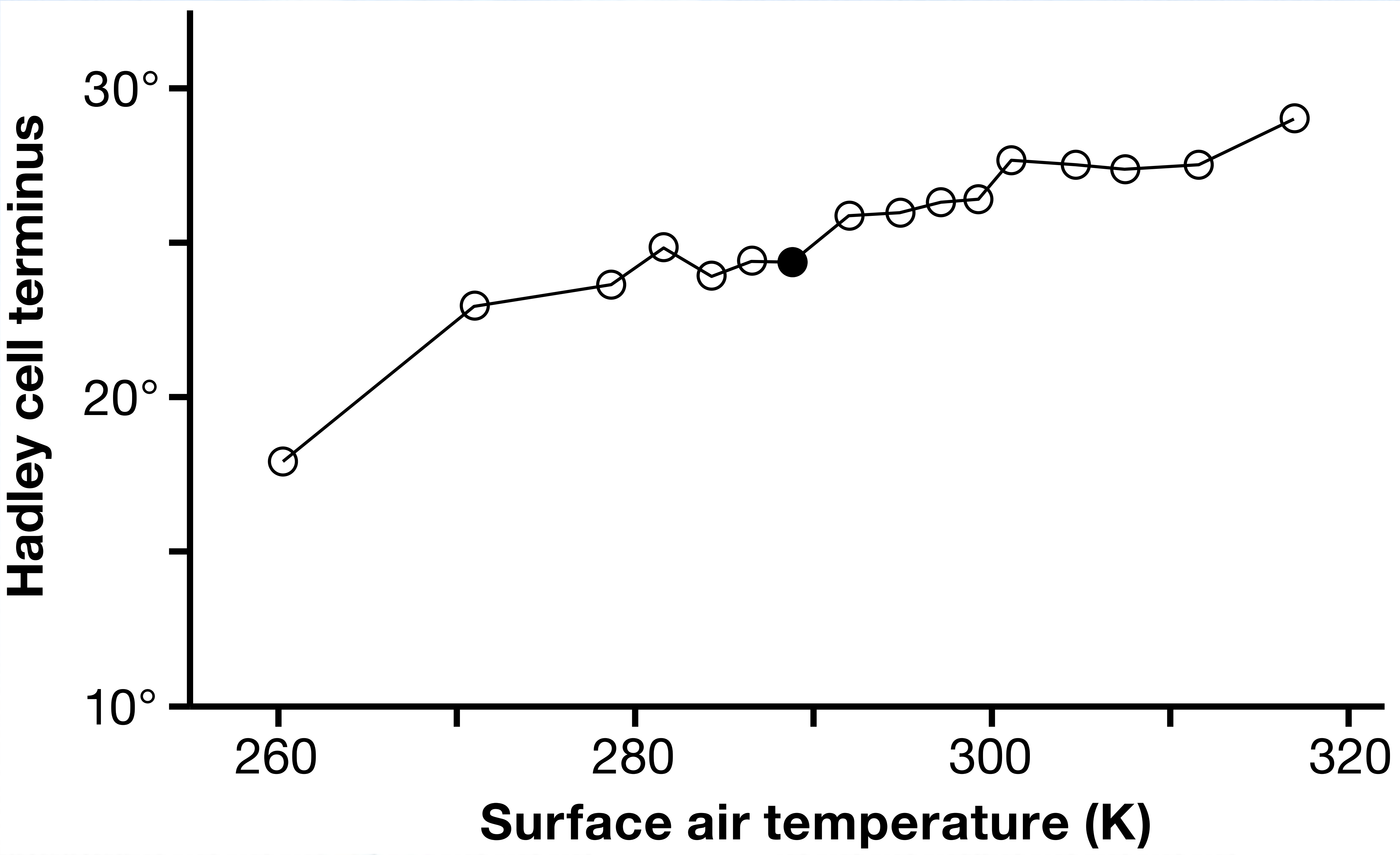
- Terminus satisfies

$$\tan\phi_h \sim \frac{\Delta_v}{a\partial_y\bar{\theta}_s}$$

- HC expands as *tropical* or *subtropical* static stability increases *(global warming)*
- HC contracts as temperature gradients increase (*El Niño!*)
- Because tan(lat) increases rapidly with latitude, HC terminus insensitive to perturbations

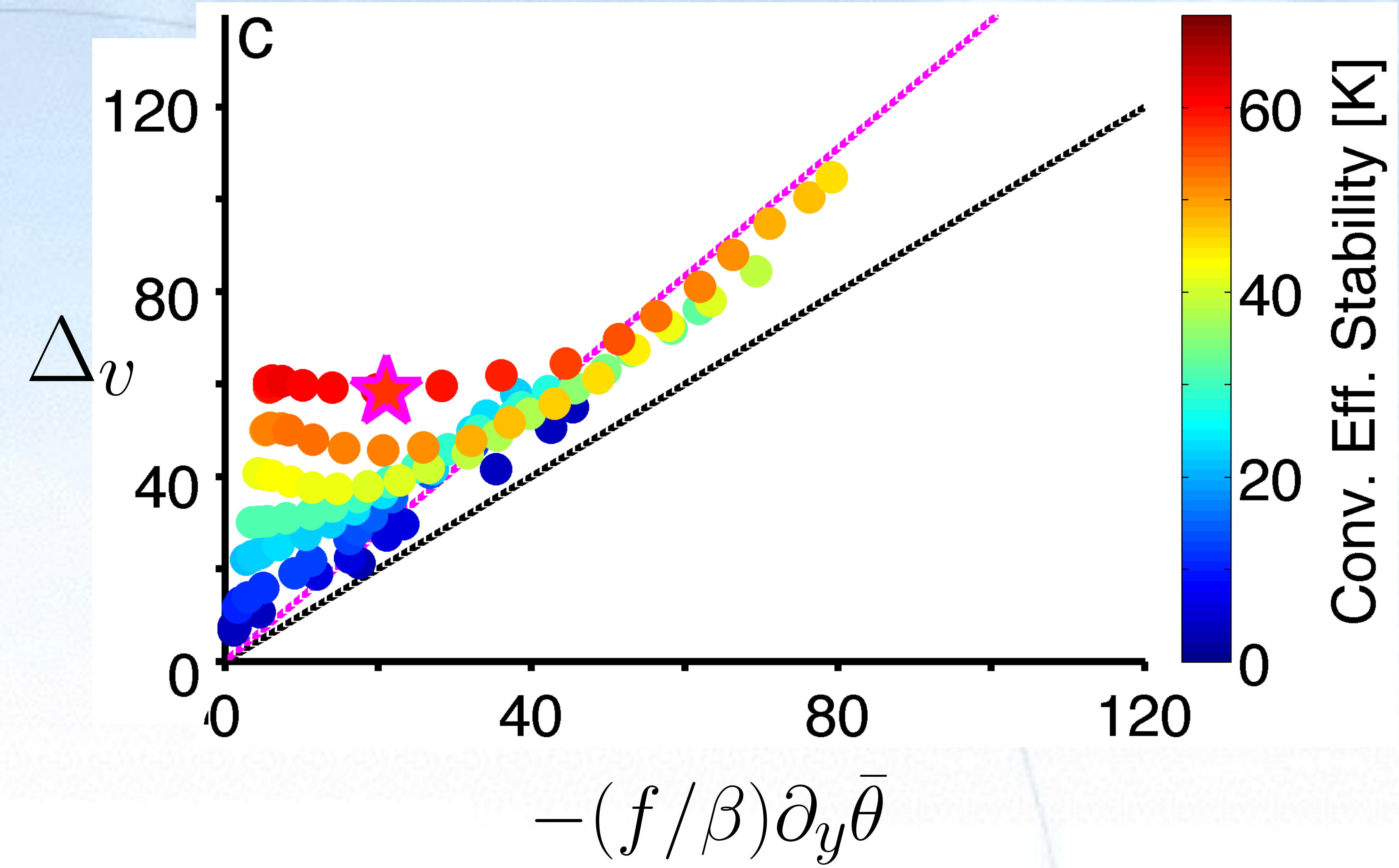
# Hadley Cell Expansion Under Global Warming

## Global Warming in Idealized GCM




Schneider, O'Gorman & Levine, *Rev. Geophys.*, 2010

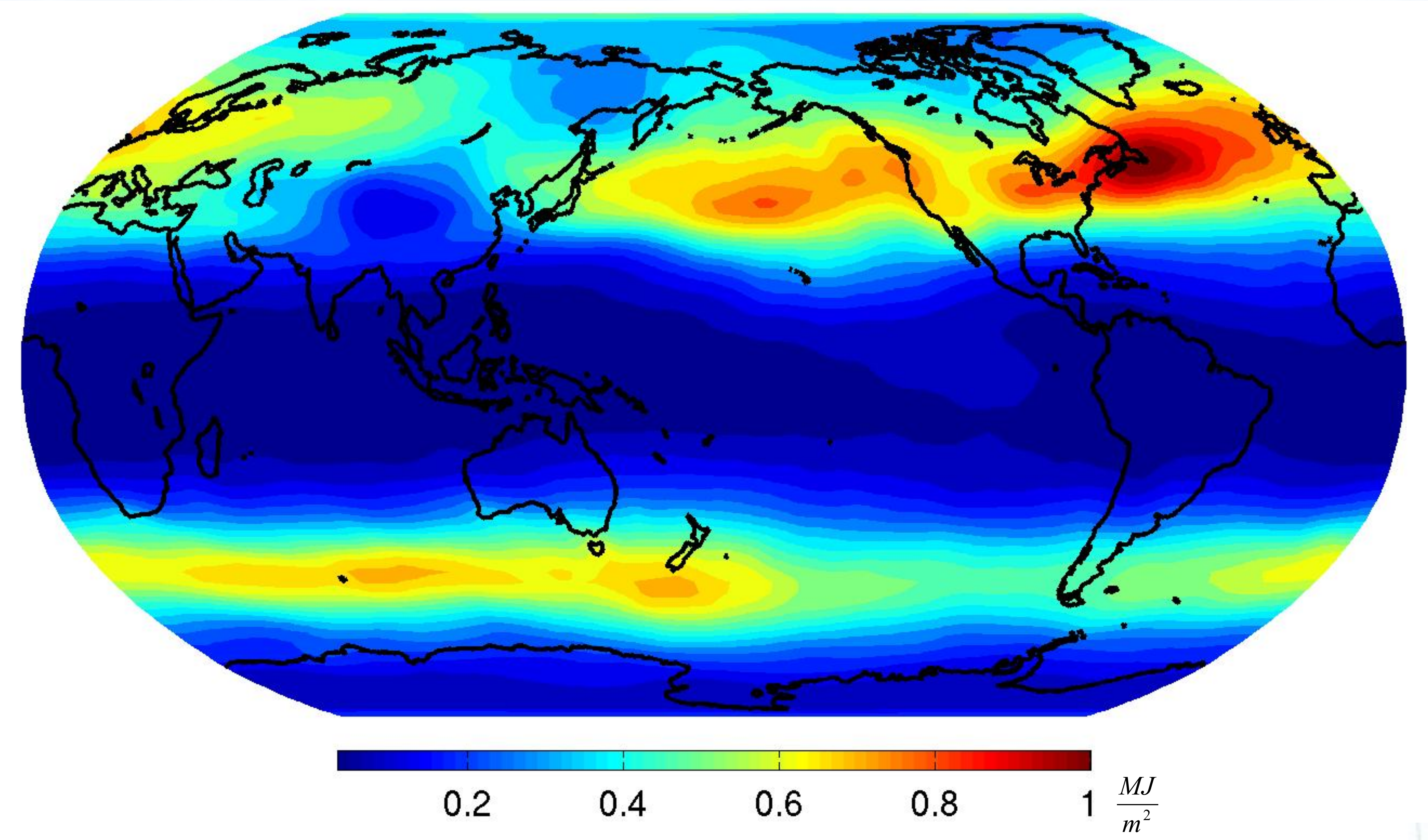
## Many More Such Simulations




Levine & Schneider, submitted

# Farther Poleward: Storm Tracks

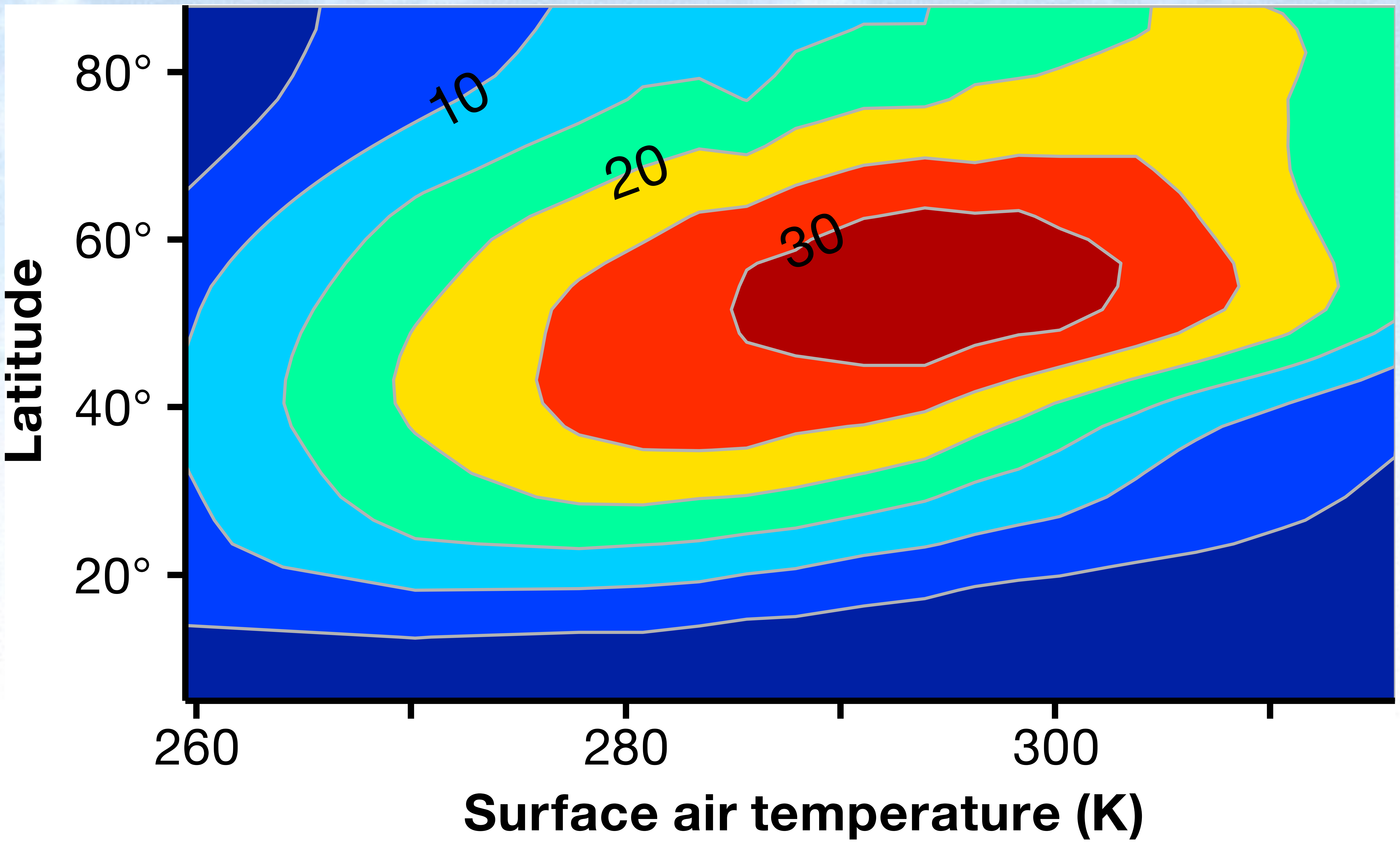
Kinetic Energy of Storms (DJF)




(Kaspi & Schneider, *J. Atmos. Sci.*, 2013)

# They Also Move Poleward As Climate Warms

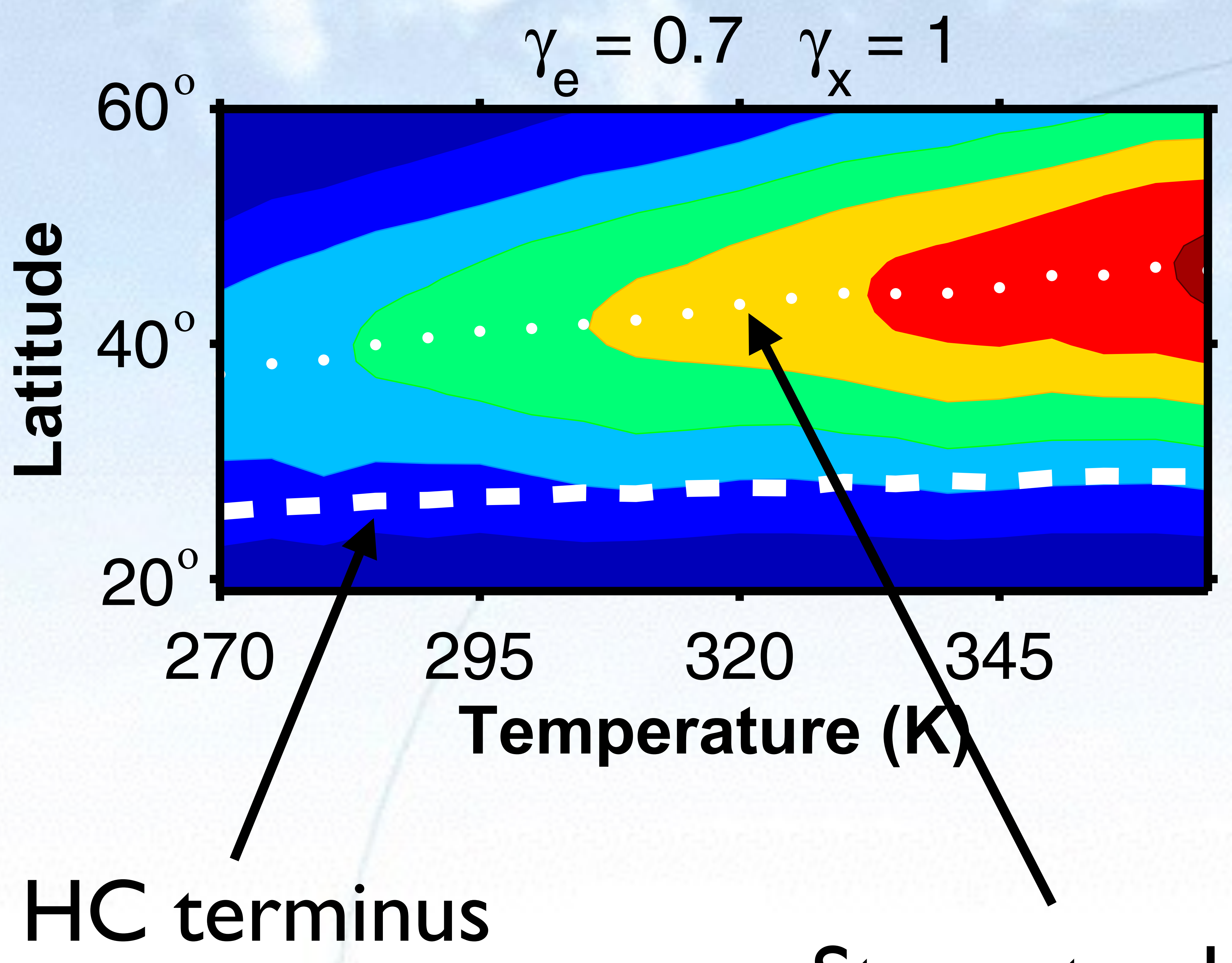
Near-Surface EKE in Idealized GCM (kJ $m^{-2}$)



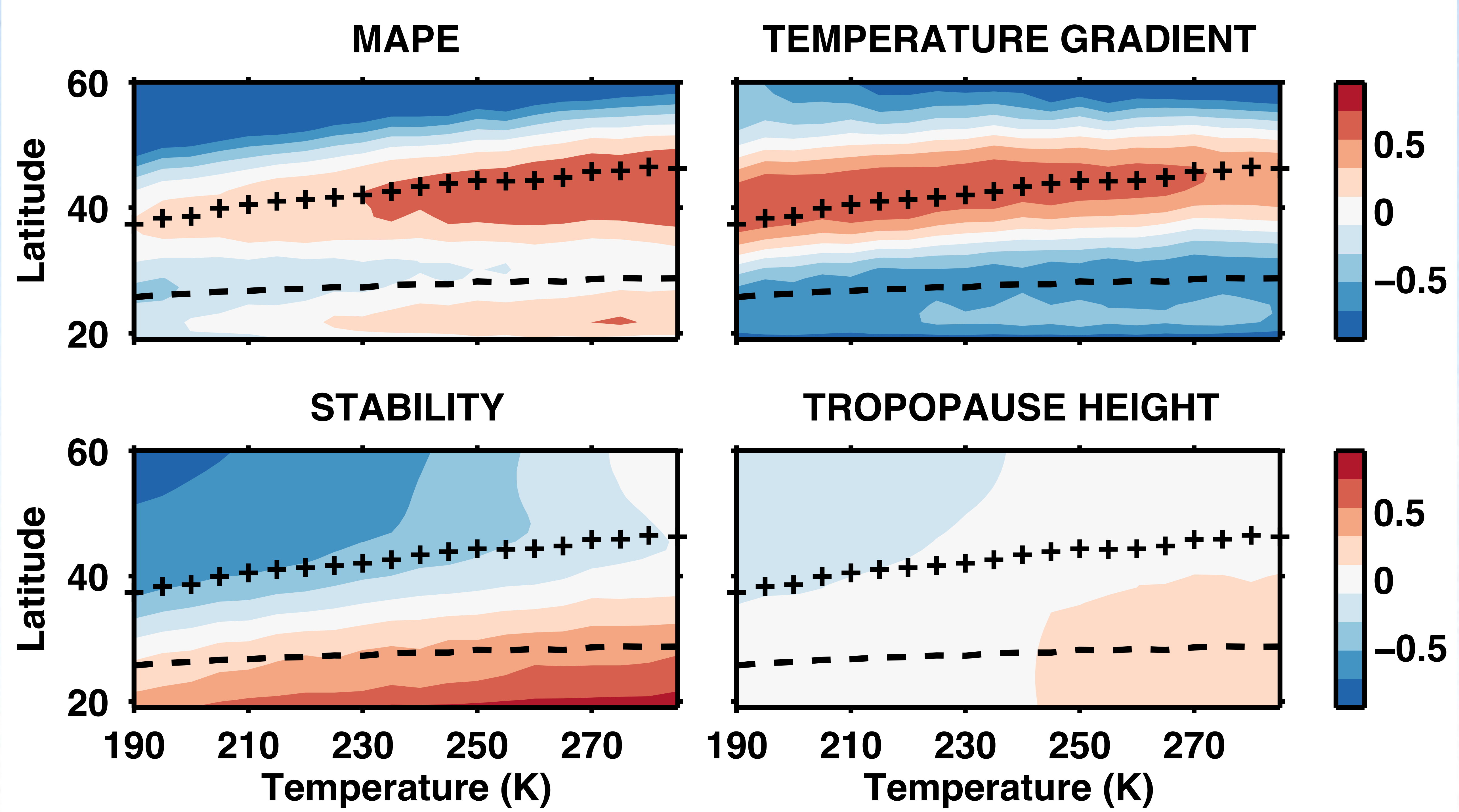

Schneider, O'Gorman & Levine, *Rev. Geophys.*, 2010; similarly in comprehensive GCMs, e.g., Yin 2005

# Storm Tracks Often Move With HC Terminus

## Barotropic EKE in dry GCM




## MAPE and its contributors




*Temperature gradient dominates!*

Mbengue & Schneider, *J. Atmos. Sci.*, 2013; Mbengue & Schneider, in prep.

# How Does Storm Track Position Relate to HC?

- HC terminus provides Neumann boundary condition to diffusive EBM

$$\partial_t T(\mu) = \partial_\mu (1-\mu^2) D \partial_\mu T(\mu) - A(T(\mu) - T_0(\mu))$$

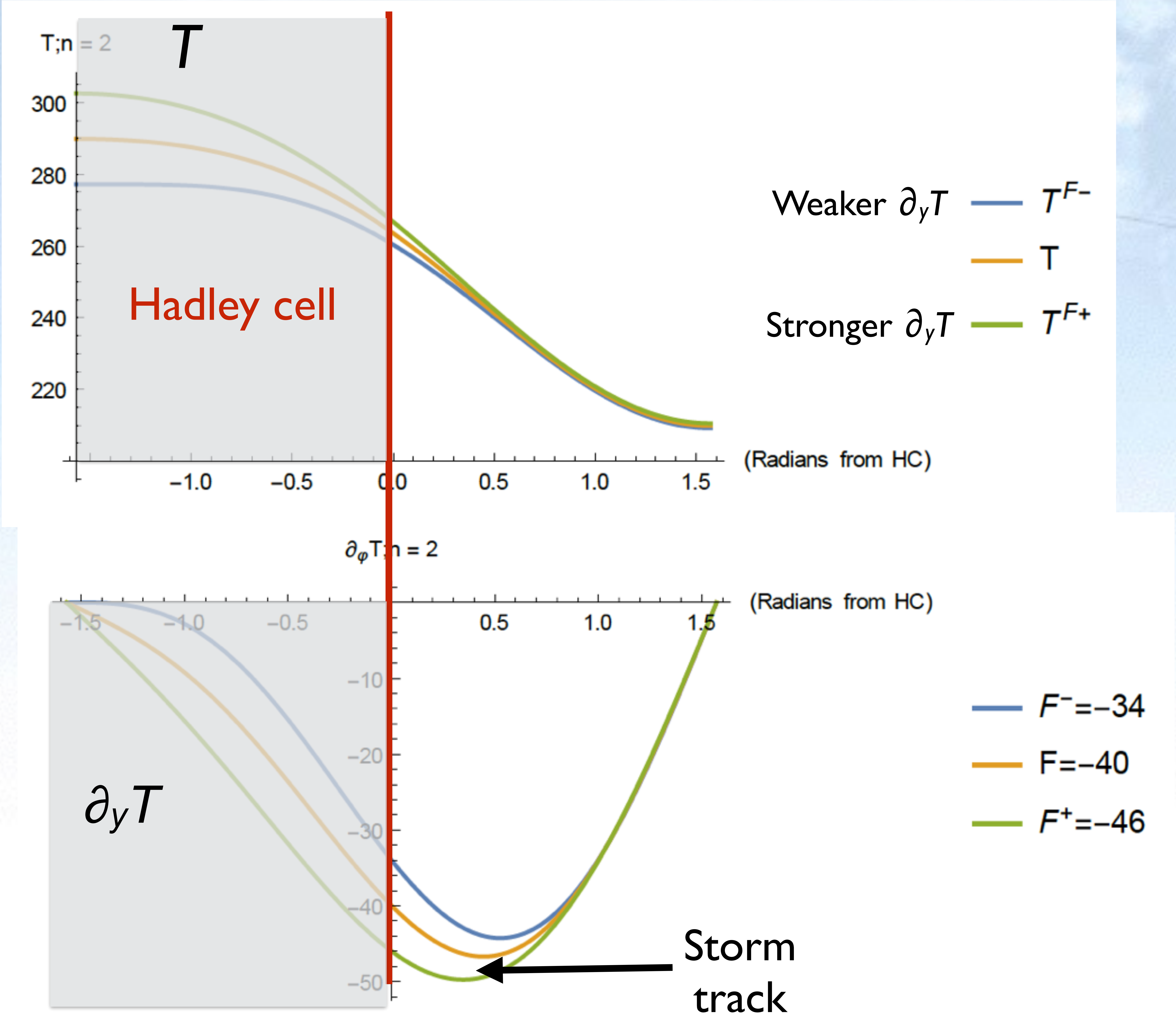
$$\partial_\mu T(\mu_h) = F(\mu_h, \Delta_v) \ \text{(at HC terminus)}$$

- For example: increased tropical static stability widens HC; b.c. on extratropical temperature gradient pushed poleward

- Storm track pushed poleward because it is associated with max temperature gradients

Mbengue & Schneider, in prep.

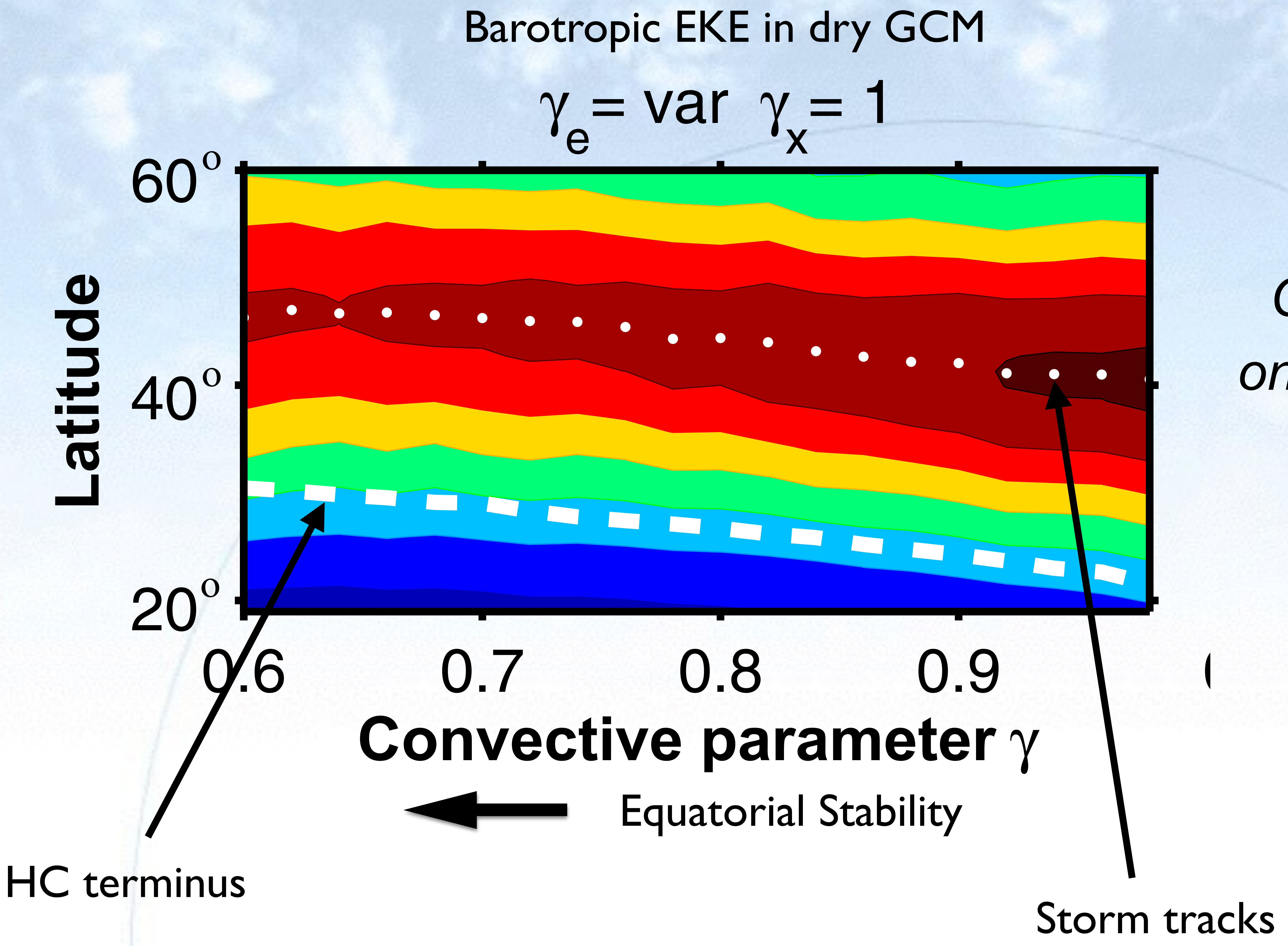
# Analytical EBM Solution (*n*=2 Truncation)




- Stronger temperature gradients move poleward when HC expands
- Max depends on subtropical $\partial_y T$
- Storm track closer to HC terminus for larger subtropical $\partial_y T$
- E.g., opposing responses to increases in static stability and $\partial_y T$

Mbengue & Schneider, in prep.

# Example: Effect of Equatorial Stability on Storm Track




*Changing convective stability only at equator suffices to move storm tracks, as in EBM*

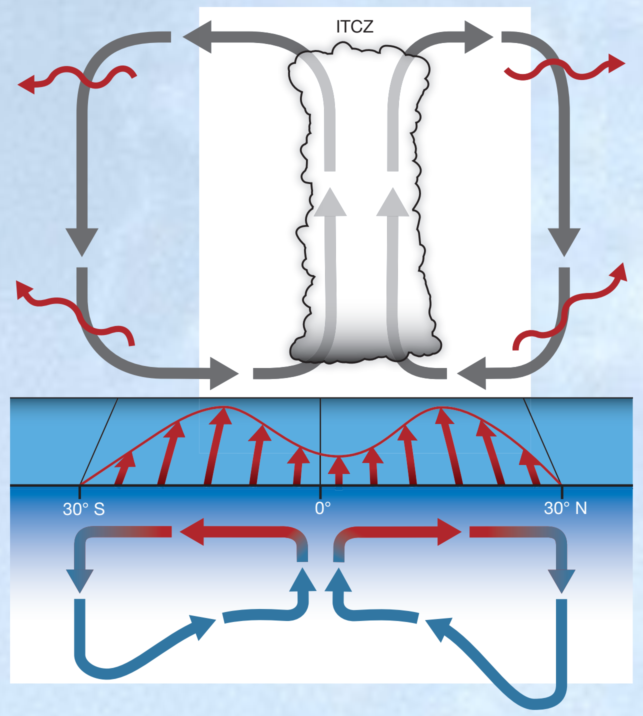
Mbengue & Schneider, *J. Atmos. Sci.*, 2013;

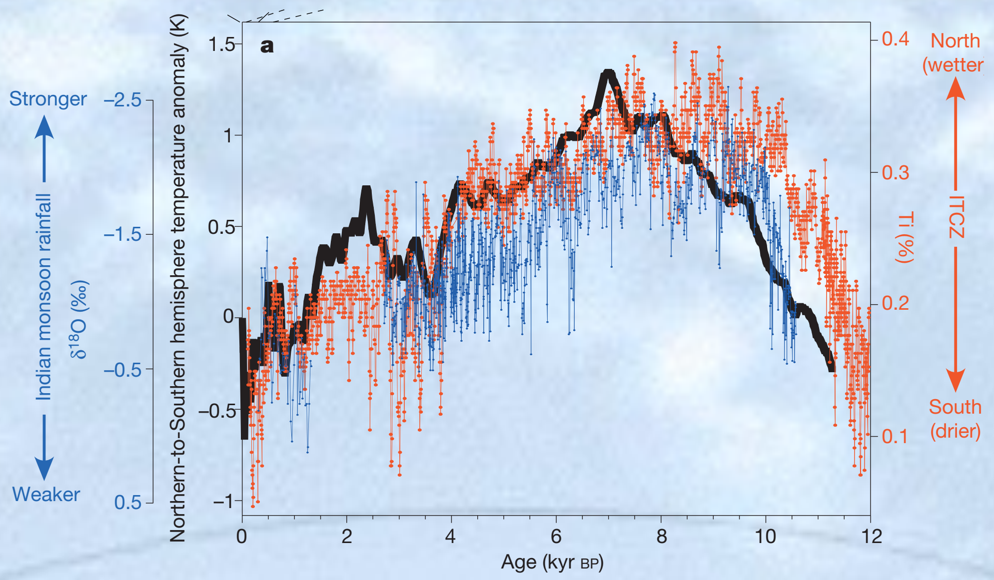
# Summary Points

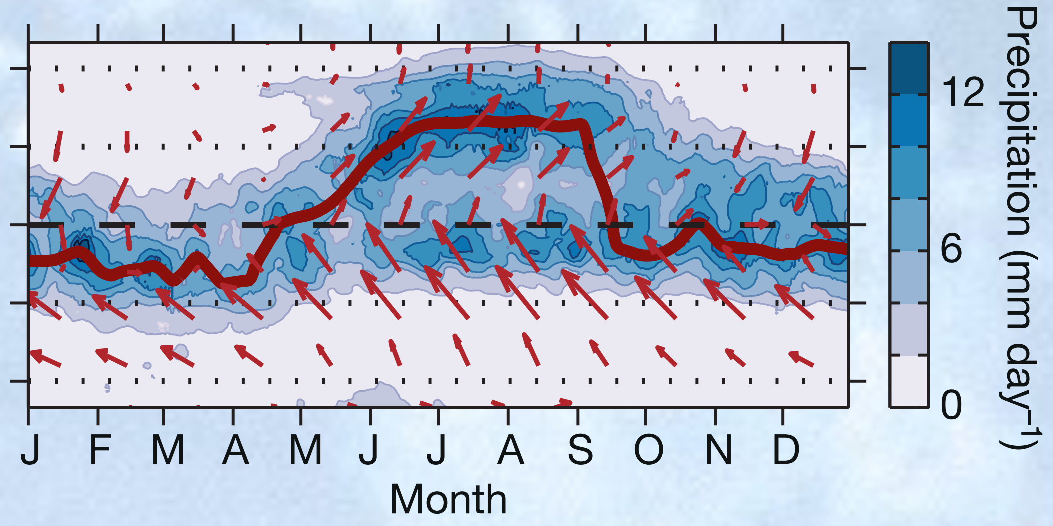
- Energy balance constrains ITCZ position through energy flux equator (somewhat surprising AM does not enter explicitly)
- Expanding energy flux around equator gives ITCZ position as function of $F_0$ and $S_0 - L_0 - O_0$ (depend on extratropical eddy fluxes and AM balance)
- Energetic terms are small residuals of large terms, so ITCZ is sensitive to small energetic shifts (e.g., Heinrich events, monsoon variability, ENSO)
- Hadley cell terminus is not so sensitive (constrained by geometry and properties of baroclinic eddies)
- Storm tracks near where temperature gradients are maximal
- Position of maximum gradient controlled by energy fluxes and boundary condition provided by Hadley circulation

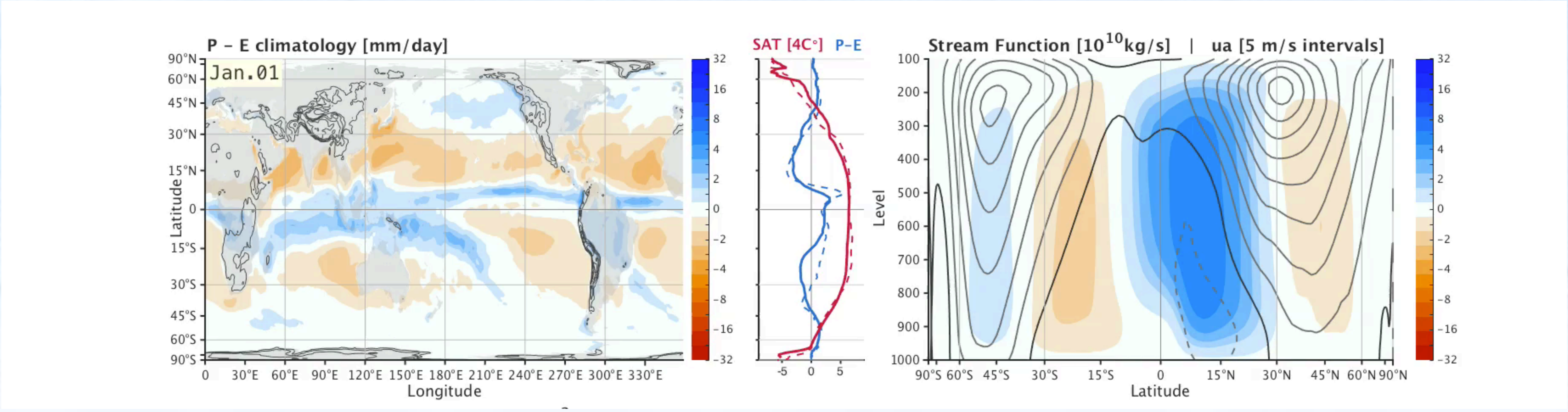
# Some of the People Making it Happen

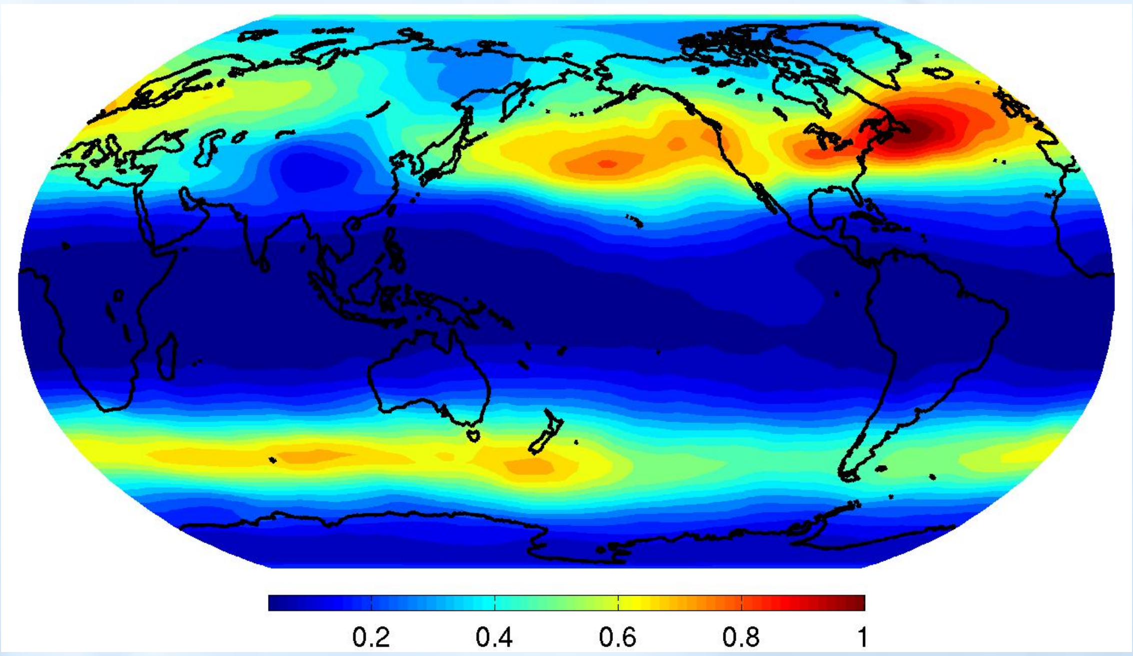
# Thank You!

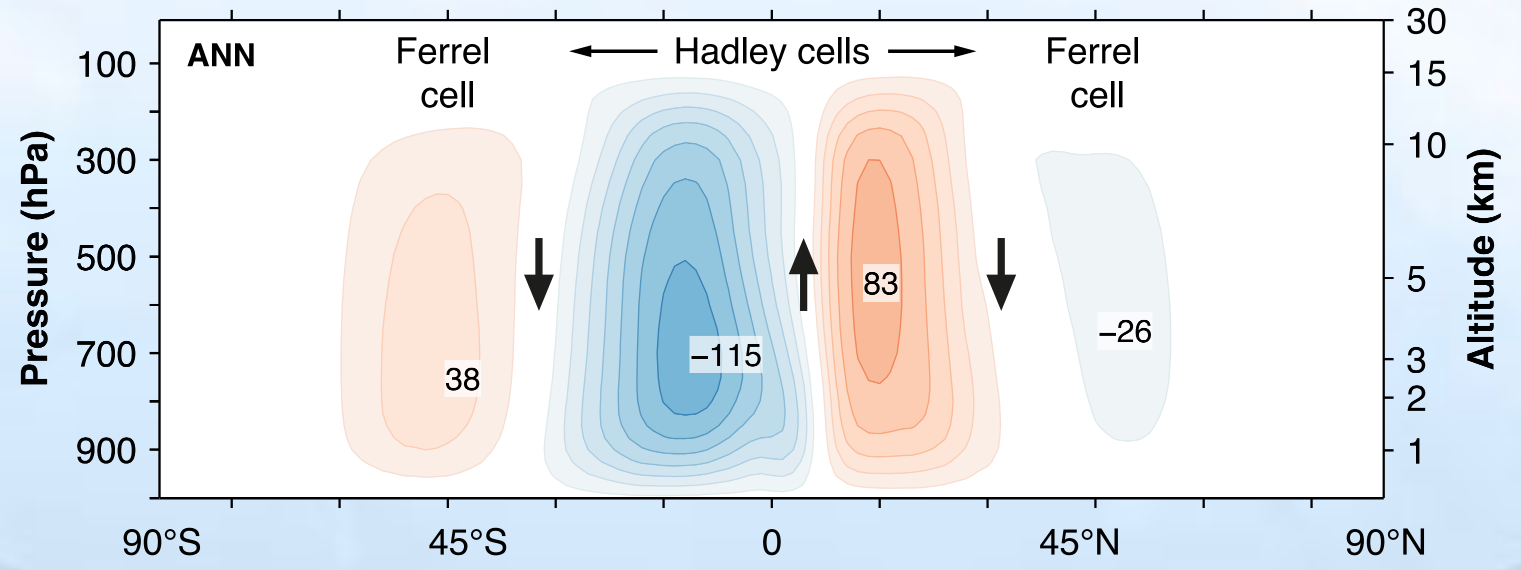

ITCZ
30° S
0°
30° N

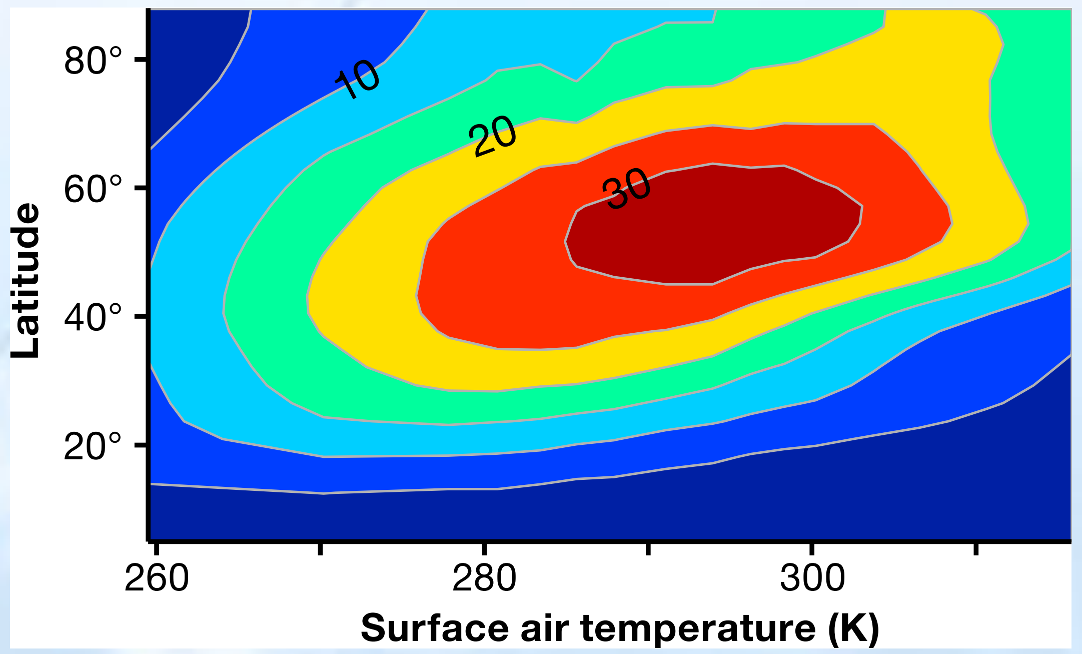

a
Stronger
Weaker
Indian monsoon rainfall
Northern-to-Southern hemisphere temperature anomaly (K)
North (wetter)
South (drier)
ITCZ
Age (kyr BP)


J F M A M J J A S O N D
Month
Precipitation (mm day-1)

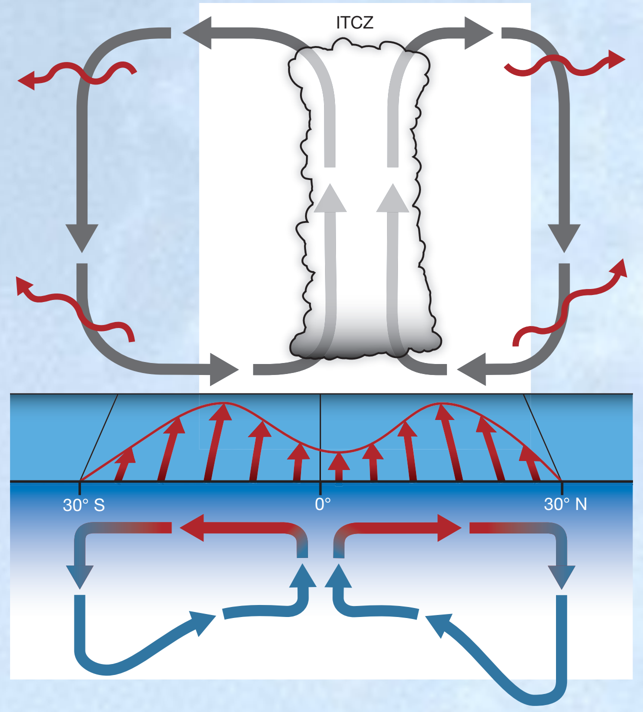

P – E climatology [mm/day]
Jan.01
Latitude
Longitude
SAT [4C°] P-E
Stream Function [10^10 kg/s] | ua [5 m/s intervals]
Level
Latitude




ANN
Ferrel cell
Hadley cells
Ferrel cell
Pressure (hPa)
Altitude (km)
38
−115
83
−26


Latitude
Surface air temperature (K)

# Thank You!



ITCZ
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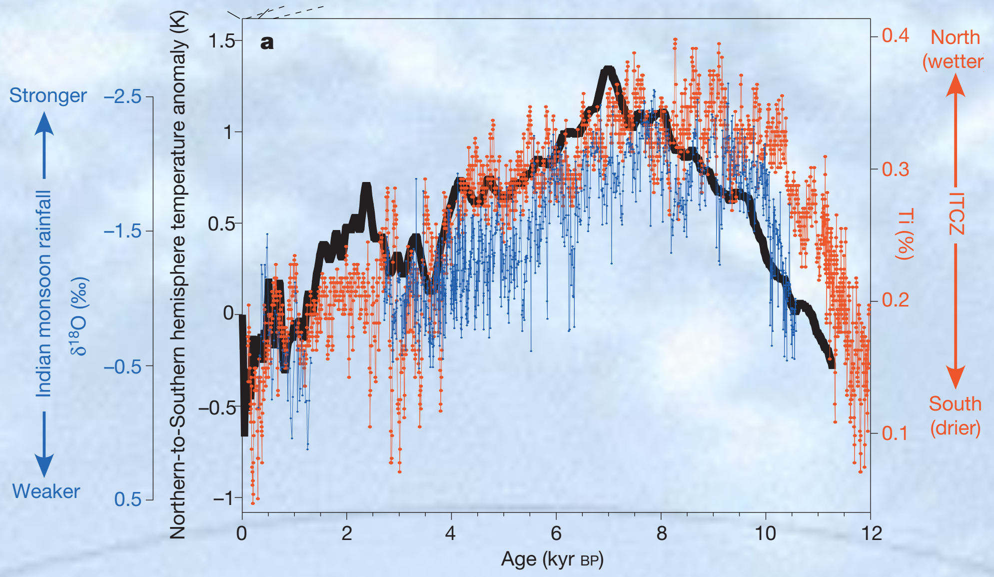
0°
30° N

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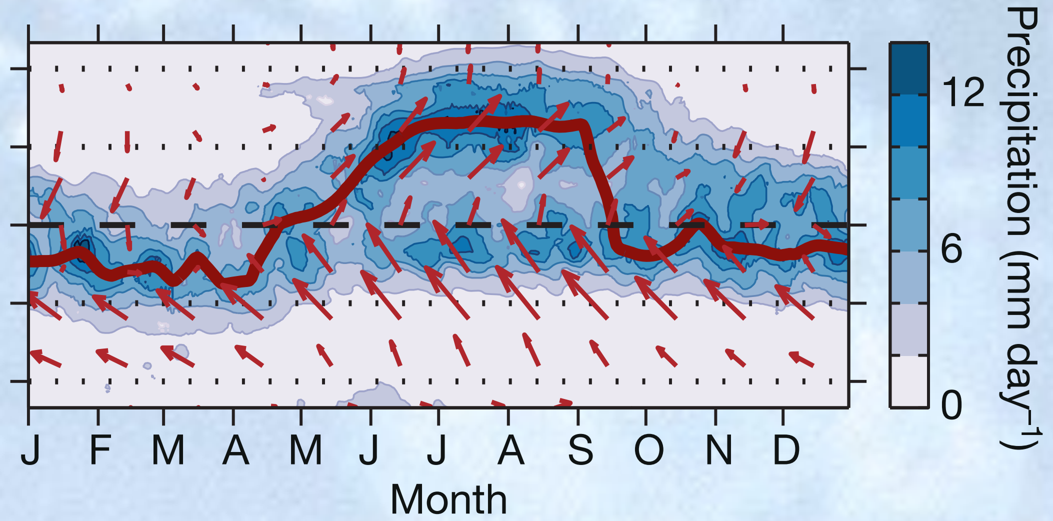
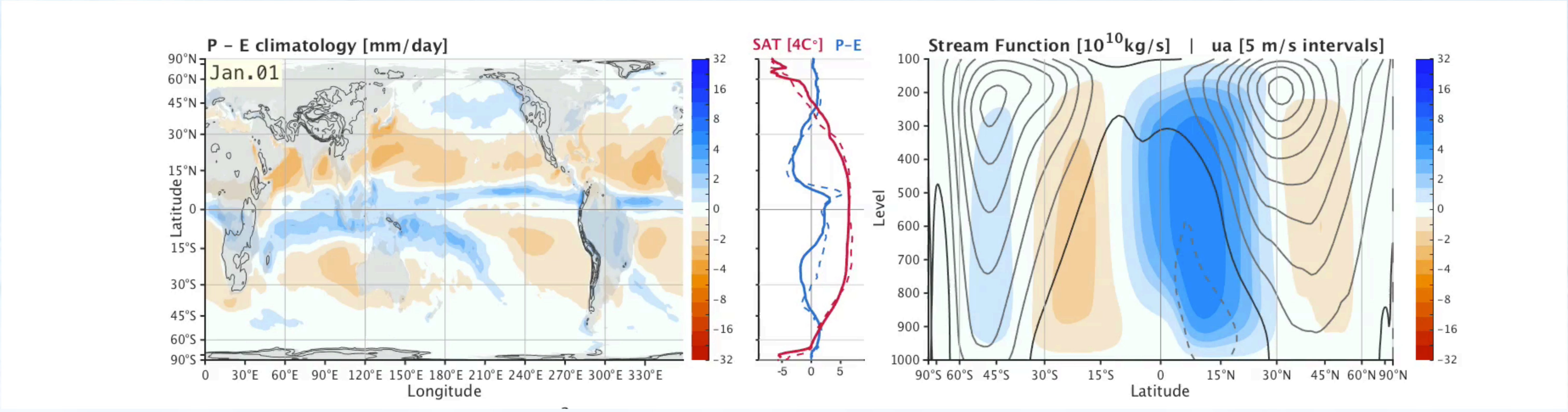


J F M A M J J A S O N D
Month
Precipitation (mm day$^{-1}$)
12
6
0

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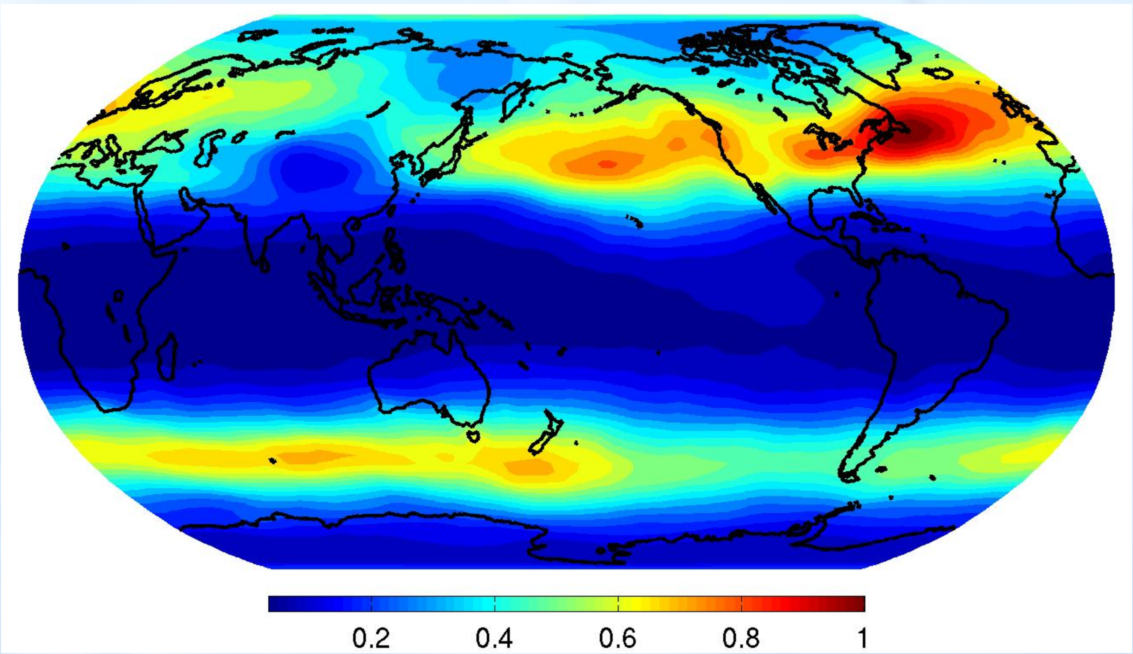
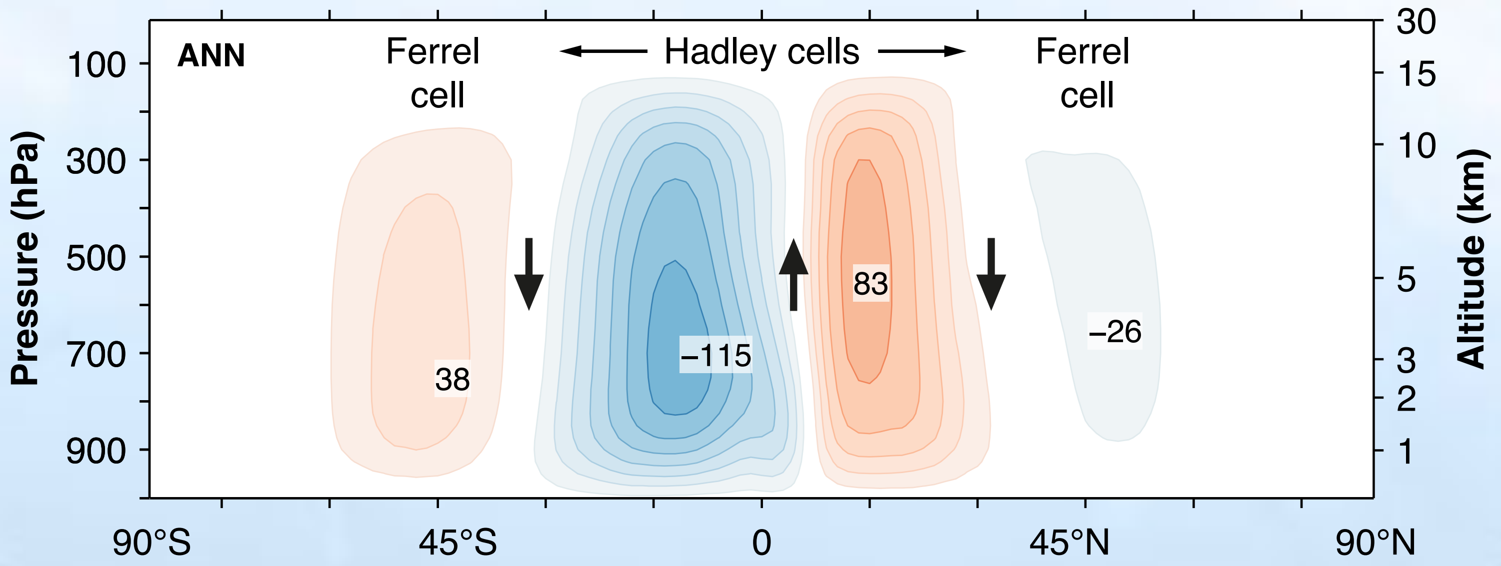
Jan.01
Latitude
Longitude
SAT [4C°] P-E
Stream Function [$10^{10}$kg/s] | ua [5 m/s intervals]
Level
Latitude

0.2
0.4
0.6
0.8
1

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Hadley cells
Ferrel cell
Pressure (hPa)
Altitude (km)
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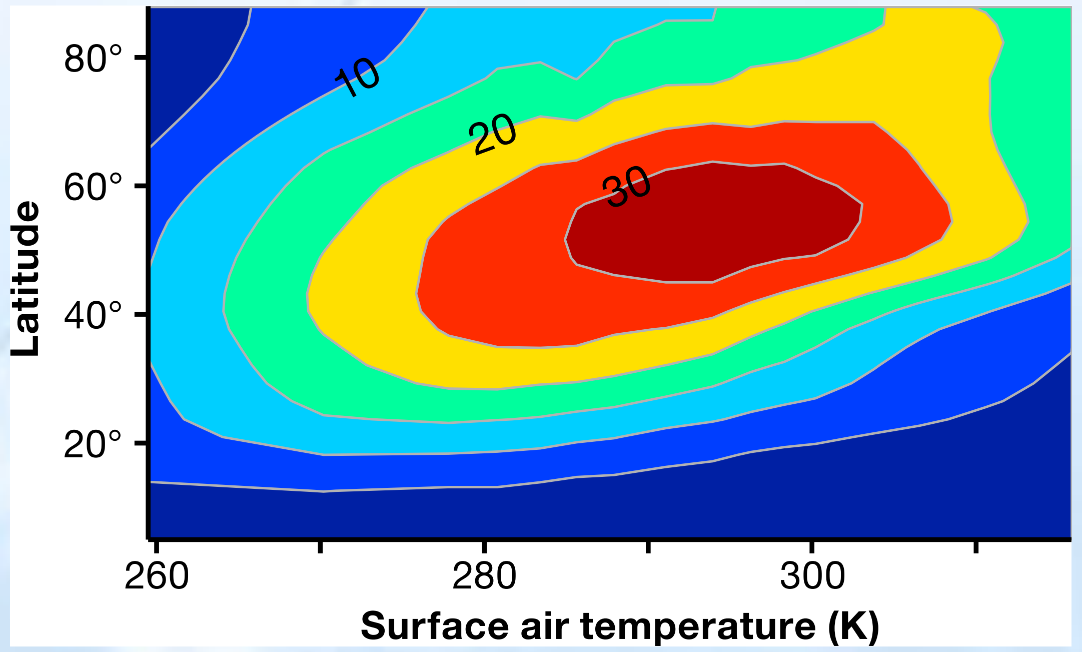
–26
90°S
45°S
0
45°N
90°N

10
20
30
Latitude
Surface air temperature (K)
260
280
300
80°
60°
40°
20°