1. Interaction between convection and large-scale tropical circulations
2. Modern theories of monsoons
3. Tipping points in monsoons?

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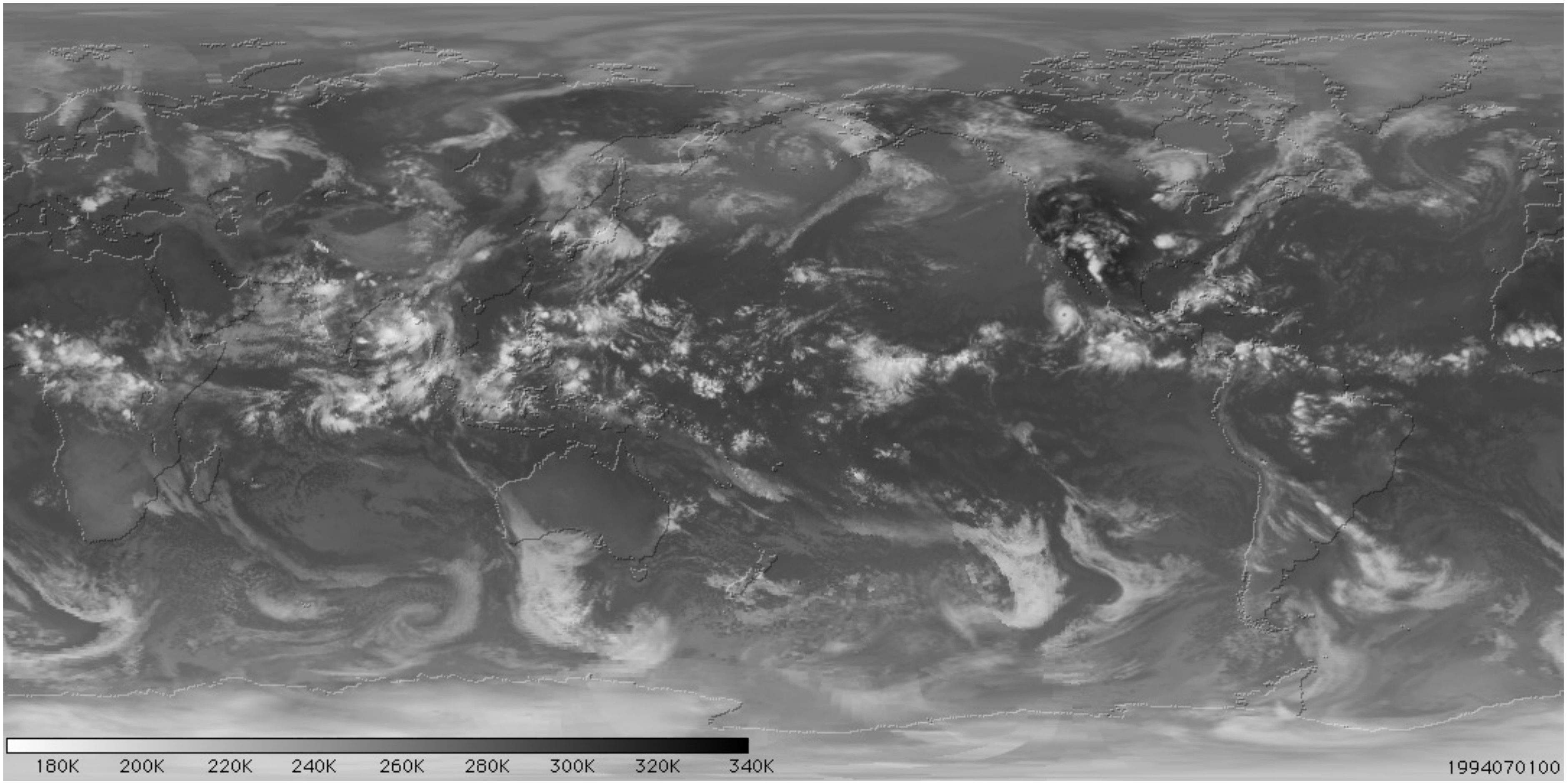
ICTP Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Multiple Equilibria in the Climate System

June 28 2018

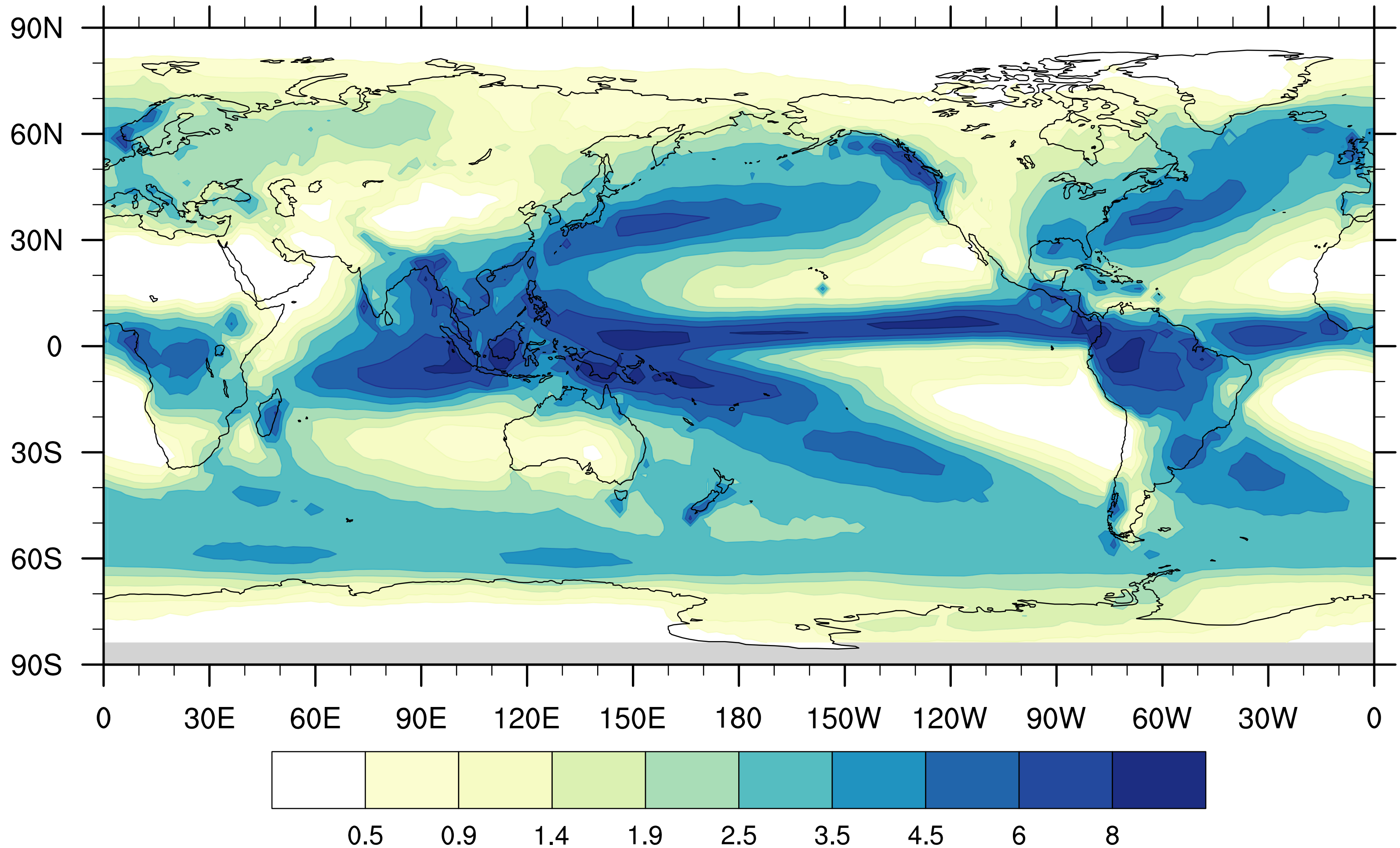
Clouds seen from above



http://badc.nerc.ac.uk/data/claus/

Where does it rain?

Annual mean precipitation



Data source: GPCP

Where does it rain?

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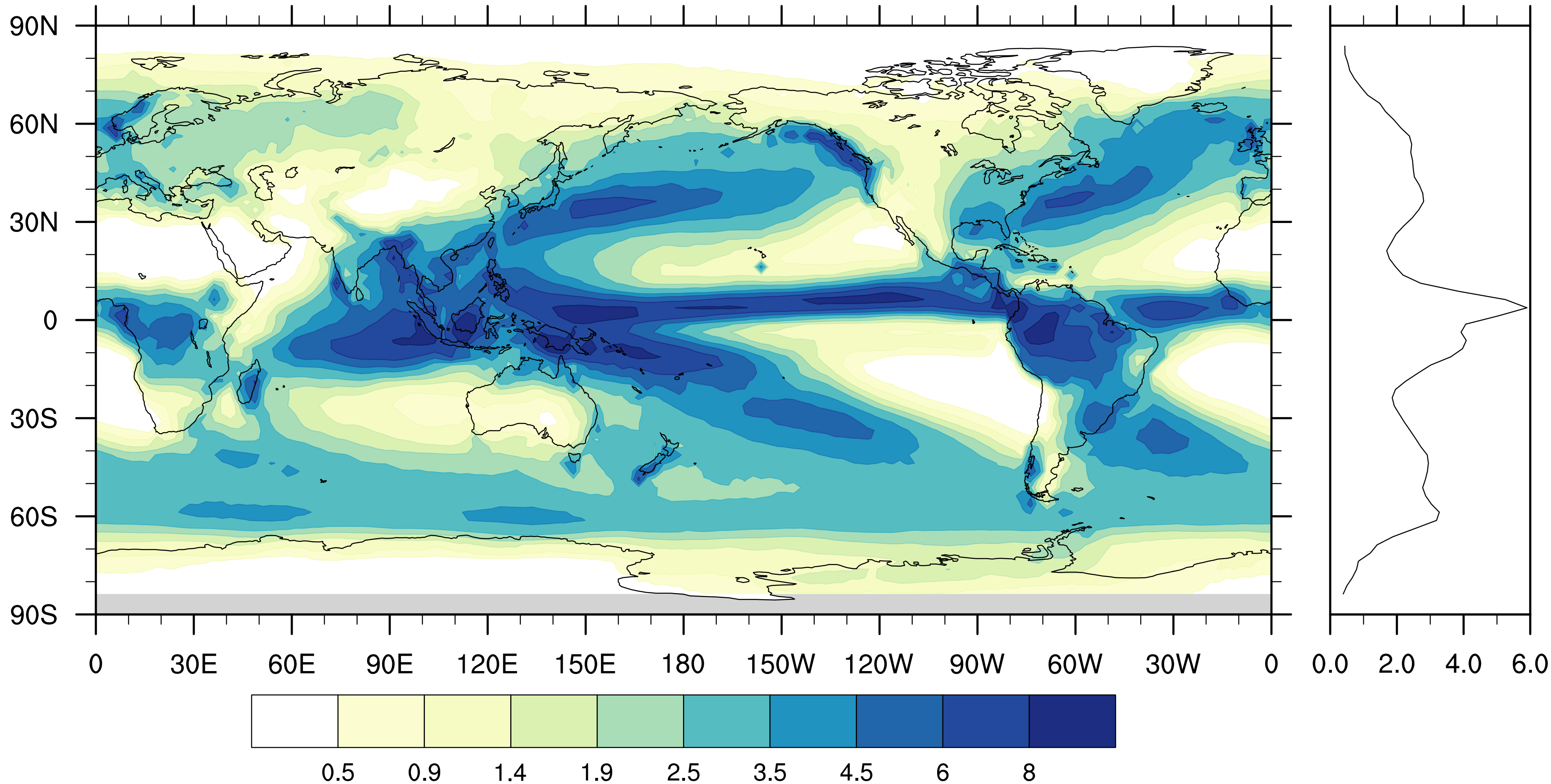

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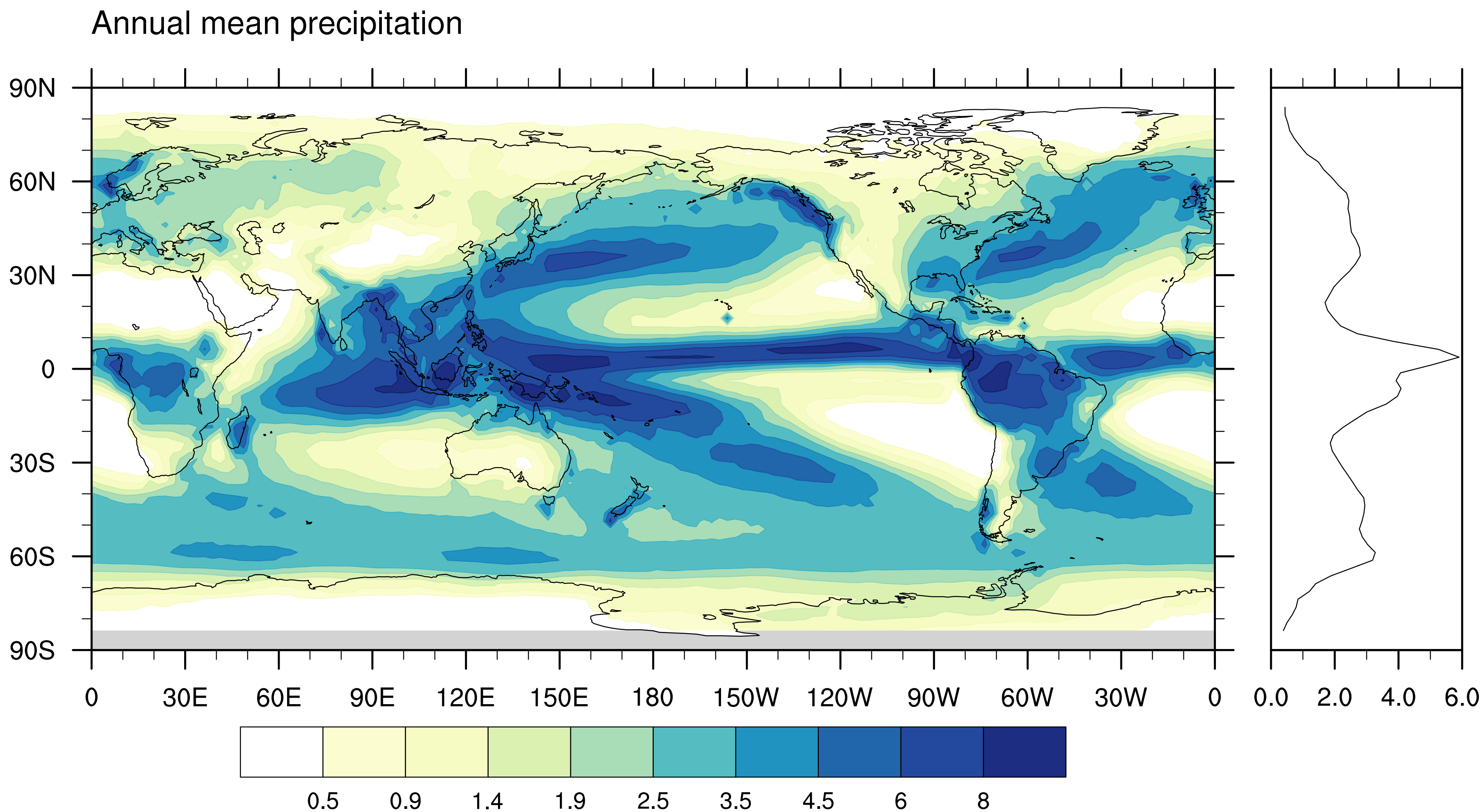
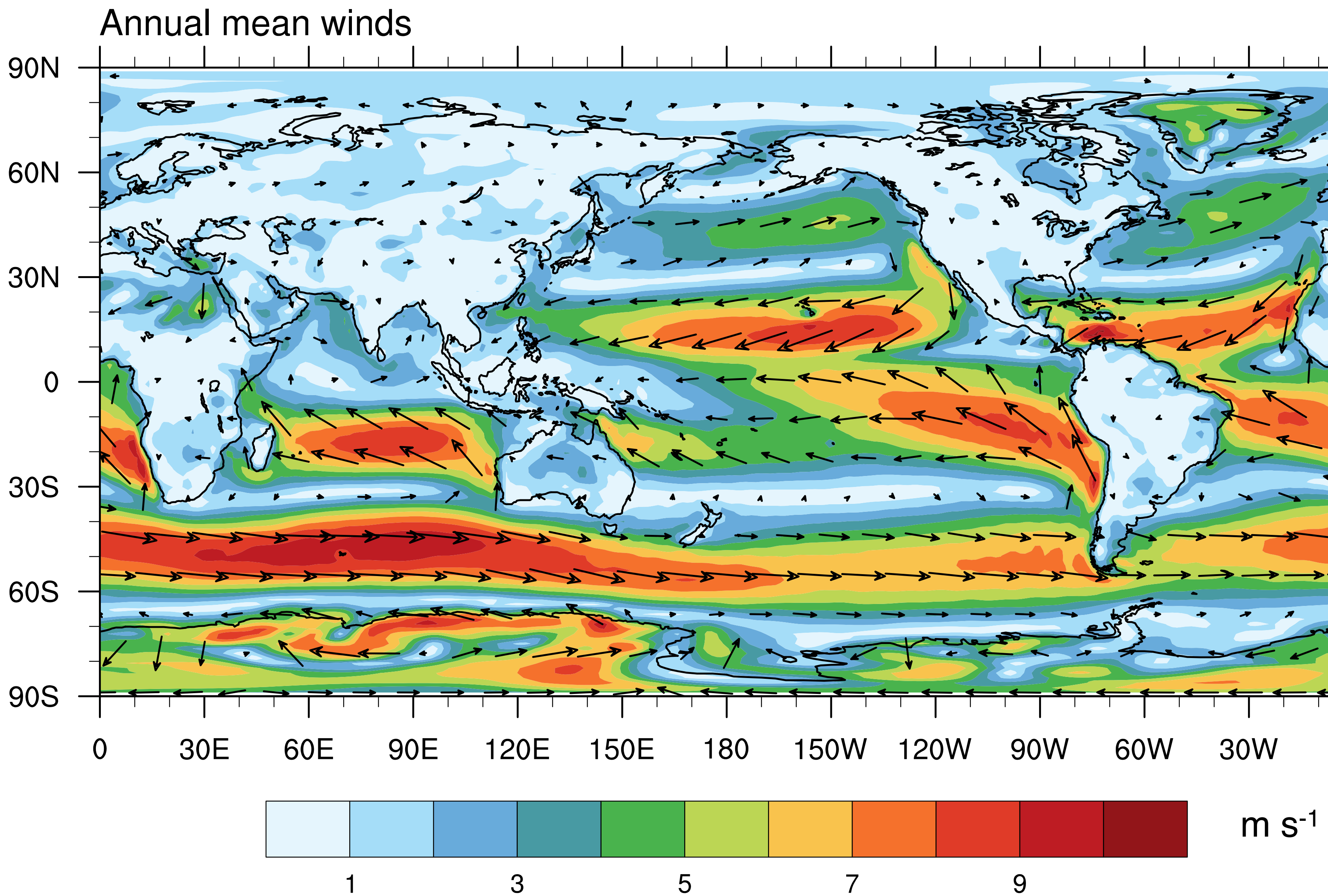
Where does it rain?



Data source: GPCP

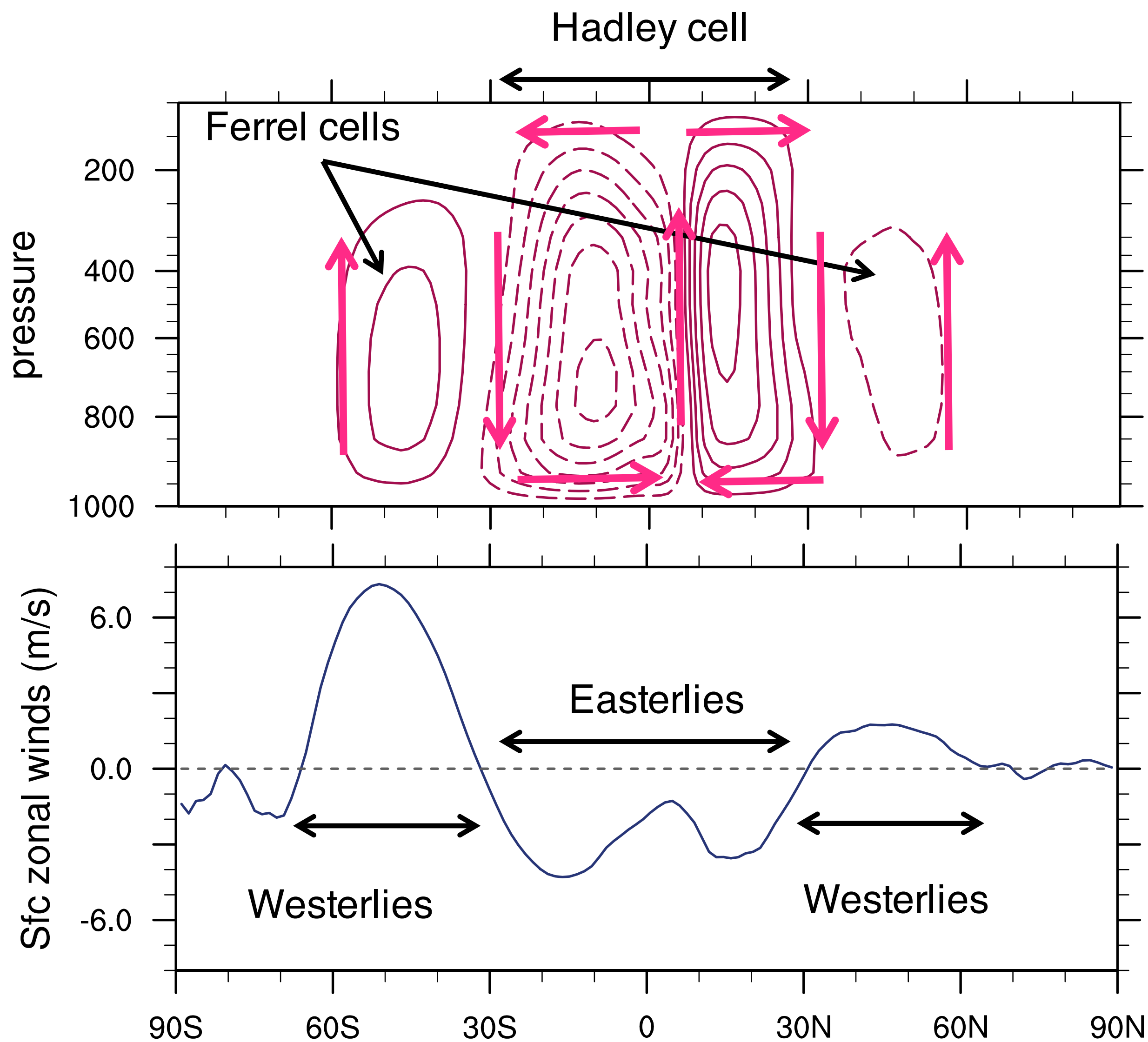
Why is the maximum precipitation (ITCZ) north of the equator?

Precipitation is tied to the atmospheric circulation



Data source: ERA40

Precipitation is tied to the atmospheric circulation



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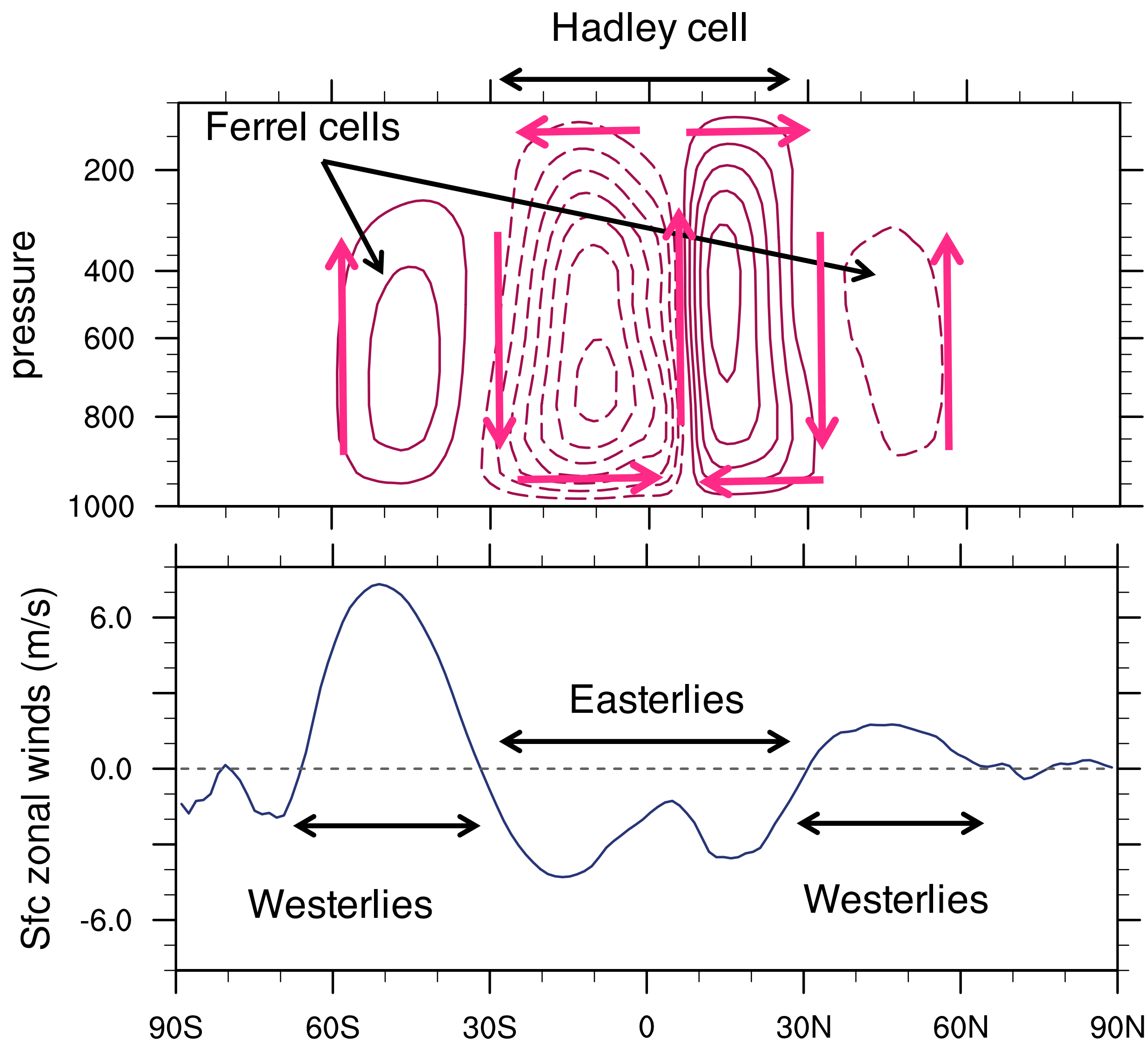
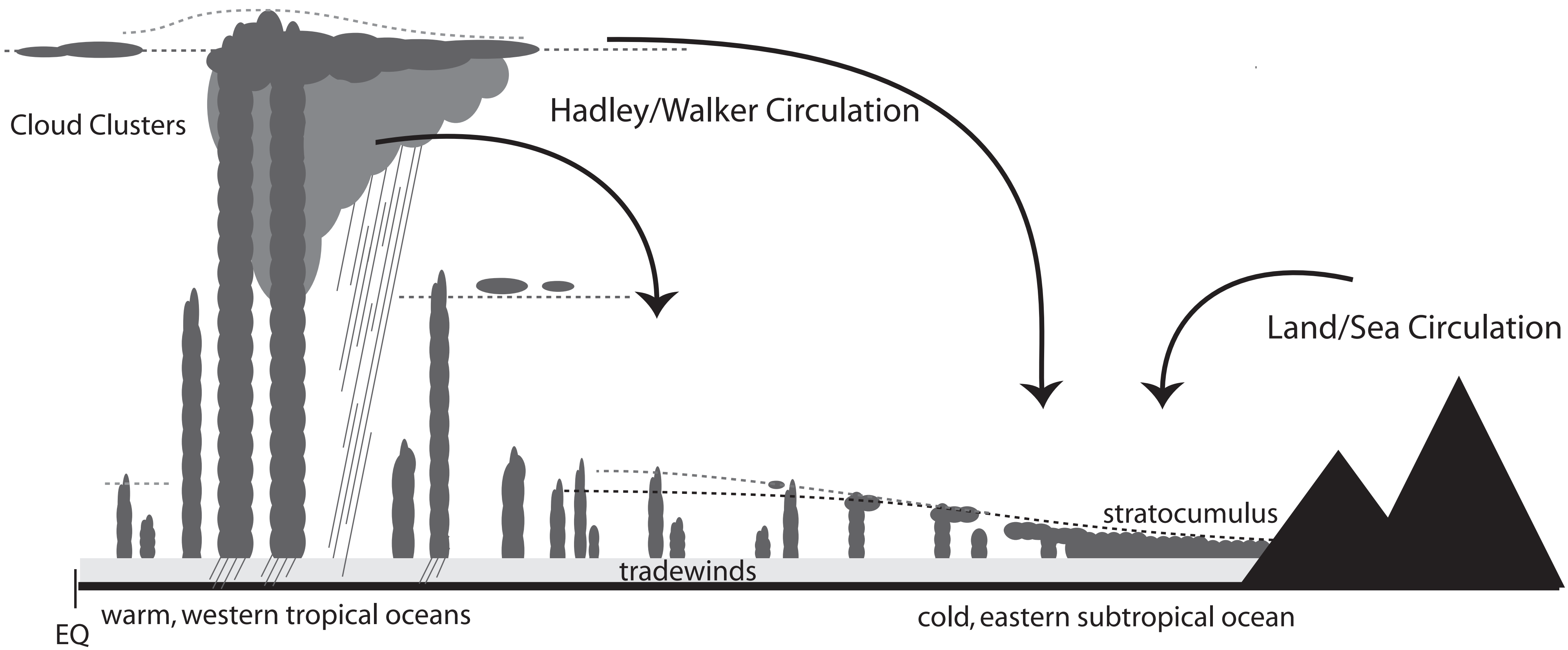


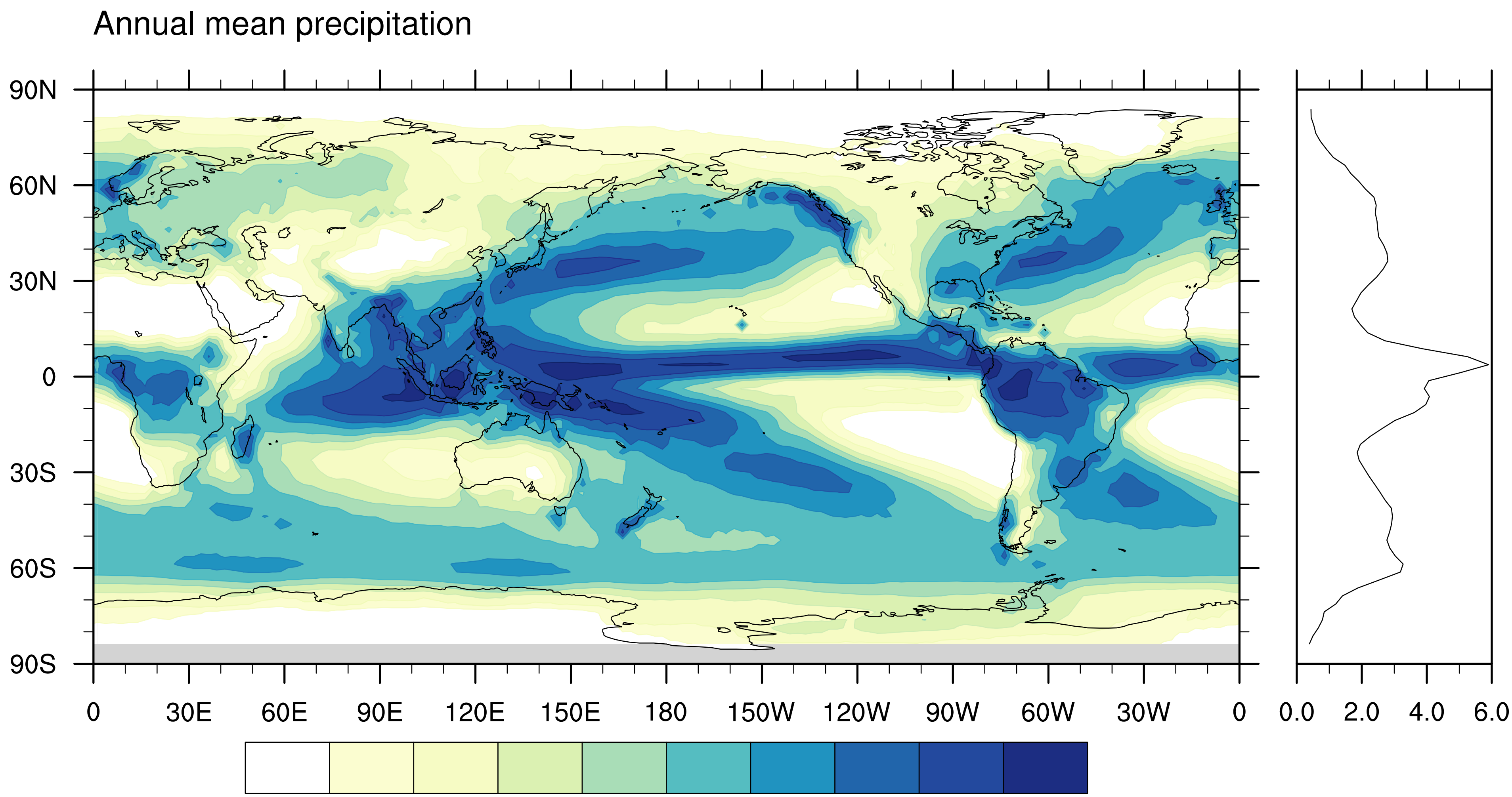
Maximum precipitation is co-located with ascending motion in the Hadley cells

Large-scale circulations and clouds



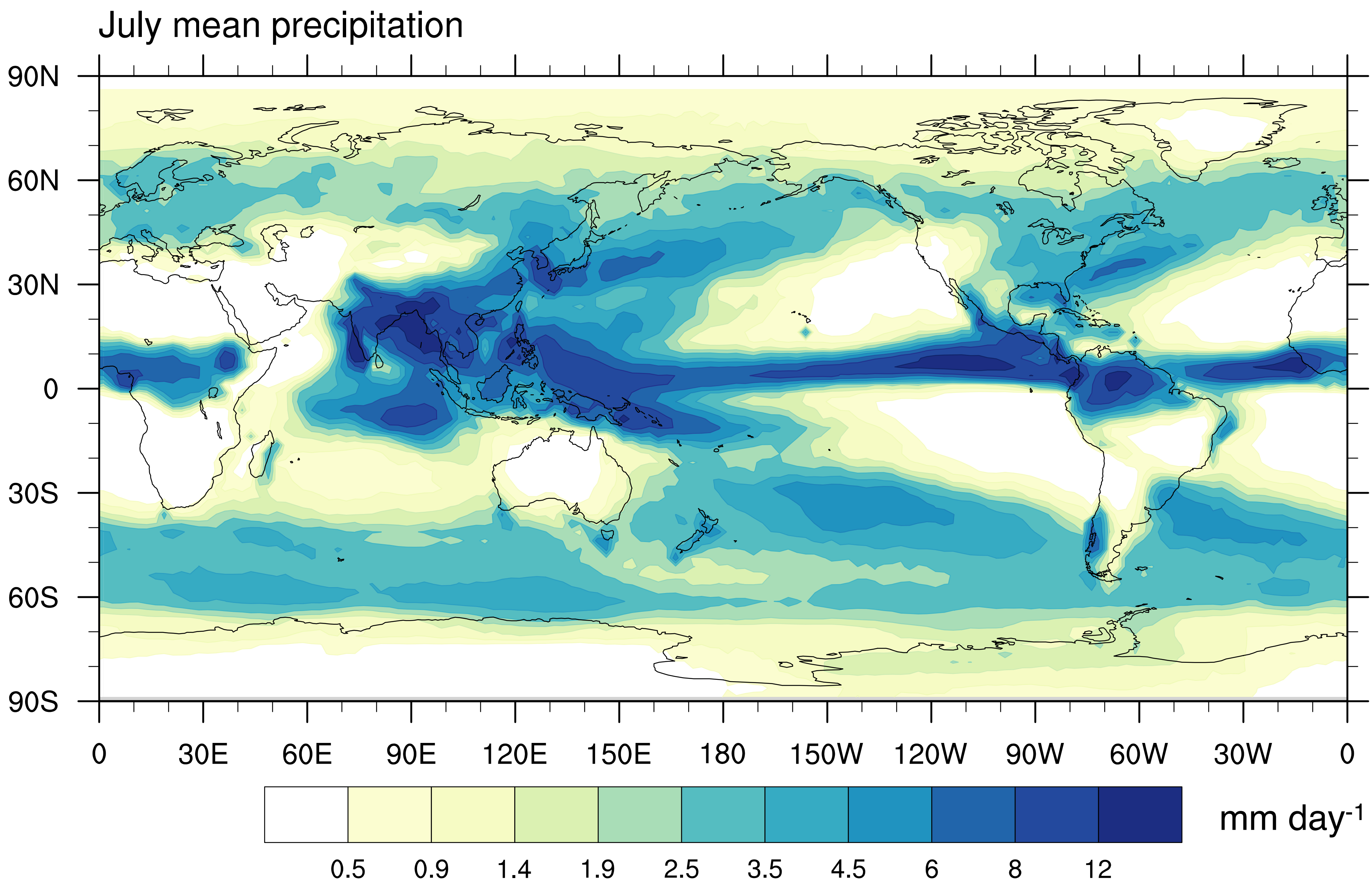
Courtesy: Bjorn Stevens

Where does it rain?



Data source: GPCP

When does it rain?



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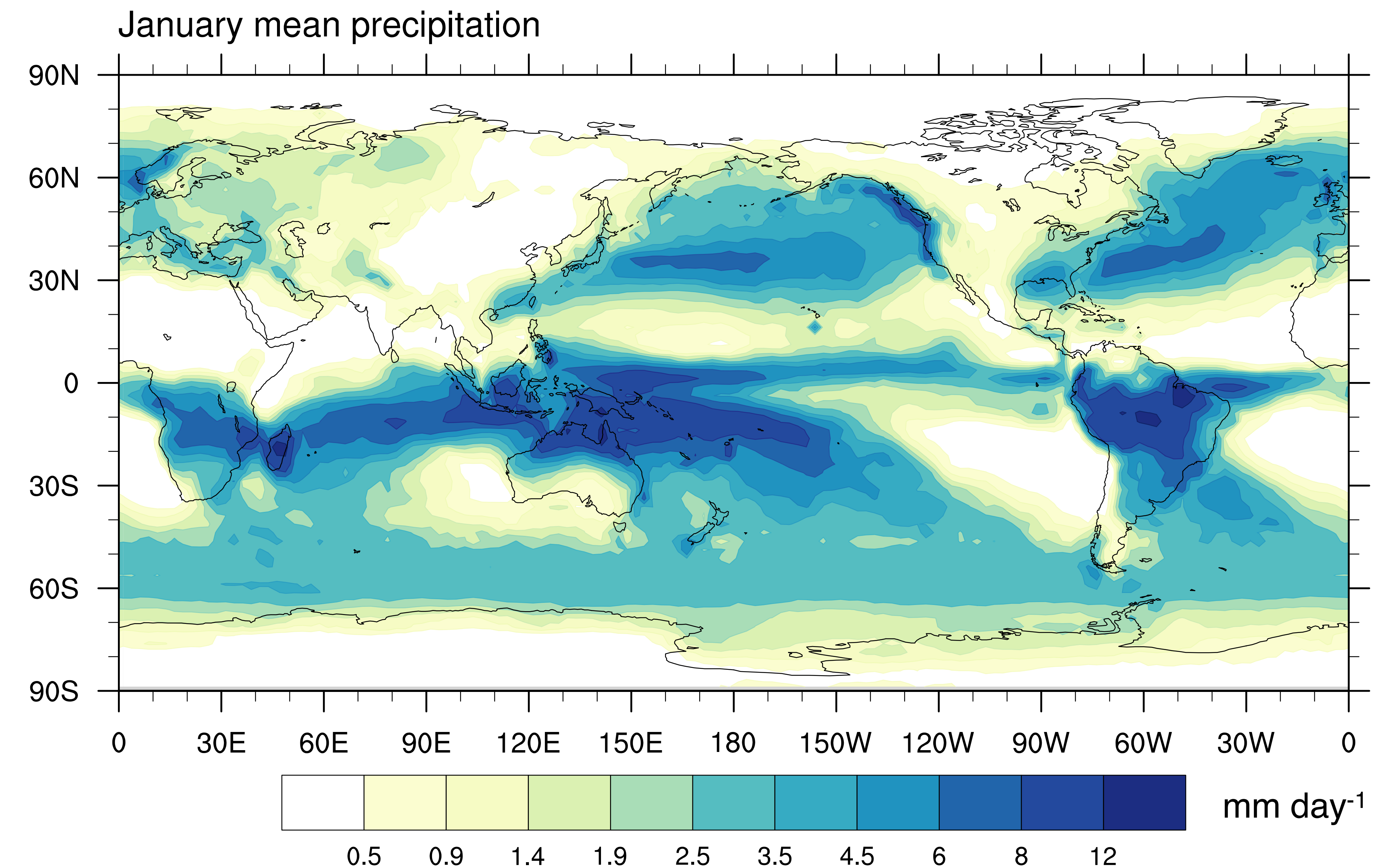
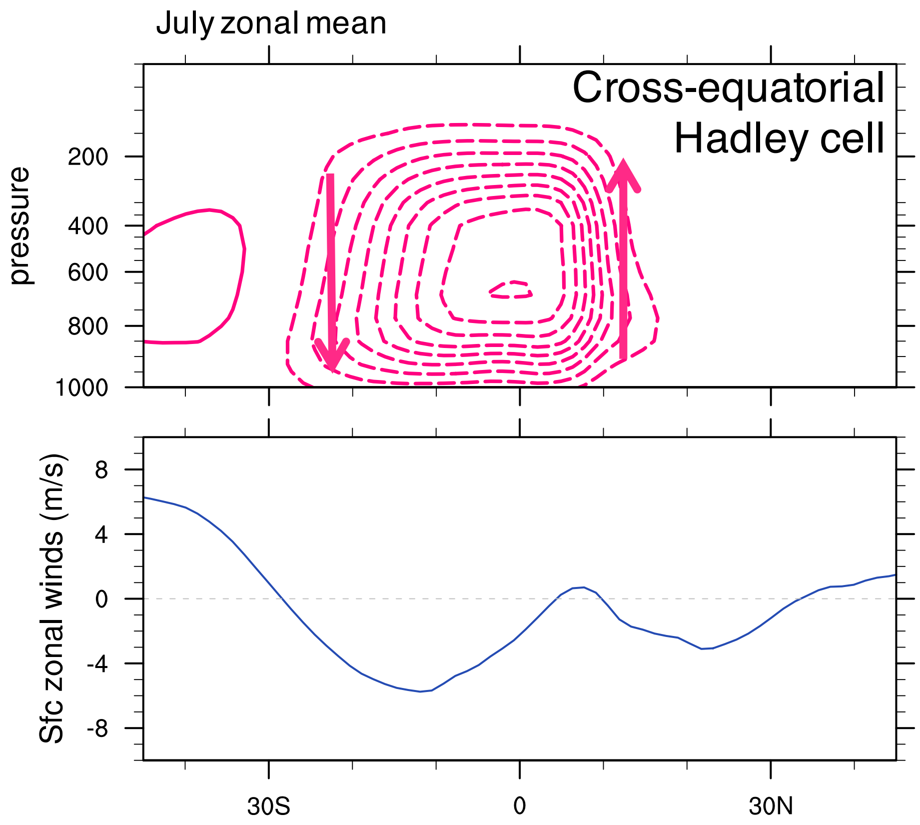
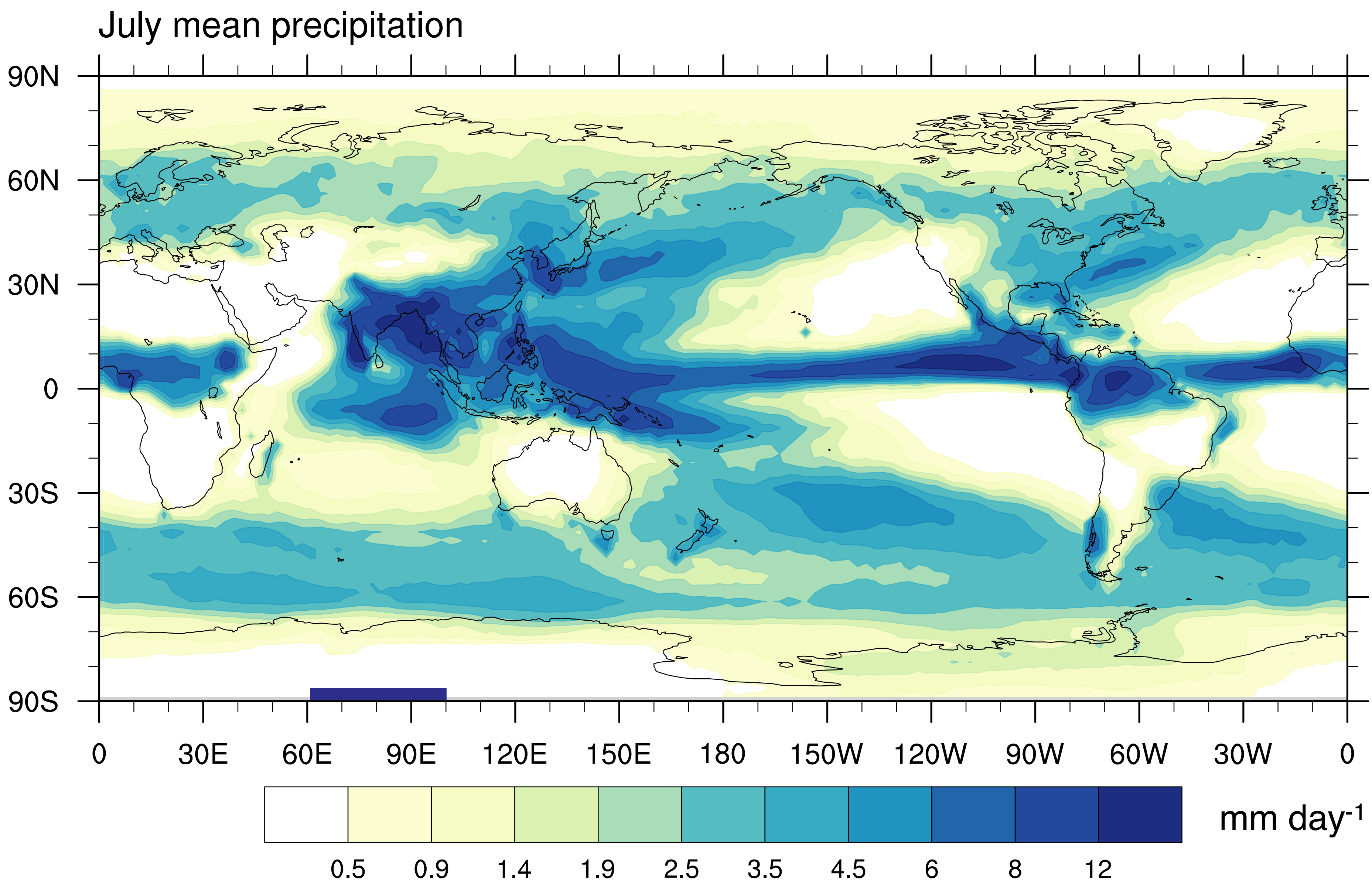


Data source: GPCP

Monsoons are part of the atmospheric overturning



When does it rain?



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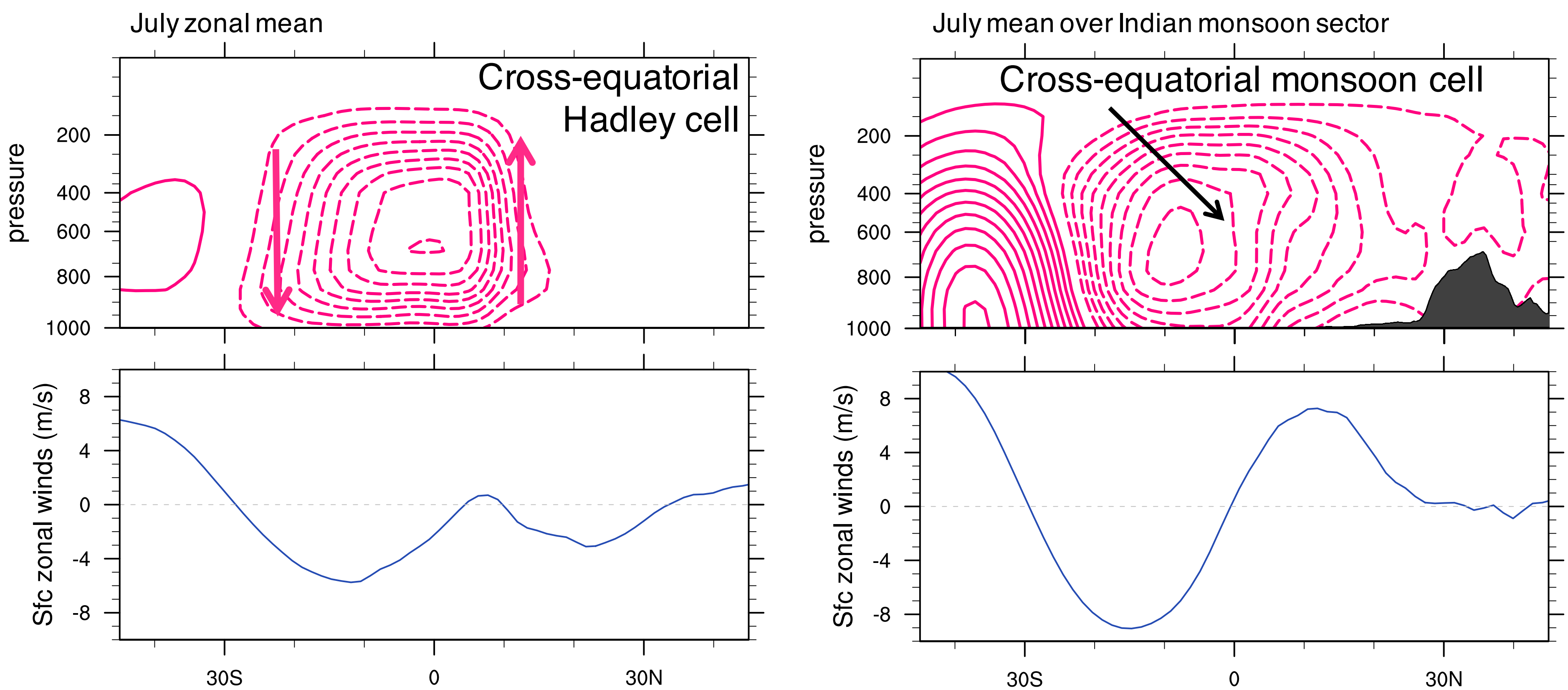
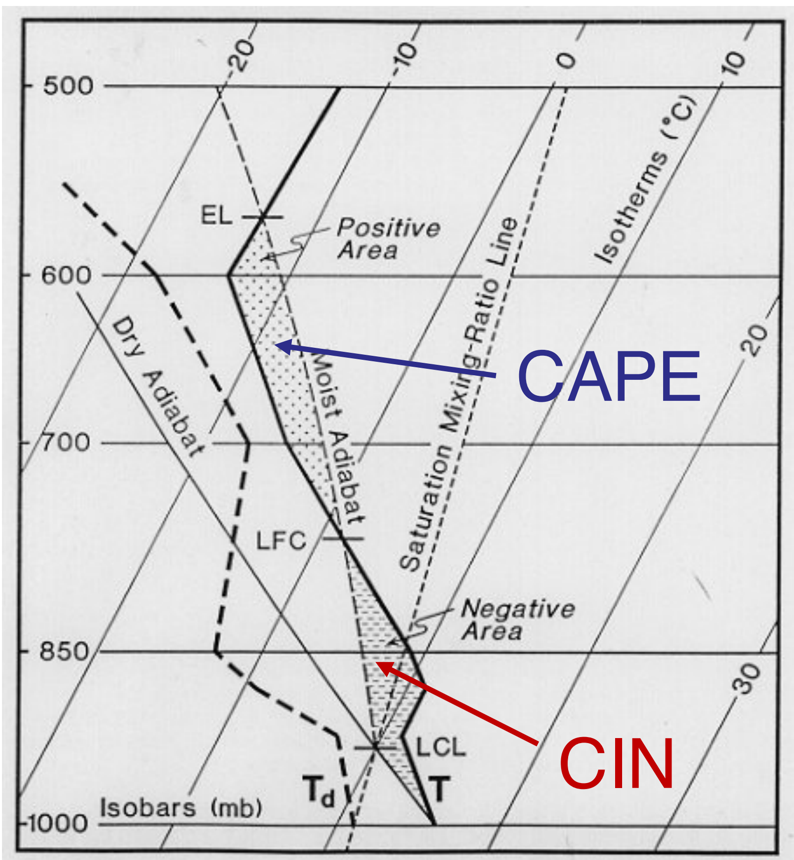


Monsoon circulations are cross-equatorial Hadley circulations that project strongly on the solstice zonal mean

e.g., Bordoni & Schneider (2008), Walker, Bordoni & Schneider (2015), Walker & Bordoni (2016)

Convection and large-scale circulations

- The concept of conditional instability has been central to the thinking about moist convection and its interaction with large-scale circulations;
- *Conditional* implies that the instability is finite amplitude in nature:



- The existence of CIN acts as a barrier to convection;
- Only large perturbations can trigger convection;
- But *unambiguosly* conditionally unstable profiles have only been demonstrated over continental areas.

Is convection a heat source for large-scale circulations?

- In this external view, energy released by convection *drives* the flow:
  - Latent heat released typically exceeds energy required to maintain the KE of large-scale motions against dissipation;
  - Latent heating leads to KE production.

- But this energy conversion requires positive correlation between heating and temperature fluctuations:
  - No *a priori* reason for this to be the case;
  - In fact, latent heat release is largely balanced by radiative and adiabatic cooling – any residual is a small percentage of large compensating terms.

Convective quasi-equilibrium

- Convective scale processes act on timescales that are much smaller than those of large-scale processes;
- Convection consumes CAPE as soon as it is generated by radiation or large-scale flow;
- CAPE can be non-zero, but it’s rate of change is approximately zero. For typical tropical conditions, net surface flux and column radiative cooling generate ~4000 J $kg^{-1}day^{-1}$, while CAPE values are below 1000 J $kg^{-1}day^{-1}$.
- The fact that CAPE is largely invariant has important implications for the temperature of convective atmospheres:
    - Moist convection does not act as a heat source for large-scale flow, but maintains free troposphere close to a moist adiabat;
    - Changes in free tropospheric temperatures are in equilibrium with changes in boundary-layer moist static energy.

e.g., Emanuel et al. (1994)

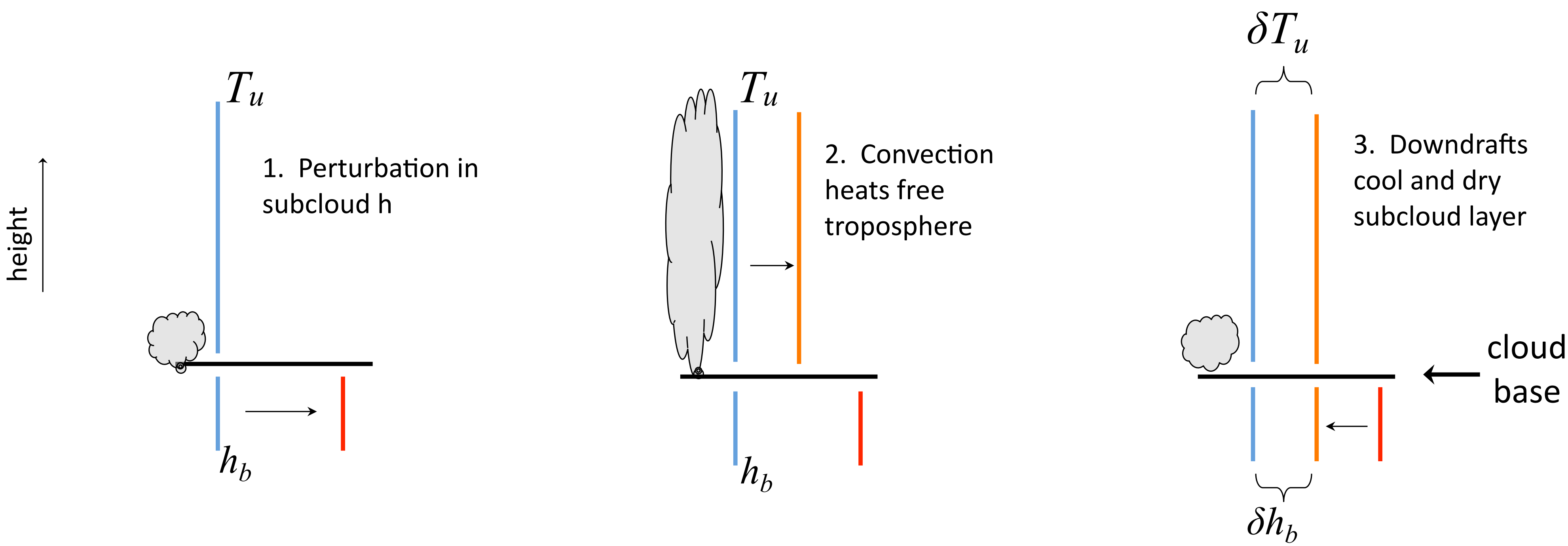
CQE and convectively coupled large-scale circulations

$$\delta T_u \sim \delta h_b$$

Free-tropospheric temperature

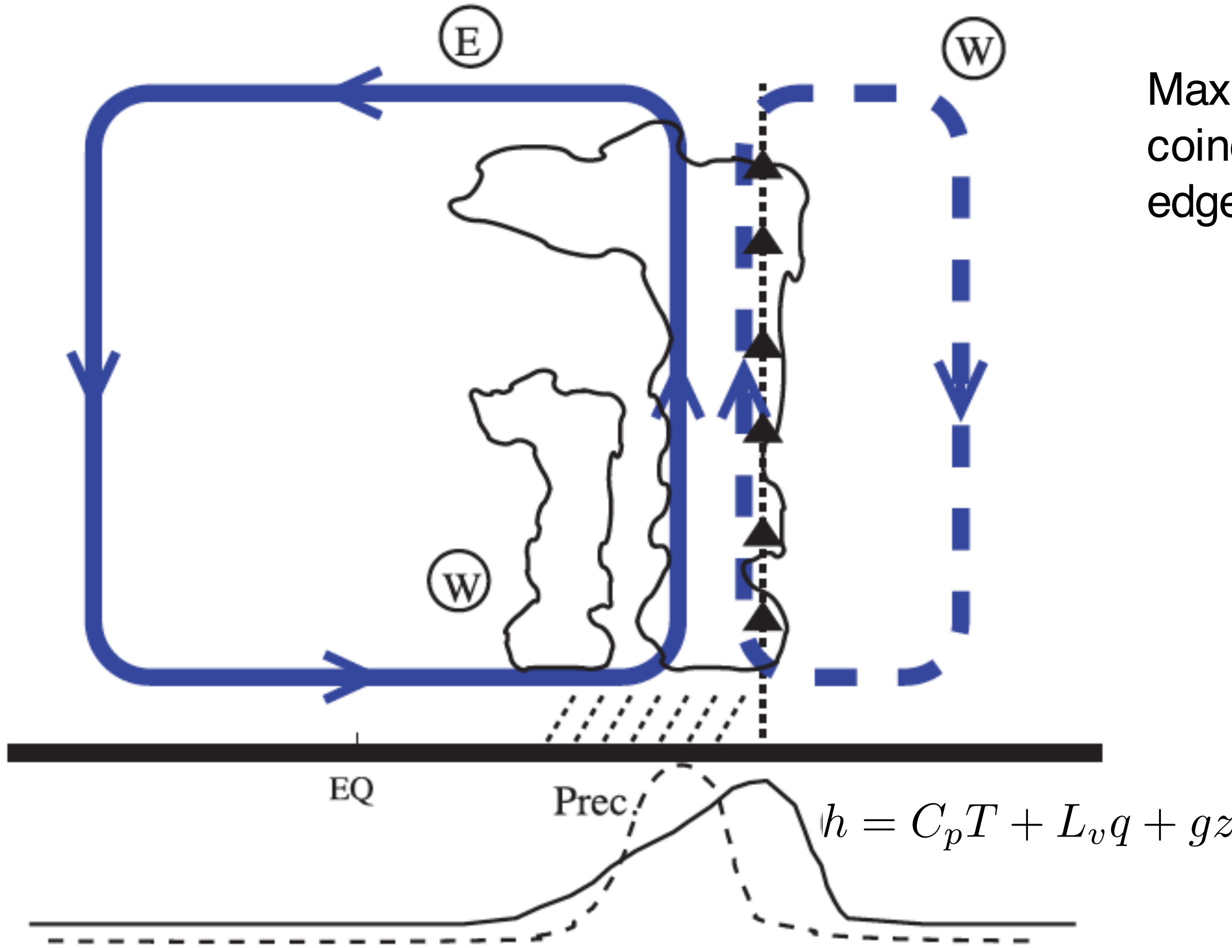
Subcloud MSE

$$C_p T + L_v q + gz$$



Courtesy Bill Boos

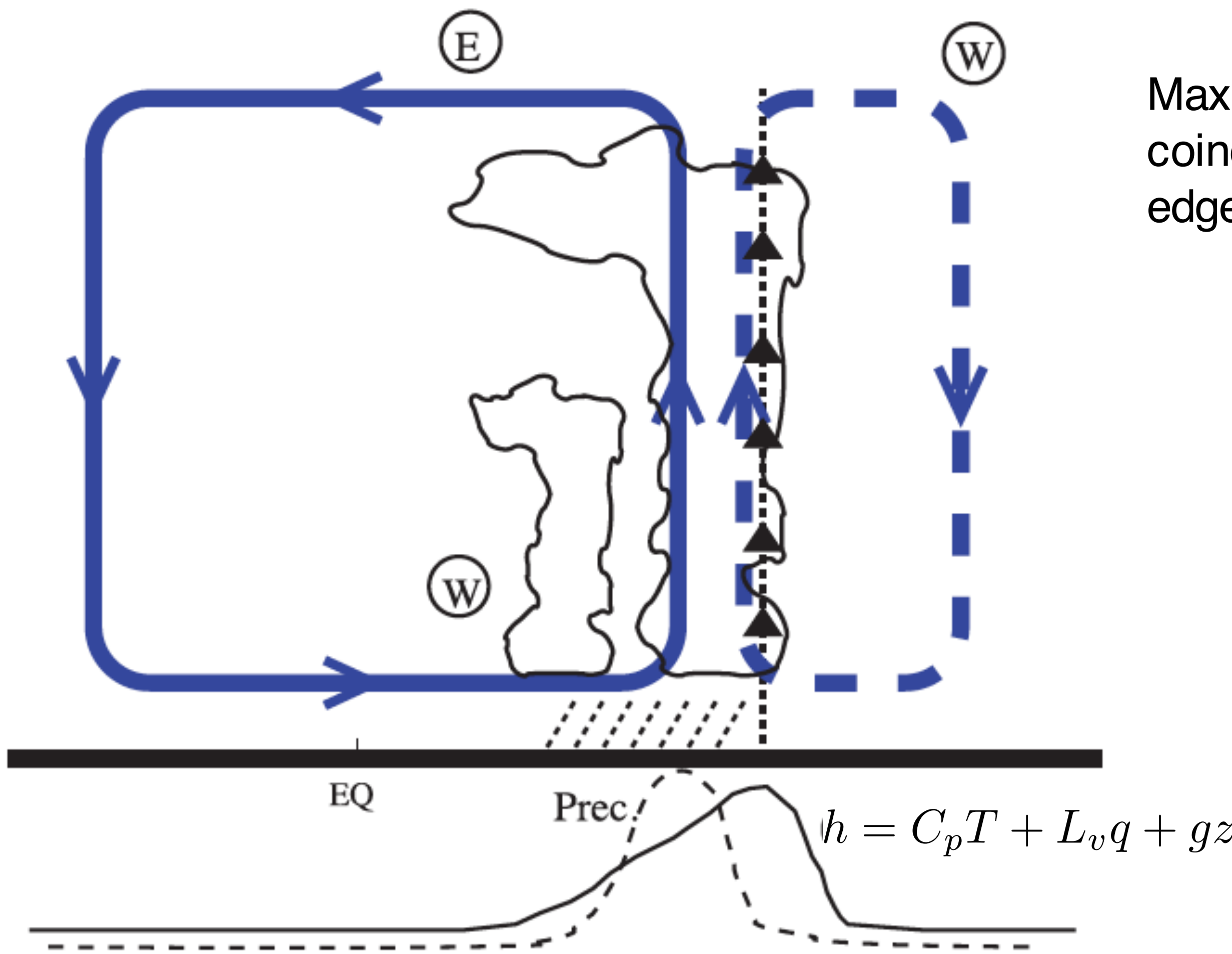
Convectively coupled view of cross-equatorial Hadley cells



Maxima of T_u and h_b coincide at poleward edge of cell

e.g., Emanuel et al. (1994), Emanuel (1995), Prive and Plumb (2007), Nie et al. (2010)

Convectively coupled view of cross-equatorial Hadley cells

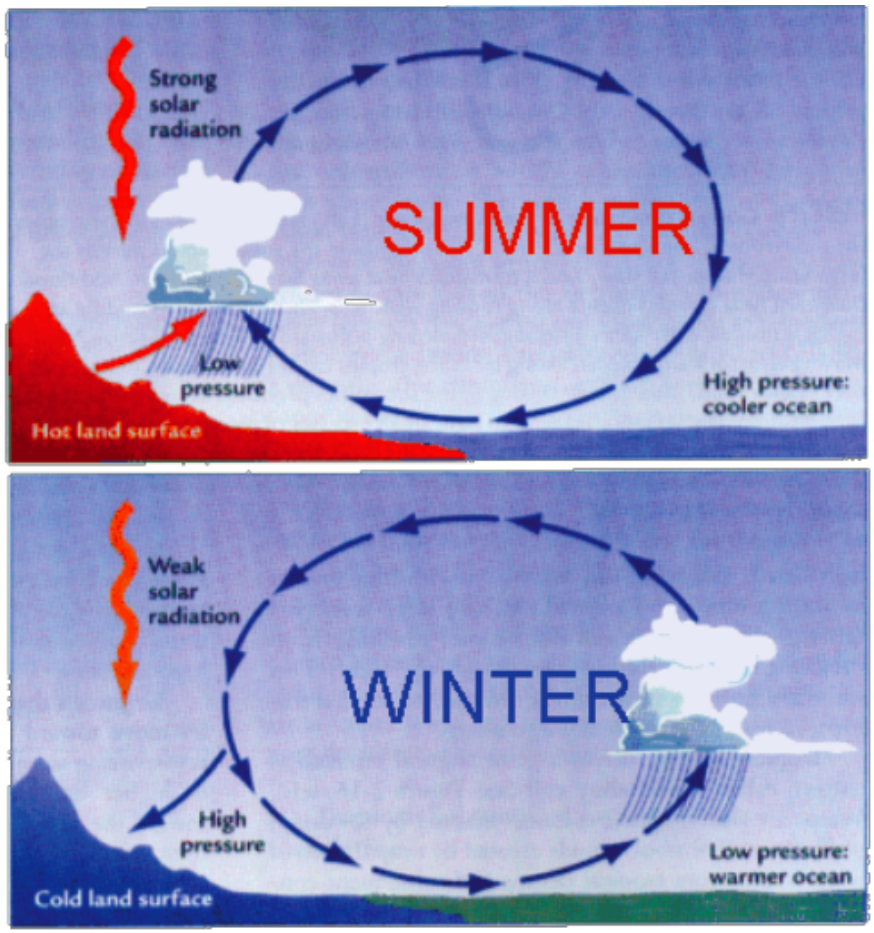


Maxima of T_u and h_b coincide at poleward edge of cell

Monsoons are NOT driven by near-surface temperature gradients!

e.g., Emanuel et al. (1994), Emanuel (1995), Prive and Plumb (2007), Nie et al. (2010)

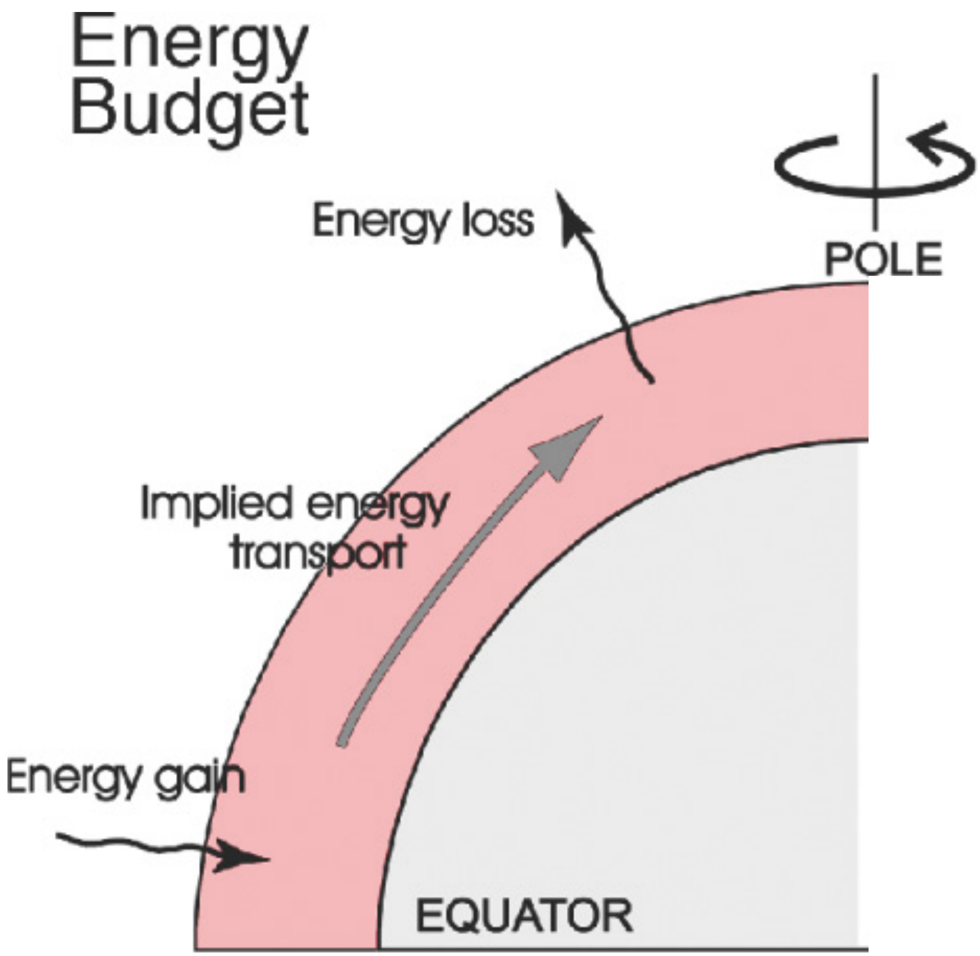
Monsoons are not large-scale sea breeze circulations!



Monsoons are NOT driven by near-surface temperature gradients!

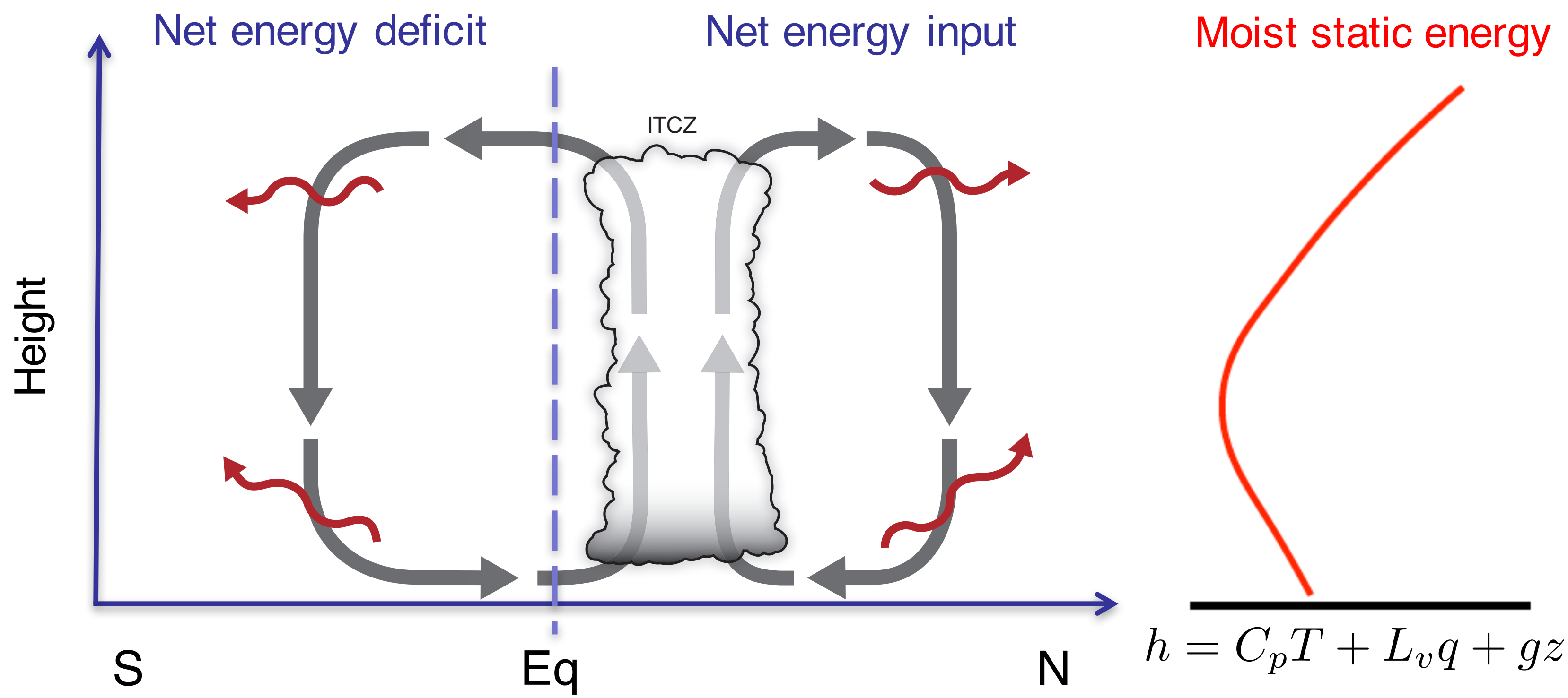
e.g., Ruddiman (2007)

What drives Hadley and monsoonal circulations



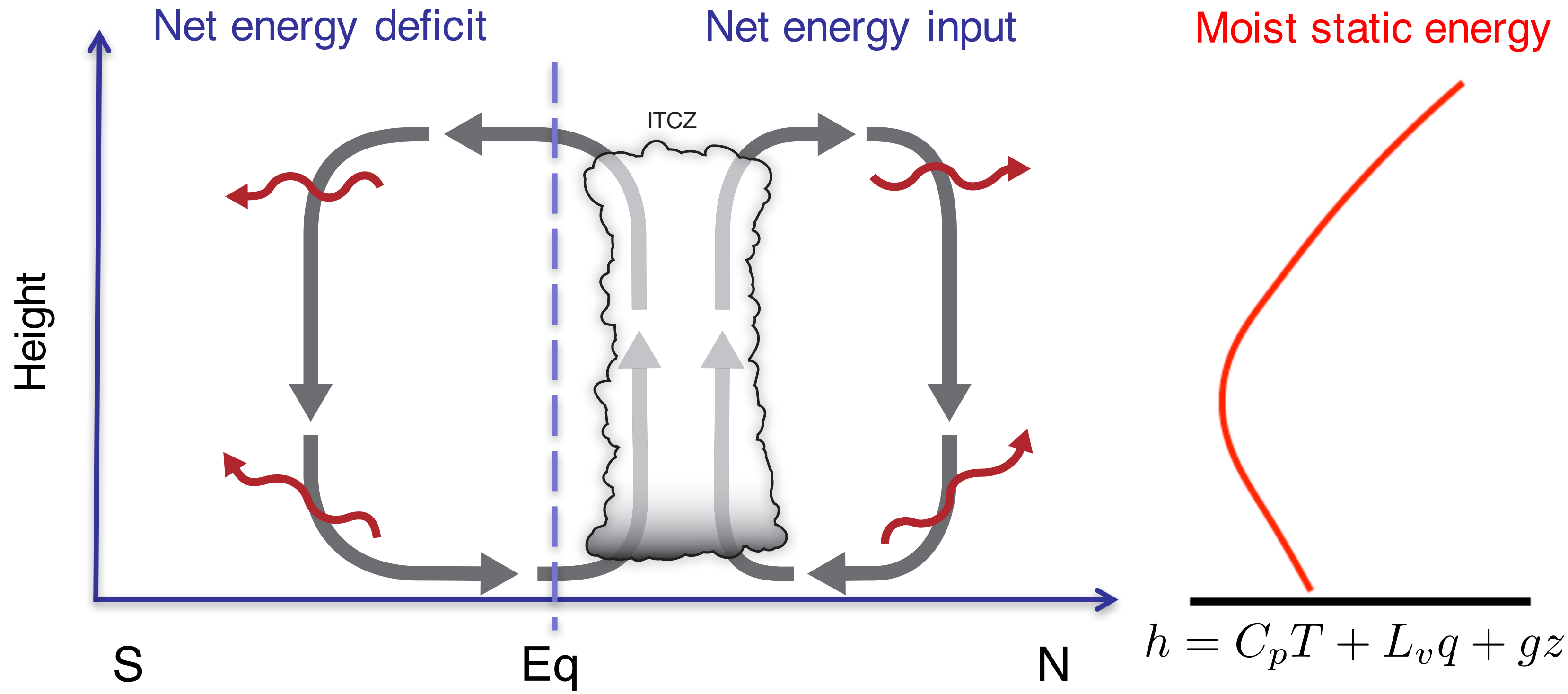
Transport energy from regions (or hemisphere) with net energy gain to regions (or hemisphere) of net energy loss

Energetically-direct circulations



Adapted from Schneider et al. 2014

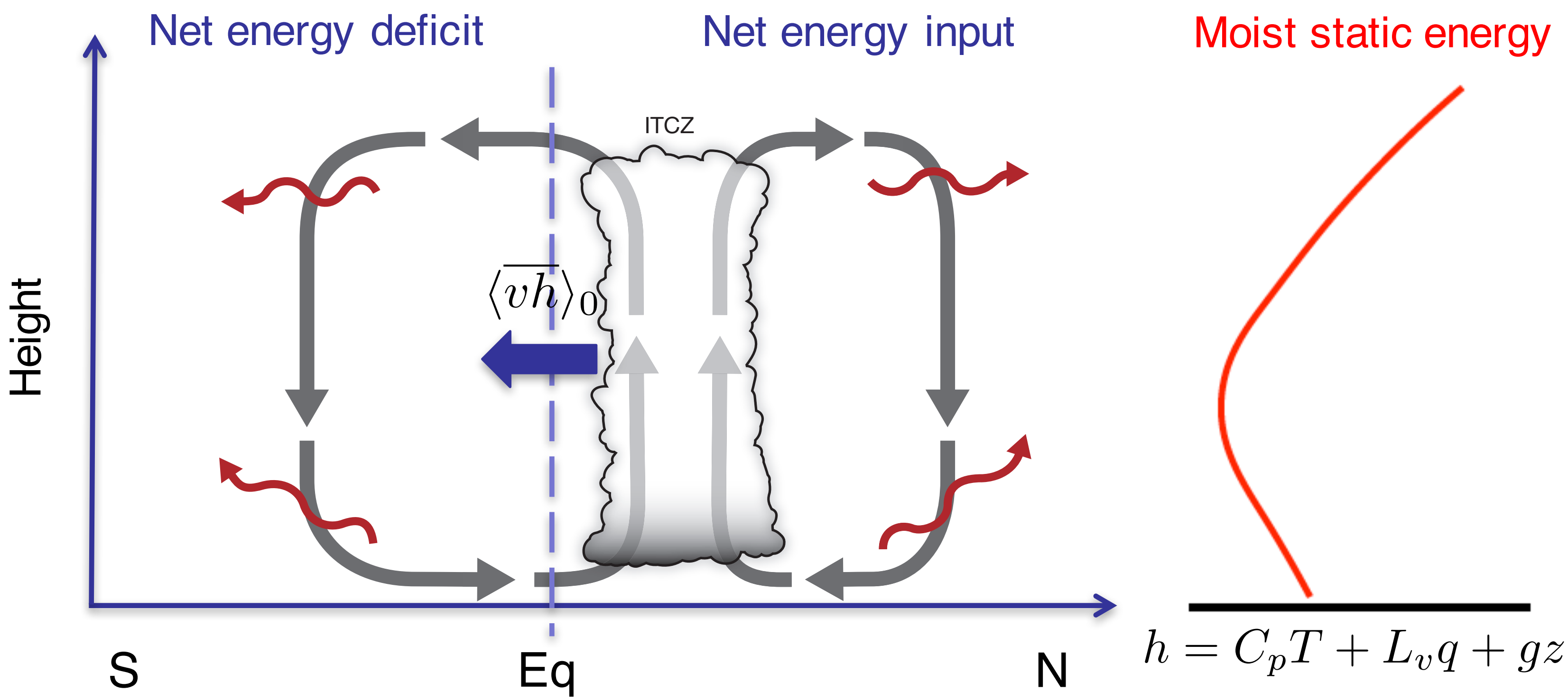
Energetically-direct circulations



Weaker energy stratification in moist circulations require a stronger circulation to accomplish same energy transport as dry circulations. Moist circulations are less efficient than dry circulations.

Adapted from Schneider et al. 2014

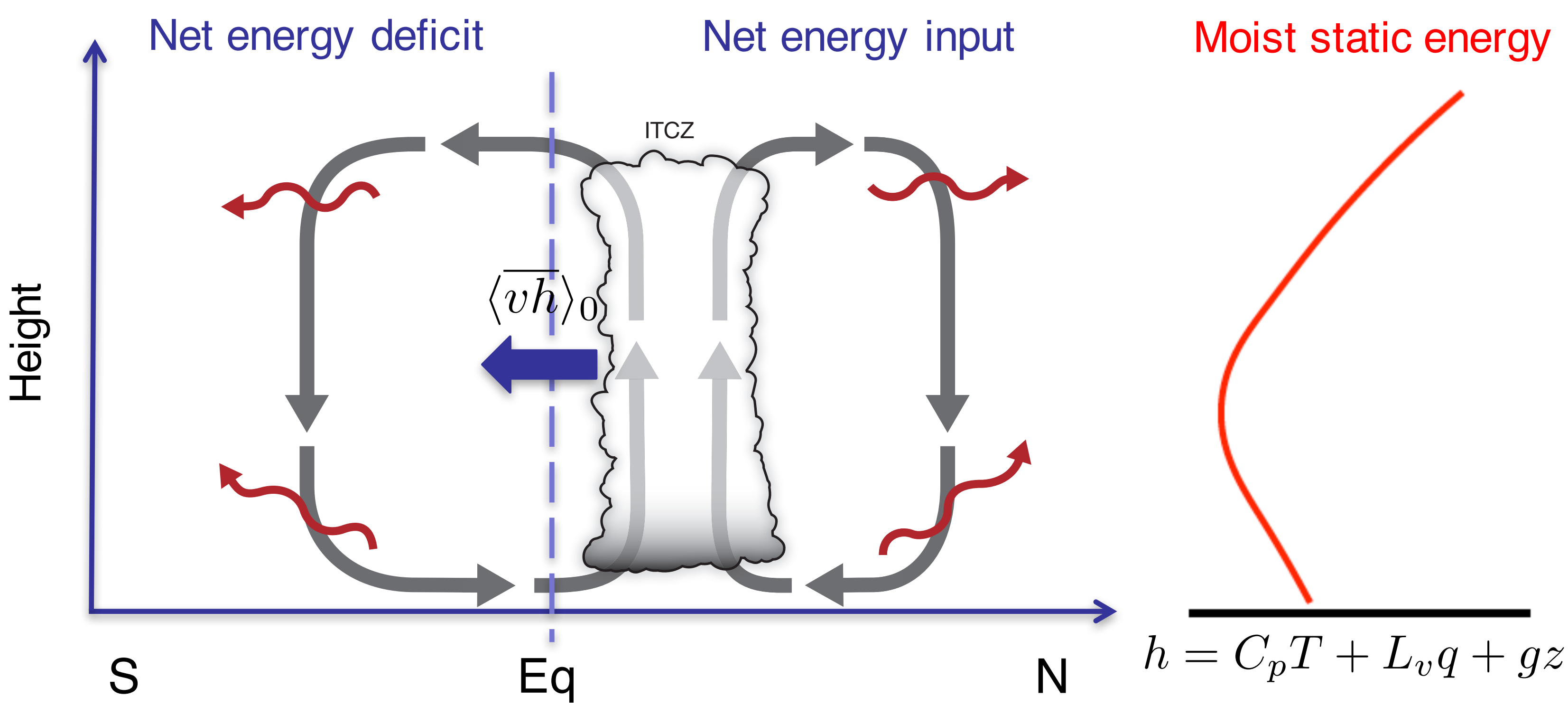
Energetically-direct circulations



Because MSE is positively stratified, Hadley and monsoonal circulations transport energy in the direction of the upper-level flow.

Adapted from Schneider et al. 2014

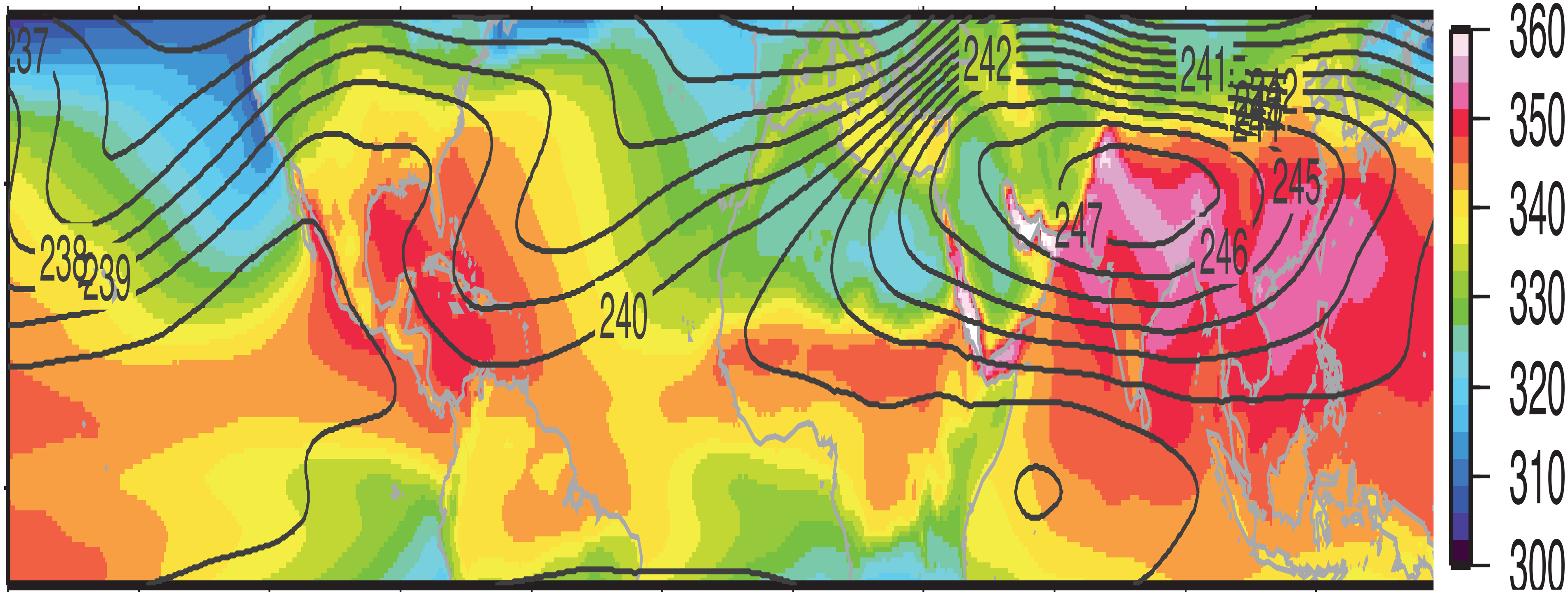
Energetically-direct circulations



The fact that the ITCZ is shifted north of the equator implies that the NH receives more energy than the SH: primarily due to ocean heat transport.

e.g., Marshall et al. (2014), Frierson et al. (2013)

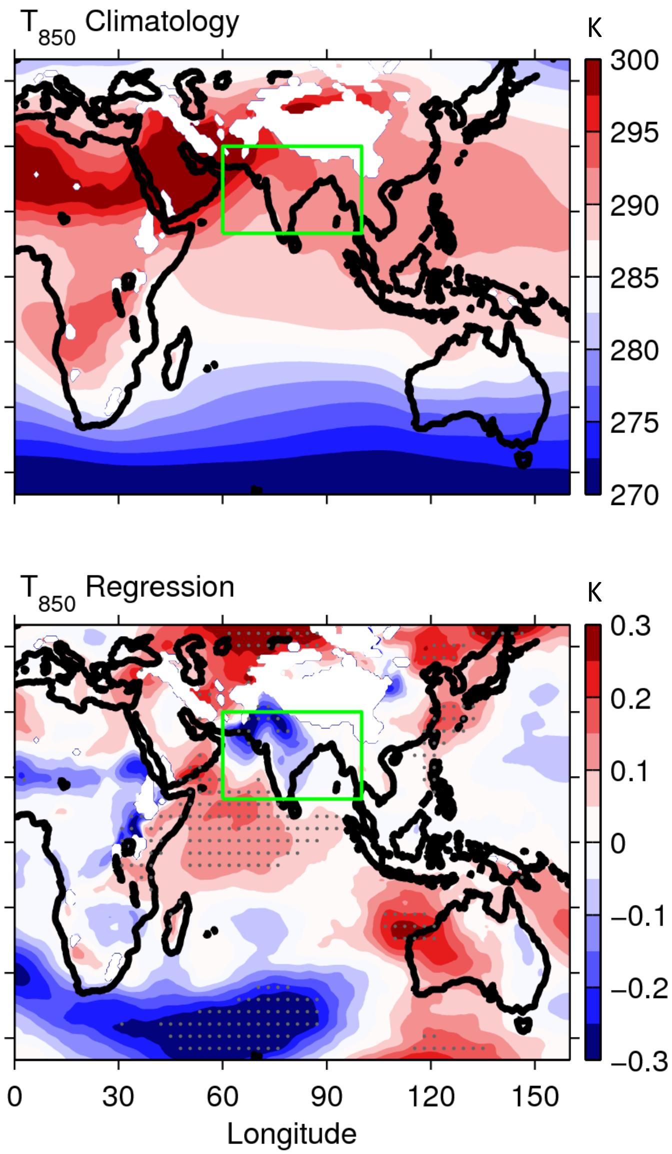
Observational evidence

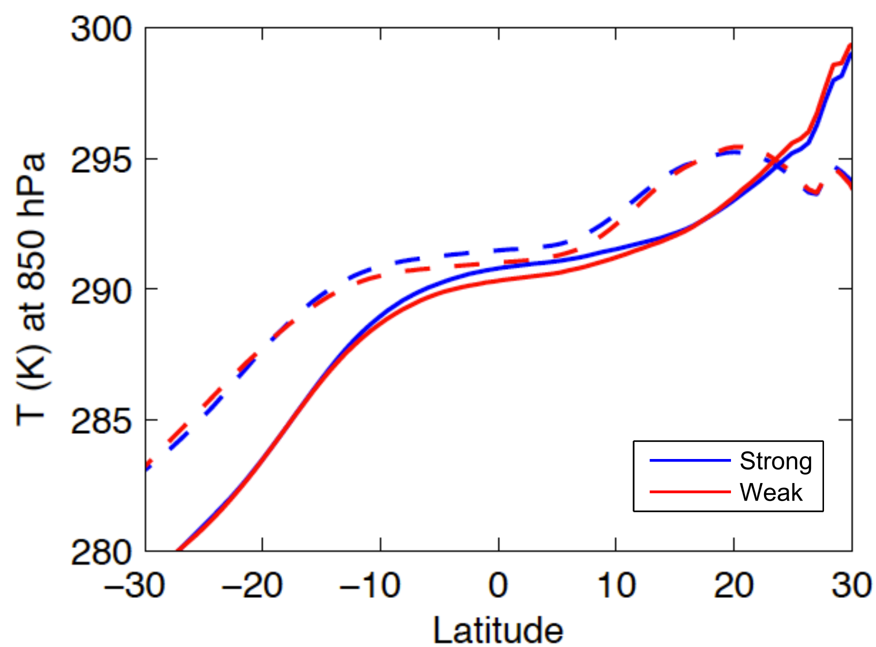


July climatology
Contours: 200-400 hPa temperature (K)
Colors: surface air moist static energy ($c_p T + g z + L_v q$), in K)

Boos and Hurley (2013)

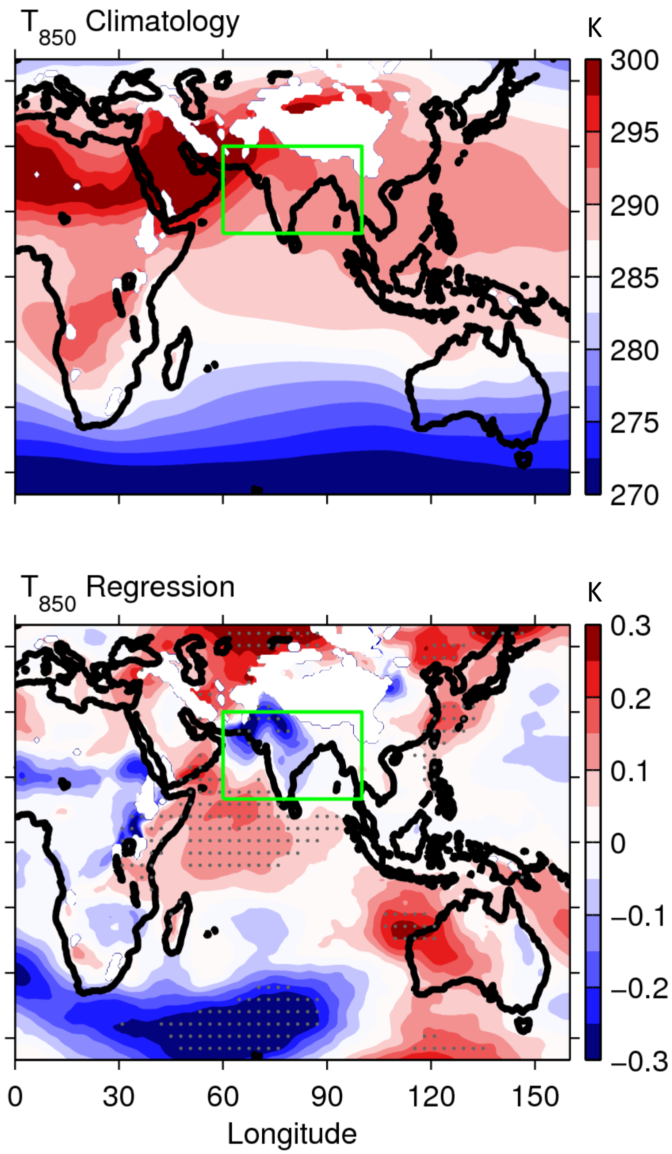
Also true on interannual timescales



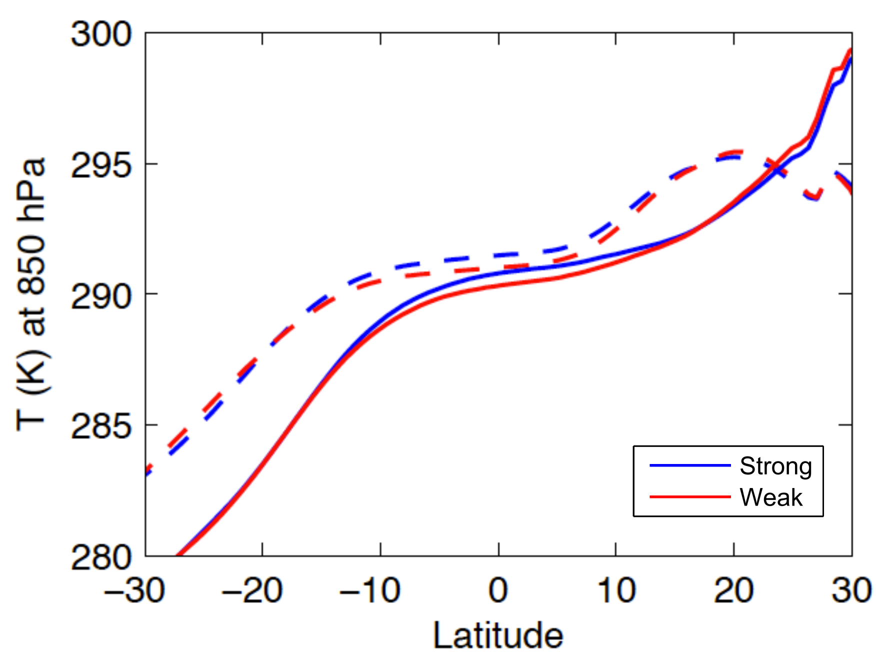


Walker, Bordoni and Schneider (2015)

Also true on interannual timescales

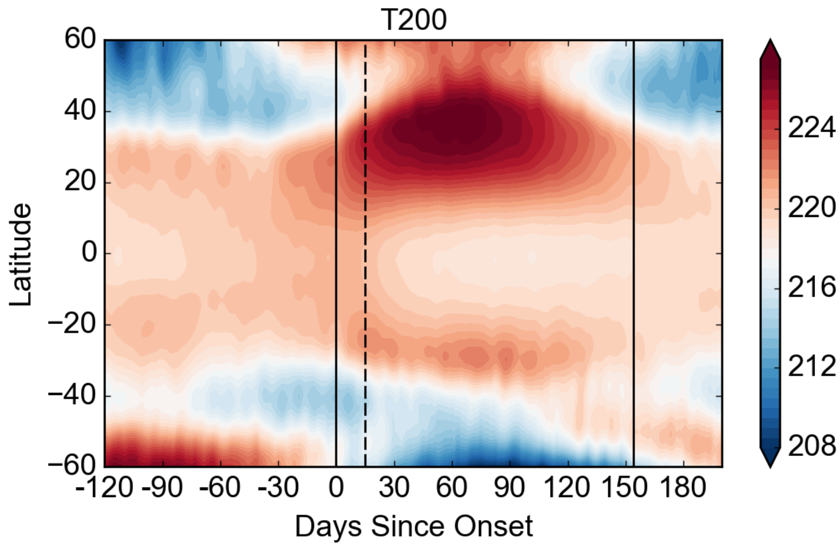


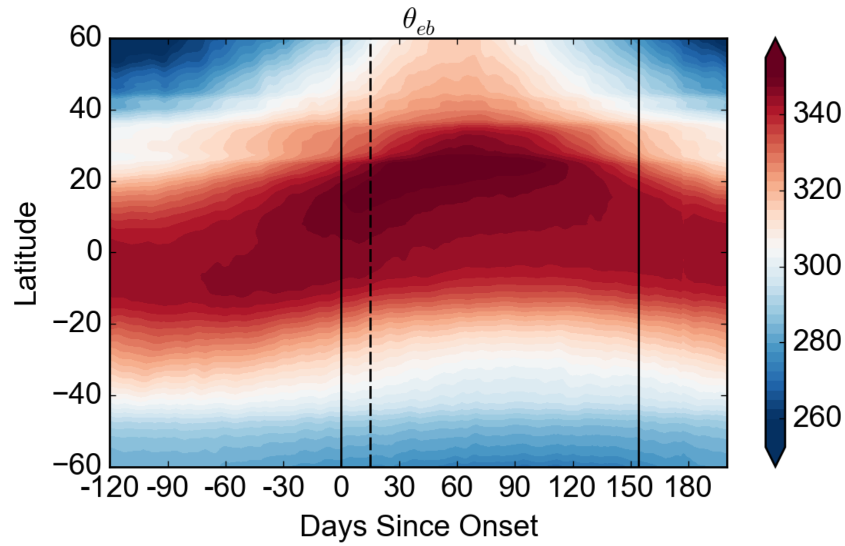
Strong monsoon years are characterized by a **weaker** near-surface meridional temperature gradient



Walker, Bordoni and Schneider (2015)

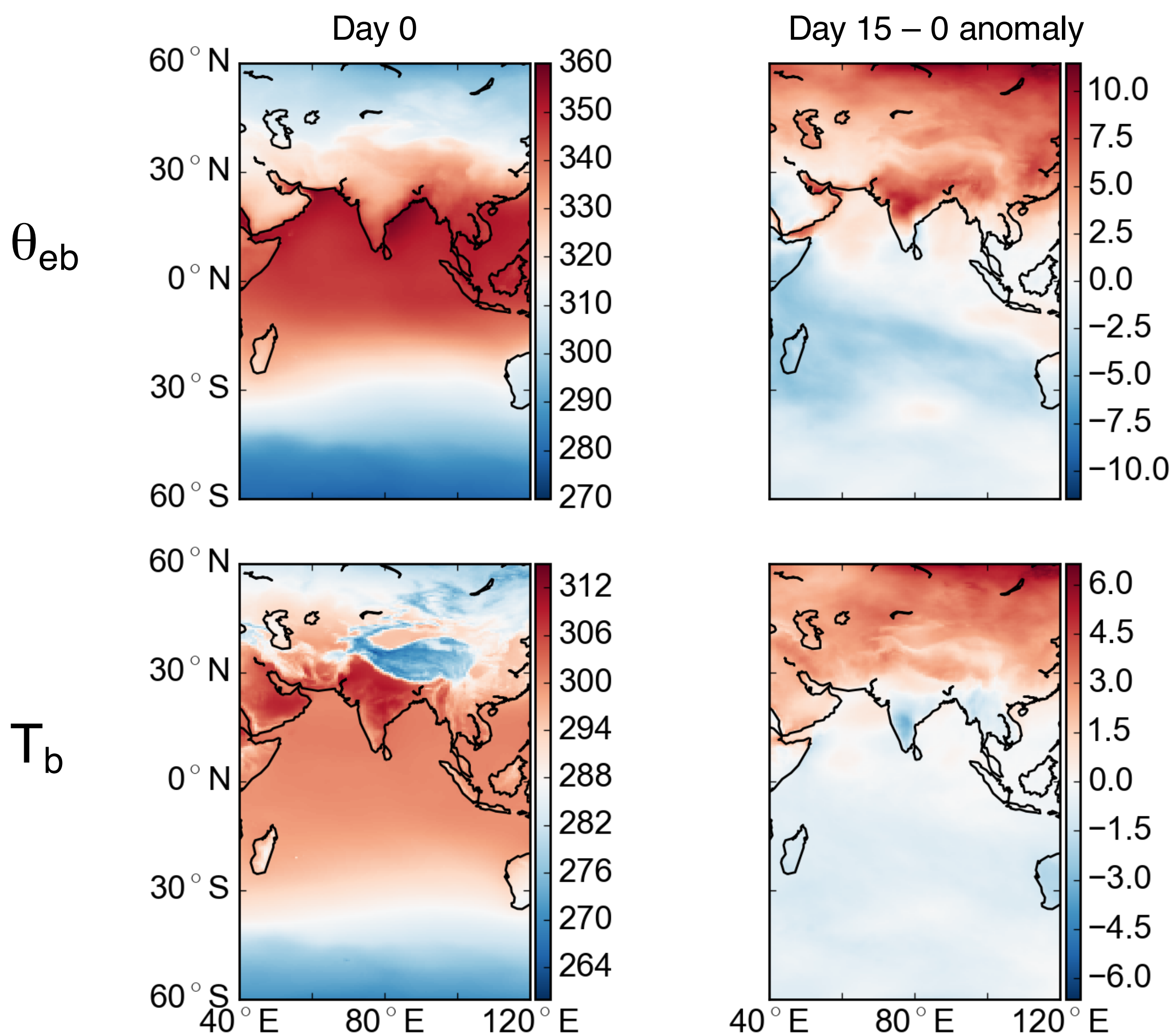
And on intraseasonal timescales





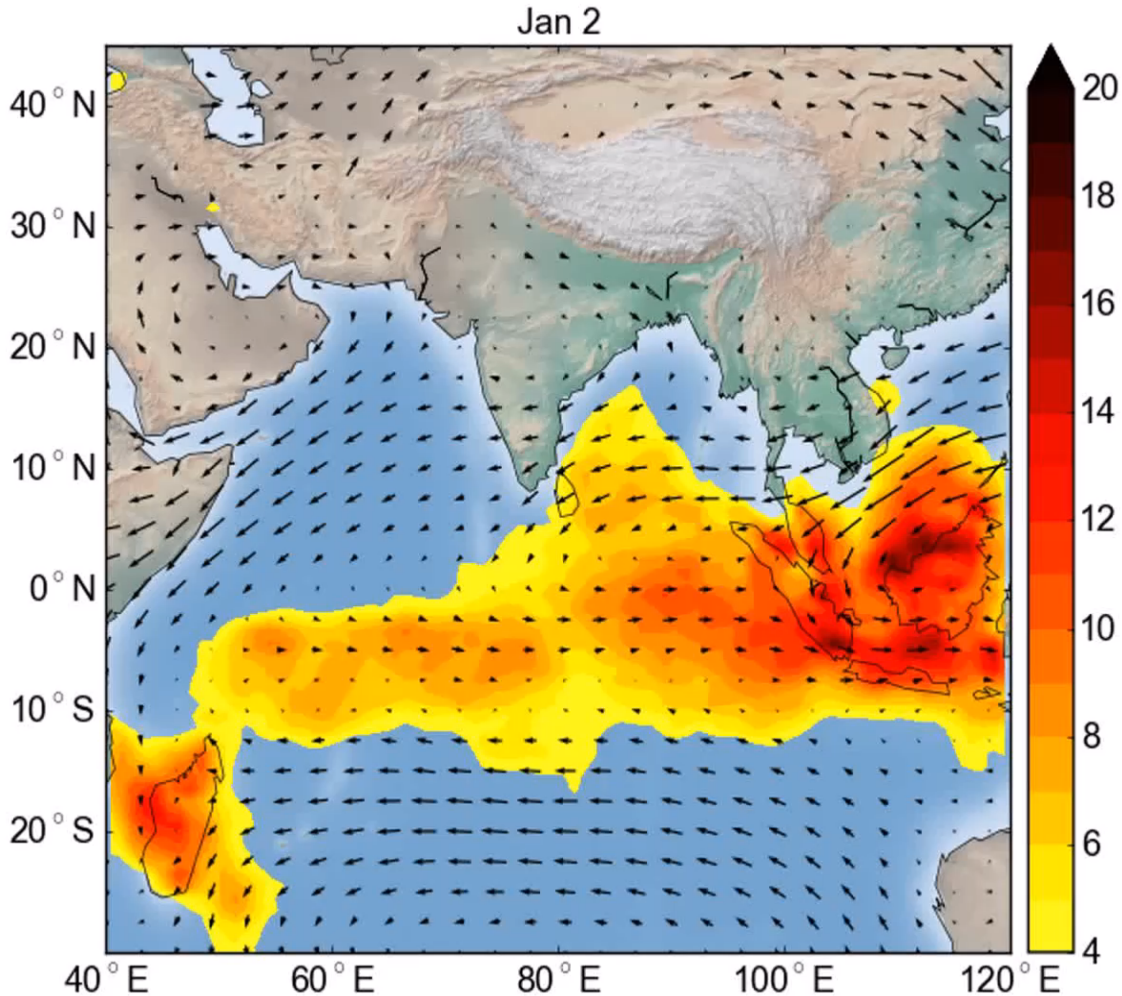
Walker and Bordoni, *in prep*

And on intraseasonal timescales



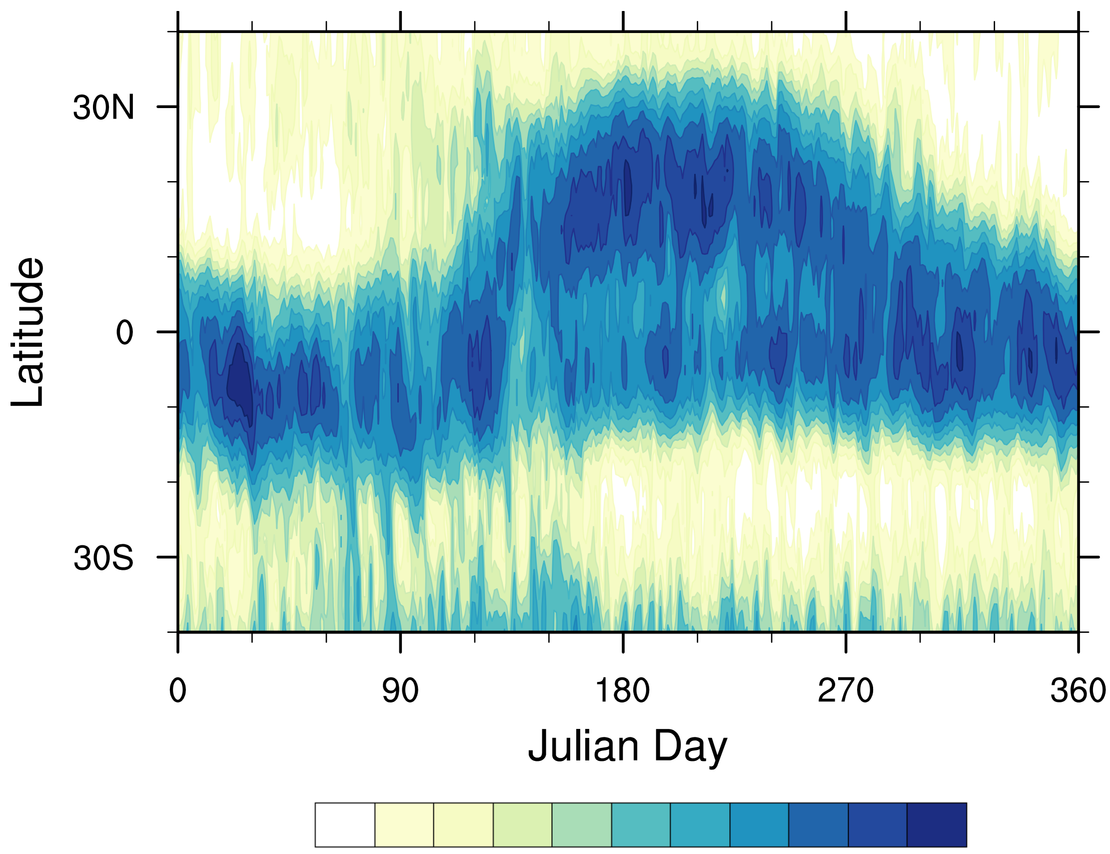
Walker and Bordoni, *in prep*

Rapid onset

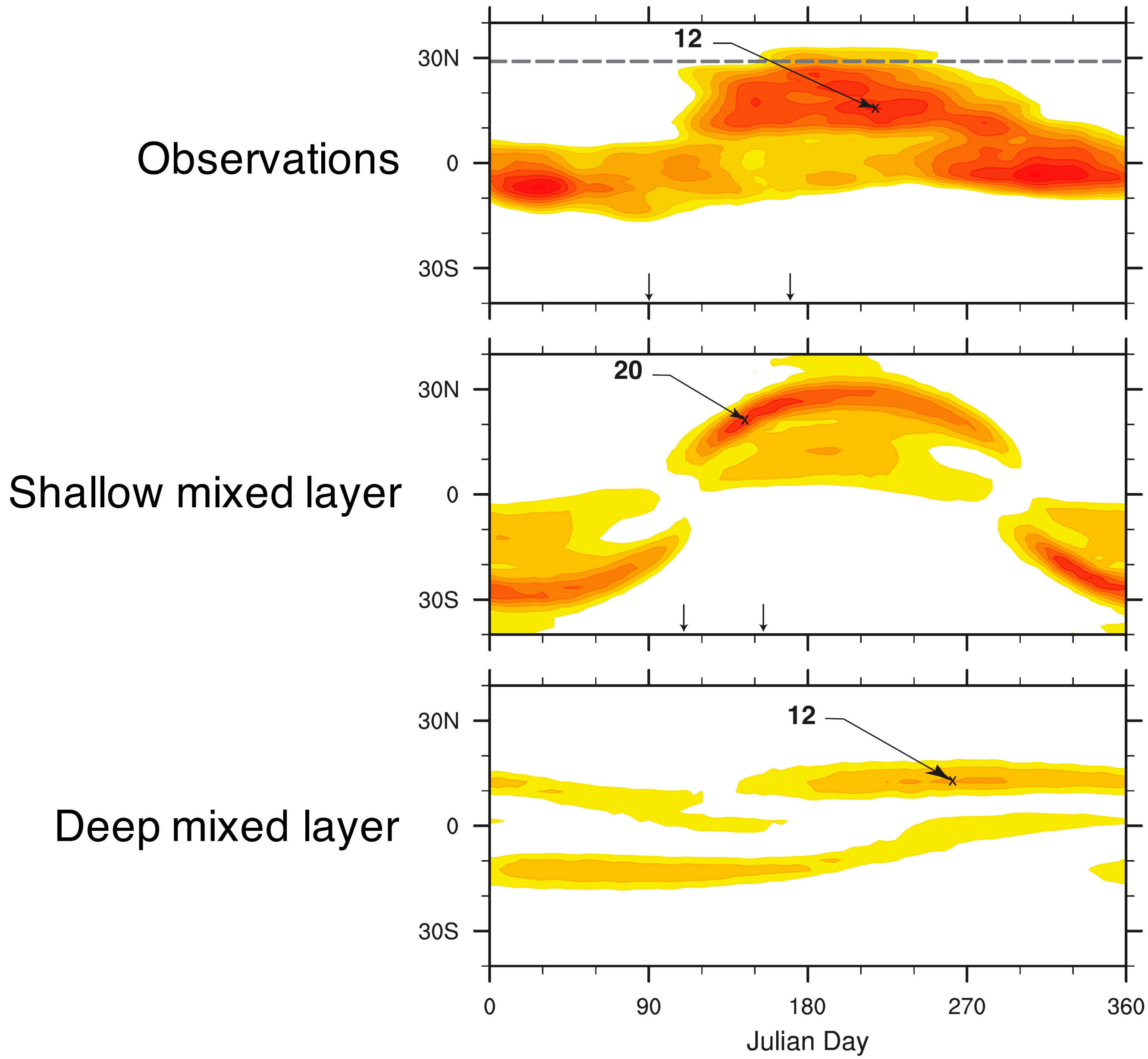


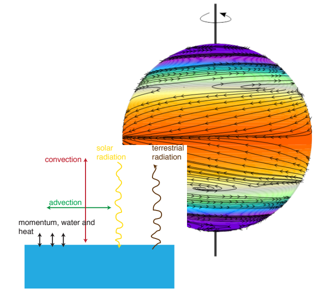
Jan 2
40° N
30° N
20° N
10° N
0° N
10° S
20° S
40° E
60° E
80° E
100° E
120° E
20
18
16
14
12
10
8
6
4

Rapid onset

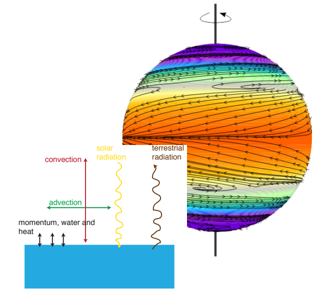

30N
0
30S
Latitude
0
90
180
270
360
Julian Day
0.5 0.9 1.4 1.9 2.5 3.5 4.5 6 8 10

Monsoons can exist over an aquaplanet





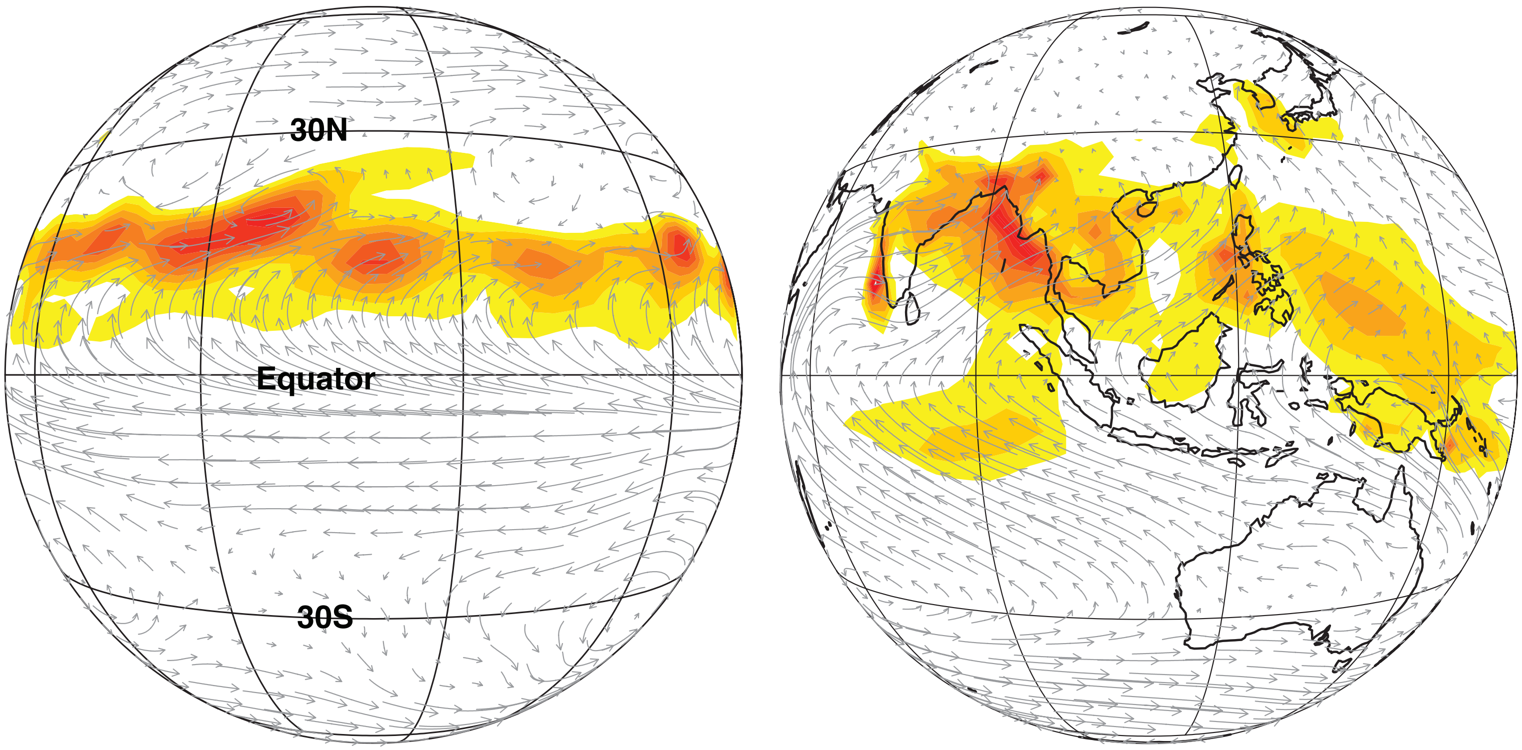
Bordoni & Schneider (2008)



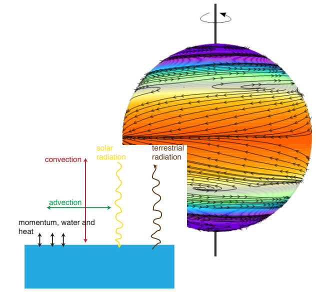
Monsoons can exist over an aquaplanet

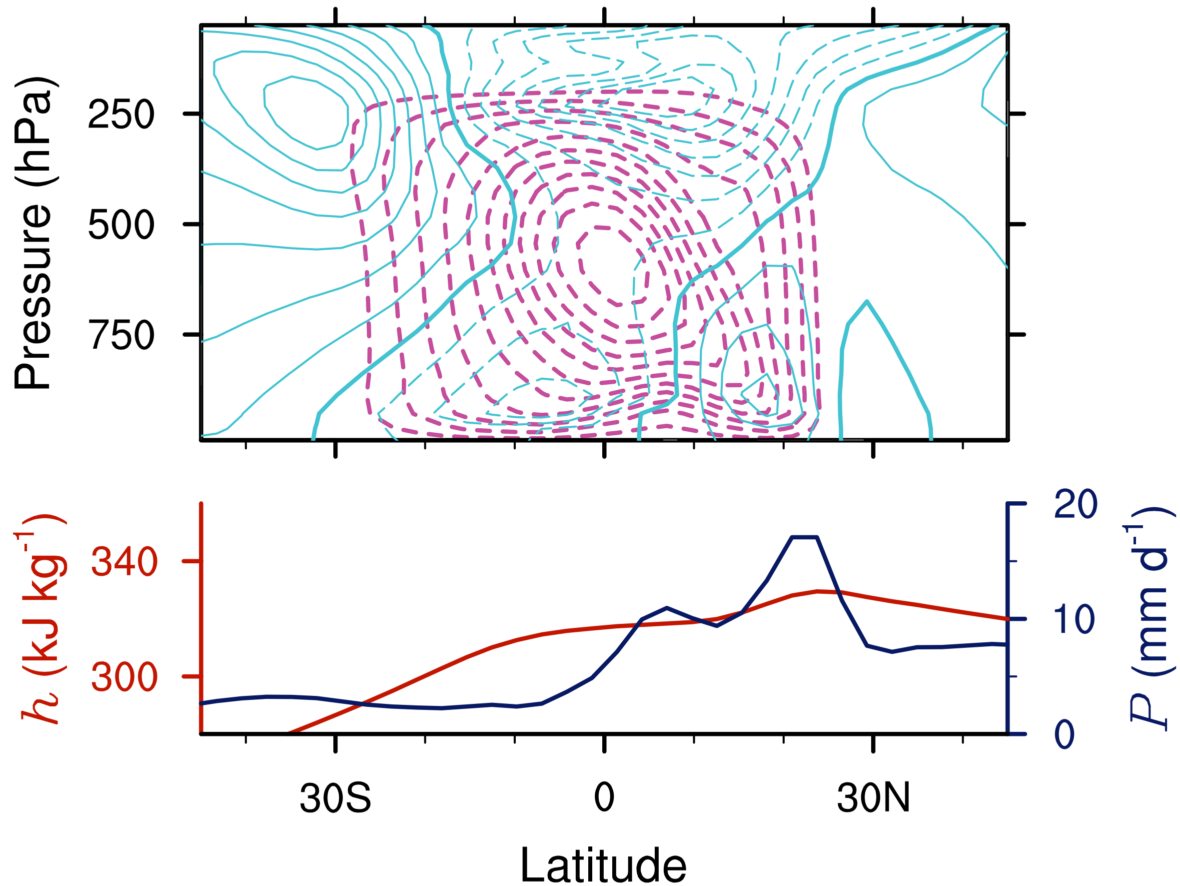
Aquaplanet

Observations



Monsoons can exist over an aquaplanet

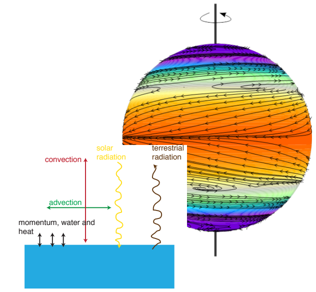


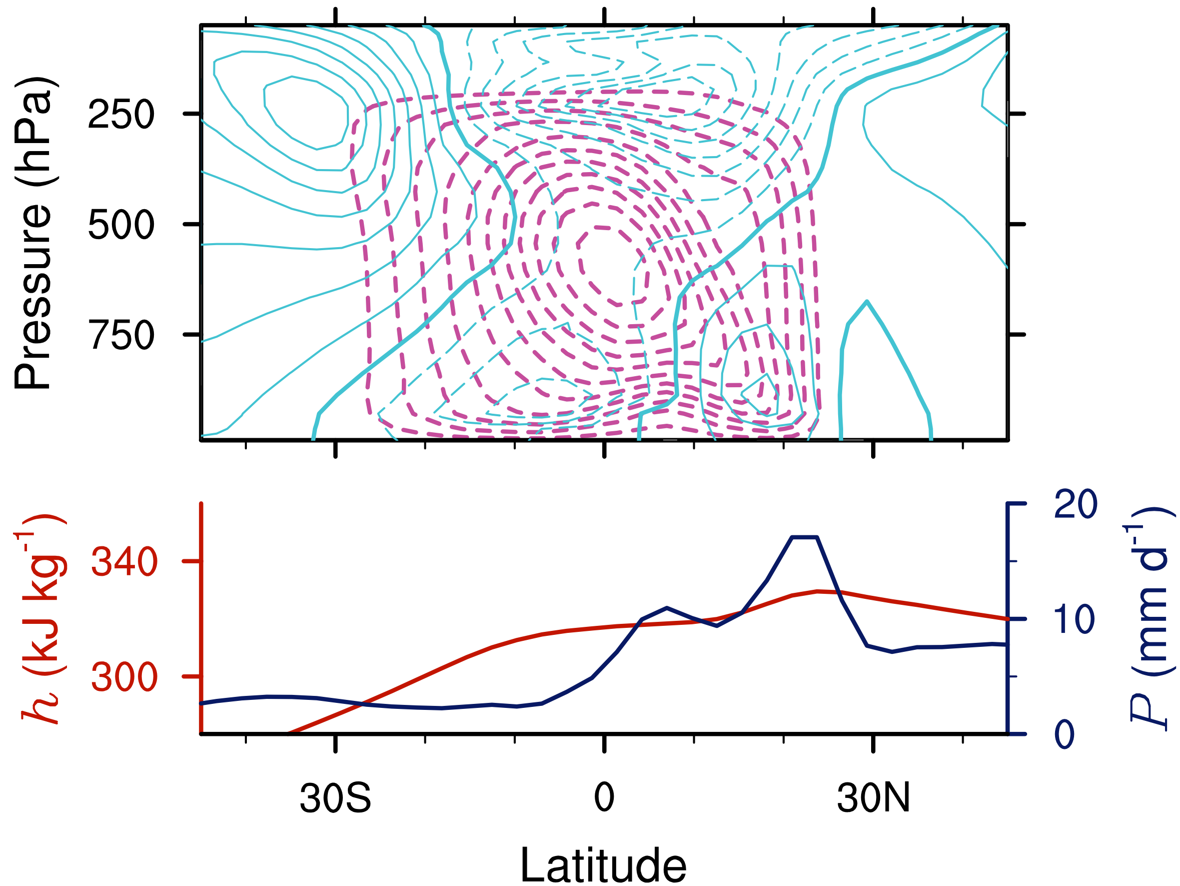


The reversed meridional temperature gradient can develop even without a subtropical landmass (let alone topography!)

Adapted from Bordoni & Schneider (2008)

Monsoons can exist over an aquaplanet

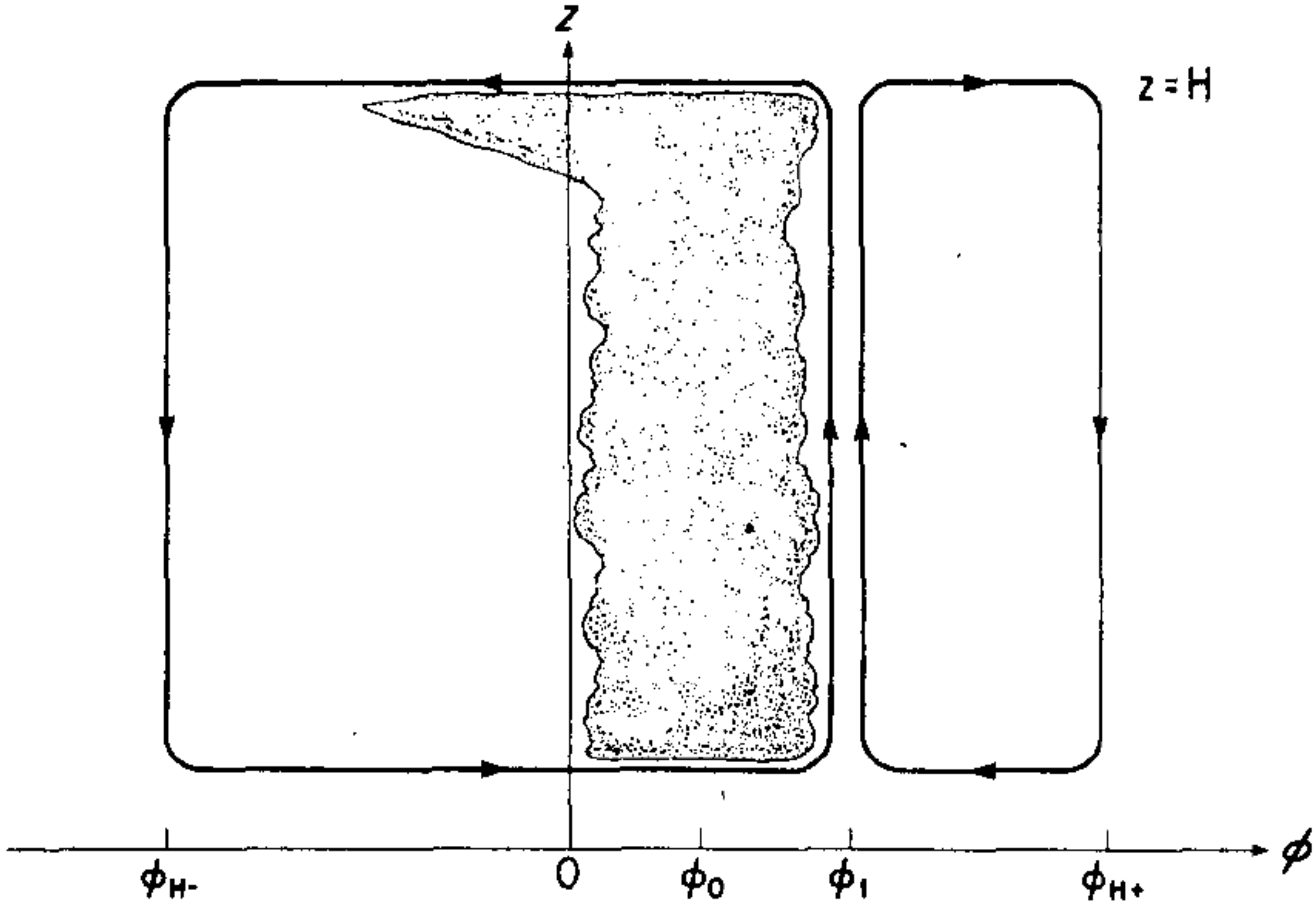




What drives the rapid development of a monsoon in these simulations?

Adapted from Bordoni & Schneider (2008)

Angular momentum-conserving cross-equatorial HC

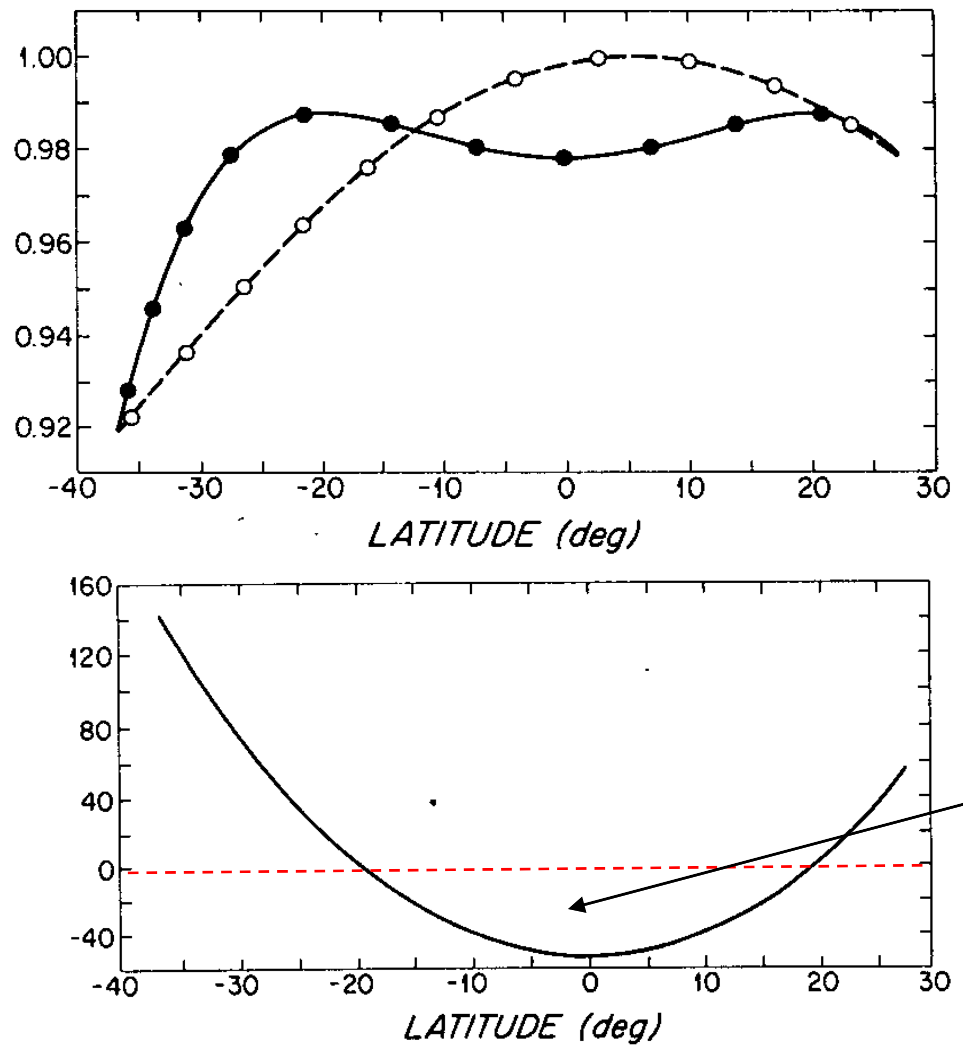


Lindzen and Hou (1988)

Angular momentum-conserving cross-equatorial HC

Potential temperature

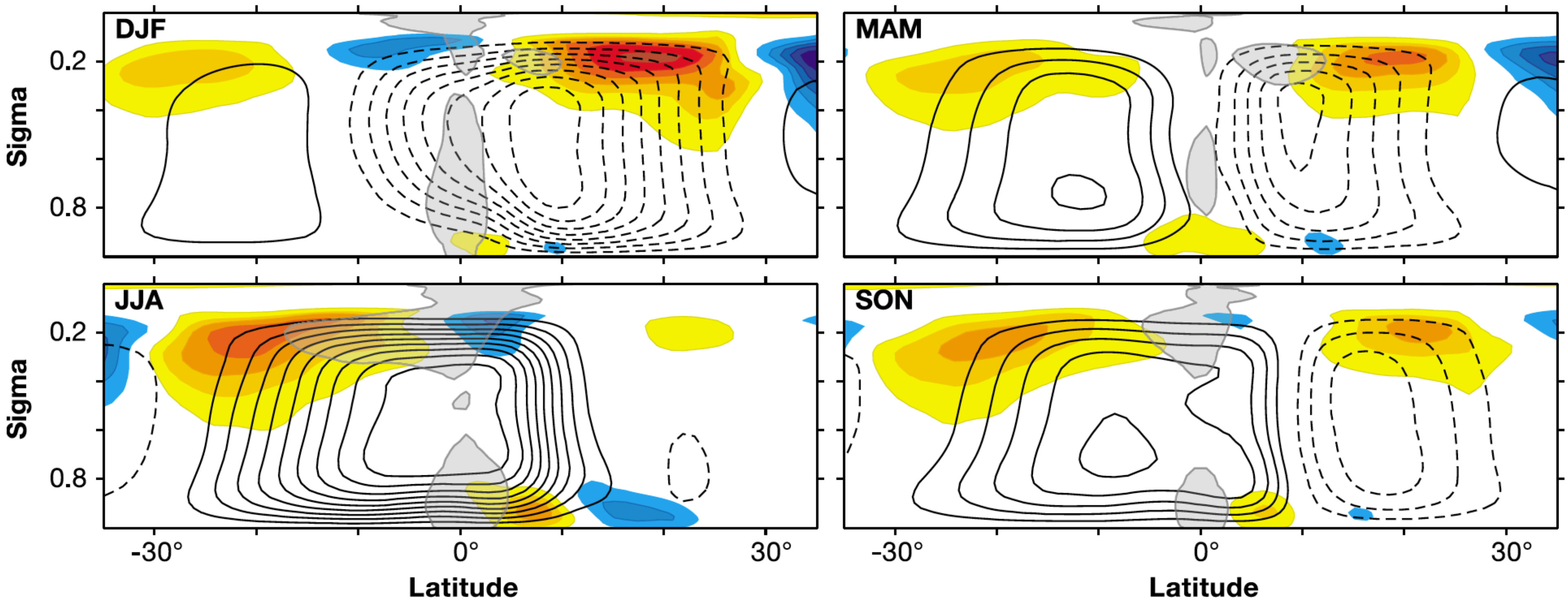
Zonal winds



Upper-level easterlies!

Lindzen and Hou (1988)

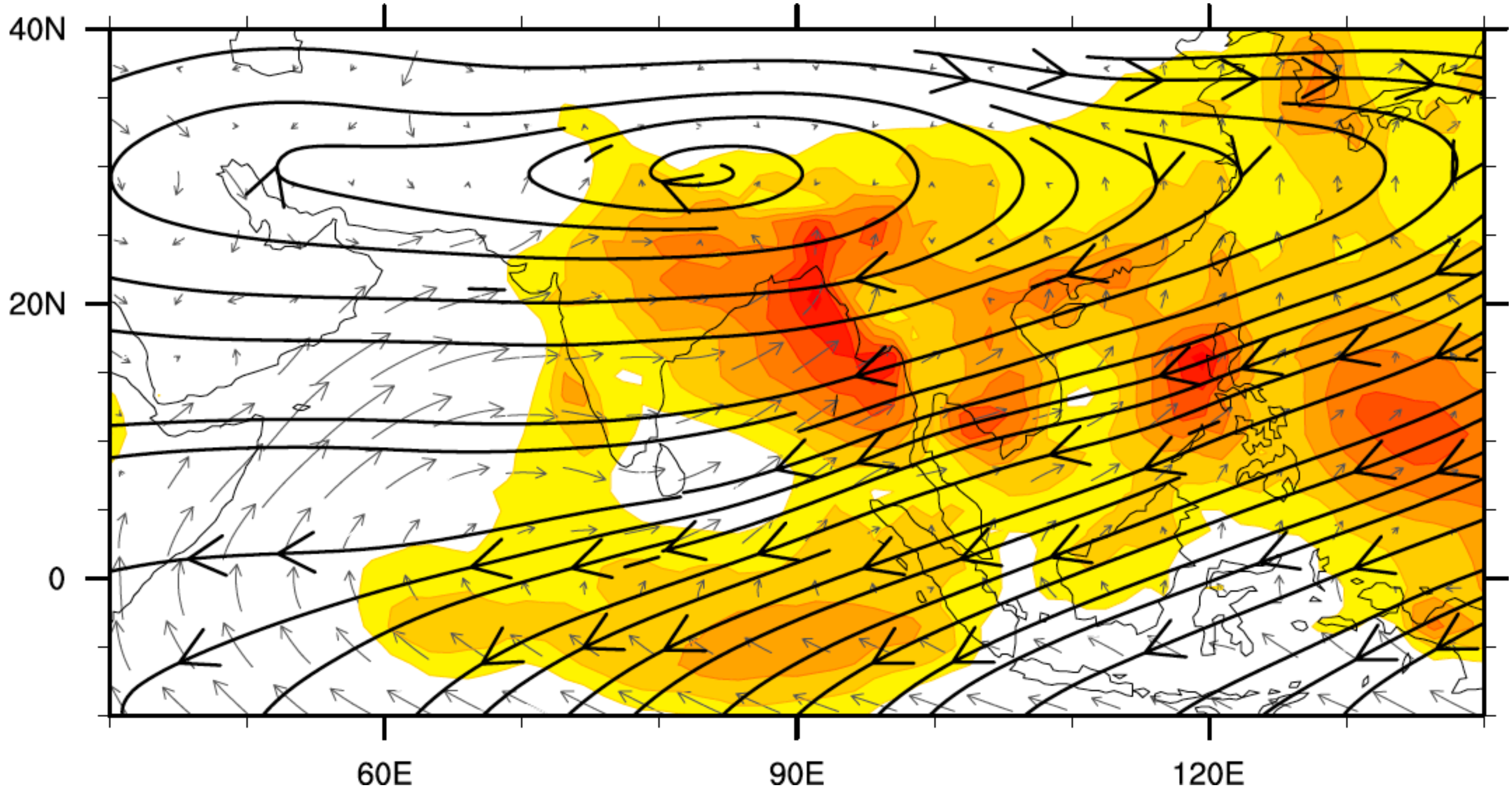
Is the observed Hadley cell AMC?



- Not on annual mean
- Not in the summer cells
- More so in the cross-equatorial winter cells
- Even more so in monsoonal circulations

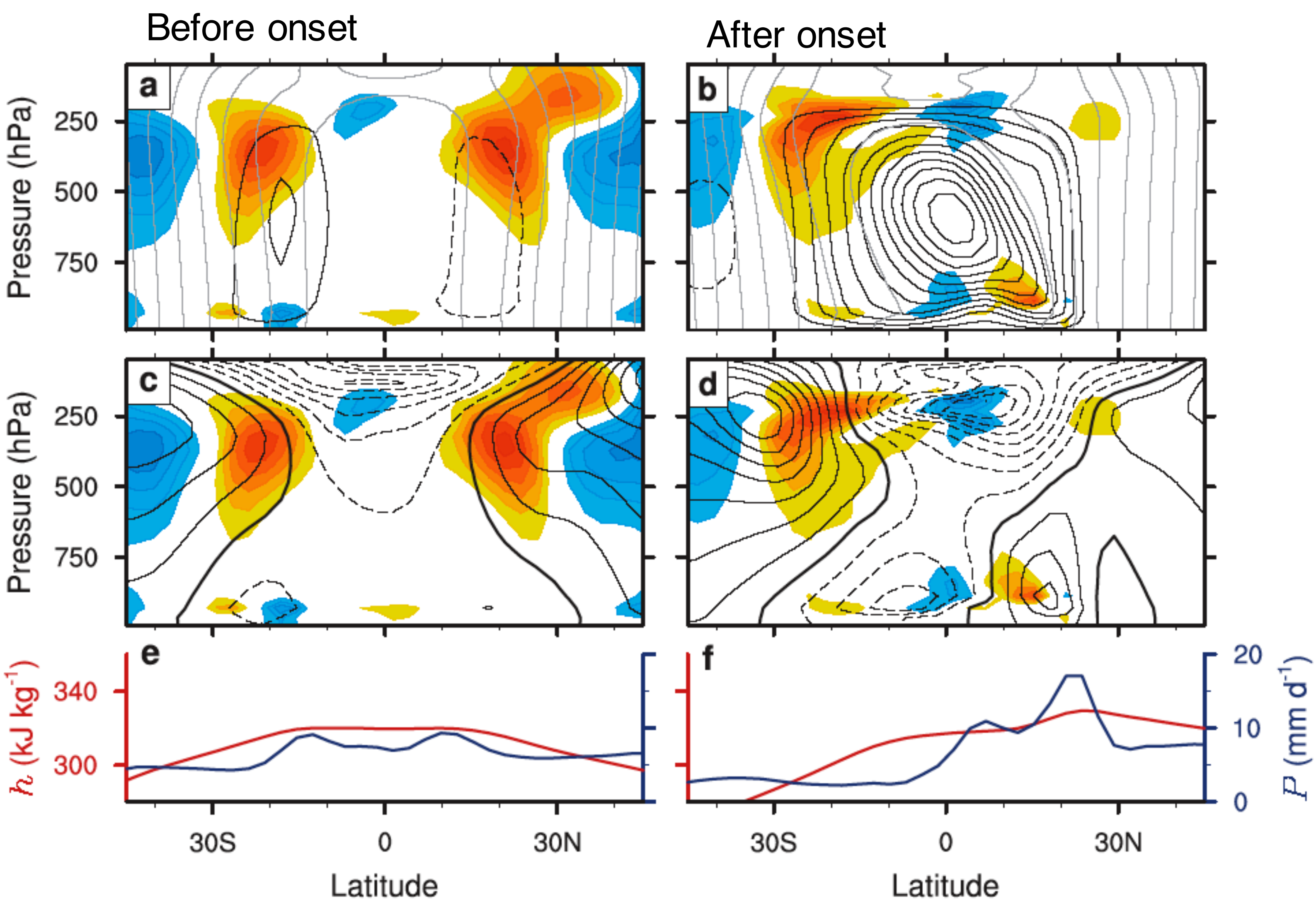
Schneider et al. (2010)

Upper-level flow of the South Asian monsoon



Data source: GPCP 1DD and ERA-40 Reanalysis

Momentum balance in aquaplanet monsoons



Bordoni and Schneider (2008)

Emerging theoretical framework

Aquaplanet simulations suggest rapid monsoon onset/end correspond to transitions in leading angular momentum budget

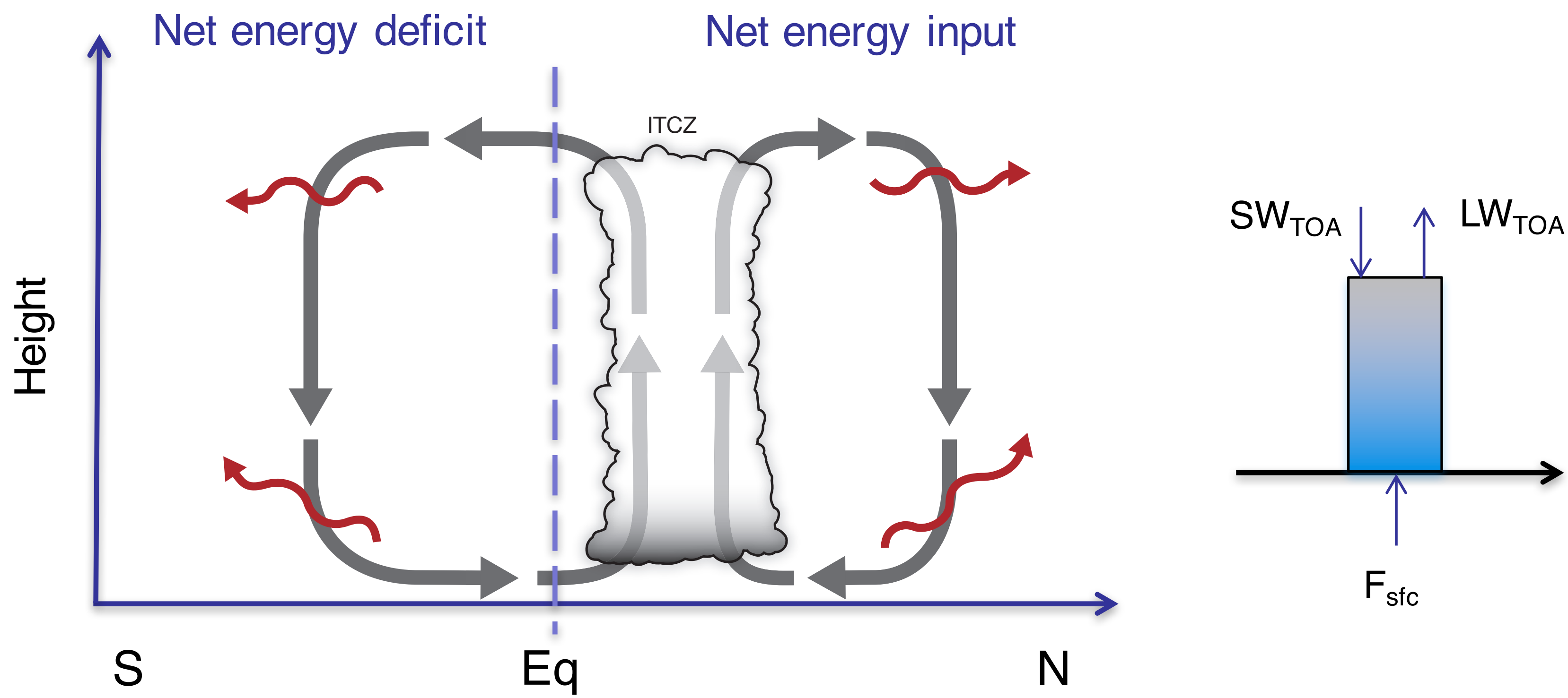
	Equinox	**Monsoon**
Role of eddies in angular momentum budget	Large	Minor – approaches angular momentum conservation

↓ Equinox: Circulation constrained by momentum budget

↓ Monsoon: Circulation constrained by energy budget

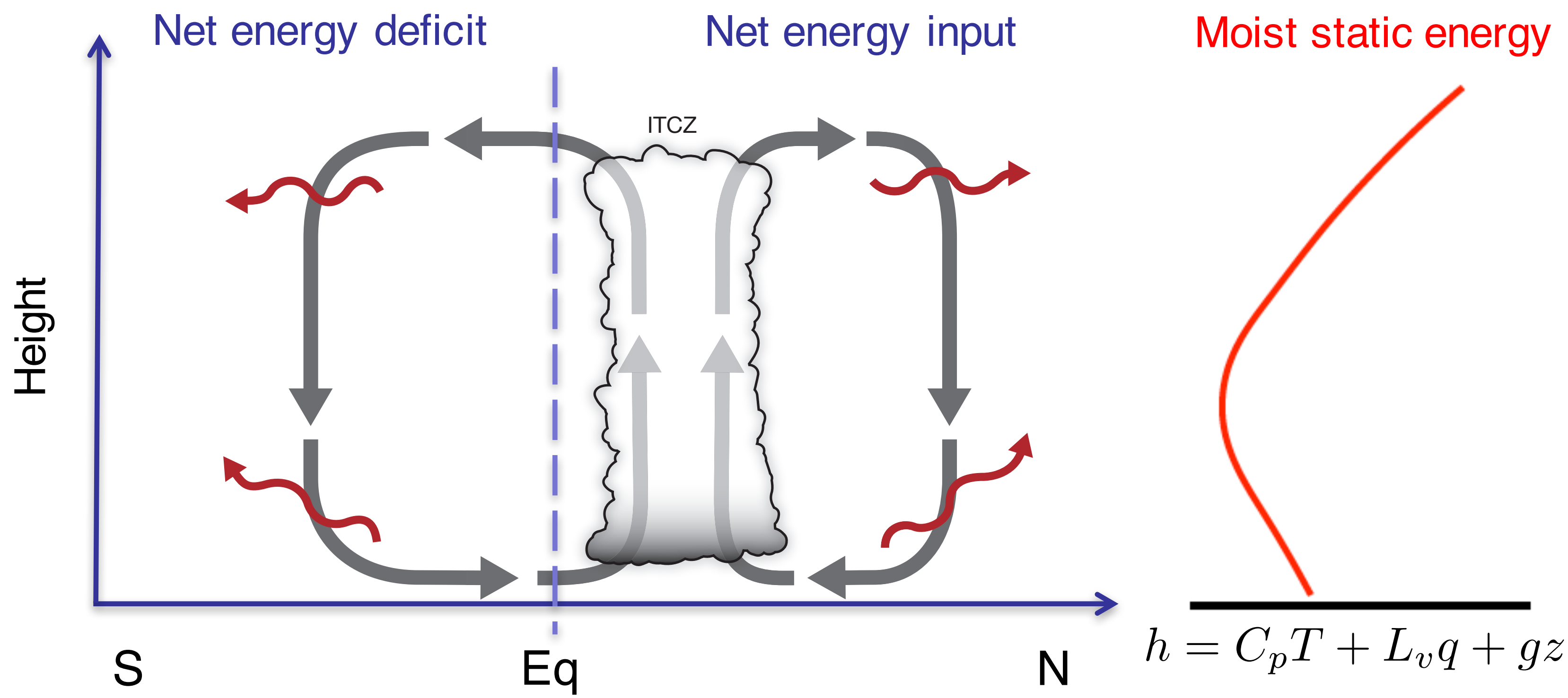
More next week on how these mechanisms are modified by presence of zonally symmetric continents, in the presence of zonal asymmetries (stationary eddies) and in the observed AM balance of the South Asian monsoon!

Energetic constraint on the ITCZ position



Adapted from Schneider et al. 2014

Energetic constraint on the ITCZ position



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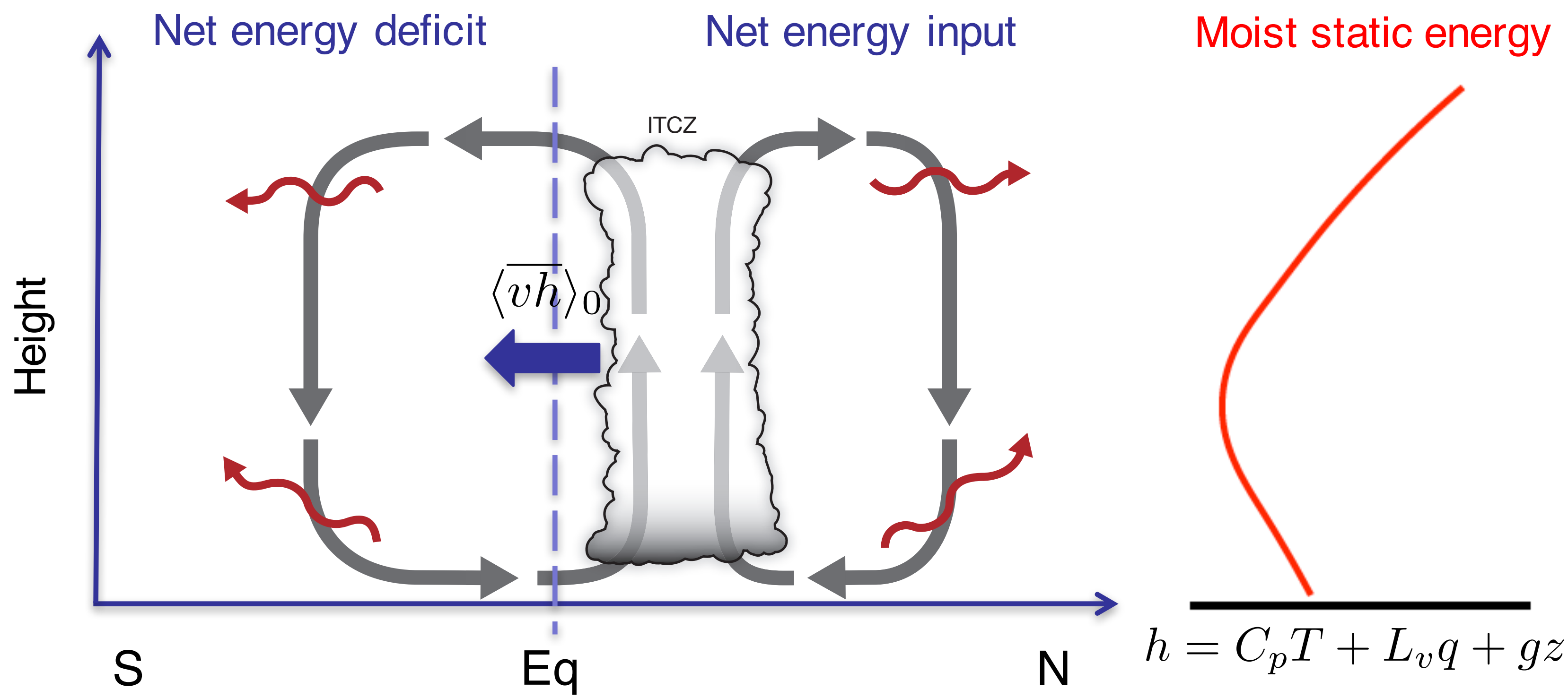

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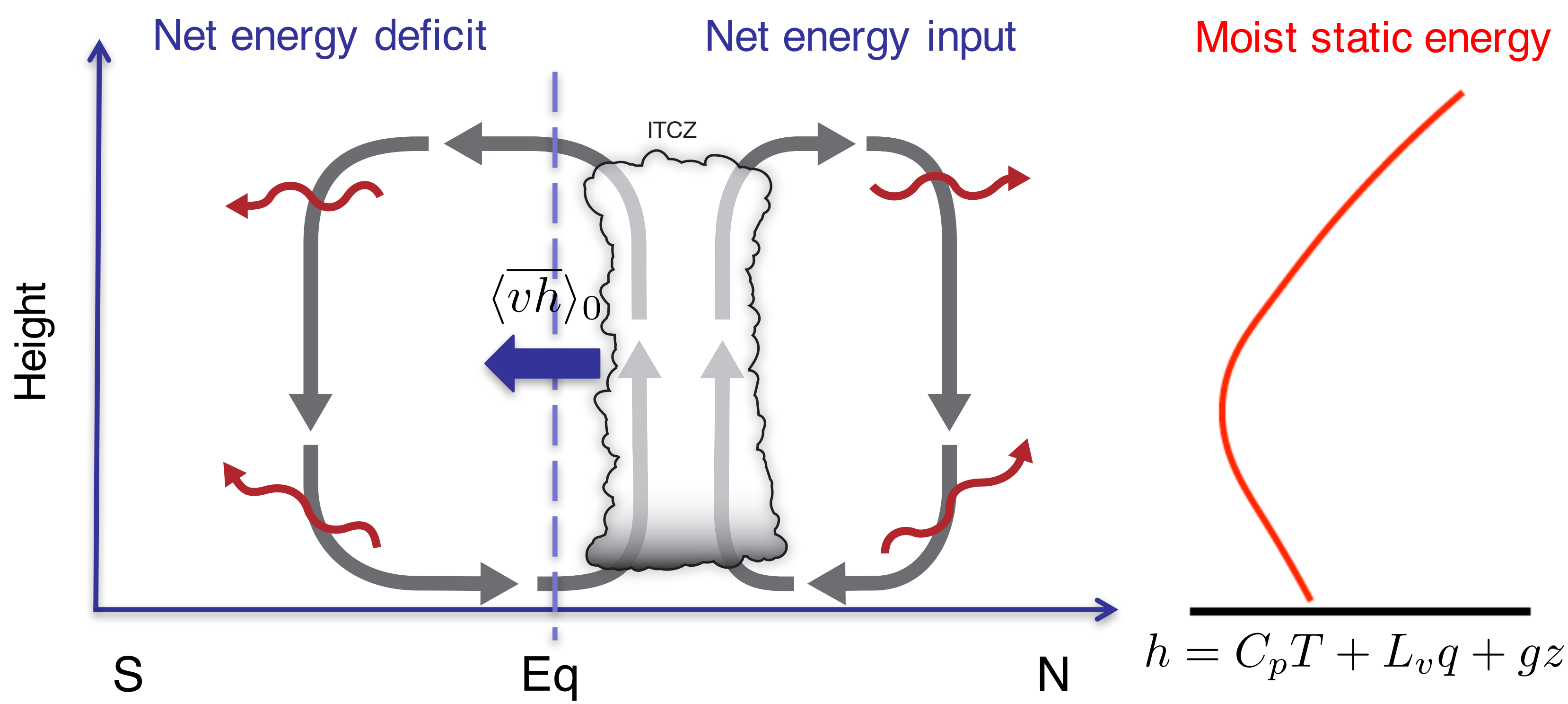
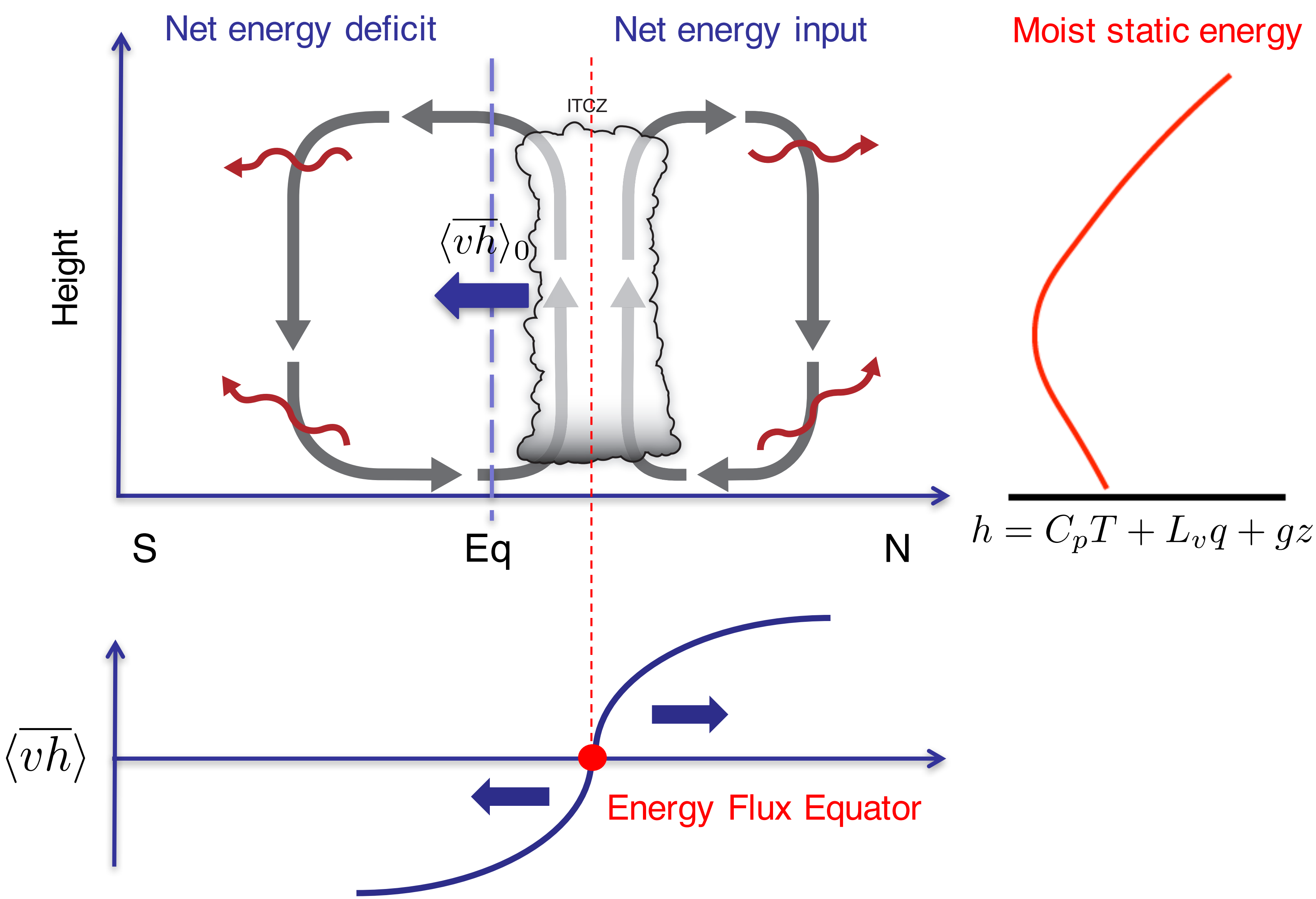


ITCZ position is anti-correlated with the cross-equatorial energy transport $\langle \overline{vh} \rangle_0$

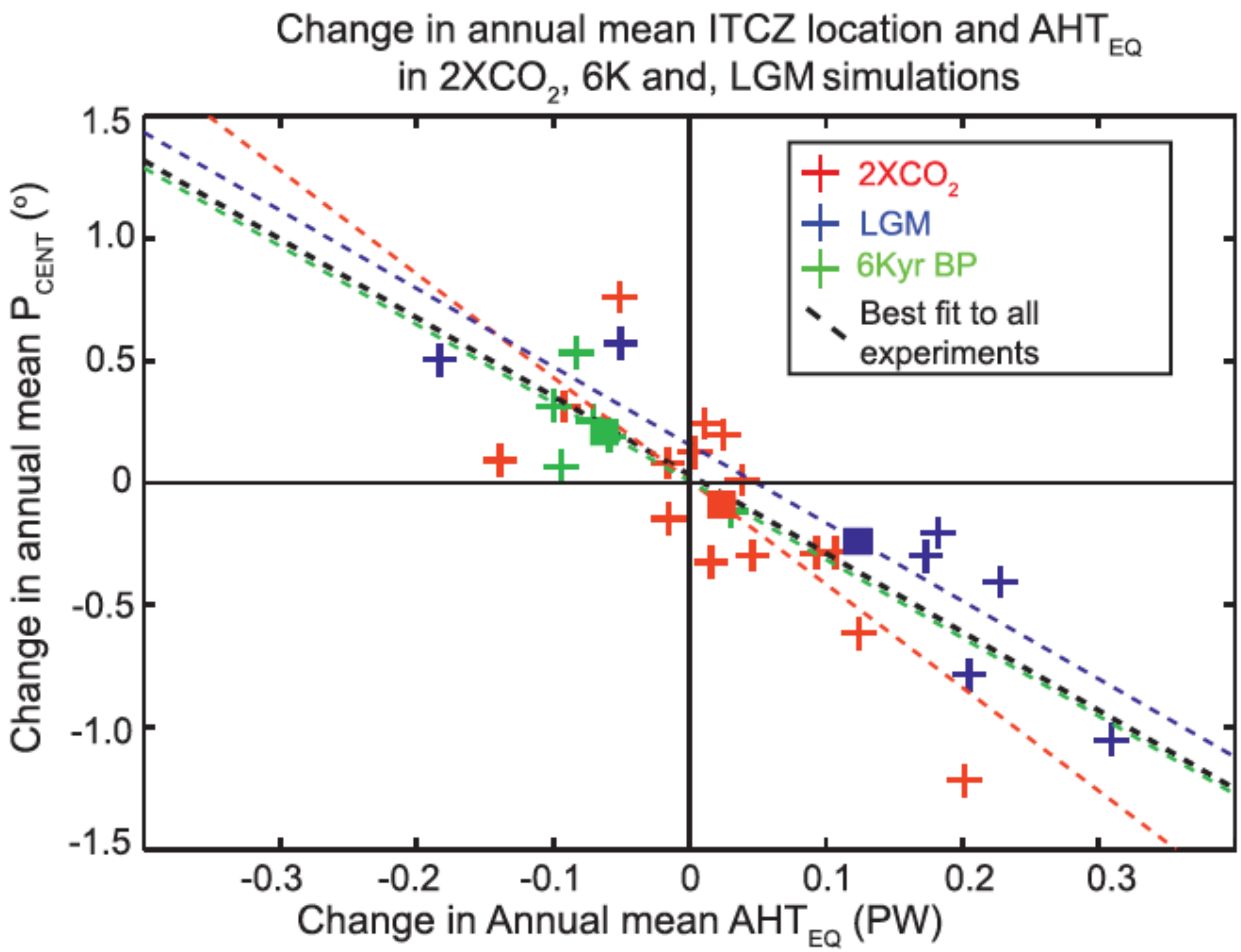
e.g., Kang et al. 2008, Hwang and Frierson 2012, Donohoe et al. 2013, Bischoff and Schneider 2014

ITCZ and EFE



e.g., Kang et al. 2008, Hwang and Frierson 2012, Donohoe et al. 2013, Bischoff and Schneider 2014

ITCZ and cross-equatorial energy transport



Donohoe et al. 2013

Open questions on energetic constraints on ITCZ/monsoons

- Is zonal mean framework useful?
- How do we modify this framework to include zonal variability? (Boos and Korty 2016, Adam et al. 2016)
- Is the GMS always constant? (Seo et al. 2017)

Tipping points in monsoons?

- Will monsoons shift abruptly and discontinuously from wet to dry states for small changes in radiative forcing past a critical threshold?
- Paleo-records show evidence of rapid changes in monsoon strength;
- The rapid onset of the monsoon on subseasonal timescales due to nonlinearity? Can same mechanism(s) produce similar response to imposed seasonal mean forcing?
  - It has been suggested that albedo increasing above 0.5 can shut down monsoons;
  - Could GHG concentration increases also cause similar nonlinear responses?

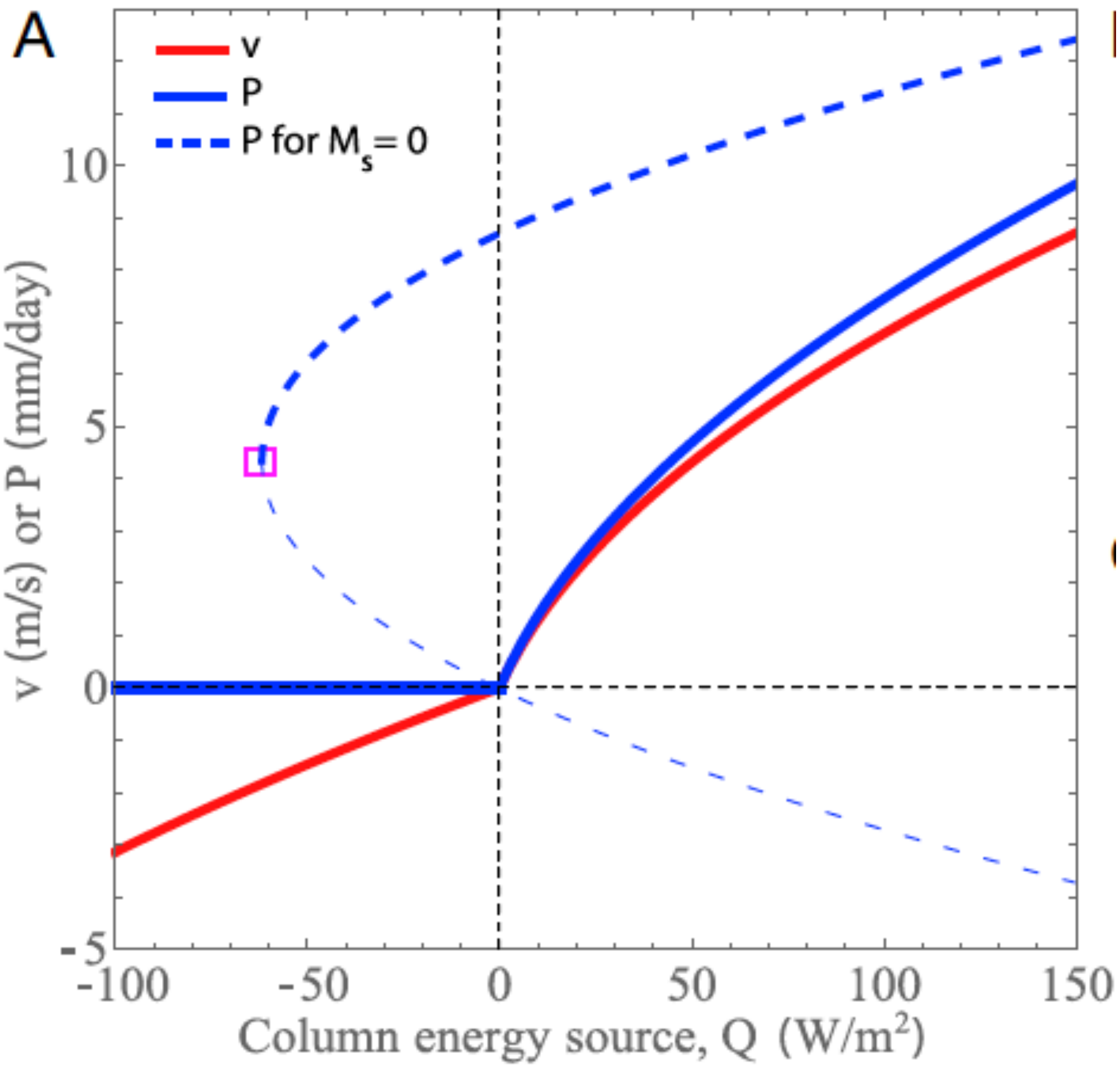
e.g., Zickfeld et al. 2005, Levermann et al. 2009, Schewe and Levermann (2012)

Tipping points in monsoons?

- Model based on vertically-integrated T and q equations (as we have discussed for derivation of MSE budget);
- Horizontal advection of T and q;
- Vertical terms representing adiabatic cooling and low-level moisture convergence;
- Meridional wind assumed proportional to meridional T gradient;
- Simple closure for precipitation, $P = q - T/\tau\ \mathcal{H}(q - T)$;
- No rotation, no non-linear momentum advection, no evaporation dependence on surface winds.

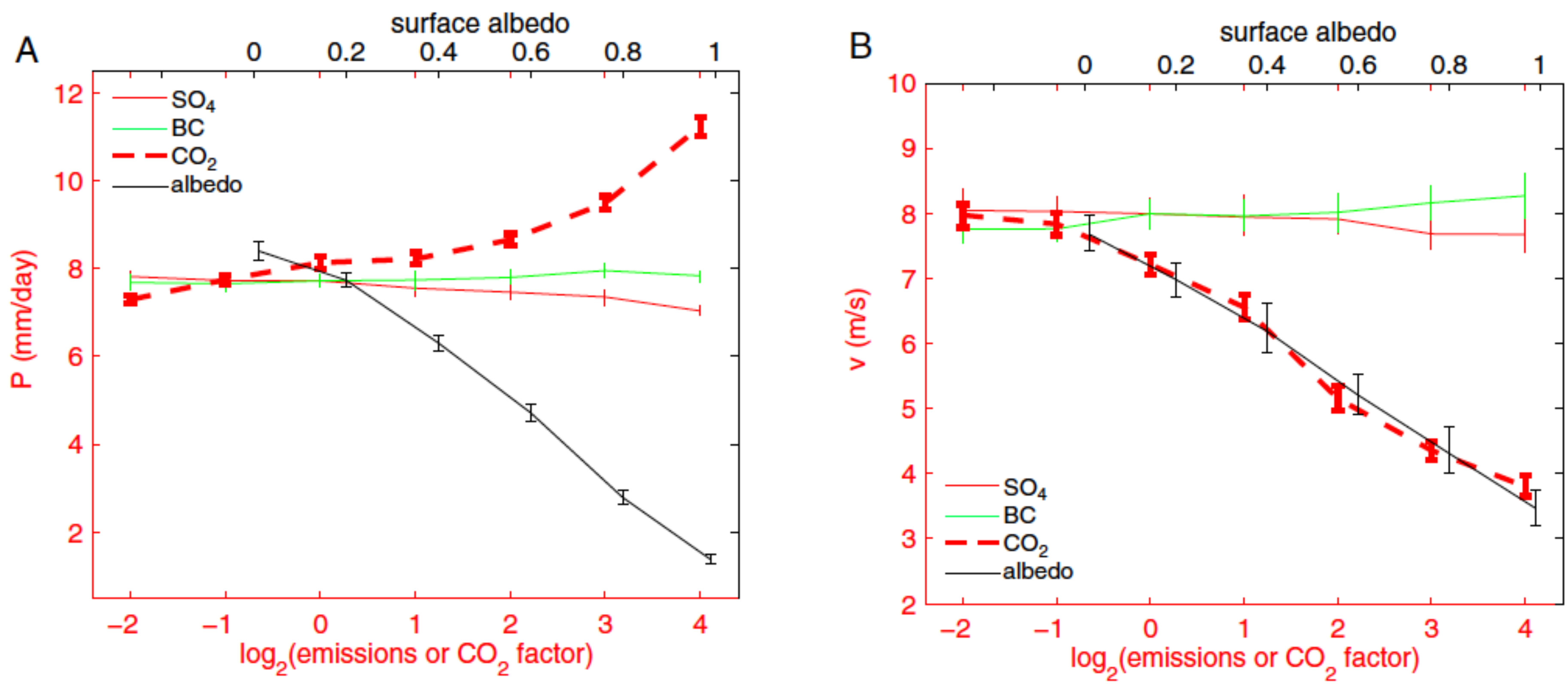
Boos and Storelvmo (2016)

Tipping points in simple models?



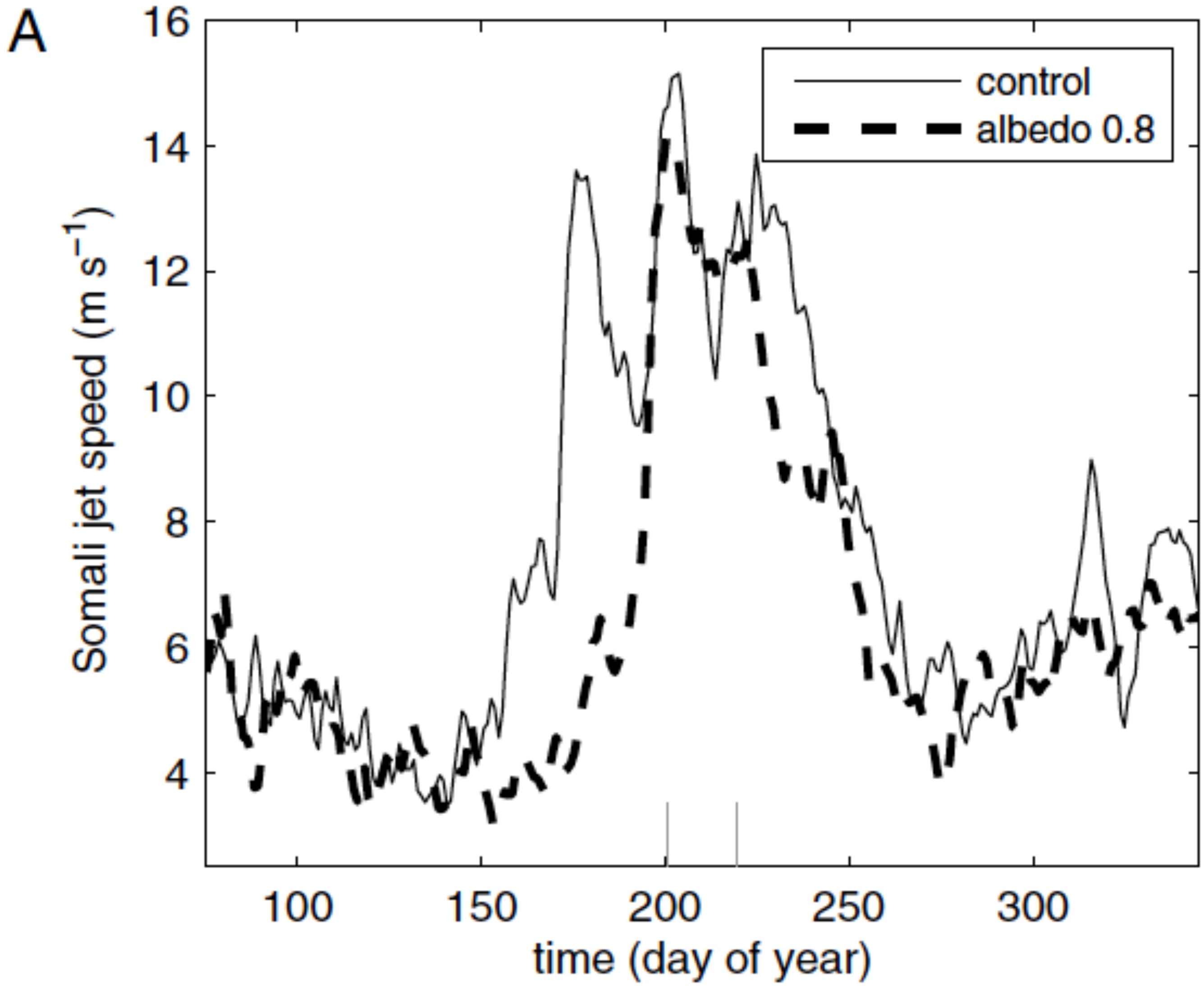
Boos and Storelvmo (2016)

Tipping points in GSMs?



Boos and Storelvmo (2016)

Changes in monsoon season length!



Boos and Storelvmo (2016)