MONSOONS, ITCZS AND THE CONCEPT OF THE GLOBAL MONSOON

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3rd Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics,
ICTP, Trieste, July 26th 2022

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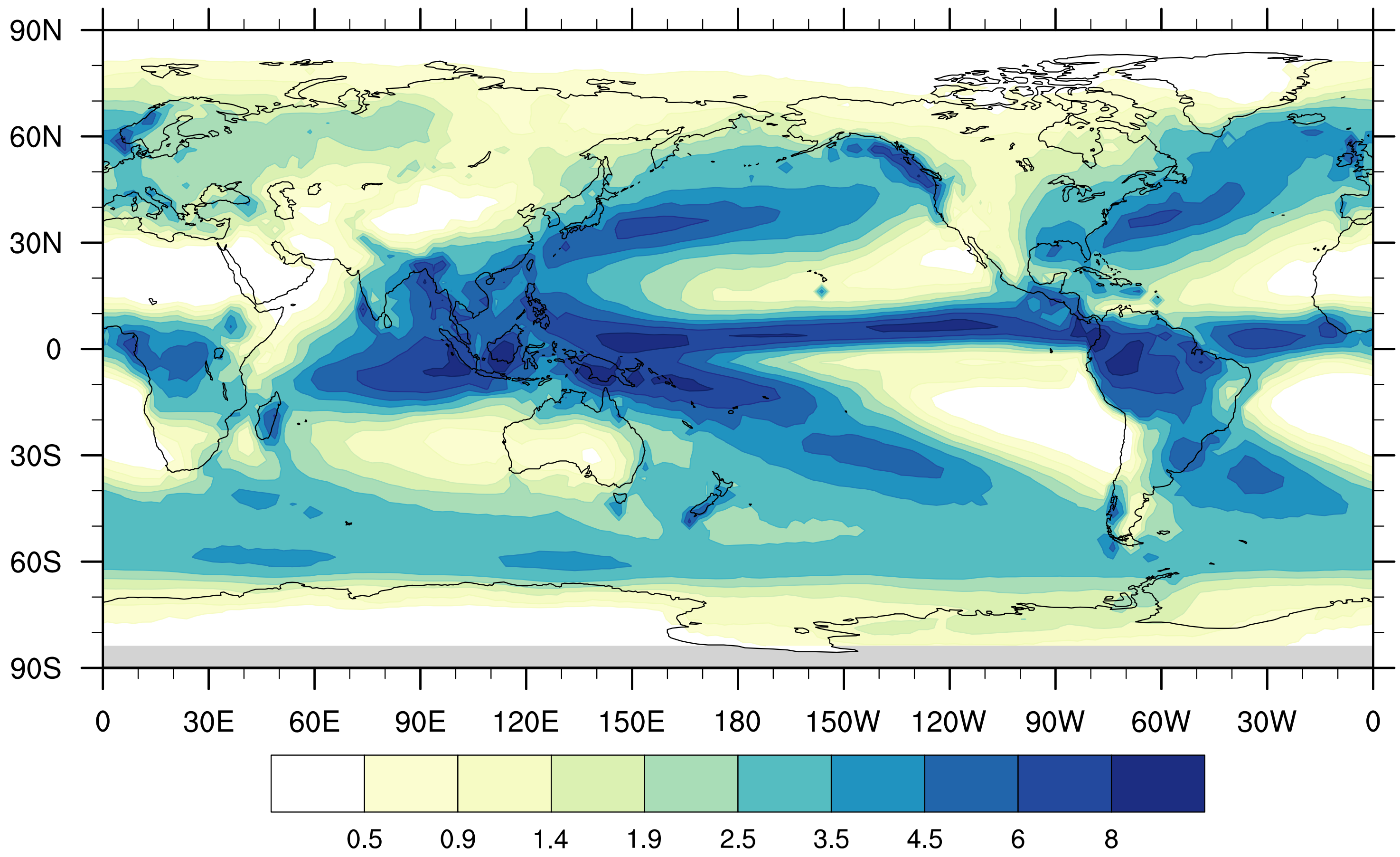
Tropical precipitation

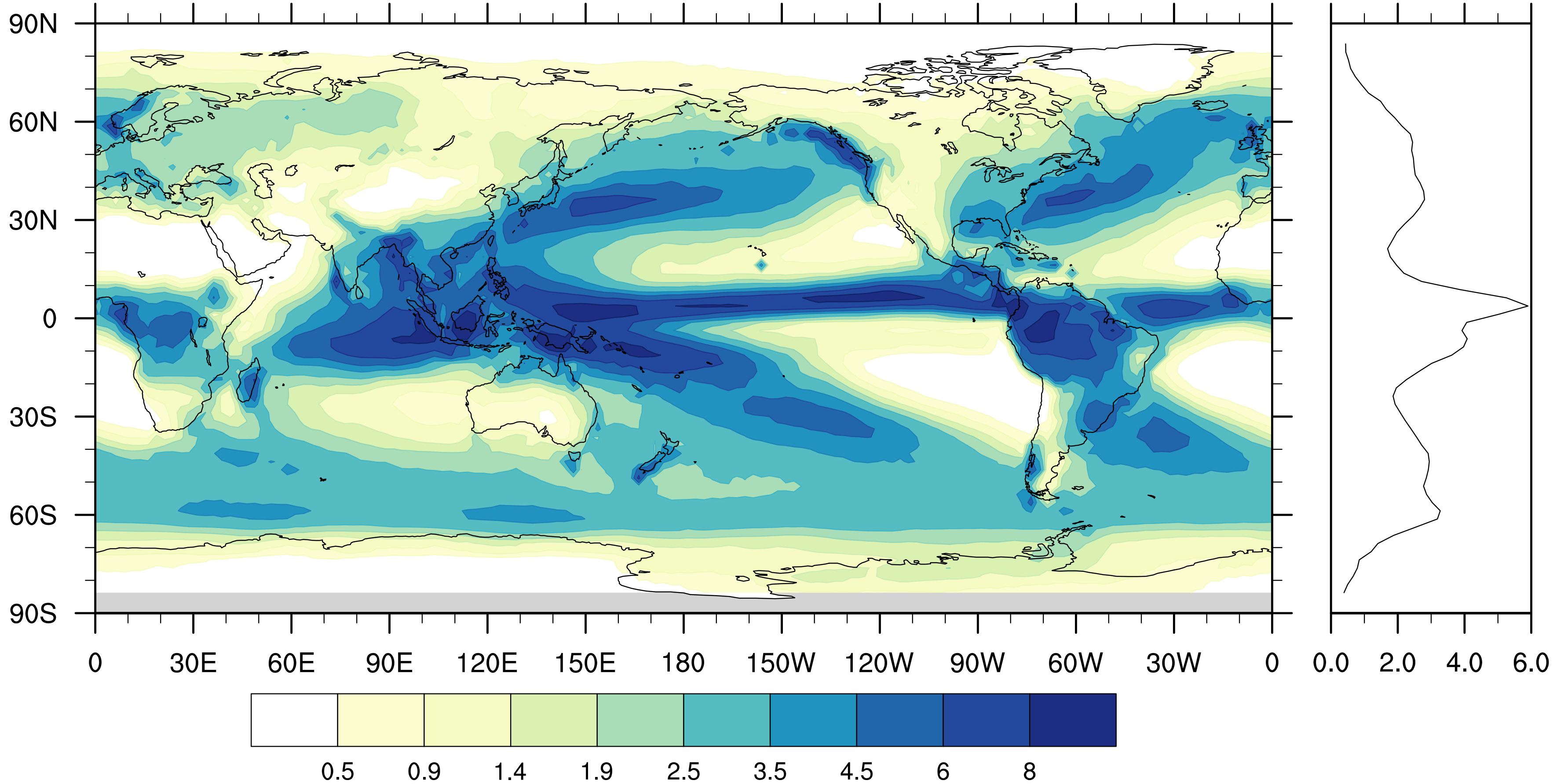
Annual mean precipitation



Data source: GPCP

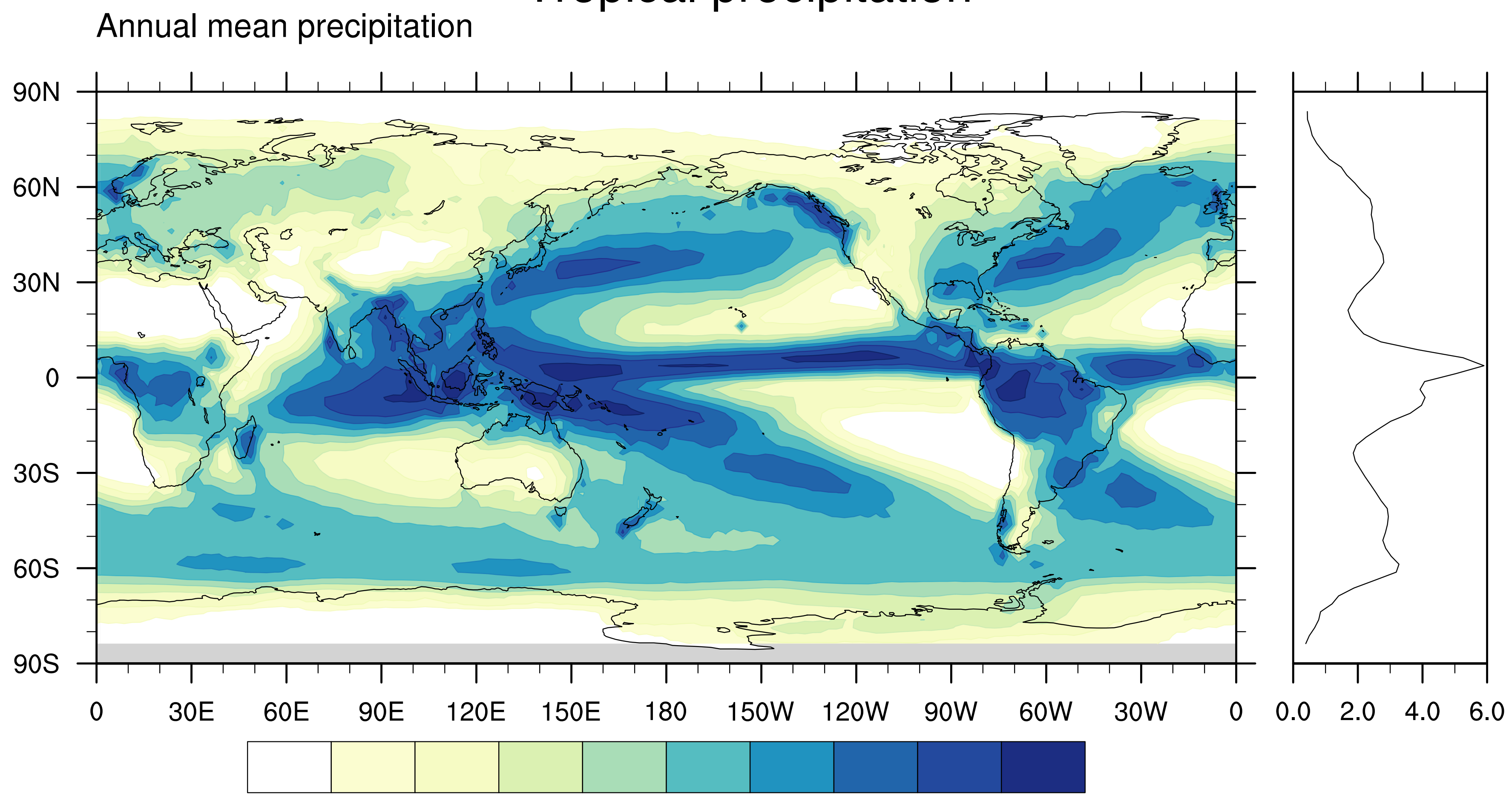
Tropical precipitation

Annual mean precipitation



Data source: GPCP

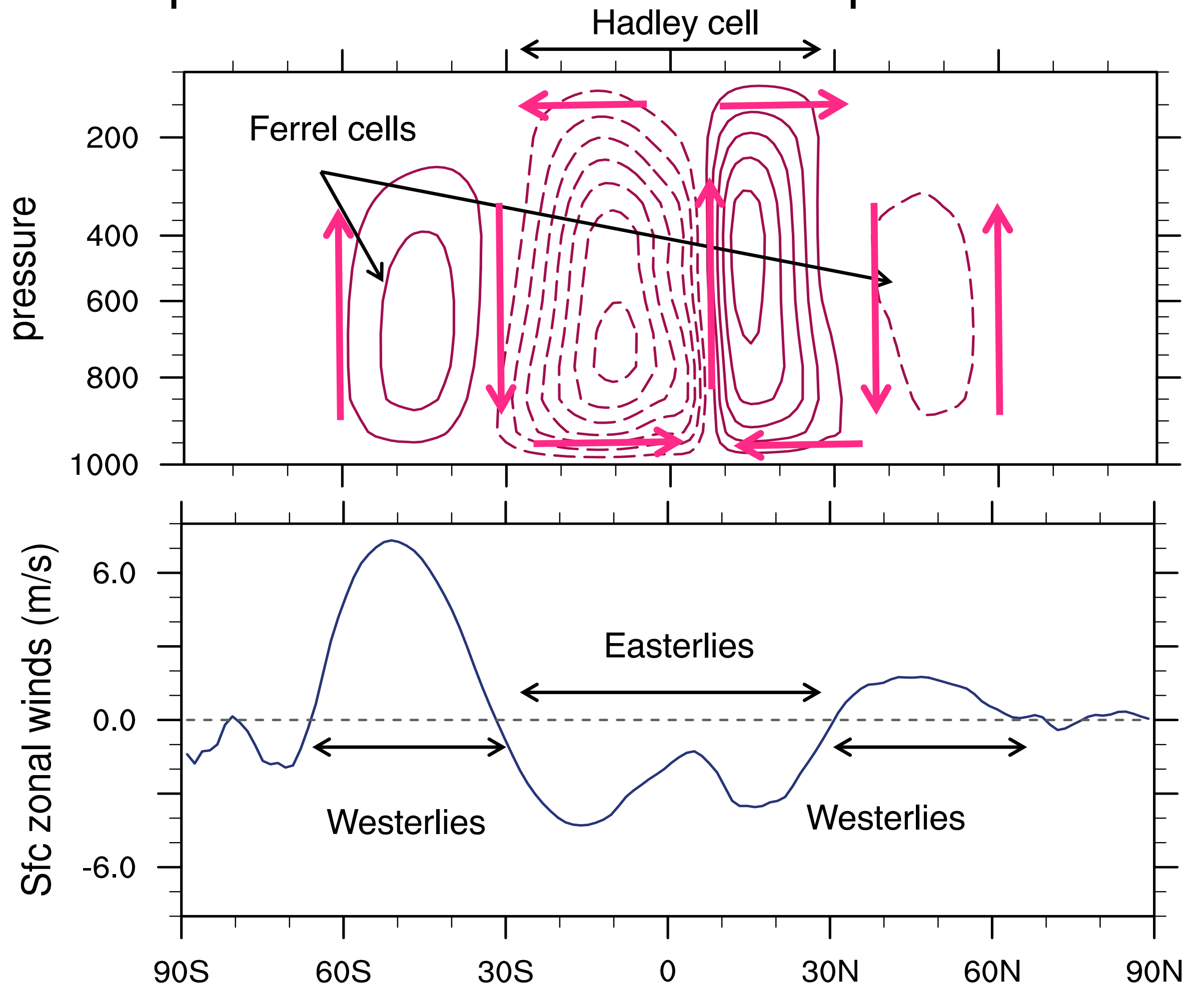
Tropical precipitation



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

Data source: GPCP

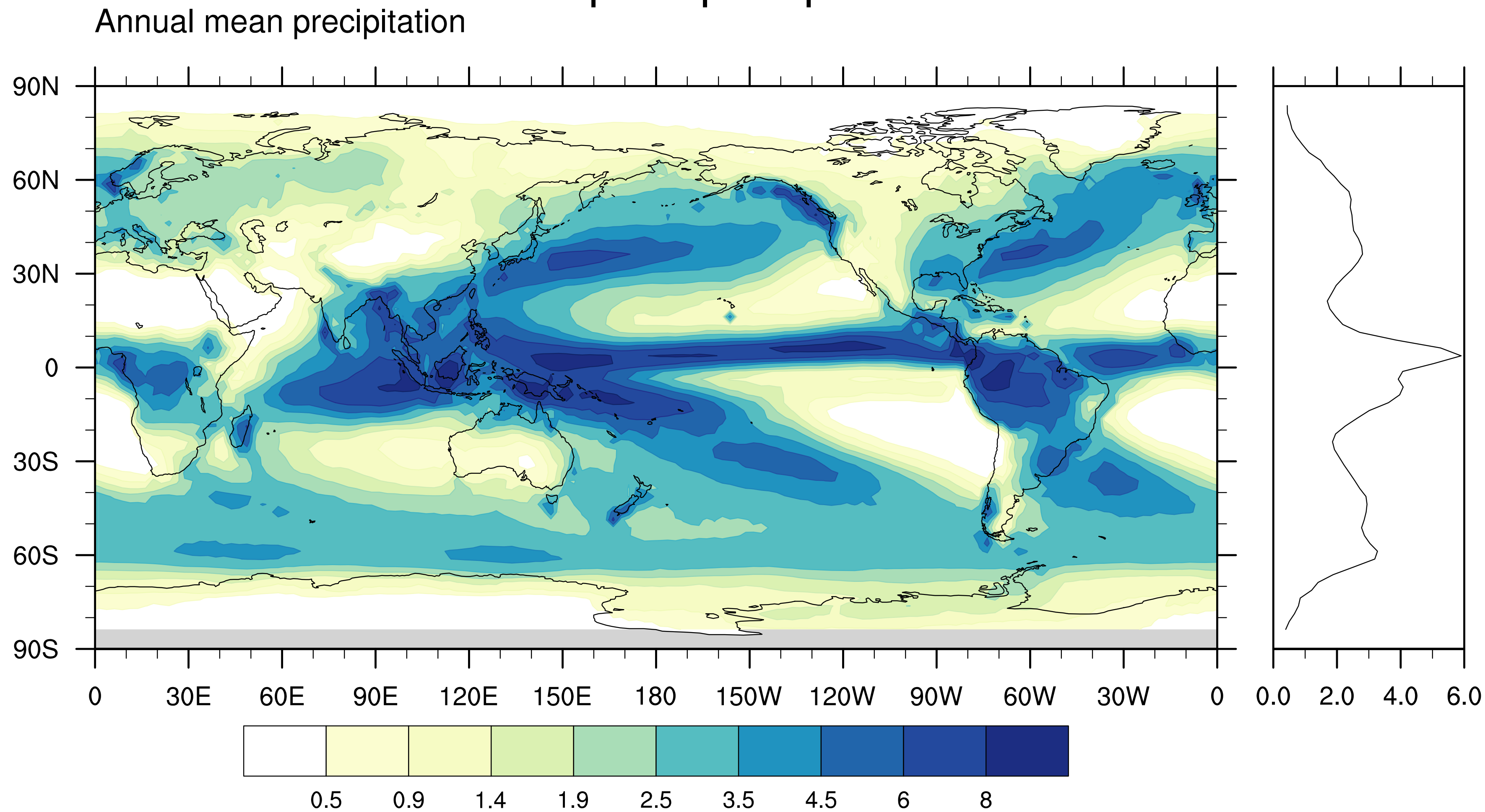
Precipitation is tied to the atmospheric circulation



Data source: ERA-I

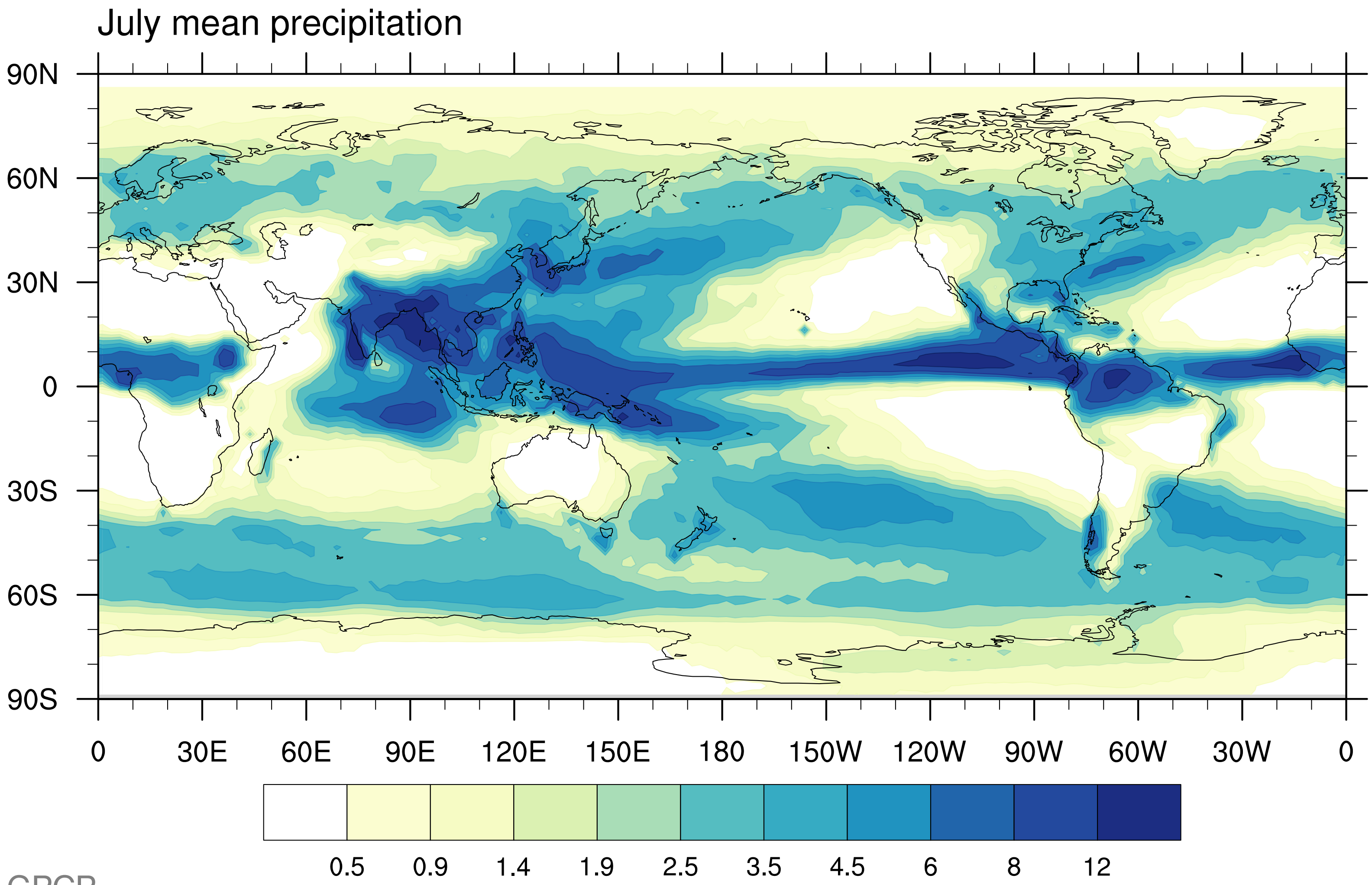
Maximum precipitation is co-located with ascending branch of the Hadley cell

Tropical precipitation



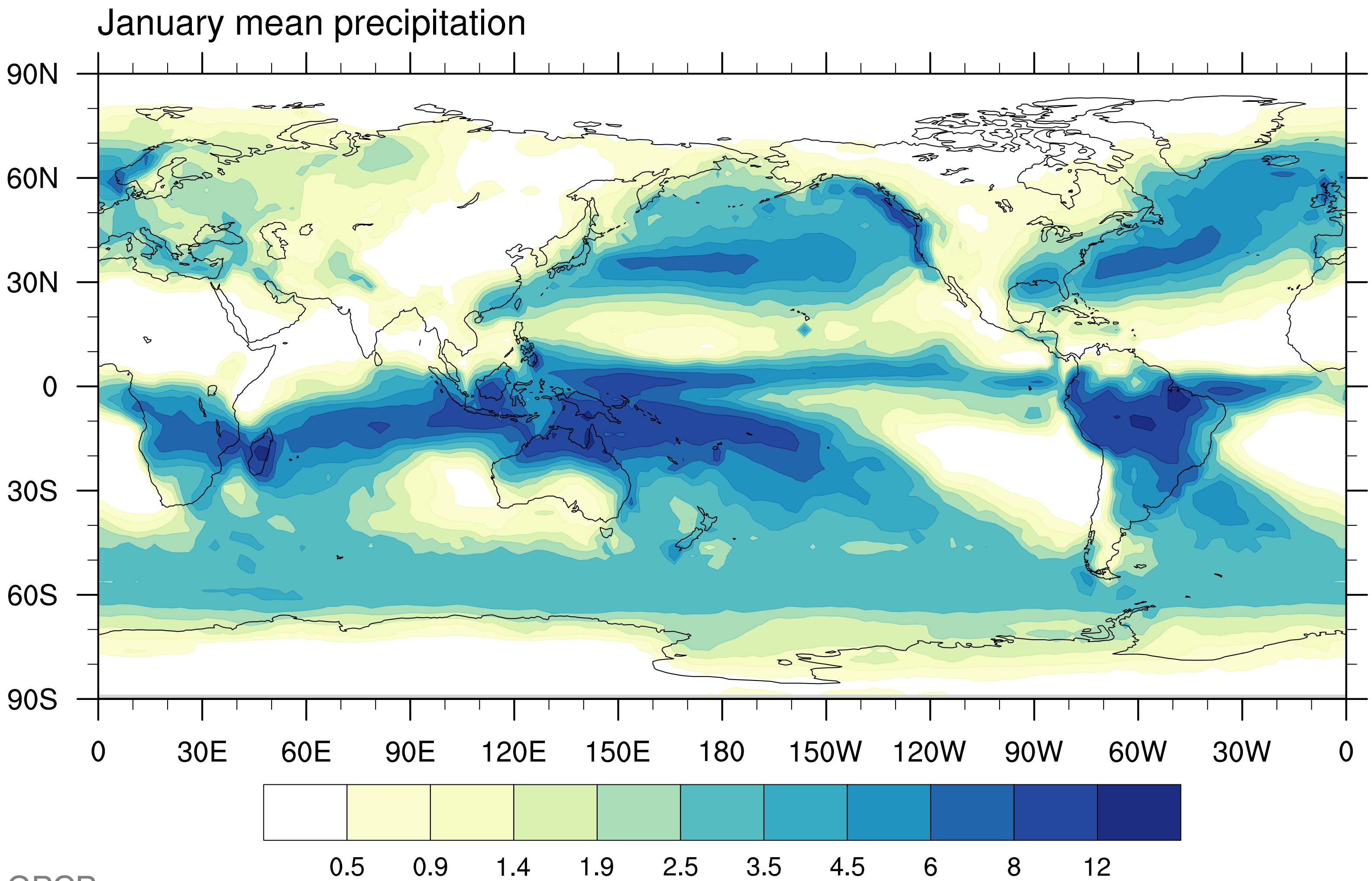
Data source: GPCP

The solstice seasons



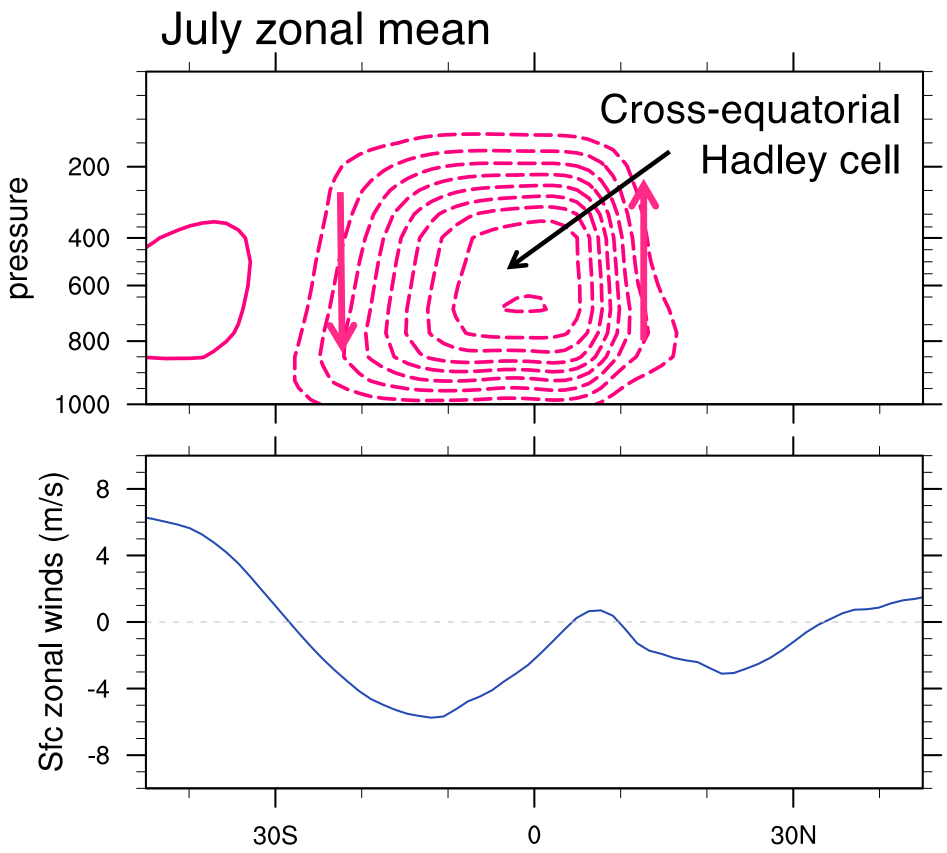
Data source: GPCP

The solstice seasons

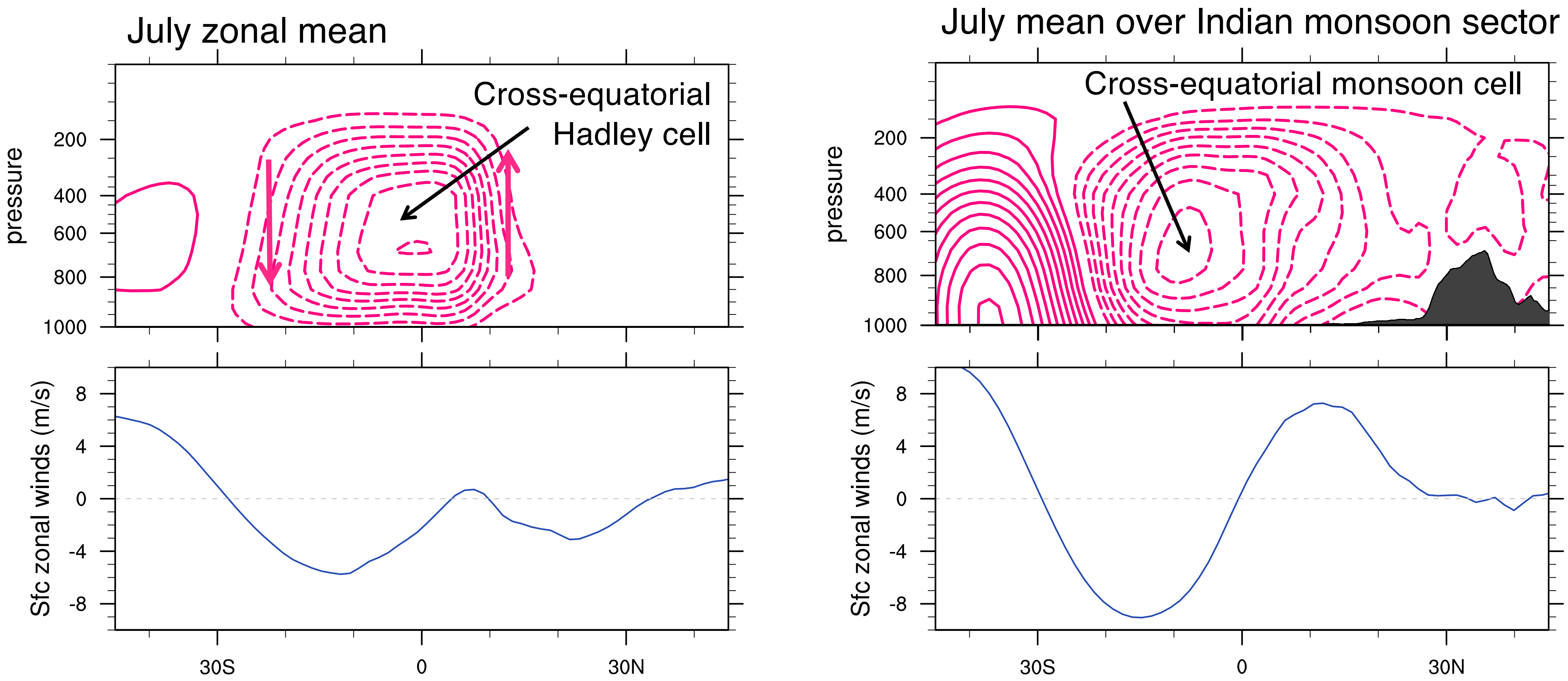


Data source: GPCP

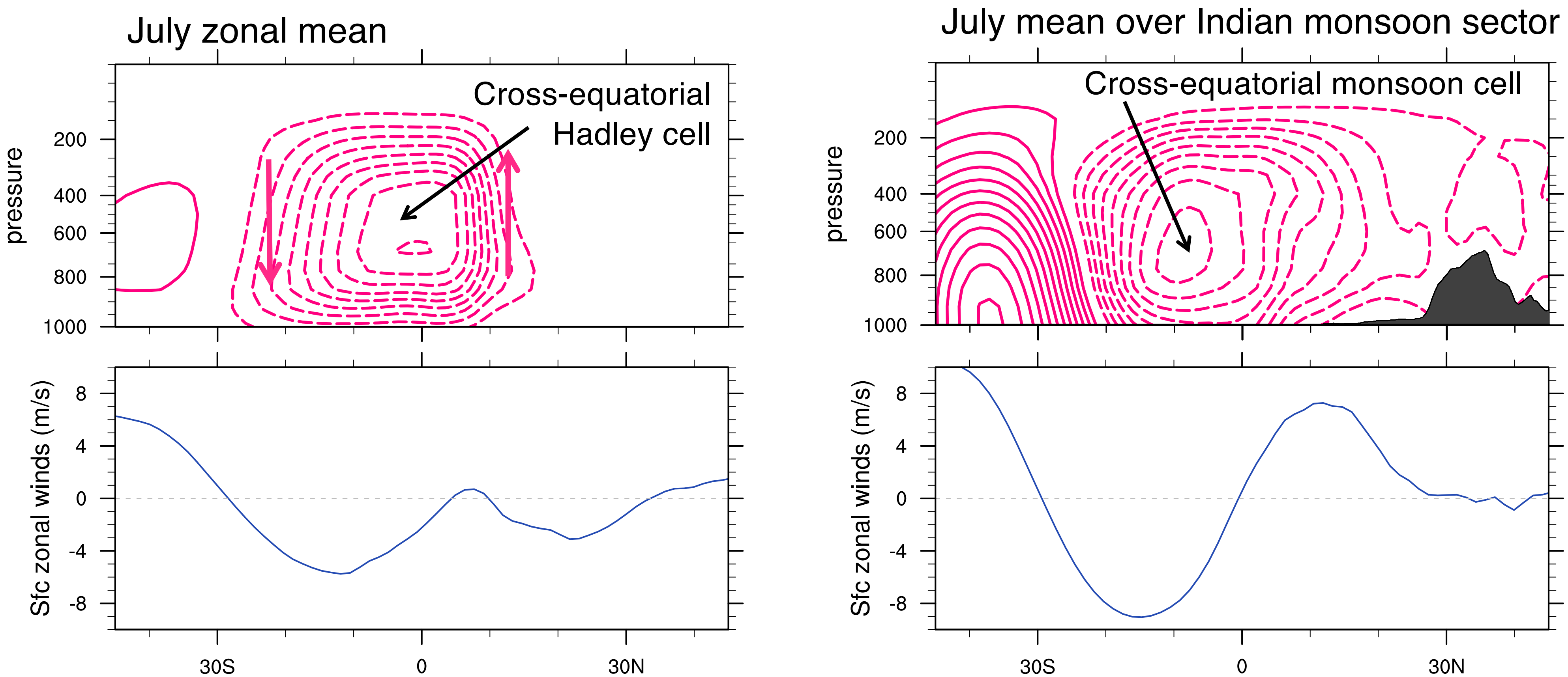
Monsoons are part of the atmospheric overturning



Monsoons are part of the atmospheric overturning



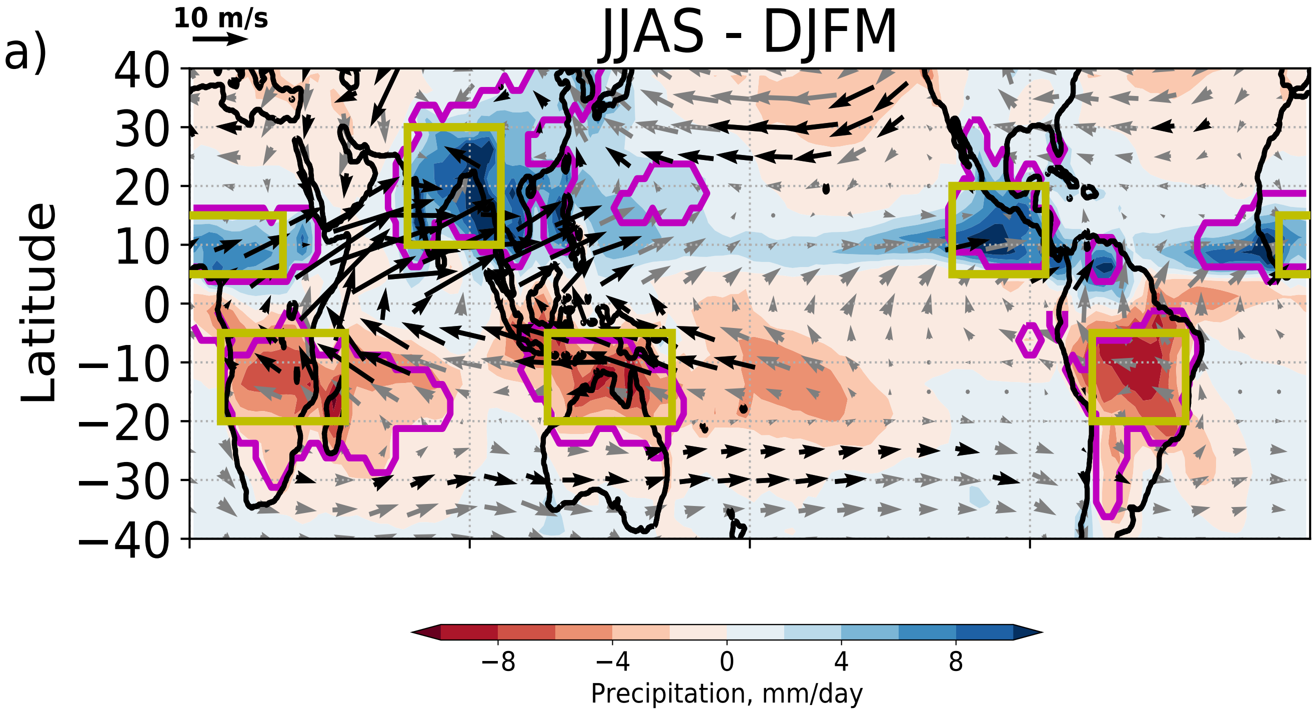
Monsoons are part of the atmospheric overturning



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

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

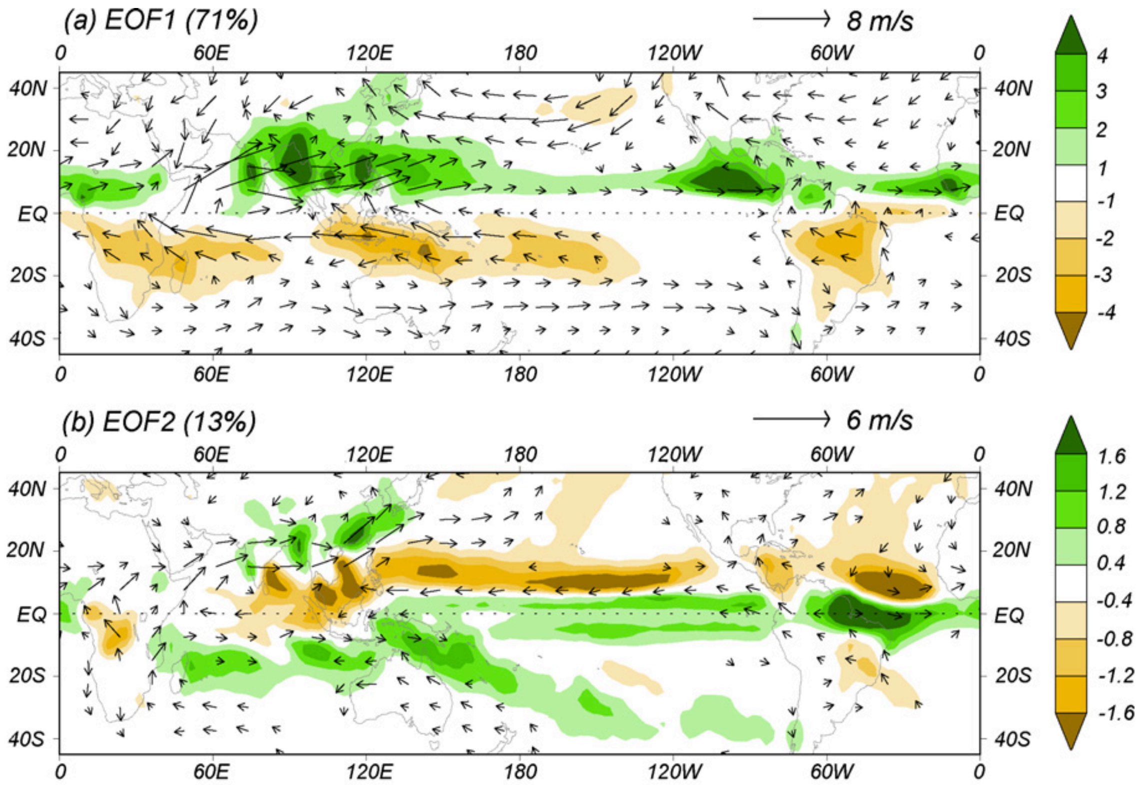
The global monsoon



Monsoons are dominant circulation features of the tropics and subtropics, characterized by rainy summers and dry winters, and accompanied by a reversal of the prevailing winds.

Data source: GPCP, JRA-55

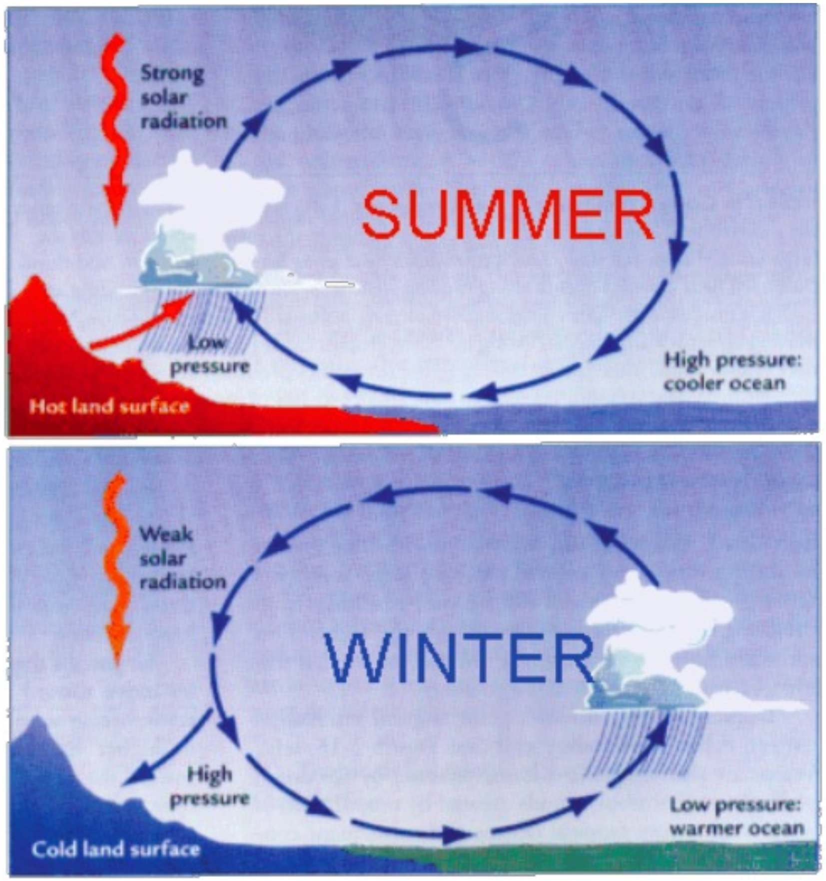
The global monsoon



EOF analyses of the annual cycle of the precipitation and lower-level winds reveal a dominant, global-scale solstitial mode, driven by the annual cycle of insolation: the Global Monsoon.

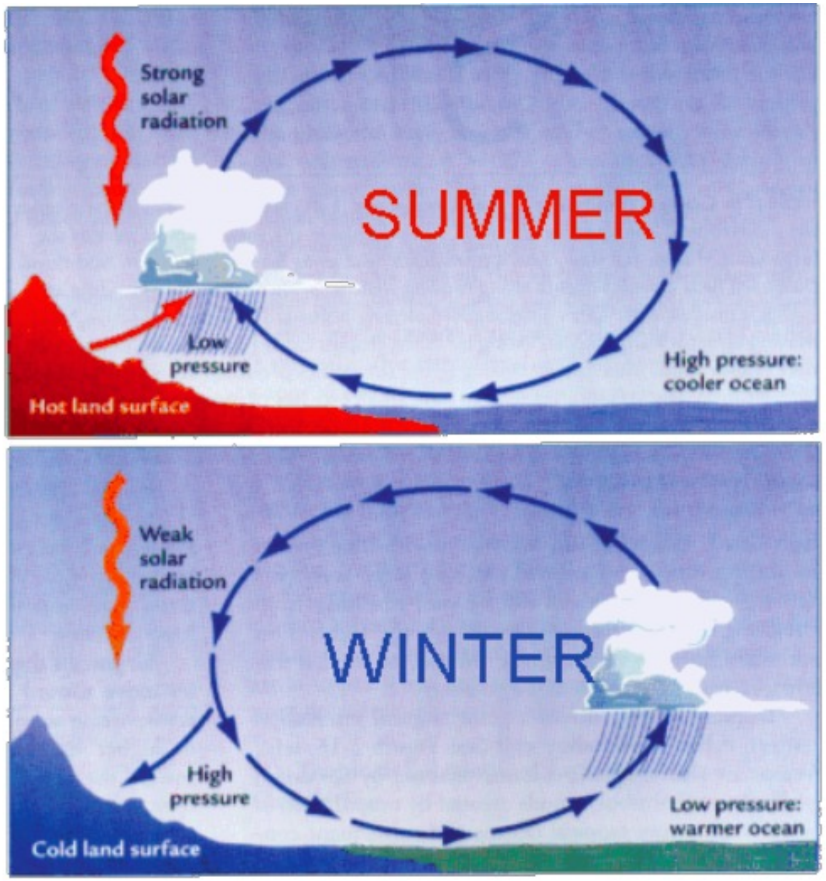
e.g., Wang and Ding 2008

Rethinking monsoons



Ruddiman (2007)

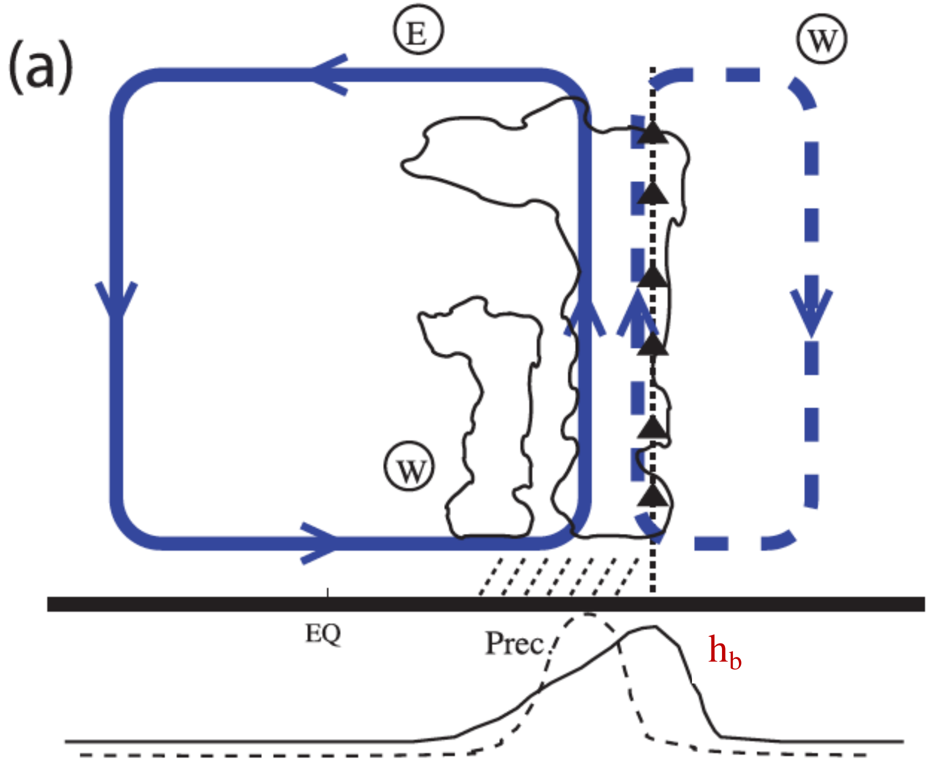
Rethinking monsoons



Monsoons are NOT land-sea breeze circulations driven by near-surface meridional temperature gradients!

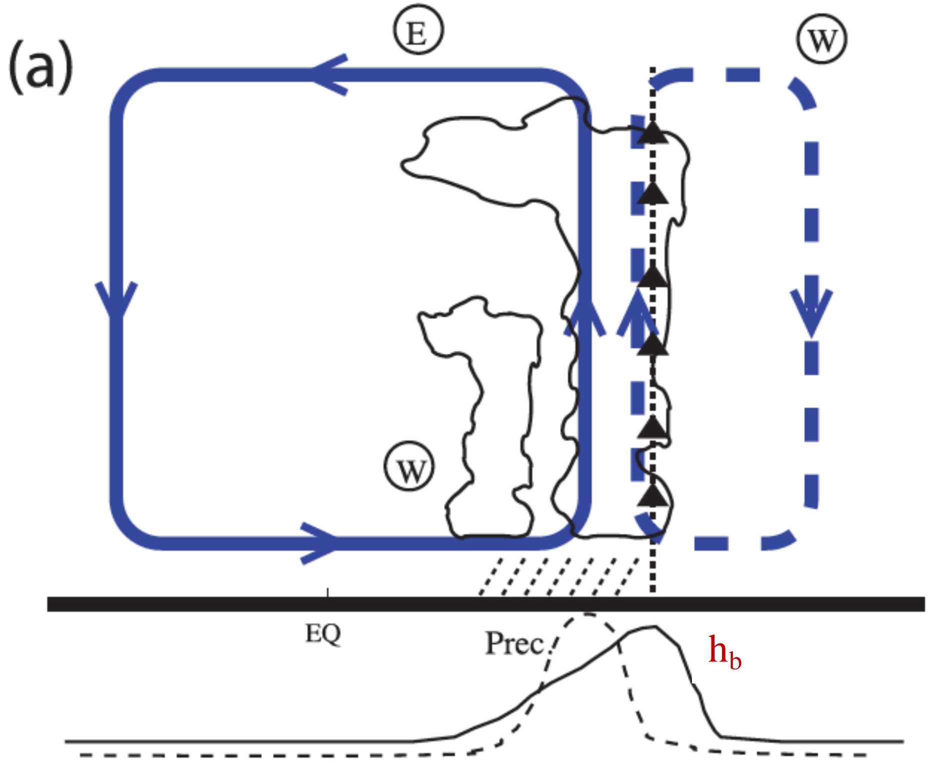
Ruddiman (2007)

Monsoons as cross-equatorial Hadley circulations



As part of the large-scale tropical overturning, monsoons participate to large-scale transports of energy and angular momentum. In particular, monsoons NEED to transport energy from the summer into the winter hemisphere.

Monsoons as cross-equatorial Hadley circulations



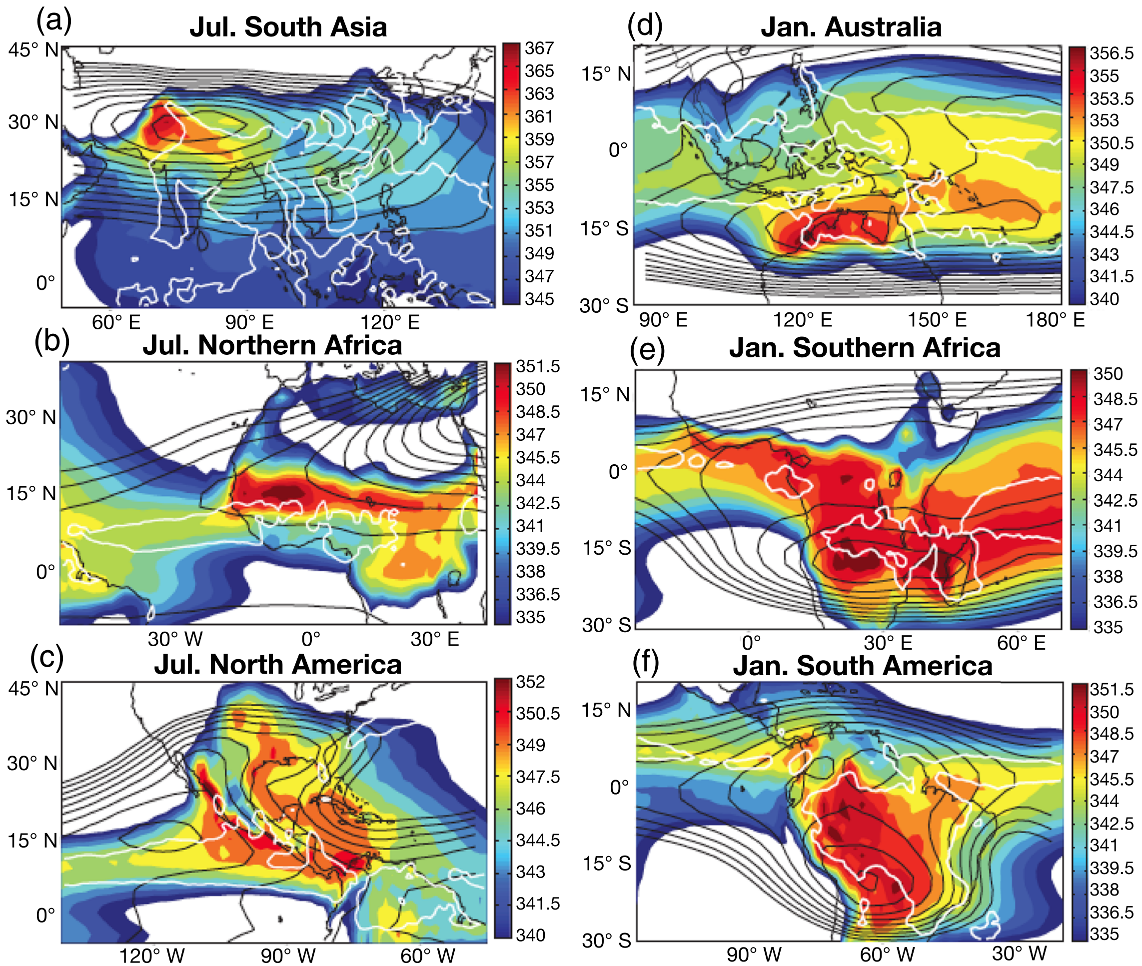
Maxima of T_u and h_b coincide at poleward edge of cell

$$h = c_pT + gz + L_vq$$

Constraints from conservation of angular momentum and modern views of convection establish link between the circulation and the distribution of low-level moist static energy

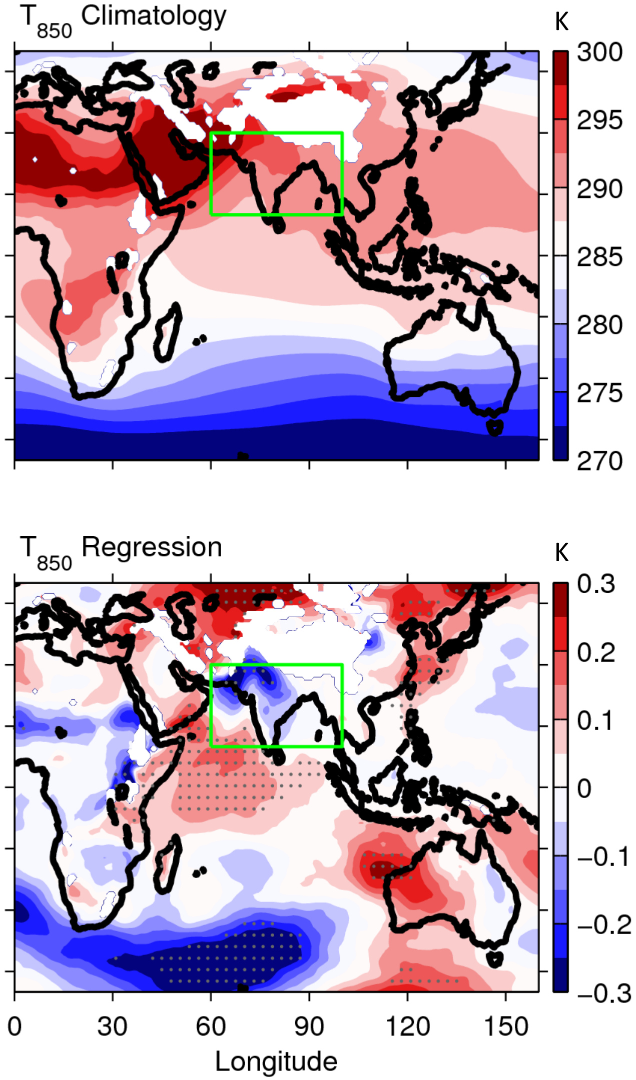
e.g., Lindzen and Hou (1988), Emanuel et al. (1994), Emanuel (1995), Prive and Plumb (2007), Nie et al. (2010)

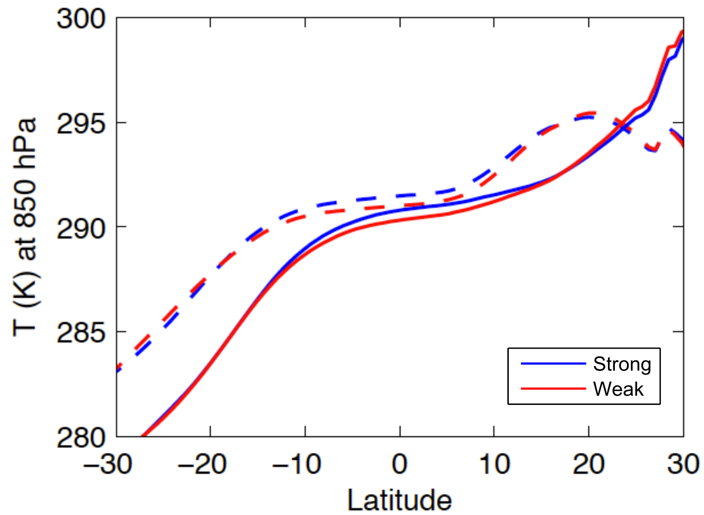
Observational evidence



Nie et al. (2010)

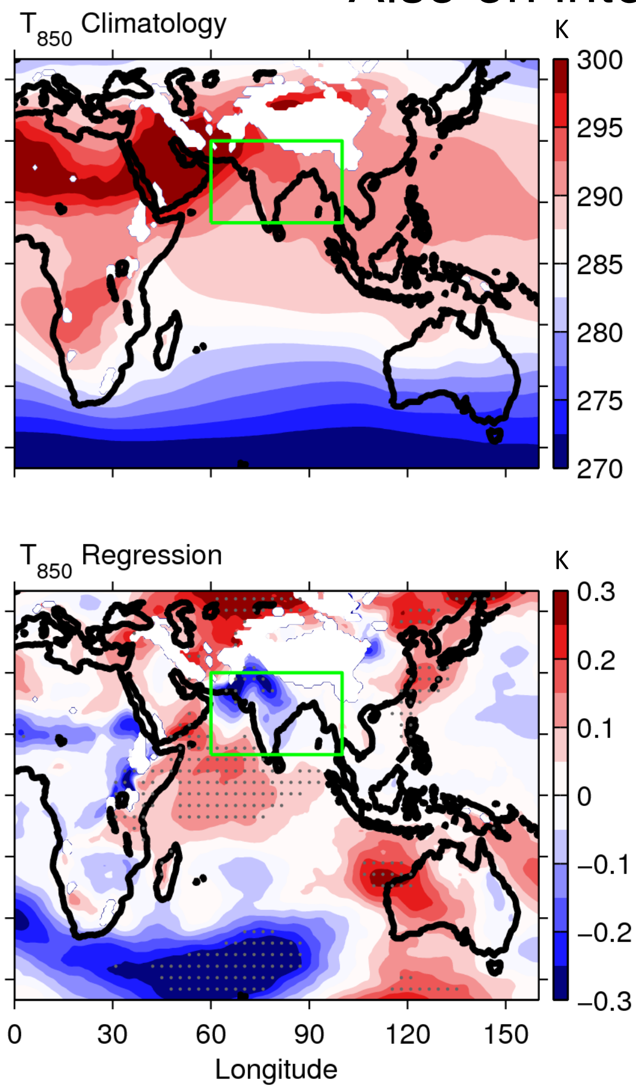
Also on interannual timescales



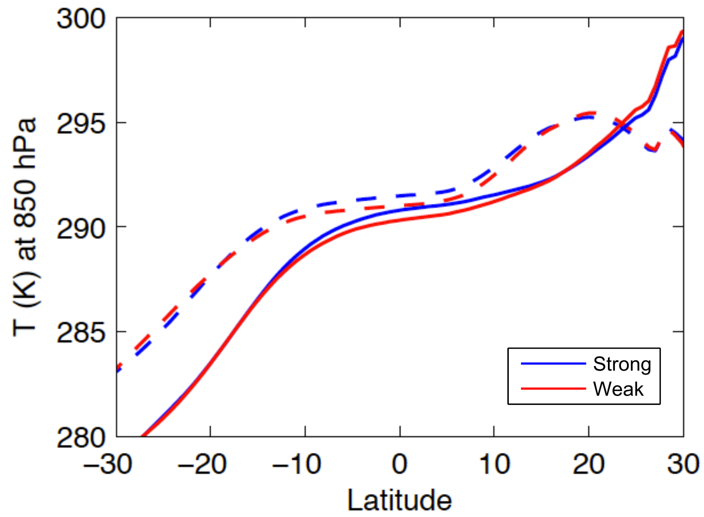


Walker et al. (2015)

Also on interannual timescales

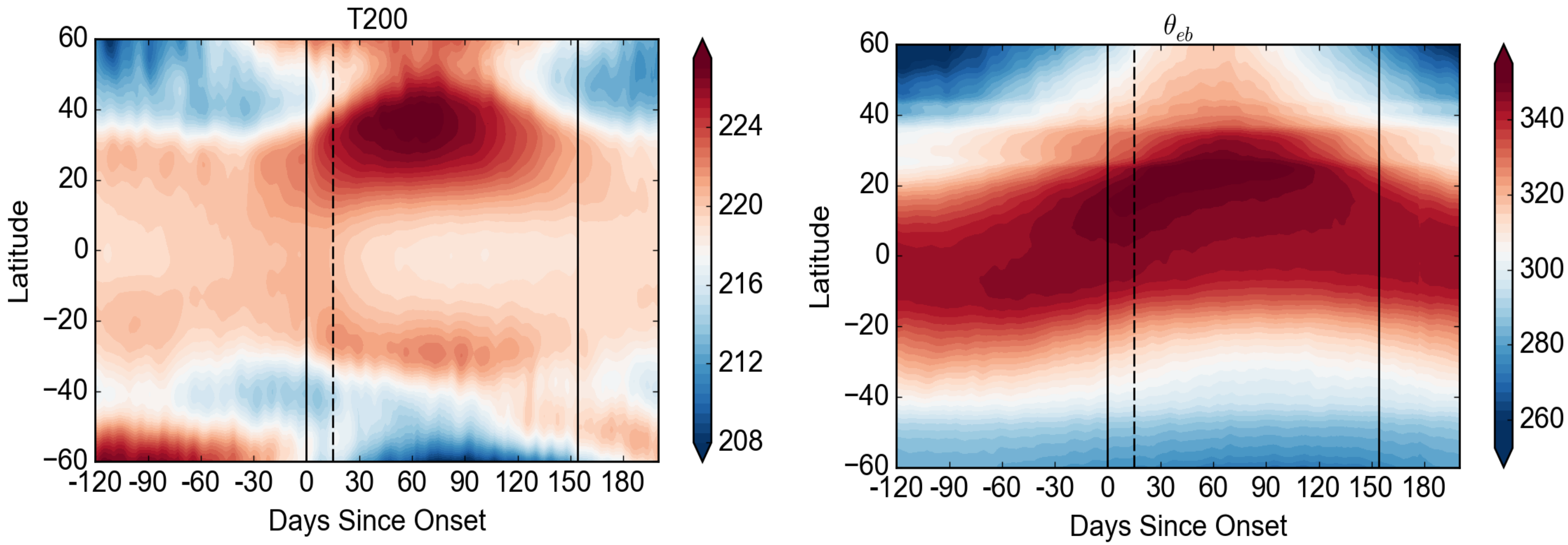


Strong monsoon years are characterized by a **weaker** near-surface meridional temperature gradient



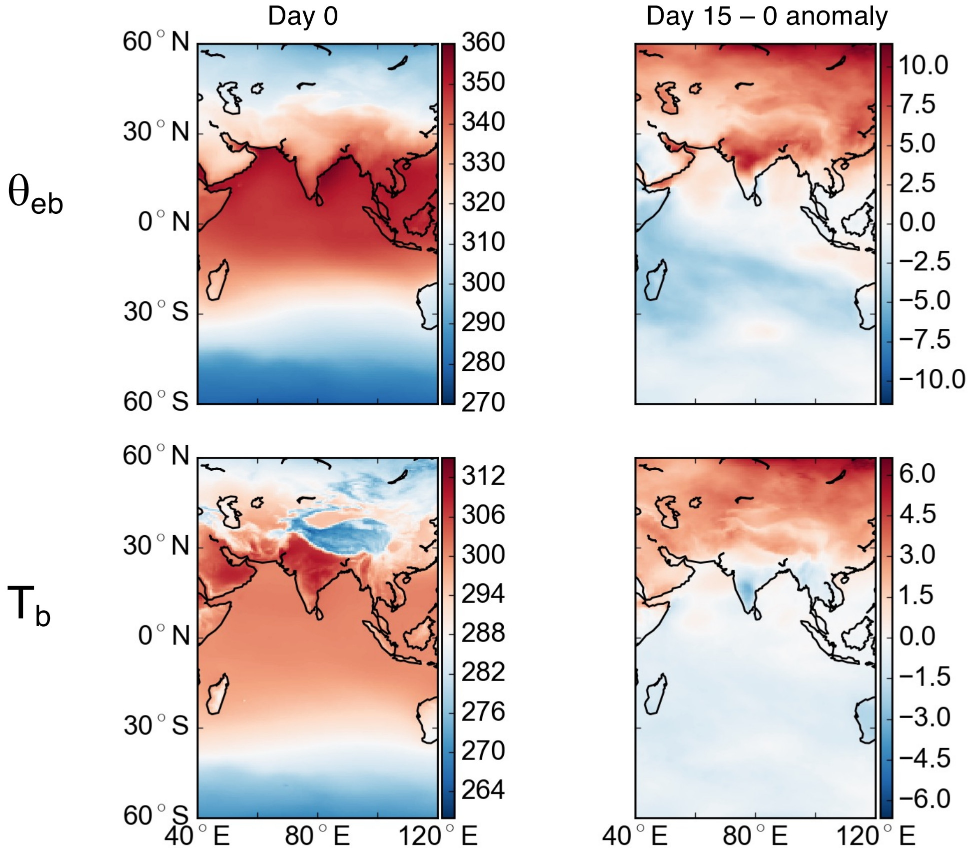
Walker et al. (2015)

And on intreaseasonal timescales



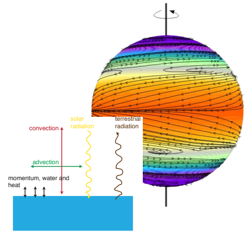
Walker and Bordoni (2016)

And on intreaseasonal timescales



Walker and Bordoni (2016)

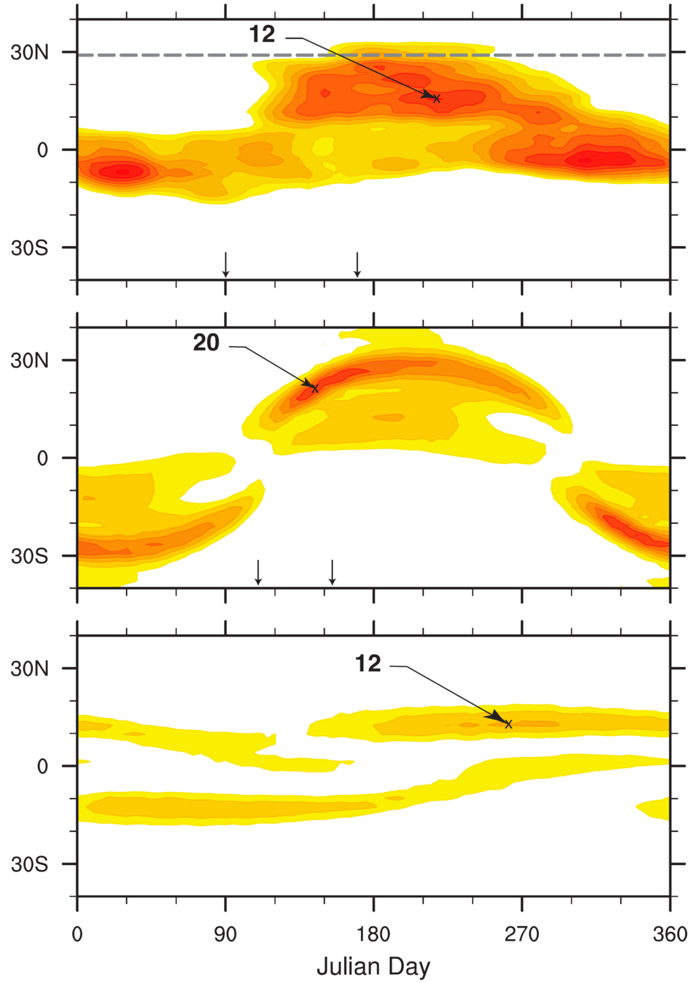
Monsoons can exist over an aquaplanet



Indian monsoon

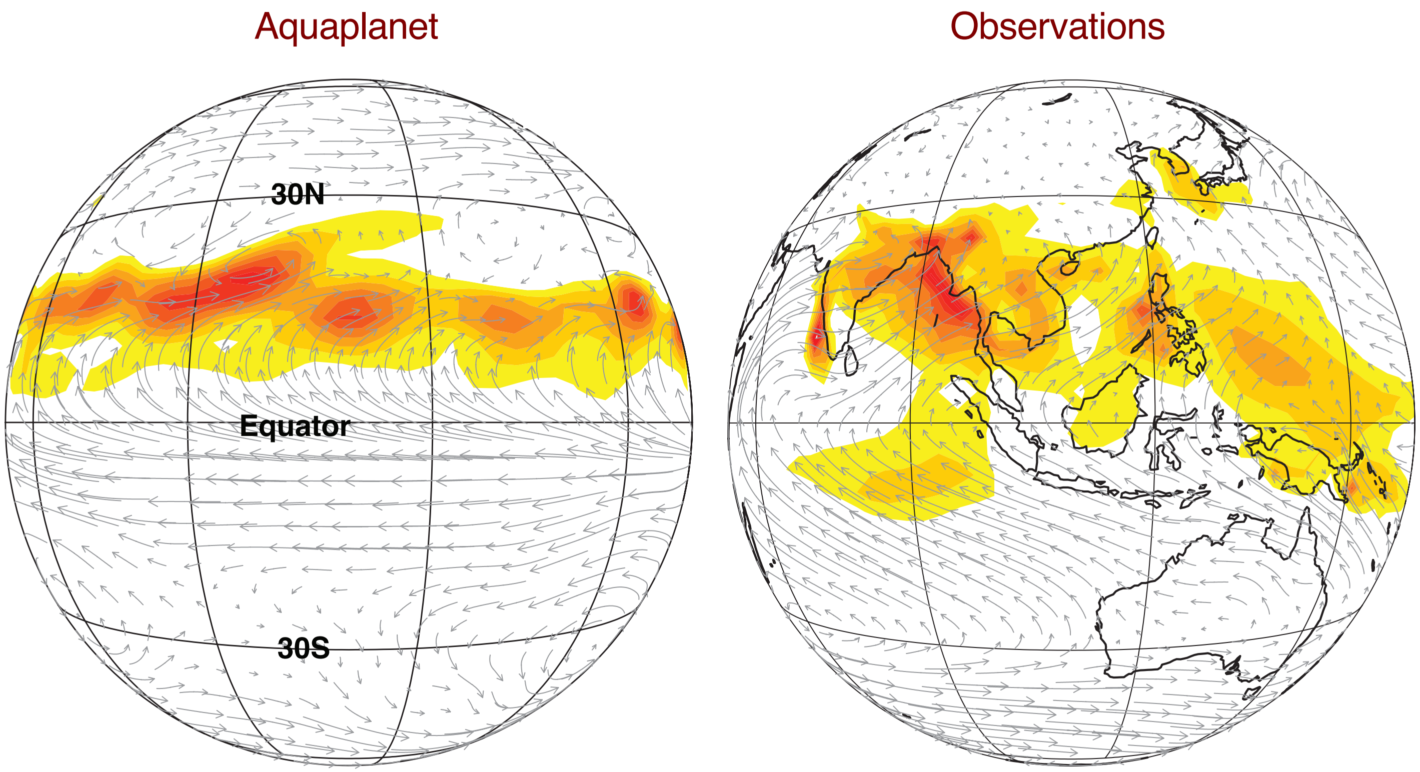
Shallow mixed layer (0.5 m)

Deep mixed layer (50 m)



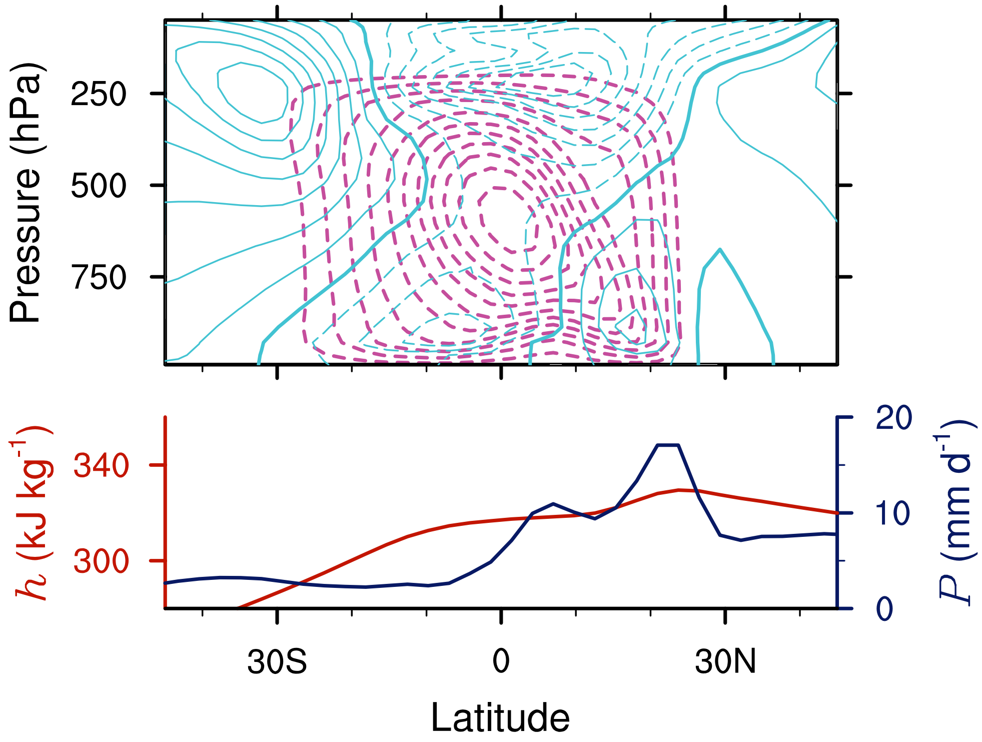
Bordoni and Schneider (2008)

Aquaplanet monsoons



Adapted from Bordoni and Schneider (2008)

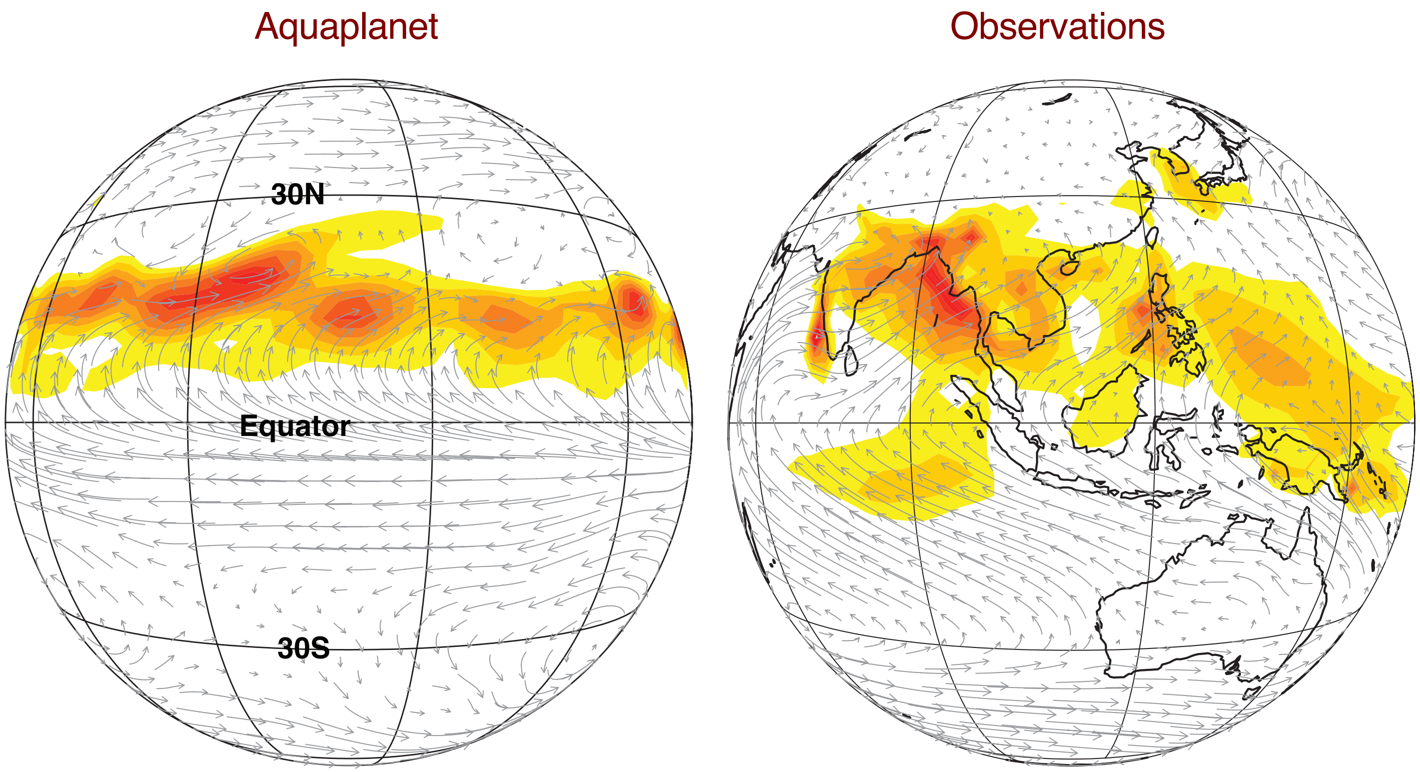
Aquaplanet monsoons



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

Adapted from Bordoni and Schneider (2008)

Aquaplanet monsoons

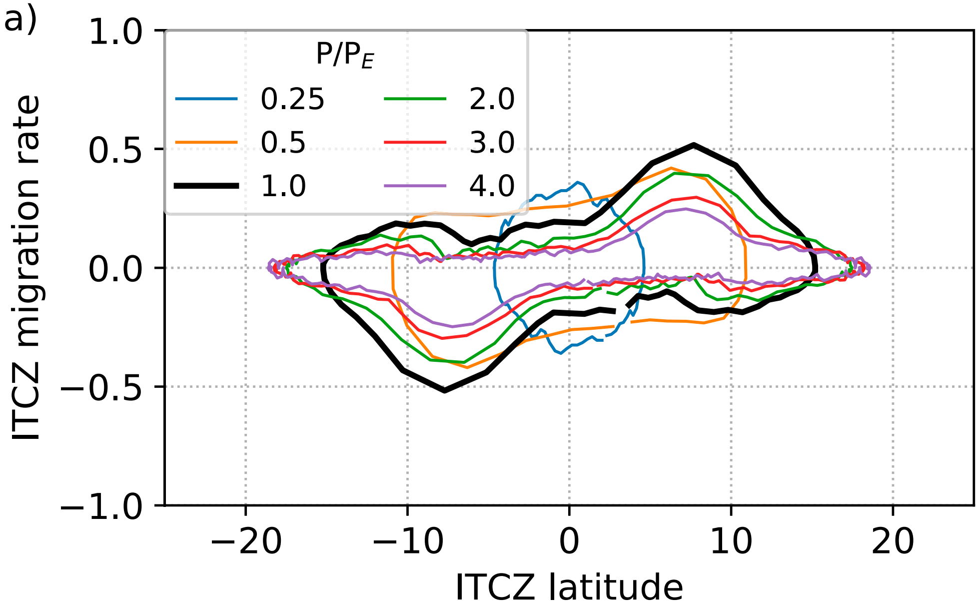


Monsoons over aquaplanets can only be simulated over shallow oceans. This suggests that land is a driver of monsoons in that it provides a surface with low enough thermal inertia, rather than driving near-surface temperature gradients.

Adapted from Bordoni and Schneider (2008)

Aquaplanet monsoons

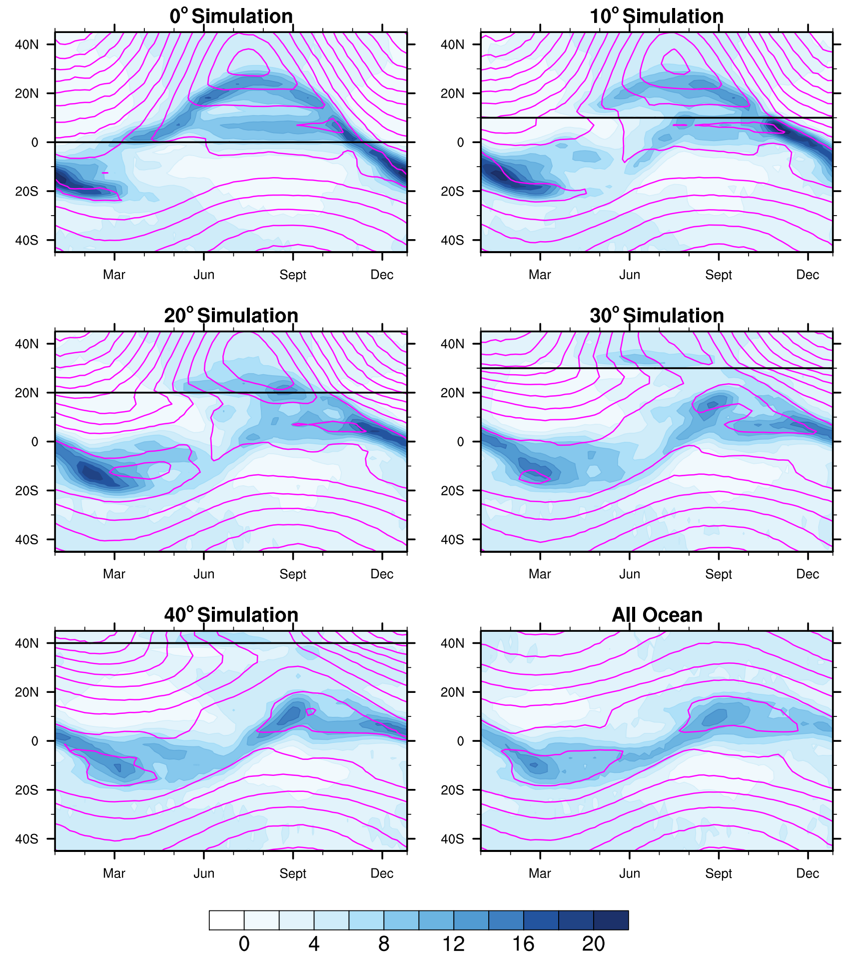
a)



In aquaplanet simulations, the convergence zone migrates poleward fastest at a latitude of ~ 7°, suggesting this to be the poleward limit of a near-equatorial ITCZ. Beyond this latitude, there is a rapid transition into a monsoon regime with convergence zone at subtropical latitudes.

Geen et al. (2019)

Monsoons over idealized continents



Hui and Bordoni (2021)

Implications for “real” monsoons

1. Monsoons cannot be thought of as large-scale sea breeze circulations driven by thermal contrast between the land and the ocean;
2. Monsoons are intimately connected to the tropical overturning; as regional Hadley cells, they need to satisfy large-scale constraints implicated by the energy and angular momentum budgets;
3. Monsoons and oceanic ITCZs are manifestation of the ascending branches of regional Hadley cells. The presence of land over monsoon regions allows for more pronounced responses to the insolation forcing, which leads to more non-linear cross-equatorial monsoonal circulations;
4. Importantly, the ITCZ and the monsoon regimes differ in their dominant angular momentum budget.

The angumal momentum budget

The large-scale circulation needs to satisfy the angular momentum budget, which in steady state in the upper branch of the circulation is

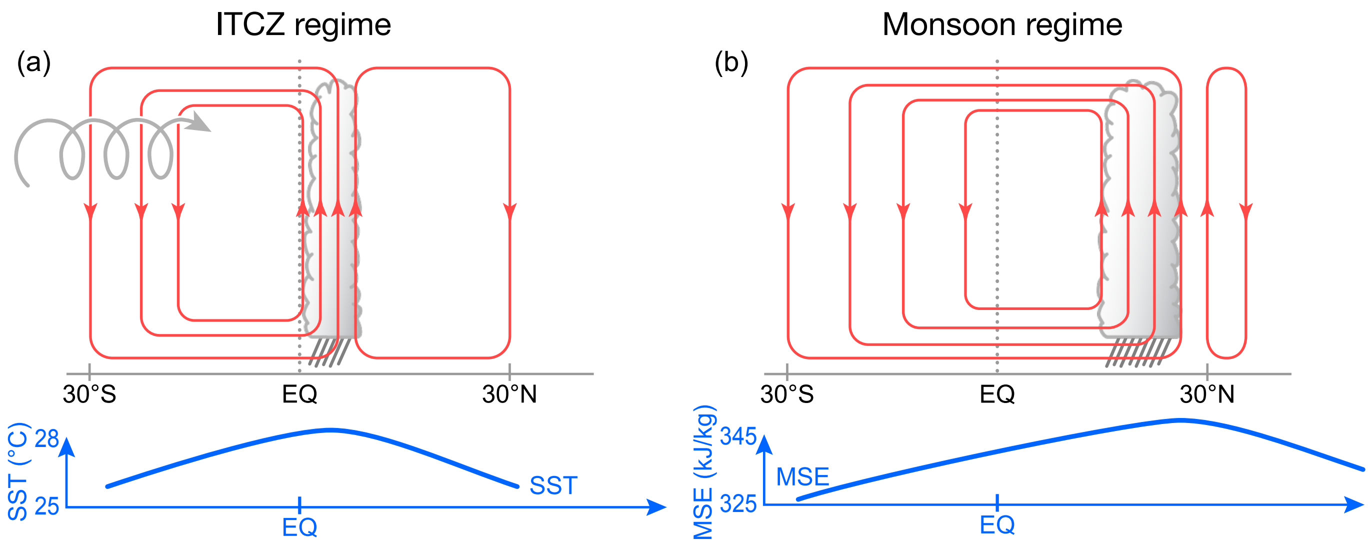
$$(f + \bar{\zeta})\bar{v} = f(1 - R_0)\bar{v} \approx \mathcal{S}$$

with local Rossby number $R_0 = -\bar{\zeta}/f$

When $\mathrm{Ro} \to 0$ the angular momentum budget reduces to $f\bar{v} \approx \mathcal{S}$ and the circulation strength is directly constrained by the large-scale eddies.

When $\mathrm{Ro} \to 1$ the angular momentum budget reduces to a trivial balance, with no constraint on the circulation strength, which responds directly to the energy balance and which conserves angular momentum.

Monsoons vs ITCZ

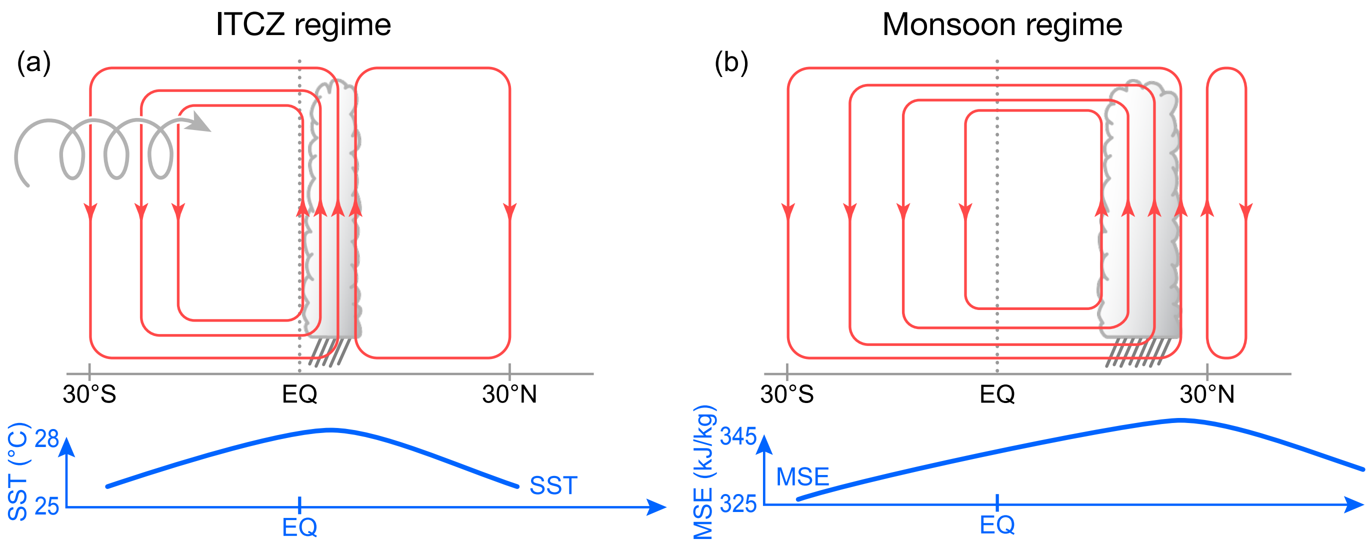


- Small Rossby number
- Linear regime
- Circulation responds directly to changes in large-scale eddies

- Large Rossby number
- Non-linear regime
- Circulation responds directly to the energetics
- Circulations approaches AM conservation

Geen et al. (2020)

Monsoons vs ITCZ



	Regime	
Property	ITCZ	Monsoon
Position of convergence zone	Within $\sim 10°$ of the Equator	Subtropics, up to $\sim 30°$N/S
Physics setting convergence zone position	Under development	Under development
Strength of overturning cell/ precipitation	Eddy momentum fluxes	Energetic controls (still under development)

Geen et al. (2020)

Implications for “real” monsoons

1. Monsoons cannot be thought as large-scale sea breeze circulations driven by thermal contrast between the land and the ocean;
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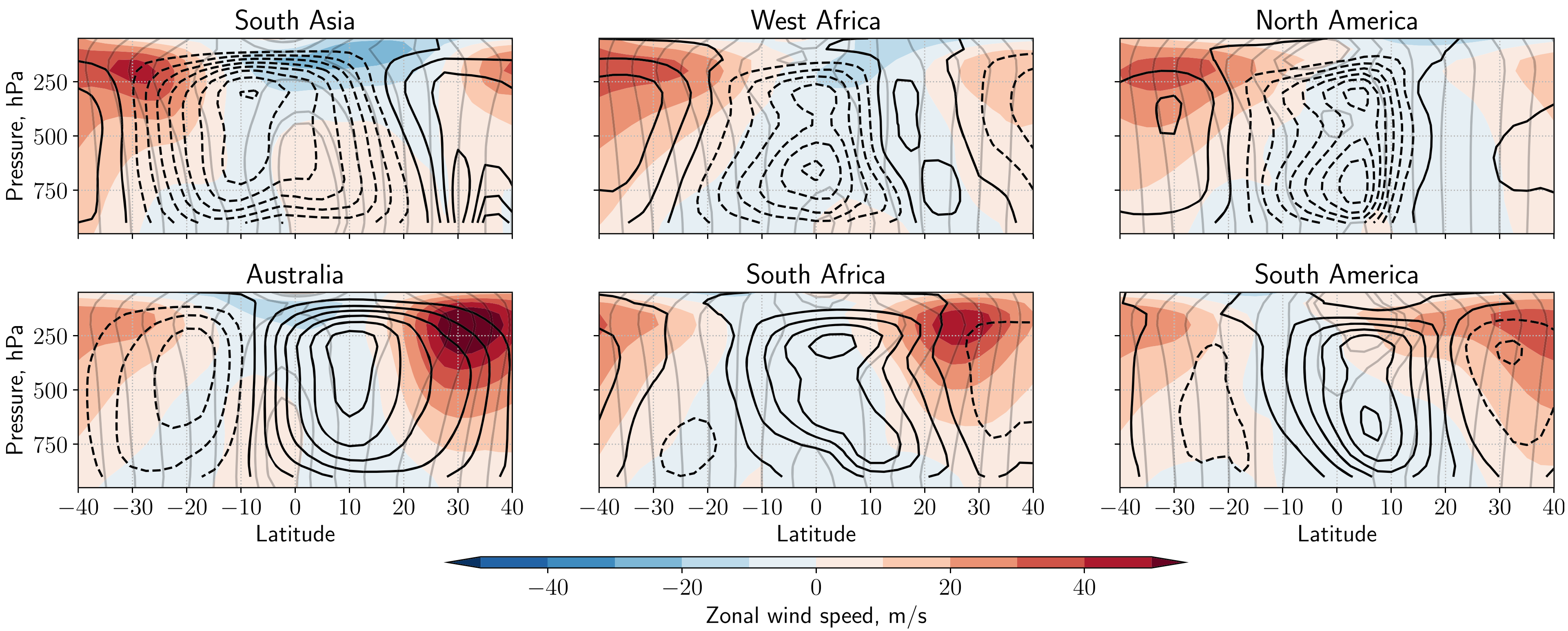
3. Monsoons and oceanic ITCZs are manifestation of the ascending branches of regional Hadley cells. The presence of land over monsoon regions allows for more pronounced responses to the insolation forcing, which leads to more non-linear cross-equatorial monsoonal circulations;
4. Importantly, the ITCZ and the monsoon regimes differ in their dominant angular momentum budget;
5. *Consequences of these emerging theoretical views on observed monsoons and how they respond to perturbations on different timescales are currently being investigated.*

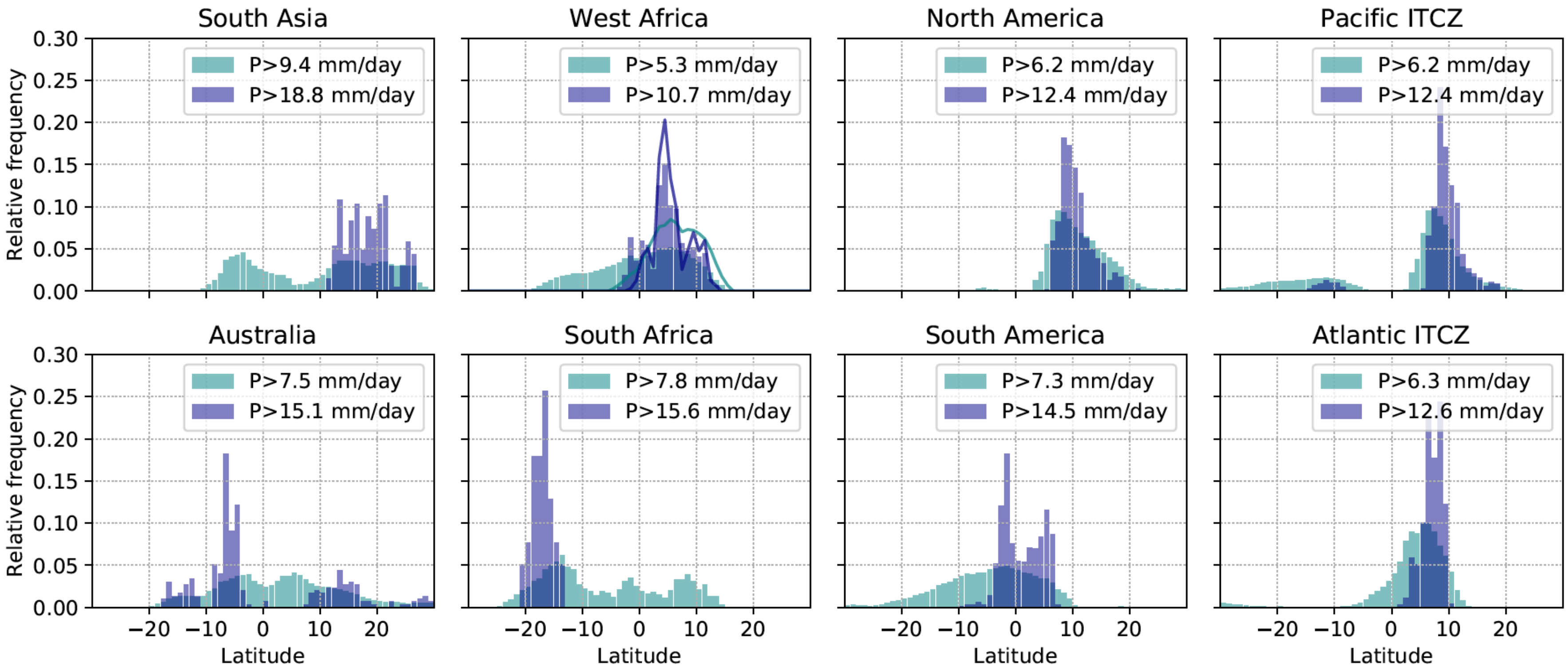
But there is some observational evidence



The overturning circulation in the South Asian and South African monsoon approaches conservation of angular momentum. Stronger deviations in other monsoon regions, especially Australia and the Americas.

Geen et al. (2020)

But there is some observational evidence



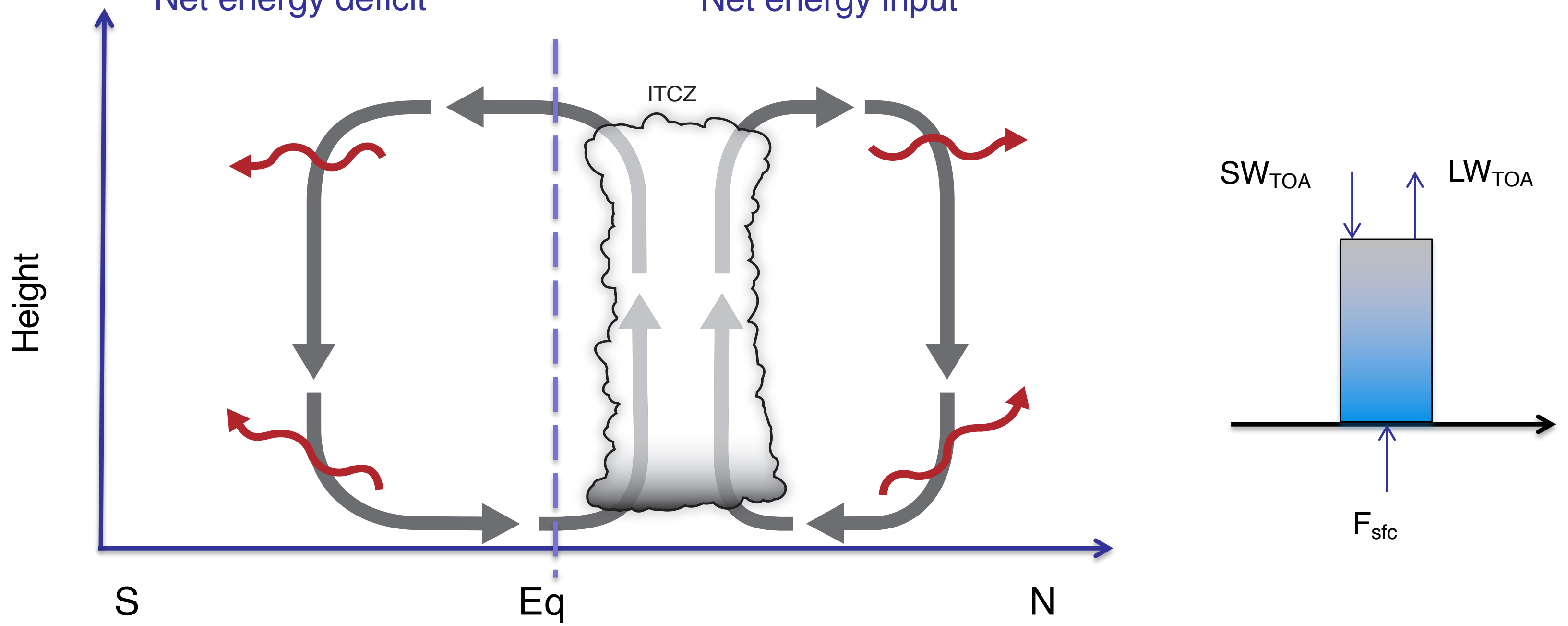
The presence of multiple precipitation peaks suggest changes in the precipitation (and circulation) regime over the year in South Asia, Australia, Southern Africa and West African.

Geen et al. (2020)

Summary

1. Theory suggests monsoons and ITCZs can be interpreted as different regimes of the tropical overturning circulation and associated convergence zone, with the monsoon regime being characterized by an angular momentum conserving circulation extending into the subtropics and coupled to the lower-level moist static energy distribution, and the ITCZ regime being characterized by an eddy-driven cell with ascending branch remaining close to the equator.
2. The differing leading order momentum budget suggests different responses of these two regimes to different forcings;
3. Observed regional systems can be differentiated and characterized in terms of these two theoretical regimes (at least to some extent);
4. Implications for their behavior on different timescales are only now beginning to be explored, but this seems to be a very promising avenue of future investigations.

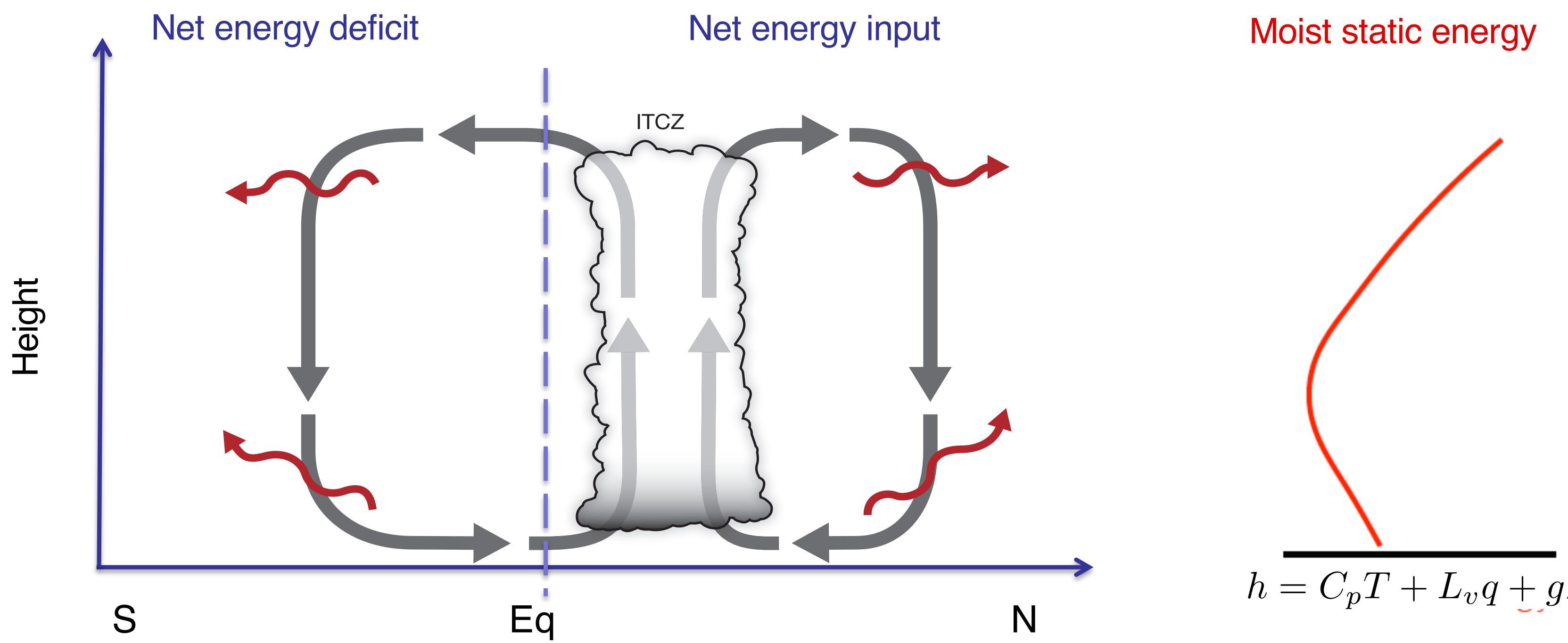
The MSE budget



If the distribution of the energy intput to the atmospheric column is hemispherically asymmetric, the atmospheric circulation needs to transport energy from the hemisphere with net energy input to the hemisphere with net energy deficit.

Adapted from Schneider et al. 2014

The MSE budget

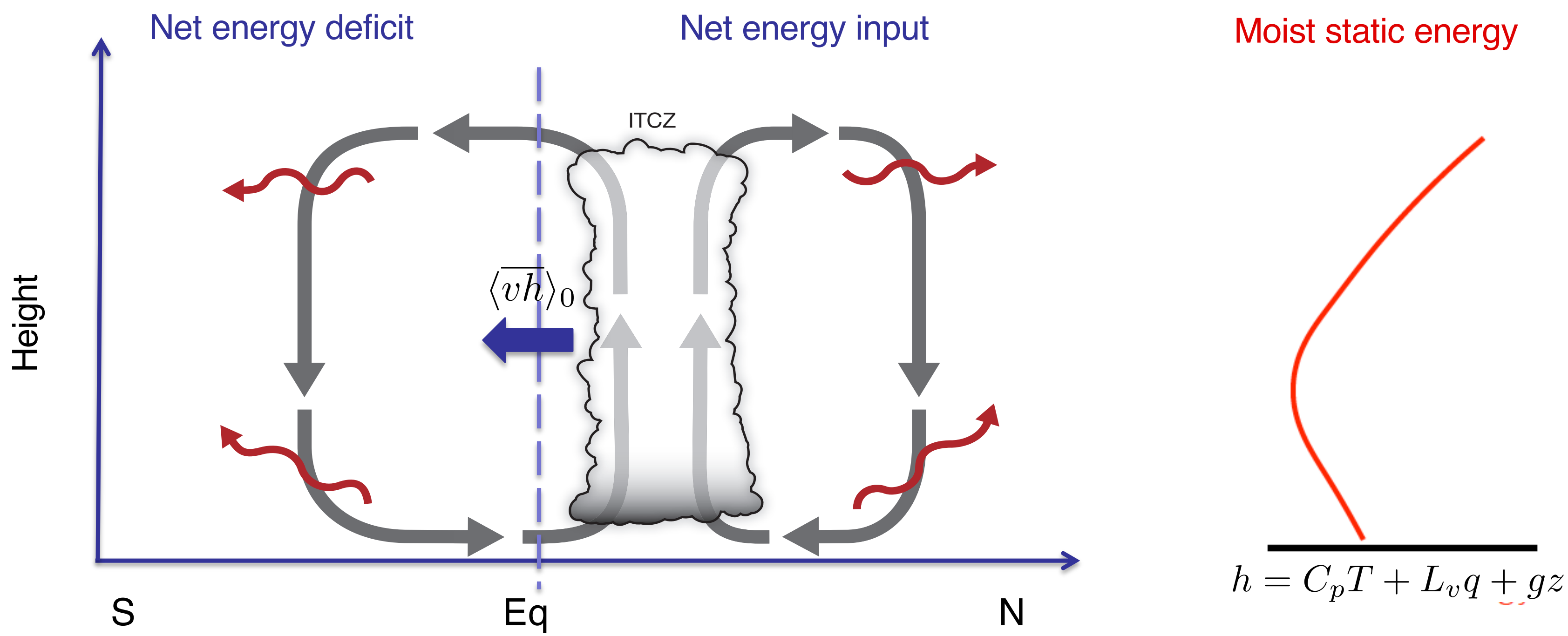


$$h = C_pT + L_vq + gz$$

Moist static energy is the relevant energy transported by large-scale circulations. It has larger values in the upper troposphere than close to the surface.

Adapted from Schneider et al. 2014

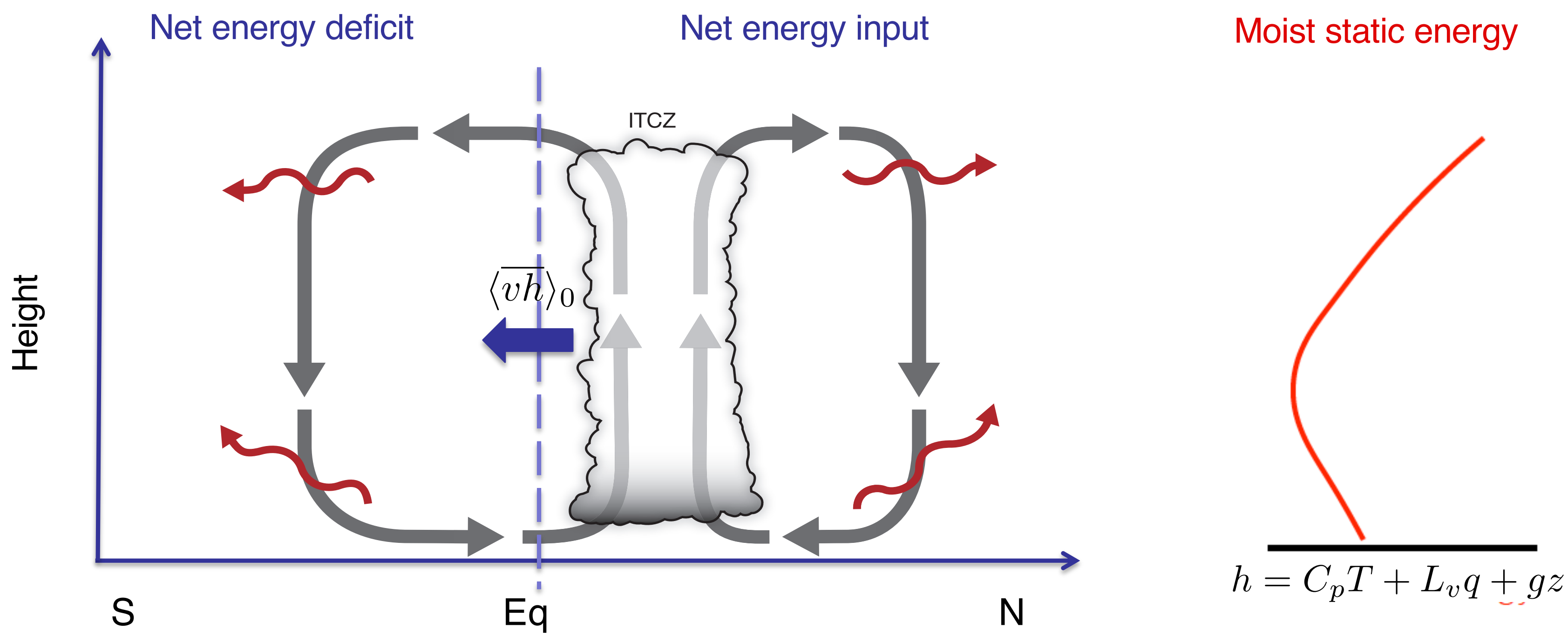
The MSE budget



Hadley and monsoonal circulations with lower and upper branches confined to thin layers close to the sfc and the tropopause transport MSE in the direction of the upper branch.

Adapted from Schneider et al. 2014

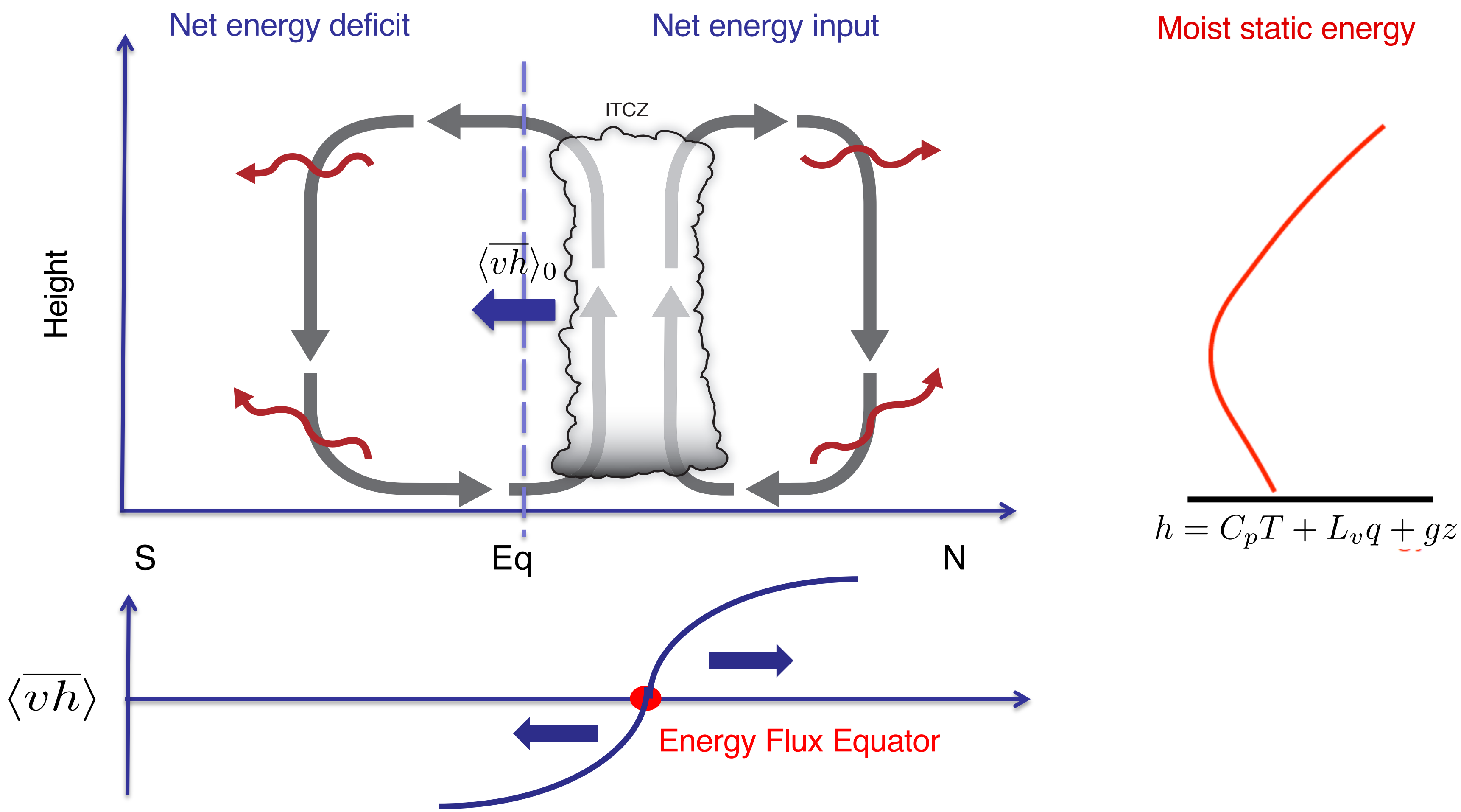
ITCZ and cross-equatorial energy transport



This view emphasizes the anticorrelation between the ITCZ position and the cross-equatorial energy transport.

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

ITCZ and EFE



Net energy deficit
Net energy input
Moist static energy
ITCZ
Height
$\langle \overline{vh} \rangle_0$
S
Eq
N
$h = C_pT + L_vq + gz$
$\langle \overline{vh} \rangle$
Energy Flux Equator

What drives rapid monsoon transitions in aquaplanet simulations

So far we have only talked about thermodynamics and energetics, but to understand the rapidity of monsoon transitions in aquaplanet simulations, we have to think about dynamics too.

Let's look at the zonal momentum budget (which one can show is equivalent to the angular momentum budget).

The zonal momentum budget

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \omega\frac{\partial u}{\partial p} - fu = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

Making the following assumptions:

1. Each variable can be decomposed in a mean an eddy term

$$u = \overline{u} - u'$$

2. Assuming continuity in both the mean and eddy velocities

the zonal and time mean zonal momentum budget becomes

$$\frac{\partial \overline{u}}{\partial t} + \overline{v}\frac{\partial \overline{u}}{\partial y} + \overline{\omega}\frac{\partial \overline{u}}{\partial p} - f\overline{v} = -\frac{\partial \overline{(u'v')}}{\partial y} - \frac{\partial \overline{(u'\omega')}}{\partial p}$$

The zonal momentum budget

Introducing the vertical component of the relative vorticity

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad\qquad \overline{\zeta} = -\frac{\partial \overline{u}}{\partial y}$$

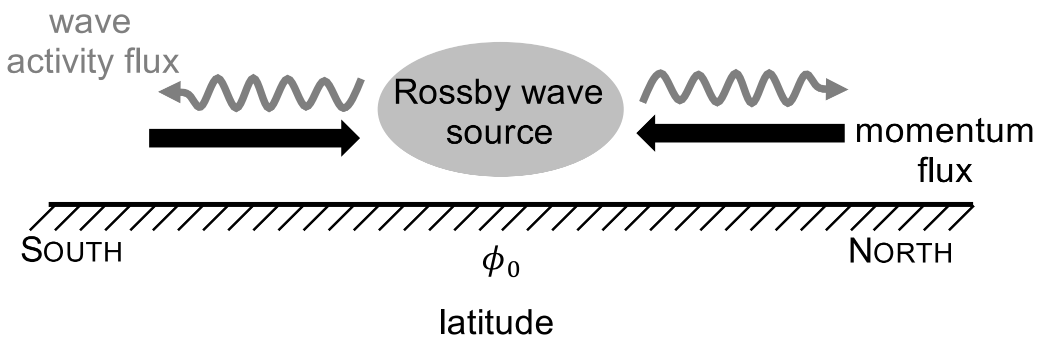
the zonal momentum budget can be rewritten as

$$\frac{\partial \overline{u}}{\partial t} - (f + \overline{\zeta})\overline{v} + \omega \frac{\partial \overline{u}}{\partial p} = -\frac{\partial (\overline{u'v'})}{\partial y} - -\frac{\partial (\overline{u'\omega'})}{\partial p}$$

Notice how convergence (divergence) of eddy momentum flux results in a westerly (easterly) tendency of the mean zonal momentum.

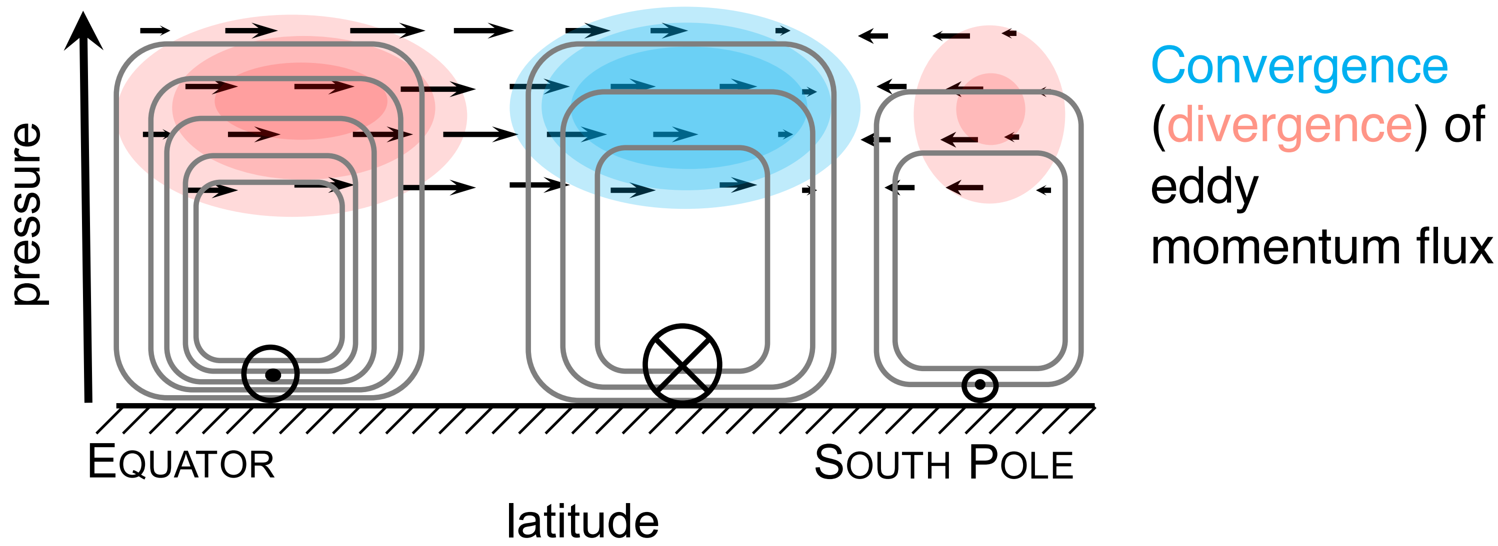
Zonal momentum and large-scale eddies

Large-scale extratropical eddies converge zonal momentum in regions in which they are generated (extratropics) and they divergence momentum from regions in which they break (subtropics). They propagate in regions of upper-level westerly flow and they tend to break as they approach their critical latitude.



Courtesy of Marty Singh

Zonal momentum and large-scale eddies



The zonal momentum budget in steady state

In steady state and neglecting the vertical advection and vertical eddy momentum flux terms, the zonal momentum budget becomes

$$(f + \overline{\zeta})\overline{v} = \mathcal{S}$$

with eddy momentum flux divergence $\mathcal{S}$

We can define a local Rossby number as $R_o = -\frac{\overline{\zeta}}{f}$

and the momentum budget becomes

$$(f + \bar{\zeta})\bar{v} = f(1 - R_0)\bar{v} \approx \mathcal{S}$$

The zonal momentum budget in steady state

Let's look at the two opposing limits of small and large local Rossy number.

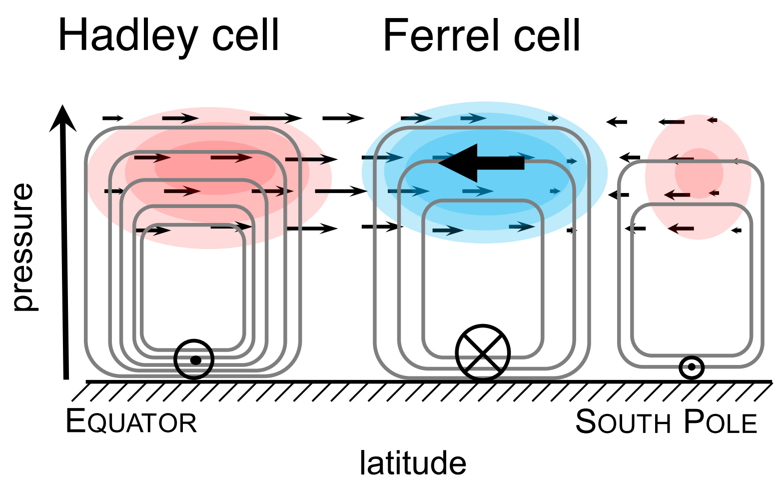
1.Small Rossby number (extratropical regime)

$$f\bar{v} \approx \mathcal{S}$$

In this regime, the overturning cell is entirely driven by the eddies, as its strength is directly linked to the eddy momentum flux convergence. Any change in eddies will have to be met by a change in the strength of the meridional circulation.

The zonal momentum budget in steady state

This is the relevant regime for the Ferrel cell. The Ferrel cell can be indirect because it is driven by dynamical constraints.



The zonal momentum budget in steady state

2. Large Rossby number (tropical regime)

$$\mathrm{Ro} \to 1$$

$$(f + \bar{\zeta}) \approx 0$$

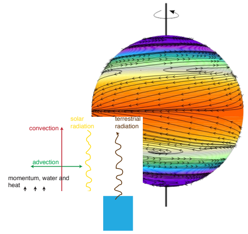
$$\mathcal{S} \approx 0$$

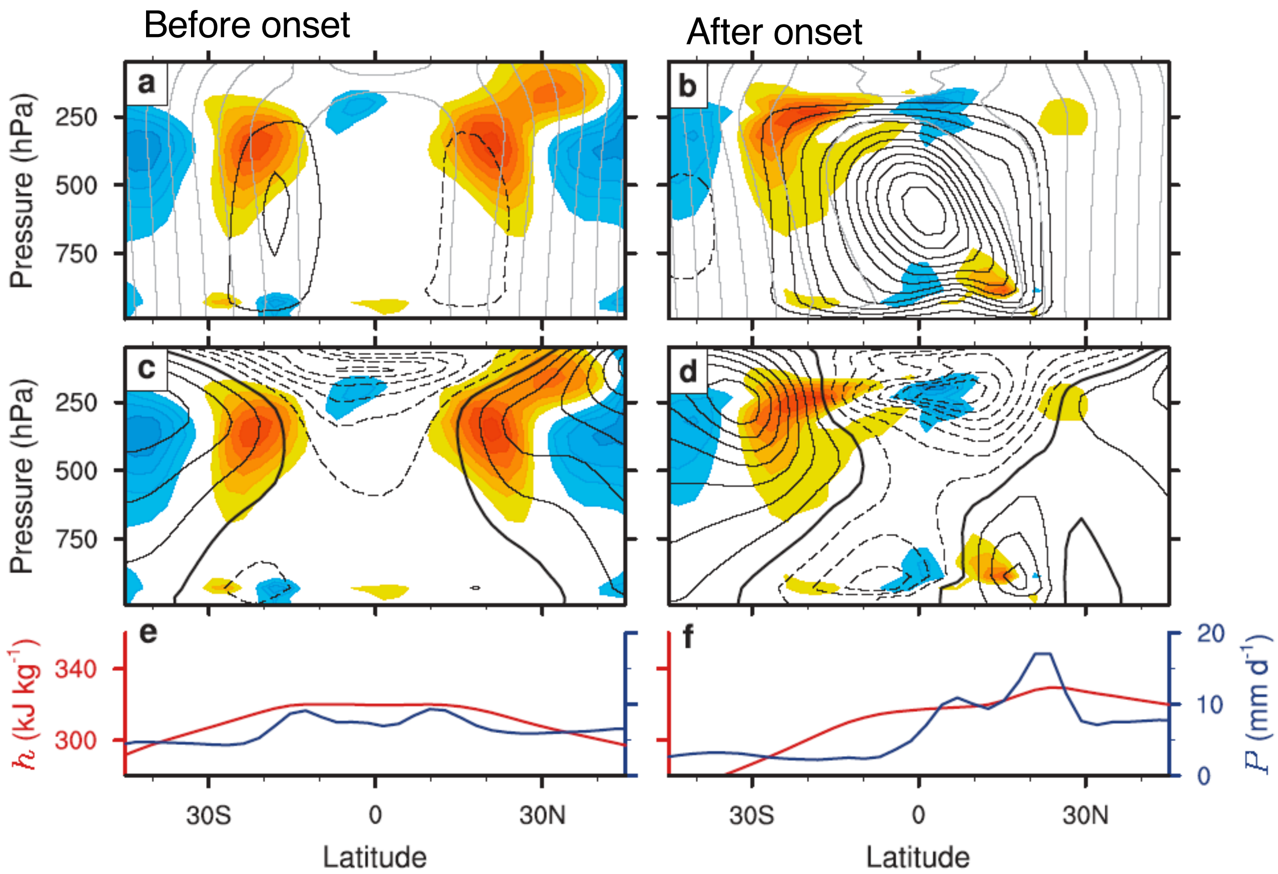
Remembering that

$$(f + \bar{\zeta}) = f(1 - \mathrm{Ro}) = -(a^2 \cos\phi)^{-1} \frac{\partial \bar{M}}{\partial \phi}$$

this limit is the limit of a cell that conserves angular momentum. AM is is homogenized by the overturning circulation in its upper branch. Streamlines and AM contours coincide.

Monsoons can exist over an aquaplanet





Bordoni and Schneider (2008)