Multiple perspectives on the monsoon

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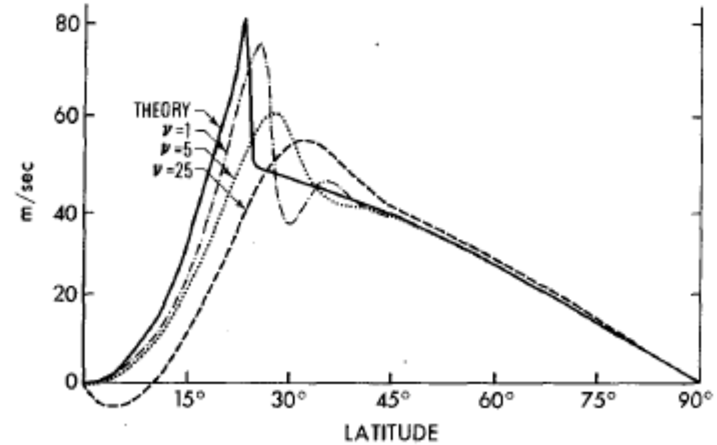
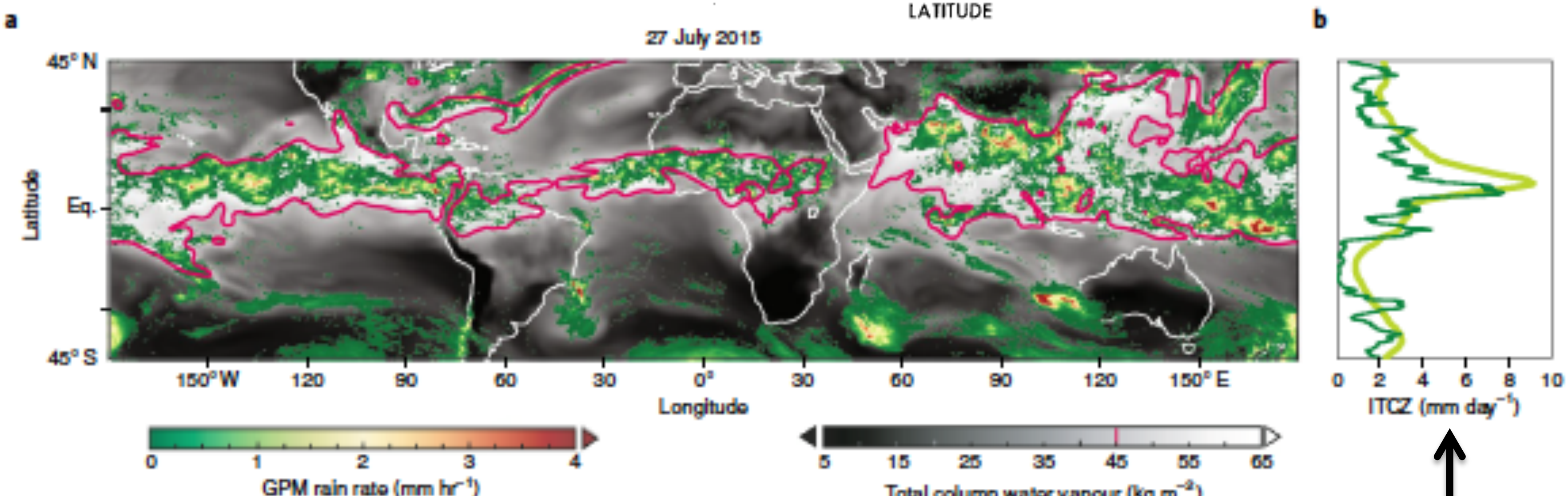
(with results from many others in the literature)

The goal of our project is to bring the simplicity of the most elegant theories and the complexity of the real monsoon closer together.

Simulated zonal wind profiles
For axisymmetric Hadley cells,
approaching the inviscid limit
(Held and Hou 1980)





Precipitation (GPM) & column water vapor from one day

Zonal mean precip from the same day & climatology of same for that date

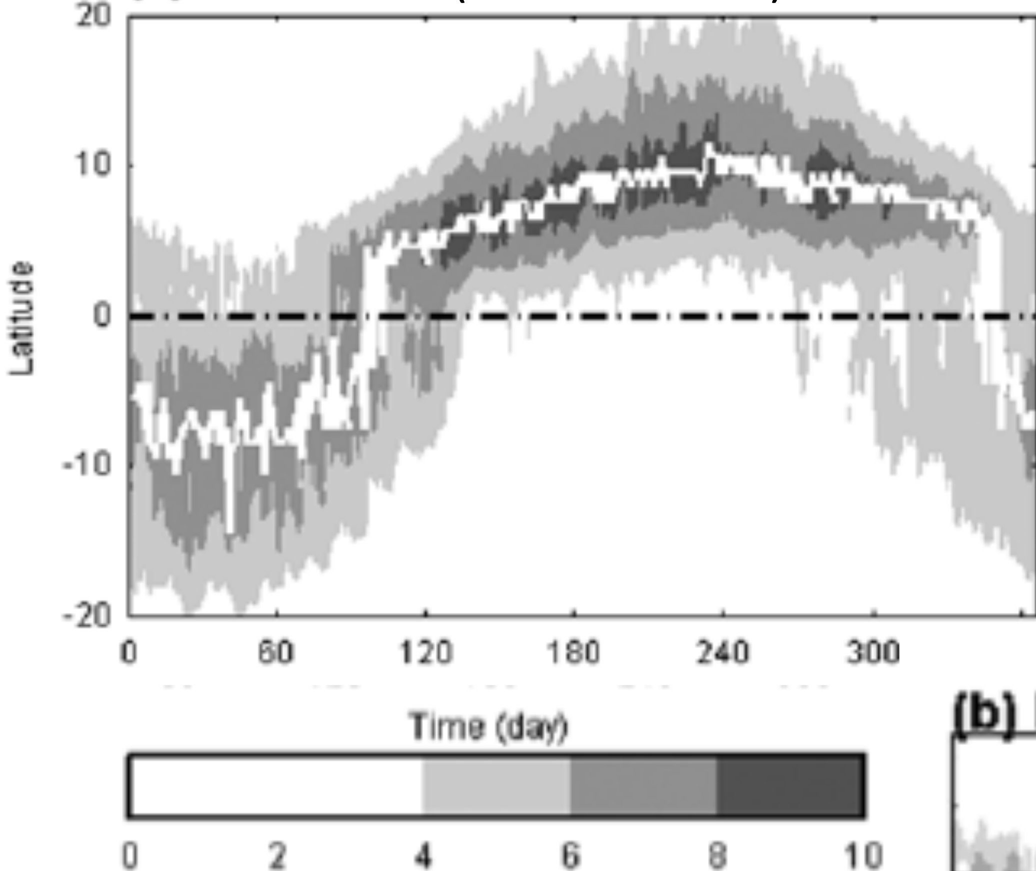
Biasutti et al. 2018

Outline

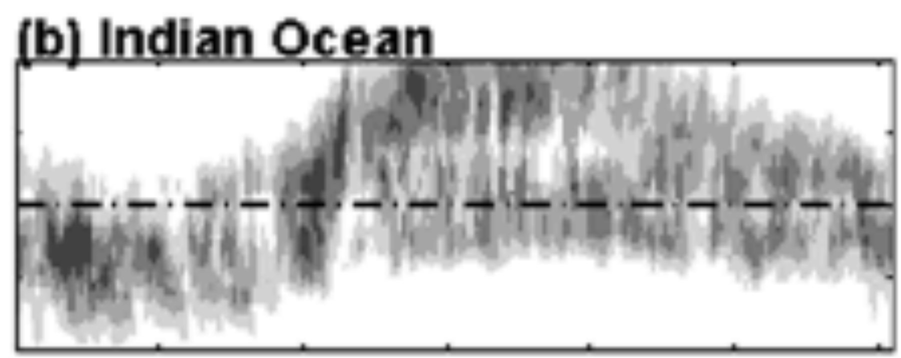
- Axisymmetric Hadley cell theory and its various revisions
- Moist static energy budget view of the ITCZ
- Challenges in applying these ideas to the monsoon
- Some recent studies that illustrate these challenges

The zonal mean has great advantages from the perspective of theory, so we start there. It seems to have some relevance ...

Zonal mean GPCP precipitation,
(a) 1997-2006 (Hu et al. 2007). White = max



Same plot for India sector



1. Dry, axisymmetric Hadley circulation models

These often assume simple vertical structure and diabatic forcing that relaxes temperature back to a latitude-dependent radiative-convective equilibrium state (E. Schneider and Lindzen 1977; Held & Hou 1980; Lindzen & Hou 1988; Plumb & Hou 1992; Fang & Tung 1996, 1997). Viscosity is assumed small away from the surface.

No eddies.

$$\left.\begin{aligned} 0 &= -\nabla\cdot(\mathbf{v}u) + fv + \frac{uv\tan\theta}{a} + \frac{\partial}{\partial z}\left(\nu\frac{\partial u}{\partial z}\right) \\ 0 &= -\nabla\cdot(\mathbf{v}v) - fu - \frac{u^2\tan\theta}{a} - \frac{1}{a}\frac{\partial\Phi}{\partial\theta} \\ &\qquad + \frac{\partial}{\partial z}\left(\nu\frac{\partial v}{\partial z}\right) \\ 0 &= -\nabla\cdot(\mathbf{v}\Theta) - (\Theta - \Theta_E)\tau^{-1} + \frac{\partial}{\partial z}\left(\nu\frac{\partial\Theta}{\partial z}\right) \\ 0 &= -\nabla\cdot\mathbf{v} \\ \frac{\partial\Phi}{\partial z} &= g\Theta/\Theta_0 \end{aligned}\right\}, \quad (1)$$

with boundary conditions

$$\left.\begin{aligned} &\text{at}\quad z = H:\quad w = 0;\quad \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = \frac{\partial\Theta}{\partial z} = 0 \\ &\text{at}\quad z = 0:\quad w = 0;\quad \frac{\partial\Theta}{\partial z} = 0; \\ &\qquad\qquad \nu\frac{\partial u}{\partial z} = Cu;\quad \nu\frac{\partial v}{\partial z} = Cv \end{aligned}\right\}. \quad (1a)$$

$$\frac{\Theta_E(\theta,z)}{\Theta_0} = 1 - \frac{2}{3}\Delta_H P_2(\sin\theta) + \Delta_v\left(\frac{z}{H} - \frac{1}{2}\right),$$

Held and Hou 1980

The Hadley cell occurs in a latitudinally confined region of uniform angular momentum in the upper troposphere. Poleward of that, the RCE state holds, and there is no circulation.

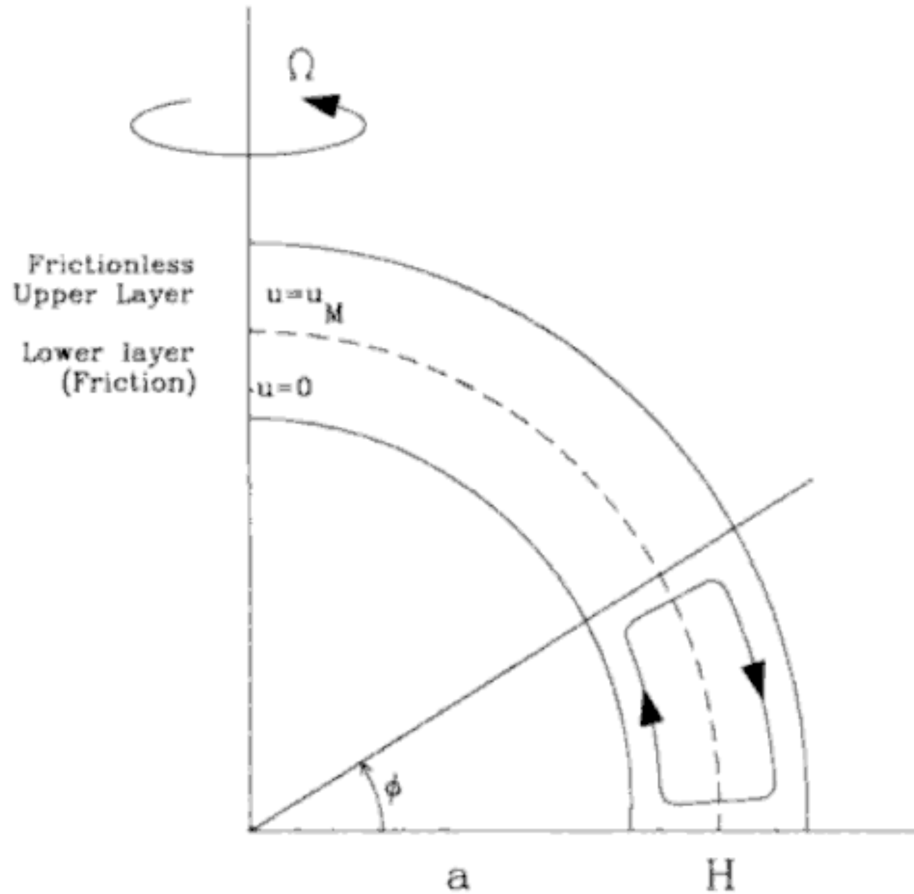
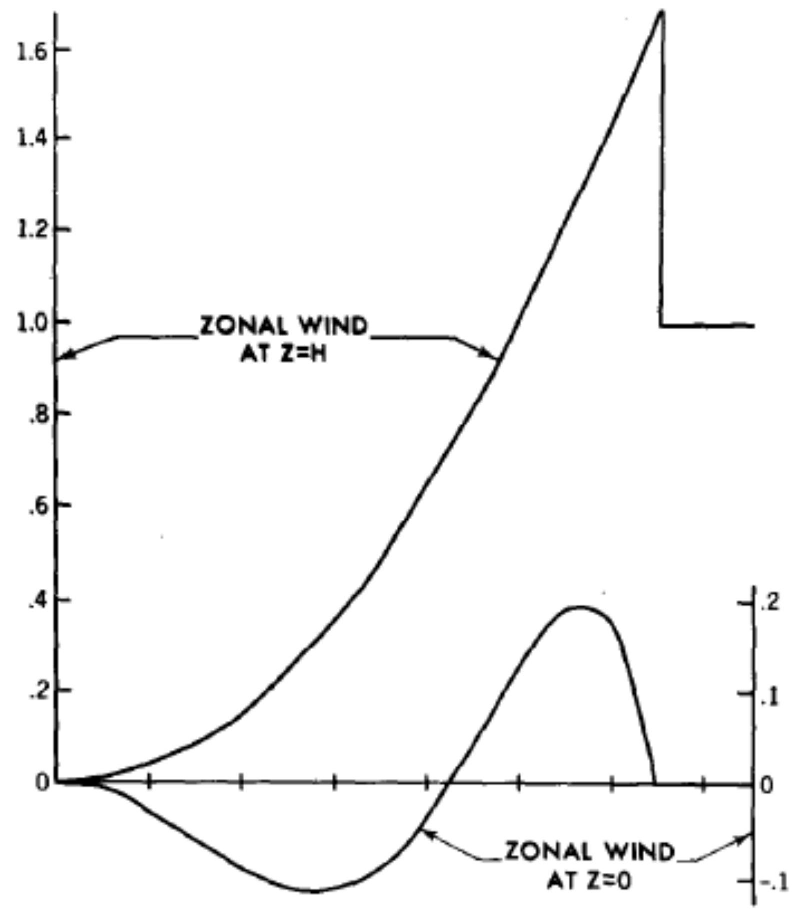


Fig. 4.4. Schematic illustration of the Held–Hou model.

Within the cell, upper-level zonal velocity has a parabolic shape consistent with uniform angular momentum. (Surface wind is what is needed for friction to restore angular momentum of parcels moving equatorward in the trades.)



The circulation homogenizes temperature in the deep tropics, as (nonlinear) thermal wind relates temperature to the zonal wind.

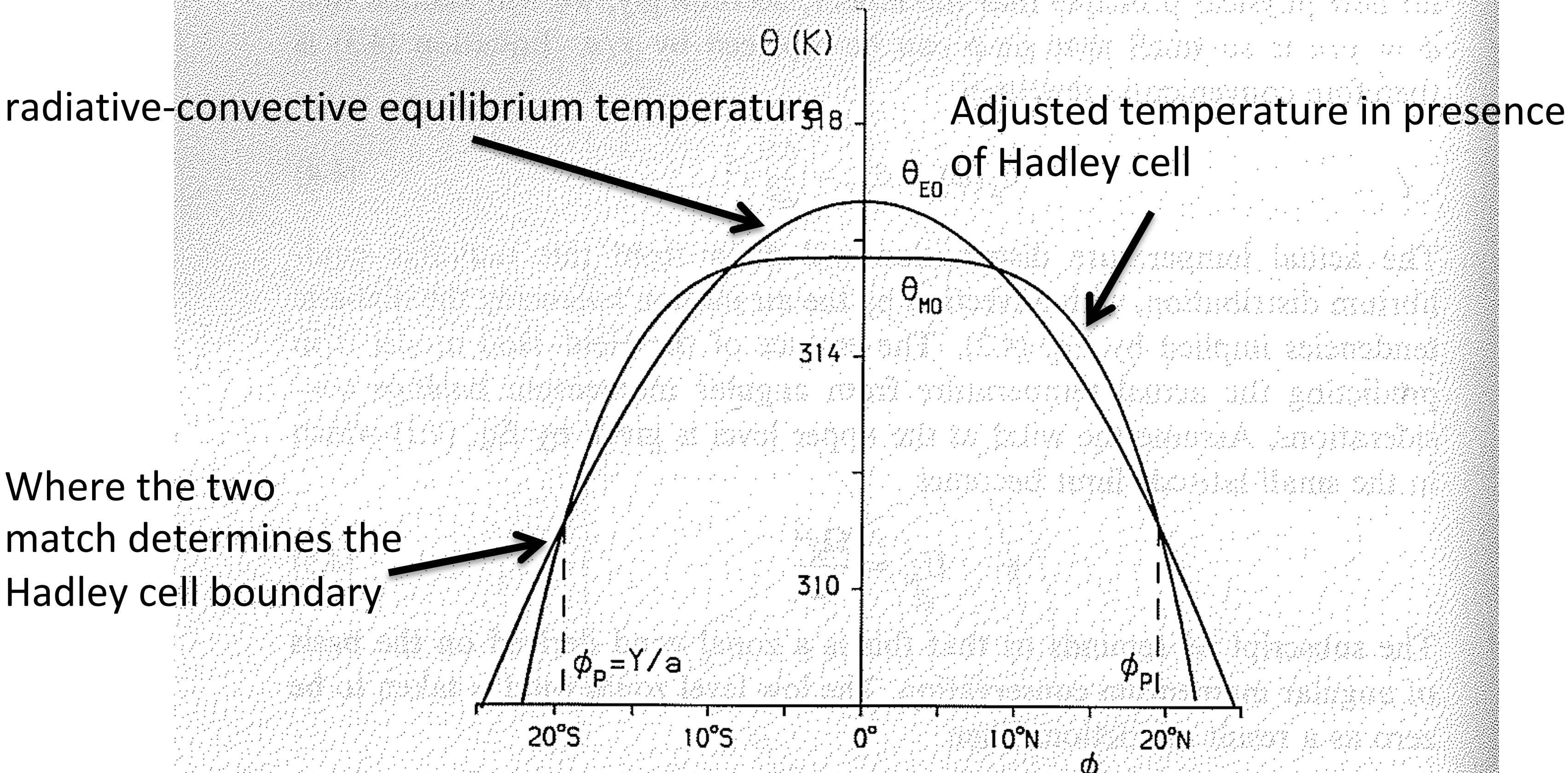


Fig. 4.5. Showing θ_E and θ_M as a function of poleward distance for the Held and Hou model. θ_{M0} must be chosen so that the areas between the two curves are equal, i.e., so that there is no net heating of air parcels.

James, 1990 Dynamics of Circulating Atmospheres

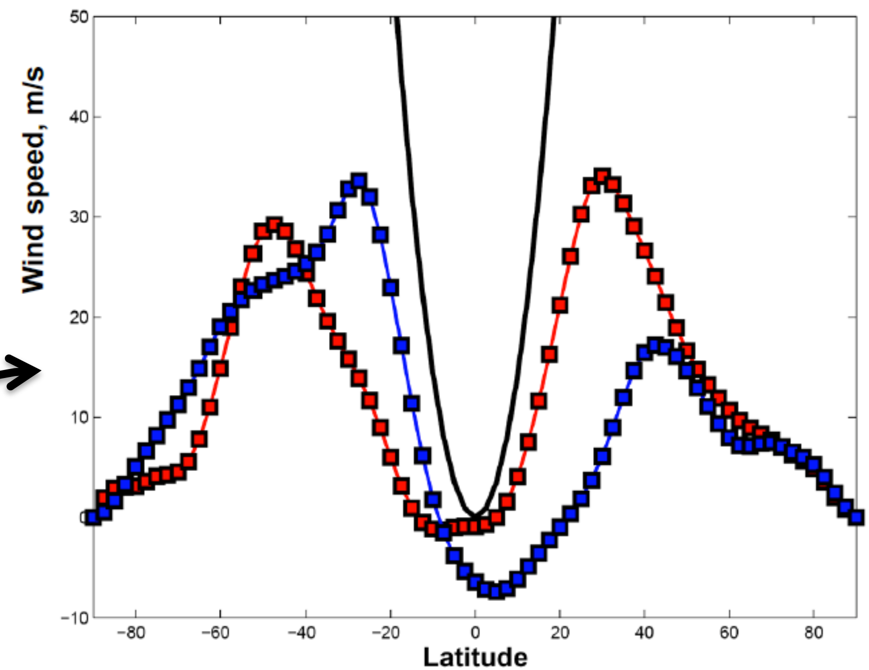
Axisymmetric theory successes

- Width of Hadley circulation (to zeroth order) ~ equatorial deformation radius
- Gross structure of meridional overturning
- Surface easterlies at low latitudes, westerlies at high latitudes
- Existence & approximate location of subtropical jets
- Flat temperature gradients in deep tropics

Axisymmetric theory failures

- Zonal winds much too strong
- Meridional circulation too weak (and Lindzen-Hou fix for this, invoking nonlinear response to seasonal cycle, has not held up)
- In observations, angular momentum is not nearly conserved (at least much of the time) due to eddy transports

Angular momentum conserving winds (black line) and 200mb zonal winds (in boreal winter and summer).



A. Federov, Yale Univ.

To address these, we consider departures from pure axisymmetry, to consider zonal mean theory including rectified effects of eddies, following T. Schneider & colleagues

In all this theory (including with eddies), zonal momentum comes first.

The zonal momentum budget for steady zonal-mean circulation with zonal torque F is

$v\,\partial u/\partial y - fv = F$

or since in zonal mean $\partial_x = 0$, the relative vorticity is $\zeta = -\partial u/\partial y$ so we can write

$v(\zeta + f) = -F$

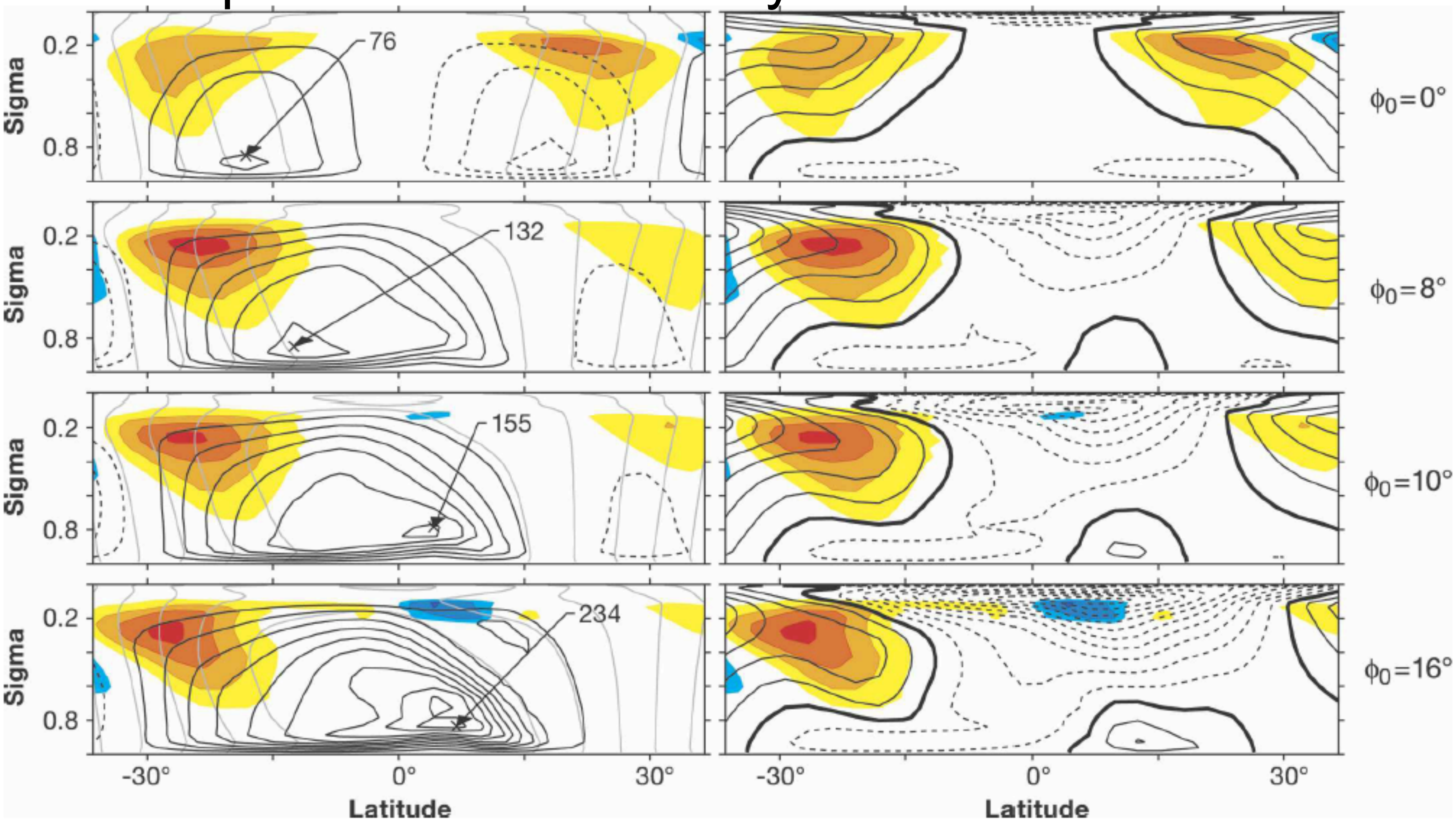
Two possible balances:

1. $F \neq 0$ and $\zeta + f \neq 0$. E.g. $F<0$ (easterly/westward torque) induces poleward flow, as is the case for observed eddy momentum flux convergence in subtropics. This is a quasi-linear balance (truly linear if $\zeta \ll f$)

2. For an inviscid axisymmetric flow, $F=0$, which implies that if $v \neq 0$, it must be the case that $\zeta + f = 0$. This equation then does not determine v, and one proceeds to consider thermodynamics etc. This is a nonlinear balance since $Ro = |\zeta/f| = 1$.

Role of eddy momentum fluxes (F ≠ 0)

Quasi-dry idealized non-axisymmetric GCM simulations of different phases of seasonal cycle



Latitude of peak heating

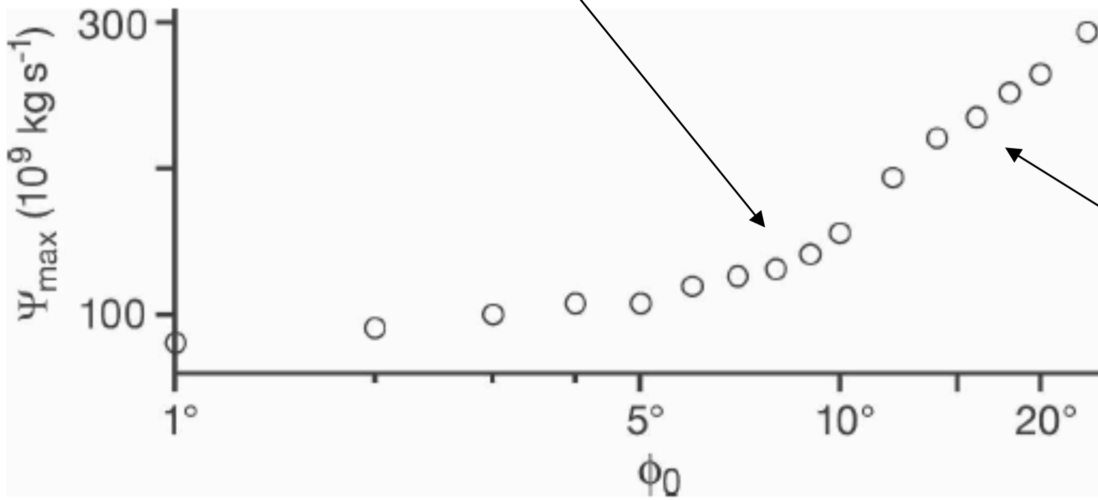
mean meridional stream fn, eddy momentum flux divergence, ang. Mom.

zonal mean zonal wind, eddy momentum flux divergence

Schneider and Bordoni 2008 *JAS* **65** 915-934

When the heating is far from the equator, the circulation is close to axisymmetric theory. When heating is near the equator, eddies are important.

transition from one power law to another

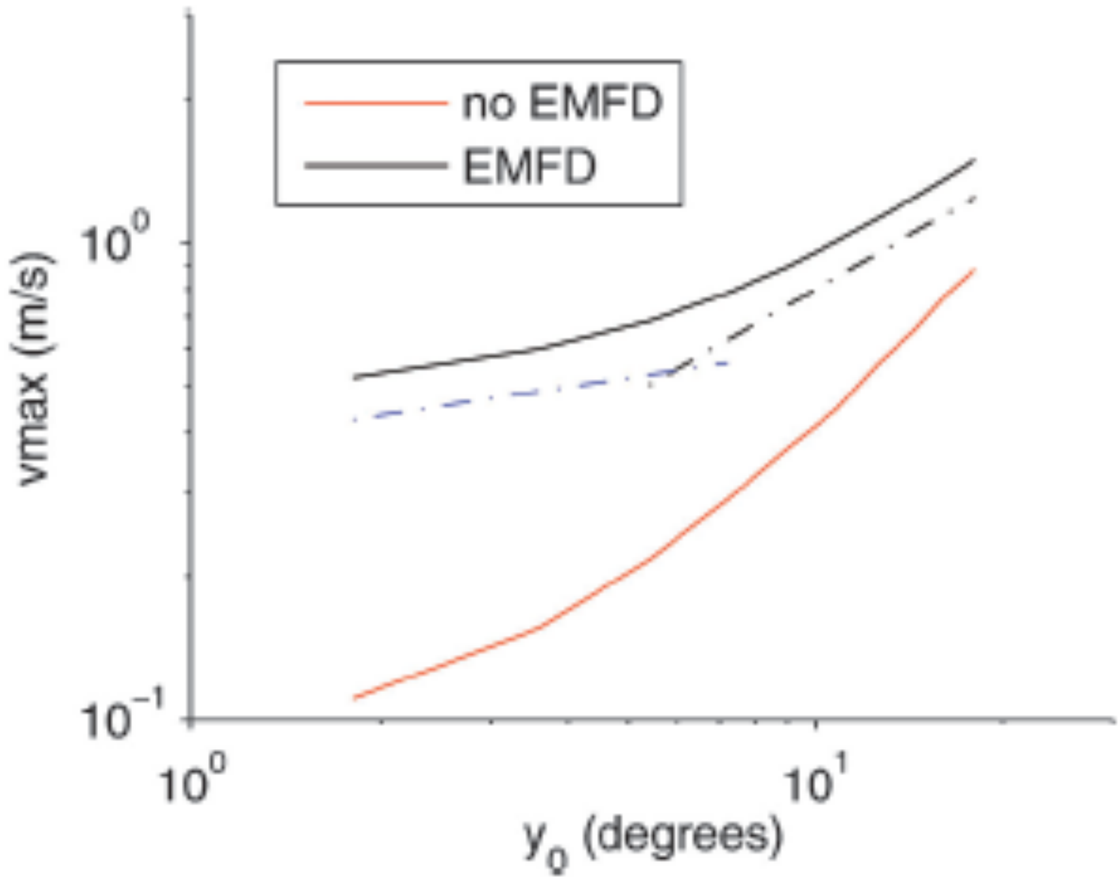


This power law close to inviscid axisym theory

FIG. 2. Strength Ψ_{max} of cross-equatorial Hadley cell as function of ϕ_0 in simulations of statistically steady states. The strength is the maximum value of the streamfunction of the mean meridional circulation above the level $\sigma = 0.85$. The scale of the ϕ_0 axis is logarithmic.

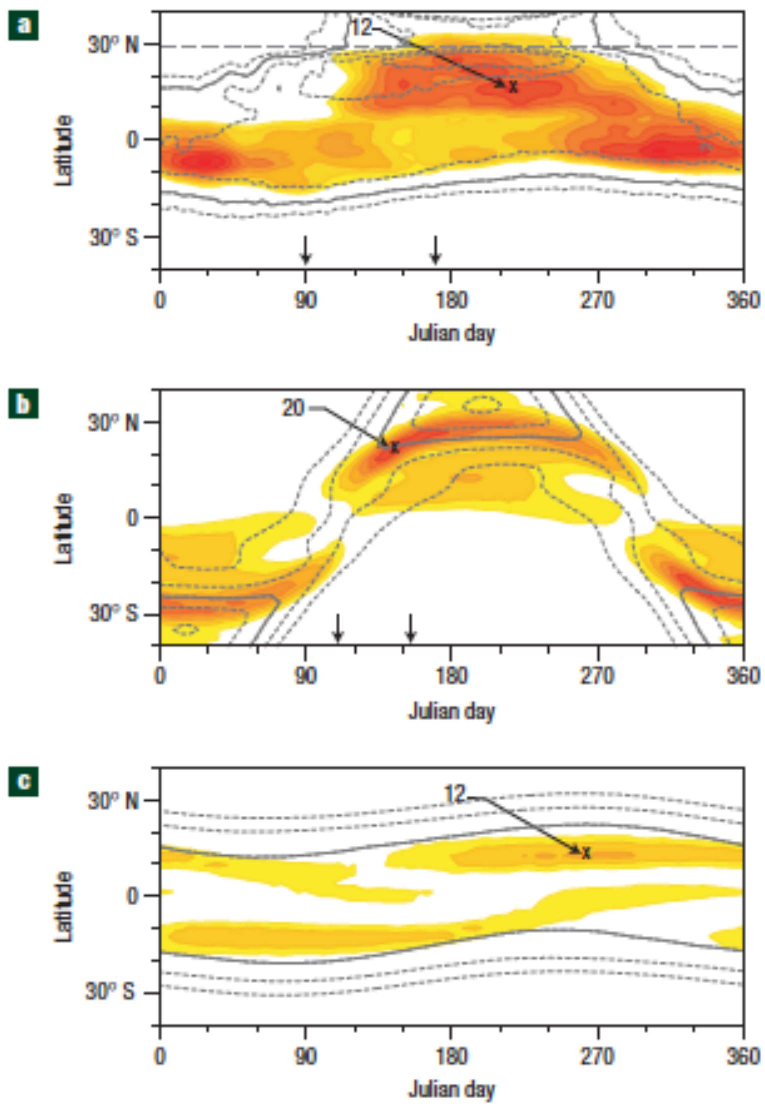
Schneider and Bordoni 2008 *JAS* **65** 915-934

The transition in behavior with heating latitude is captured in an axisymmetric model with simply parameterized eddy momentum fluxes



Sobel and Schneider 2009

Bordoni and Schneider (2008) argue that the transition in eddy momentum fluxes with heating latitude determines the rapid onset in “aqua planet monsoons”. (No clouds in this model!)



observations

Simulation with
1m ocean mixed layer

Simulation with
100m ocean mixed layer

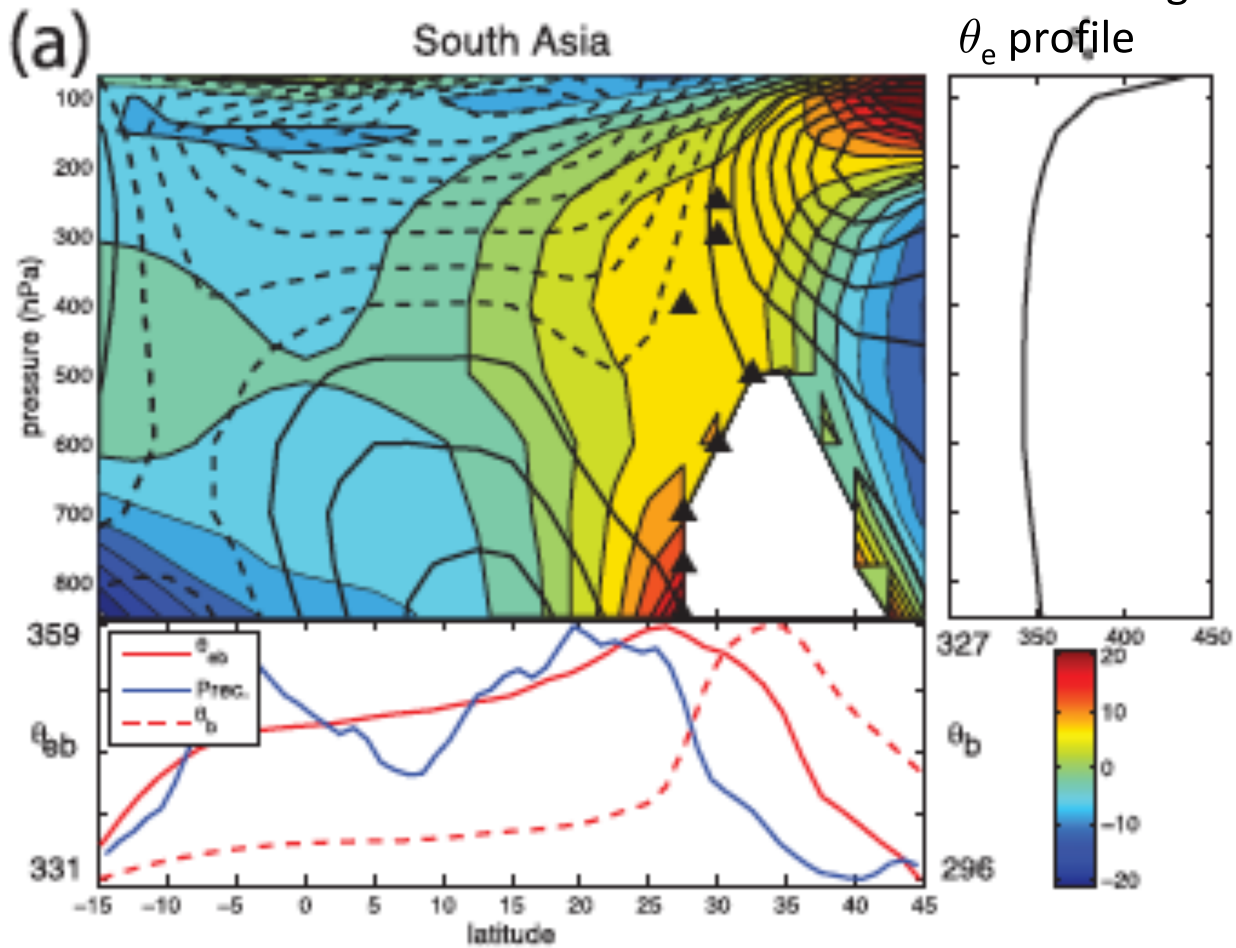
Moisture & quasi-equilibrium

- In the dry axisymmetric theory, distributions of radiative-convective equilibrium temperature can be either super- or sub-critical, such that a circulation does or doesn't develop
- Emanuel (1995) extended this to consider moisture under "quasi-equilibrium theory", deriving a criticality condition for **boundary layer moist static energy**, h_b (or boundary layer moist entropy, or equivalent potential temperature θ_e)
- In observations and simulations, maximum precipitation is close to maximum h_b or θ_{eb} (Prive and Plumb 2007; Nie et al. 2010; Singh 2019) though this is not predictive since h_b is part of the solution (e.g., Hill 2019)

Observed relationship between precipitation, θ_e, and θ (~equivalent to moist & dry static energy) in India sector

Colors: θ_e deviation from level domain average
Triangles = θ_e maximum
Black contours = zonal wind
(dashed = easterly)

Domain avg. θ_e profile



Subcloud θ_e (red), subcloud θ (dashed), and precipitation (blue)

Nie et al. 2010

Moist static energy budget, 1

- Though it also involves moist static energy, this line of argument is entirely distinct from the QE one just presented
- Monsoons & ITCZs are associated with thermally direct circulations which move energy from regions of surplus TOA input to regions of deficit
- Single-column arguments relate divergent circulation & precipitation to **surface fluxes, radiation and the "gross moist stability"** (.e.g, Neelin and Held 1987; Srinivasan 2001; Raymond et al. 2009; Wang and Sobel 2011)

$$L[P - E] = \{F_B - F_T\}/\{\delta - 1\},$$

where

$$\delta = -\{\int_0^1 \omega\ [\partial s/\partial p^*]\partial p^*\}\ /\ \{\int_0^1 \omega\ L[\partial q/\partial p^*]\partial p^*\}.$$

Srinivasan 2001

F_B and F_T are surface & TOA fluxes; δ -1 is *normalized gross moist stability*

Moist static energy budget, 2

- To think about the position of the zonal mean ITCZ, it can be useful to consider not just the divergence of the MSE flux, but the flux itself, in latitude
- If one hemisphere is warmed relative to the other, a stronger flux from warm to cold results, and the ITCZ moves towards the warm hemisphere (e.g., Kang et al. 2008) − ITCZ position is related to cross-equatorial MSE flux
- This has proved quite powerful in the axisymmetric context (Kang, Frierson, Schneider, Byrne, Singh); but not trivial to generalize to the non-axisymmetric case (e.g., Biasutti et al. 2018)

Kang et al. 2008: impose ocean heating at one pole & cooling at the other, implying an inter-hemispheric flux which the atmosphere must counter (no TOA radiative feedback in this model)

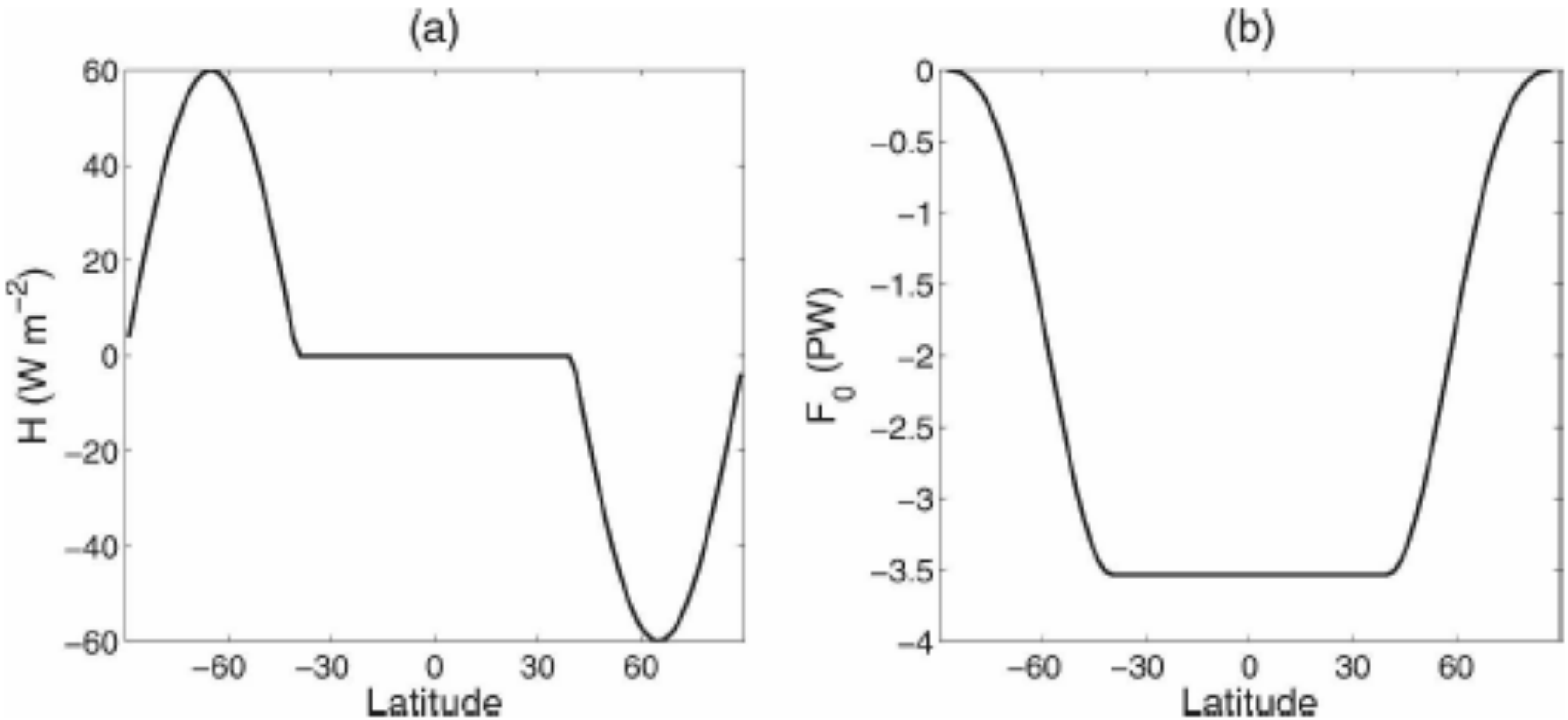


FIG. 1. (a) Latitudinal distribution of imposed forcing H (W m^{-2}) and (b) associated implied ocean flux F_0 (PW) when A = 60 W m^{-2}.

ITCZ moves to the warmed hemisphere

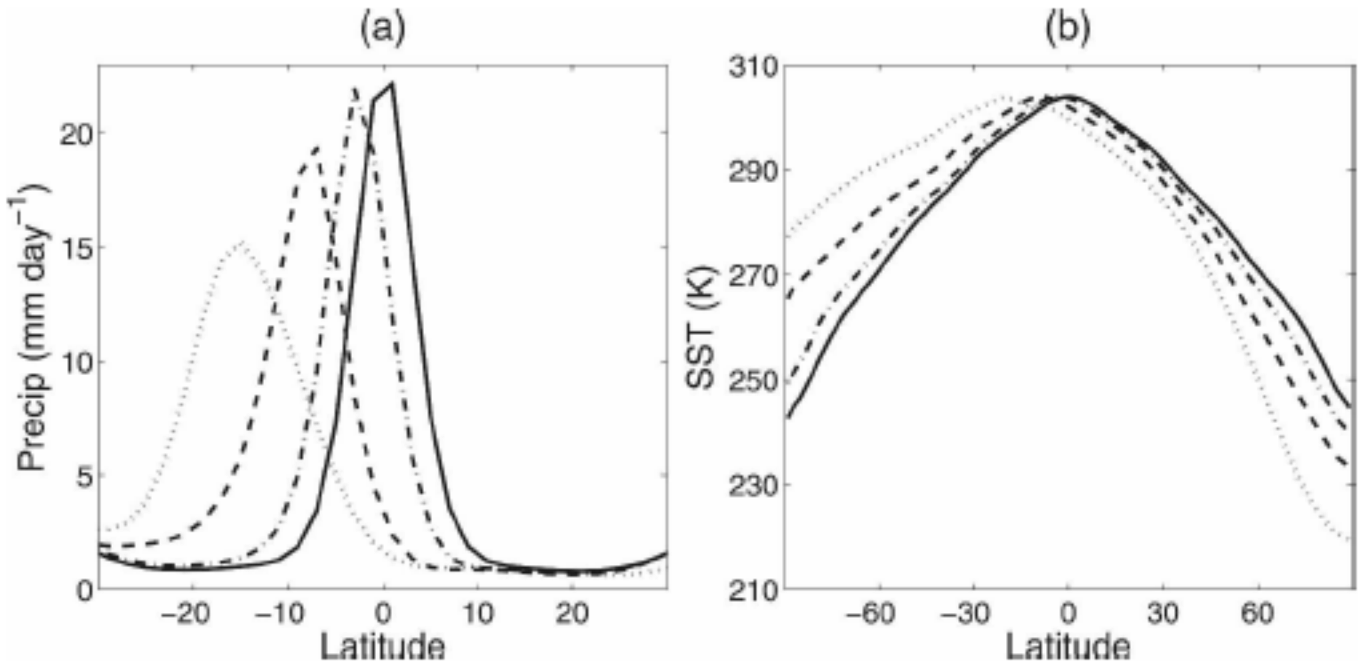
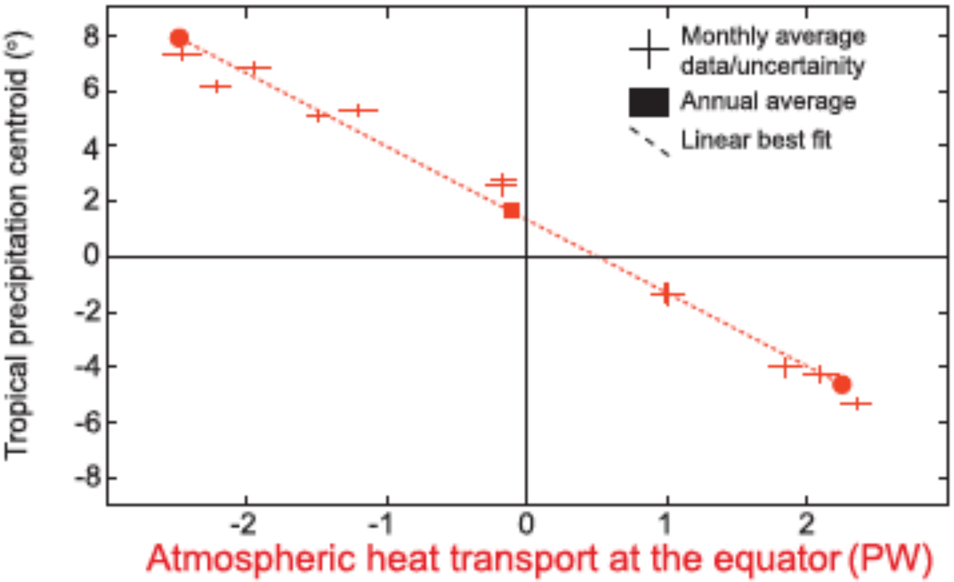


FIG. 2. Time mean, zonal mean (a) precipitation (mm day^{-1}) in the tropics, and (b) SST (K) for $A = 0$ (solid), 10 (dashed–dotted), 30 (dashed), and 60 W m^{-2} (dotted), with a control value of α (=1X).

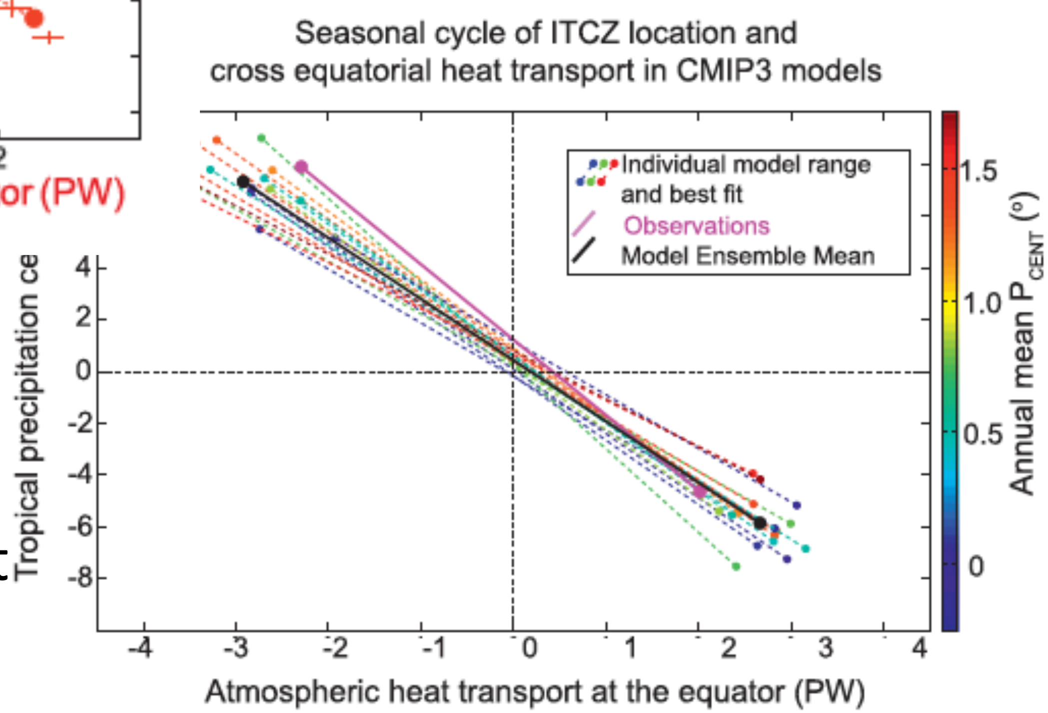
Kang et al. 2008

Donohoe et al. 2014: linear relationship between cross-equatorial atmospheric heat (MSE) transport and zonal mean ITCZ position

Seasonal cycle in observations



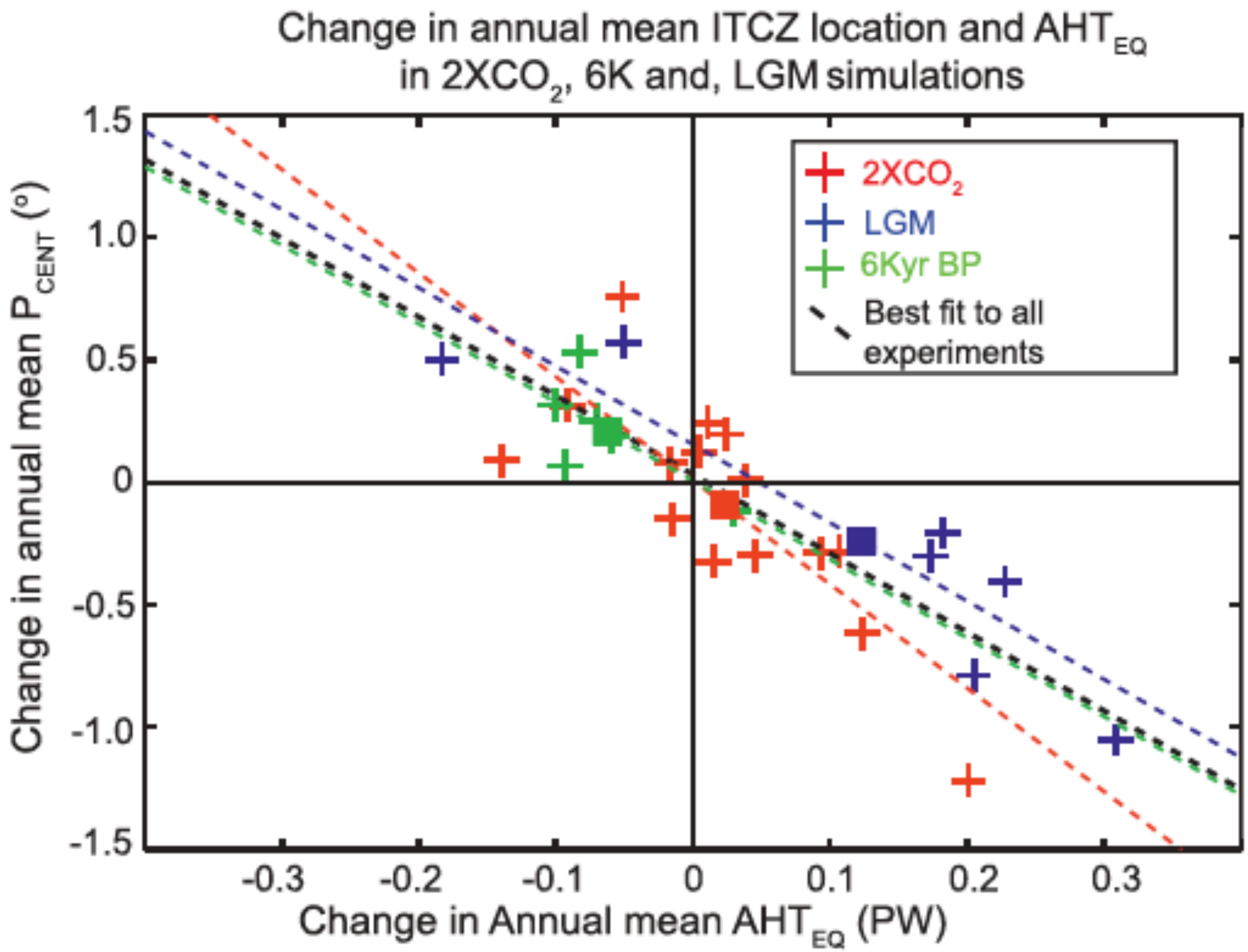
Seasonal cycle in models



Latitude of zonal mean ITCZ (y axis)

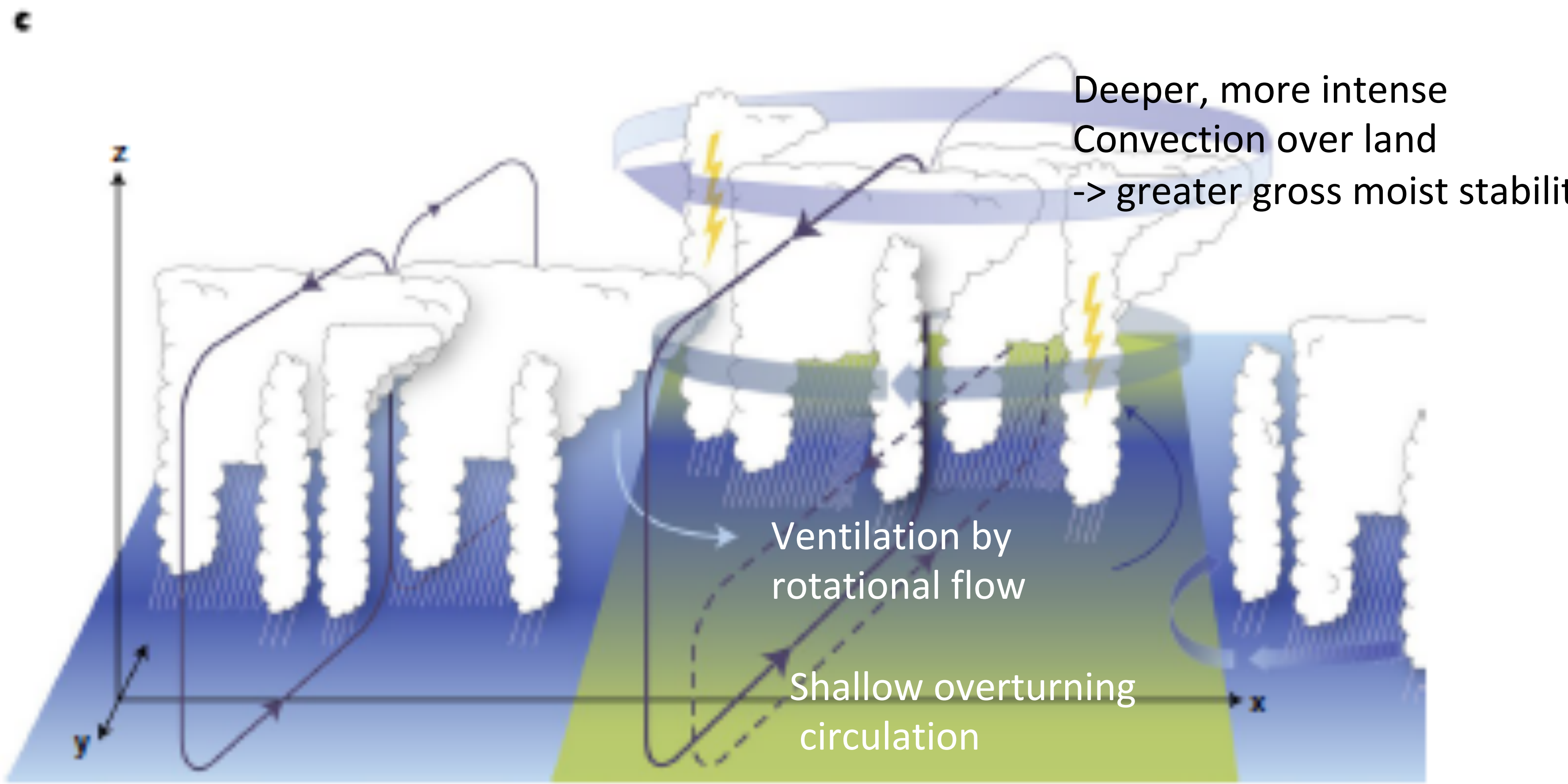
vs. atmospheric heat transport at equator (x axis)

Similar linear relationship seems to explain simulations of diverse climate changes!



Donohoe et al. 2019

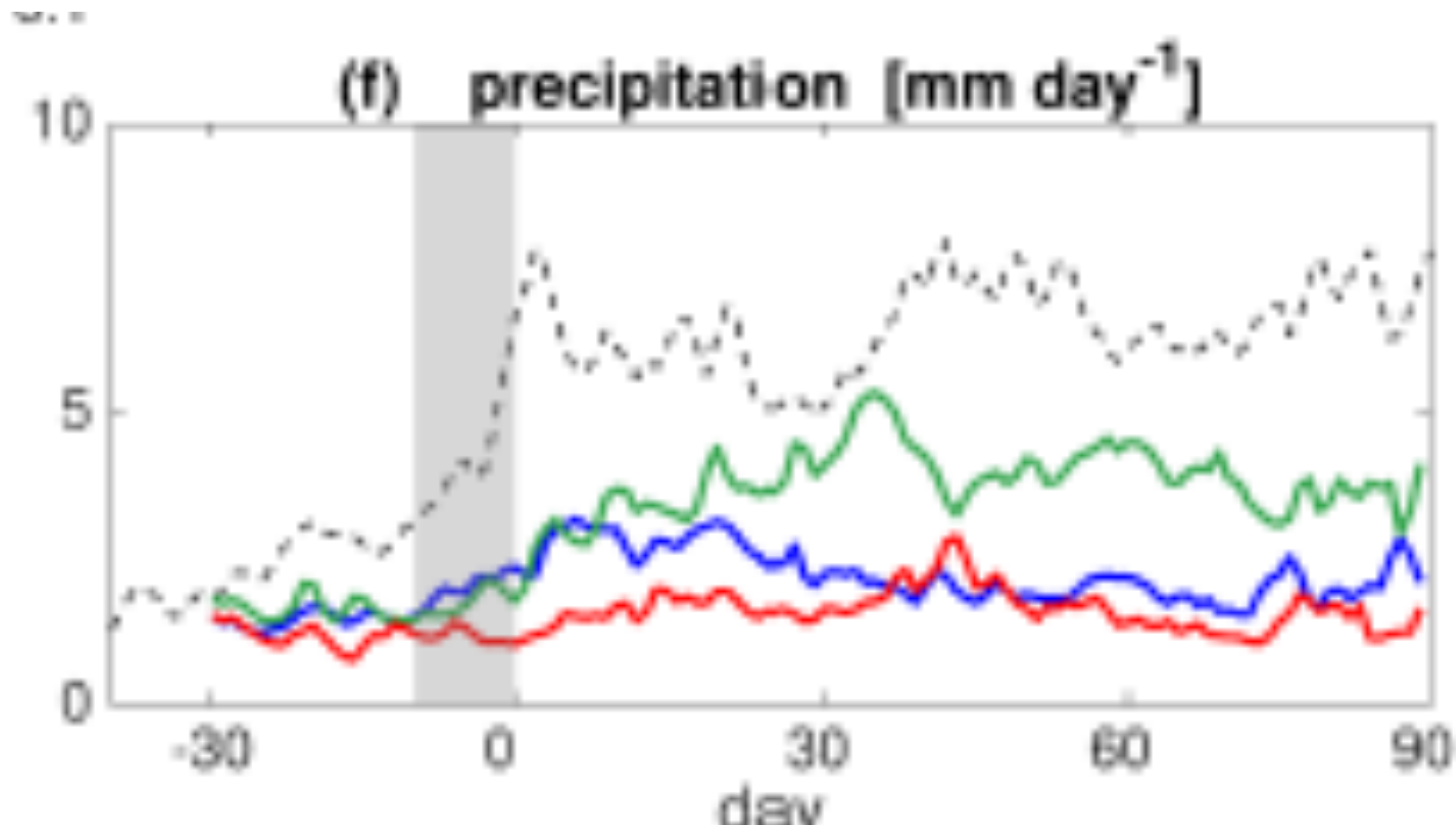
Complexities not addressed satisfactorily yet: varying depth of convection (& thus GMS); shallow circulations; “ventilation”



Biasutti et al. (2018)

Some recent (and ongoing) modeling studies by our group

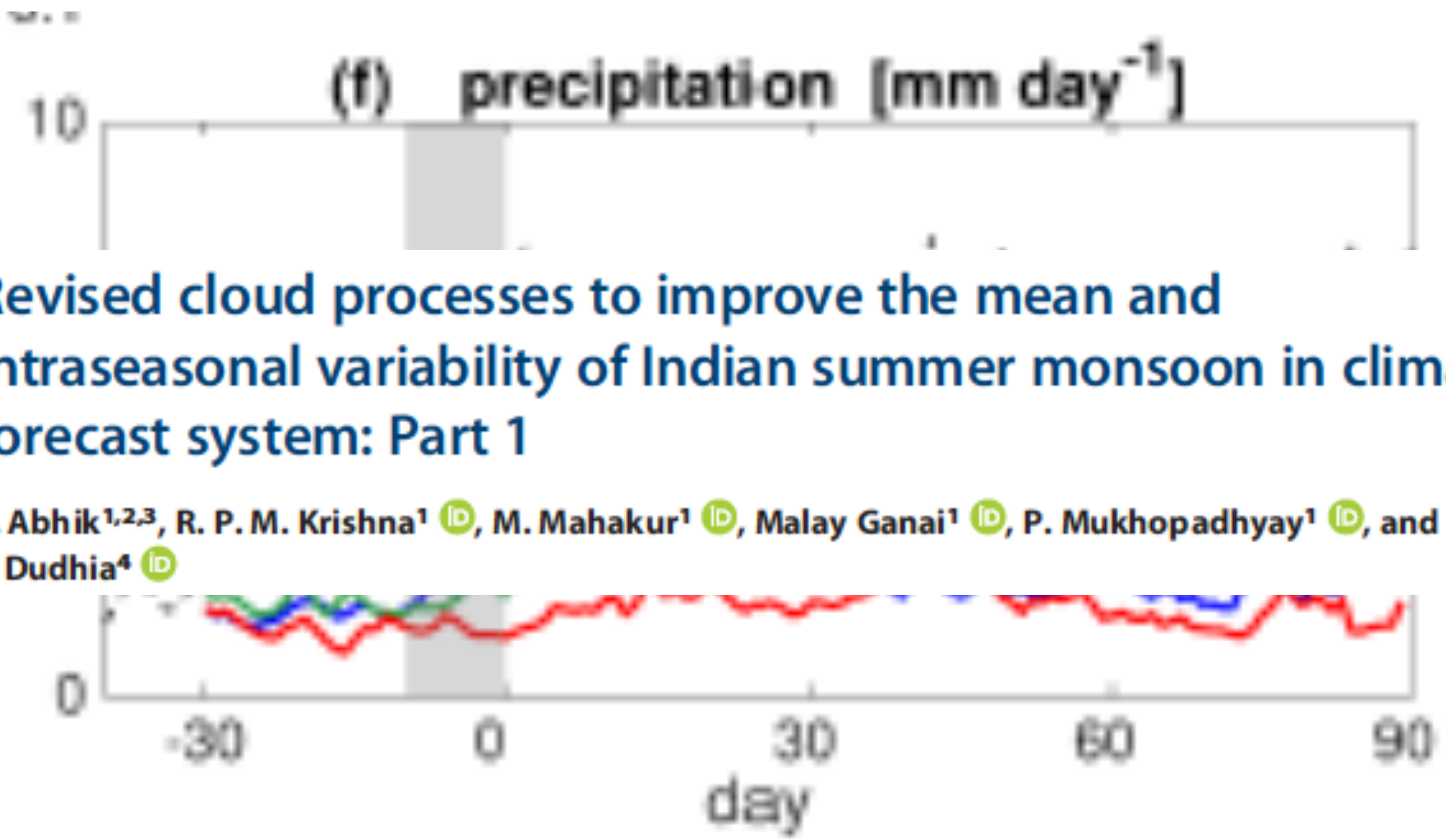
Ma et al. 2019, *GRL*: In global WRF (explicit convection) simulations, radiative & surface flux feedbacks are essential to rapid monsoon onset



10-25N, 60-100E box; dashed = control; green = no surface flux feedback; blue=no cloud-radiative feedback; red=neither feedback

No feedback means field is set to pre-monsoon climatology

Ma et al. 2019, *GRL*: In global WRF (explicit convection) simulations, radiative & surface flux feedbacks are essential to rapid monsoon onset



Revised cloud processes to improve the mean and intraseasonal variability of Indian summer monsoon in climate forecast system: Part 1

S. Abhik[1,2,3], R. P. M. Krishna[1], M. Mahakur[1], Malay Ganai[1], P. Mukhopadhyay[1], and J. Dudhia[4]

Perhaps this is one reason cloud microphysics has such an impact?

TRACMIP: Tropical Rain belts with an Annual Cycle and Continent Model Intercomparison Project (Voigt et al. 2016) - 12 models participating

Aqua

30-m slab ocean

Implied ocean heat transport (obs-like)

Circular orbit

Present-day CO2

Land

Flat continent: 0-45E 30S-30N

Low heat capacity

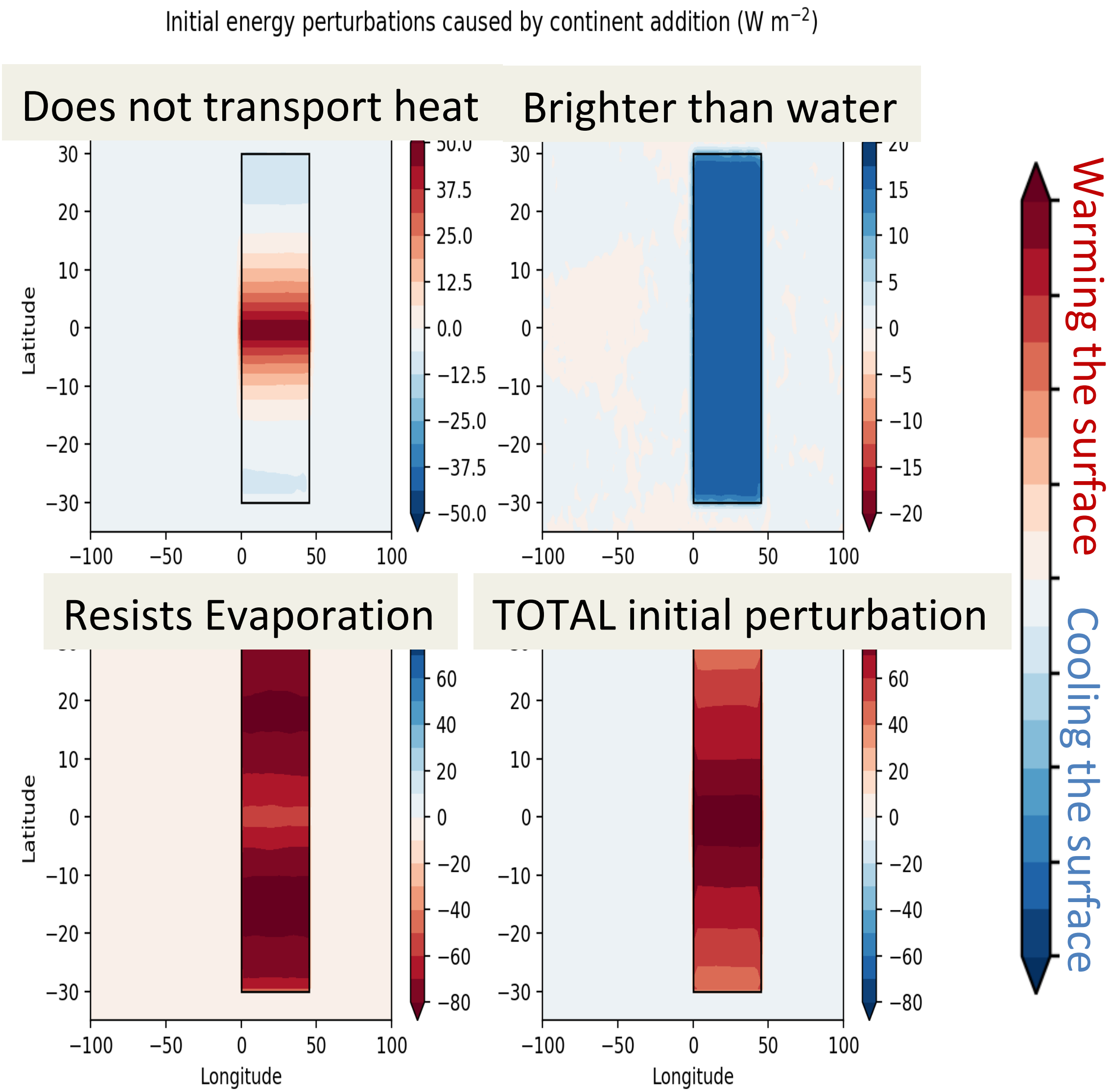
Brighter than water

Resists evaporation

Does not transport heat

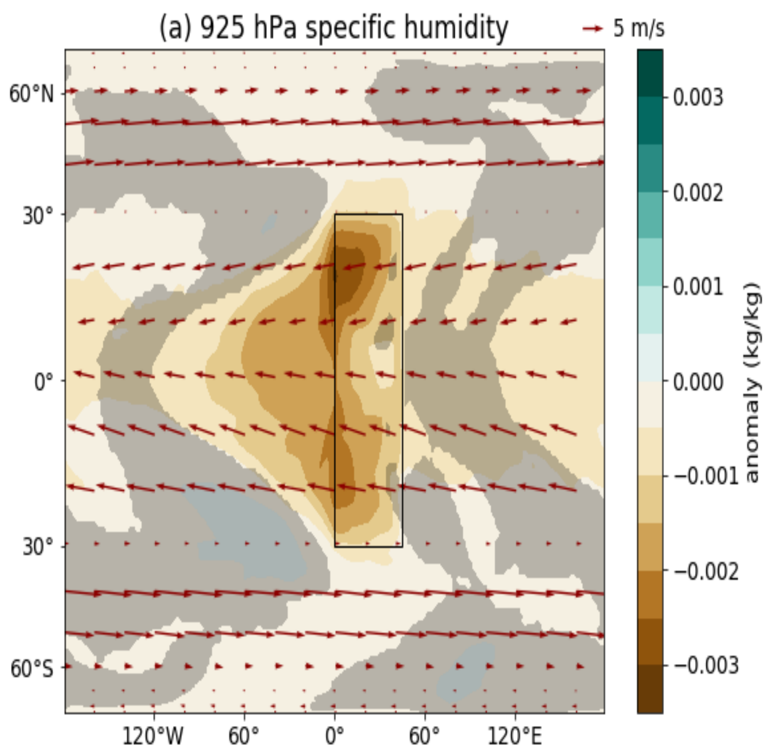
Michela Biasutti

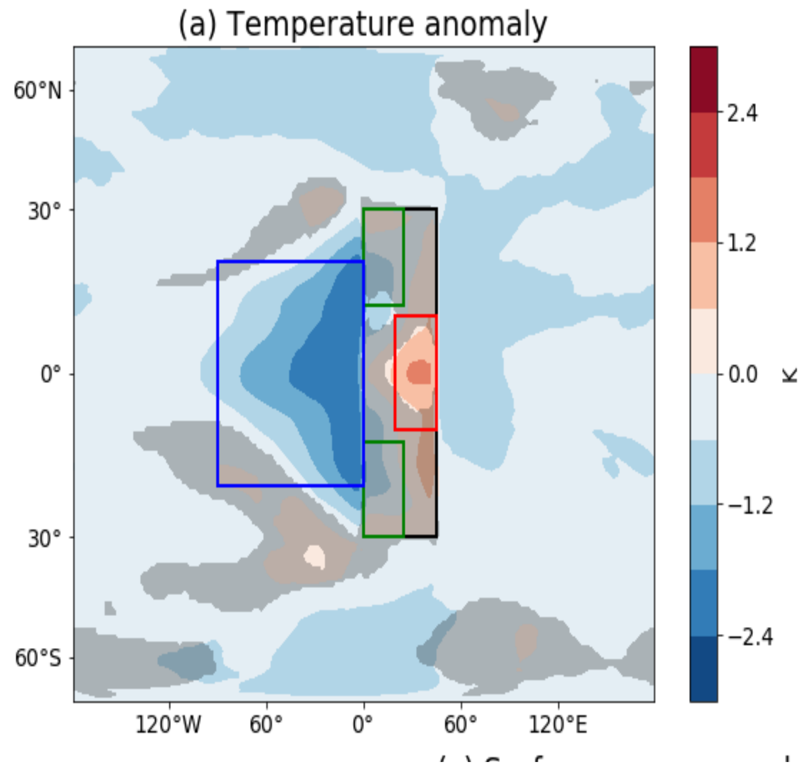
The initial effects of the TRACMIP continent on surface energy fluxes



If there were no feedbacks, we'd expect the annual mean response to be a warmer surface in correspondence with the continent and no effect on the ocean.

Instead, the largest annual mean surface temperature anomalies are seen downwind, over the equatorial ocean.

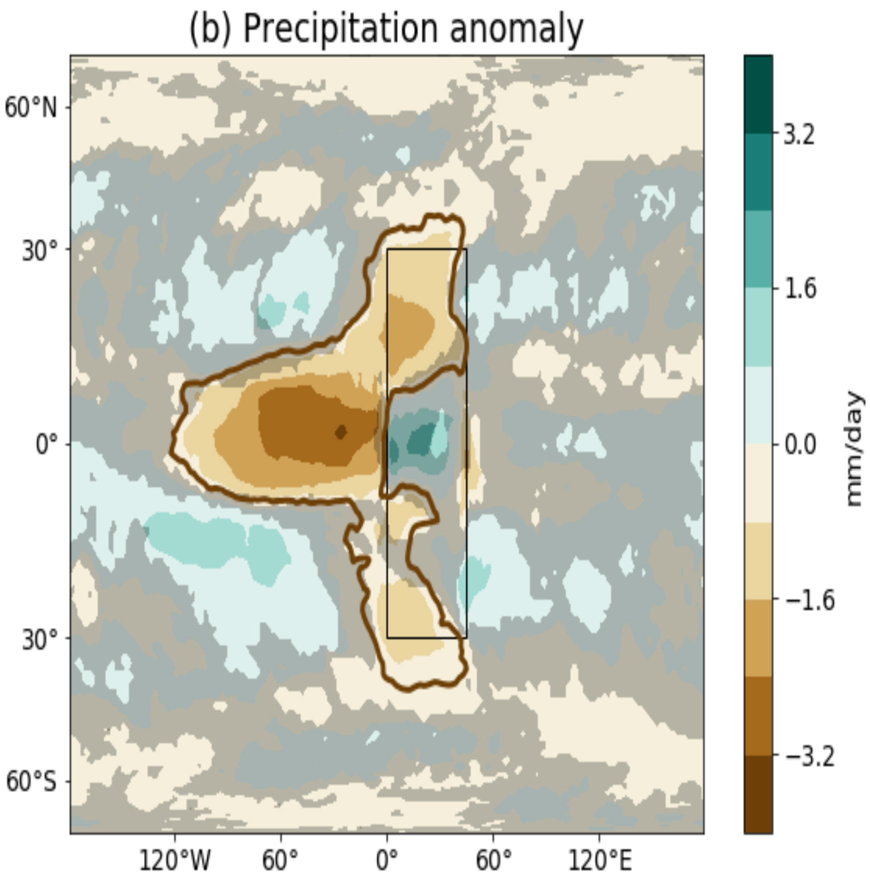


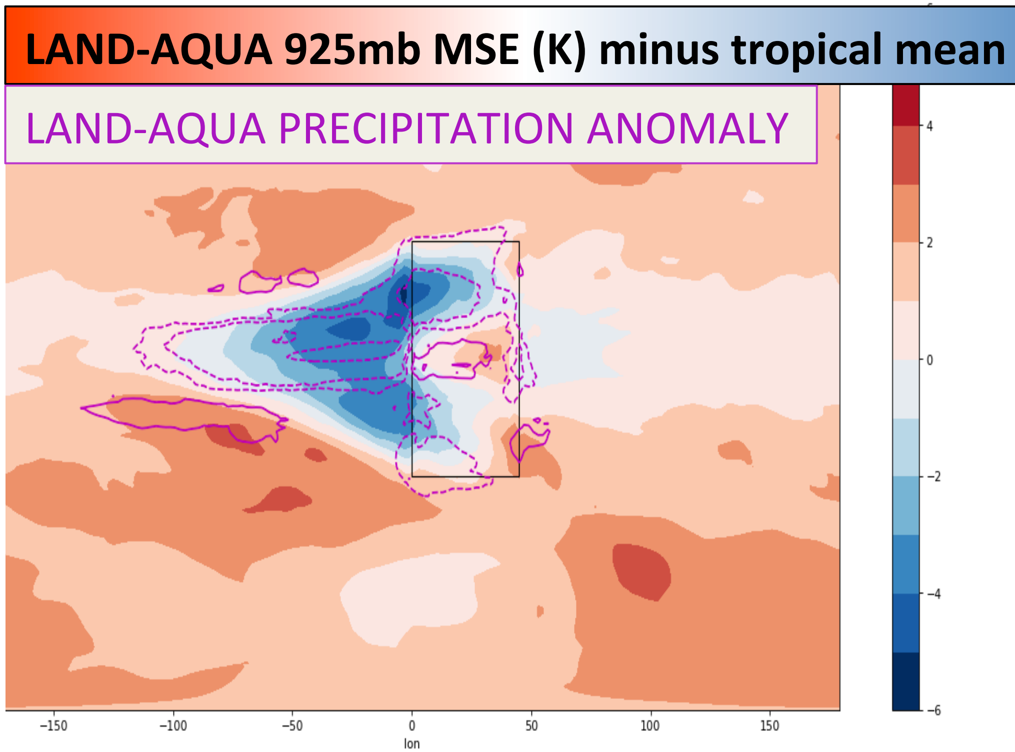


The evaporative resistance dries the continent and low-moisture air is advected downwind. The dry atmosphere cools more efficiently to space and the surface cools in response.

The idealization of the land-surface moisture fluxes (soil/vegetation) is key!

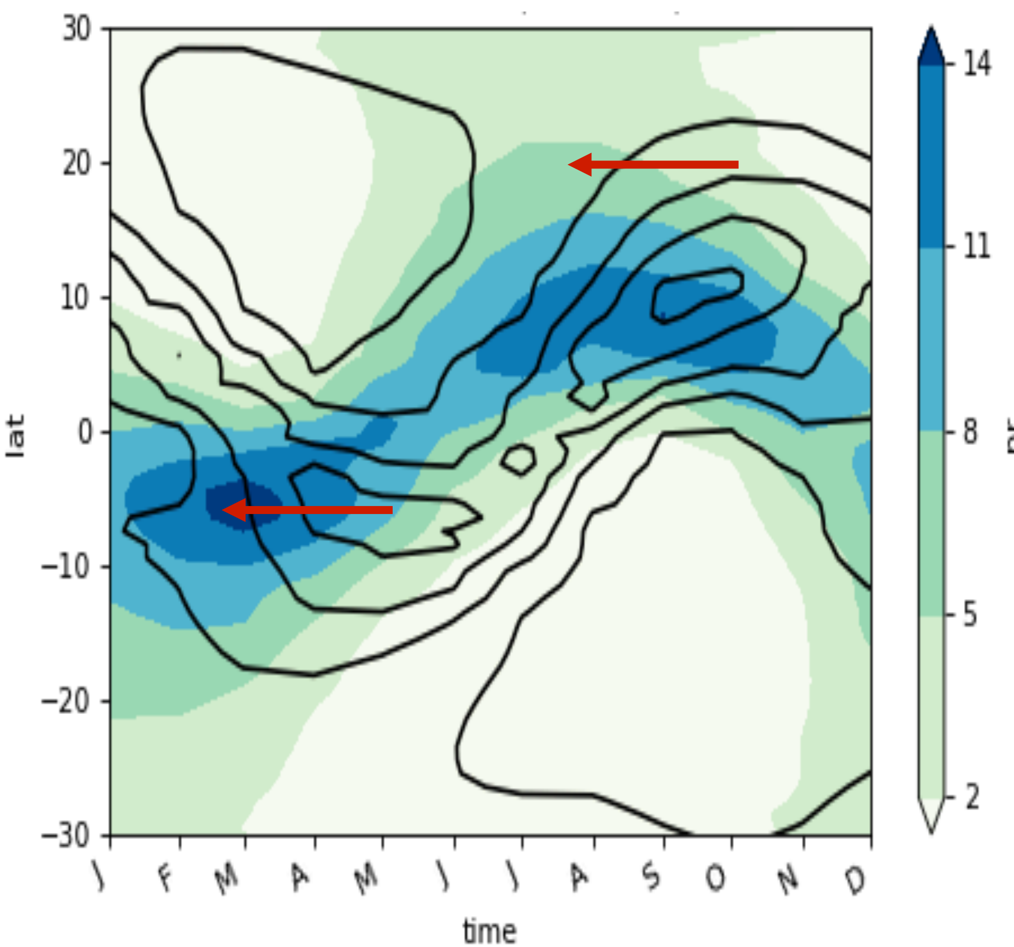
The annual mean precipitation response is mostly governed by thermodynamics, i.e. by low-level relative MSE.





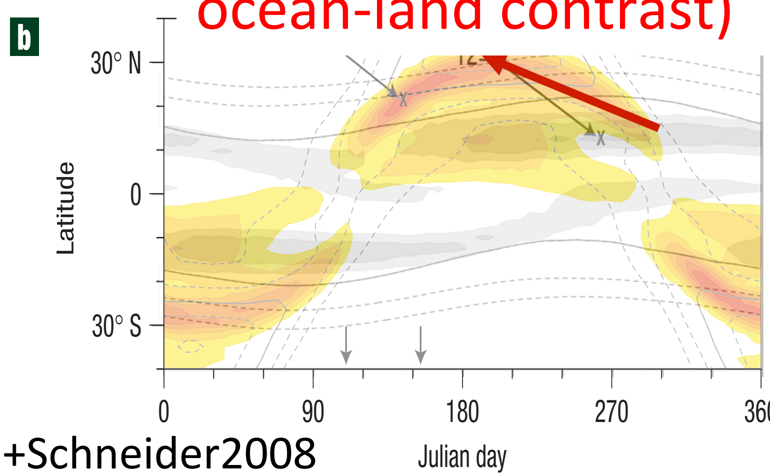
Thus, the choice of idealization of the land-surface moisture fluxes (soil/vegetation) is key for the mean state of rainfall as well.

The annual cycle of precipitation over the continent is shifted early, consistent with the earlier build up of atmospheric energy



This "monsoon" is ITCZ-like
- Onset is not more abrupt
- Rainband does not broaden
- Latitudinal reach is not larger

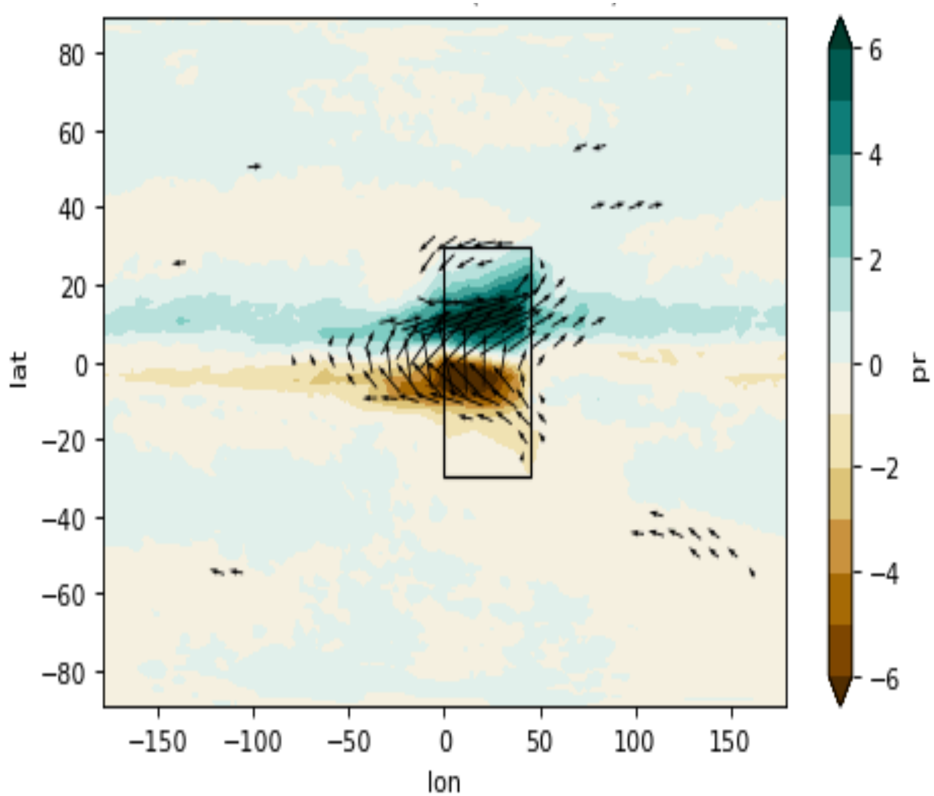
This is different than in "aquaplanet monsoons" (with no ocean-land contrast)



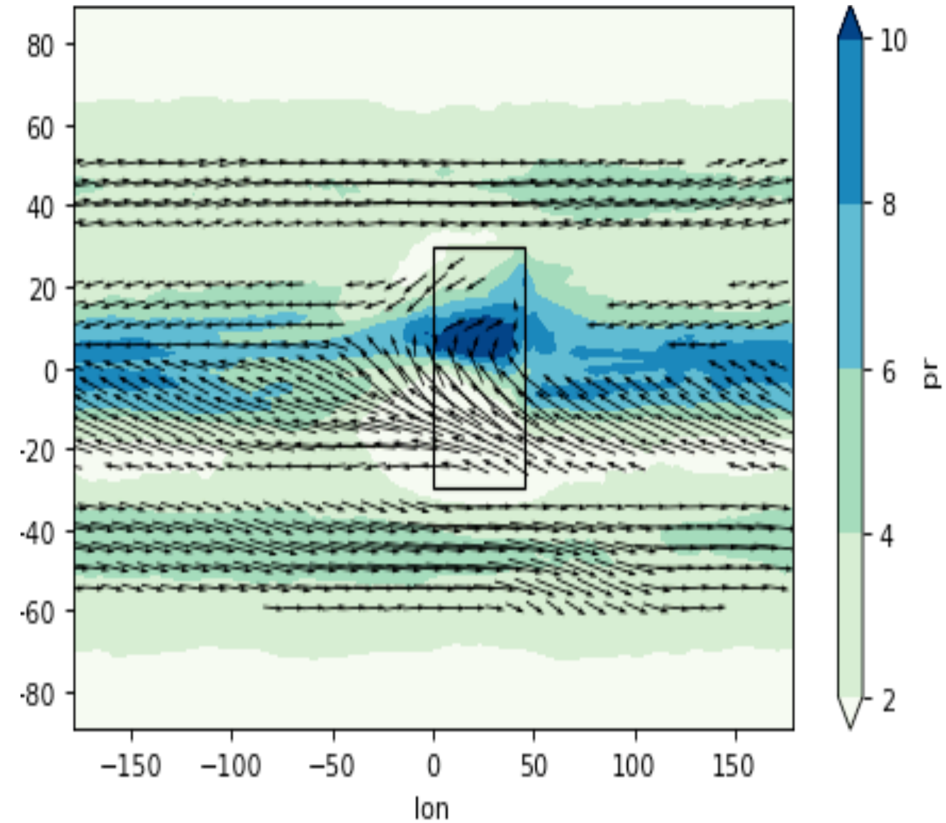
Bordoni+Schneider2008

The geography of the continent determines the advection of cold, low-MSE air from the subtropics and thus the extent of the "monsoon".

JJA 925mb Winds and Rainfall ANOMALIES



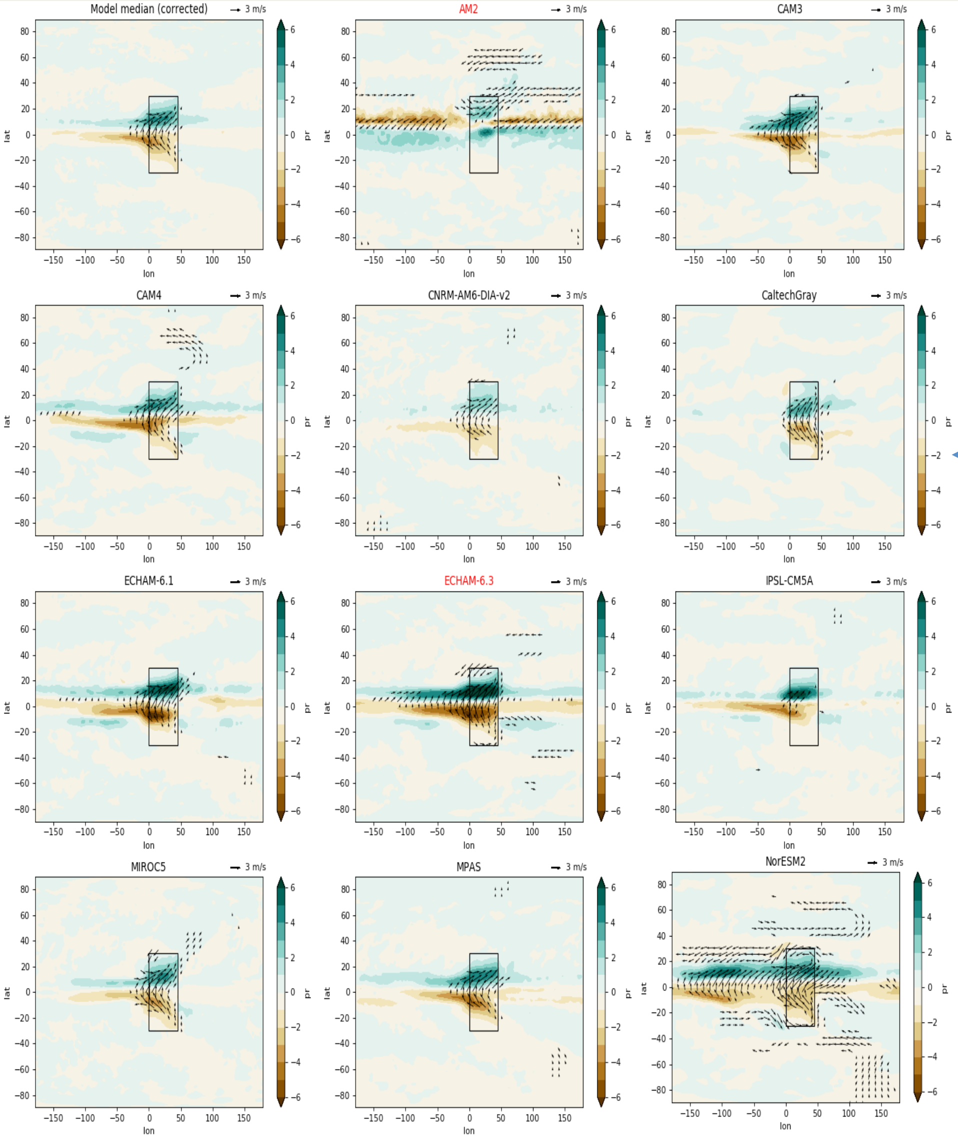
JJA 925mb Winds and Rainfall FULL FIELD



Thus, the choice of idealization in continental geometry (width, position, orographic barriers) is key for the latitudinal reach of the monsoon.

Feedbacks between moisture, clouds, and radiation act to connect rainfall over land and ocean and are model dependent.

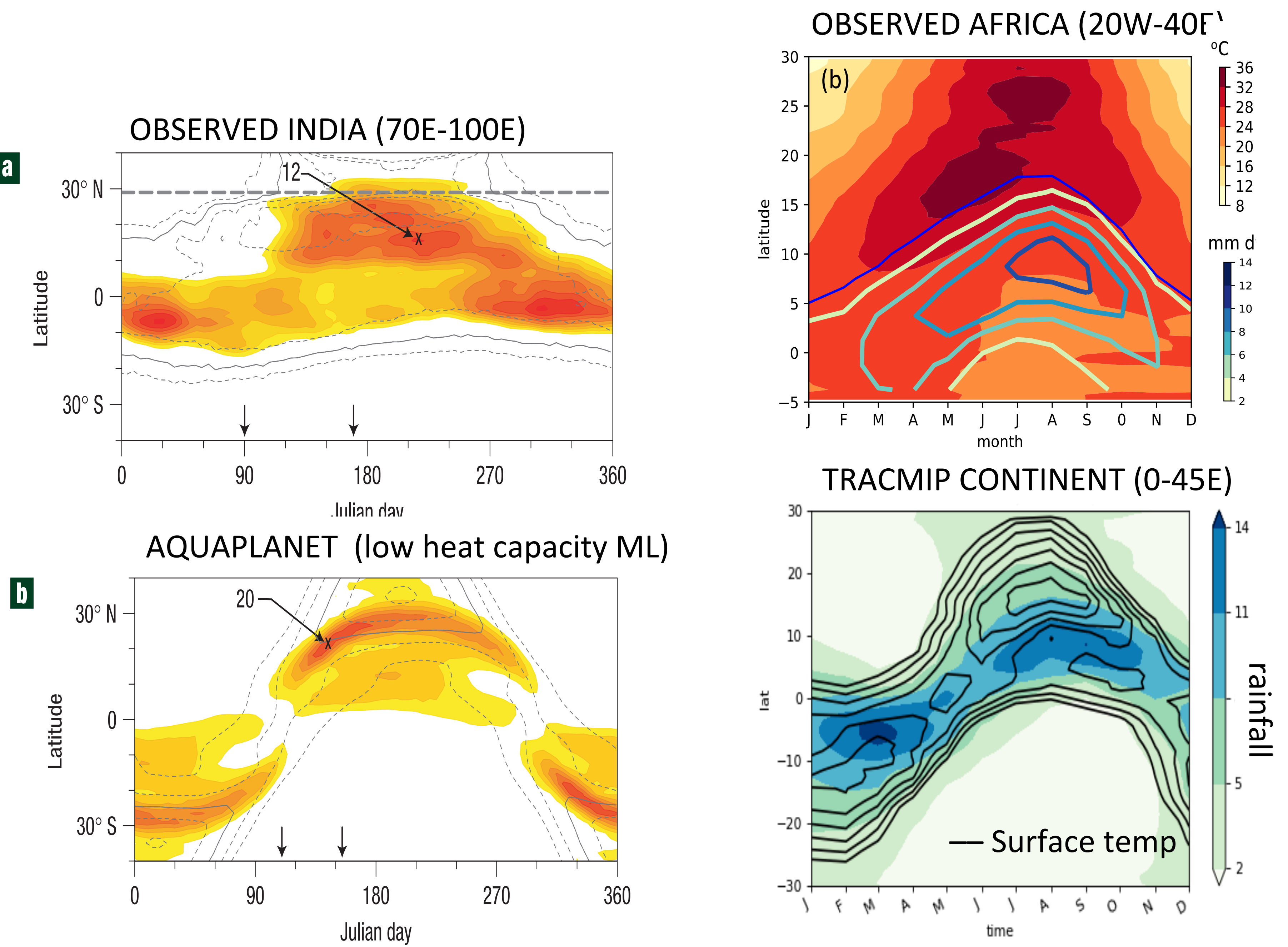
LAND-AQUA Northern Hemisphere Summer (MAMJJA) Anomalies



Grey Radiation

Problems

- Classic axisymmetric theory, and its extensions to include eddies, emphasize the zonal momentum budget
- Recent zonal mean ITCZ theory emphasizes moist static energy budget
- Both budgets must be satisfied; which is more fundamental to monsoon behavior?
- Still need to predict the gross moist stability, and the zonal ventilation of the non-axisymmetric monsoon
- How can all this macroscopic theory be related to prediction and model development?



a
OBSERVED INDIA (70E-100E)
12
30° N
0
30° S
Latitude
Julian day
0
90
180
270
360
b
AQUAPLANET (low heat capacity ML)
20
30° N
0
30° S
Latitude
Julian day
OBSERVED AFRICA (20W-40E)
(b)
latitude
month
J F M A M J J A S O N D
°C
36 32 28 24 20 16 12 8
mm d
14 12 10 8 6 4 2
TRACMIP CONTINENT (0-45E)
lat
time
rainfall
14 11 5 2
— Surface temp

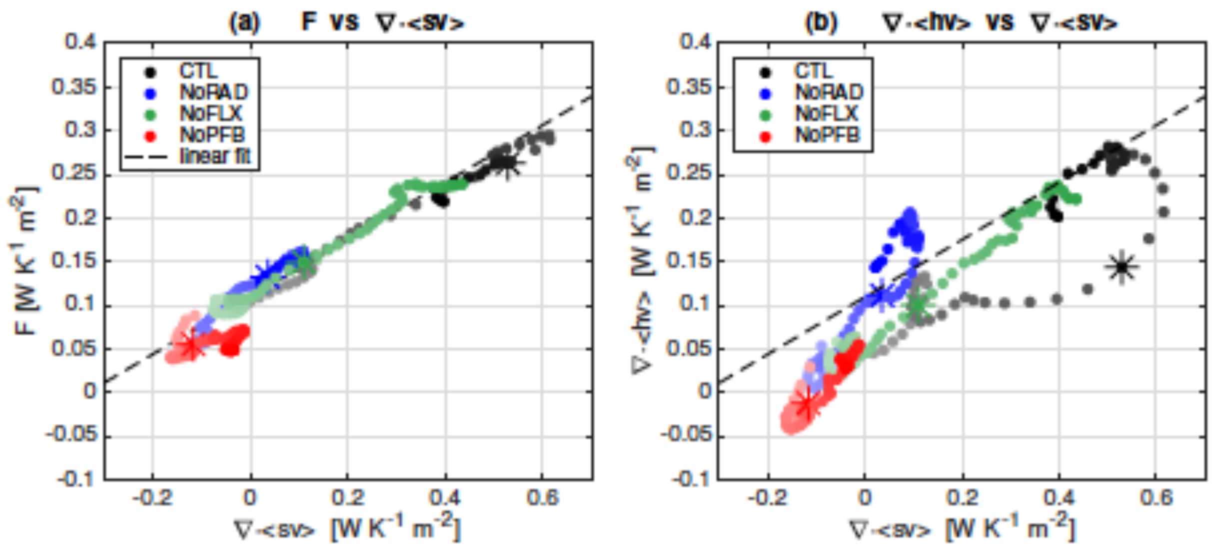


Figure 5. (a) Scatterplots of the sum of the source terms of column-integrated moist entropy against the divergence of column-integrated dry entropy. Each marker corresponds to one day from Day -30 to Day 30 with respect to the date of monsoon onset in CTL (denoted by the stars), and lighter colors indicate earlier dates. (b) The same as (a), but for the divergence of column-integrated moist entropy against the divergence of column-integrated dry entropy.

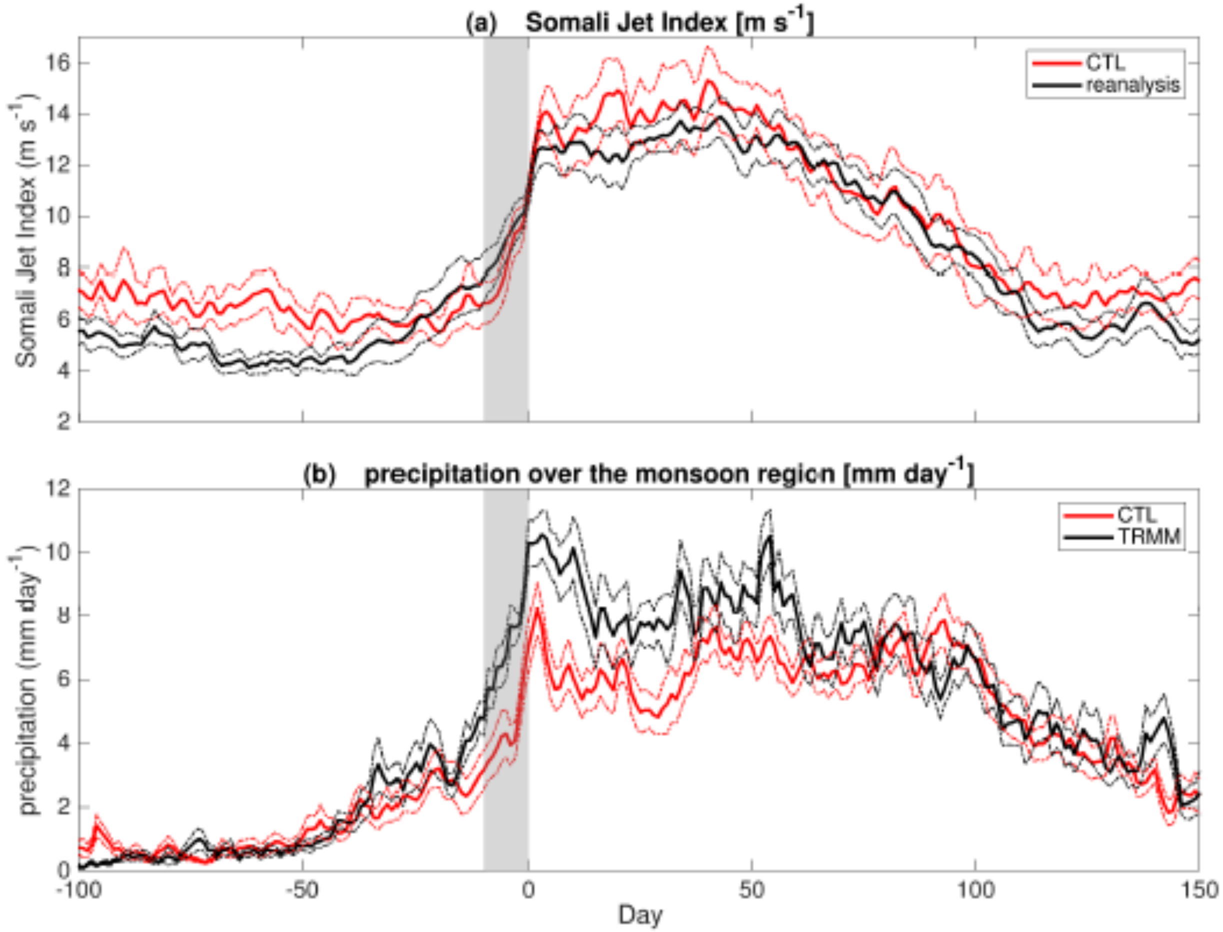


Figure 1. Composite evolution of (a) the Somali Jet index and (b) averaged precipitation over the South Asian monsoon region in the control simulation (red) and reanalysis data or satellite observation (black). The dashed curves denote 95% confidence intervals. The day of onset is shifted to Day 0. The grey shading marks the period from Day -10 to Day 0.

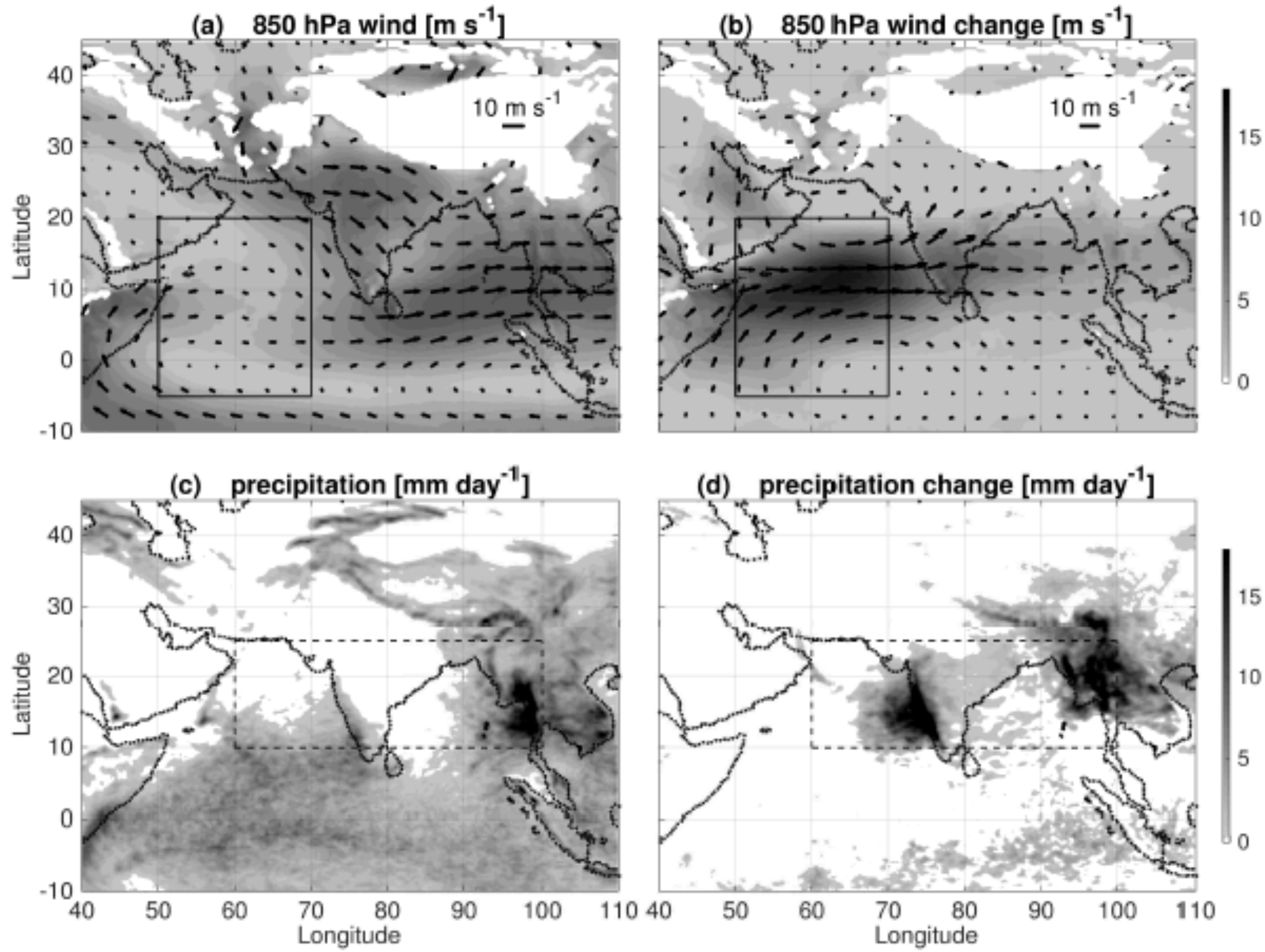


Figure 2. Composite of (a) 850 hPa winds and (c) precipitation 10 days before monsoon onset, and composite change in (b) 850 hPa winds and (d) precipitation between Day -10 and Day 0. The black box (ab) denotes the region where the SJI is computed, and the dashed box (cd) denotes the region over which the precipitation and moist entropy budget is averaged.

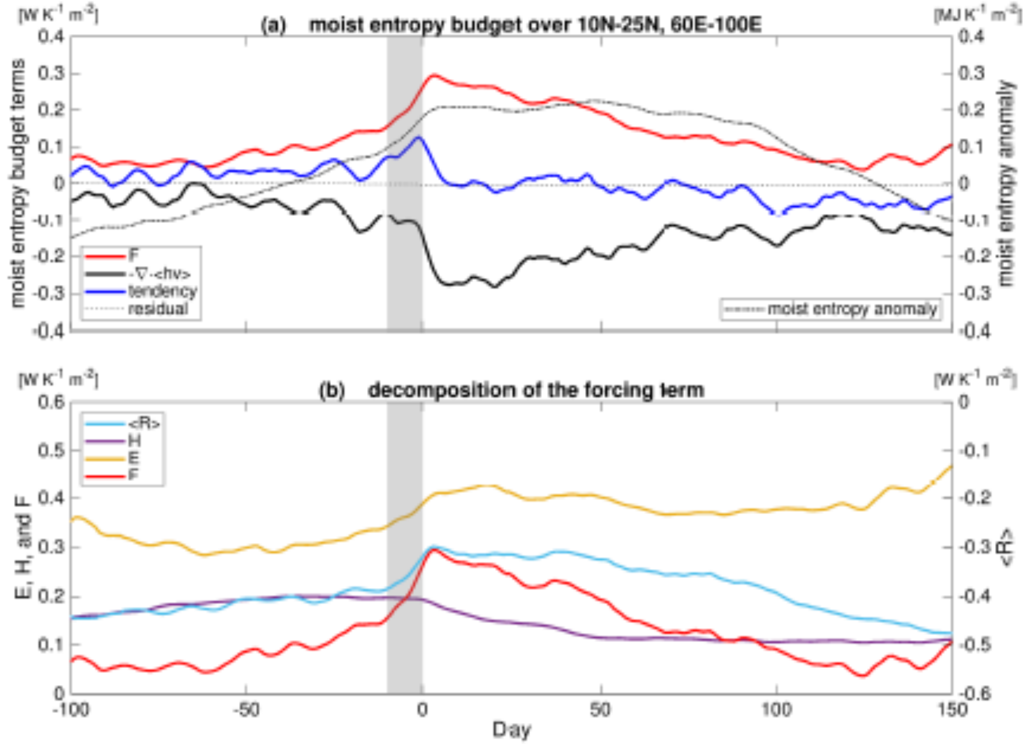


Figure 3. Composite evolution of column-integrated moist entropy budget averaged over 10°N-25°N; 60°N-100°E in the control run. (a) The red, black, blue and dashed curves denote the source term, the export by large-scale advection, the temporal tendency term, and the residual of the moist budget, respectively, and correspond to the left y-axis. The dashed-dot curve denotes anomalous column-integrated moist entropy, and corresponds to the right y-axis. (b) The light blue curve denotes the contribution from radiative heating, and corresponds to the right y-axis. The purple, yellow and red curves denote the sensible heat flux, the latent heat flux, and the sum of the source terms, respectively, and correspond to the left y-axis.

In spherical geometry, angular momentum is

$M=\Omega a^2\cos^2\phi + ua\cos\phi$

For axisymmetric flow the absolute vorticity is

$\zeta_a = \zeta + f = 2\Omega\sin\phi + (a\cos\phi)^{-1}\partial_\phi(u\cos\phi) = (a^2\cos\phi)^{-1}\partial_\phi M$

Thus $\zeta_a = 0$ corresponds to vanishing latitudinal angular momentum gradient.

However in the presence of eddies, even for inviscid flow we have an effective torque F; starting from momentum equation and zonally averaging gives

$v\zeta_a = -F + \partial_y \overline{u'v'}$

where here F is true frictional torque, can $\rightarrow 0$

Axisymmetric simulations approach the theoretical solution

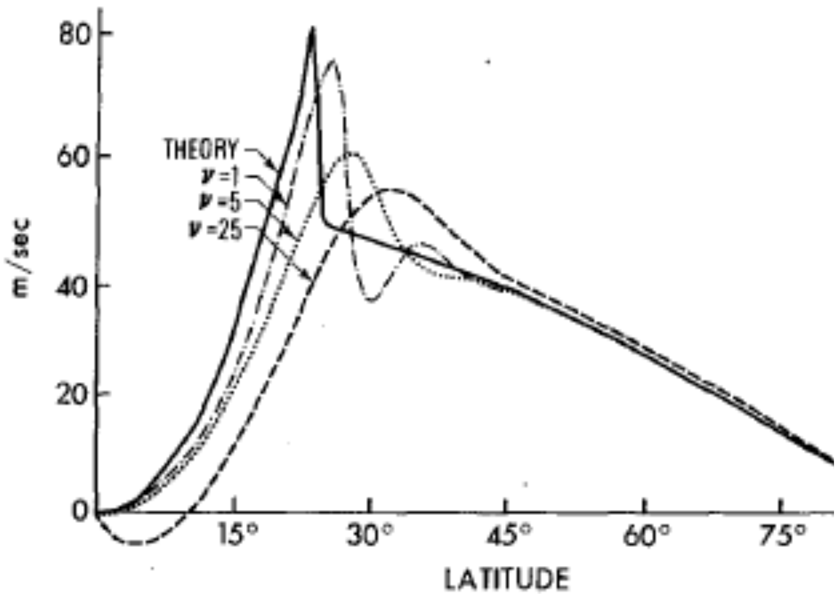


FIG. 5. Zonal winds at $z = H$ in the standard case for three
of ν, compared with the theoretical prediction for ν –

Zonal wind

Angular momentum

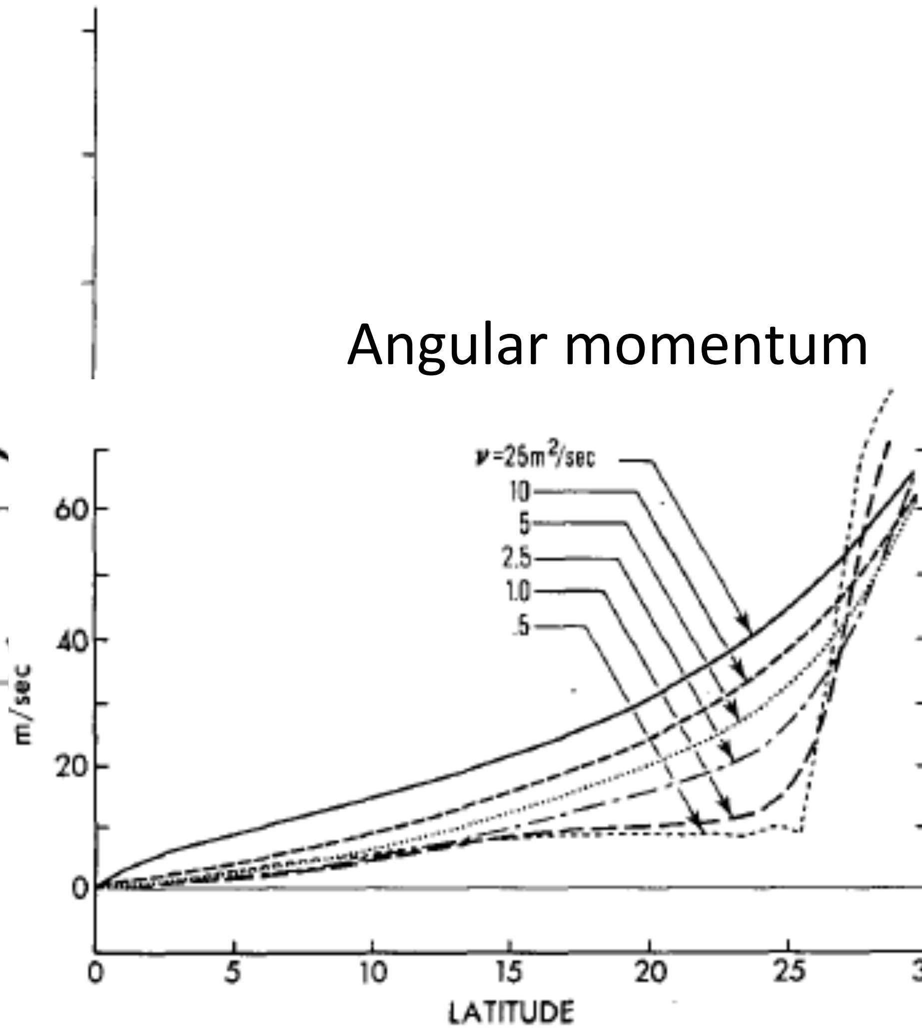


FIG. 6. $\Omega a \sin^2(\theta) - u \cos(\theta)$ at $z = H$ for various values of ν in the standard case.

Sector zonal mean GPCP precipitation, 1997-2006 (Hu et al. 2007)