A review of energetic and dynamic theories of monsoons

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Yale

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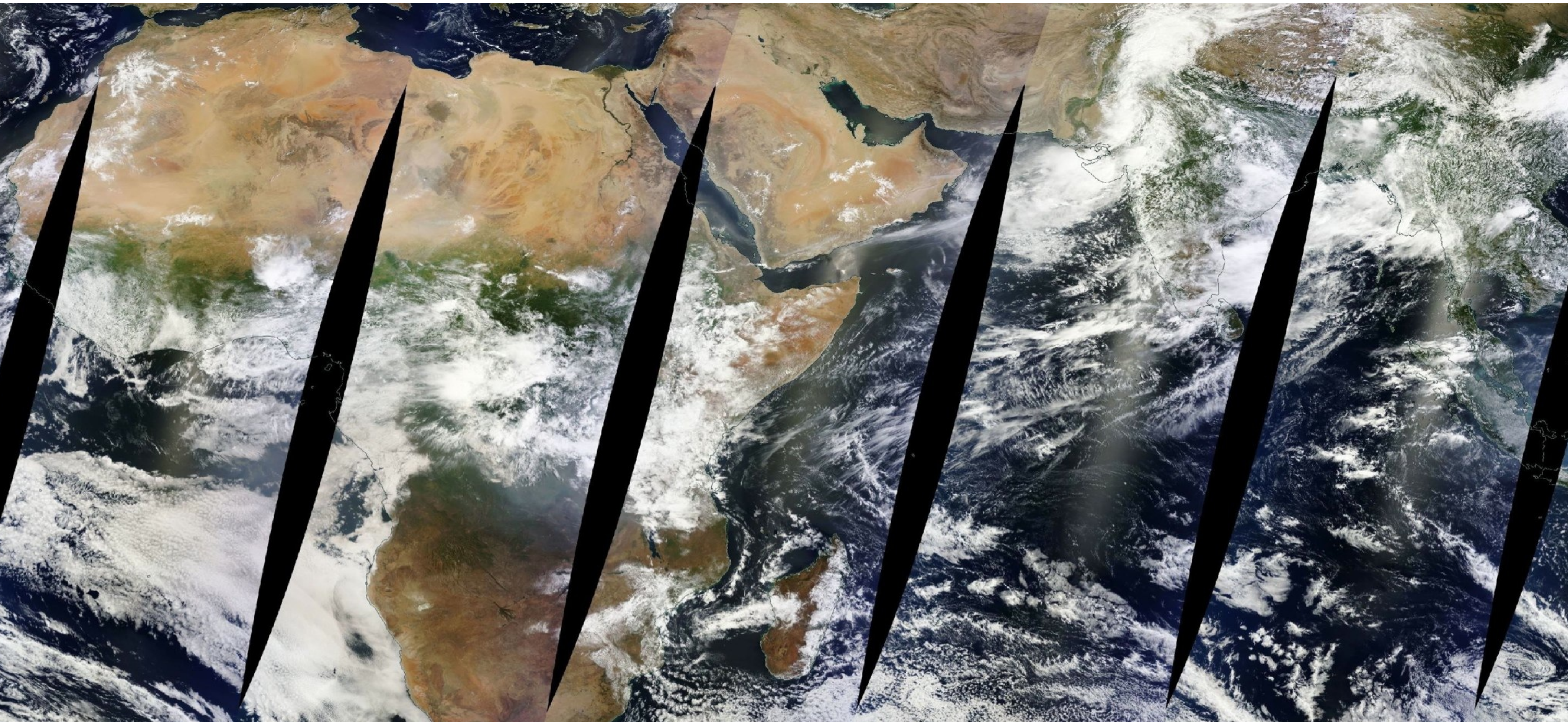
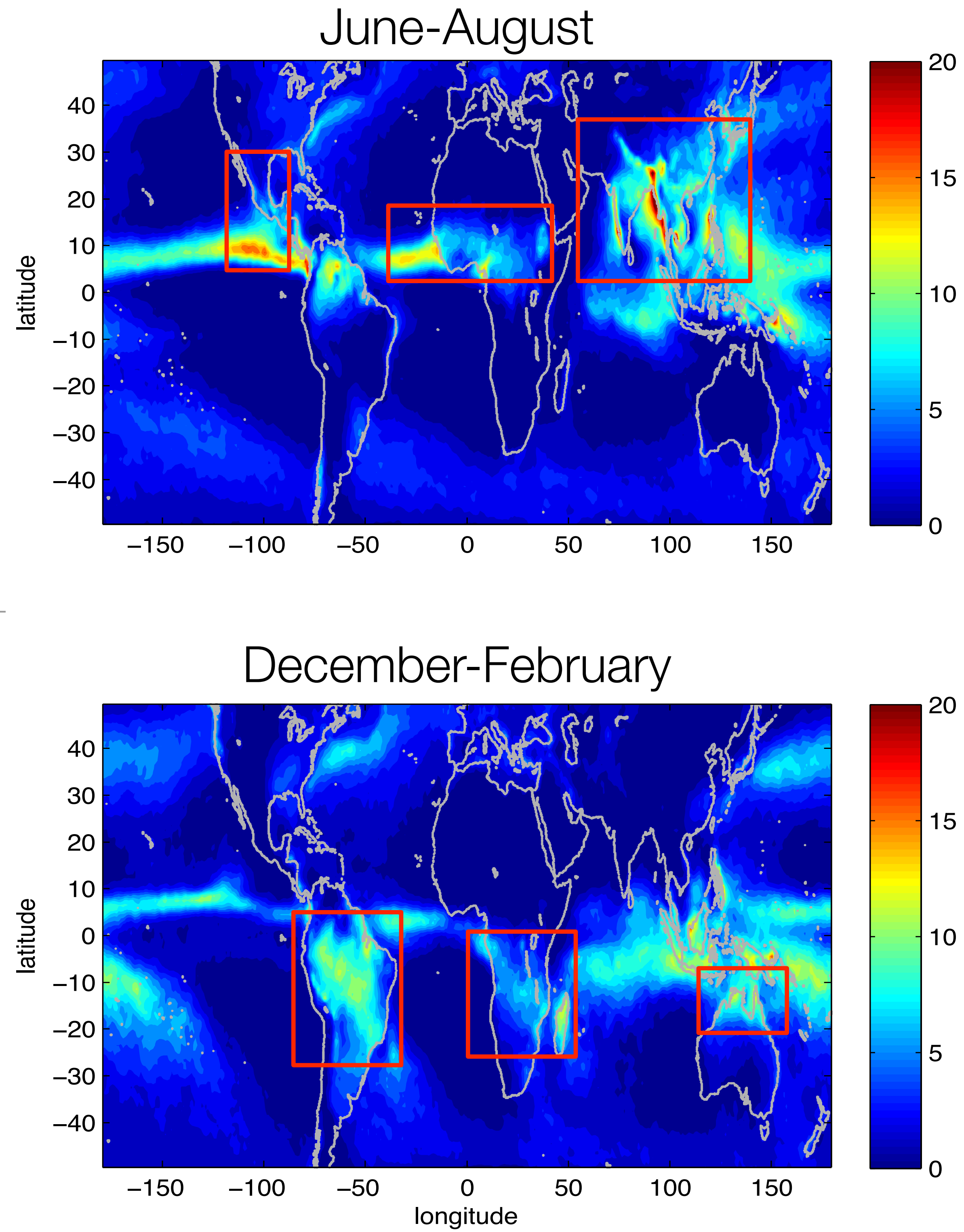


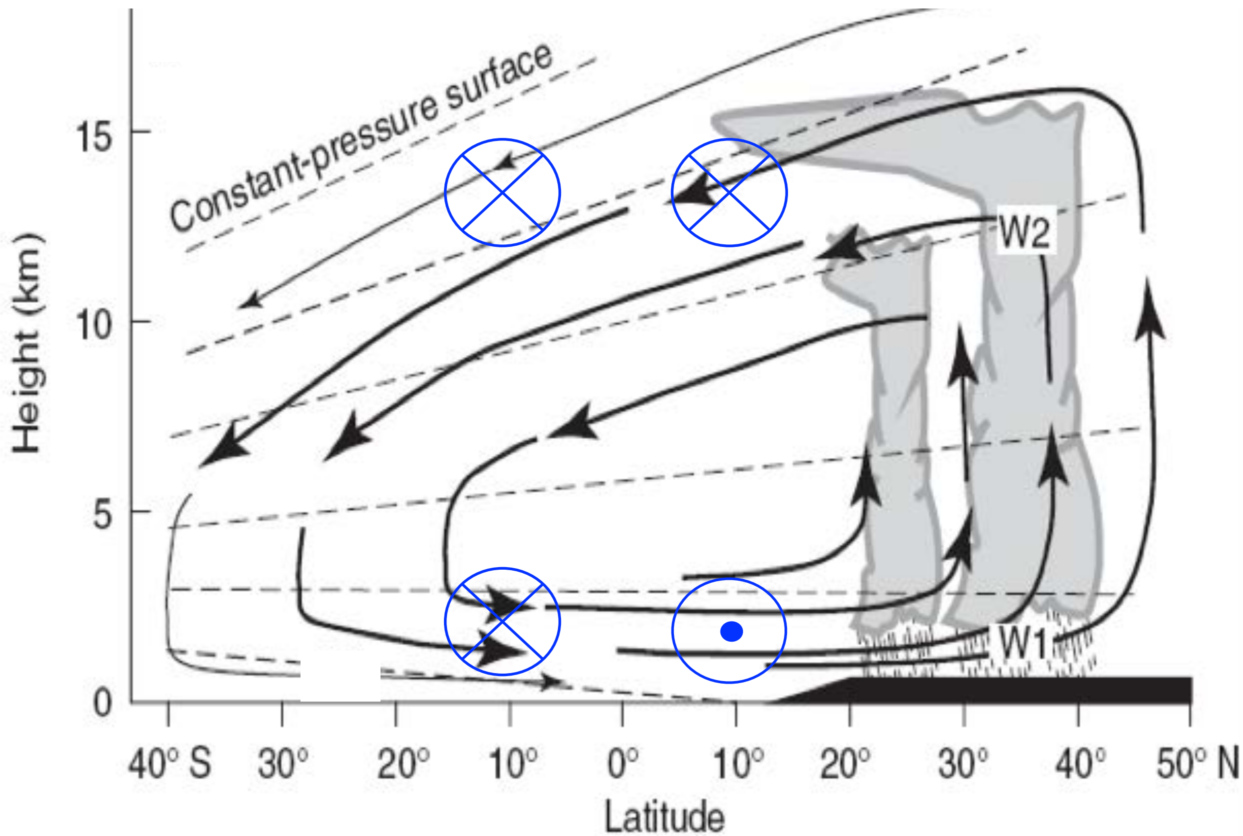
Sept. 4, 2014 Terra/MODIS true color reflectance from NASA's EOSDIS Worldview

The global monsoon

Globally, a large fraction of rain falls in monsoon regions during solstice seasons



An idealized view of monsoons

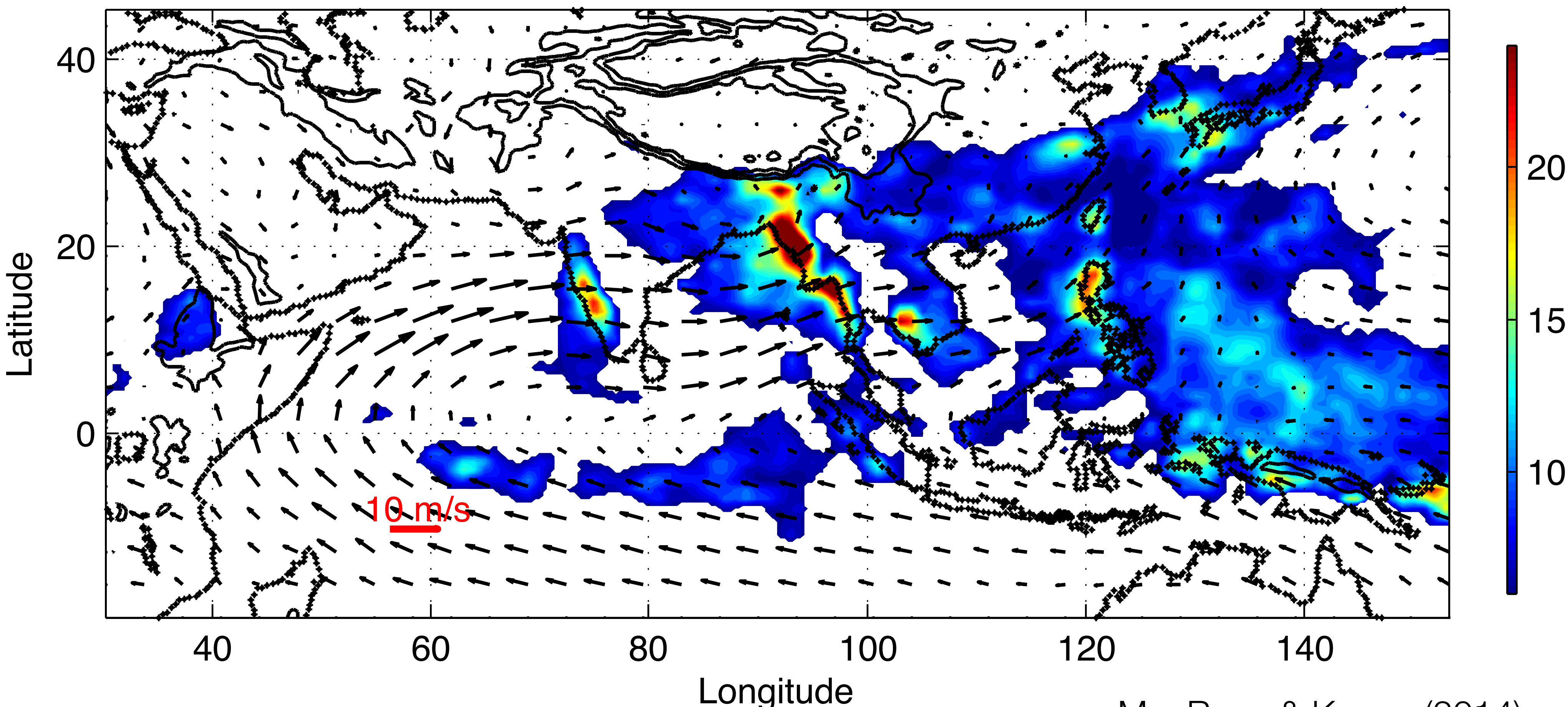


Webster and Fasullo (2003)

- precipitation occurs in ascending air in summer hemisphere
- circulation is closed by cross-equatorial flow and descent in winter hemisphere
- reversal of typical “trade winds” in summer hemisphere

This 2D view hides much complexity, but accurately describes zonal mean structure

JJA climatology of TRMM precipitation (mm/day) and ERA-40 850 hPa wind



Ma, Boos & Kuang (2014)

Going beyond the descriptive: how can we ***understand*** the variability of monsoons?

Limit our focus to seasonal-mean behavior:

- Interannual variability (2002 drought in India)
- Decadal variability (1970s-80s Sahel drought; past 30-year drying trend in East Africa)
- Response to anthropogenic forcings (greenhouse gases, aerosols, land use change)
- Paleoclimate variability (mid-Holocene North African humid period)

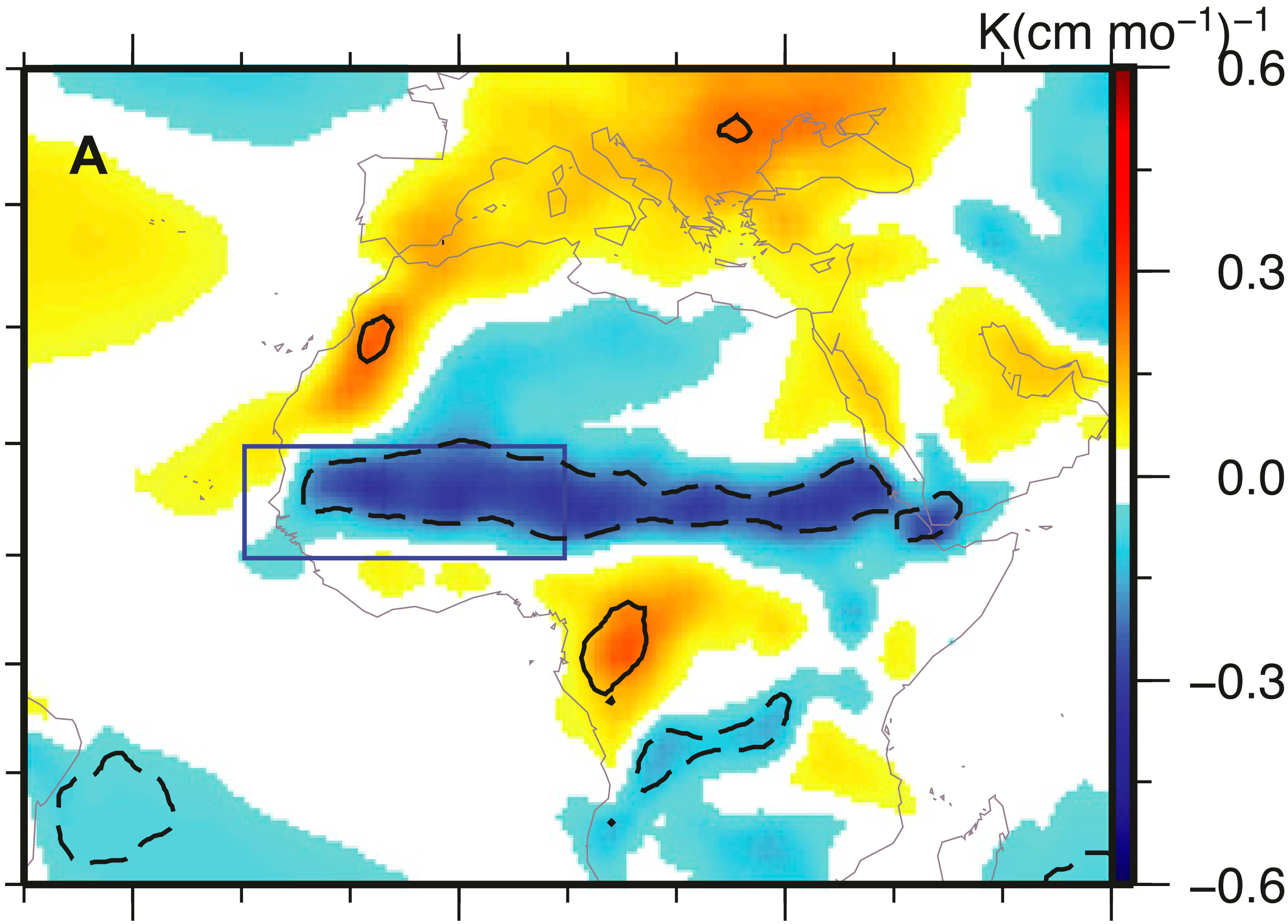
How to think about monsoon circulations?

i.e. given a forcing, how will the precipitating circulation respond?
Dominant categories of theory:

- Surface temperature gradients drive flow **wrong**
- Convective quasi-equilibrium **mechanistic but diagnostic**
- Vertically integrated atmospheric energy budget **prognostic but not mechanistic**

Disproof of idea that surface temperature gradients drive flow

regression of near-surface air temperature on Sahel rainfall



Data: GHCN rainfall & ERA-Interim near-surface air temperature

Black contours surround regions significant at 5% level

Hurley & Boos (2013)

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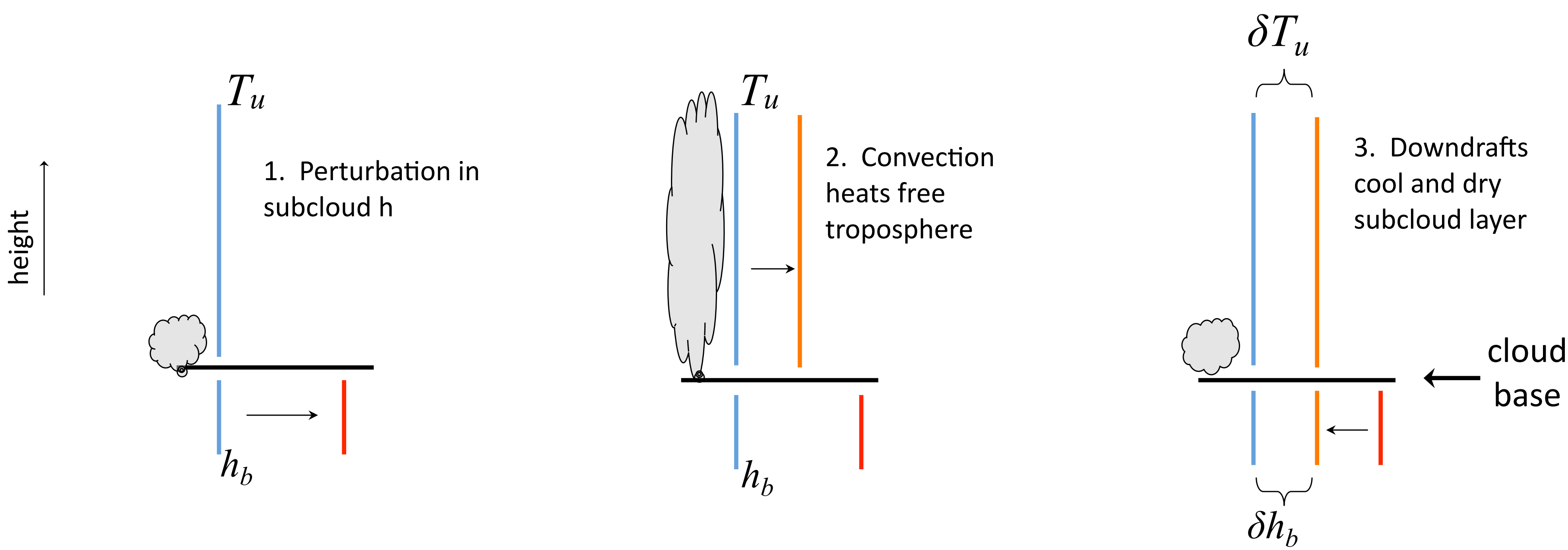
Convective quasi-equilibrium: a modern way to think about convectively coupled large-scale flow

- Moist convection does not act as "heat source" for large-scale flow, but maintains free-troposphere near moist adiabat
- Changes in free-tropospheric temperature are in equilibrium with changes in subcloud entropy:

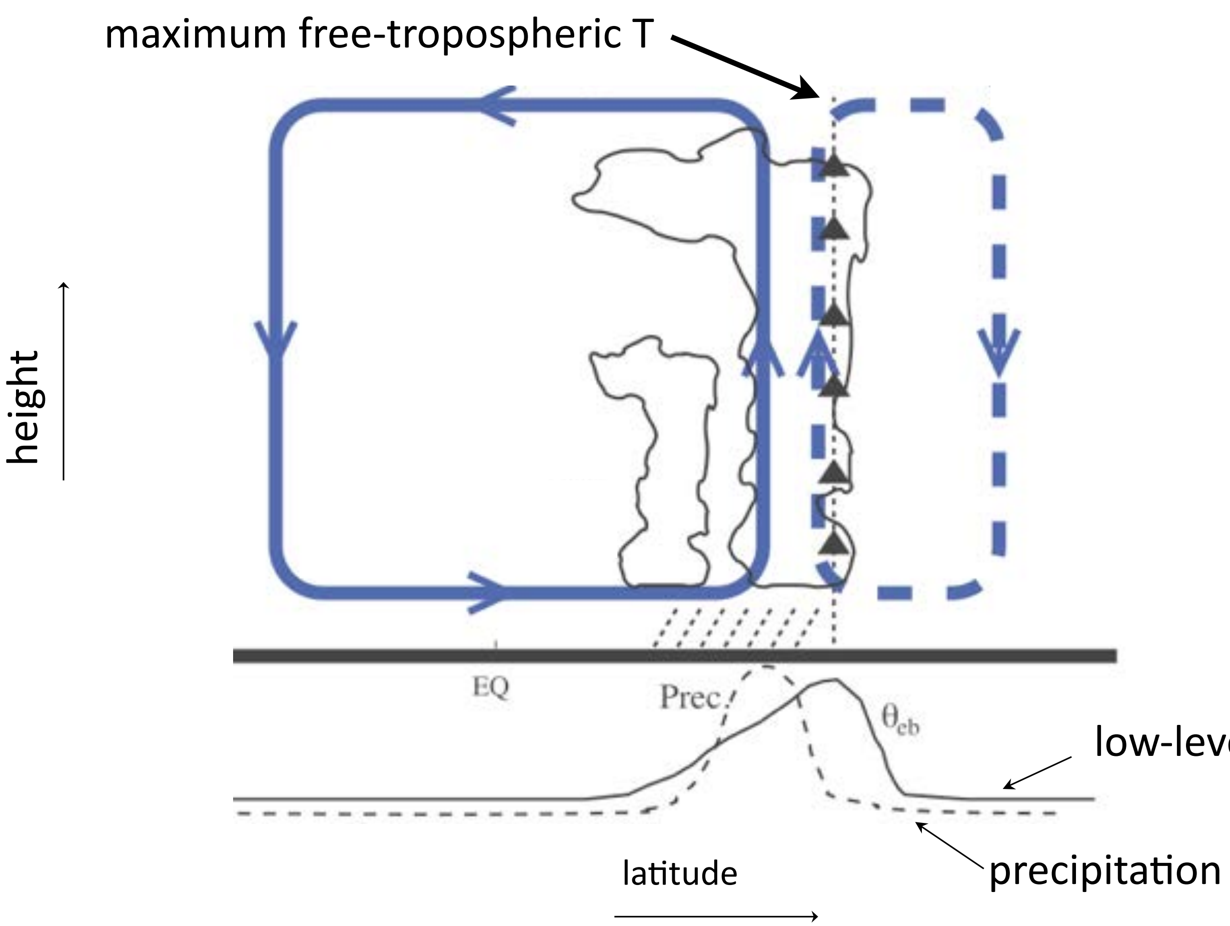
$$\delta T_u \sim \delta h_b$$

free-tropospheric temperature (δT_u)

subcloud moist static energy $(c_p T + g z + L_v q)$ (δh_b)



Convective quasi-equilibrium monsoons



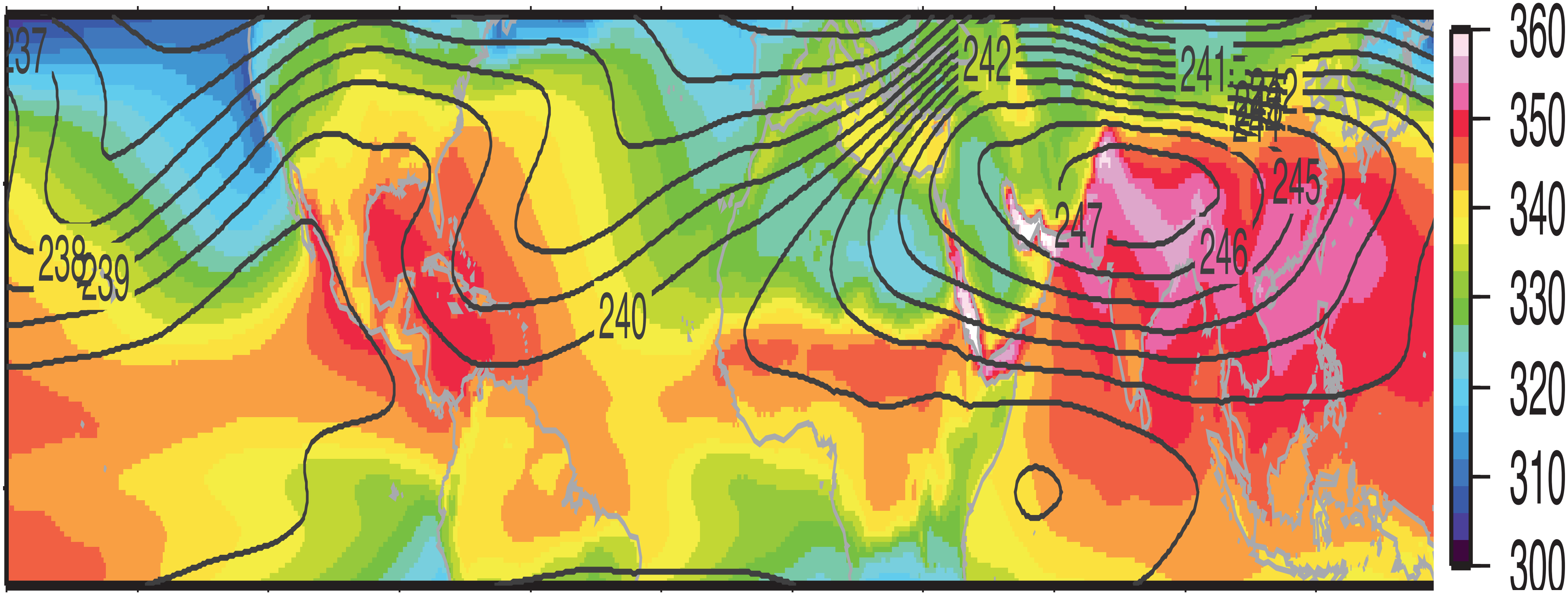
Maxima of h_b and T_u should be coincident in monsoons, at poleward edge of cross-equatorial cell.

T_u gradients are weak

$T_u > h_b$ away from the ascent branch

Convective quasi-equilibrium framework describes South Asian summer mean state

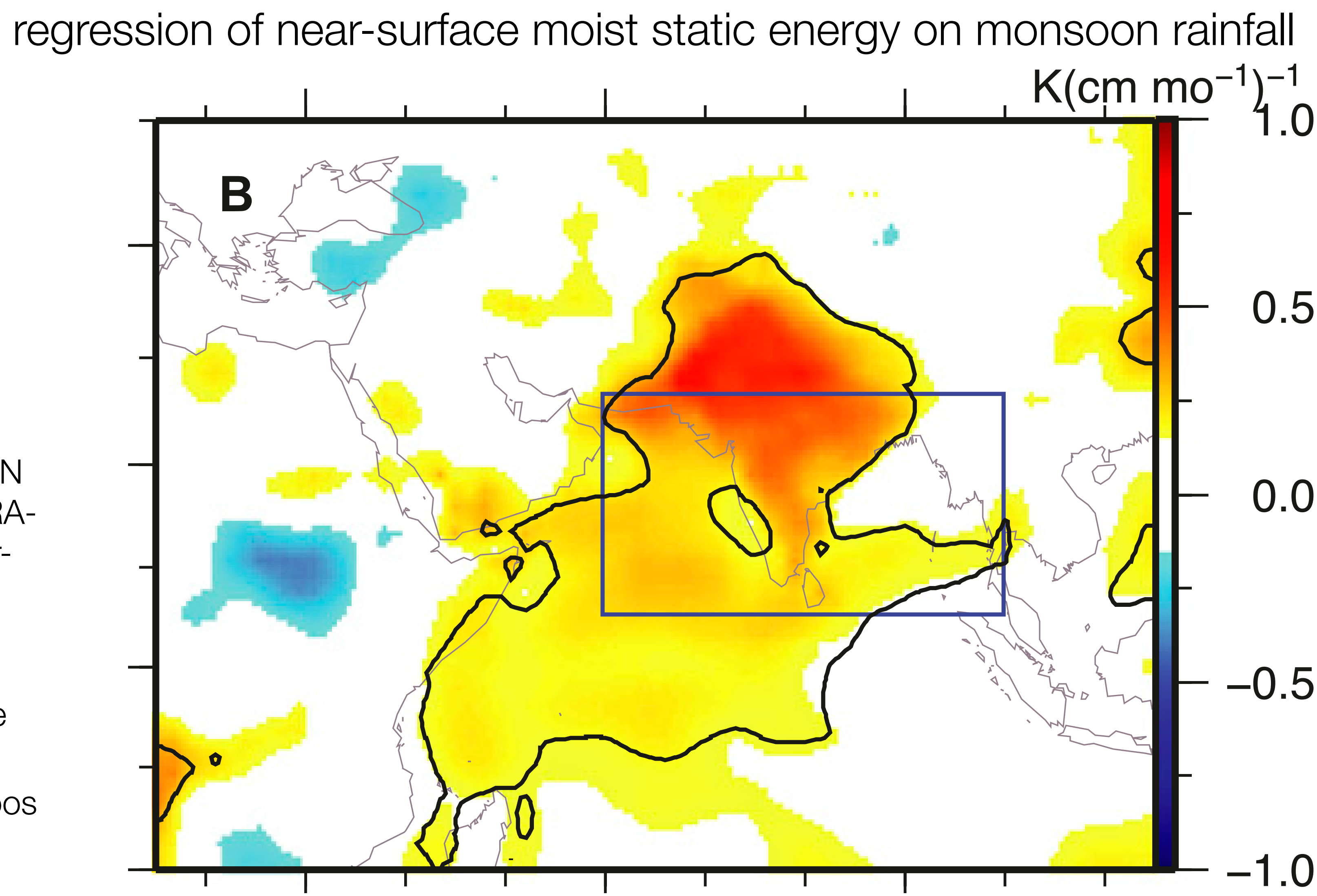
July climatology
Contours: 200-400 hPa temperature (K)
Colors: surface air moist static energy ($c_p T + g z + L_v q$), in K



Data: ERA-Interim

Boos & Hurley (2013)

Convective quasi-equilibrium framework is also consistent with South Asian interannual variability

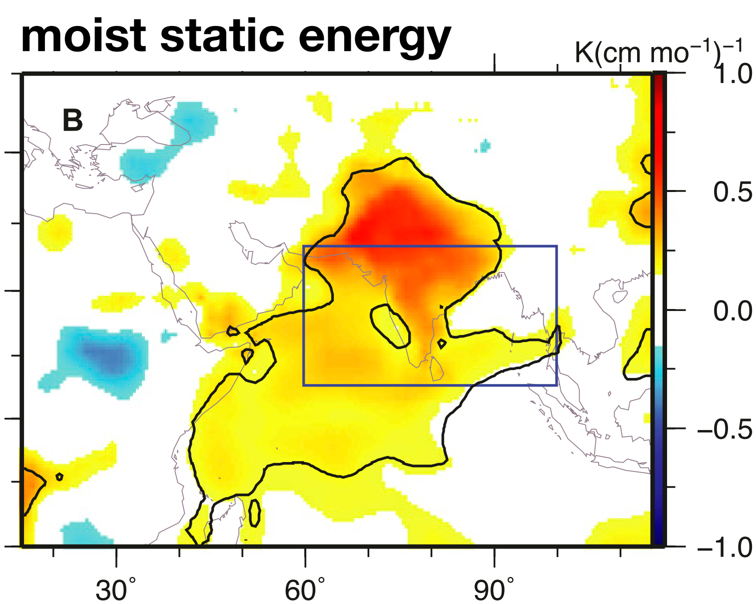


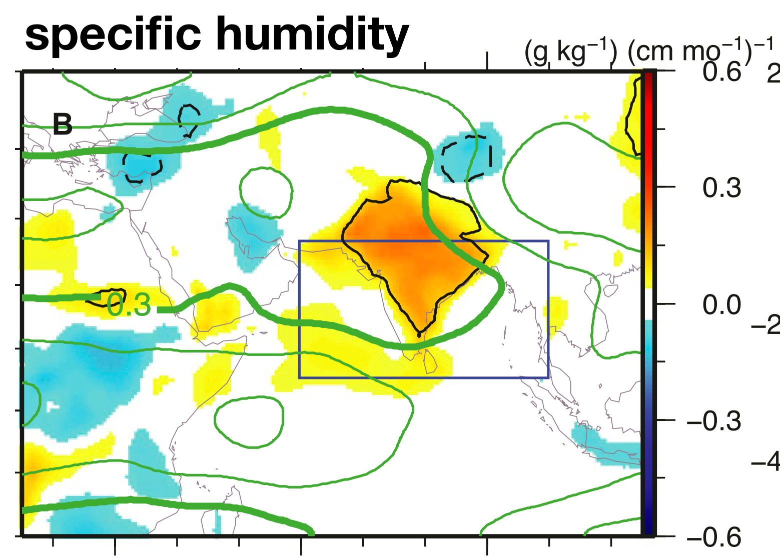
Data: GHCN rainfall & ERA-Interim near-surface equivalent potential temperature

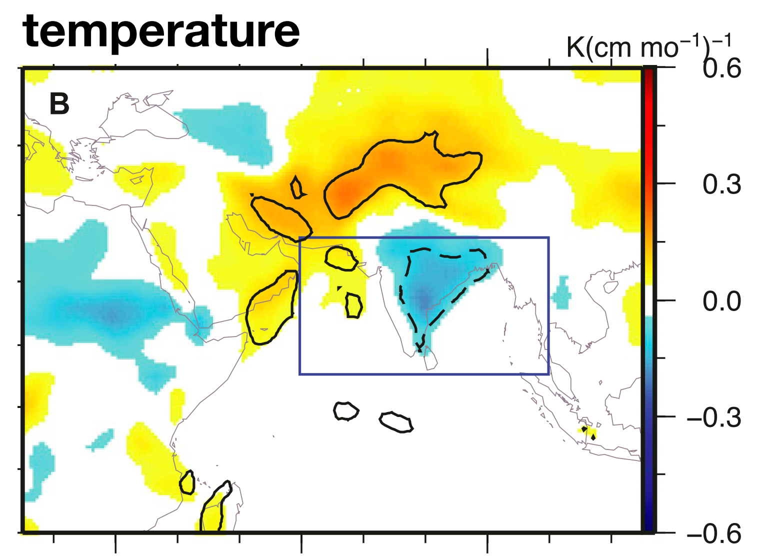
Hurley & Boos (2013)

Convective quasi-equilibrium framework is also consistent with South Asian interannual variability

regressions on South Asian monsoon rainfall of near-surface …







Data: GHCN rainfall & ERA-Interim T, q, moist static energy

Hurley & Boos (2013)

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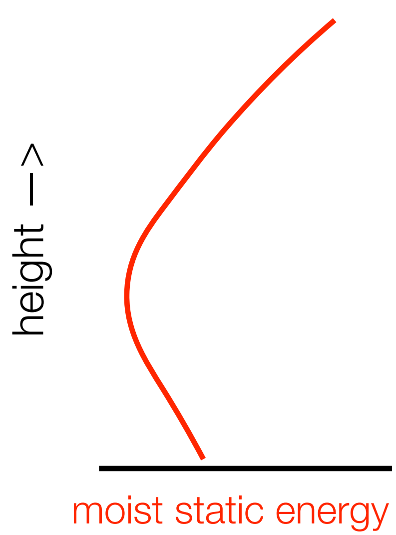
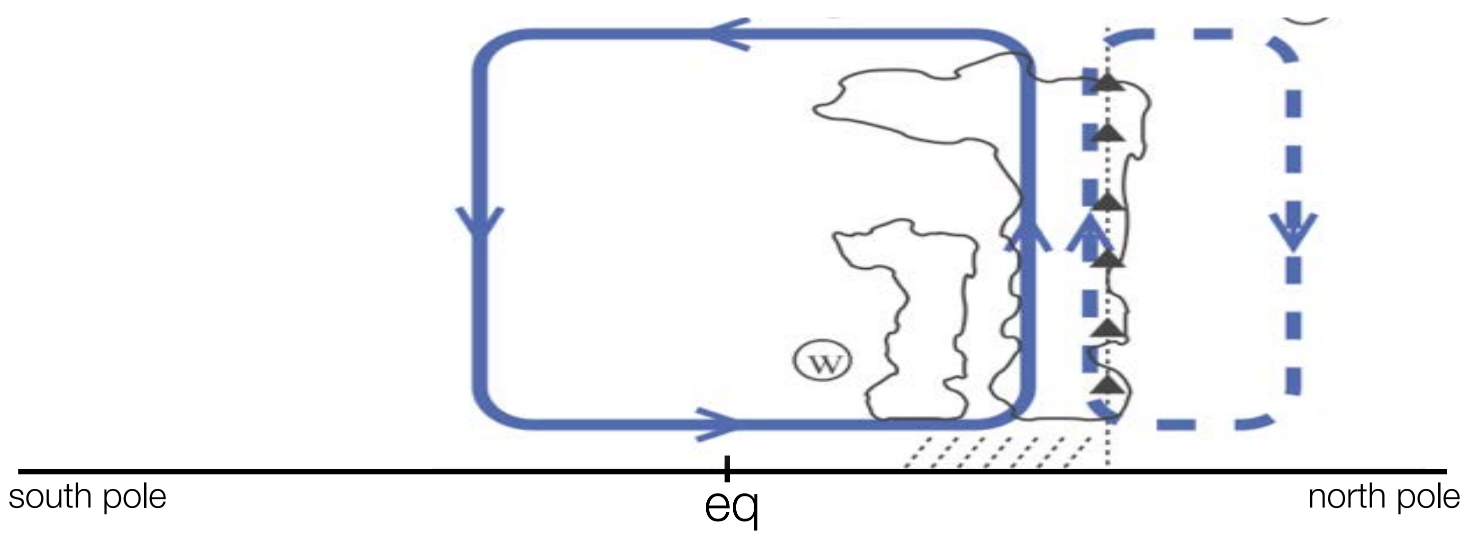
Atmospheric meridional overturning circulations transport energy

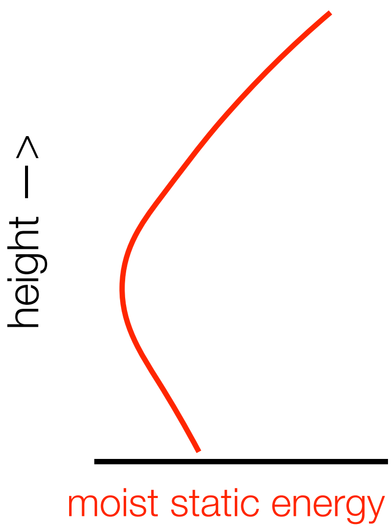
$$\nabla \cdot \int_{p_s}^{0} vh \frac{\mathrm{d}p}{g} = Q$$

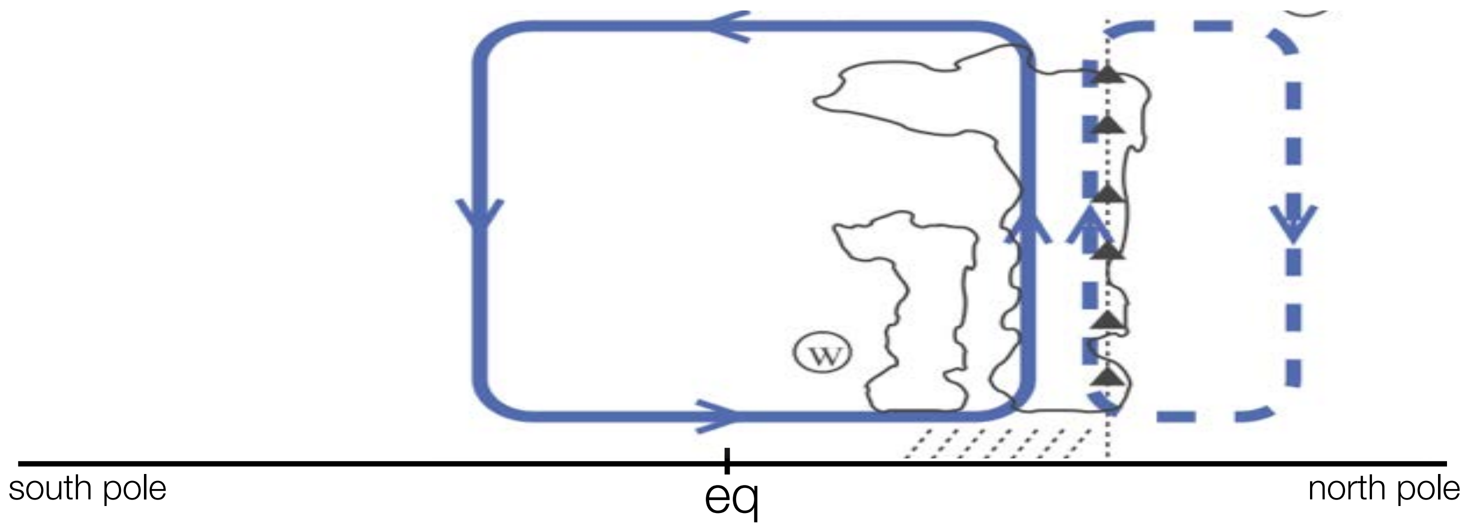
energy input to atmospheric column

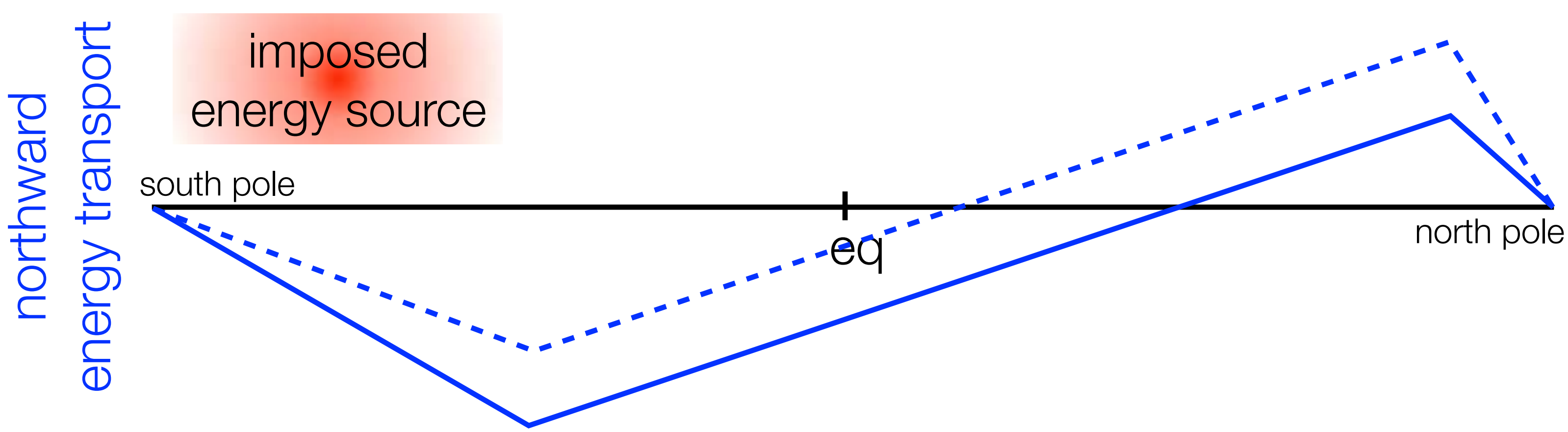




Precipitation peak shifts in response to an imposed high latitude energy source

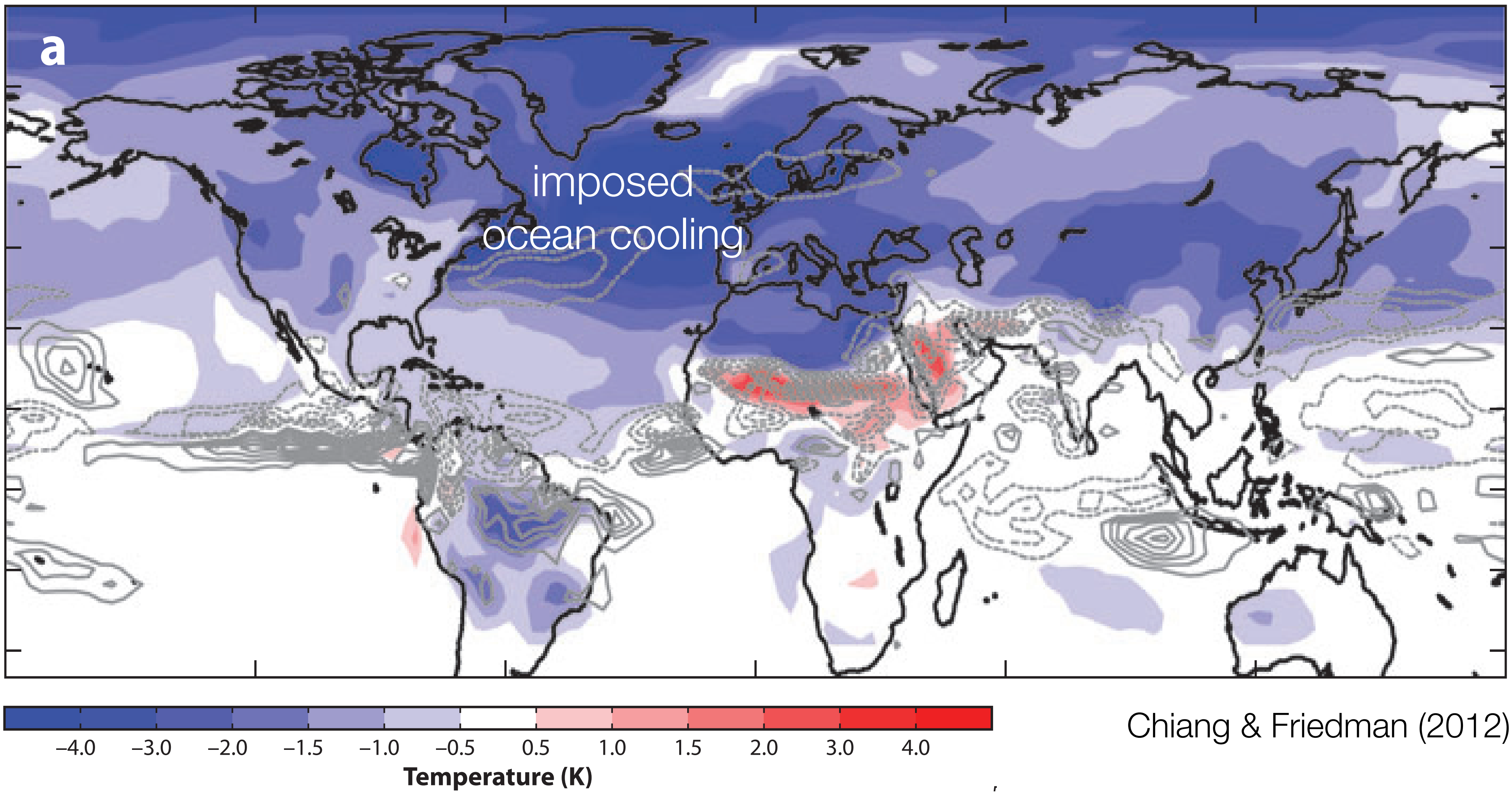






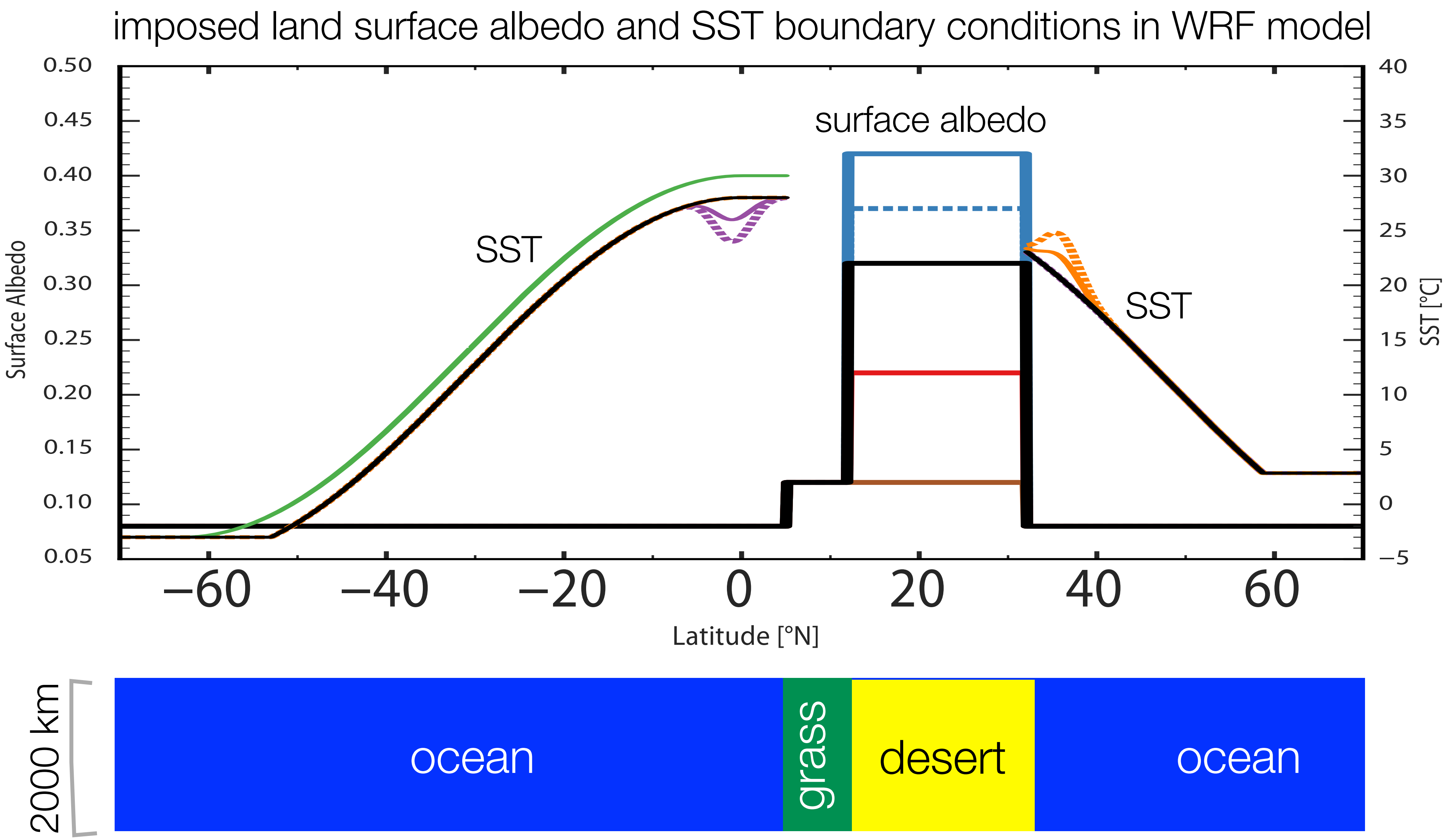
GCMs & paleo proxies show that high-latitude thermal forcings can produce ITCZ shifts

colors = surface temperature anomaly, contours = precipitation anomaly

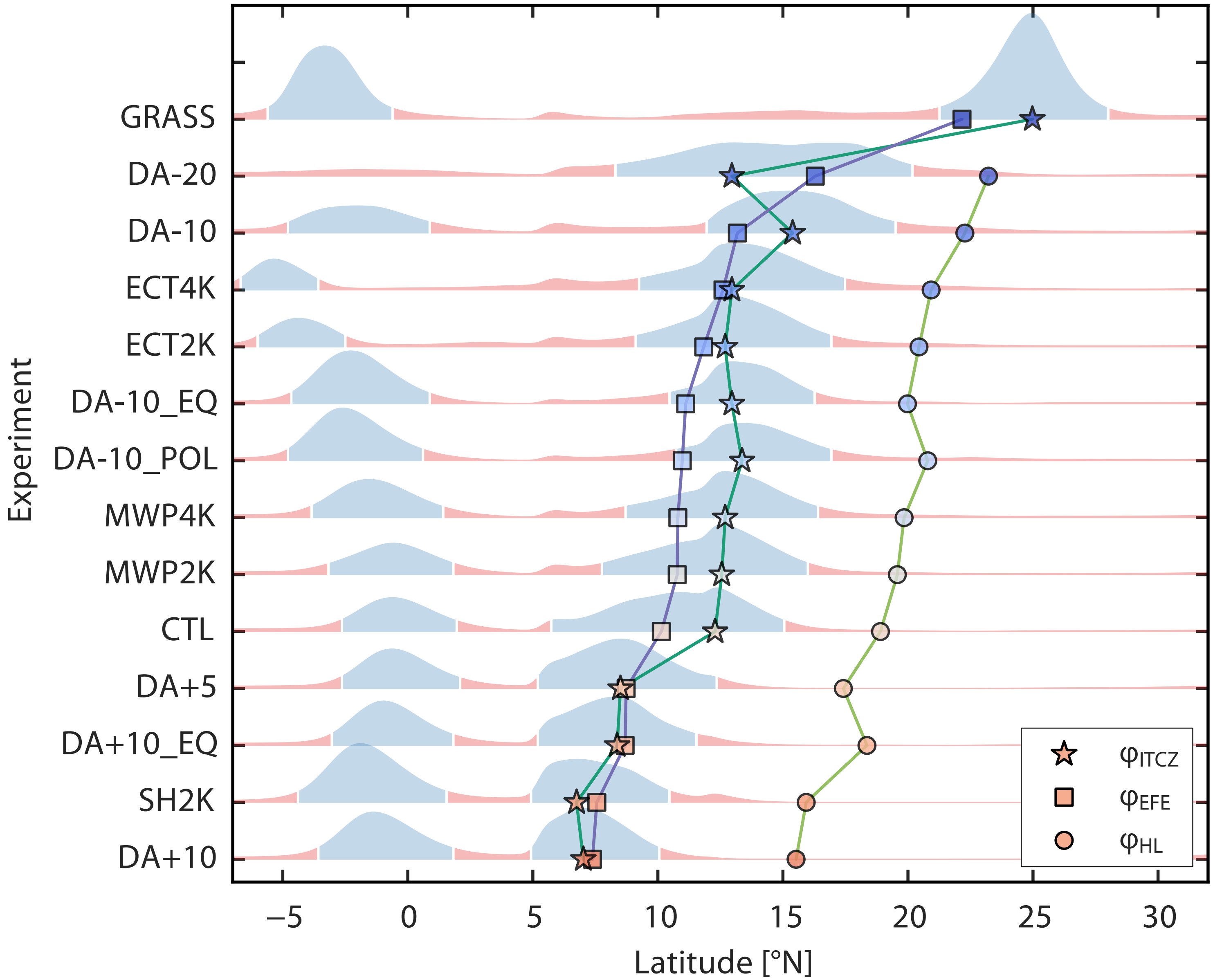


Chiang & Friedman (2012)

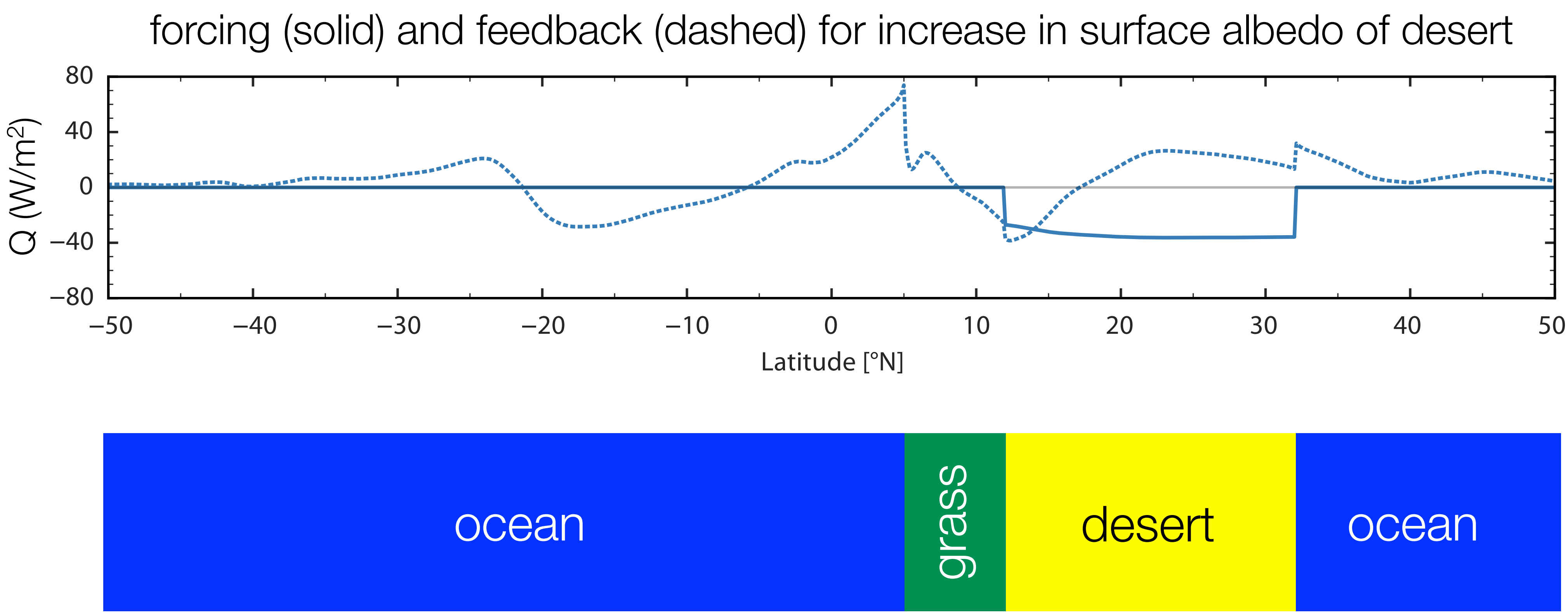
This works quantitatively for a variety of forcings in an idealized beta-plane model



Precipitation maximum and energy flux equator generally shift together



But energetic feedbacks are just as large as the imposed forcing



Summary

- Convective quasi-equilibrium and the vertically integrated atmospheric energy budget can both be used to understand the response of monsoons to forcings:
  - interannual variability (enhanced land-ocean h contrast = more rain)
  - ITCZ shifts toward an applied energy source, but there are large energetic feedbacks
- An energetically closed simple model & a GCM show that monsoon strength exhibits no threshold response to a broad range of forcings