The Importance of Convection from a Large Scale Dynamical Perspective

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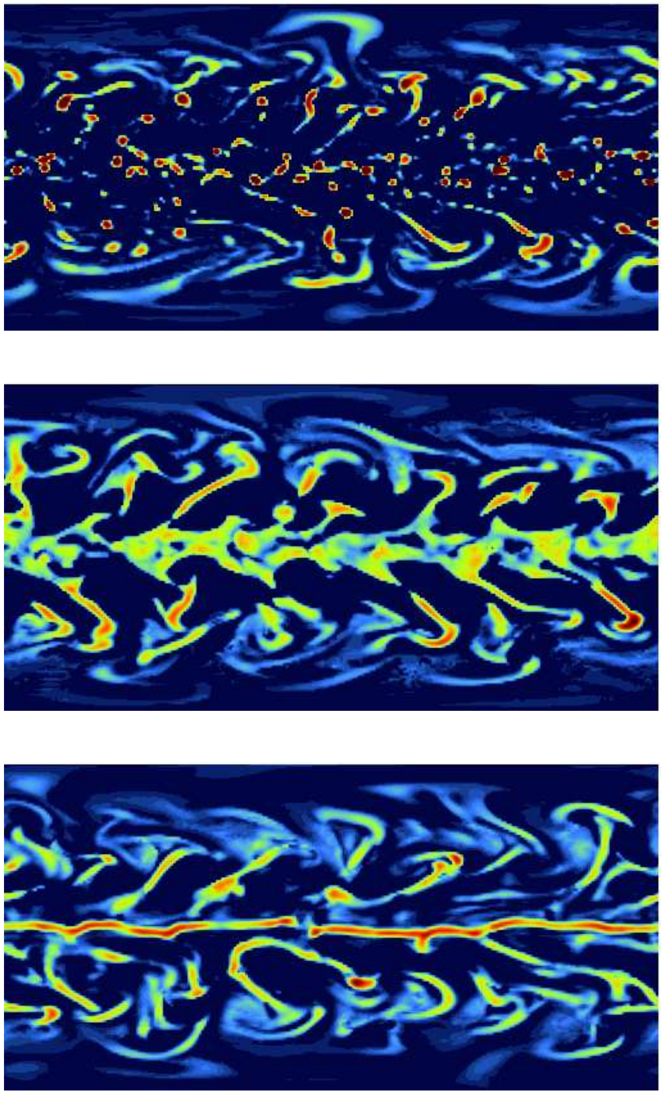
Some Motivation



Talk Outline

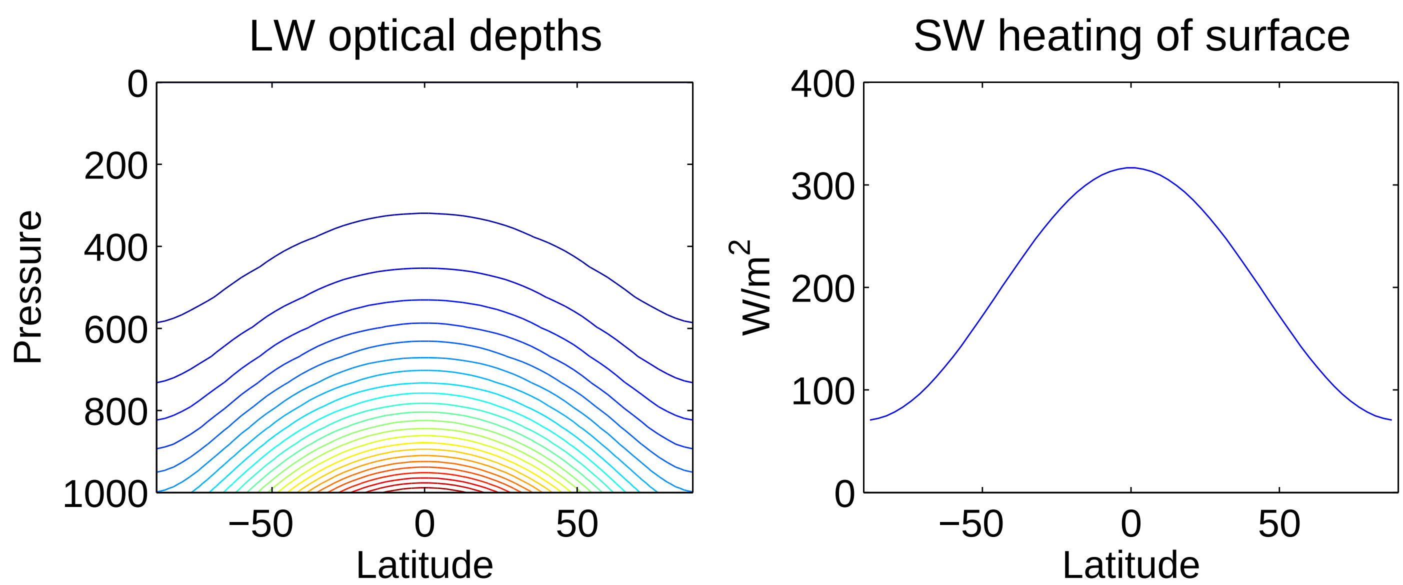
- A Simplified Moist GCM – model description
- A Simple Convection Scheme
  - Formulation
  - Effect on Zonally Averaged Circulation
    - Hadley circulation (energy and mass transports), tropical precipitation
  - Effect on Transient Dynamics/Equatorial Waves
    - Speed/strength of equatorial Kelvin waves

A Simplified Moist GCM

- Goal:
  - Design a simplified GCM that incorporates the dynamical effect of moisture in the simplest possible manner, while remaining fully modular with full GCM physical parameterizations whenever possible
- The model:
  - Primitive equations: up to T170 resolution, 25 levels
  - Gray radiative transfer (next slide)
  - Aquaplanet slab mixed layer ocean
    - Closed system in terms of energetics (atmosphere performs all the energy transports)
  - Simplified Monin-Obukhov surface flux scheme, K-profile boundary layer scheme

Radiation Scheme

- Gray radiation: Water vapor, clouds, other tracers have no effect on radiation.
- Parameters: longwave optical depths, shortwave heating



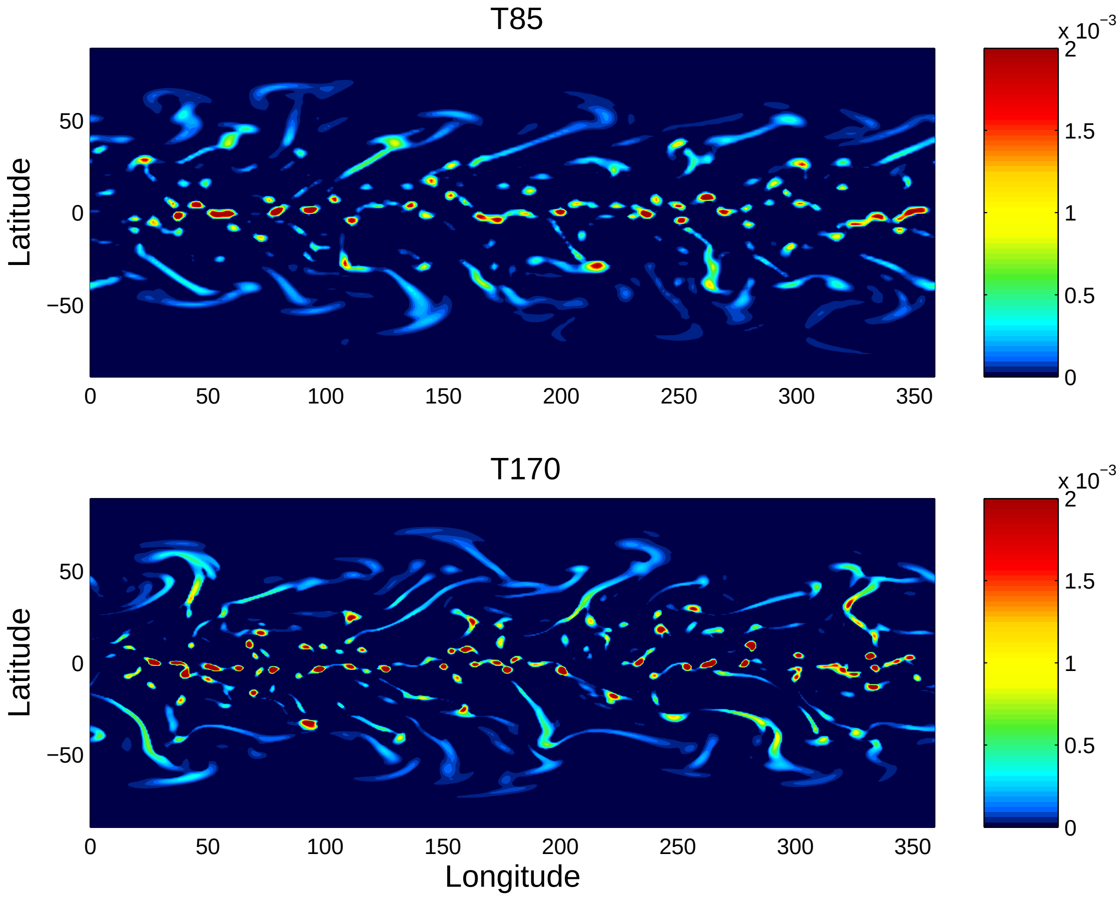
- All shortwave (solar) heating into surface

Moisture/Convection

- No condensate, no microphysics, no freezing
- Simplest convection scheme: **no convection scheme!** (large scale condensation (LSC) only)
  - Precipitation occurs when a gridbox becomes saturated
  - Model can be integrated with this
  - Revaporate precipitation into unsaturated areas
  - Similar in practice to moist convective adjustment

No Convection Scheme Simulations

- Instantaneous precip, T85 and T170 resolutions



No Convection Scheme Simulations

- Precipitation is concentrated at the **grid scale** in the tropics
- Tropics are **sensitive to resolution** in this model: however midlatitudes are not
- This version of the model used in studies of moisture effects on **midlatitude** static stability, eddy scales, energy fluxes, and jet latitude. (Frierson, Held and Zurita-Gotor 2006a, b)
- Also used in a nonhydrostatic GCM to study the "hypohydrostatic" rescaling (Garner et al 2006)

A Simplified Betts-Miller (SBM) Convection Scheme

- Basic principle: **relax** temperature, humidity to some post-convective equilibrium profile (Betts 1986, Betts and Miller 1986, see also Arakawa 2004)

$$\delta T = -\frac{T - T_{eq}}{\tau_c}, \delta q = -\frac{q - q_{eq}}{\tau_c}$$

- Equilibrium temperature profile: **moist adiabat** from surface parcel (relax up to LZB)
- Equilibrium humidity profile: **specified relative humidity** with respect to the equilibrium temperature
- First complication: enthalpy conservation ($-\int \delta q dp/g = \int \frac{c_p}{L} \delta T dp/g$, or drying must equal heating)

Enthalpy Conservation

- **Shift reference temperatures** by a uniform amount in height to satisfy enthalpy conservation (simplest method that is continuous, similar to real Betts-Miller scheme)

$$\Delta k = \frac{1}{\Delta p} \int_{p_0}^{p_{LZB}} -(c_p \delta T + L \delta q) dp$$
$$T_{eq2} = T_{eq} - \frac{\Delta k}{c_p}$$

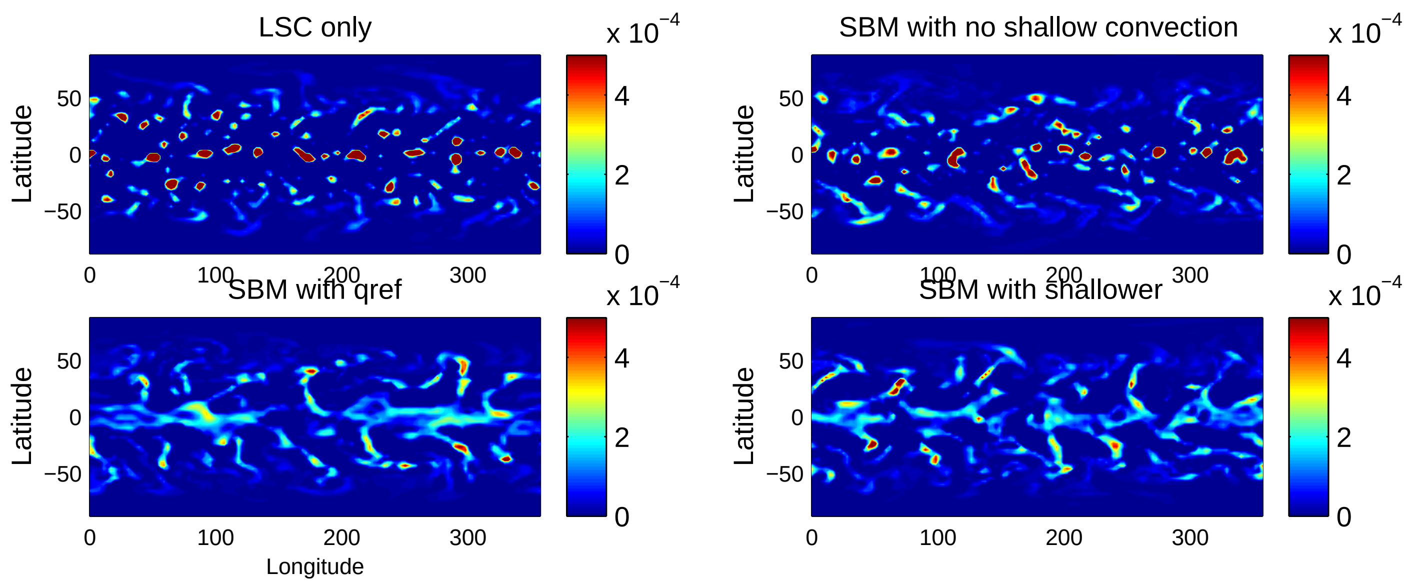
- If the column is too dry, the temperature correction is negative (rough simulation of **downdrafts**)
- Implies precipitation is **no longer correlated** with CAPE.
- Second complication: what if predicted precipitation after this adjustment is **negative**?

Shallow Convection

- When predicted precipitation is negative, set precip to zero and perform "shallow convection"
- Three methods of doing this:
  - **No adjustment** of temperature and humidity: baseline for comparison ($\delta T = \delta q = 0$)
  - **Change humidity profile** by uniform fraction (Choose f_q in $q_{eq2} = f_q q_{eq}$ such that net drying equals zero): "**qref**"
  - **Lower depth** to where net drying equals zero (Choose p_{shall} such that $0 = \int_{p0}^{p_{shall}} (-\frac{q - q_{ref}}{\tau_c})$): "**shallower**"

Sensitivity to Shallow Scheme

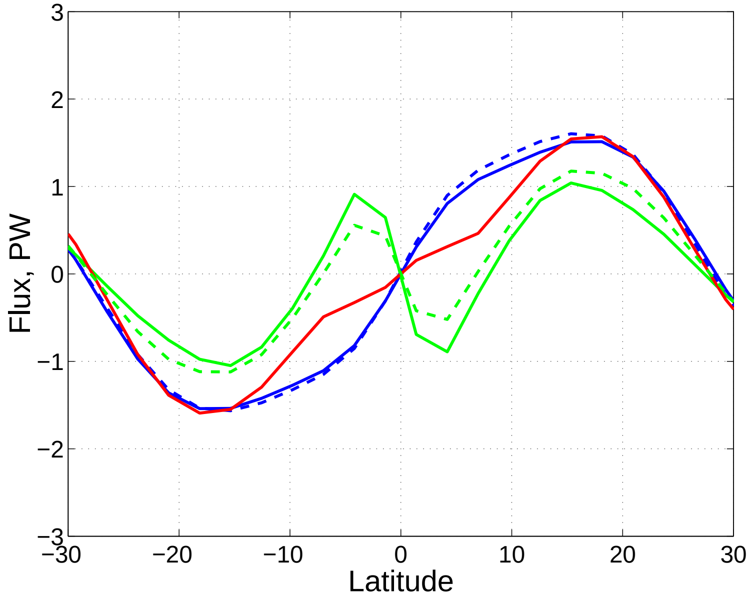
- Simulations with $\tau_c = 2h$, $RH_{SBM} = .7$, instantaneous precip



- With no shallow convection scheme, the convection scheme is much less effective
- Two shallow schemes are qualitatively similar

Hadley Circulation

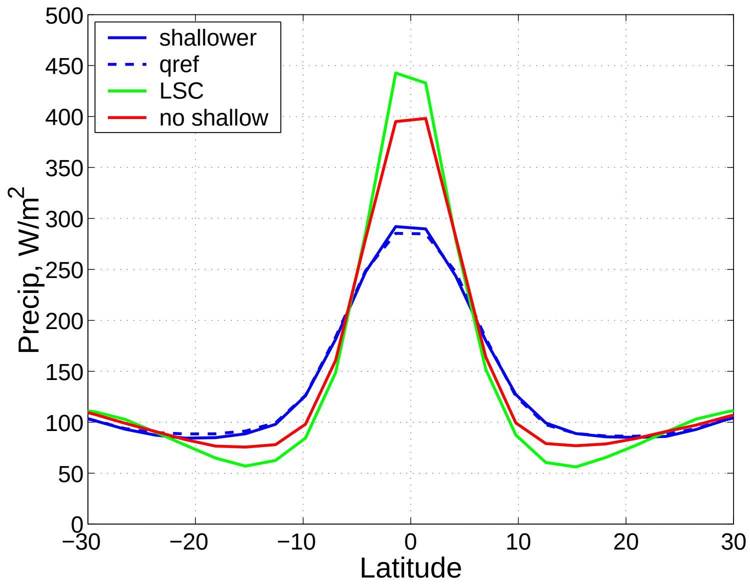
- Moist static energy fluxes by Hadley circulation (30N-30S):



- **Equatorward transport** by Hadley circulation for LSC only
- Two SBM shallow convection schemes are similar
- LSC has **50% larger mass flux** compared with SBM!

Precipitation

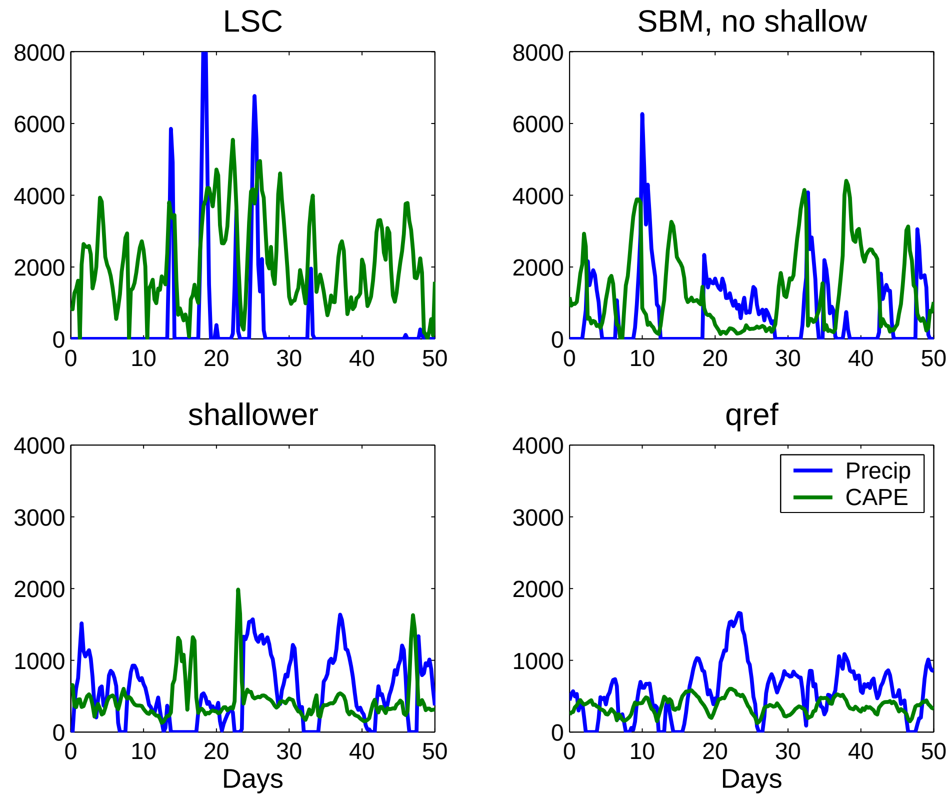
- Zonal mean precip (30N-30S):



- ITCZ precip scales with Hadley circulation strength (larger for LSC and no shallow)
- Increased precip within ITCZ in LSC and no shallow cases are **accompanied by reduction within subtropics** (total precip remains similar)

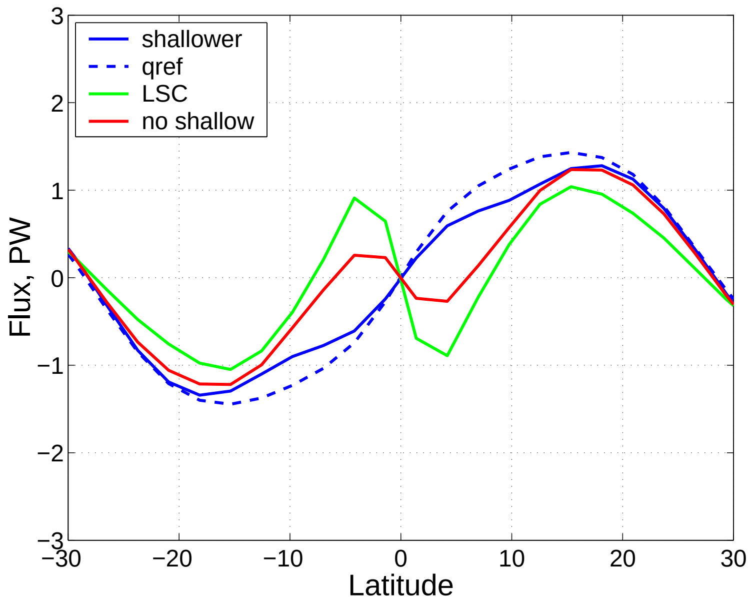
Ability to Build Up CAPE

- Claim: key categorization of convection schemes is ability to **build up and rapidly release CAPE** (abruptness of convective trigger)
- Time series of precip and CAPE along the equator:



Ability to Build Up CAPE

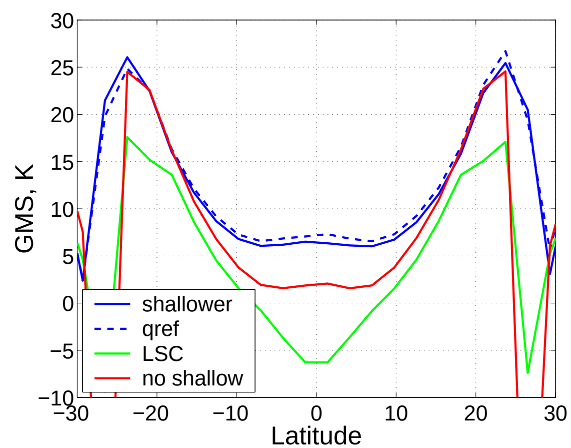
- Test with a more stringent convective criteria: $RH_{SBM} = .8$



- Two shallow schemes begin to diverge
- No shallow scheme looks more like LSC only simulations

Shallow Convection Summary

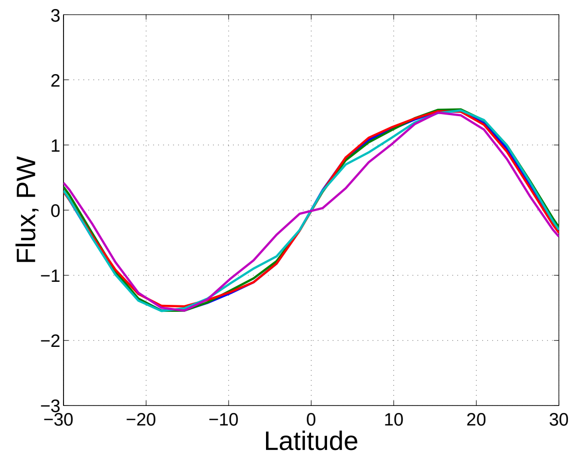
- Properties of schemes that have abrupt release of CAPE (LSC, or SBM with no shallow scheme):
  - Smaller energy transports by Hadley cell
  - Larger Hadley circulation mass flux
  - Smaller/negative "gross moist stability" = $\frac{\overline{mv}}{\bar{v}}$



  - Larger eddy moisture fluxes
  - More resolution dependence

Effect of Convective Relaxation Time

- Vary relaxation time: $\tau_c = 1h, 2h, 4h, 8h, 16h$
- Significant effects on many aspects of the circulation: transients, relative humidity, fraction of convection, etc
- However there is **no effect on Hadley circulation system** (provided large scale precip does not occur)



- Mass transport and ITCZ precip are within **2 %** for first 4 cases (then an abrupt increase of 35%)

Effect of Convective Relaxation Time

- How is the circulation so insensitive to relaxation time?
- Rewrite the precipitation expression:

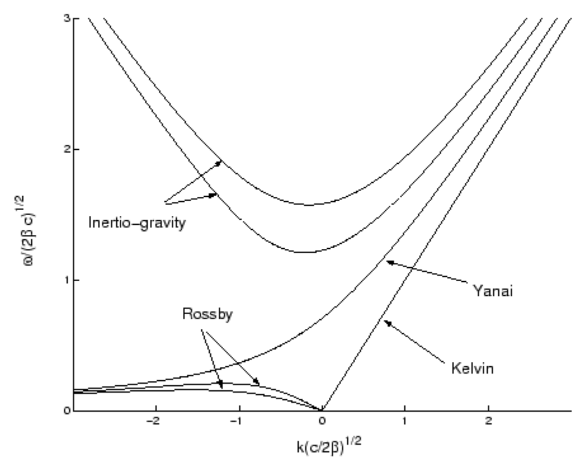
$$\bar{q} = \bar{q}_{eq} + \tau_c P$$

Humidity adjusts to keep precip the same.

- This same adjustment occurs in simple models such as Frierson, Majda and Pauluis 2004.
- Sensitivity to RH_{SBM} is more complicated due to changes in surface budget, but circulation is still relatively insensitive

Tropical Waves

- Method of Wheeler and Kiladis (1999):
  - **Fourier transform** over the tropics in space and time
  - Separate into **eastward and westward** propagation
  - Take out “background spectrum”
  - Observations show Kelvin waves, Rossby waves, etc with reduced phase speeds



Gross Moist Stability

- Dry wave equation:

$$\frac{\partial u}{\partial t} = -\frac{\partial T}{\partial x} \quad (1)$$

$$\frac{\partial T}{\partial t} = -\Delta s \frac{\partial u}{\partial x} + P \quad (2)$$

where Δs is dry stability

- But precip is correlated with convergence ($P = -\Delta q \frac{\partial u}{\partial x}$)

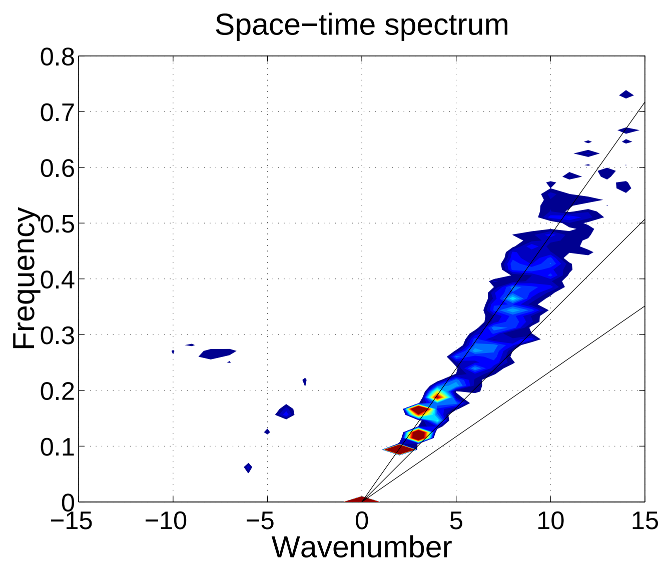
$$\frac{\partial T}{\partial t} = -\Delta m \frac{\partial u}{\partial x}$$

with $\Delta m = \Delta s - \Delta q$, the **gross moist stability**

- Phase speed goes as $\sqrt{\Delta m}$

Tropical Waves

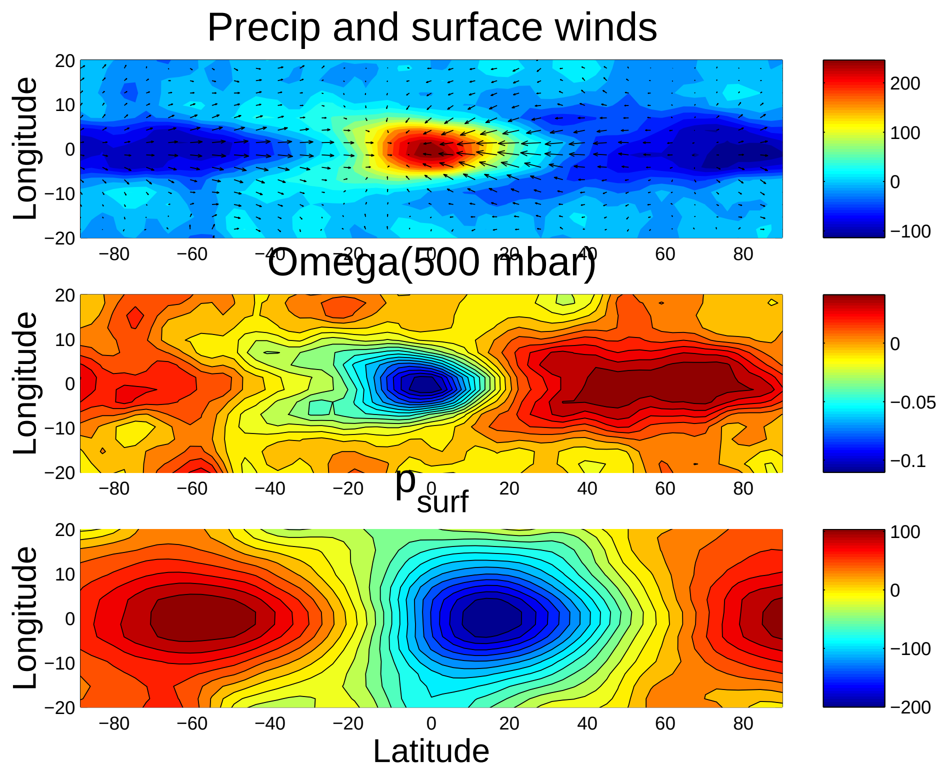
- Wheeler-Kiladis diagram for precip for simulation with $\tau_c = 2h$, $RH_{SBM} = .6$



- Strong, persistent **Kelvin wave** dominates the spectrum
- Speed ≈ 20 m/s (40 m equivalent depth), only slightly faster than observations. What sets speed? Sensitive to convection scheme parameters?

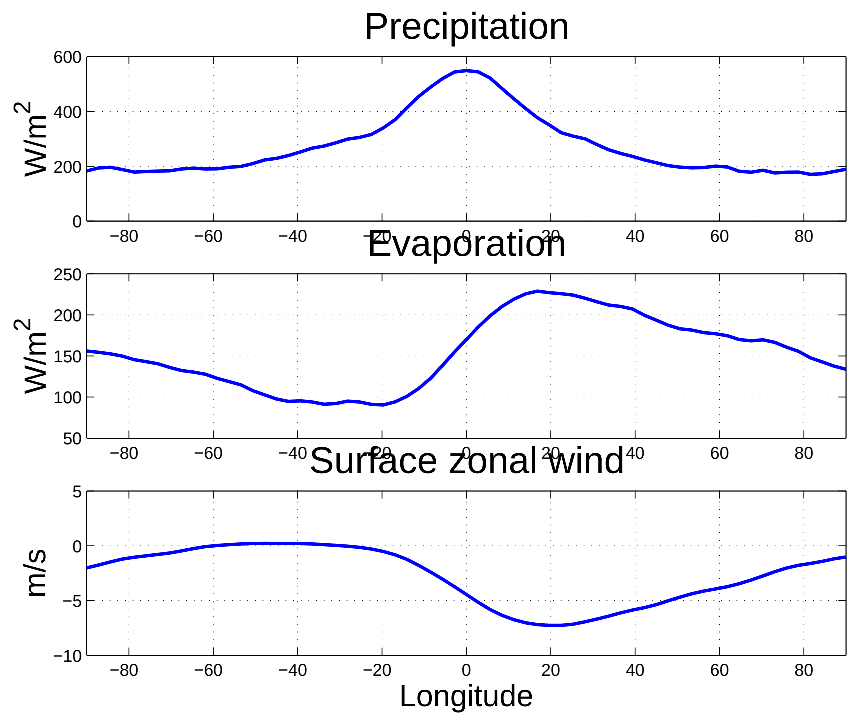
Control Simulation Kelvin Wave Composite

- Method of Wheeler, Kiladis, and Webster: take Kelvin filtered time series at a point on the equator, regress this against other fields



Control Simulation Composite

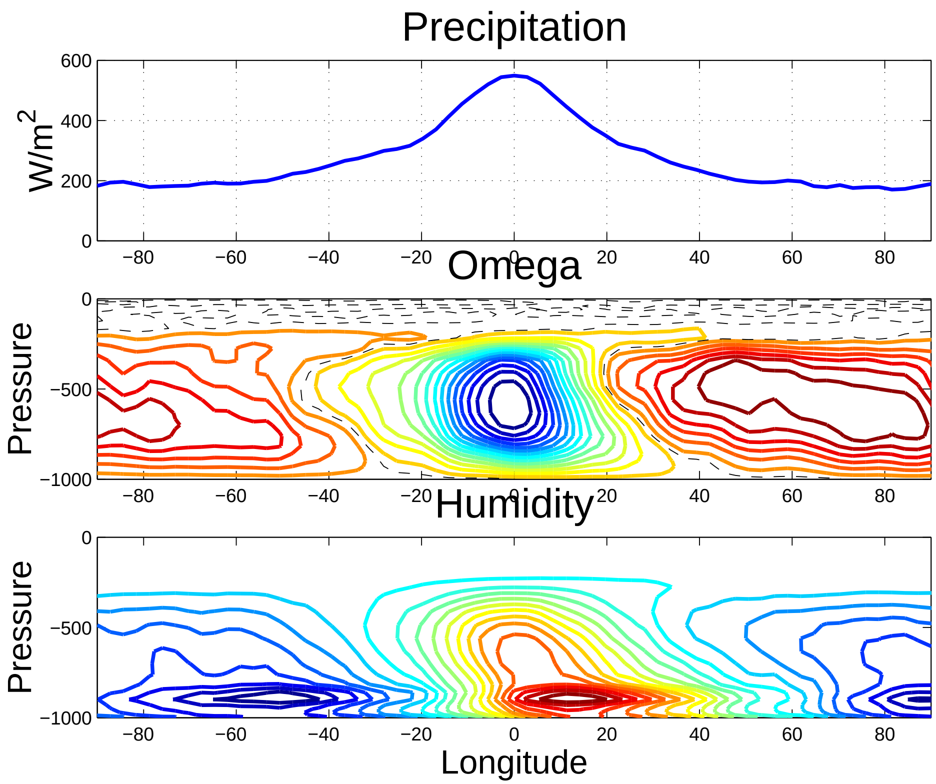
- P, E, u_{surf} on the equator:



- Evaporation leads and provides strength for wave: evaporation-wind feedback is energy source $(E = C_D|u|(q_s - q))$

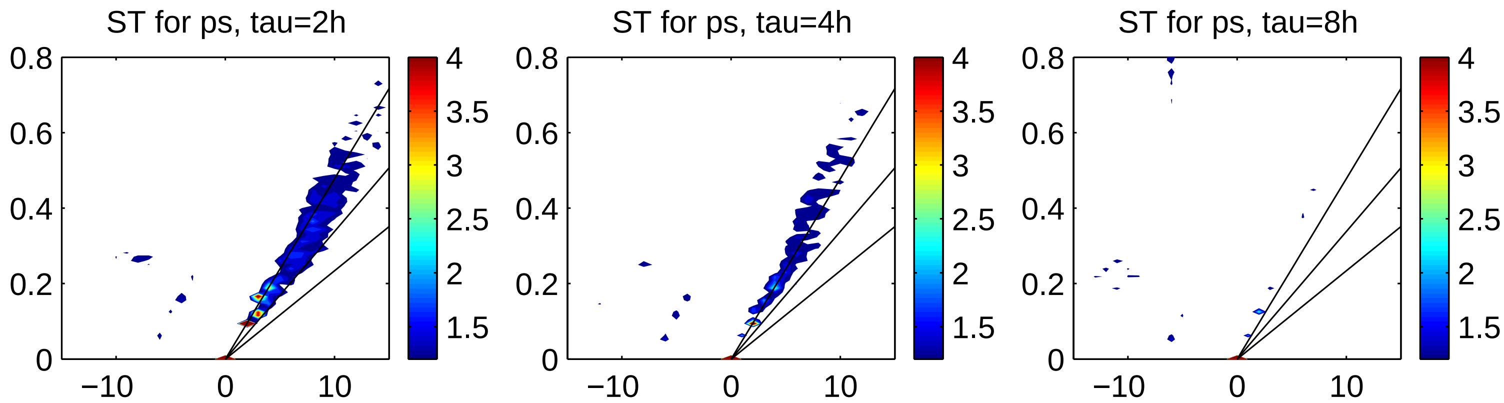
Control Simulation Composite

- Shallow convection leads and propagates moisture upwards



Sensitivity to Relaxation Time

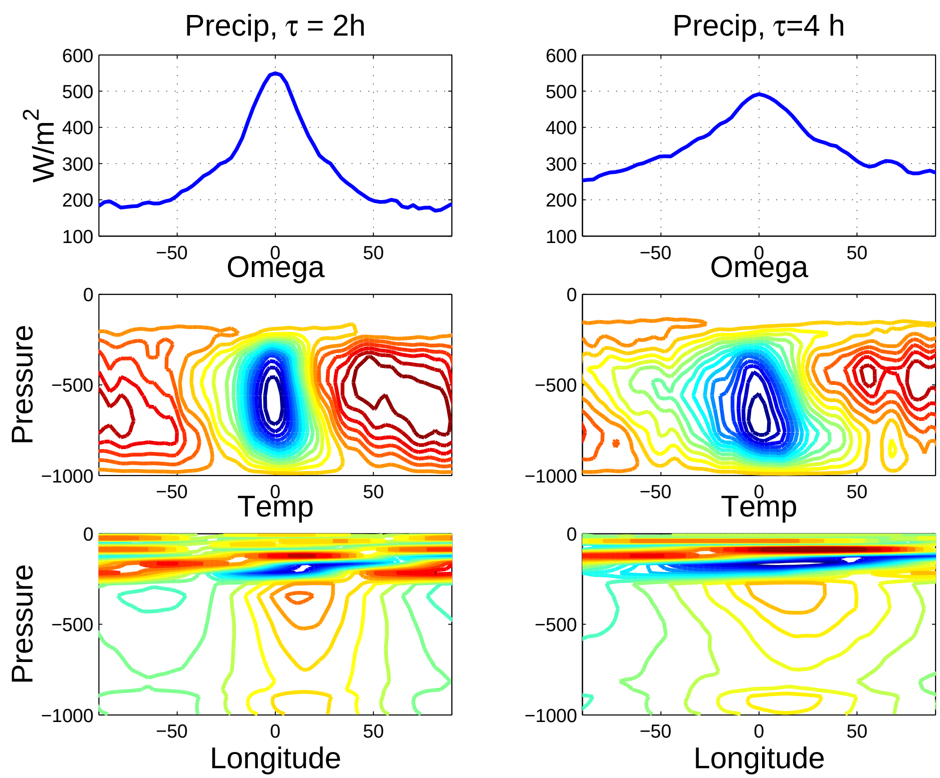
- Wheeler-Kiladis diagram for different τ_c (2 h, 4 h, 8 h)



- Longer relaxation time causes additional convective damping (Emanuel 1993)

Relaxation Time Composites

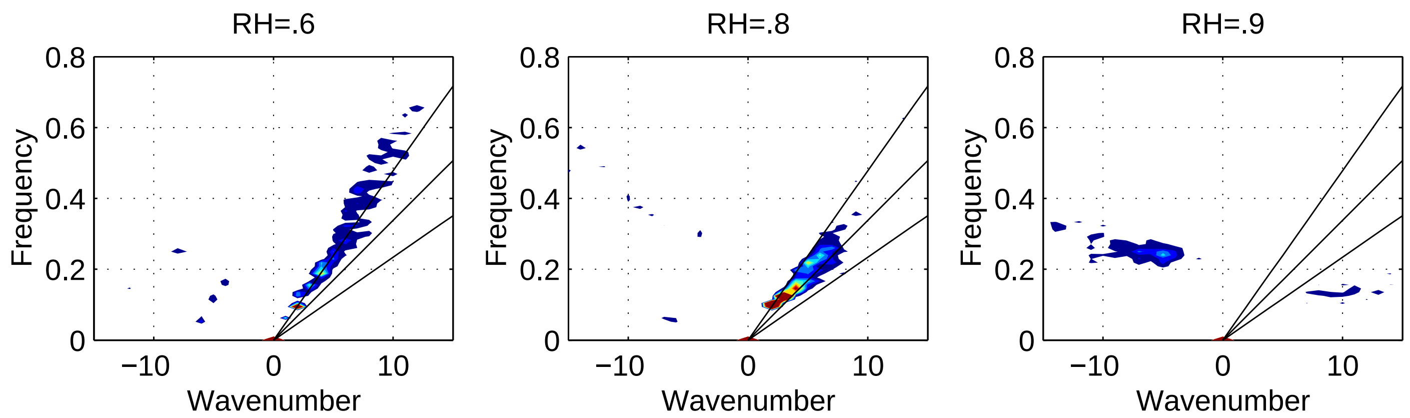
- Kelvin wave composite of P, omega, q for $\tau_c = 2h, 4h$:



- Temperature more out of phase with vertical velocity with longer relaxation time

Simulations With Some Large Scale Precip

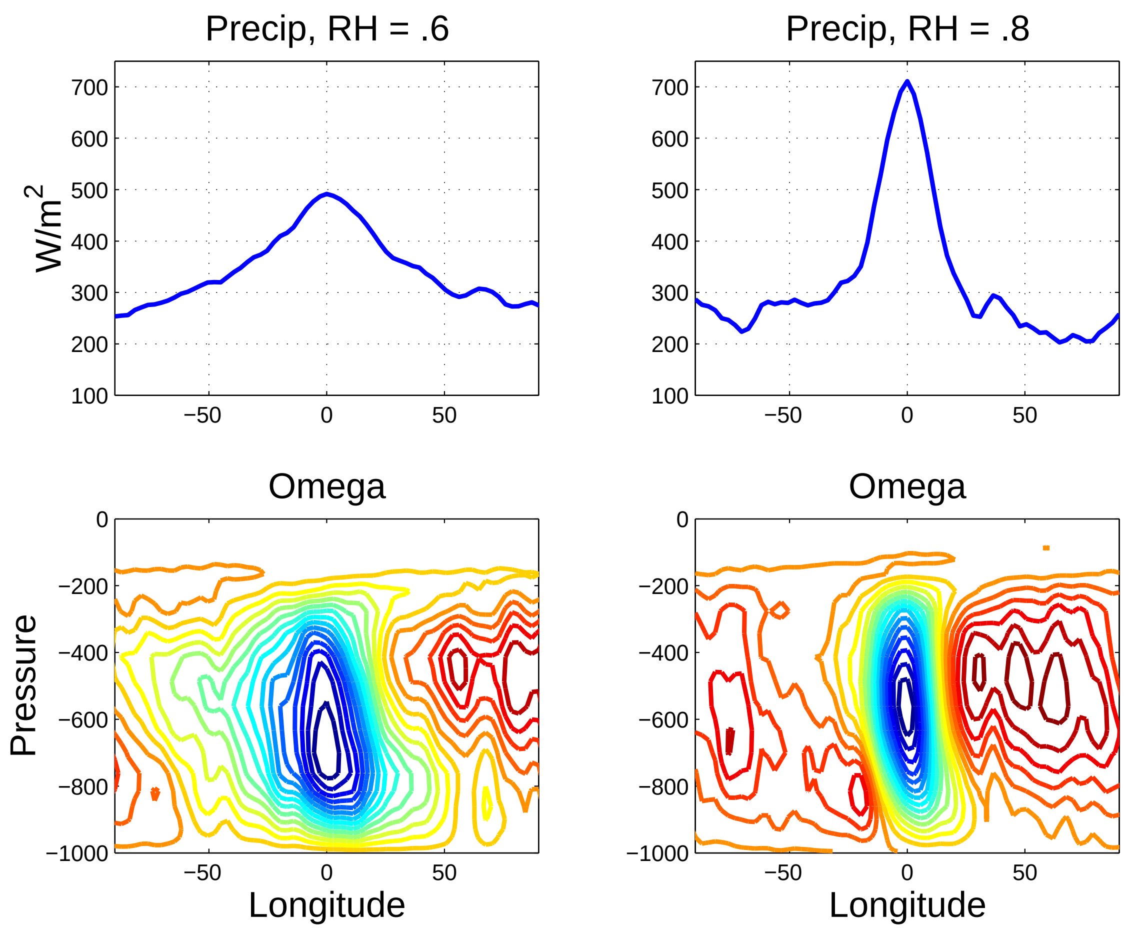
- Next increase RH_{SBM} from the control value to cause some large scale precip to occur (with $\tau = 4h$ here)



- Percent of large scale precip: (0%, 18%, 99%)
- When there's mostly large scale precip, no Kelvin wave
- With some large scale precip, the variability is enhanced, and the propagation speed becomes slower

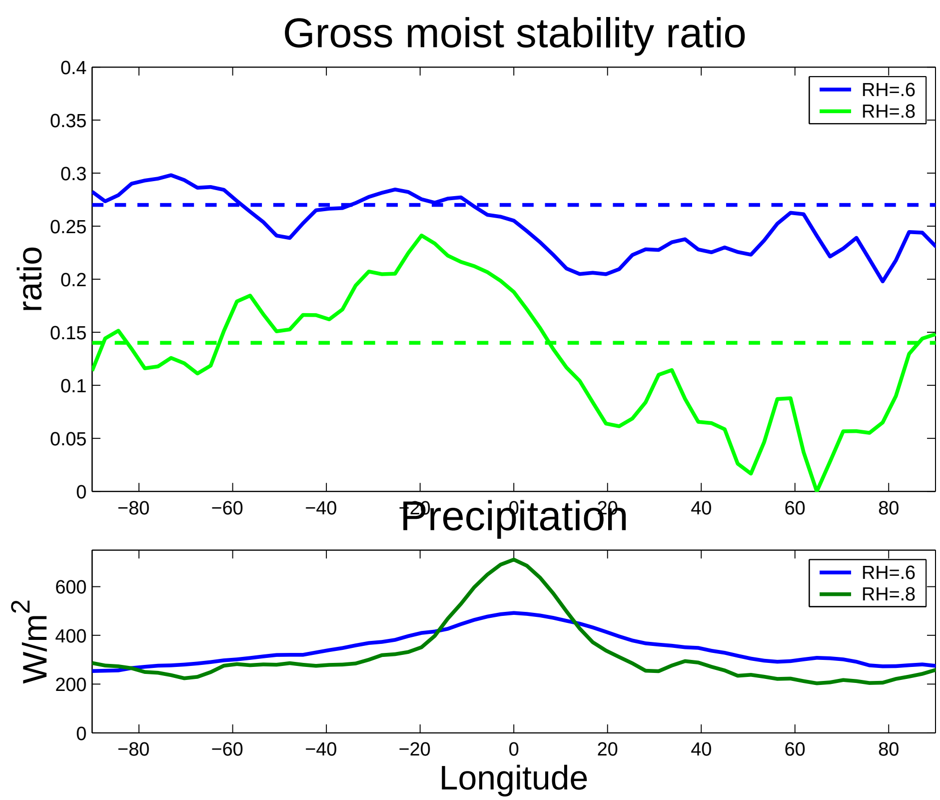
Composites

- Composites of RH=.6 and .8 cases



Gross Moist Stability

- Vertical advection of moist static energy divided by vertical advection of dry static energy:



Conclusions

- Convection can have significant effect on zonally averaged tropical circulation
- Key classification of convection schemes: ability to build up and rapidly release CAPE
- Relative insensitivity to convection scheme parameters, provided LSC precip is not allowed to occur
- LSC precip enhances and slows simulated equatorial Kelvin waves
- Concurrent and future work
  - 2-D Walker cell – within this model and full GCM
  - Quantitative theory for gross moist stability
  - Fully moist Hadley circulation theory