Hadley Circulation Effect on Climate

- Water vapor transport
- Precipitation distribution and the Intertropical Convergence Zone (ITCZ)
- Fraction and types of clouds
- Redistributes heat and momentum
- Surface winds drive ocean currents
Hierarchical Approach

- Models of increasing complexity to build understanding
  - Isolate particular physical effects

- Main focus here:
  - Intermediate complexity moist GCM
  - Isolate the dynamical effect of moisture (latent heating when condensation occurs)

- Interaction between different levels of complexity is key
  - Frequent comparison with more complex models
Outline

- Introduction to Moisture and Moist GCM Description
- Effect of Convection on the Hadley Circulation
- Convectively Coupled Kelvin Waves
- ITCZ Response to Extratropical Forcing
- Hadley Cell Expansion with Global Warming
Introduction to Moisture

- Saturation vapor pressure: how much water vapor can exist in air before condensation
  - Increases rapidly with temperature:
    \[ e_s = e_{s0} \exp \left( -\frac{L}{R_v} (T^{-1} - T_0^{-1}) \right) \]

- Water vapor releases latent heat when it condenses
- Typical tropical lower tropospheric moisture values: 40 K of latent energy
Idealized Moist GCM

- Gray radiative transfer
  - Water vapor, other radiative feedbacks suppressed
  - Radiative fluxes only a function of temperature

- Aquaplanet surface (ocean-covered Earth)
  - Slab mixed layer
  - Zonally symmetric

- Simplified parameterizations of moisture and convection
Model Climatology

- Zonal wind and temperature
Tropical General Circulation Theories

- One traditional view: latent heating “drives” the circulation
  - Would expect increases in strength with more moisture
- In idealized GCM simulations, Hadley cell weakens (by up to a factor of 10) as moisture is increased!
  - Hadley cell weakens in global warming simulations too
- Problems with traditional view:
  - Moisture affects aspects of “basic state,” e.g. static stability
  - Precipitation constrained by energy balance
- Need to consider energy budget
Energy Budget

- Dry static energy budget:

\[ \nabla \cdot (\rho \nu s) = LP + SH - R \]

\[ s = c_p T + gz \] = dry static energy, \( L \) = latent heat constant, \( P \) = precipitation, \( SH \) = sensible heat flux, \( R \) = radiative cooling

- Globally, \( LP \approx R \)
Moisture Budget

- Moisture budget:

\[
\nabla \cdot (\rho \nu q) = E - P
\]

E = evaporation, q = specific humidity
Moist Static Energy Budget

- Moist static energy budget:
  \[ \nabla \cdot (\rho vm) = LE + SH - R \]
  \[ m = c_p T + gz + Lq \]
  \[ = \text{moist static energy} \]

- If no net flux through mixed layer,
  \[ LE + SH + R_s = 0 \]
  \[ \nabla \cdot (\rho vm) = SW - OLR \]
Effect of Convection Scheme

- Instantaneous precipitation, idealized GCM:
Simple Convection Schemes

- Large scale condensation only (LSC only):
  - Only precipitate when gridbox is saturated
- Simplified Betts-Miller scheme (SBM):
  - Relax temperature to moist adiabat (up to level of zero buoyancy)
  - Relax humidity to specified relative humidity w.r.t. adiabat
    \[
    \frac{T - T_{eq}}{T}, \quad \frac{q - q_{eq}}{T}
    \]
  - Make energy correction
  - Perform shallow convection when \( P < 0 \)
Effect of Convection on ITCZ

- Control SBM and LSC only precipitation comparison:
  - Maximum precip increased by 50% in LSC case
  - Total precip stays approximately the same
Effect of Convection on ITCZ

- Control SBM and LSC only midtropospheric streamfunction comparison:

- Hadley circulation fluxes more moisture equatorward in LSC only case

\[ \delta P \approx q \frac{\partial}{\partial y} (\delta v) \]
Varying Convection Scheme Parameters

- Change SBM convective relaxation time from 1 hr to 8 hrs:
Varying Convection Scheme Parameters

- Change SBM convective relaxation time from 1 hr to 16 hrs:
Varying Convection Scheme Parameters

- Explanation:

$$P = \frac{\bar{q} - \bar{q}_{eq}}{\tau}$$

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

- Higher relaxation times have higher relative humidity until LSC occurs
Varying Convection Scheme Parameters

- Can have intermediate regimes as well:
  - Hadley cell can attain any intermediate value
  - Reference profile humidity parameter can change LSC fraction as well
  - Fraction of convective versus large scale condensation is key
Gross Moist Stability

- Introduce the “gross moist stability” (energy transport per unit mass transport):

\[ \Delta m = \frac{\int_0^{p_s} \bar{v} \bar{m} \, dp}{\int_{p_m}^{p_s} \bar{v} \, dp} \]

- Gives efficiency of Hadley cell at transporting energy
Gross Moist Stability

- GMS:

\[ \Delta m = \frac{\int_0^{P_s} \bar{v} \bar{m} \, dp}{\int_{P_m}^{P_s} \bar{v} \, dp} \]

- More large scale precip => smaller GMS
- Can have negative values!
Gross Moist Stability

- Smaller GMS => less efficient Hadley cell
  - More mass flux required to transport same amount of MSE (to keep temperature gradients weak)

- Negative GMS cases:
  - Eddy fluxes increase significantly for these cases (so total transport is poleward)

- What sets GMS in the ITCZ?
Gross Moist Stability

- Typical moist static energy profile:

\[ \Delta m = \frac{\int_0^{P_s} \bar{v} \bar{m} \, dp}{\int_{P_m}^{P_s} \bar{v} \, dp} \]

- Upper tropospheric outflow
- Lower tropospheric inflow
Gross Moist Stability

- Typical moist static energy profile:

\[
\Delta m = \frac{\int_0^{P_s} \bar{v} \bar{m} \, dp}{\int_{P_m}^{P_s} \bar{v} \, dp}
\]

Smaller GMS

Lower outflow

Lower tropospheric inflow
Theory for Gross Moist Stability

- **GMS is larger when:**
  - Convection can easily occur up to high levels
  - The convection scheme is penetrative

- **GMS is smaller when:**
  - Abrupt trigger for convection (e.g., saturation of gridbox required)
  - CAPE built up and rapidly released

- **GMS then influences strength of Hadley circulation**

Frierson 2007a (JAS, in press)
“Hypohydrostatic” Experiments

- Non-hydrostatic model (GFDL ZETAC model)
- Same idealized physics (LSC only)
- Transform equations so that maximum convective growth is at a larger scale (after Kuang, Blossey and Bretherton 2005)
- Examine effect on tropical general circulation

Collaboration with Steve Garner, Olivier Pauluis, Isaac Held, and Geoff Vallis
Depth of Convection

- Convection gets deeper:
  - Vertical velocity reaches 13 km instead of 10 km
  - Wider updrafts

Control

Hypohydrostatic
Effect on Zonally Averaged Circulation

- Has same effect on tropical circulation as adding a convection scheme
  - Deeper convection, larger GMS, weaker Hadley cell

Garner et al 2007 (JAS, in press)
Summary to this point

- Properties of convection scheme can strongly influence Hadley cell
  - “Deep tropical control” on Hadley circulation
- Can increase strength up to 50% by tuning parameters
- Can vary gross moist stability over wide range as well
- Excellent test grounds for theories of tropical general circulation
Kelvin Waves

- Standard two-layer model:
  \[
  \frac{\partial u}{\partial t} = -\frac{\partial T}{\partial x} \quad \frac{\partial T}{\partial t} = -\Delta s \frac{\partial u}{\partial x} + LP
  \]
  Dry equations give wavespeed of \( \sqrt{\Delta s} \)
- But precip is correlated with convergence
  \[
  P = -\Delta q \frac{\partial u}{\partial x}
  \]
  so
  \[
  \frac{\partial T}{\partial t} = -\Delta m \frac{\partial u}{\partial x}
  \]
- Phase speed goes as \( \sqrt{\Delta m} \)
Kelvin Waves in Idealized GCM

- Does GMS reduction lead to slower Kelvin waves?

Wavenumber-frequency spectra (Wheeler-Kiladis):

- GMS = 7 K
- GMS = 4.5 K
- GMS = 2.5 K
- GMS = -2.5 K

Frierson 2007b (JAS, in press)
Equatorial Waves in a Full GCM

- Experiments with SNU atmospheric GCM
  - Run over observed SST’s
  - Simplified Arakawa-Schubert (SAS) convection scheme
  - Vary strength of convective trigger

Collaboration with Jialin Lin, In-Sik Kang, Myong-In Lee, and Daehyun Kim