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

![T85 Simulation](image)

![T170 Simulation](image)
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)

\[
\delta T = -\frac{T - T_{eq}}{\tau_c}, \quad \delta q = -\frac{q - q_{eq}}{\tau_c}
\]

- 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
  \[-\int \delta q dp/g = \int \frac{c_p}{L} \delta T dp/g, \text{ or drying must equal heating}\]
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)

\[
\Delta k = \frac{1}{\Delta p} \int_{p_0}^{p_{LB}} - (c_p \delta T + L \delta q) \, dp
\]

\[
T_{eq2} = T_{eq} - \frac{\Delta k}{c_p}
\]

- 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): “$q_{ref}$”
  - **Lower depth** to where net drying equals zero (Choose $p_{shall}$ such that $0 = \int_{p_0}^{p_{shall}} \left( -\frac{q - q_{ref}}{\tau_c} \right)$): “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” \( \frac{m v}{\bar{v}} \)

- 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

  - **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 \(\Delta s\) 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 \( \tau_c = 2h, RH_{SBM} = 0.6 \)

- Strong, persistent **Kelvin wave** dominates the spectrum

- Speed \( \approx 20 \text{ m/s (40 m equivalent depth)}, \) 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 $\tau_c$ (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:

![Gross moist stability ratio graph]

- Precipitation
- Longitude

RH = 0.6
RH = 0.8
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