An Introduction to Physical Parameterization Techniques Used in Atmospheric Models

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Outline

• Frame broader scientific problem

• Hierarchy of atmospheric modeling strategies

• Scale interaction problem
  – concept of resolvable and unresolvable scales of motion

• Parameterization of physical processes
  – approaches rooted in budgets of conserved variables

• Some science drivers
Top of Atmosphere Radiation Component Fluxes

ERBE Absorbed Solar and Outgoing Longwave Fluxes

Absorbed Solar

OLR

latitude

Wm$^{-2}$
Top of Atmosphere Net Radiation Budget and Implied Meridional Energy Transport

Zhang and Rossow (1997)
Total Versus Ocean Energy Transport

Mean Annual Transport: CCM3

- Required by ocean
- Simulated total
- Observationally derived total

(Global Mean Radiation Budget Zerosed)

$10^{15} \text{ W}$

J. J. Hack/SAMSI Multiscale Workshop 2 February 2003
Principles of Atmospheric Modeling

• Scientific basis for atmospheric simulation
  – rooted in laws of classical mechanics/thermodynamics
  – developed during 18th and 19th centuries (see Thompson, 1978)
  – early mathematical model described by Arrhenius (1896)
  – surface energy balance model

• Two modeling approaches developed over last century
  – based on energy balance requirements
  – dynamical models (e.g., explicit transports)
Atmospheric modeling hierarchy

Understanding has been aided by a hierarchy of approaches

Consider the flux form of thermodynamic energy equation

\[ c_p \frac{\partial T}{\partial t} = -c_p \nabla \cdot (\mathbf{V} T) - c_p \frac{\partial (\omega T)}{\partial p} + c_p \frac{\kappa \omega T}{p} + Q_{\text{rad}} + Q_{\text{conv}} \]  

where \( T \) - temperature; \( \mathbf{V} \) - horizontal wind vector; \( p \) - pressure; \( \omega \) - vertical pressure velocity; \( Q_{\text{rad}} \) and \( Q_{\text{conv}} \) - net radiative and convective heating

- Simple Zero-Dimensional (Energy Balance) Climate Model

- Averaging (1) over horizontal and vertical space dimensions yields

\[ c_p \frac{\partial < \hat{T} >}{\partial t} = < S > - < F > \]

where \( S \) is net absorbed solar radiation and \( F \) is longwave radiation emitted to space

For a long-term stable climate, \( < S > - < F > = 0 \)
Atmospheric modeling hierarchy

- Simple One-Dimensional (Radiative-Convective) Climate Model
  
  Averaging (1) over horizontal space dimensions yields
  
  \[ c_p \frac{\partial \langle T \rangle}{\partial t} = \langle Q_{\text{rad}} \rangle + \langle Q_{\text{conv}} \rangle \]

  where a globally averaged vertical profile of \( T \) can be determined from expressions for \( \langle Q_{\text{rad}} \rangle \) and \( \langle Q_{\text{conv}} \rangle \)

- Higher-order models determined by form of averaging operators
Atmospheric General Circulation Models and Climate Simulation

- Reduced models of the climate system
  - apply “averaging operator” to governing equations

- Atmospheric General Circulation Models (AGCMs)
  - simulate detailed “weather” fluctuations in the fluid system
  - day-to-day solution details are non-deterministic (Lorenz, 1962)
  - apply “averaging operator” to detailed solution sequence
  - utility lies in prediction of statistical properties of the fluid system
    - chronological sequence of intermediate states unimportant
Example of State of the Art Global Model Simulation

Precipitable Water (gray scale) and Precipitation Rate (orange)

Animation courtesy of NCAR SCD Visualization and Enabling Technologies Section
Modeling the Atmospheric General Circulation

• Economic and social relevance
  – agriculture and food production
  – transportation
  – energy
  – water resources
  – policy and planning

• Understanding of climate and global scale dynamics
  – atmospheric predictability/basic fluid dynamics
  – physics/dynamics of phase change
  – radiative transfer (aerosols, chemical constituents, etc.)
  – atmospheric chemistry (trace gas sources/sinks, acid rain, etc.)
  – interactions between the atmosphere and ocean (e.g., El Nino, etc.)
  – solar physics (solar-terrestrial interactions, solar dynamics, etc.)
  – impacts of anthropogenic and other biological activity
Global Heat Flows

107 W m\(^{-2}\): Reflected Solar Radiation
77 W m\(^{-2}\): Reflected by Clouds and Atmosphere
30 W m\(^{-2}\): Reflected by Surface
168 W m\(^{-2}\): Absorbed by Surface
342 W m\(^{-2}\): Incoming Solar Radiation

67 W m\(^{-2}\): Absorbed by Atmosphere
24 W m\(^{-2}\): Thermals
78 W m\(^{-2}\): Evapotranspiration

235 W m\(^{-2}\): Outgoing Longwave Radiation
40 W m\(^{-2}\): Atmospheric Window
324 W m\(^{-2}\): Back Radiation
324 W m\(^{-2}\): Absorbed by Surface
350 W m\(^{-2}\): Surface Radiation
165 W m\(^{-2}\): Emitted by Atmosphere
30 W m\(^{-2}\): Greenhouse Gases

Kiehl and Trenberth, 1997
Climate System Components

Figure 3.1: Schematic illustration of the components of the coupled atmosphere-ocean-ice-land climatic system. The full arrows are examples of external processes, and the open arrows are examples of internal processes in climatic change (from Houghton, 1984).
Atmospheric Energy Transport

Synoptic-scale mechanisms

- hurricanes
- extratropical storms

http://www.earth.nasa.gov

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Clouds are a fundamental component of larger-scale organized energy transport mechanisms

http://www.earth.nasa.gov
Other Energy Budget Impacts From Clouds

http://www.earth.nasa.gov
Other Energy Budget Impacts From Clouds

http://www.earth.nasa.gov
Energy Budget Impacts of Atmospheric Aerosol

A massive sandstorm blowing off the northwest African desert has blanketed hundreds of thousands of square miles of the eastern Atlantic Ocean with a dense cloud of Saharan sand. The massive nature of this particular storm was first seen in this SeaWiFS image acquired on Saturday, 22 February 2003, when it reached over 1,000 miles into the Atlantic. These storms and the rising warm air can lift dust 15,000 feet or so above the African desert and then carry the particles across the Atlantic, many times reaching as far as the Caribbean where they often trigger local weather services to issue air pollution alerts as was recently the case in San Juan, Puerto Rico. Recent studies by the U.S.G.S. (http://www.usgs.gov/afghan_dust) have linked the occurrence of the dust outbreaks in the Caribbean to the increasing frequency and intensity of Saharan Dust events. Additionally, other studies suggest that Saharan Dust may play a role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean (http://www.nicdbworld.org/article.html).

Provided by the SeaWiFS Project, NASA/GSFC and ORSDACE

http://www.earth.nasa.gov
Energy Budget Impacts of Atmospheric Aerosol

http://www.earth.nasa.gov
Scales of Atmospheric Motions

Anthes et al. (1975)
Examples of Global Model Resolution

Typical Climate Application

Next Generation Climate Applications
Global Modeling and Horizontal Resolution

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Capturing Principle Phenomenological Scales of Motion in Global Models

Simulation of Tropical Cyclone Impacts on Climate

Courtesy, Raymond Zehr, NOAA CIRA
High-Resolution Global Modeling

Simulation of Tropical Cyclone Impacts on Climate

~500 km
High-Resolution Global Modeling

Still a Need to Treat Subgrid-Scale Processes

Satellite Image Courtesy, NASA GSFC Scientific Visualization Studio
Meteorological Primitive Equations

• Applicable to wide scale of motions; > 1 hour, > 100 km

\[
\frac{d\vec{V}}{dt} + f k \times \vec{V} + \nabla \phi = \mathbf{F},
\]
(horizontal momentum)

\[
\frac{dT}{dt} - \kappa \frac{\vec{V} \cdot \vec{V}}{p} = Q/c_p,
\]
(thermodynamic energy)

\[
\nabla \cdot \vec{V} + \frac{\partial \omega}{\partial p} = 0,
\]
(mass continuity)

\[
\frac{\partial \phi}{\partial p} + \frac{R \vec{V}}{p} = 0,
\]
(hydrostatic equilibrium)

\[
\frac{dq}{dt} = S_q.
\]
(water vapor mass continuity)

Harmless looking terms \( \mathbf{F}, Q, \) and \( S_q \) \( \Rightarrow \) “physics”
Numerical Approximations

- Horizontal representations
  - finite difference
    simple to implement
derivatives evaluated as differences
local technique

- spectral transform
derivatives evaluated exactly
improved accuracy for similar number of degrees of freedom
non-local technique (global basis functions)

- finite element
local basis functions
requires inversion of large sparse matrix

- Vertical representation
  - finite difference
    most convenient for representation of column physics

- finite element
  improved accuracy ?

- Temporal representation
  - explicit
    simple to implement
severe linear computational stability constraint

  - semi-implicit
    treat fast propagating gravity–inertia waves implicitly
slower Rossby motions explicitly

  - fully implicit
    prohibitively expensive inversion procedure
Global Climate Model Physics

Terms $F$, $Q$, and $S_q$ represent physical processes

- **Equations of motion, $F$**
  - turbulent transport, generation, and dissipation of momentum

- **Thermodynamic energy equation, $Q$**
  - convective-scale transport of heat
  - convective-scale sources/sinks of heat (phase change)
  - radiative sources/sinks of heat

- **Water vapor mass continuity equation**
  - convective-scale transport of water substance
  - convective-scale water sources/sinks (phase change)
Physical Parameterization

To close the governing equations, it is necessary to incorporate the effects of physical processes that occur on scales below the numerical truncation limit

- Physical parameterization
  - express unresolved physical processes in terms of resolved processes
  - generally empirical techniques

- Examples of parameterized physics
  - dry and moist convection
  - cloud amount/cloud optical properties
  - radiative transfer
  - planetary boundary layer transports
  - surface energy exchanges
  - horizontal and vertical dissipation processes
  - ...
Cumulus Convection

*If the atmosphere is buoyantly unstable to small vertical displacements, it can be said to be convectively unstable*

- Convective overturning
  - with or without phase change
  - space scale $\sim 1-10$ km; time scale $\sim 1$ hour

- Moist convection
  - most common and energetically important
  - affects the general circulation on wide range of time scales
  - provides fundamental coupling of dynamics and hydrological cycle
Diagnostic Budget Studies (heat & moisture)

Thermodynamic equation (in terms of dry static energy)

$$\frac{\partial \overline{s}}{\partial t} + \nabla \cdot \mathbf{V} \overline{s} + \frac{\partial \overline{\omega s}}{\partial p} = L(C - \overline{E}) + Q_R$$

Water mass continuity equation

$$\frac{\partial \overline{q}}{\partial t} + \nabla \cdot \mathbf{V} \overline{q} + \frac{\partial \overline{\omega q}}{\partial p} = - (C - \overline{E})$$

where horizontal area averages are denoted as $\overline{()}$. These budget equations can be rearranged to give
Diagnostic Budget Studies (heat & moisture)

Thermodynamic equation

\[
Q_1 = \frac{\partial \bar{s}}{\partial t} + \nabla \cdot \overline{V \bar{s}} + \frac{\partial \omega \bar{s}}{\partial p} = -\frac{\partial}{\partial p} \left( \overline{\omega' s'_l} \right) + L(C - E) + Q_R
\]

Water mass continuity equation

\[
Q_2 = -L \left( \frac{\partial q}{\partial t} + \nabla \cdot \overline{V q} + \frac{\partial \omega q}{\partial p} \right) = L \frac{\partial}{\partial p} \left( \overline{\omega' (q' + \ell')} \right) + L(C - E)
\]

where deviations from the area averages are denoted with primes, and small-scale eddies in the momentum field are assumed to be uncorrelated with \( s' \) and \( q' \).
Diagnostic Budget Studies (heat & moisture)

\[ Q_1 = \frac{\partial \bar{s}}{\partial t} + \nabla \cdot \bar{V} \bar{s} + \frac{\partial \omega \bar{s}}{\partial p} = -\frac{\partial}{\partial p} \left( \omega' s'_l \right) + L(C - E) + Q_R \]

\[ Q_2 = -L \left( \frac{\partial q}{\partial t} + \nabla \cdot \bar{V} q + \frac{\partial \omega q}{\partial p} \right) = L \frac{\partial}{\partial p} \left( \omega' (q' + \ell') \right) + L(C - E) \]

\( Q_1 \) is called the apparent heat source, while \( Q_2 \) is called the apparent moisture sink (cf Yanai et al., 1973), and represent the unresolvable collective diabatic effects of moist convection and radiation. Note that the structure of this forcing can be derived from observations of the large-scale flow field.
Diagnostic Budget Studies (heat & moisture)

These budget relationships can be arranged to give the relationship

$$Q_1 - Q_2 - Q_R = -\frac{\partial}{\partial p} \left( \omega' (s' + L(q' + \ell')) \right) = -\frac{\partial}{\partial p} \left( \omega'h' \right)$$

where $\omega'h'$ is a measure of the vertical transport of total heat, and an overall measure of cumulus convection.

The heat budget equation can be integrated over the depth of the atmospheric column to give

$$\frac{1}{g} \int_{p_T}^{p^*} (Q_1 - Q_R) dp = LP_0 + S_0$$

while the vertically integrated moisture budget equation gives

$$\frac{1}{g} \int_{p_T}^{p^*} Q_2 dp = L(P_0 - E_0)$$

where $P_0$, $S_0$, and $E_0$ are surface values for precipitation, sensible heat flux, and latent heat flux.
Diagnostic Budget Studies (heat & moisture)

Determination of Bulk Properties of Tropical Cloud Clusters from Large-Scale Heat and Moisture Budgets

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Fig. 5. Island stations in the Marshall Islands region. The pentagon connecting the five stations indicated by large circles was used for the large-scale budget computations.
Diagnostic Budget Studies (heat & moisture)

Fig. 10. The mean apparent heat source $Q_1$ (solid) and moisture sink $Q_2$ (dashed). On the left is the radiational heating rate given by Dopplick (1970).

Fig. 11. The derived vertical eddy heat flux.

$F = -\frac{1}{2} \frac{h}{\rho} \frac{d}{dx} \left[ (Q_1 - Q_2 - Q_r) dp \right]_x$
Large scale observations can be used to determine $Q_1$ and $Q_2$.

Observational Studies of Tropical Convective Systems:

Fig. 6.23. Variation with height of apparent sensible heat source $Q_1$ and apparent latent heat sink $Q_2$; (a) mean radiational heating $Q_R$ and (b) vertical eddy flux of moist static energy for GATE B-scale area and west Pacific triangle. [From Thompson et al. (1979).]
Cumulus Parameterization Example A

If

\[ q \geq q^* \]

and

\[ \Gamma \geq \Gamma_m = \Gamma_d / (1 + \gamma) \]

where \( \gamma \equiv \left( \frac{L}{c_p} \right) \left( \frac{\partial q^*}{\partial T} \right) \), iteratively solve the system

\[
\begin{align*}
\frac{\partial}{\partial p} \left[ h(T + \delta T, q + \delta q, p) \right] = 0 \\
q + \delta q = q^*(T + \delta T, p) \\
\frac{1}{g} \int_{p_B}^{p_T} (c_p \delta T + L \delta q) dp = 0
\end{align*}
\]

where \( h \equiv c_p T + L q + gz \) is the moist static energy (\( \sim \theta_e \))

No Process Model
Process Models and Parameterization
Parameterization of Cumulus Convection

To extract the details of how the observed $Q_1$ and $Q_2$ forcing is maintained by moist convection, it is necessary to use an abstraction for the collective behavior of convective motions.

- **Convective mass flux**
  - how much overturning is associated with convective activity

- **Breakdown of total diabatic forcing**
  - where is the water condensing and/or raining out
  - what role do the convective eddy transports play
Parameterization of Cumulus Convection

Assumptions associated with the introduction of a cloud model

- Cumulus clouds in statistical equilibrium with large-scale
  - exploit idealized characterization for cloud elements
  - mass, energy, and water budgets can be derived

\[
\frac{\partial \eta(p, \hat{p})}{\partial p} = - \lambda(\hat{p}) \eta(p, \hat{p})
\]

\[
\frac{\partial}{\partial p} \left[ \eta(p, \hat{p}) h_c(p, \hat{p}) \right] = - \lambda(\hat{p}) \eta(p, \hat{p}) \overline{h}(p)
\]

\[
\frac{\partial}{\partial p} \left\{ \eta(p, \hat{p}) [q_c(p, \hat{p}) + \ell(p, \hat{p})] \right\} = - \lambda(\hat{p}) \eta(p, \hat{p}) \overline{q}(p) + \eta(p, \hat{p}) c_o(\hat{p}) \ell(p, \hat{p})
\]

Dry Mass

Energy

Water Mass
Parameterization of Cumulus Convection

**Closure assumption:** Incorporate process regulating convection

- **Neutral or “specified” thermodynamic stratification**
  - moist convective adjustment
    - Manabe et al. (1965), Kurihara (1973)
  - thermodynamic adjustment schemes
    - Betts (1986), Emanuel (1991)

- **Moisture convergence**
  - Kuo (1965; 1974), Anthes (1977)

- **Simple buoyancy closures**
  - Gregory and Roundtree (1990), Kreitzberg-Perkey (1976), ...

- **Quasi-equilibrium**
  - Arakawa and Schubert (1974)
SIMPLIFIED LARGE-SCALE: CONVEXTIVE INTERACTION

CONTROL BY LARGE-SCALE
OF CONVEXTIVE SCALE

Vertical Shear, Vapor Stratification, Vorticity, Others?
Destabilization
Low Level Mass Convergence

Large-Scale Model

LARGE-SCALE PROCESSES

FEEDBACK FROM CONVEXTIVE SCALE
TO LARGE SCALE

Condensation Rain Evaporation
Influence of Clouds on Radiation Fields
Convective Scale Mass, Energy and Water Transports
Radiative Changes in $T(p)$
Convective Changes in $T(p)q(p)$

Modified Large-Scale Thermodynamic Fields
Convective Scale Momentum Generation and Transports
Convective Changes in $\omega_h(p)$

Modified Large-Scale Wind Fields
Cumulus Parameterization Example B

\[ \frac{\partial h}{\partial t} + \nabla \cdot (\hat{v} h) + \frac{\partial h}{\partial \tau} = \frac{\partial}{\partial \tau} \left[ F_{p,\tau} - L \right] + LR + Q_R \]

\[ \frac{\partial \bar{q}}{\partial t} + \nabla \cdot (\bar{v} \bar{q}) + \frac{\partial \bar{q}}{\partial \tau} = \frac{\partial}{\partial \tau} \left[ F_{p,\tau} \right] \]

\[ \frac{\partial \tilde{h}}{\partial t} + \nabla \cdot (\tilde{v} \tilde{h}) = \frac{\partial}{\partial \tau} \left[ F_{p,\tau} \right] \]

\[ \frac{\partial \tilde{q}}{\partial t} + \nabla \cdot (\tilde{v} \tilde{q}) = \frac{\partial}{\partial \tau} \left[ F_{p,\tau} \right] \]

\[ \frac{\partial \tilde{M}}{\partial t} + \nabla \cdot (\tilde{v} \tilde{M}) = \frac{\theta}{\tilde{p}} \left[ (F_p)_S + \frac{k \Delta T_{\text{air}}}{\Delta \tilde{h}} \right] + \left( Q_R \right)_M \]

\[ \frac{\partial \bar{M}}{\partial t} + \nabla \cdot (\bar{v} \bar{M}) = \frac{\theta}{\bar{p}} \left[ (F_p)_S + \frac{k \Delta T_{\text{air}}}{\Delta \bar{h}} \right] \]

\[ \frac{\partial \tilde{p}}{\partial t} + \nabla \cdot (\tilde{v} \tilde{p}) = \tilde{g} M_{\tilde{p}} - \frac{\theta}{\tilde{h}} \left( F_{p,\tau} \right)_S \]

\[ \frac{\partial \bar{p}}{\partial t} + \nabla \cdot (\bar{v} \bar{p}) = \bar{g} M_{\bar{p}} - \frac{\theta}{\bar{h}} \left( F_{p,\tau} \right)_S \]

**STATIC CONTROL**

\[ \frac{\partial \tilde{h}}{\partial p} = -\lambda(\tilde{h}) \psi(\tilde{h}) \]

\[ \frac{\partial}{\partial p} \left[ \psi(\tilde{h}) \lambda(\tilde{h}) \right] = -\lambda(\tilde{h}) \psi(\tilde{h}) \lambda(\tilde{h}) \]

\[ \left\{ \begin{array}{l}
\psi(\tilde{h}) = \tilde{q}^*(\tilde{p}) + \frac{\gamma(p)}{1+\gamma(p)} \left[ h_0(p,\tilde{p}) - \tilde{q}^*(\tilde{p}) \right] \quad \text{if} \quad p < \tilde{p}^c \\
\psi(\tilde{h}) = 1 \quad \text{if} \quad p > \tilde{p}^c \\
\psi(\tilde{h}) = 0 \quad \text{if} \quad p = \tilde{p}^c \\
\end{array} \right. \]

**DYNAMIC CONTROL**

\[ \text{minimize } \left\{ \int_{\tilde{p}} \frac{\partial \tilde{h}}{\partial t} \frac{\partial M_{\tilde{p}}}{\partial \tilde{p}} \, d\tilde{p} \right\} \]

subject to

\[ \frac{\partial \tilde{h}}{\partial t} + \int_{\tilde{p}} \left[ K(\tilde{p},\tilde{p}') m_{\tilde{p}}(\tilde{p},\tilde{p}') \right] d\tilde{p}' + F_{L,\tau}(\tilde{p}) \]

\[ m_{\tilde{p}}(\tilde{p}) \geq 0, \quad \frac{\partial \tilde{h}}{\partial t} \leq 0 \]

**FEEDBACK**

\[ F_{p,\tau}(\tilde{p}) = \int_{\tilde{p}}^{\tilde{p}_{\tau}} \tilde{q}(\tilde{p}) \right( \tilde{h}(p,\tilde{p}) - \tilde{q}^*(\tilde{p}) \right) m_{\tilde{p}}(\tilde{p},\tilde{p}') \, d\tilde{p}' \]

\[ F_{\tau,\tau}(\tilde{p}) = \int_{\tilde{p}}^{\tilde{p}_{\tau}} \tilde{j}(\tilde{p}) \right( \tilde{h}(p,\tilde{p}) - \tilde{j}(\tilde{p}) \right) m_{\tilde{p}}(\tilde{p},\tilde{p}') \, d\tilde{p}' \]

\[ R(\tilde{p}) = \int_{\tilde{p}}^{\tilde{p}_{\tau}} \tilde{j}(\tilde{p}) \right( \tilde{h}(p,\tilde{p}) - \tilde{j}(\tilde{p}) \right) m_{\tilde{p}}(\tilde{p},\tilde{p}') \, d\tilde{p}' \]

\[ M_{\tilde{p}} = \int_{\tilde{p}}^{\tilde{p}_{\tau}} m_{\tilde{p}}(\tilde{p},\tilde{p}') \, d\tilde{p}' \]

**CUMULUS CLOUD ENSEMBLE**

Solution of the Static Control Yields

\[ \psi(\tilde{p},\tilde{p}) \]

\[ \lambda(\tilde{p},\tilde{p}) \]

\[ \gamma(\tilde{p},\tilde{p}) \]

\[ h_0(\tilde{p},\tilde{p}) \]

\[ q_0(\tilde{p},\tilde{p}) \]

\[ \lambda(\tilde{p}) \]

**Hack et al. (1984)**
Does Process Formulation Matter?

- Changes to the parameterization of deep convection
  - incorporation of precipitation evaporation mechanism

Simulated response to evaporation of falling condensate
Diabatic Forcing of the Deep Tropics

Total diabatic forcing (sum of components) is almost identical
Heat and Moisture Budget Equations

\[
\frac{\partial s}{\partial t} = -\nabla \cdot \mathbf{V} - \frac{\partial \bar{\omega}}{\partial p} - \frac{\partial}{\partial p} (\bar{\omega}'s_i') + LR + c_p Q_R
\]

\[
\frac{\partial q}{\partial t} = -\nabla \cdot \mathbf{V} - \frac{\partial \bar{\omega}q}{\partial p} - \frac{\partial}{\partial p} (\bar{\omega}'(q' + l')) - R
\]

But, the moisture budget is closely coupled to the total diabatic heating!
Diabatic Forcing of the Deep Tropics

Convective component change results in significant moisture budget change
Examples of Science Drivers

• Climate Sensitivity: the final frontier
  – what is the real climate sensitivity to anthropogenic forcing?
    – Clouds!!

• Separating the signal from the noise
  – non-deterministic system with large natural variability
IPCC 1995: Climate Model Projections

![Graph showing global temperature change vs. year from start of experiment]
CMIP 2001: Temperature and Precipitation

Global+Annual Means (1% / yr CO₂ - control)

Covey et al. (2001)
Some Fundamental Physical Sources of Uncertainty

IPCC Working Group I (2001)
Parameterization of Clouds

Another major source of model projection uncertainty

Fig. 1. Clear-sky and global sensitivity parameters (K m² W⁻¹) for the 19 GCMs. The model numbers correspond to the ordering in Table 9.

Cess et al. (1990)
Parameterization of Clouds

*Cloud amount (fraction) as simulated by 25 atmospheric GCMs*

Weare and Mokhov (1995)
Parameterization of Clouds

Seasonal cycle of cloud fraction as simulated by 25 AGCMs

Weare and Mokhov (1995)
Evaluating parameterization/simulation quality

- Continue to compare long term mean climatology
  - average mass, energy, and momentum balances
  - tells you where the physical approximations take you
    - but you don’t necessarily know how you get there!

- Must also consider dominant modes of variability
  - provides the opportunity to evaluate climate sensitivity
    - response of the climate system to a specific forcing factor
  - evaluate modeled response on a hierarchy of time scales
  - exploit natural forcing factors to test model response
    - diurnal and seasonal cycles, El Niño Southern Oscillation, intraseasonal variability, solar variability, volcanic aerosol loading

- High-resolution, limited area, process modeling
  - explicitly resolve additional scales of motion (several more orders of magnitude)
  - proper definition of experimental framework of central importance
    - solutions appear to be strongly constrained by boundary conditions
El Niño Composite

Fig. 18.2 Sea surface temperature anomalies (°C) for a composite El Niño (Rasmusson and Carpenter, 1982), constructed by averaging over 6 events (1951, 1953, 1957, 1965, 1969, 1972; cf. Fig. 18.1). Shown are maps for May and December of the El Niño year and April of the following year.
Testing AGCM Sensitivity

Pacific SST Anomalies and ENSO

SST Anomalies (10S-10N)

Hack (1998)
Testing AGCM Sensitivity

OLR Anomalies and ENSO

Hack (1998)
Improving simulation quality

- Examine role of parameterization techniques on transient behavior
  - oversimplifications playing a role in inadequate variability?
  - Inadequate process formulation; deficiencies in closure assumptions, ...?

- Understand role of scale interaction on transient and mean state

**ITCZ behavior as function of horizontal resolution**

Fig. 6. January average, zonal average over Atlantic (30°W to 7.5°E) pressure vertical velocity ($\omega$) for R15, T21, T31, T42, T63, and T106 simulations. Contour interval is 20 mb day$^{-1}$, negative (upward) regions *stippled*

Summary

- Global Climate Modeling
  - complex and evolving scientific problem
  - parameterization of physical processes pacing progress
  - observational limitations pacing process understanding

- Parameterization of physical processes
  - opportunities to explore alternative formulations
    - exploit higher-order statistical relationships in physical process formulations?
    - stochastic strategies
  - exploration of scale interactions using modeling and observation
    - high-resolution process modeling to supplement observations
      - e.g., identify optimal truncation strategies for capturing major scale interactions
    - provide better characterization of statistical relationships between resolved and unresolved scales
The End