Atmospheric Modeling I: Physics in the Community Atmosphere Model (CAM)

CESM Tutorial
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Outline

- **Physical processes** in an atmosphere GCM
- Distinguishing GCMs from other models (scales)
- Concept of ‘Parameterization’
- Physics representations (CESM)
  - **Clouds** (different types), cloud fraction and microphysics
  - Radiation
  - Boundary layers, surface fluxes and gravity waves
- **Process interactions**
- Model **complexity, sensitivity** and **climate feedbacks**
Community Atmosphere Model (CAM)
Atmosphere Model Working Group (AMWG)

http://www.cesm.ucar.edu/management
Scales of Atmospheric Processes

Determines the formulation of the model

Resolved Scales

Climate Models
Forecast models
Future Climate Models
Cloud/Mesoscale/Turbulence Models

Cloud Drops Microphysics

1 week
1,000,000 s
1 day
10,000 s
100 s
1 m
1 km
10 km
100 km
1000 km
10,000 km
100,000 km
Circumference of earth (40,000 km)

1 sec
1 m
10 m
100 m
1000 m
10000 m
100000 m
1000000 m
10000000 m
100000000 m
1000000000 m
10000000000 m
100000000000 m
1000000000000 m
10000000000000 m
100000000000000 m
1000000000000000 m
10000000000000000 m
100000000000000000 m
1000000000000000000 m
10000000000000000000 m
Hydrostatic Primitive Equations

Where do we put the physics?

Horizontal scales $\gg$ vertical scales

Vertical acceleration $\ll$ gravity

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

\[
\frac{d\bar{T}}{dt} - \kappa \bar{T} \omega /p = \frac{Q}{c_p}, \quad \mathbf{F}_T \quad \text{(thermodynamic energy)}
\]

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

\[\partial \bar{\phi} / \partial p + R \bar{T} / p = 0, \quad \text{(hydrostatic equilibrium)}\]

\[
\frac{d\bar{q}}{dt} = S_q, \quad \mathbf{F}_{QV}, \mathbf{F}_{QL}, \mathbf{F}_{QI} \quad \text{(water vapor mass continuity)}
\]

Harmless looking terms $\mathbf{F}$, $Q$, and $S_q \implies \text{“physics”}$
What is a ‘Parameterization’?

- Usually based on
  - Basic physics (conservation laws of thermodynamics)
  - Empirical formulations from observations
- In many cases: no explicit formulation based on first principles is possible at the level of detail desired. Why?
  - Non-linearities & interactions at ‘sub-grid’ scale
  - Often coupled with observational uncertainty
  - Insufficient information in the grid-scale parameters

Vertical eddy transport of χ

\[ w'\chi' = -K_x \frac{\partial \chi}{\partial z} \]

- ‘Diffusivity’
- Resolved ‘grid-scale’
- Unresolved ‘sub-grid’
Community Atmosphere Model

Representing the key atmospheric processes in CAM5
Clouds
Multiple Categories

- **Stratiform (large-scale) clouds**
  - Responds to large-scale saturation fraction, RH (parameterized)
  - Coupled to presence of condensate (microphysics, advection)

- **Shallow convection clouds**
  - Symmetric turbulence in lower troposphere
  - Non precipitating (mostly)
  - Responds to surface forcing

- **Deep convection clouds**
  - Asymmetric turbulence
  - Penetrating convection (surface -> tropopause)
  - Precipitating
  - Responds to surface forcing and conditional instability
Stratiform Clouds (macrophysics)

Sub-Grid Humidity and Clouds

- Liquid clouds form when RH = 100% \((q=q_{sat})\)
- But if there is variation in RH in space, some clouds will form before mean RH = 100%
- \(RH_{crit}\) determines cloud fraction \(> 0\); Value is lower over land due to higher humidity variance

![Assumed Cumulative Distribution function of Humidity in a grid box with sub-grid variation](image-url)
Shallow and Deep Convection
Exploiting conservation properties

Common properties
Parameterize consequences of vertical displacements of air parcels

**Unsaturated:** Parcels follow a dry adiabat (conserve dry static energy)

**Saturated:** Parcels follow a moist adiabat (conserve moist static energy)

**Shallow (10s-100s m)**
Parcels remain stable (buoyancy<0)
Shallow cooling mainly
Some latent heating and precipitation
Generally a source of water vapor
Small cloud radius large entrainment

**Deep (100s m-10s km)**
Parcels become unstable (buoyancy>0)
Deep heating
Latent heating and precipitation
Generally a sink of water vapor
Large cloud radius small entrainment
Shallow and Deep Convection Closure: How much and when?

**Shallow**
- Local conditional instability **CAM4**
- Convective inhibition and turbulent kinetic energy (TKE) **CAM5**

**Deep**
- Convective Available Potential Energy (CAPE) **CAM4 and CAM5**
  - $\text{CAPE} > \text{CAPE}_{\text{trigger}}$
  - Timescale = 1 hour

Shallow and deep convection and stratiform cloud fractions combined for radiation
Cloud Microphysics

- **Condensed phase water processes**
  - Properties of condensed species (=liquid, ice)
    - size distributions, shapes
  - Distribution/transformation of condensed species
    - Precipitation, phase conversion, sedimentation

- **Important for other processes:**
  - Aerosol scavenging
  - Radiation

- **In CAM = ‘stratiform’ cloud microphysics**
  - Convective microphysics simplified
  - Formulations currently being implemented into convection
CAM5 Microphysics

$q = \text{mixing ratio}
N = \text{number concentration}$

Morrison & Gettelman 2008

Aerosol (CCN Number)

$q, N$
Cloud Droplets (Prognostic)

Convective Detrainment

$q, N$
Cloud Ice (Prognostic)

Aerosol (IN Number)

$q$
Water Vapor (Prognostic)

Vapor Dep Freezing

$q, N$
Rain (Diagnostic)

$q, N$
Snow (Diagnostic)

Activation

Autoconversion

Accretion

Evap/Cond
Dep/Sub

Evaporation
Sublimation

Nucleation/Freezing

Autoconversion (Au)

Accretion (Ac)

$Au \sim \frac{q_c}{N_c}$

$Ac \sim q_r q_c$

Melting/Freezing

Sedimentation
The Earth’s Energy Budget

Global Energy Flows W m\(^{-2}\)

<table>
<thead>
<tr>
<th>Gas</th>
<th>GW Absorption (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>1</td>
</tr>
<tr>
<td>O(_2)</td>
<td>2</td>
</tr>
<tr>
<td>O(_3)</td>
<td>14</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>43</td>
</tr>
</tbody>
</table>

Thanks to: Bill Collins, Berkeley & LBL
Goals of GCM Radiation Codes

- Accurately represent the input and output of energy in the climate system and how it moves around
  - Solar Energy
  - Thermal Emission
  - Gases
  - Condensed species: Clouds & Aerosols
Solar Radiation Spectrum

- Sunlight at Top of the Atmosphere (TOA)
- 5250°C Blackbody Spectrum
- Radiation at Sea Level

Input at TOA, Radiation at surface

IR absorption

1000nm = 1μm
k-distribution Band Models

- Line-by-line calculations
  - Very expensive/slow, accurate

- k-distribution band model, sort absorption coefficients by magnitude
  - Cheaper/fast, less accurate
Planetary Boundary Layer (PBL)

Regime dependent representations

- Vital for near-surface environment (humidity, temperature, chemistry)
- Exploit **thermodynamic conservation** (liquid virtual potential temperature $\theta_{vl}$)
- **Conserved** for rapidly well mixed PBL
- **Not conserved** for stable PBL
- Critical determinant is the presence of turbulence
- **Richardson number** $Ri = \frac{g\beta}{(\partial u / \partial z)^2}$
- $<<1$, flow becomes turbulent

- **CAM4**: Gradient $Ri$ # + non-local transport (Holtslag and Boville, 1993)
- **CAM5**: TKE-based Moist turbulence (Park and Bretherton, 2009)
Gravity Waves and Mountain Stresses
Sub-grid scale dynamical forcings

- **Gravity Wave Drag**
  - Determines flow effect of upward propagating (sub-grid scale) gravity waves that break and dump momentum
  - Generated by surface orography (mountains) and deep convection
  - Important for closing off jet cores in the upper troposphere (strat/mesosphere)

- **Turbulent mountain stress**
  - Local near-surface stress on flow
  - Roughness length < scales < grid-scale
  - Impacts mid/high-latitude flow (CAM5)

- More difficult to parameterize than thermodynamic impacts (conservation?)
Surface Exchange

• Surface fluxes (bulk formulations)

\[ \tau_x = -\rho_1 (u'w') = -\rho_1 u_*^2 \left( \frac{u_1}{V_a} \right) = \rho_1 \frac{u_s - u_1}{r_{am}} \]

\[ \tau_y = -\rho_1 (v'w') = -\rho_1 u_*^2 \left( \frac{v_1}{V_a} \right) = \rho_1 \frac{u_s - v_1}{r_{am}} \]

Stresses

Specific Heat

\[ H = \rho_1 c_p (w'\theta') = -\rho_1 c_p u_* \theta_* = \rho_1 c_p \frac{\theta_s - \theta_1}{r_{ah}} \]

Latent heat (evaporation)

\[ E = \rho_1 (w'q') = -\rho_1 u_* q_* = \rho_1 \frac{q_s - q_1}{r_{aw}} \]

• Resistances \( r_{ax} \) based on
  – Monin-Obhukov similarity theory
Parameterization Interactions

Direct and Indirect Process Communication

- Cloud Processes & Radiation
  - Feedbacks
- Boundary Layer / Cumulus & Dynamics
- Precipitation & Scavenging
  - Chemical (gas phase) constituents
  - Aerosols (condensed phase constituents)
- Microphysics and Aerosols
- Physics and surface components (ice, land, ocean)
- Resolved scales and unresolved scales
Clouds in GCMs
State of the Art from CMIP3

Outgoing Long-wave Radiation
(Annual, 1990-1999)

TOA Outgoing Long Wave Radiation (W/m²)

CMIP3 Models
(~20 models)
Clouds in GCMs
State of the Art from CMIP3

Total Cloud Fraction
(Annual, 1990-1999)

CMIP3 Models
(~20 models)
Structural Clouds in GCMs
State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)

CMIP3 Models
(~20 models)
Future Clouds in GCMs
State of the Art from CMIP3 – response to climate change

Total Cloud Fraction Change
Climate Sensitivity

What happens to clouds when we double CO₂?

GFDL Model +4.2K

NCAR Model +1.8K

Change in low cloud amount (%)

- Significant range in **low-cloud sensitivity** (low and high end of models)
- Cloud regimens are largely **oceanic stratocumulus** (difficult to model)
- Implied temperatures change is due to (higher/lower) solar radiation reaching the ground because of **clouds feedbacks**.
Community Atmosphere Model

Representing the key atmospheric processes in CAM5
Community Atmosphere Model

Representing the key atmospheric processes in CAM6

- Aerosols
  - M1
  - M2
  - M3
  - M4
- Radiation
  - SW
  - LW
- Emission
  - Abs/Emis/Ref
- Albedo
  - σT^4
- Emission Deposition
- Detrainment
- Surface Fluxes
  - F_{UV}
  - F_{LH}
  - F_{SH}
- MO stability
- Gravity Wave Drag
- Wind
- Turbulent Mountain Stress
- Dynamics
  - Spectral Element

CLUBB
MG2
ZM

PBL
Surface Fluxes
Deep Convection
Detrainment
CAPE
CLUBB: Cloud Layers Unified By Binormals

- Unifies moist and dry turbulence (except deep convection)
- Unifies microphysics
- High order closures (1 third order, 9 second order)
- Use two Gaussians to described the sub-grid multivariate PDF: $P = P(w, q_t, \theta_L)$

Model physics: The future

1. How to operate in varying grid scale environments

New and more complex processes

Cloud super-parameterization

High Resolution, Regional grid refinement and scale-aware physics
Summary

• GCMs physics = unresolved processes = parameterization

• Parameterization (CESM) = approximating reality
  – Starts from and maintains physical constraints
  – Tries to represent effects of smaller ‘sub-grid’ scales

• Fundamental constraints, mass & energy conservation

• Clouds are fiendishly hard: lots of scales, lots of phase changes, lots of variability

• Clouds are coupled to radiation (also hard) = biggest uncertainties (in future climate); largest dependencies

• CESM physics increasingly complex and comprehensive

• Future parameterizations aim to be process scale-aware and model grid-scale independent
Questions?