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

Representing the key atmospheric processes in CAM5

- Turbulent Mountain Stress
- Wind
- UV, LH, SH
- Wind + Gravity Wave Drag
- Albedo
- SW, LW, Abs/Emis/Ref
- Aerosols
- Activation
- SWCF, LWCF
- Macrophysics and Microphysics
- Cloud
- Detrainment
- Deep Convection
- Planetary Boundary Layer
- Shallow Convection
- CAPE
- Spectral Element
- Radiation SW, LW
- Abs/Emis/Ref
- Emission Deposition
- TKE, CIN
- MO stability
- Surface Fluxes
- P
- Detrainment
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
Hydrostatic Primitive Equations

Where do we put the physics?

Horizontal scales $>>$ vertical scales

Vertical acceleration $<<$ gravity

\[
\frac{d\vec{V}}{dt} + f_k \times \vec{V} + \nabla \phi = F, \quad F_V \quad \text{(horizontal momentum)}
\]

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

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

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

\[
\frac{dq}{dt} = S_q, \quad F_{QV}, F_{QL}, F_{QI} \quad \text{(water vapor mass continuity)}
\]

Harmless looking terms $F$, $Q$, and $S_q \implies \text{“physics”}$

(Peter Lauritzen (NCAR) talked about the dynamics yesterday)
Effect of Physics on the Model

What do we need to consider?

- **Thermodynamic energy equation (temperature)** $F_T$
  - Radiation (gas and aerosol; absorption/emission)
  - Cloud phase change (latent heating/evaporation)
  - Turbulence

- **Water substance continuity equation**, $F_{QV,QL,QI}$
  - Cloud-scale transport (vapor/liquid/ice?)
  - Cloud phase changes (e.g. vapor->water/ice->precipitation)
  - Turbulence

- **Momentum (horizontal velocity)** $F_V$
  - Turbulence: Transport, generation, and dissipation of momentum
  - Cloud-scale transport (updrafts/downdrafts)
  - Drag (surface roughness, mountain stress, gravity waves)

- **Other continuity equations for other tracers**, $F_{\text{tracers}}$
  - Includes chemistry and aerosols
  - Wet deposition, scavenging, etc
  - Turbulence
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 $X$

\[ w'X' = -K_x \frac{\partial X}{\partial z} \]
Community Atmosphere Model
Representing the key atmospheric processes in CAM5
Clouds
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
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**

\[ \text{CAPE} > \text{CAPE}_{\text{trigger}} \]

Time scale = 1 hour

\[ \text{KE} = \text{TKE} + \varepsilon \sum (b' dz) > 0 \]

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
Different types of Microphysics

• **Bulk Microphysics (RK-CAM4)**
  - **Mass-based only** (2 species: liquid and ice)
  - Bulk transformations and processes
  - Specified sizes or size distributions

• **Modal Microphysics (MG-CAM5)**
  - Use an analytic representation of the size distribution and carry around moments of the distribution
  - First moment = mass; **2nd moment = number**
  - Size distribution reconstructed from an assumed shape.
  - Advantage: represent sizes consistently with computational efficiency

\[
P W \ AUT = C_{l,aut}\hat{q}_l^2\rho_a/\rho_w(\hat{q}_l\rho_a/\rho_w N)^{1/3}H(r_{3l} - r_{3lc}).
\]
RadiaJon

The Earth’s Energy Budget

Trenberth & Fasullo, 2008

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

<table>
<thead>
<tr>
<th>Gas</th>
<th>SW Absorption (Wm(^{-2}))</th>
</tr>
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<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>1</td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>2</td>
</tr>
<tr>
<td>( \text{O}_3 )</td>
<td>14</td>
</tr>
<tr>
<td>( \text{H}_2\text{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

Input at TOA, Radiation at surface

IR absorption

![Graph showing IR absorption]
k-distribution Band Models

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

\[
T(w) = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \exp[-\kappa(\lambda)w] \, d\lambda
\]

- k-distribution band model, sort absorption coefficients by magnitude
- **Cheaper/fast, less accurate**

\[
\hat{T}(w) = \sum_{i=1}^{N} \exp[-\hat{\kappa}_i w] \, \delta g_i \, dg
\]
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)

\[ \tau_x = -\rho_1(u'w') = -\rho_1u_*^2(u_1/V_a) = \rho_1 \frac{u_s - u_1}{r_{am}} \]

\[ \tau_y = -\rho_1(v'w') = -\rho_1u_*^2(v_1/V_a) = \rho_1 \frac{v_s - v_1}{r_{am}} \]

Stresses

Specific Heat

\[ H = \rho_1c_p(w'\theta') = -\rho_1c_pu_\theta = \rho_1c_p \frac{\theta_s - \theta_1}{r_{ah}} \]

Latent heat (evaporation)

\[ E = \rho_1(w'q') = -\rho_1u_*q_\star = \rho_1 \frac{q_s - q_1}{r_{aw}} \]

• 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
The Cloud Overlap Challenge
Radiation and micro/macro-physics impact

Clouds extend through whole layer

Maximum Overlap

Minimum Overlap

- Contiguous cloudy layers generally maximally overlapped
- Non-contiguous layers randomly overlapped; function of de-correlation length-scale
Clouds in GCMs
State of the Art from CMIP3

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

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)
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?

- 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**.
More Processes = more feedbacks

The Development of Climate Models: Past, Present and Future
Older CAM workflow
Up to CAM4

Dynamics
- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag

Turbulent mixing

Moist processes
- Deep convection
- Shallow Convection
- Large-scale condensation

Surface models
- Surface fluxes from land/ocean/ice
  - from full models
  - from specified surface conditions (Ex: Sea Surface Temperature)

Cloud + Radiation
- Macrophysics
- Microphysics
- Radiation

Dynamical core (Eulerian, Finite volume) solves fluid equations on resolved scales
New CAM workflow
Community Atmosphere Model (CAM) Version 5

A = cloud fraction, q=H$_2$O, re=effective radius (size), T=temperature (i)ce, (l)iquid, (v)apor

- **Dynamics**
- **Surface Fluxes**
- **Shallow Convection**
- **Deep Convection**
- **Microphysics**
- **Aerosols**
- **Surface Models**

**Radiation**

**Mass, Number Conc**

**Clouds (A$_i$), Condensate (q$_v$, q$_c$)**

**Precipitation**

**Detained q$_c$, q$_i$**

**T, A$_{deep}$, A$_{sh}$**

**Community Atmosphere Model (CAM) Version 5**

A = cloud fraction, q=H$_2$O, re=effective radius (size), T=temperature (i)ce, (l)iquid, (v)apor
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
Precipitation Response to Mesh Refinement

CAM5 (2°)

CAM5 (2° → 0.25°)

CAM5 (0.25°)
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