Clouds in General Circulation Models (GCMs)

A practical perspective

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CESM Atmosphere Model Working Group

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General Circulation Models (GCMs)

Now
✓ Resolutions at or above mesoscale (Δx ~20s to 100s kms)
✓ Long timestep (minutes not seconds)
✓ Hydrostatic
✓ Coupled and efficiently integrated for 1000s of modeled years
✓ Mass, water, energy conserving
✓ Stable to climate perturbations
  • GHGs, paleoclimate, aerosols idealization

Future
✓ Resolutions at or below mesoscale (Δx ~1s to 10s kms)
✓ Non-hydrostatic
✓ Anthropogenic affects on clouds
  • Aerosols, chemistry
  • Urban heat island
  • Aircraft/contrails
  • Pyroclastic clouds
The Role of Clouds in GCMs
Historical Priorities

- Radiation processes
  - Solar reflectance/absorption/scattering
  - Long-wave emission and absorption
- Moist processes
  - Representation of condensed water species
  - Source of precipitation
  - Microphysical processes
    - Cloud particle activation/growth/decay
  - Macrophysical processes
    - Phase changes
- Interaction with atmospheric constituents
  - Aerosol activation of cloud particles
  - Wet deposition
  - Hydrophilic interactions
Clouds in GCMs
State of the Art from CMIP3

Clear-sky outgoing long-wave Radiation
(Annual, 1990-1999)

CMIP3 Models
(~20 models)
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

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

Loeb et al. (2009)
Clouds in GCMs
State of the Art from CMIP3

Total Cloud Fraction
(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)
Clouds in GCMs
State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)

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

Ice Water Path
(Annual, 1990-1999)
Clouds in GCMs
State of the Art from CMIP3 – response to climate change

Total Cloud Fraction Change

[Graph showing cloud fraction change across latitudes for CMIP3 models]
The Cloud Fraction Challenge

Cloud_Frac=f(RH,w,water,aerosols,time,…)

- Frac=0.6
  - 100% > RH > RH_{crit}
- Frac=0
  - RH < RH_{crit}
- Frac=1
  - RH >= 100%

Large Δx
(10s to 100s kms GCMs)

Small Δx
(CRMs, forecast models)

Community Earth System Model
The Cloud Overlap Challenge
Radiation and micro/macro-physics impact

- Contiguous cloudy layers generally maximally overlapped
- Non-contiguous layers randomly overlapped; function of de-correlation length-scale
The Cloud Type Challenge

Convection
- Stability based
- Diagnose tendencies based on (CAPE, CIN)
- Separate shallow and deep calculations

Stable Boundary Layer
- Relative humidity
- Turbulence
- Radiative cooling
- Instantly occupies entire level

Cirrus Ice Cloud
- Ice processes
- Fall speed
- Particle sizes
- Turbulence

- What is the occupied space relationship amongst cloud types?
  - Convection detraining cirrus
  - Simultaneous shallow and deep

- What are the transition relationships among clouds?
  - Shallow to deep
  - Deep to anvil stratiform

\[ \Delta z \]

\[ \text{Frac} = F(\text{mass flux}) \]

\[ \text{Frac} = 1 \quad \text{RH} \geq 100\% \]

\[ \text{Frac} = 0 \quad \text{RH} < 100\% \]

\[ \text{Frac} = 1 \quad \text{RH} \geq 100\% \]
Other Major Challenges

- Changing horizontal/vertical resolution
  - Simulations do not necessarily converge with increased resolution

- Interaction of condensate and cloud fraction
  - Condensate is predicted; fraction is often diagnosed
  - Inconsistencies between fraction and condensate
  - Cloud fraction with no condensate; condensate with no cloud

- Consequences of a long (physics) timesteps
  - Precipitation diagnosed; condensate lost in a single timestep
  - Process splitting versus time splitting (time split in CESM, order can matter)
  - Process split risks some double counting; but order should not matter (WRF)
Parameterization near(er) the cloud scale

**Assumed PDFs**
- Integrates moments of q, w
- Source from processes to moments (e.g., convection, q³)
- CLUBB (Larson)

**Sub-columns**
- Sample PDF of water
- Perform physics on each sub-column

**Embedded CRM**
- CRM in each grid-column
- SP-CAM
- Dynamics?

**Grid-Condensation**
- No cloud-fraction

- Helps with
  - Performing some physics at near-cloud scale regardless of GCM grid
- Does not solve
  - Overlap (except SP)
  - Cost
The Path to Higher Resolution
The deep convection question

✔ As horizontal resolution increases the expectation is deep convective cloud will become resolved and will not need to be parameterized
✔ Unclear what the resolution will be (5-10km?)

Aqua-planet experiments, precipitation rates (mm/day)
~200-km resolution with convection parameterization
The Path to Higher Resolution
Interaction of physics and dynamics

- Some parameterizations were not designed to act at higher resolutions
- Convection schemes required sufficient population of clouds for ‘quasi-equilibrium’ QE
- At 25-km (T340); too course for explicit convection; too fine for QE.
- Very intense precipitation events; convection cannot stabilize quickly enough

Reducing timestep allows convection to respond more effectively in build-up, and heads off extreme events
Community Earth System Model

• April 1, 2010: **CCSM4.0 release**
  ✓ full documentation, including User's Guide, Model Reference Documents, and experimental data

• June 25, 2010: **CESM1.0 release**
  ✓ ocean ecosystem, interactive chemistry, WACCM, land ice, and CAM5.0 (indirect affects)

[Link to CESM website](http://www.cesm.ucar.edu/models/)
**CAM5: Physics Changes**

Cloud-aerosol interaction focus -> community efforts

*UW PBL and shallow cumulus*

- Rapid Radiative Transfer Model (RRTM)
  - Park, Bretherton (UW)

*3-mode Modal Aerosol Model (MAM)*

- Liu, Ghan (PNNL)

*2-moment microphysics + ice cloud*

- Iacono (AER), Conley (NCAR), Collins (UCB)
- Morrison, Gettleman (NCAR)
Physical processes in a GCM
Community Atmosphere Model (CAM) Version 5

Aerosols
- Mass, Number Conc
- Clouds ($A_i$), Condensate ($q_v, q_c$)

Microphysics
- $A, q_c, q_i, q_v, re_i, re_l$

Macrophysics
- Detained $q_c, q_i$

Dynamics

Surface Fluxes
- Precipitation

Boundary Layer
- Clouds & Condensate
- $T, A_{\text{deep}}, A_{\text{sh}}$

Shallow Convection
- Clouds & Condensate

Deep Convection

A = cloud fraction, $q = H_2O$, $re =$ effective radius (size), $T =$ temperature
(i)ce, (l)iquid, (v)apor
Validating and Improving CAM4

Clouds and Cloud Processes in CAM5

Shallow Convective Mass Fluxes

Radiative heating rate/Flux

SO\textsubscript{4} concentration

Drop size distribution

Community Earth System Model
Anthropogenic aerosol affects on climate in CESM1-CAM5 (1970-1999) minus 1850 climate

- Increased aerosol burdens in SE Asia, Europe, NE America
- Increases cloud droplet number concentration; strongest over land
- Increased droplet activation = increased numbers of smaller drops = brighter clouds with more liquid

Net negative combined low-cloud affects over the 20th century

IPCC
20th Century Surface Temperature Change

OBSERVATIONS

Ave. = 0.73

Ave. = 0.72

Ave. = 0.37

Ave. = 0.48

CCSM4 (1 deg)

CCSM4 (2 deg)

CESM1-CAM5 (2 deg)

OBSERVATIONS

Weaker warming in CESM1.0 (CAM5)
Summary

✓ Role of clouds in GCMs; most important radiatively for GCMs
✓ GCMs agree very well on this
✓ But for very different reasons microphysically (obs. should help, in high latitudes)

✓ Timestep and resolution restrictions provide conceptual “grey areas” for parameterization methods
✓ Increasing resolution and decreasing timestep?
  ✓ Solves many conceptual problems
  ✓ But too expensive for most GCM applications
✓ Interim methods exist
  ✓ Sub-column approximations
  ✓ Super-parameterizations

✓ At increasing horizontal resolution convective clouds should be thermodynamically permitted/resolved
✓ Requires much high resolution to be dynamically resolved

✓ Multi moment microphysical schemes now available
✓ Early efforts at quantifying indirect affects
✓ Validation constrained by lack of global observations
CAM5: 20th Century Cloud changes

Global

Cloud anomaly (fraction)

Year

1860 1890 1920 1950 1980

CAM4 CAM5

CAM5

Land

Cloud anomaly (fraction)

Year

1860 1890 1920 1950 1980

Northern Hemisphere

Cloud anomaly (fraction)

Year

1860 1890 1920 1950 1980

Southern Hemisphere

Cloud anomaly (fraction)

Year

1860 1890 1920 1950 1980
CAM5: 20th Century Cloud Forcing Changes

Global

Heating

Cooling

Year

1860 1890 1920 1950 1980

Flux anomaly (Wm\(^{-2}\))

0.0 1.0 2.0

-2.0 -1.0 0.0

CAM4

CAM5

Year

Northern Hemisphere

Southern Hemisphere

1860 1890 1920 1950 1980

1860 1890 1920 1950 1980

Flux anomaly (Wm\(^{-2}\))

0.0 1.0 2.0

-2.0 -1.0 0.0

Land