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NESL

Clouds in General Circulation Models (GCMs)

A *practical* perspective

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NCAR

Thanks

CESM Atmosphere Model Working Group

NCAR is sponsored by the National Science Foundation

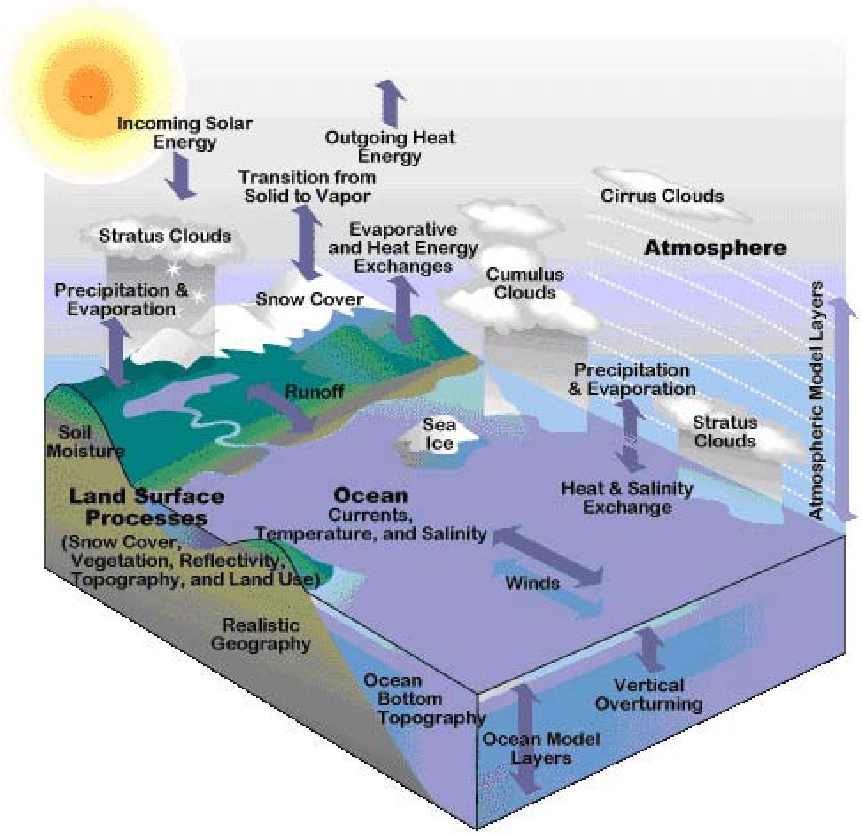
General Circulation Models (GCMs)

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

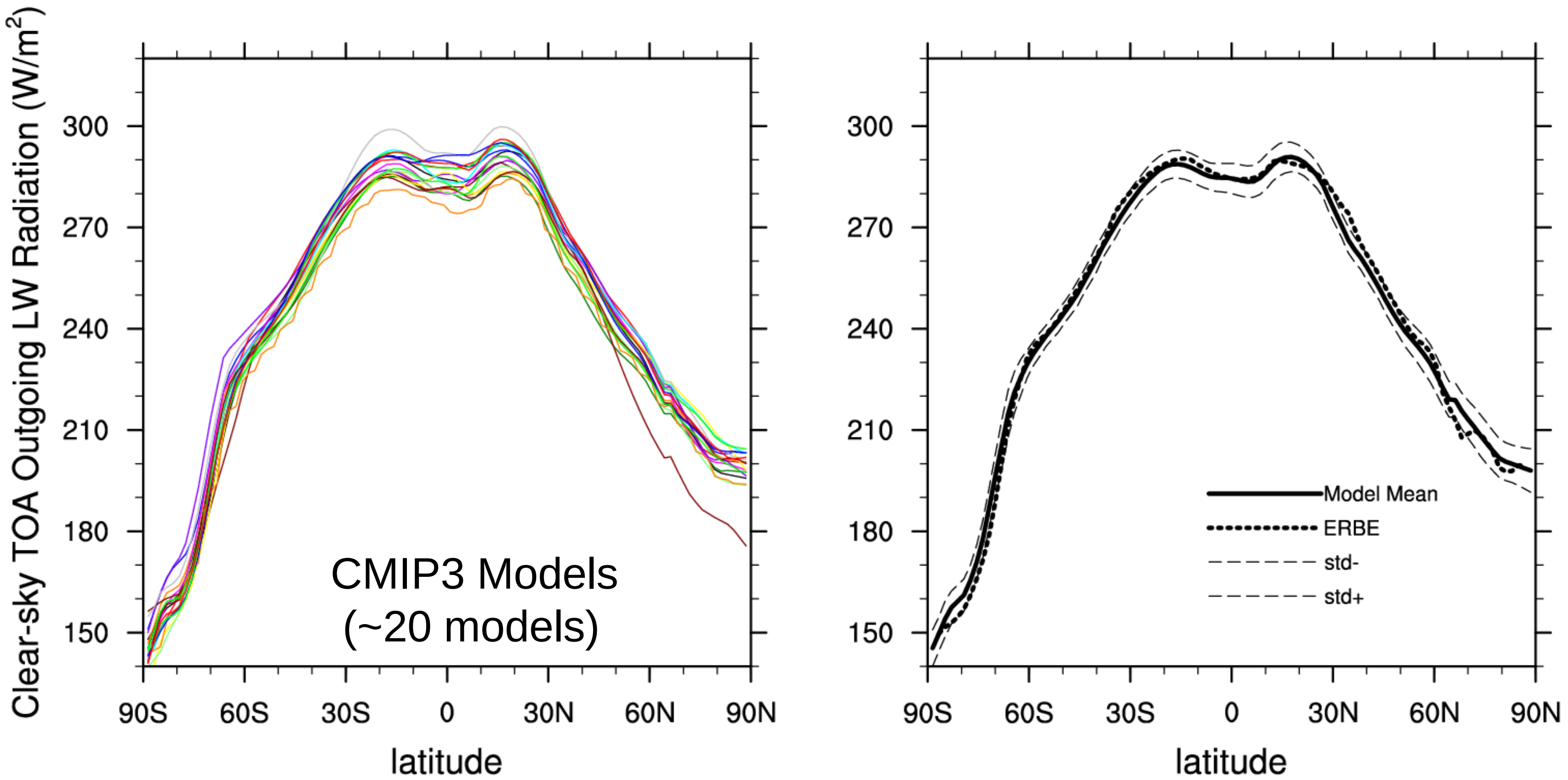
- ✓Moist processes
  - ✓Representation of condensed water species
  - ✓Source of precipitation
  - ✓Microphysical processes
    - ✓Cloud particle activation/growth/decay
  - ✓Macrophysical processes
    - ✓Phase changes

- ✓Interaction with atmospheric constituents
  - ✓Aerosol activation of cloud particles
  - ✓Wet deposition
  - ✓Hydrophilic interactions

Clouds in GCMs

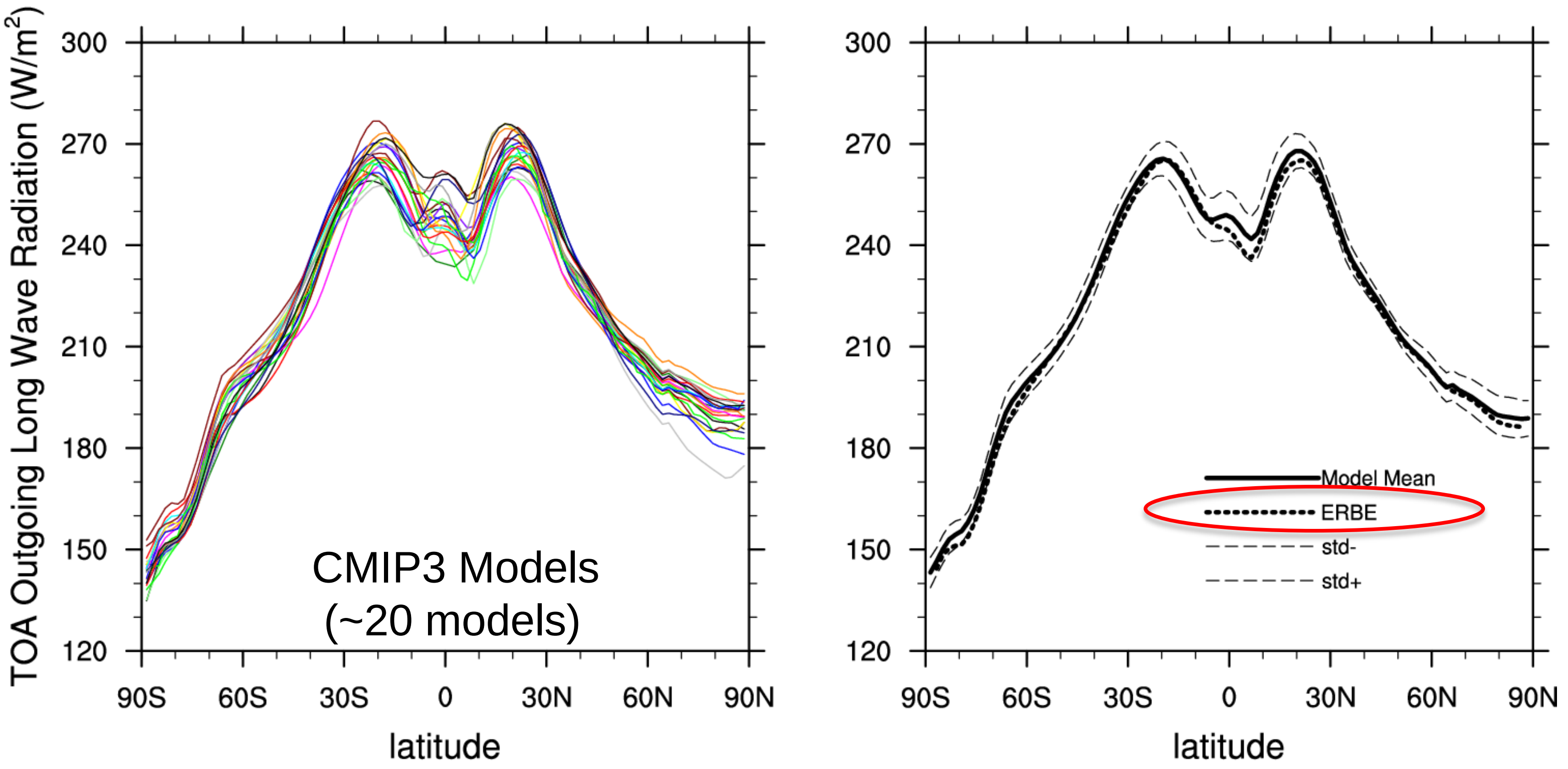
State of the Art from CMIP3

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

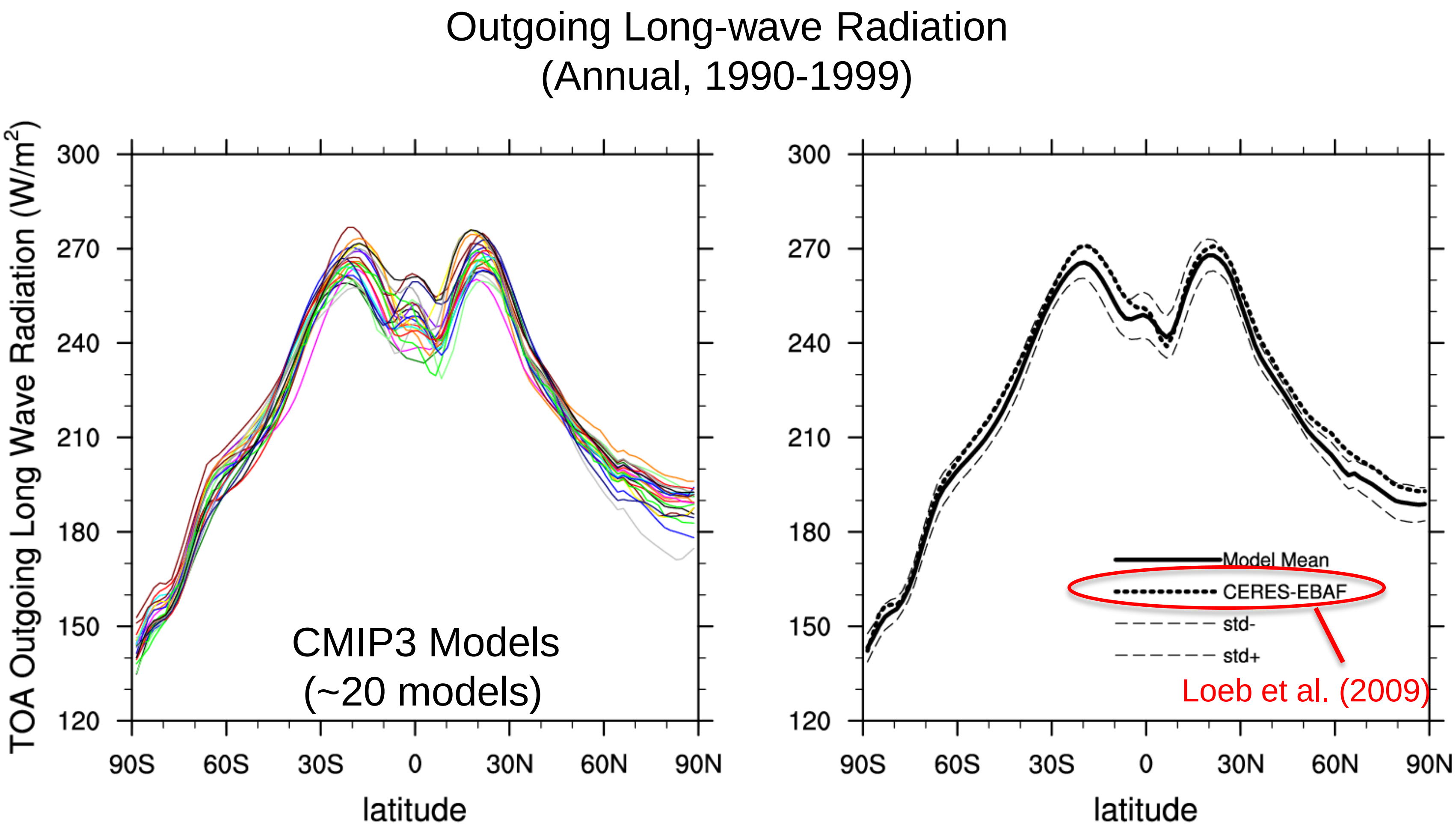


Clouds in GCMs
State of the Art from CMIP3

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

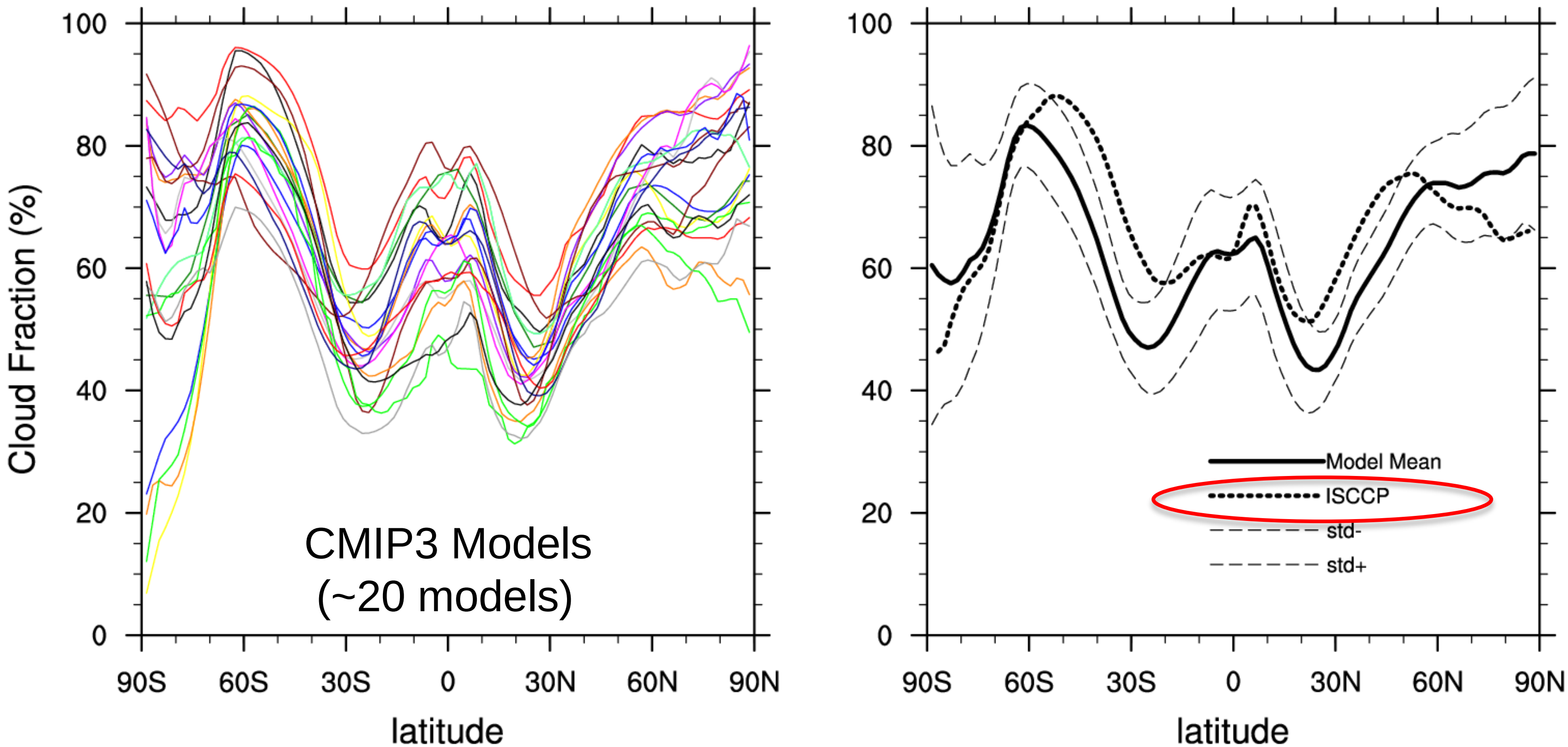


Clouds in GCMs
State of the Art from CMIP3



Clouds in GCMs
State of the Art from CMIP3

Total Cloud Fraction
(Annual, 1990-1999)



Clouds in GCMs

State of the Art from CMIP3

Total Cloud Fraction
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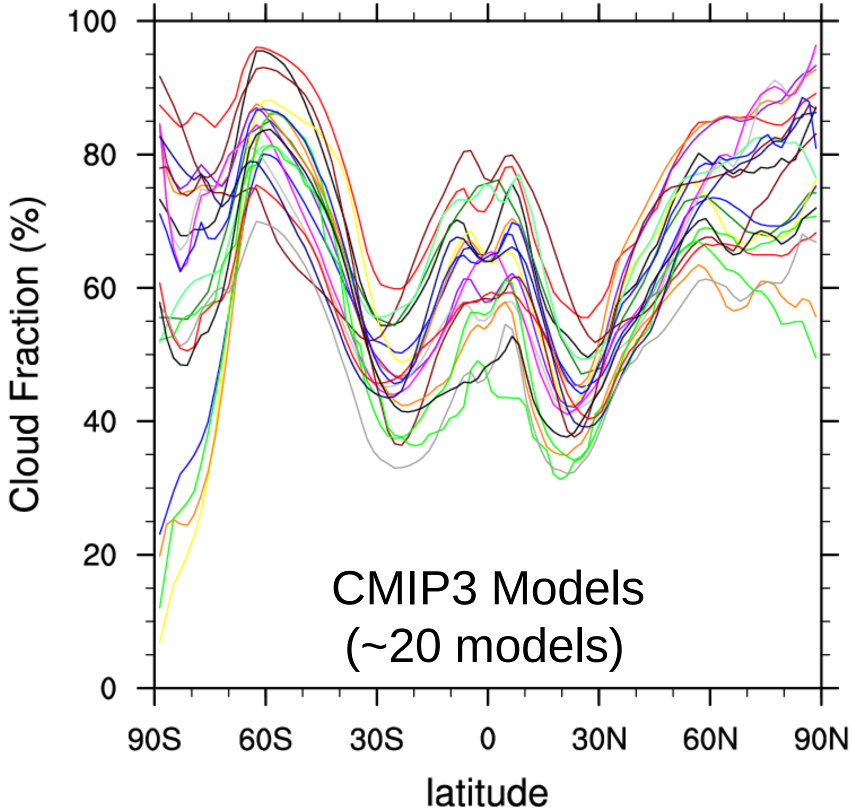
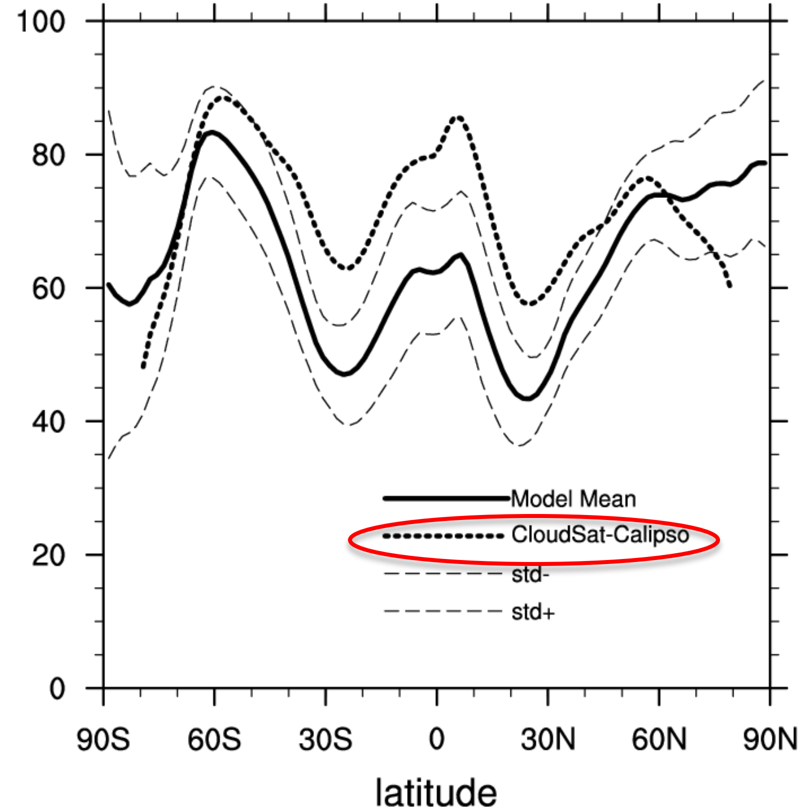
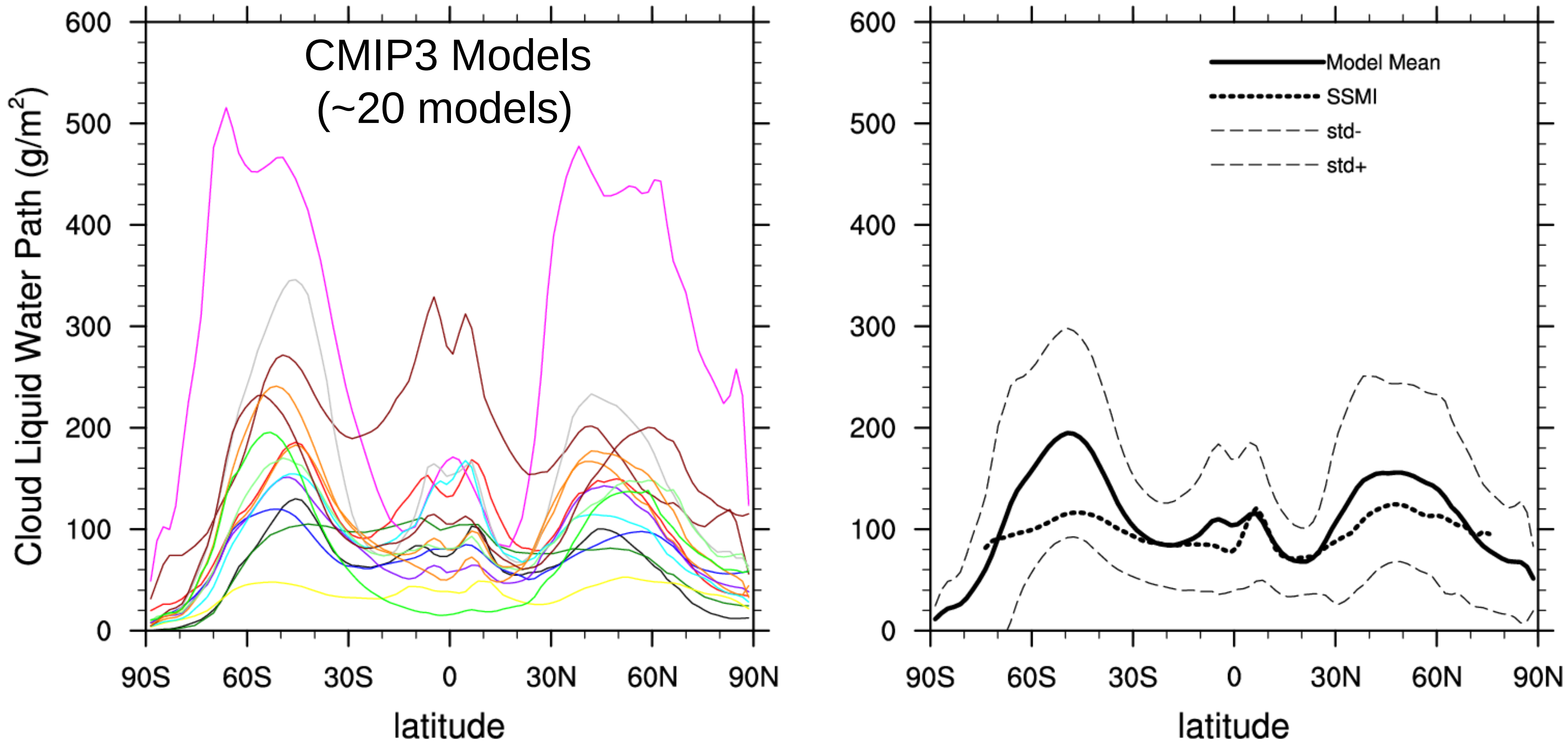




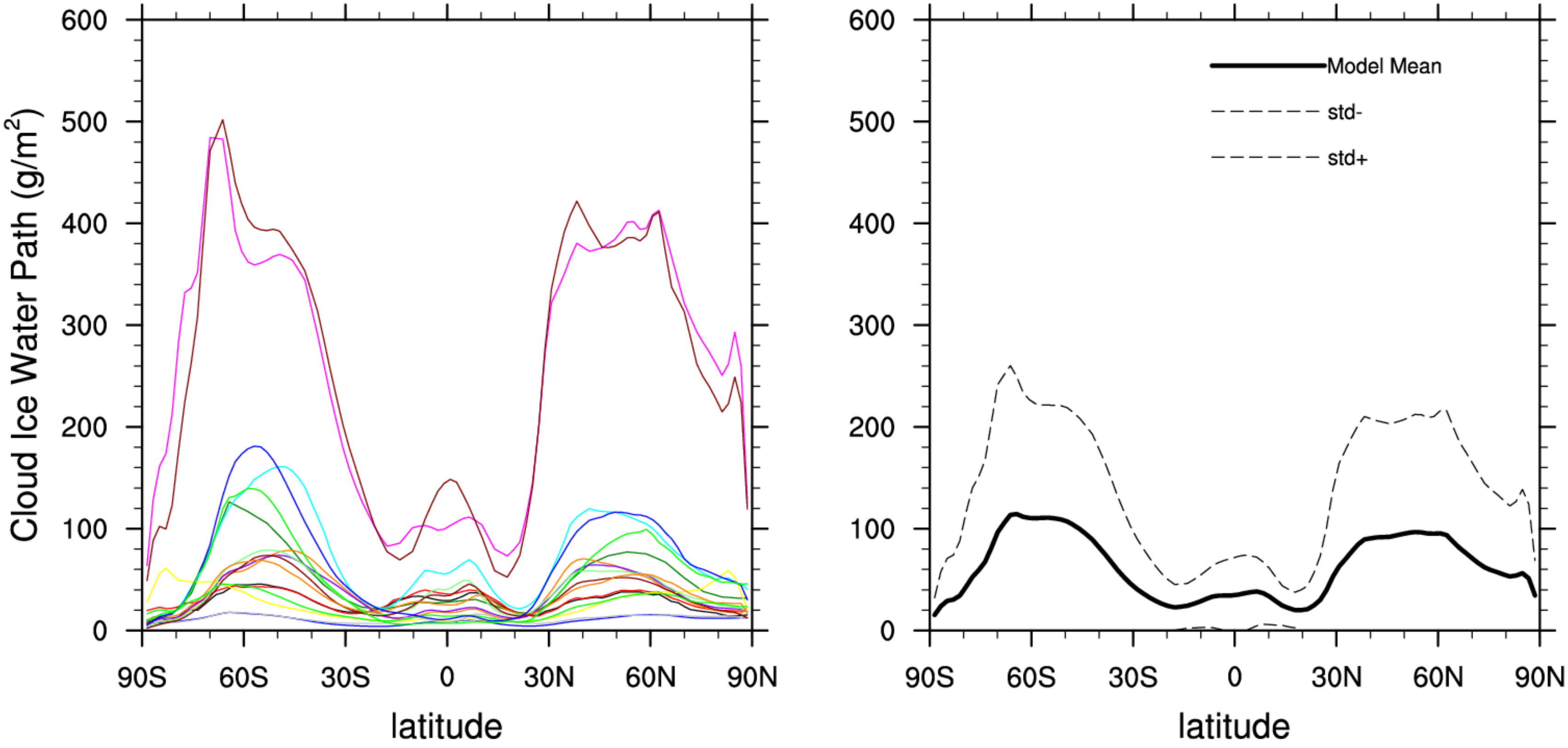
Clouds in GCMs
State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)



Clouds in GCMs
State of the Art from CMIP3

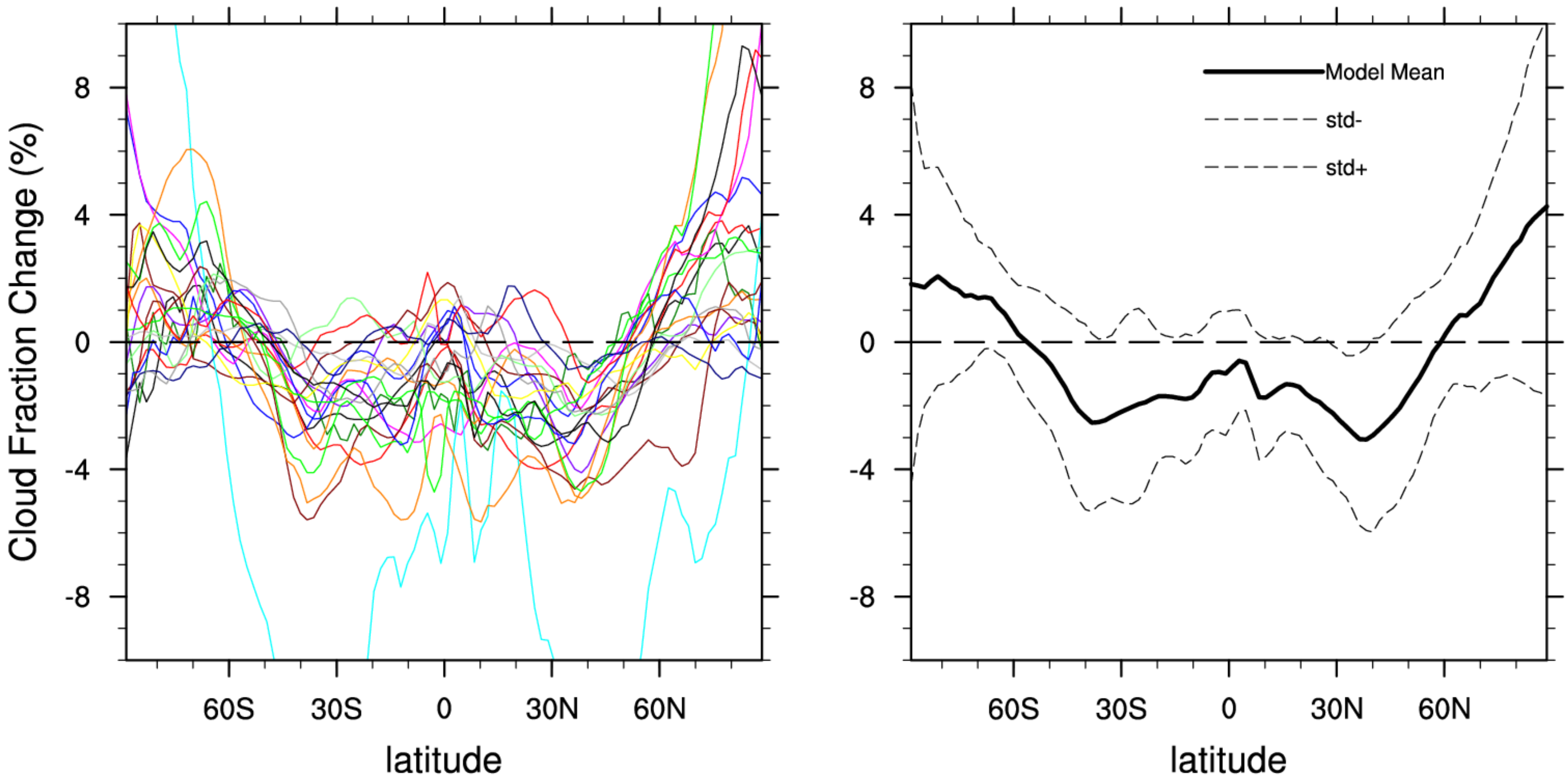
Ice Water Path
(Annual, 1990-1999)



Clouds in GCMs

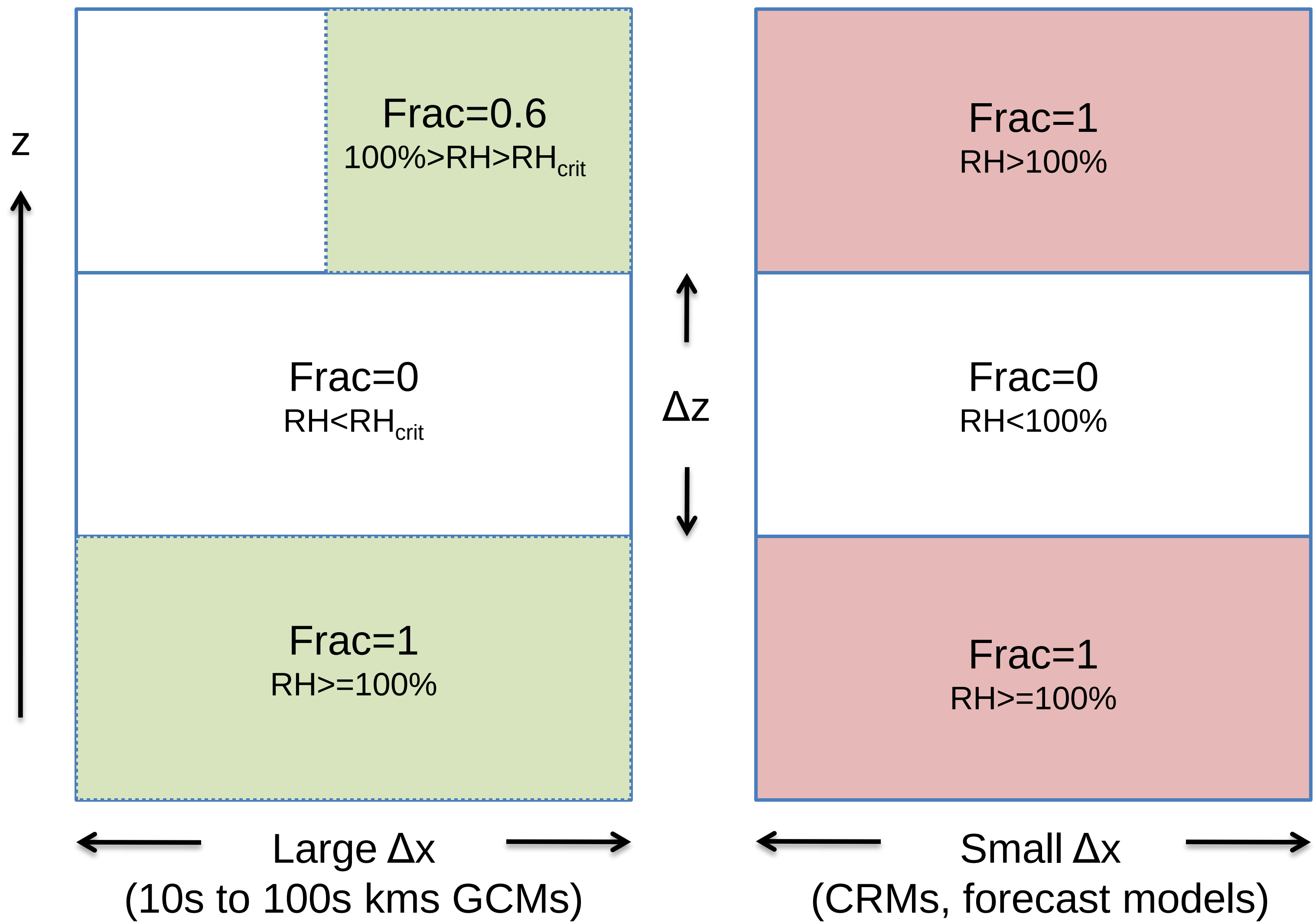
State of the Art from CMIP3 – response to climate change

Total Cloud Fraction Change
(Annual, SRES A1B: 2090-2099 minus 1990-1999)



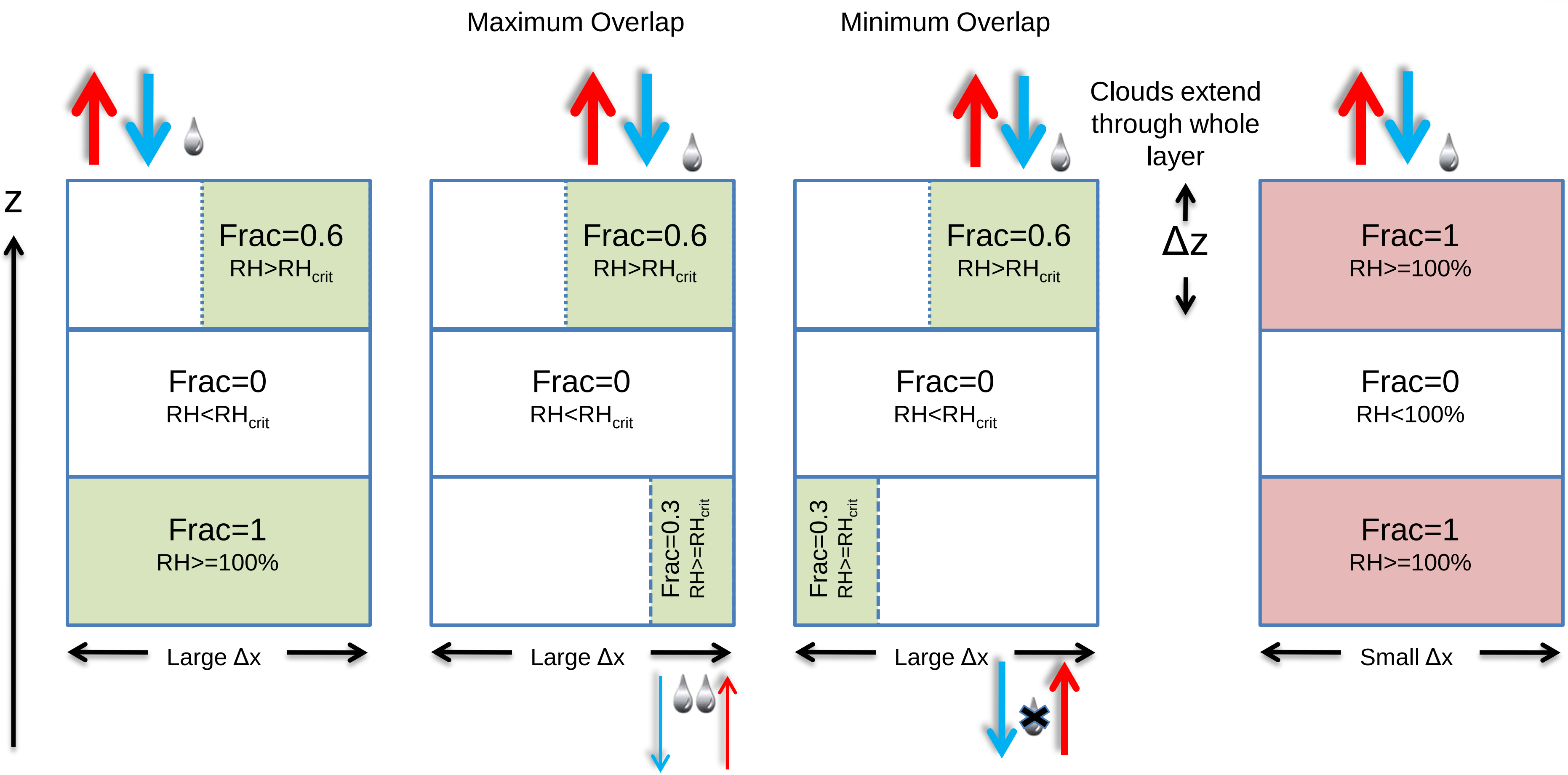
The Cloud Fraction Challenge

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



The Cloud Overlap Challenge

Radiation and micro/macro-physics impact



•Contiguous cloudy layers generally maximally overlapped

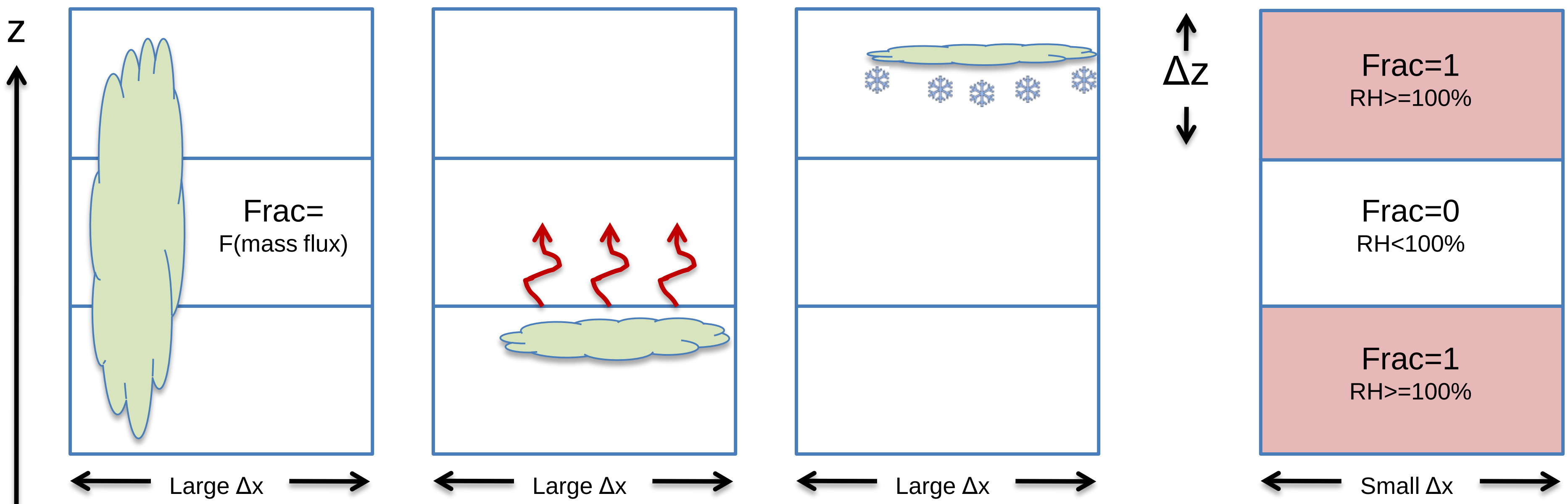
•Non-contiguous layers randomly overlapped; function of de-correlation length-scale

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

Other Major Challenges

✓Changing horizontal/vertical resolution

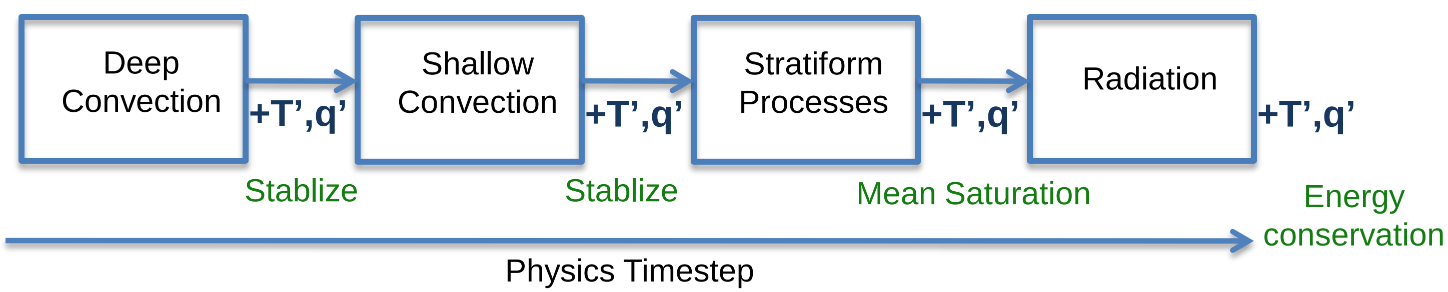
- Simulations do not necessarily converge with increased resolution

✓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)



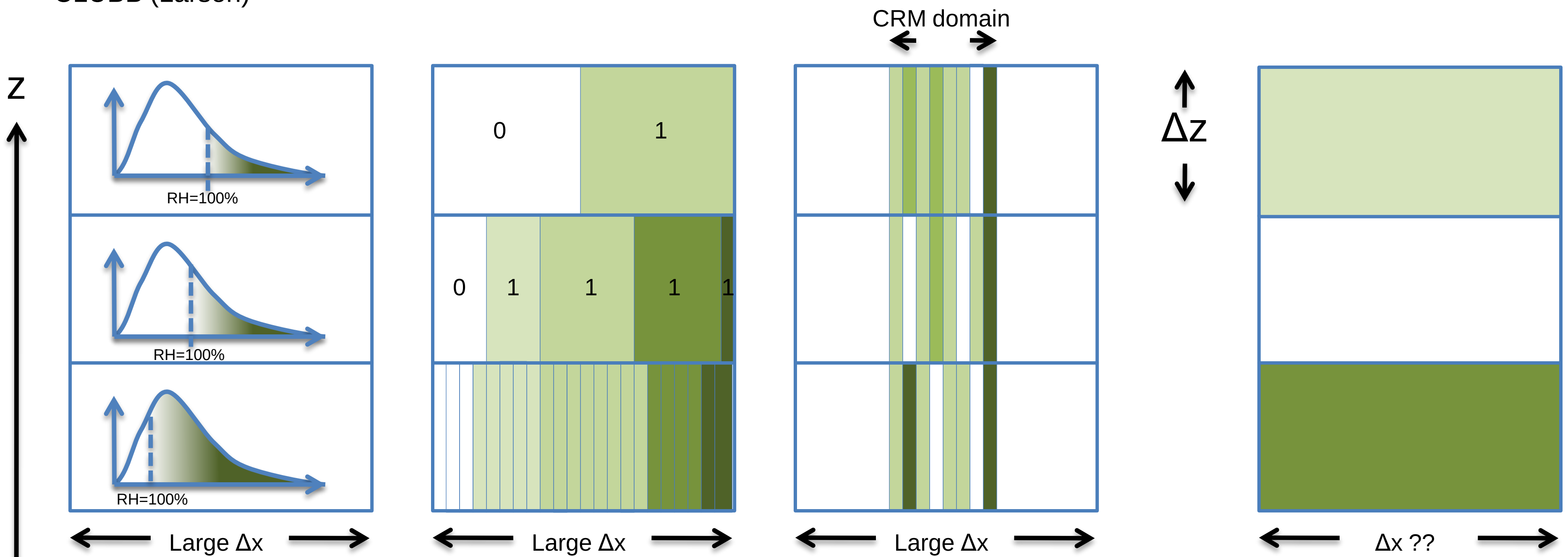
Parameterization near(er) the cloud scale

Assumed PDFs
✓Integrates moments of q, w
✓Source from processes to moments (e.g., convection ,q'[3])
✓CLUBB (Larson)

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

Embedded CRM
✓CRM in each gird-column
✓SP-CAM
✓Dynamics?

Grid-Condensation
✓No cloud-fraction



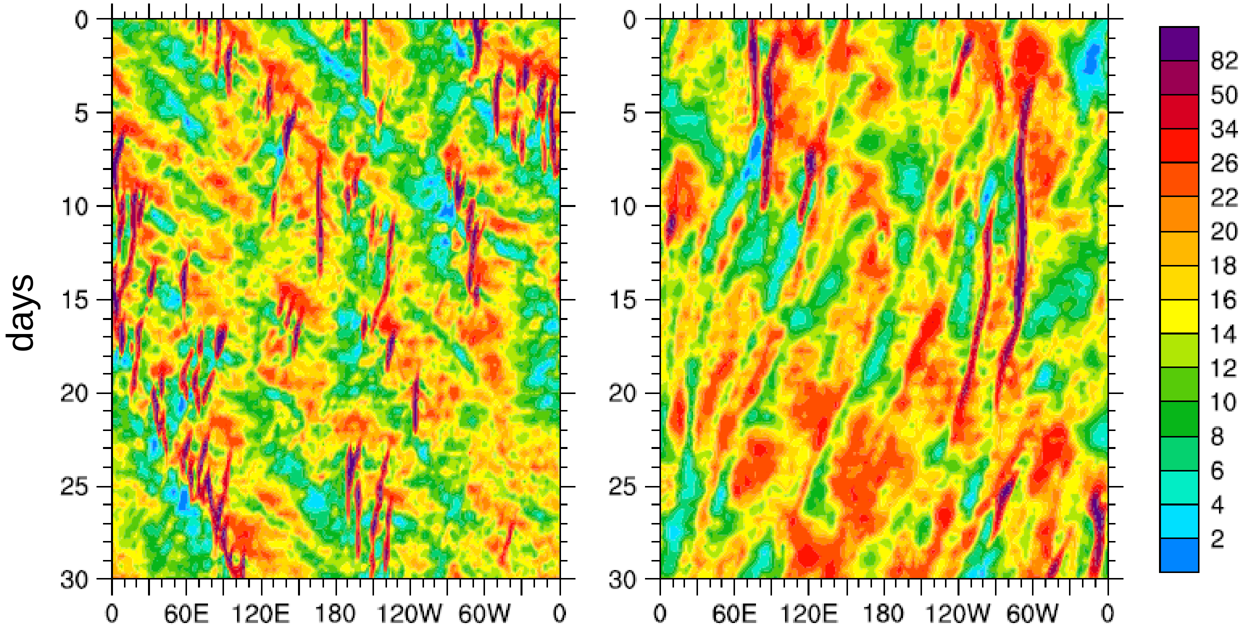
- Helps with
  - Performing some physics at near-cloud scale regardless of GCM grid
- Does not solve
  - Overlap (except SP)
  - Cost

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?)

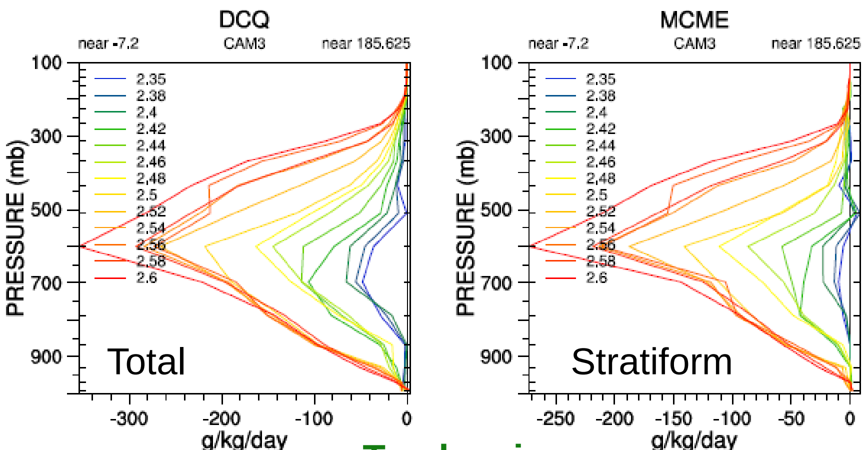


Aqua-planet experiments, precipitation rates (mm/day)
~200-km resolution with convection parameterization

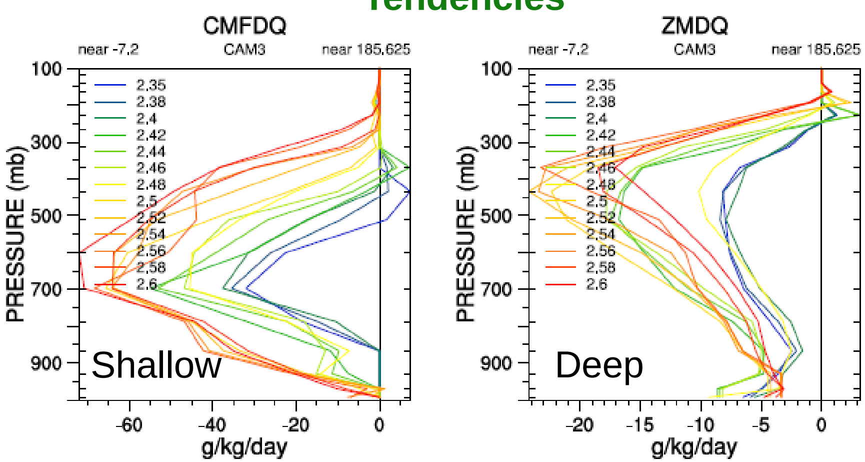
The Path to Higher Resolution

Interaction of physics and dynamics

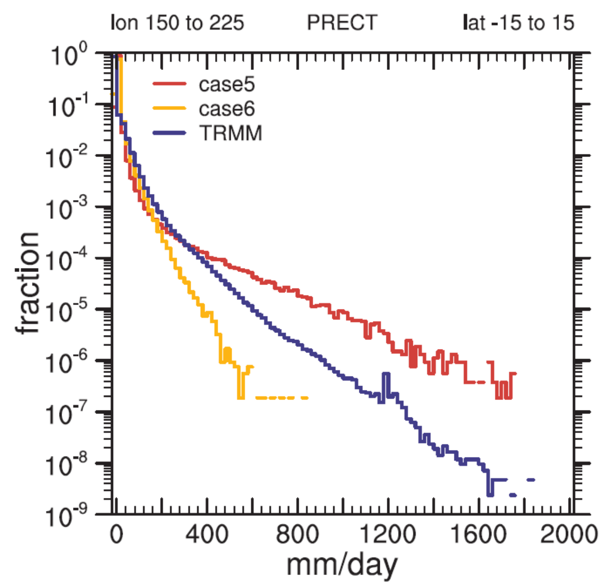
- ✓Some parameterizations were not designed to act at higher resolutions
- ✓Convection schemes required sufficient population of clouds for ‘quasi-equilibrium’ QE
- ✓At 25-km (T340); too course for explicit convection; too fine for QE.
- ✓Very intense precipitation events; convection cannot stabilize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



Tendencies



✓Reducing timestep allows convection to respond more effectively in build-up, and heads off extreme events

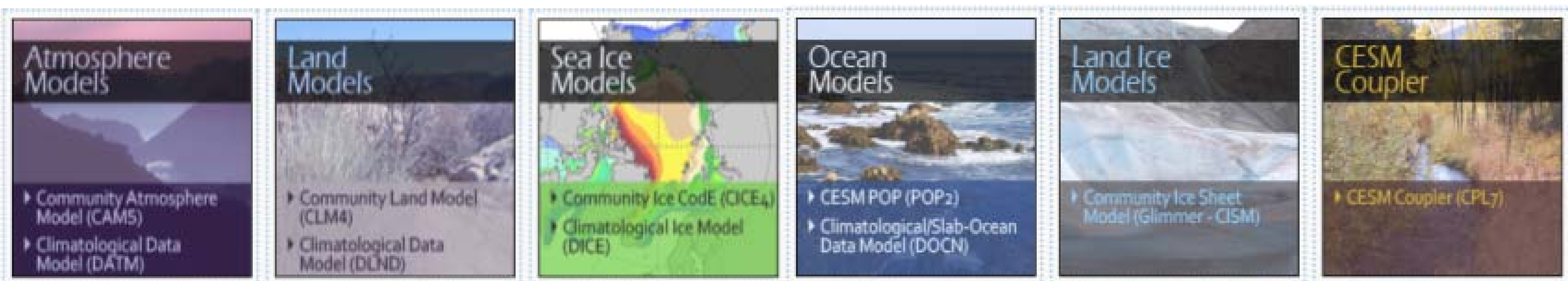


3-hour precipitation rates (mm/day)

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)

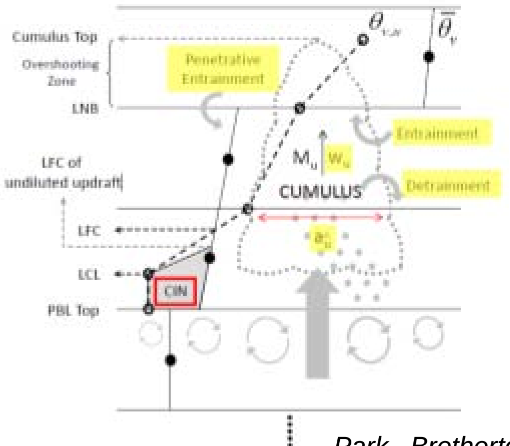


http://www.cesm.ucar.edu/models/

CAM5: Physics Changes

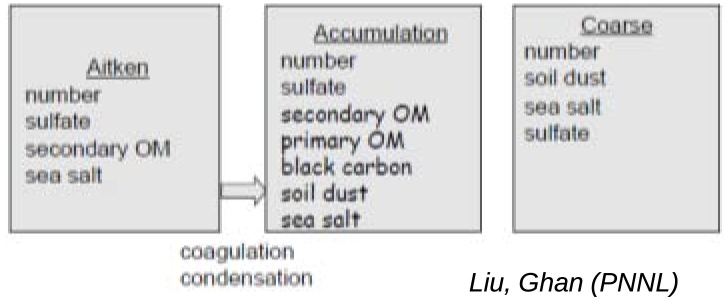
Cloud-aerosol interaction focus -> community efforts

UW PBL and shallow cumulus



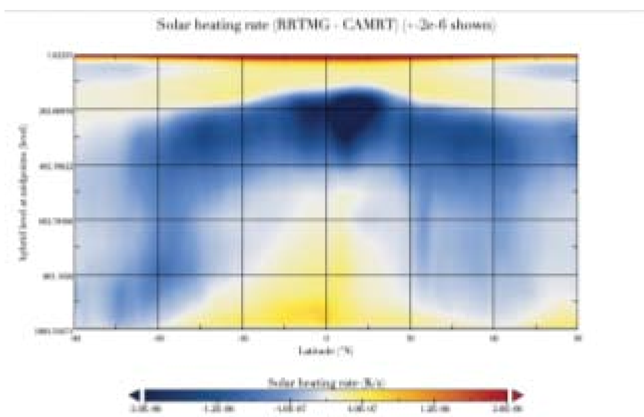
Park , Bretherton (UW)

3-mode Modal Aerosol Model (MAM)



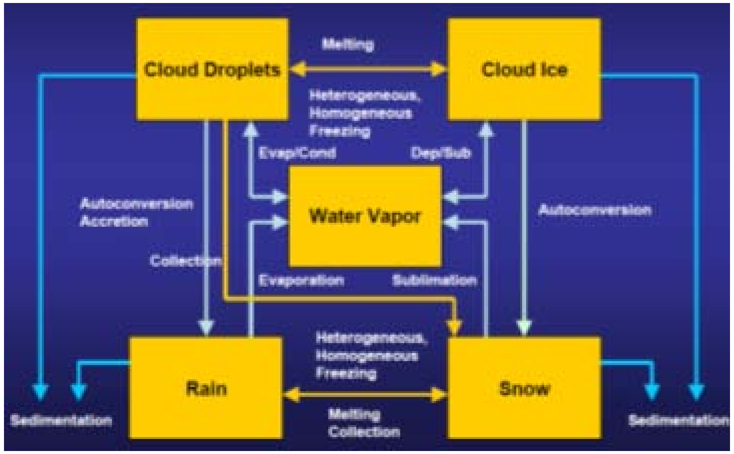
Liu, Ghan (PNNL)

Rapid Radiative Transfer Model (RRTM)



Iacono (AER), Conley (NCAR), Collins (UCB)

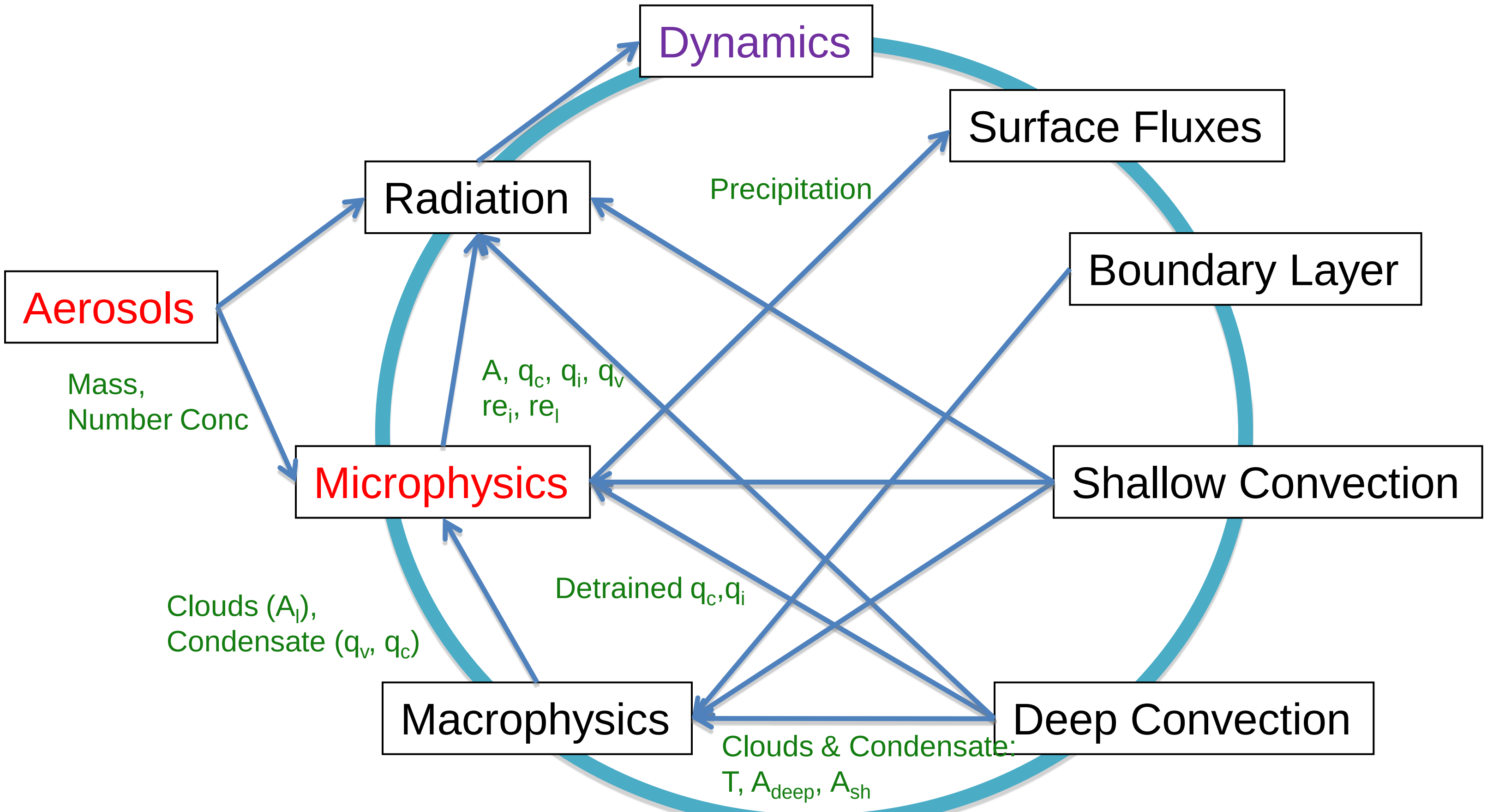
2-moment microphysics + ice cloud



Morrison, Gettleman (NCAR)

Physical processes in a GCM

Community Atmosphere Model (CAM) Version 5

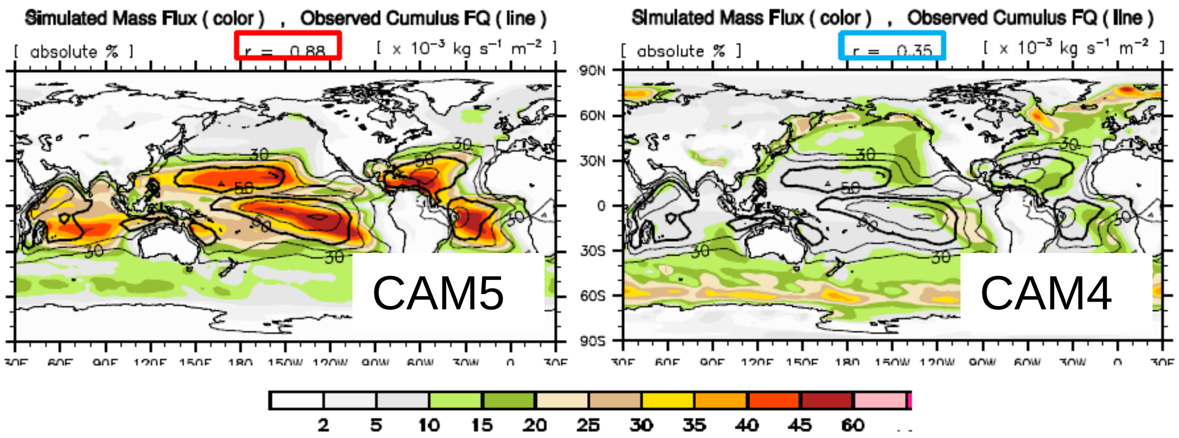


A = cloud fraction, q=H_2O, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor

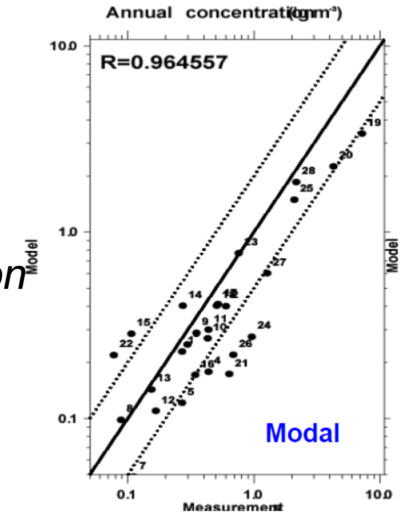
Validating and Improving CAM4

Clouds and Cloud Processes in CAM5

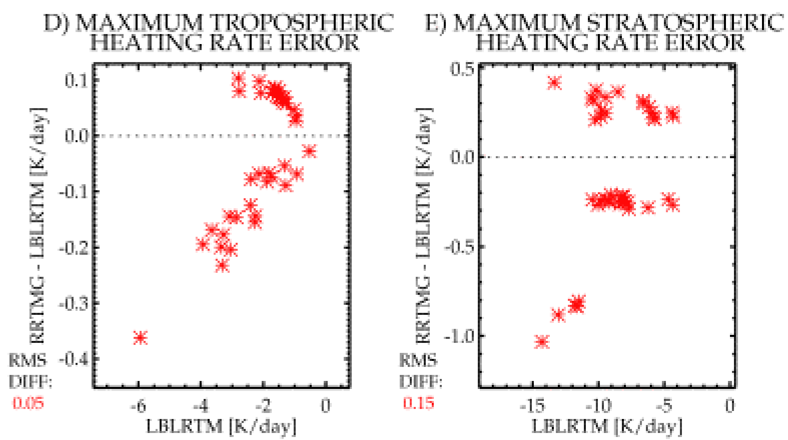
Shallow Convective Mass Fluxes



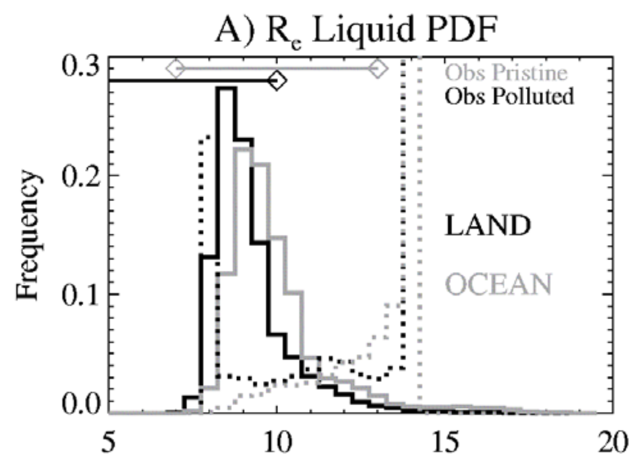
SO_4 concentration



Radiative heating rate/Flux



Drop size distribution



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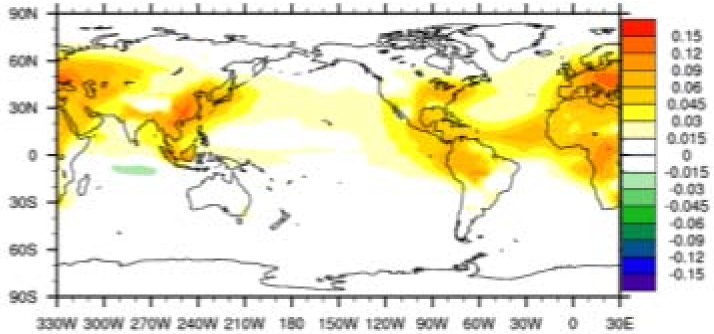
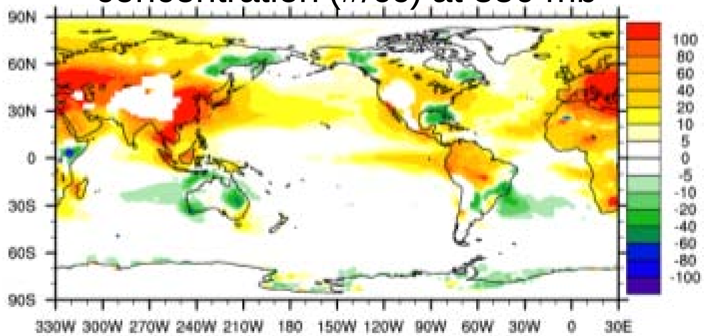
Anthropogenic aerosol affects on climate in CESM1-CAM5

(1970-1999) minus 1850 climate

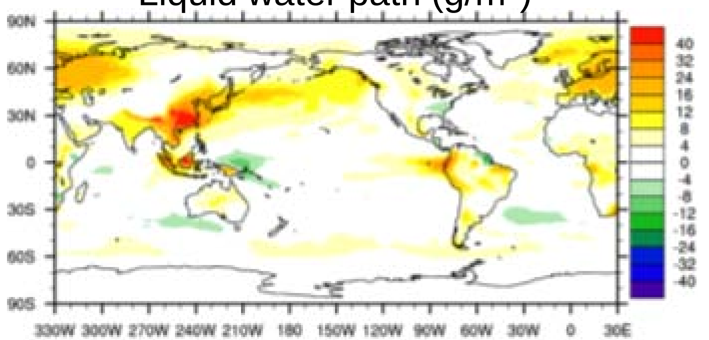
Total aerosol change (optical depth)



Cloud water droplet number concentration (#/cc) at 850 mb



Liquid water path (g/m²)

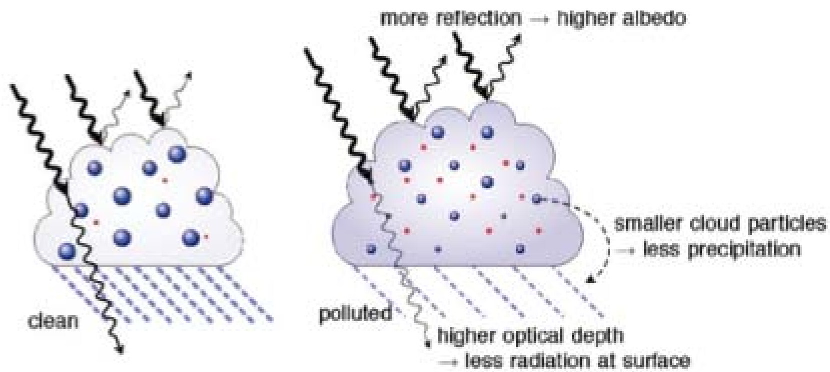


✓Increased aerosol burdens in SE Asia, Europe, NE America

✓Increases cloud droplet number concentration; strongest over land

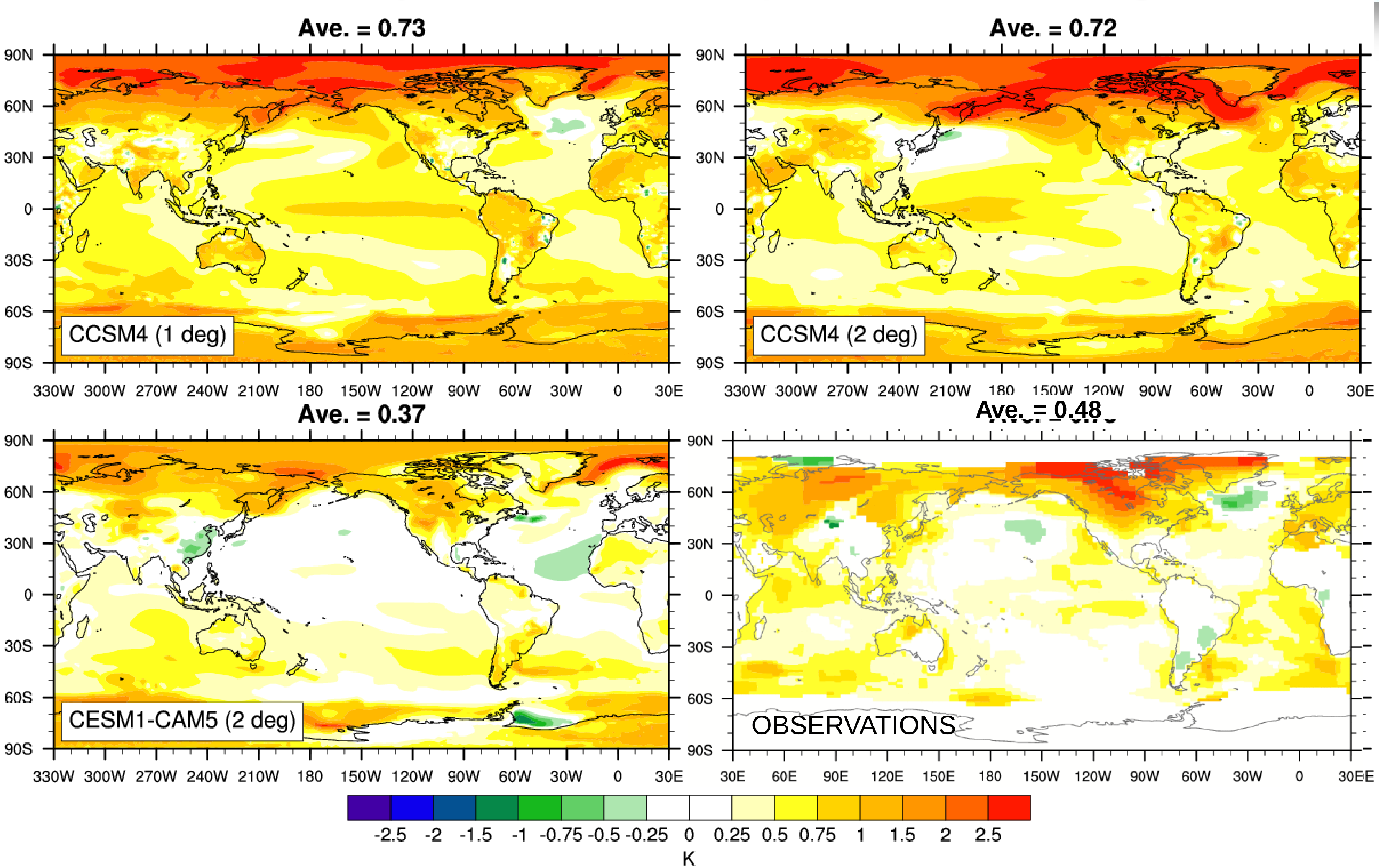
✓Increased droplet activation = increased numbers of smaller drops = brighter clouds with more liquid

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



IPCC

20th Century Surface Temperature Change



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)

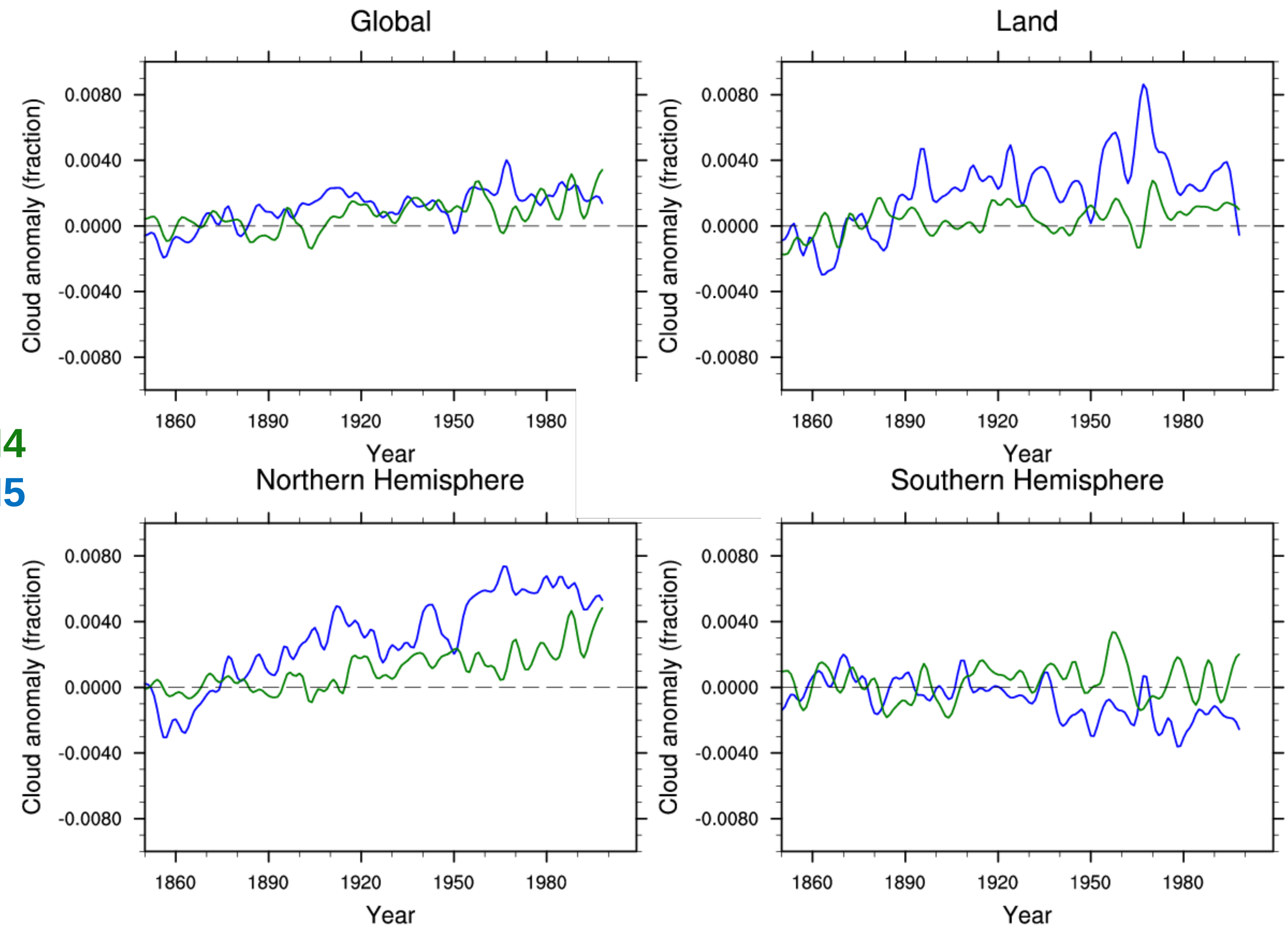
✓Timestep and resolution restrictions provide conceptual "grey areas" for parameterization methods
✓Increasing resolution and decreasing timestep?
- ✓Solves many conceptual problems
- ✓But too expensive for most GCM applications

✓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

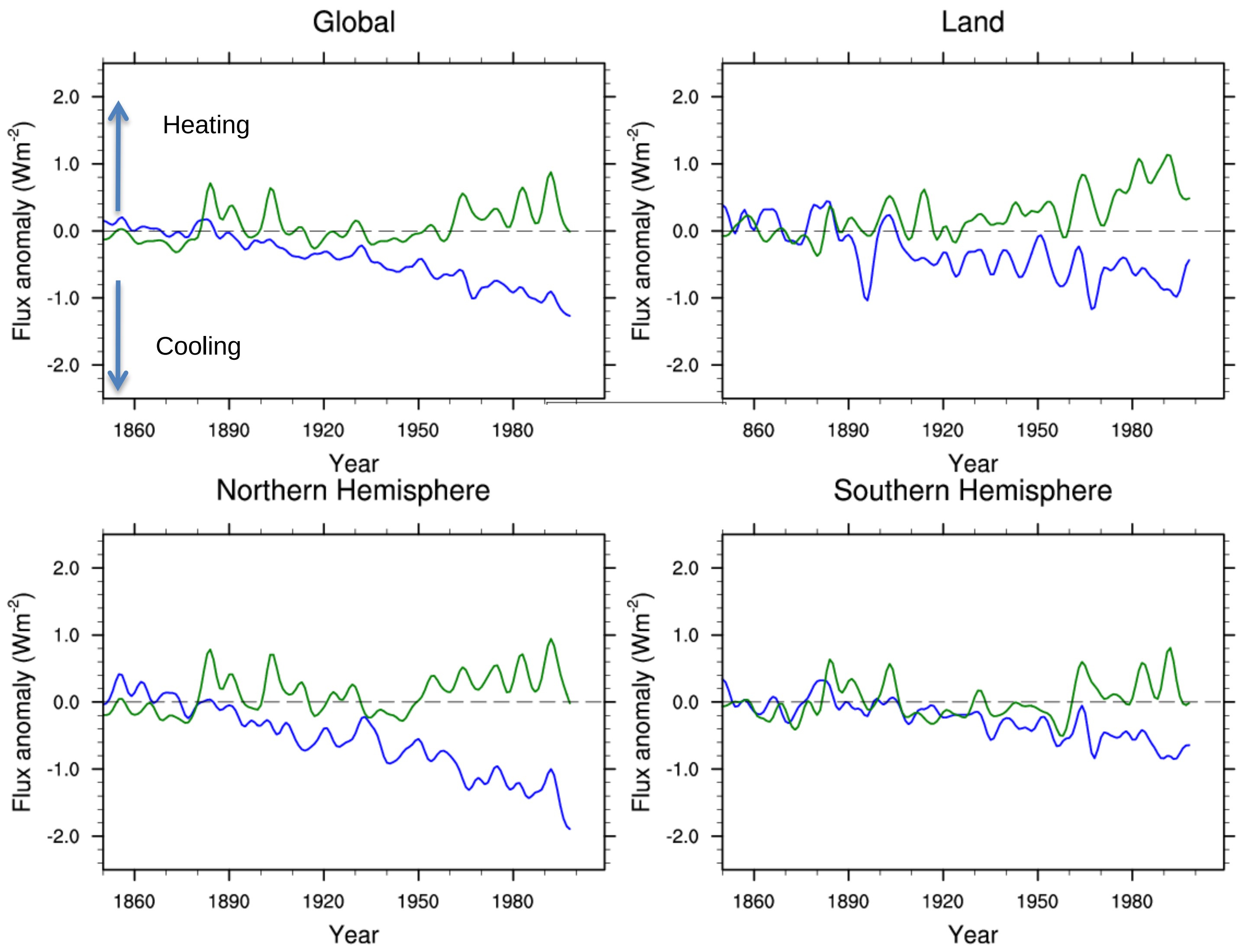
✓Multi moment microphysical schemes now available
✓Early efforts at quantifying indirect affects
✓Validation constrained by lack of global observations

CAM5: 20th Century Cloud changes



CAM4
CAM5

CAM5: 20th Century Cloud Forcing Changes



CAM4
CAM5