Atmospheric Modeling I:

Physics in the Community Atmosphere Model (CAM)

CESM Tutorial

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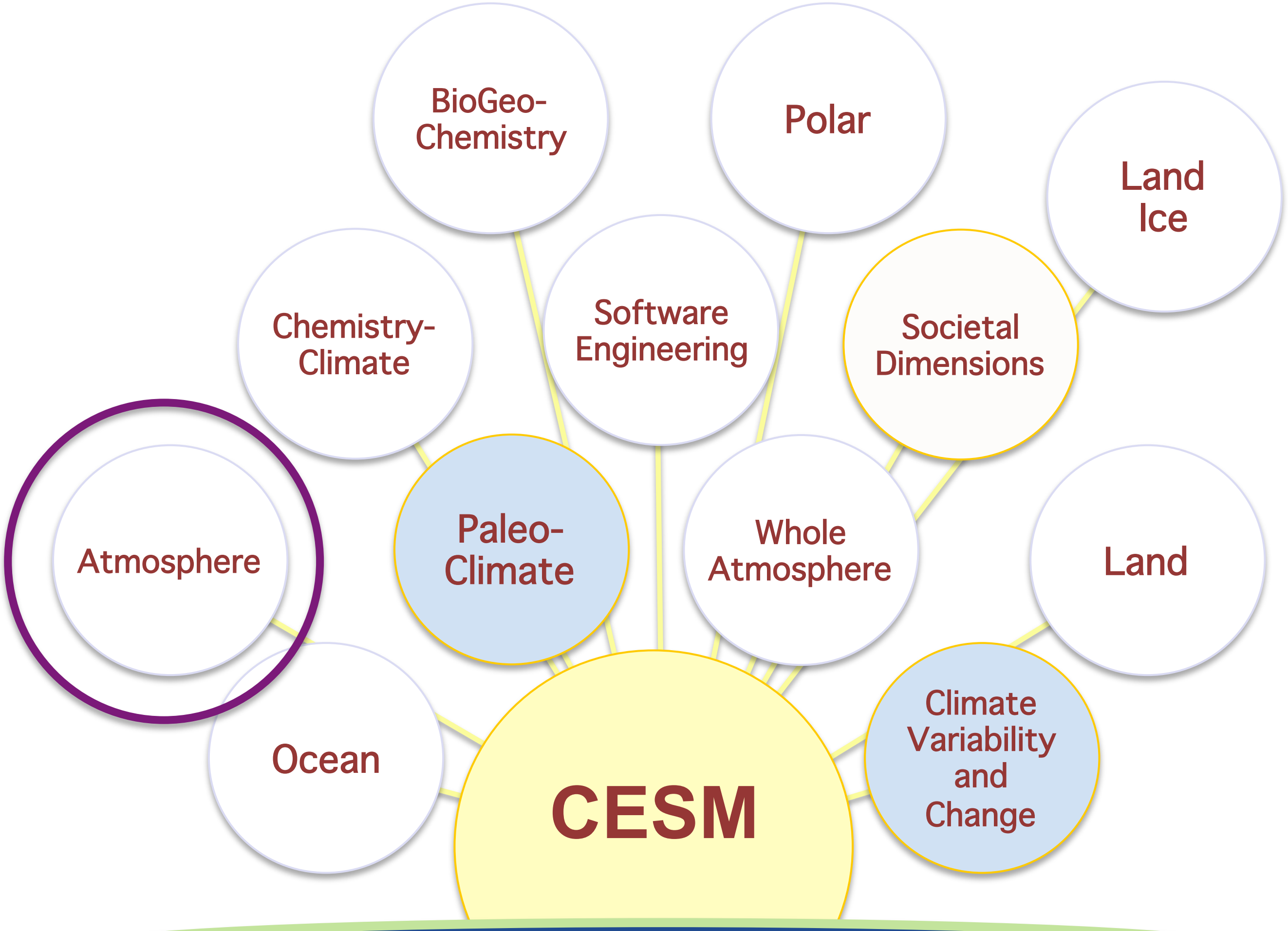
Outline

- **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)

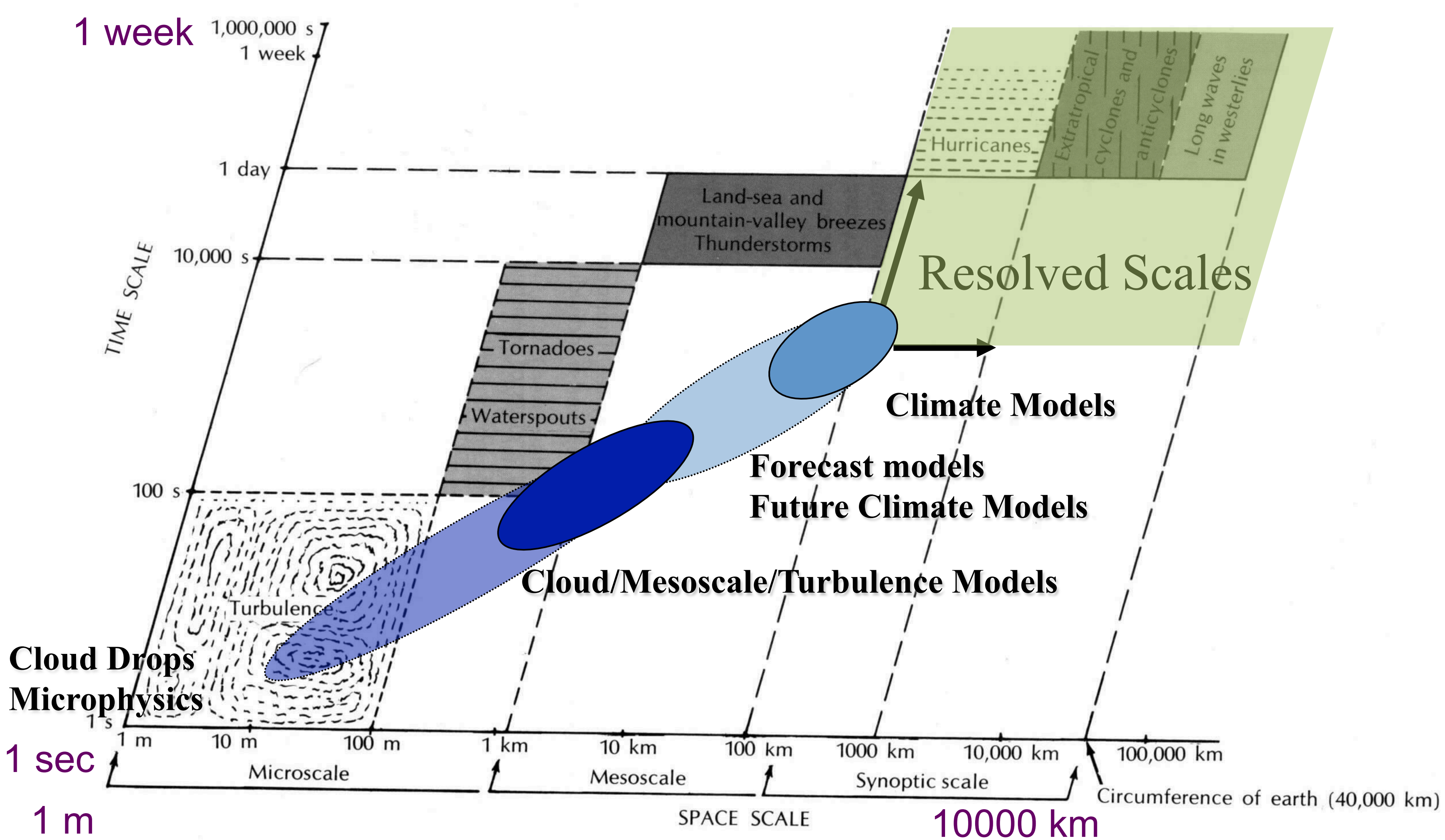
Atmosphere Model Working Group (AMWG)



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

Scales of Atmospheric Processes

Determines the formulation of the model



Hydrostatic Primitive Equations

Where do we put the physics?

Horizontal scales >> vertical scales

Vertical acceleration << gravity

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F},$$ F_V *(horizontal momentum)*

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p,$$ F_T *(thermodynamic energy)*

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0,$$ *(mass continuity)*

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$$ *(hydrostatic equilibrium)*

$$d\overline{q}/dt = S_q.$$ F_{QV}, F_{QL}, F_{QI} *(water vapor mass continuity)*

+transport

Harmless looking terms F, Q, and S_q $\Longrightarrow$ "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

$$\overline{w'\chi'} = -K_\chi \frac{\partial \chi}{\partial z}$$

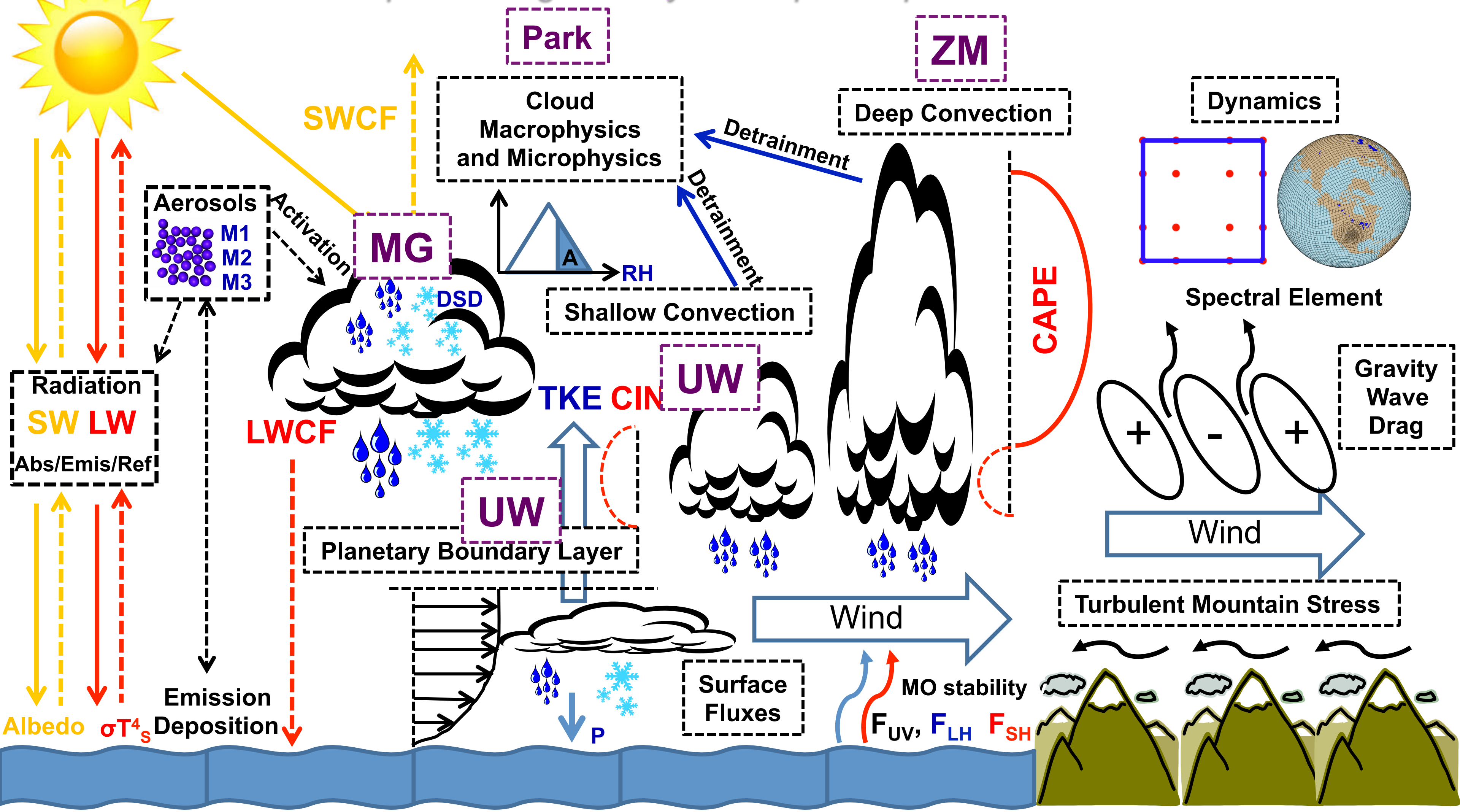
‘Diffusivity’

Unresolved ‘sub-grid’

Resolved ‘grid-scale’

Community Atmosphere Model

Representing the key atmospheric processes in CAM5



Clouds

Clouds

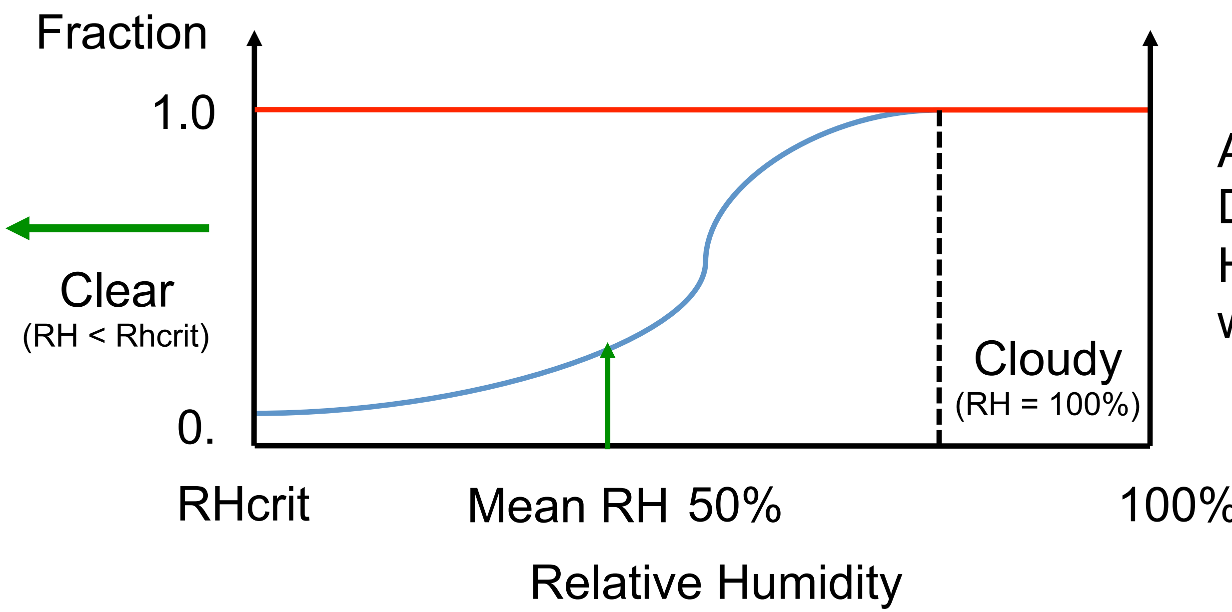
Multiple Categories

- **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%
- ✓ *RHcrit* 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

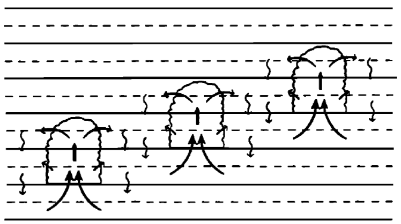
Large cloud radius small entrainment

Shallow and Deep Convection

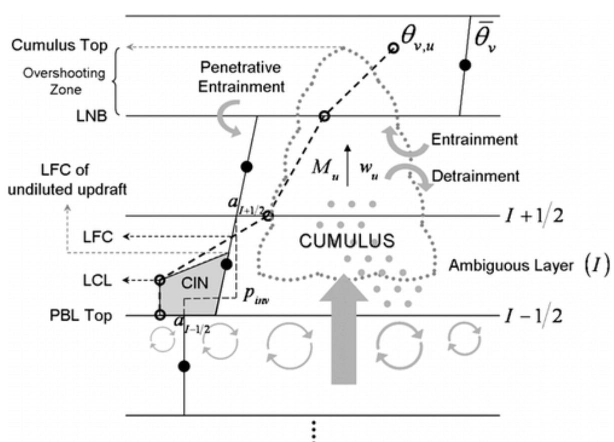
Closure: How much and when?

Shallow

Local conditional instability CAM4



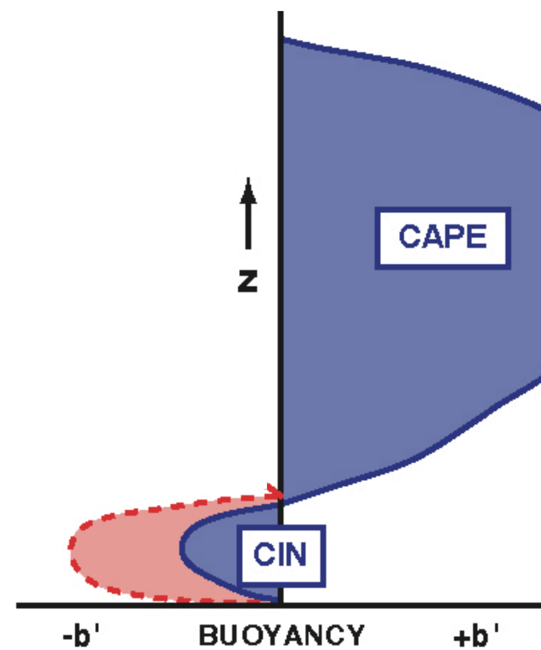
Convective inhibition and turbulent kinetic energy (TKE) CAM5



Deep

Convective Available Potential Energy (CAPE) CAM4 and CAM5

$CAPE>CAPE_{trigger}$ Timescale=1 hour



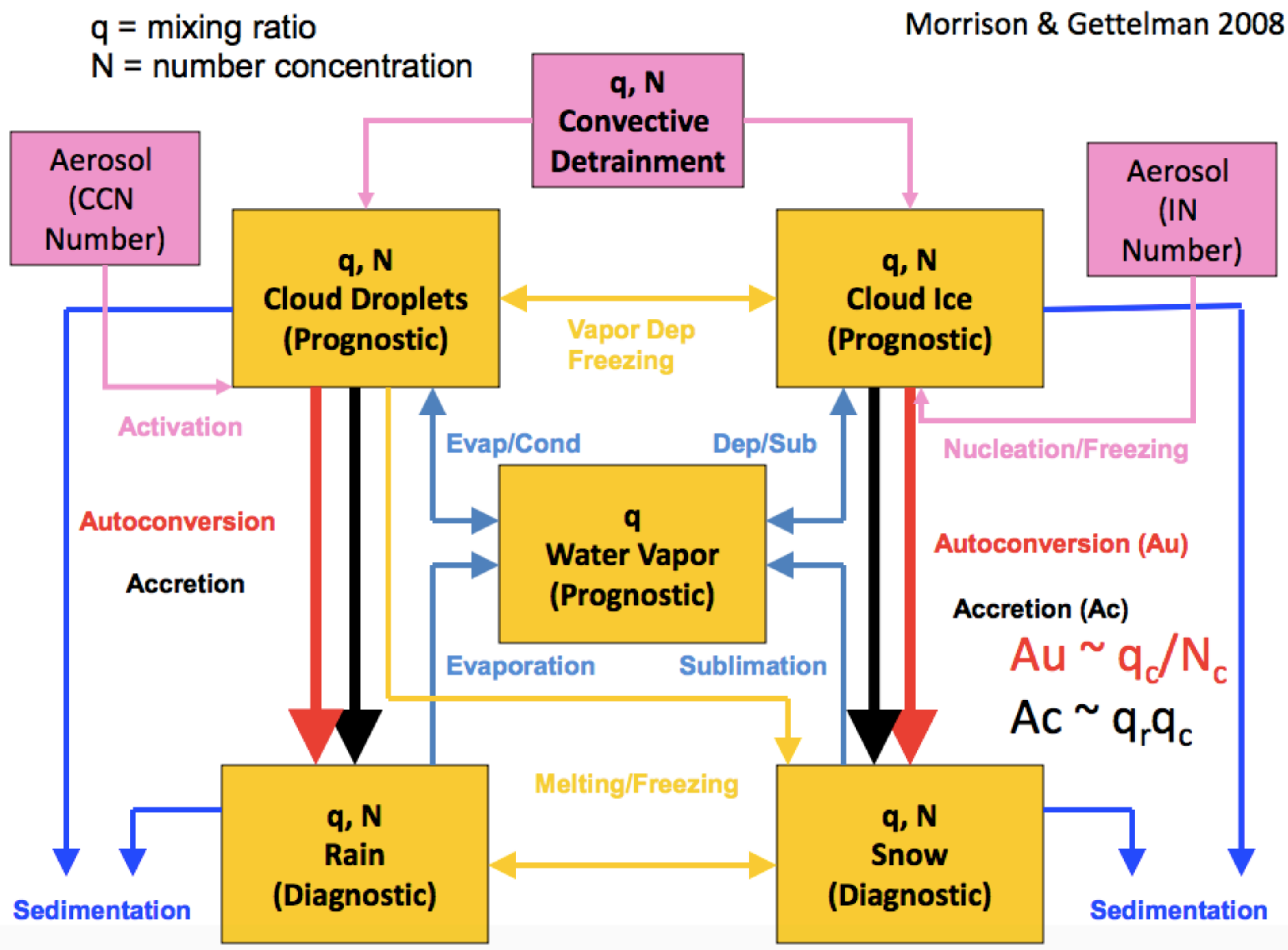
Shallow and deep convection and stratiform cloud fractions combined for radiation

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

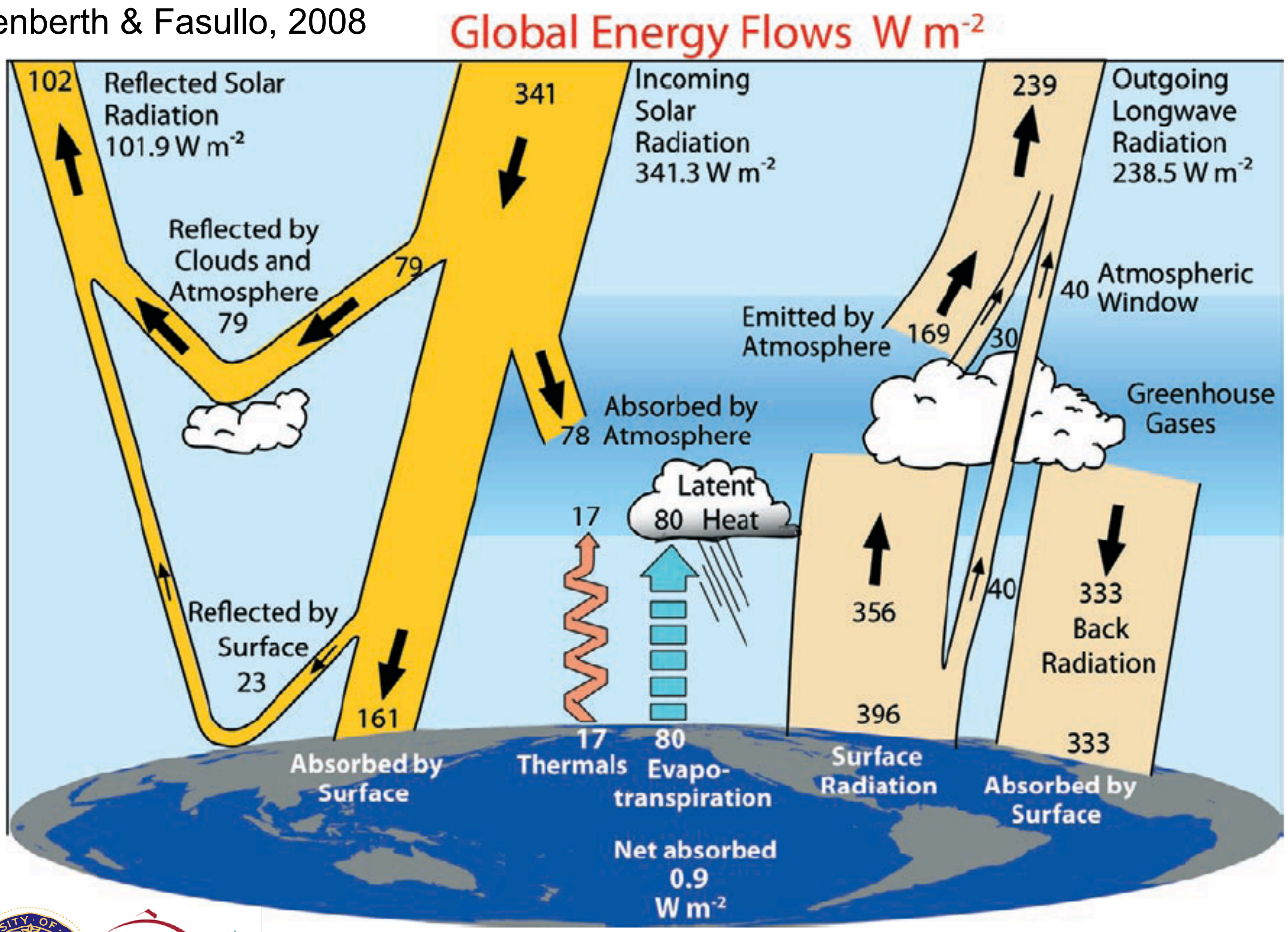
CAM5 Microphysics



Radiation

The Earth's Energy Budget

Trenberth & Fasullo, 2008

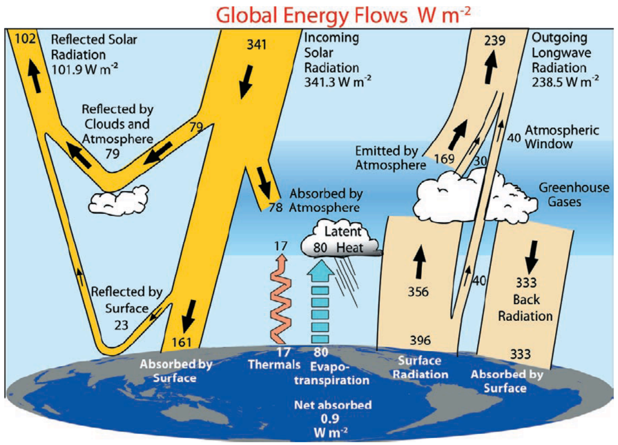


Gas	SW Absorption (Wm^{-2})
CO_2	1
O_2	2
O_3	14
H_2O	43

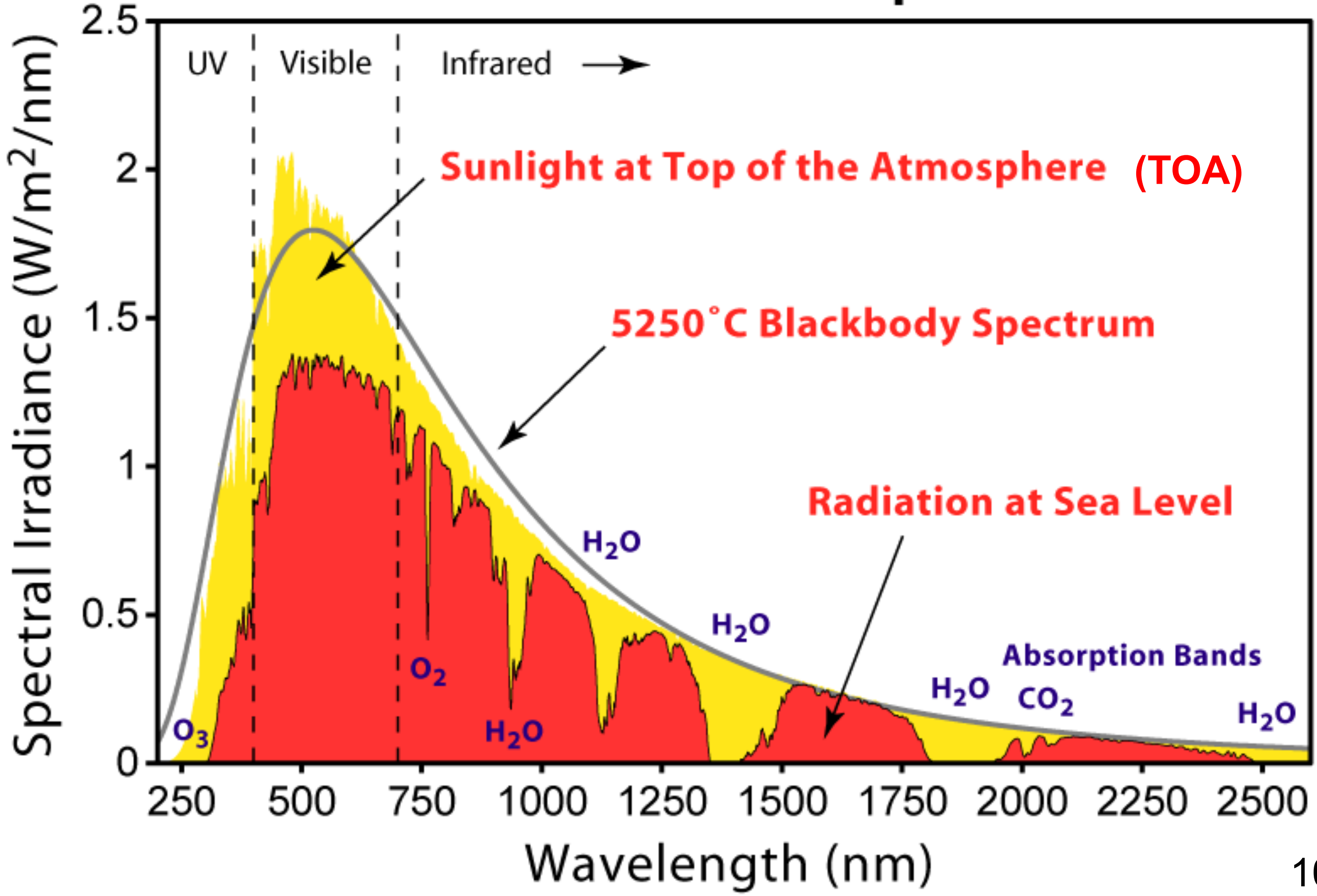
Thanks to: Bill Collins, Berkeley & LBL

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

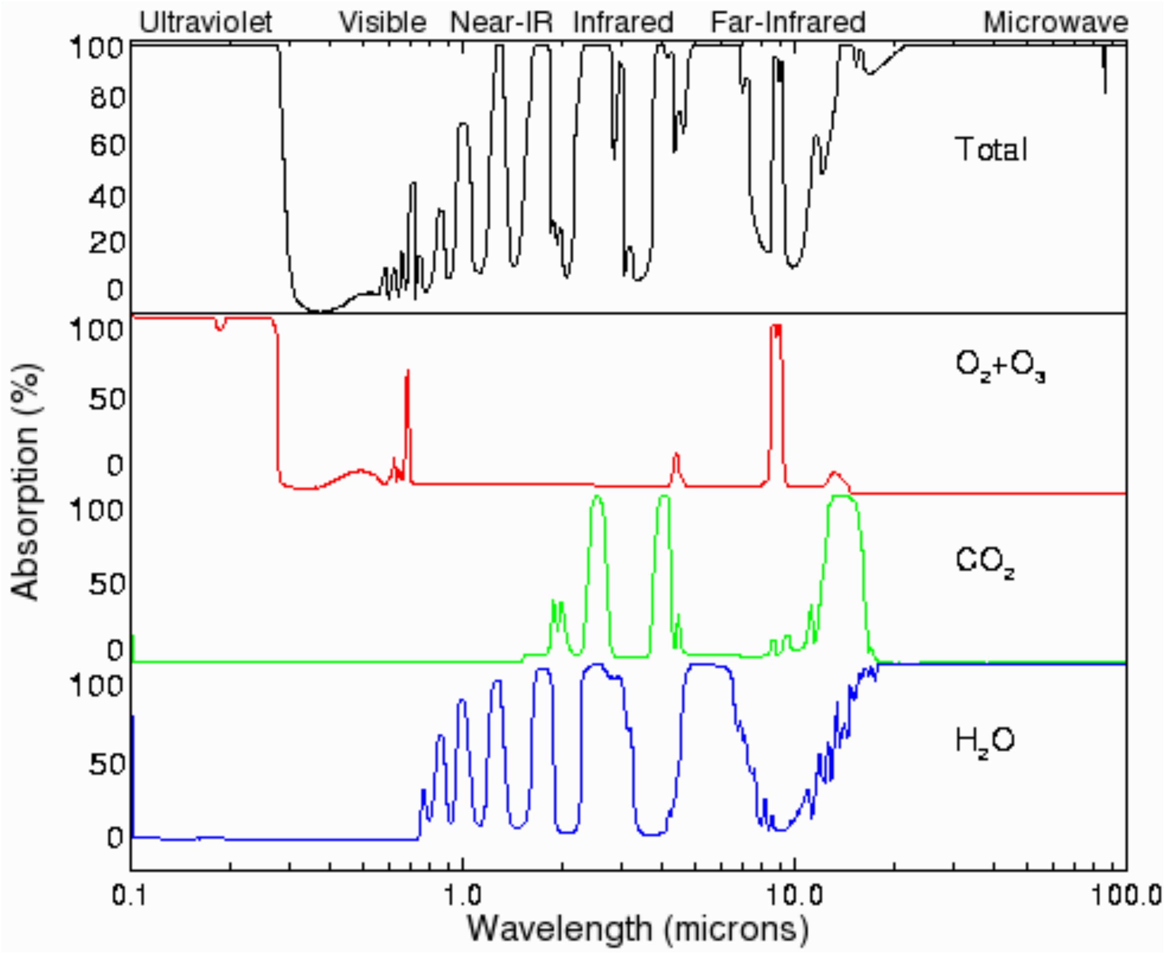


1000nm = 1μm

Input at TOA, Radiation at surface

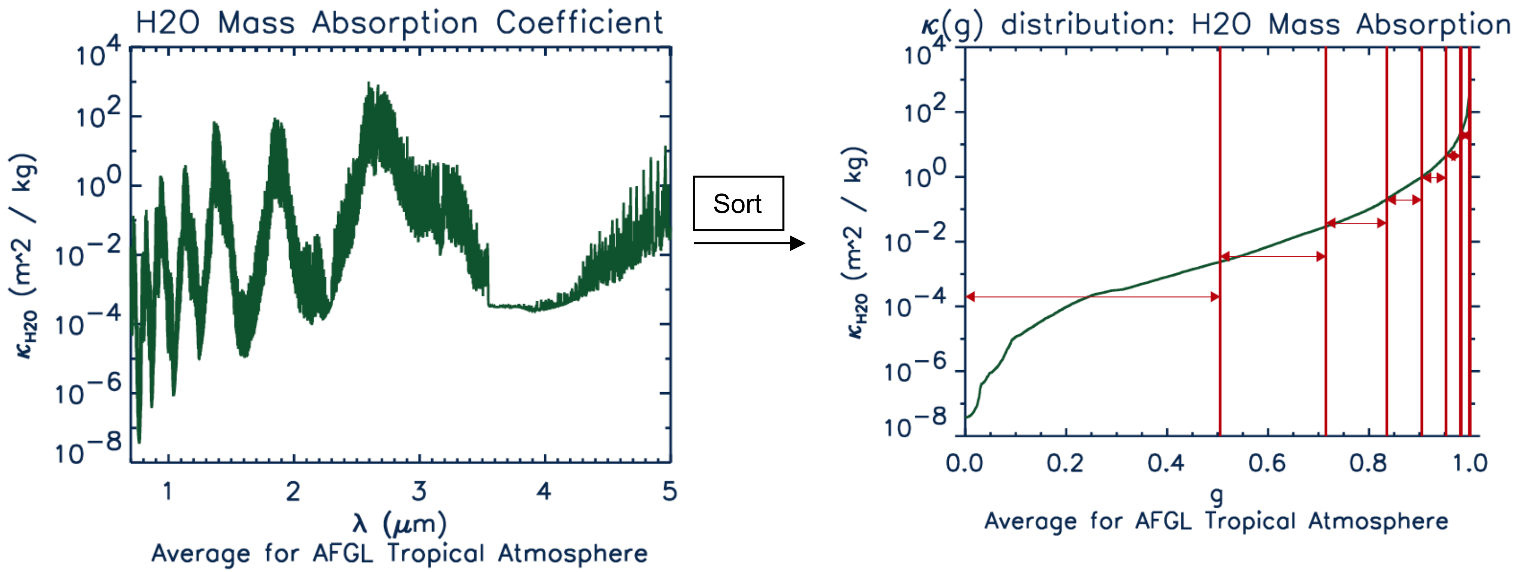
From: 'Sunlight', Wikipedia

IR absorption



1000nm = 1μm

k-distribution Band Models



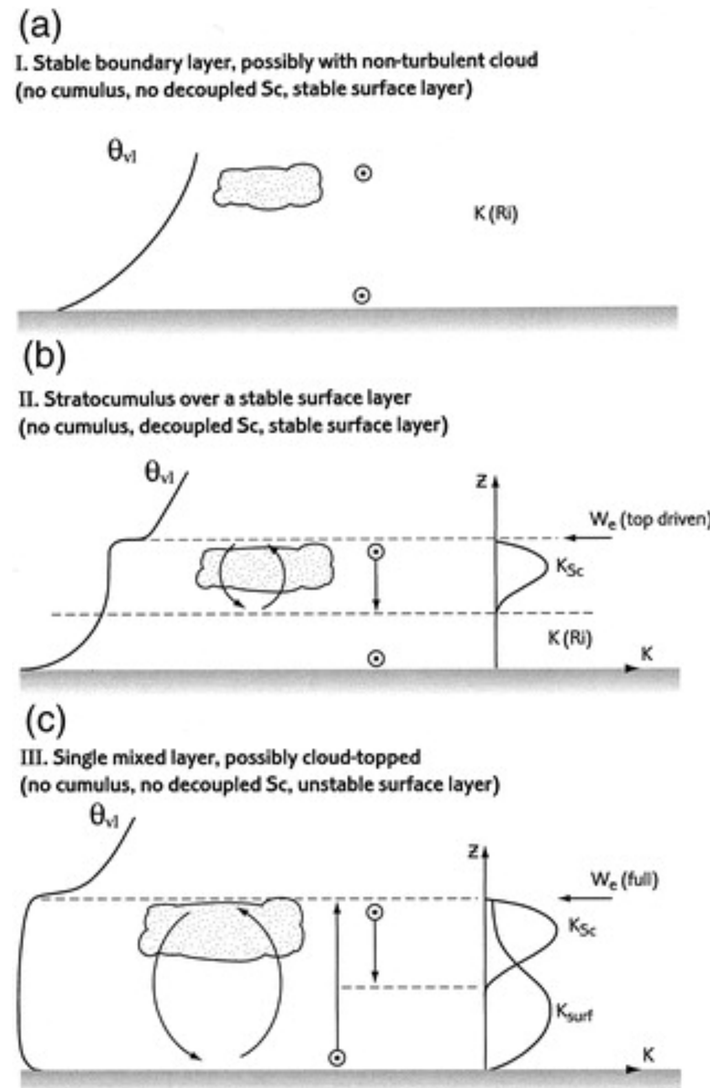
- Line-by-line calculations
- **Very expensive/slow, accurate**

- 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 θ_{vl})
- **Conserved** for rapidly well mixed PBL
- **Not conserved** for stable PBL
- Critical determinant is the presence of turbulence
- **Richardson number** $\mathrm{Ri} = \frac{g\beta}{(\partial u/\partial z)^2}$,
- <<1, flow becomes turbulent

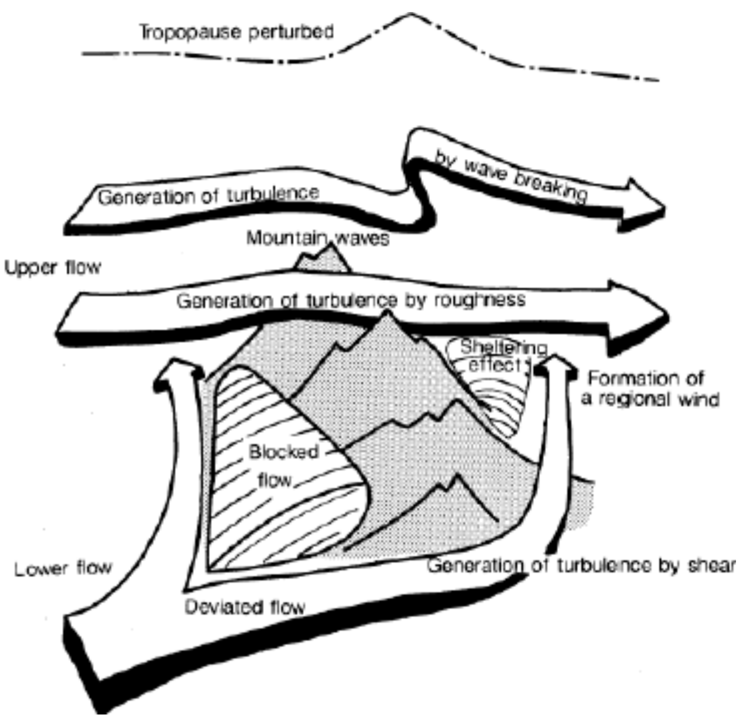


- CAM4: Gradient Ri # + non-local transport (Holtslag and Boville, 1993)
- CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)

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)

Stresses

$$\tau_x = -\rho_1 \overline{(u'w')} = -\rho_1 u_*^2 (u_1/V_a) = \rho_1 \frac{u_s - u_1}{r_{am}}$$

$$\tau_y = -\rho_1 \overline{(v'w')} = -\rho_1 u_*^2 (v_1/V_a) = \rho_1 \frac{v_s - v_1}{r_{am}}$$

Specific Heat

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

Latent heat (evaporation)

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

- Resistances r_{ax} based on
  - Monin-Obhukov similarity theory

Parameterization Interactions

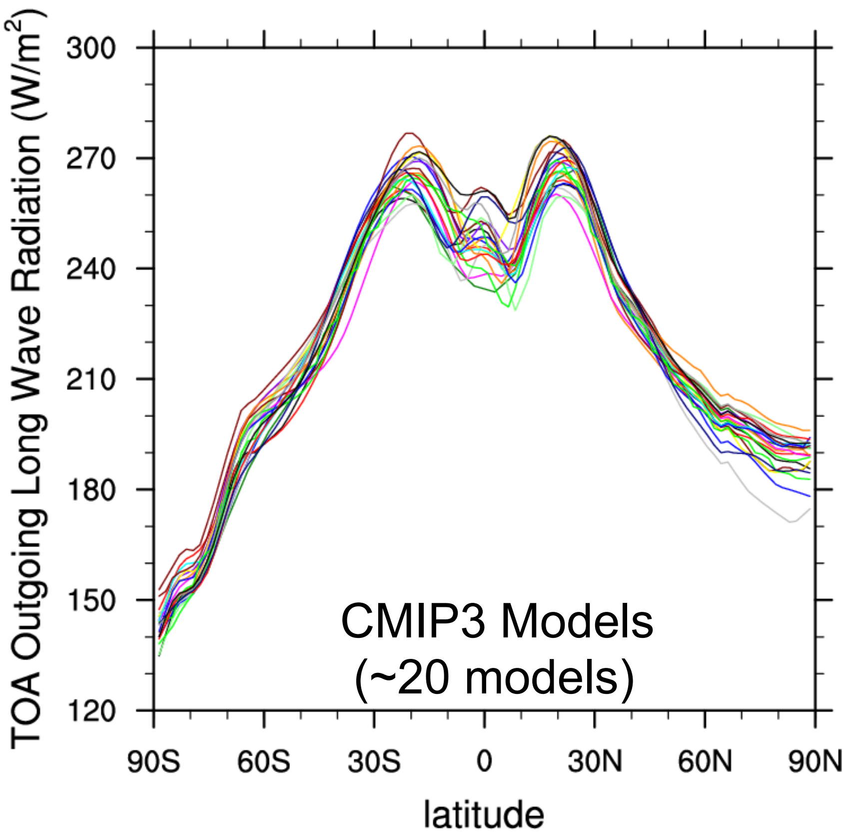
Direct and Indirect Process Communication

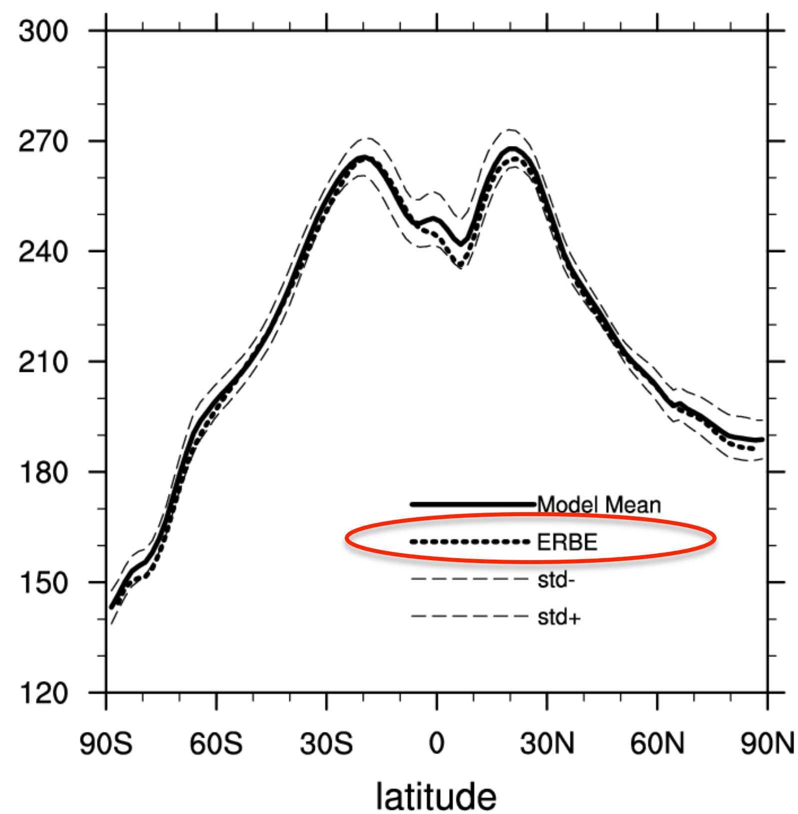
- Cloud Processes & Radiation
  - Feedbacks
- Boundary Layer / Cumulus & Dynamics
- Precipitation & Scavenging
  - Chemical (gas phase) constituents
  - Aerosols (condensed phase constituents)
- Microphysics and Aerosols
- Physics and surface components (ice, land, ocean)
- Resolved scales and unresolved scales

Clouds in GCMs

State of the Art from CMIP3

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

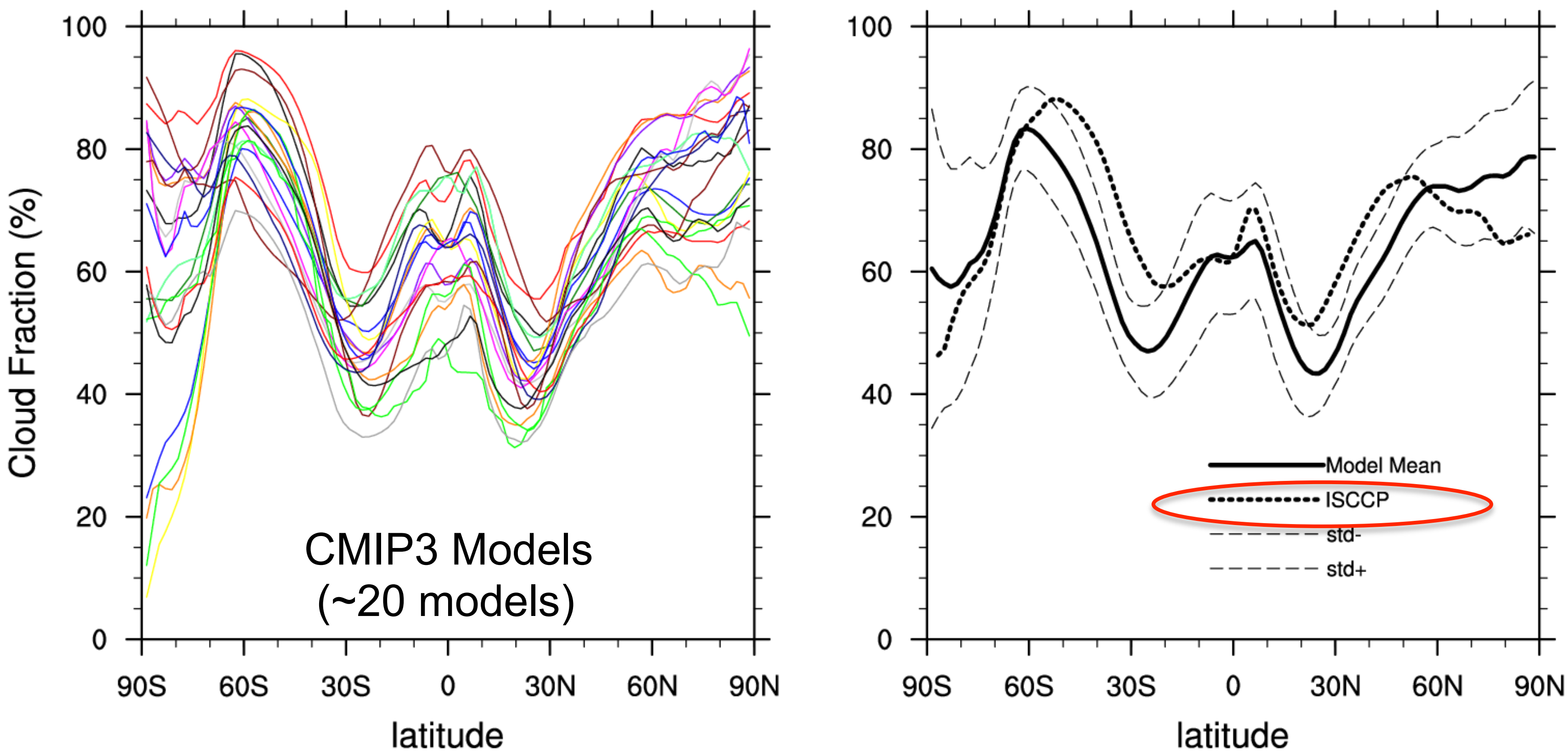




Clouds in GCMs

State of the Art from CMIP3

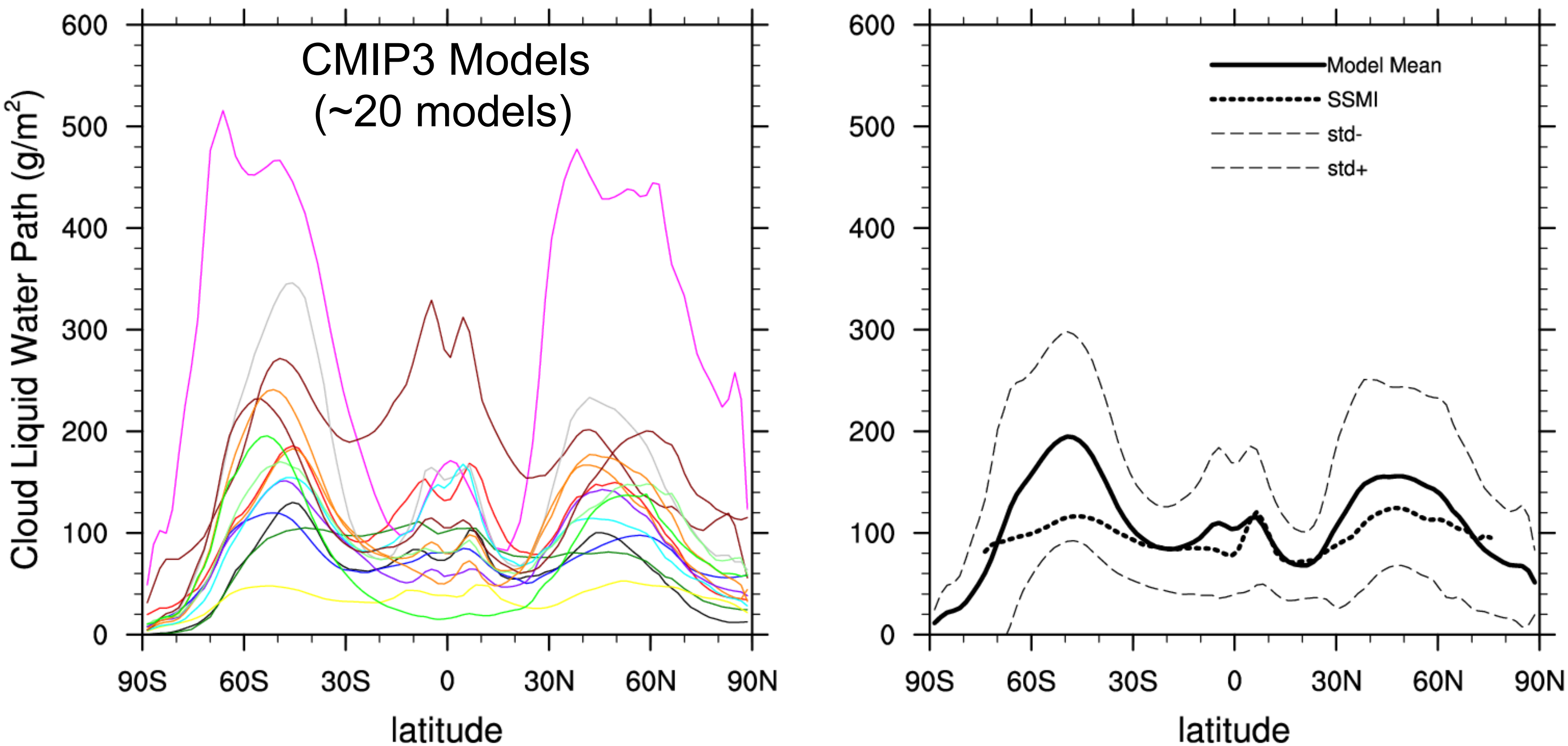
Total Cloud Fraction
(Annual, 1990-1999)



Structural Clouds in GCMs

State of the Art from CMIP3

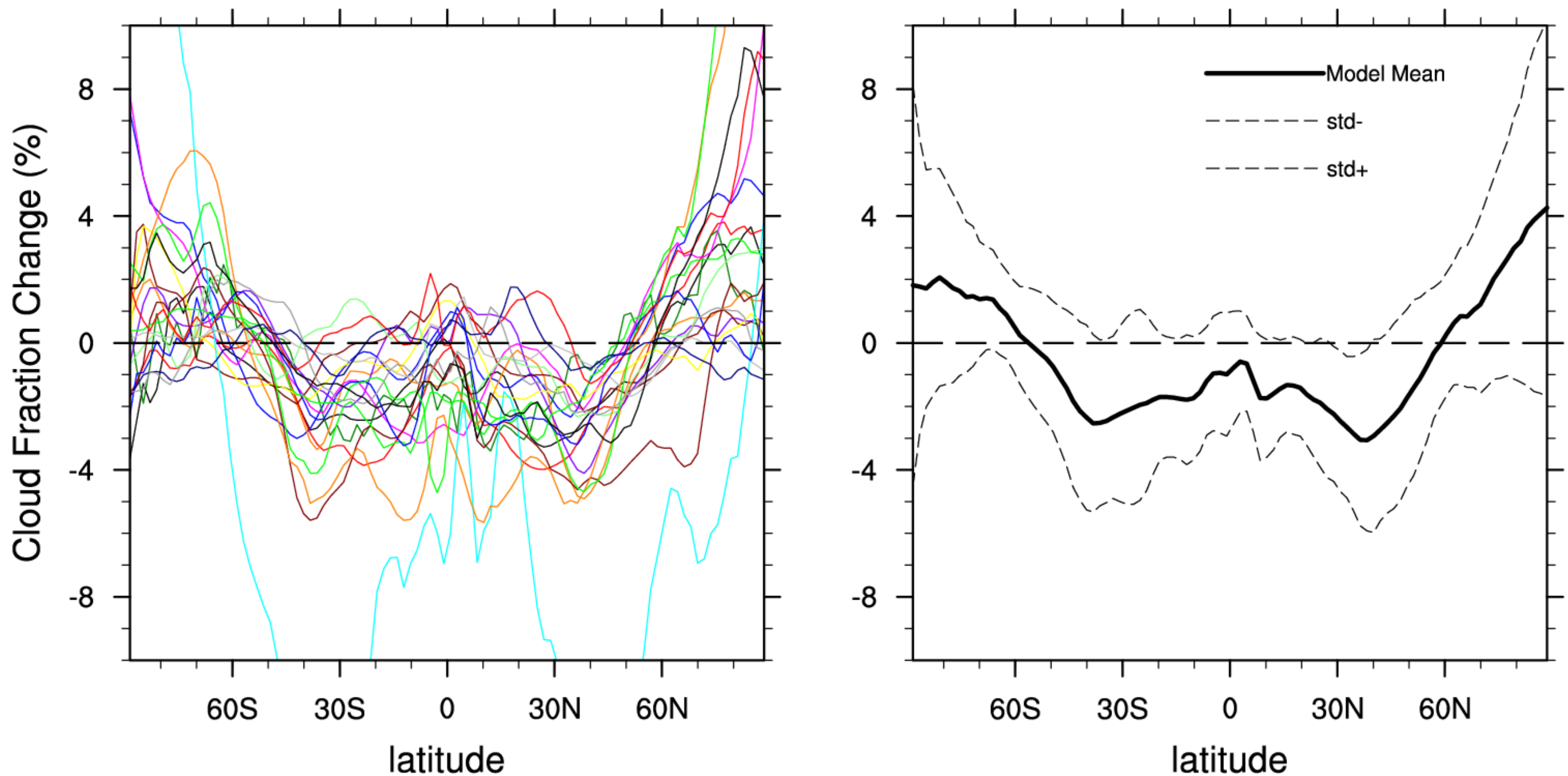
Liquid Water Path
(Annual, 1990-1999)



Future Clouds in GCMs

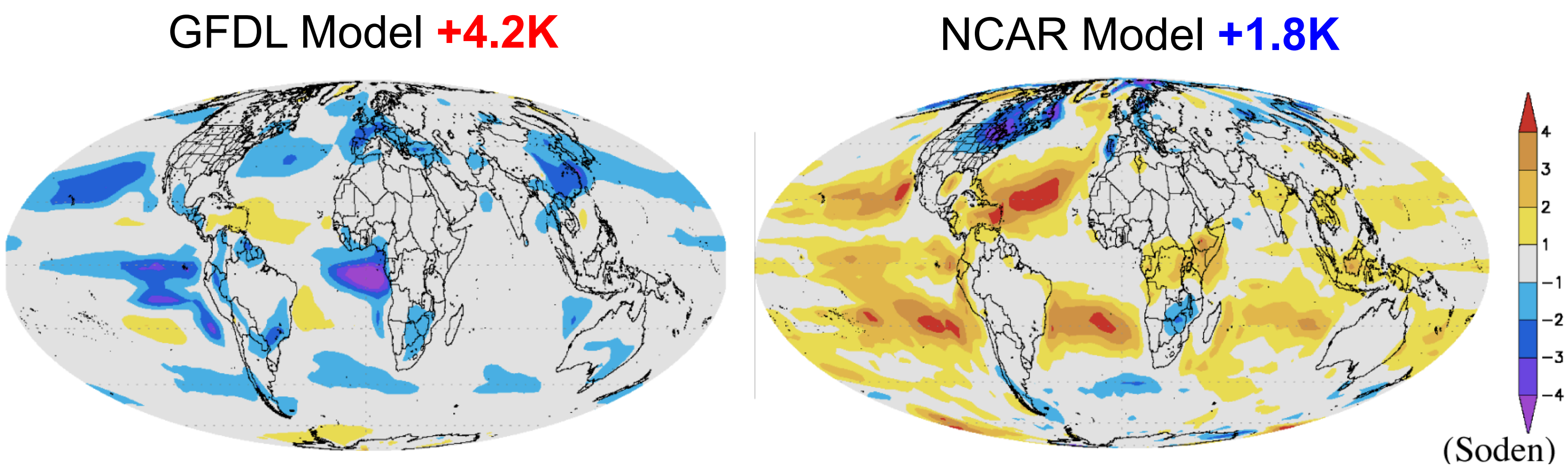
State of the Art from CMIP3 – response to climate change

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



Climate Sensitivity

What happens to clouds when we double CO_2?

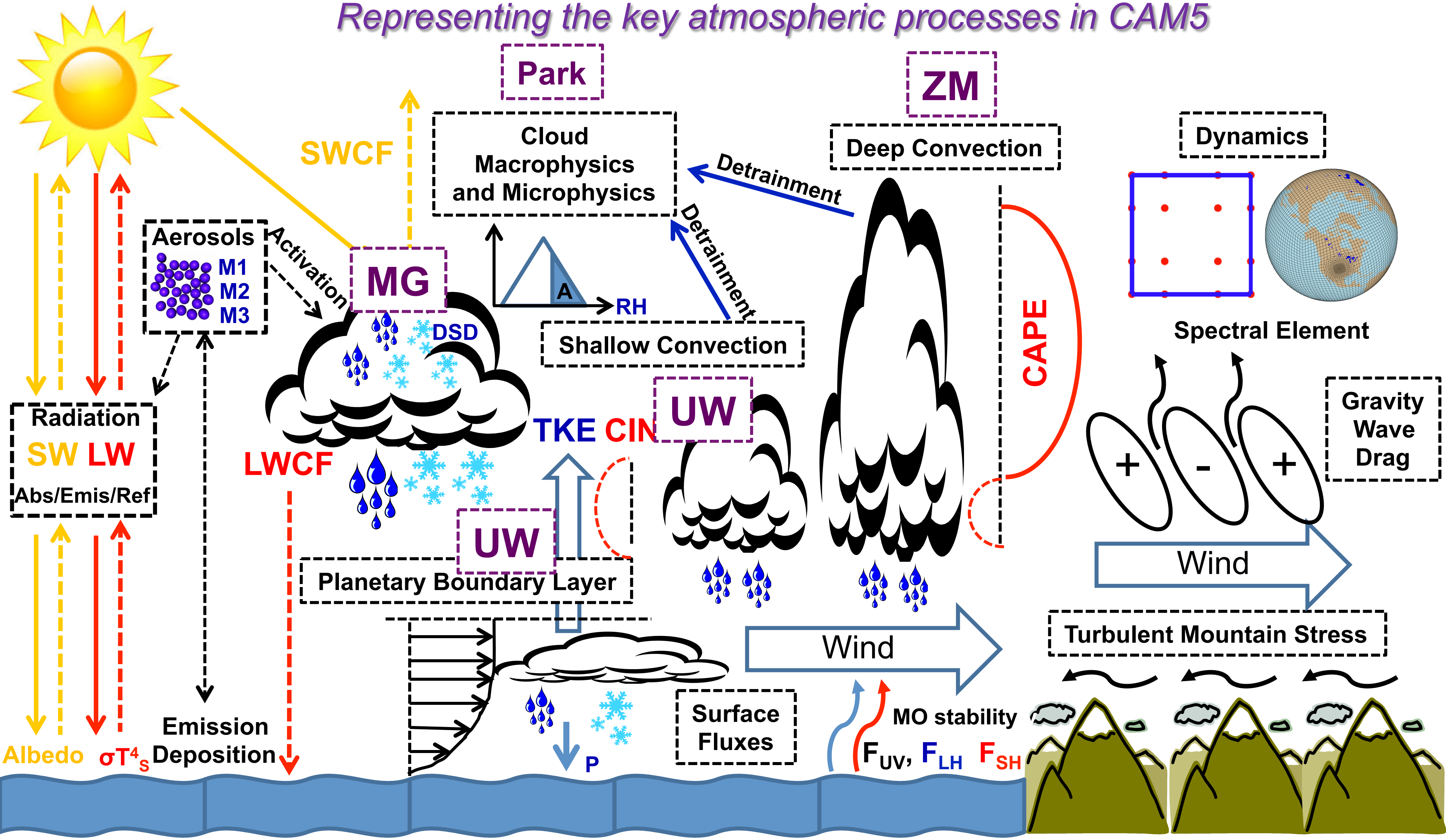


Change in low cloud amount (%)

- 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.**

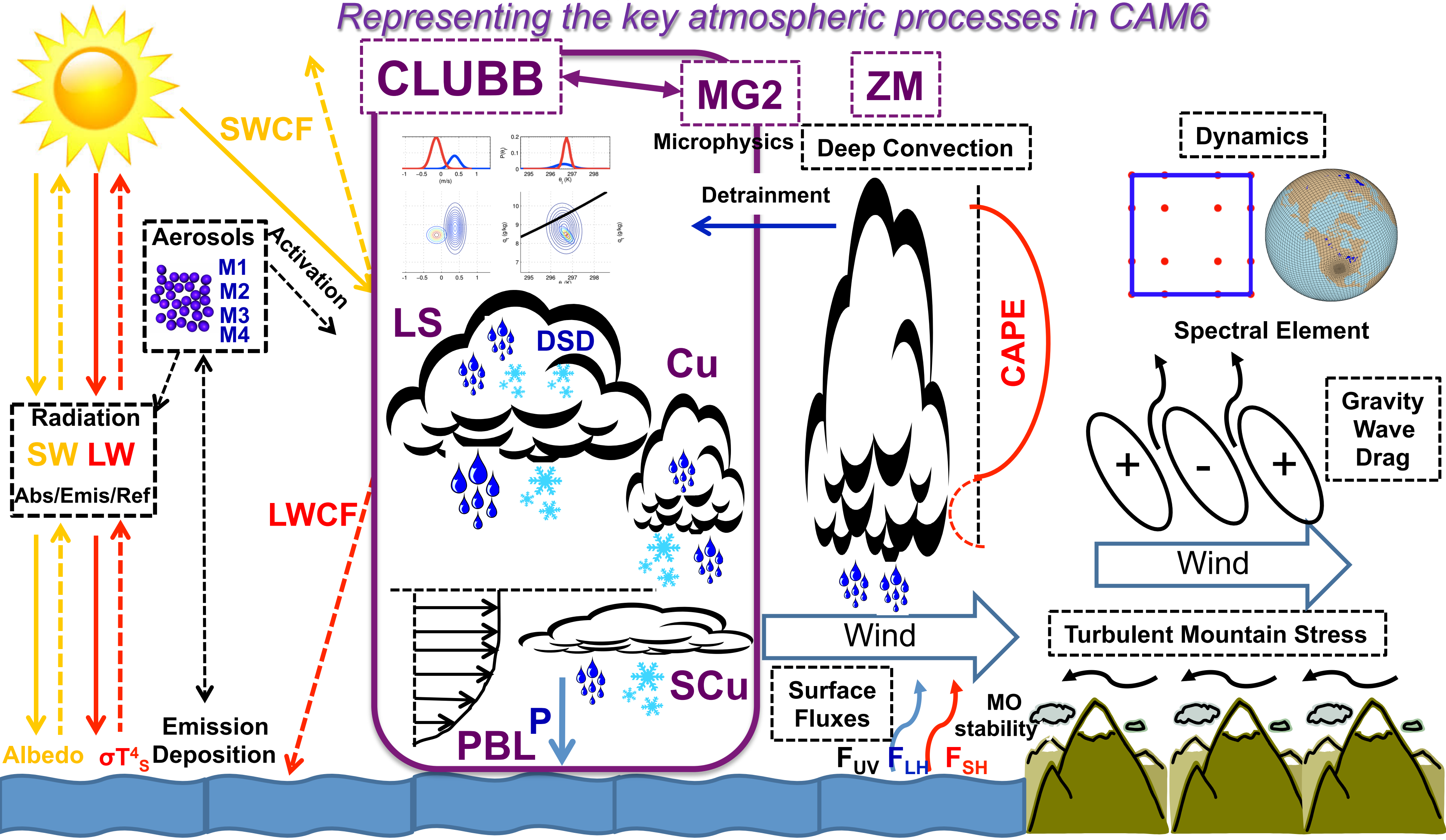
Community Atmosphere Model

Representing the key atmospheric processes in CAM5



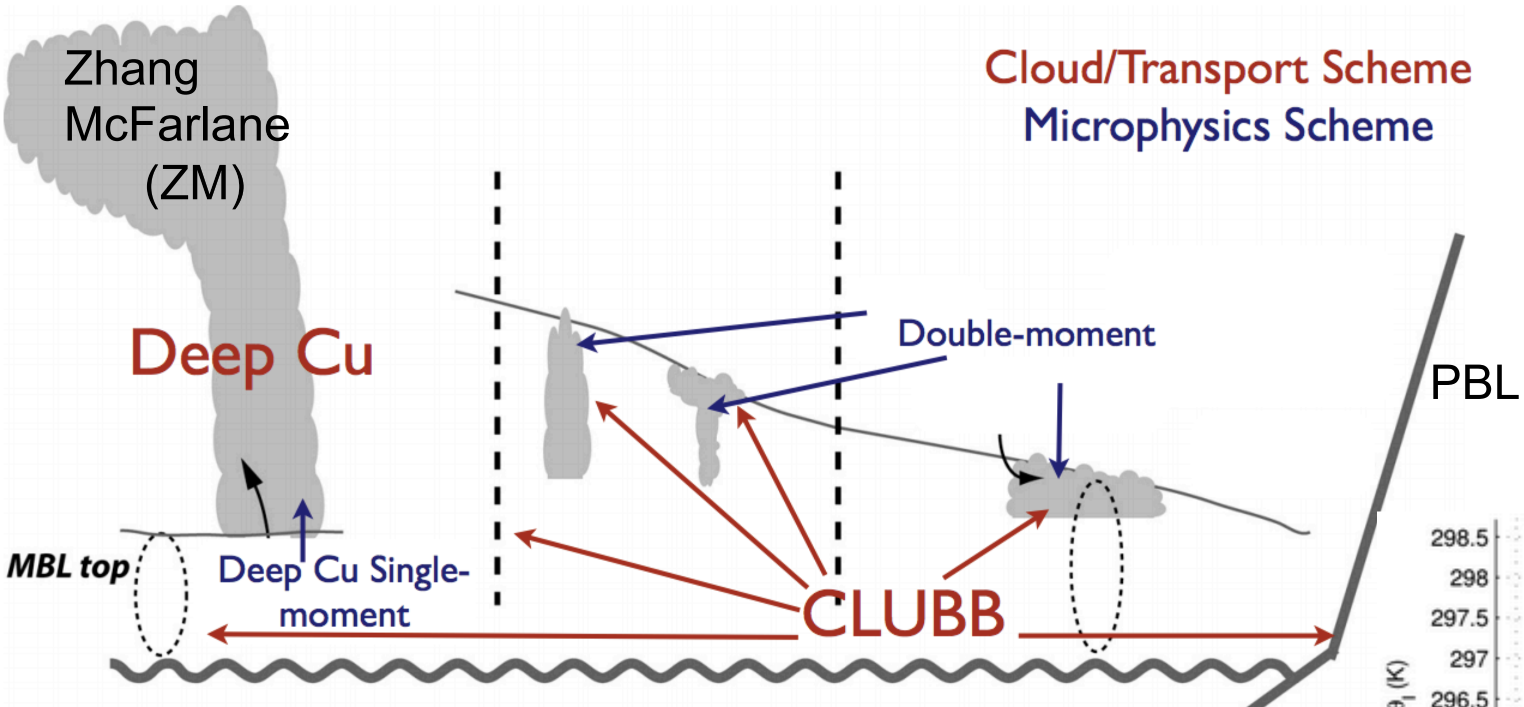
Community Atmosphere Model

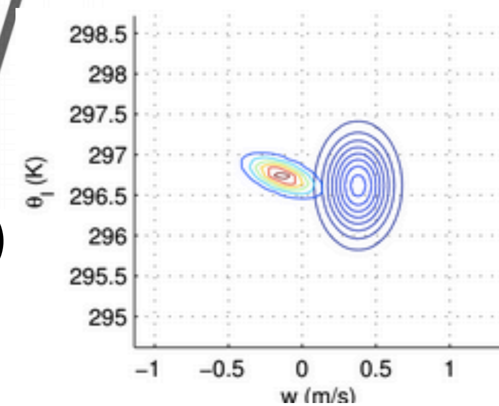
Representing the key atmospheric processes in CAM6



CLUBB: Cloud Layers Unified By Binormals

Golaz 2002b, J. Atmos. Sci.

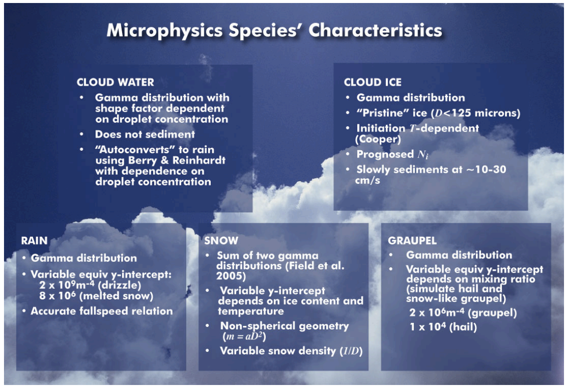




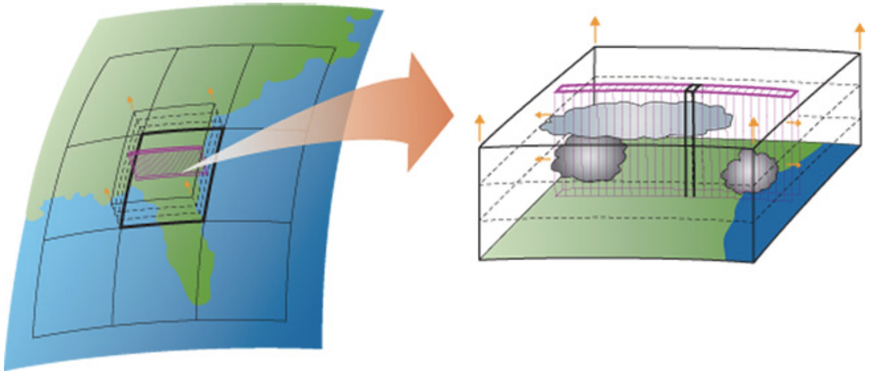
- Unifies moist and dry turbulence (except deep convection)
- Unifies microphysics
- High order closures (1 third order, 9 second order)
- Use two Gaussians to described the sub-grid multivariate PDF: $P=P(w,q_t,\theta_L)$

Model physics: The future

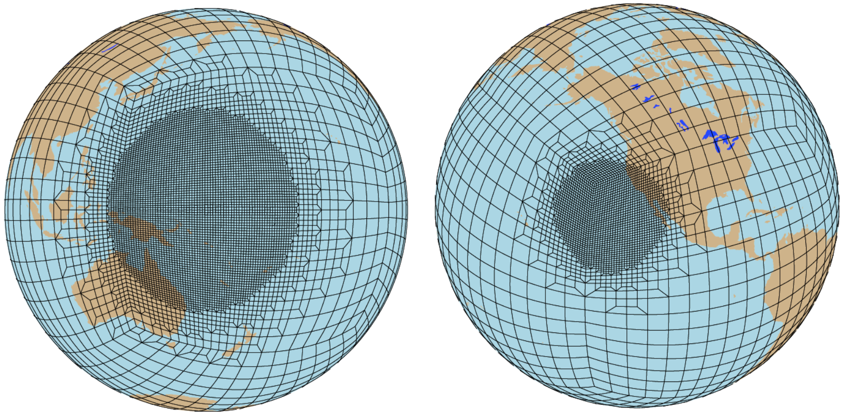
- 1. How to operate in varying grid scale environments
- 2. Advanced representation of processes.



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?