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

CESM Tutorial

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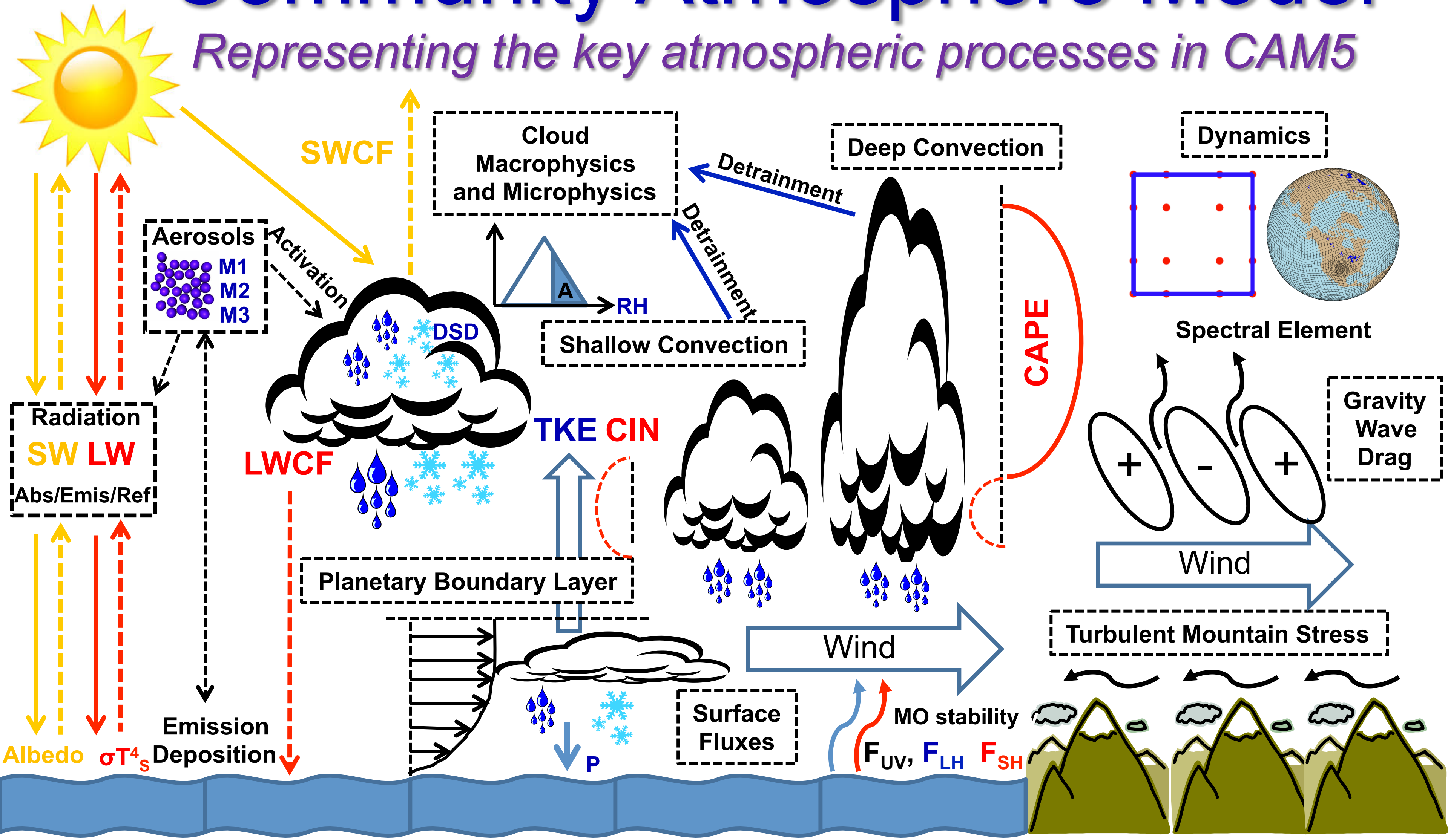
# Outline

- **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**

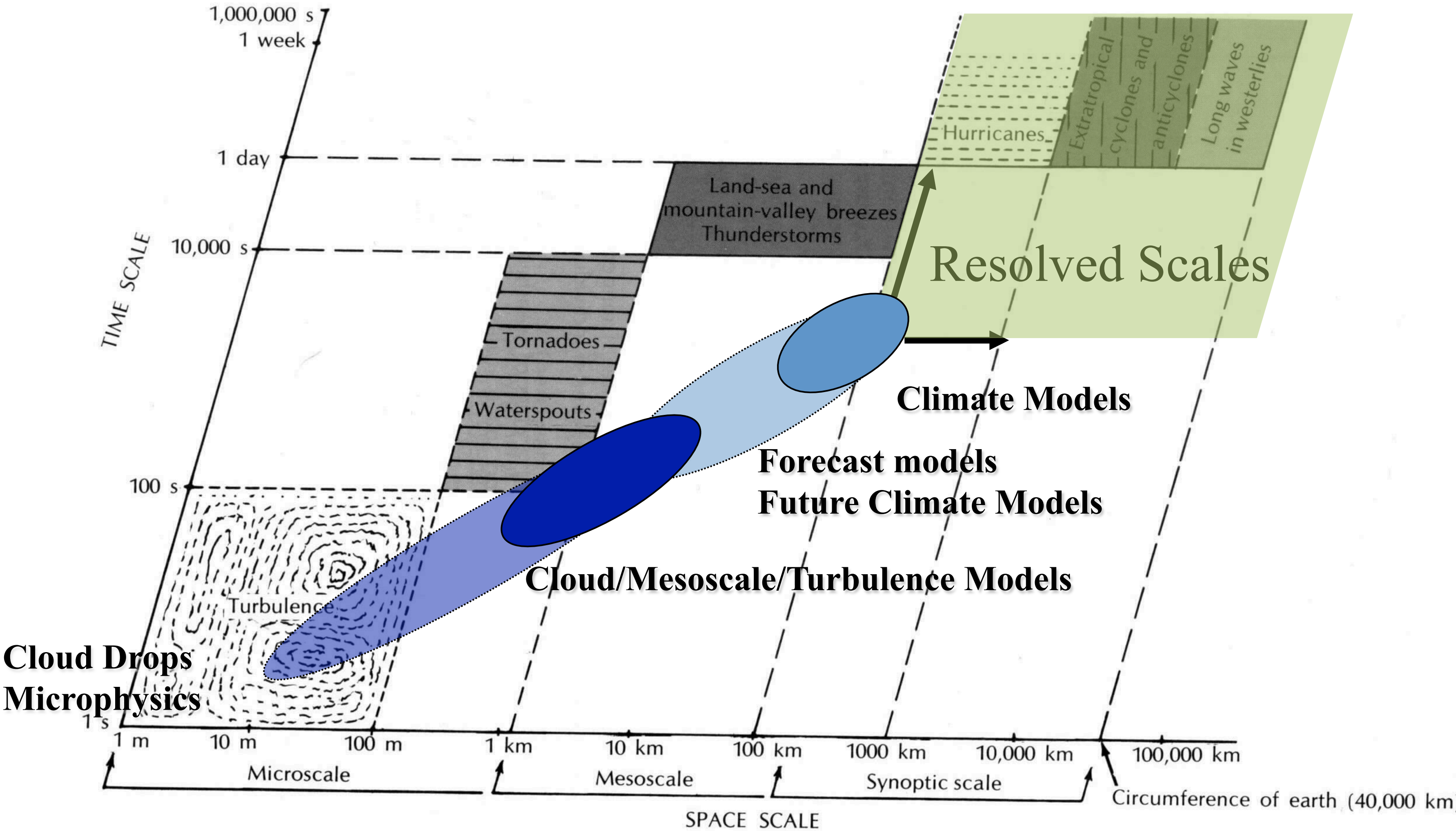
# Community Atmosphere Model

*Representing the key atmospheric processes in CAM5*



# 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)*

**Harmless looking terms F, $Q$, and $S_q \Longrightarrow$ "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,** $F_{tracers}$
  - 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


<u>Vertical eddy transport of X</u>

‘Diffusivity’

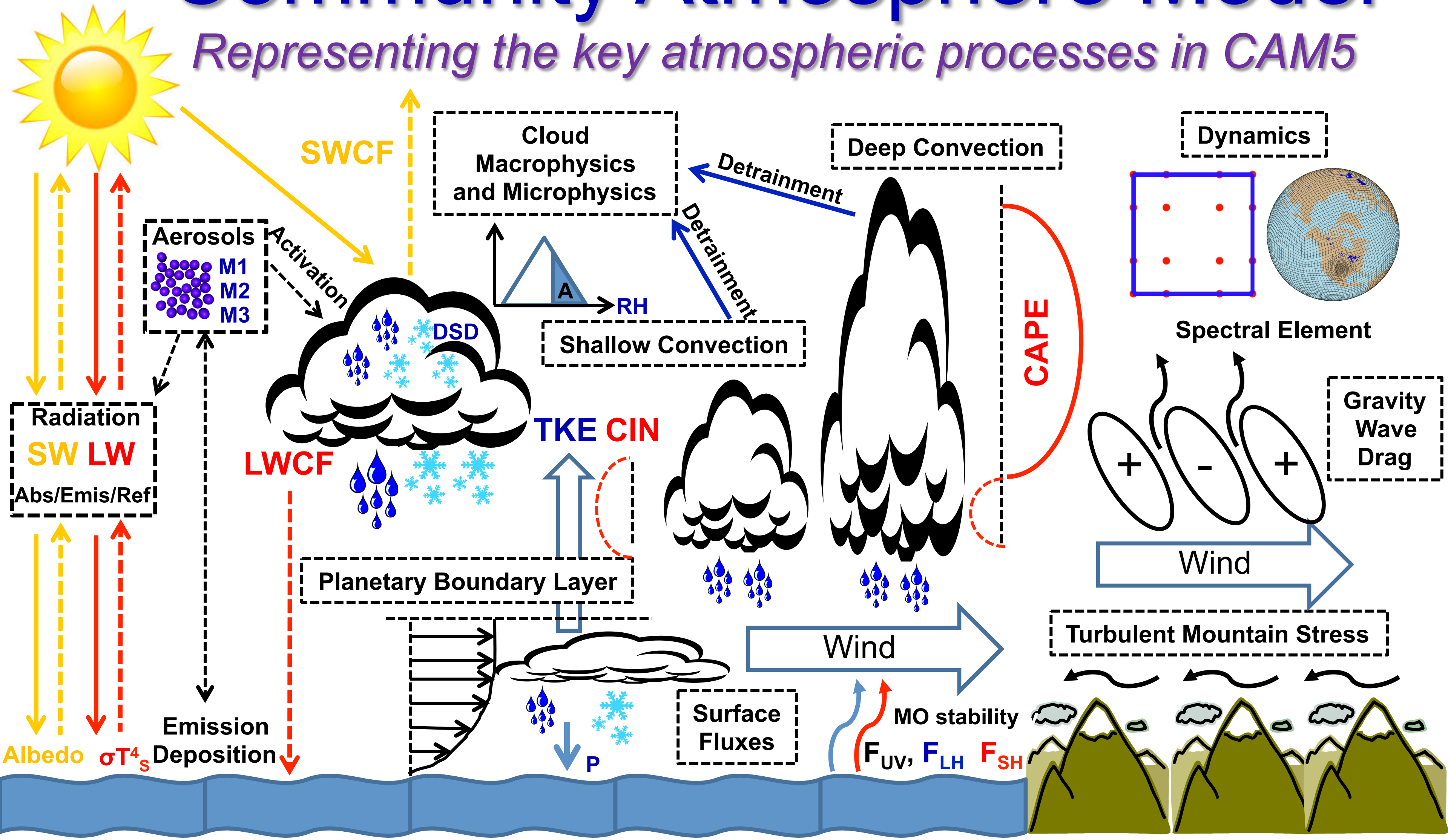
$$\overline{w'\chi'} = -K_\chi \frac{\partial \chi}{\partial z}$$

Unresolved ‘sub-grid’

Resolved ‘grid-scale’

# Community Atmosphere Model

*Representing the key atmospheric processes in CAM5*



# Clouds

# Clouds

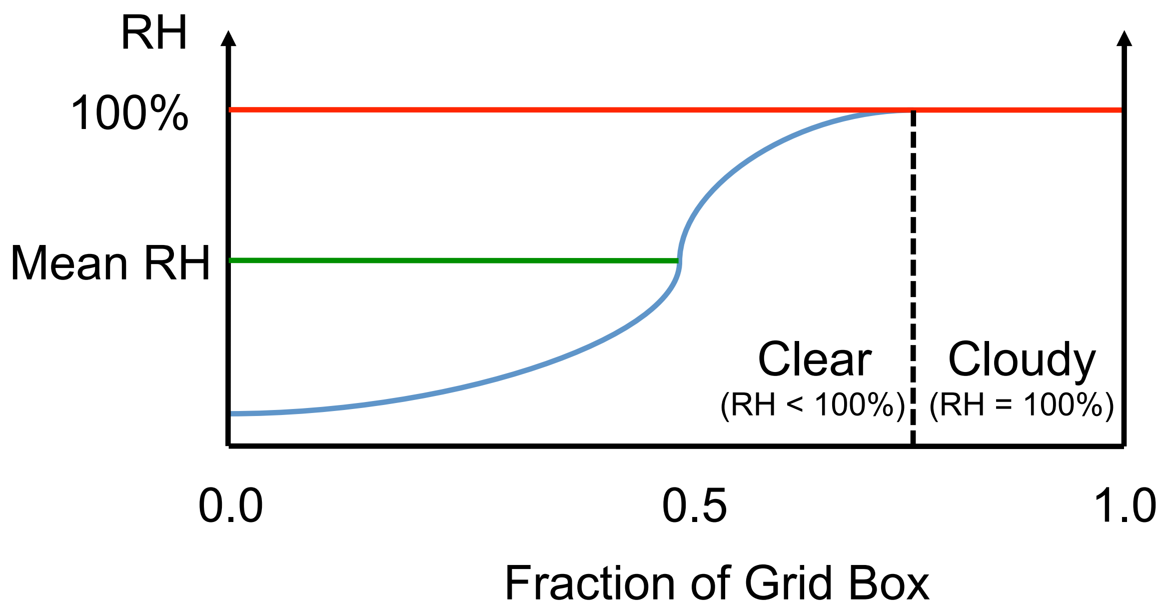
## Multiple Categories

- **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

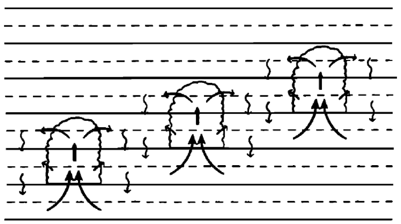
Large cloud radius small entrainment

# Shallow and Deep Convection

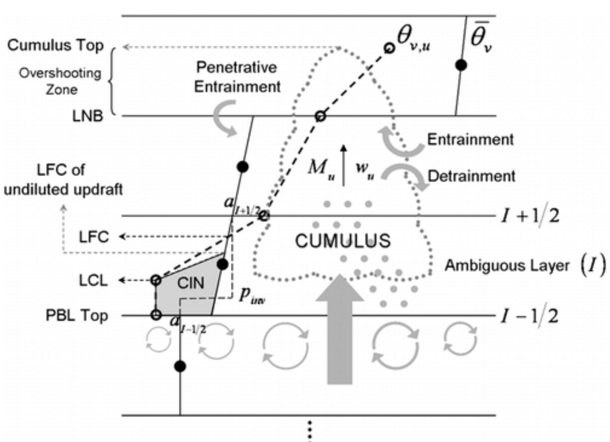
## Closure: How much and when?

### Shallow

Local conditional instability CAM4



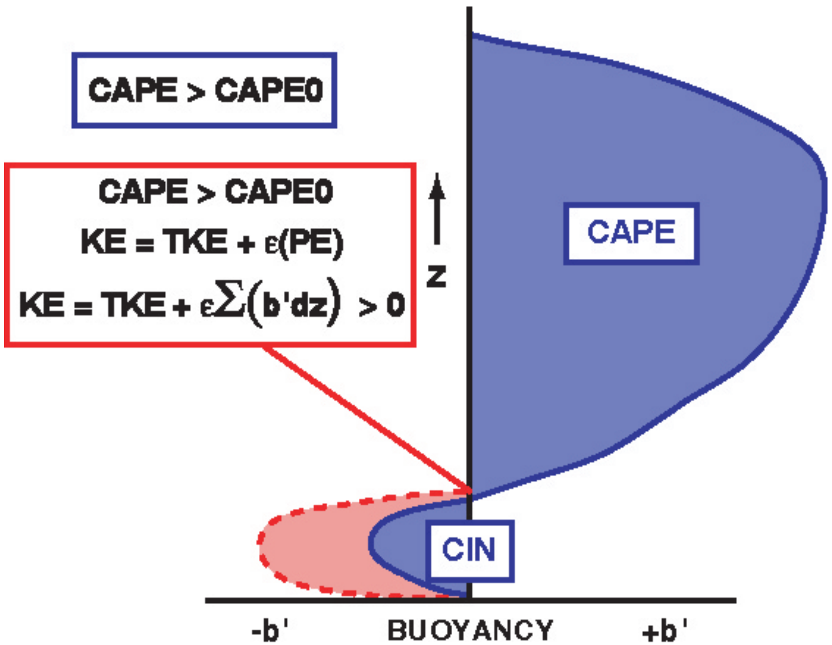
Convective inhibition and turbulent kinetic energy (TKE) CAM5




### 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

# 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

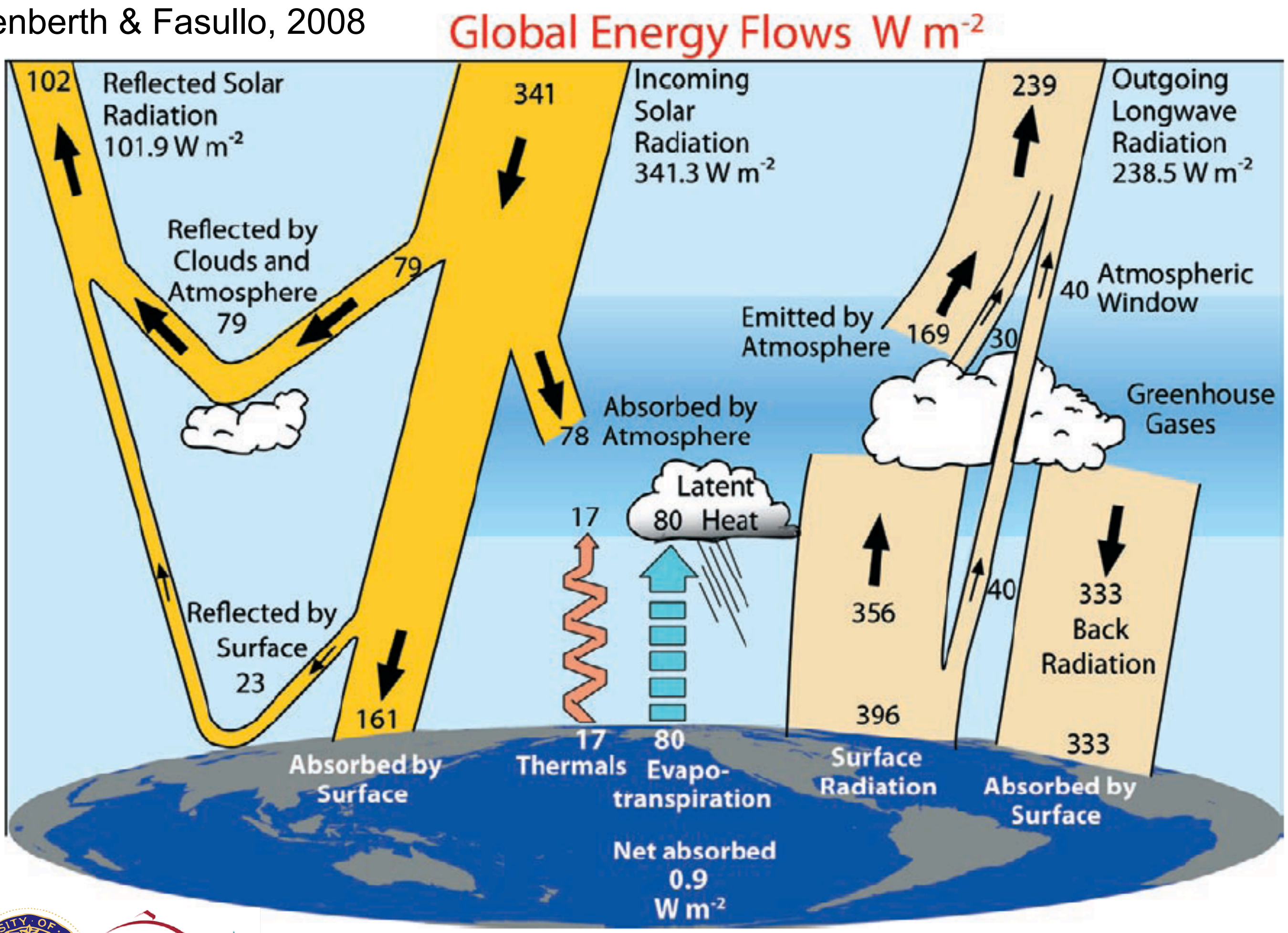
- **Modal Microphysics (MG-CAM5)**
  - Use an analytic representation of the size distribution and carry around moments of the distribution
  - First moment = mass; **2nd moment = number**
  - Size distribution reconstructed from an assumed shape.
  - Advantage: represent sizes consistently with computational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

$$PW\,AUT = C_{l,aut}\hat{q}_l^2 \rho_a/\rho_w(\hat{q}_l\rho_a/\rho_w N)^{1/3} H(r_{3l} - r_{3lc}).$$

# Radiation

## The Earth's Energy Budget

Trenberth & Fasullo, 2008

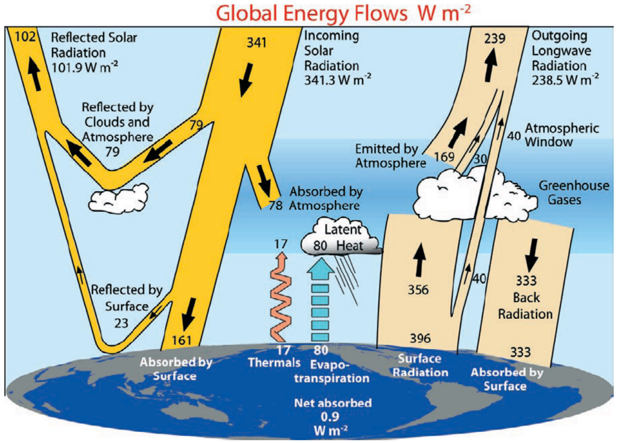



| Gas | SW Absorption ($Wm^{-2}$) |
|---|---|
| $CO_2$ | 1 |
| $O_2$ | 2 |
| $O_3$ | 14 |
| $H_2O$ | 43 |

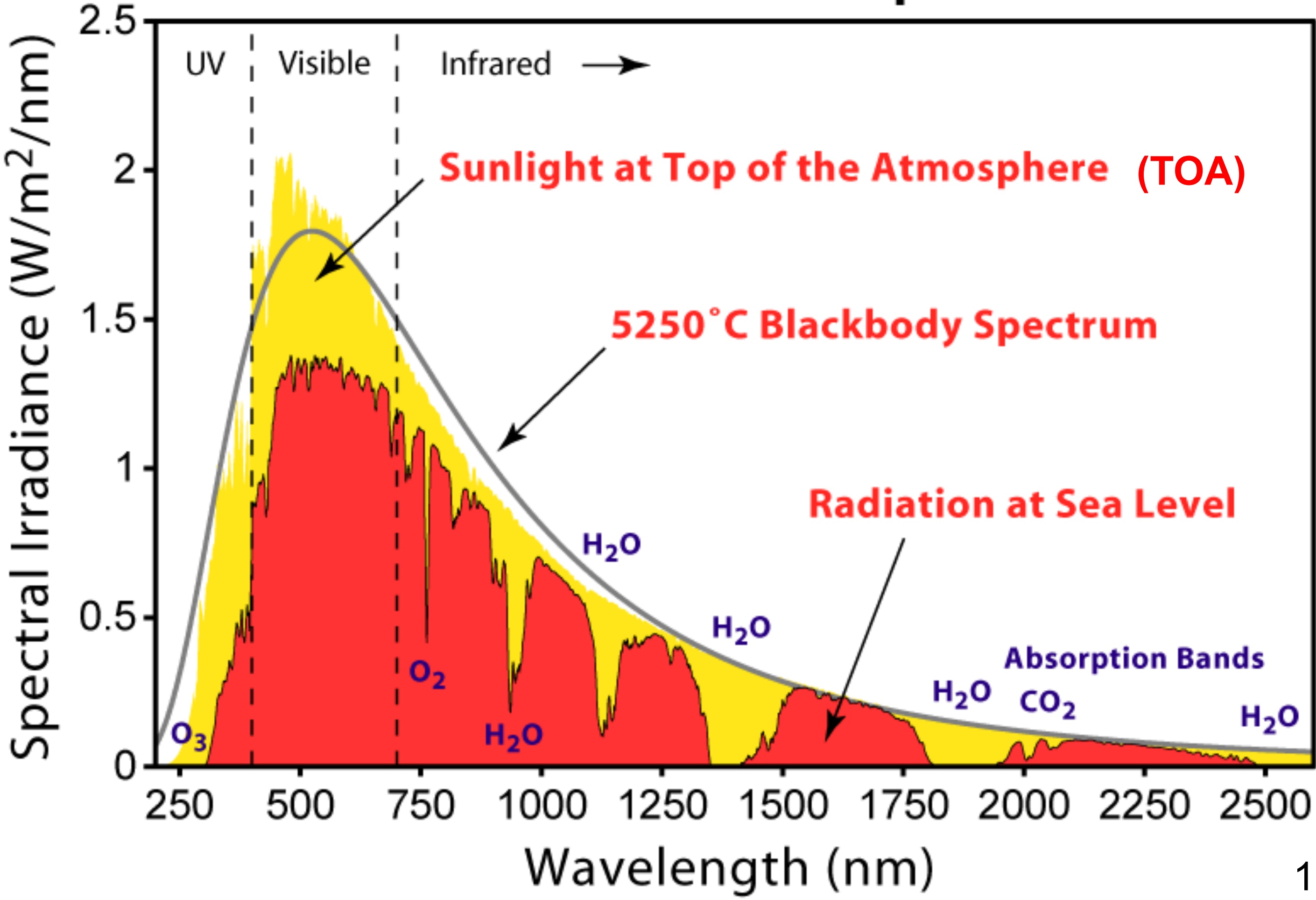
Thanks to: Bill Collins, Berkeley & LBL

# 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

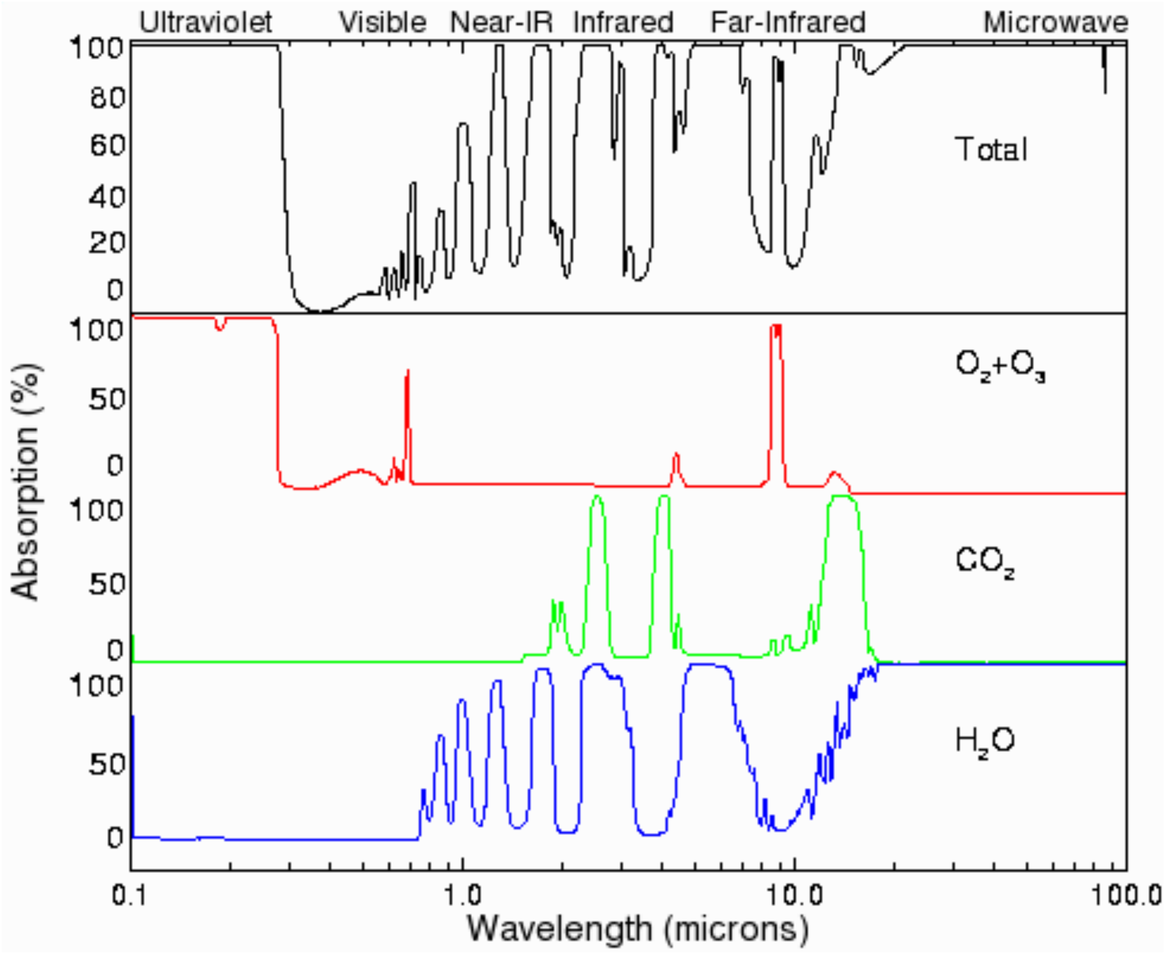



1000nm = 1μm

Input at TOA, Radiation at surface

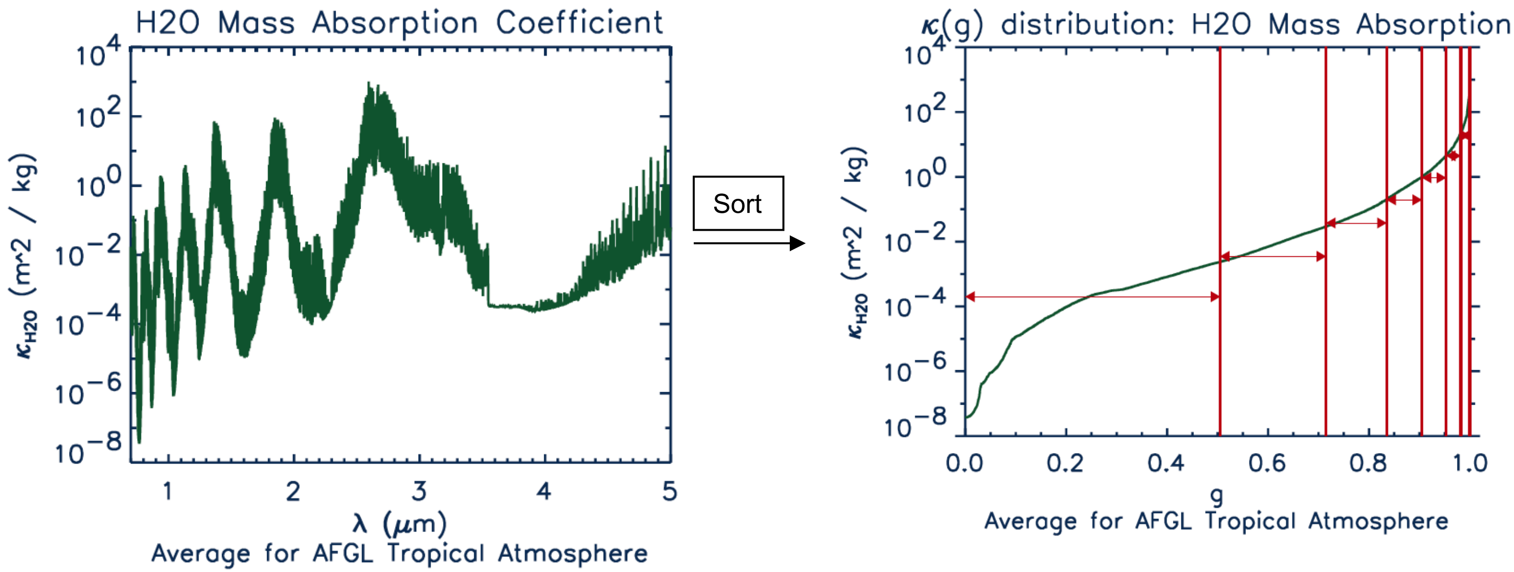
From: ‘Sunlight’, Wikipedia

# IR absorption




1000nm = 1μm

# k-distribution Band Models




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

$$T(u \; \hat{T}(u) \simeq \sum_{i=1}^{N} \exp[-\hat{\kappa}_i u]\; \delta g_i \; dg$$

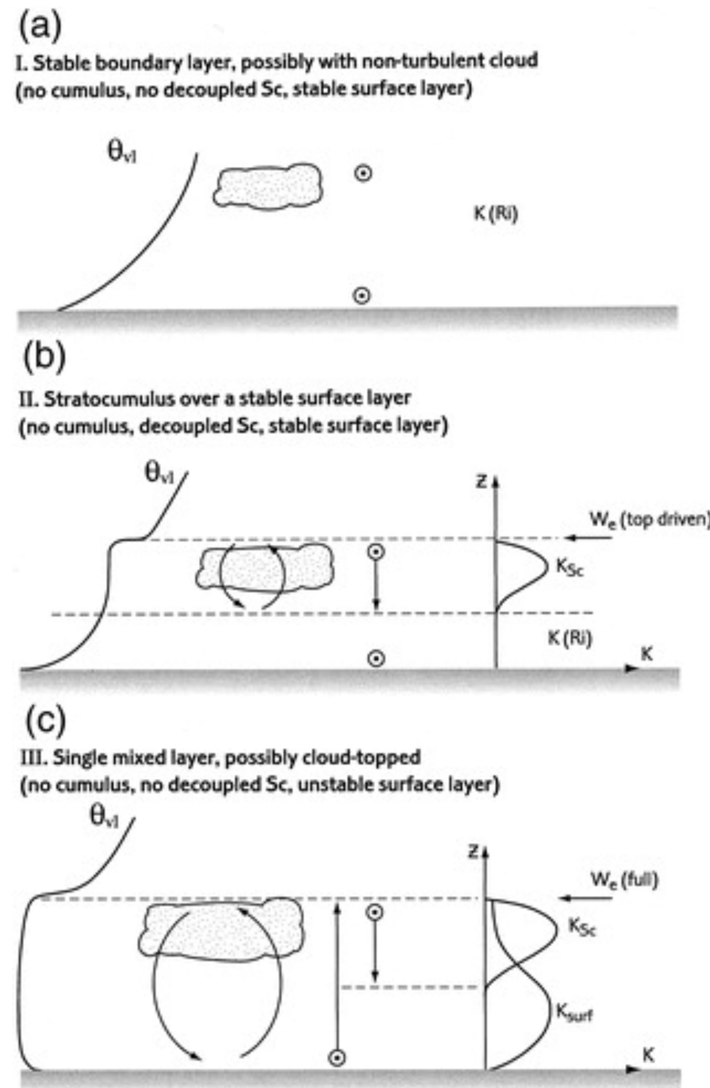
- Line-by-line calculations
- **Very expensive/slow, accurate**

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

# Planetary Boundary Layer (PBL)

## Regime dependent representations

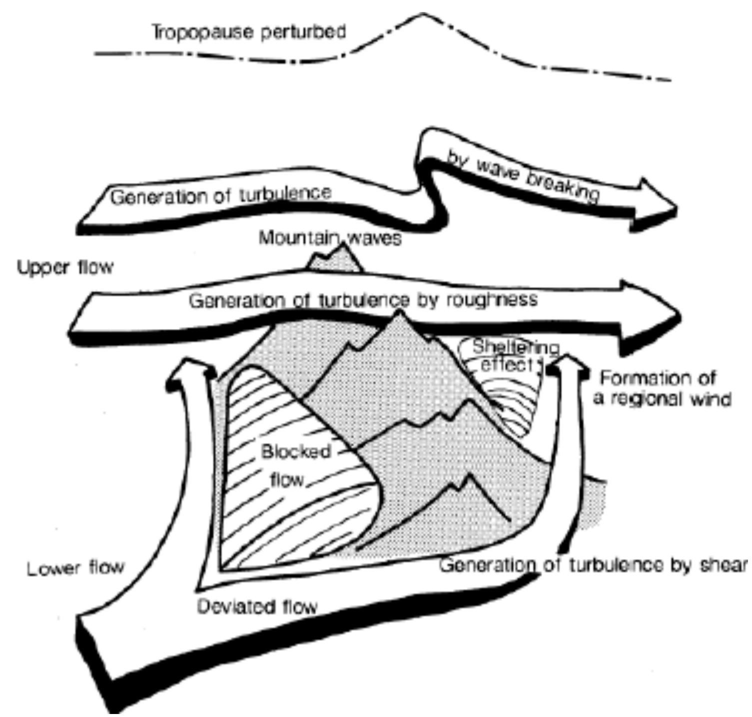
- Vital for near-surface environment (humidity, temperature, chemistry)
- Exploit **thermodynamic conservation** (liquid virtual potential temperature $\theta_{vl}$)
- **Conserved** for rapidly well mixed PBL
- **Not conserved** for stable PBL
- Critical determinant is the presence of turbulence
- **Richardson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

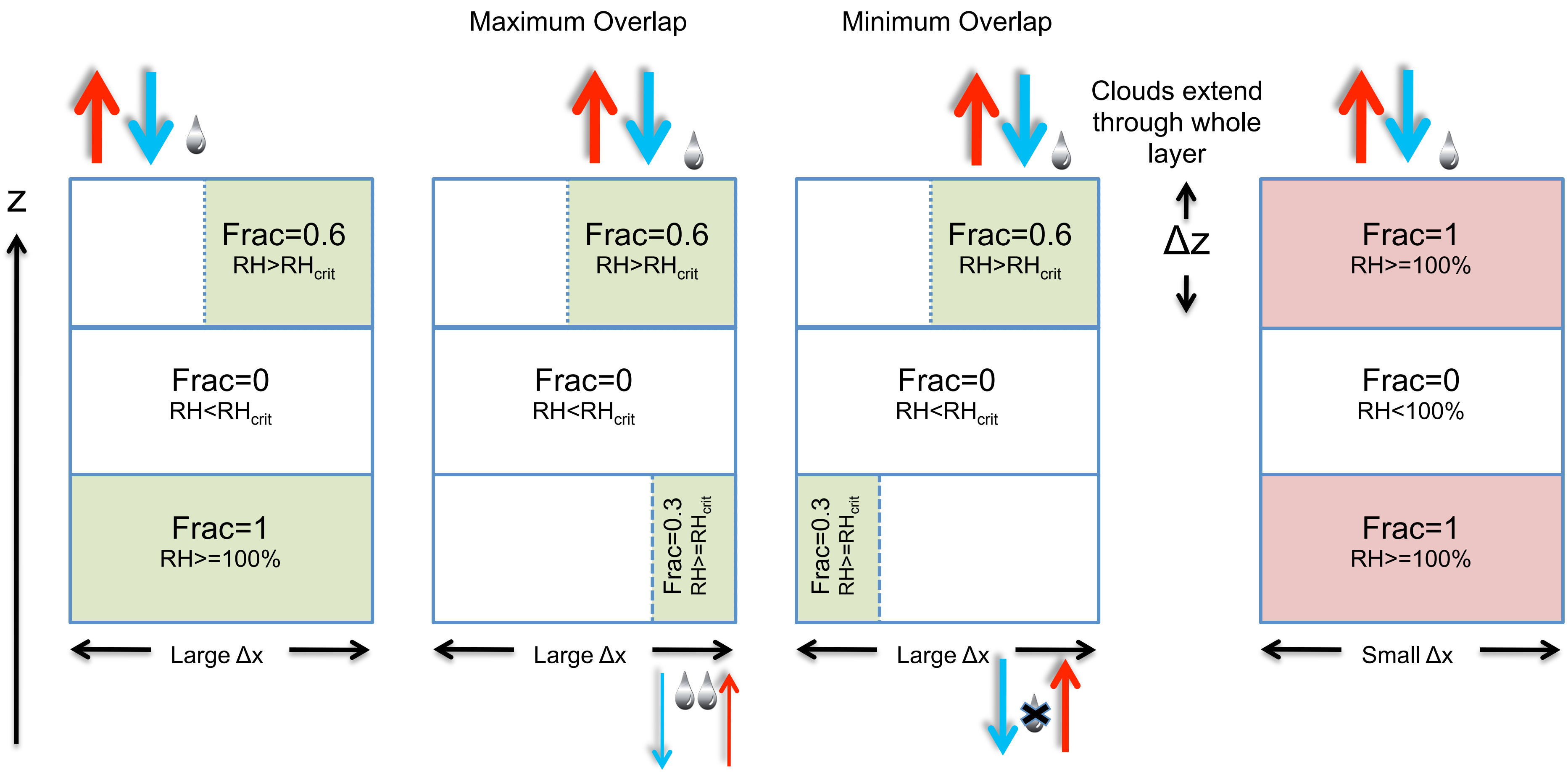
# Parameterization Interactions

## 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

# The Cloud Overlap Challenge

## Radiation and micro/macro-physics impact

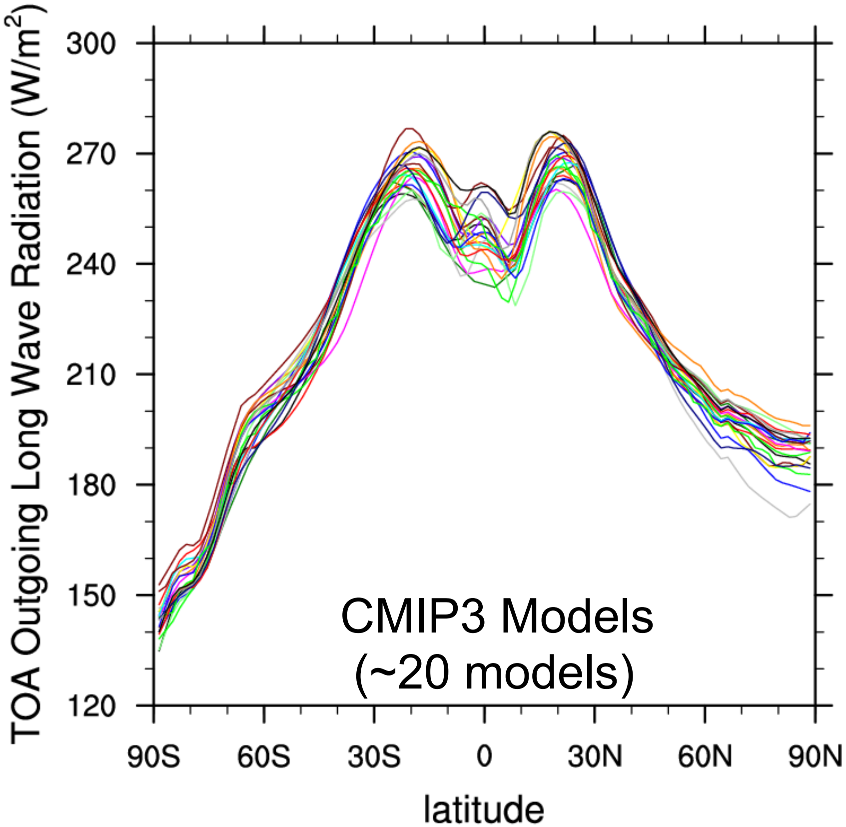


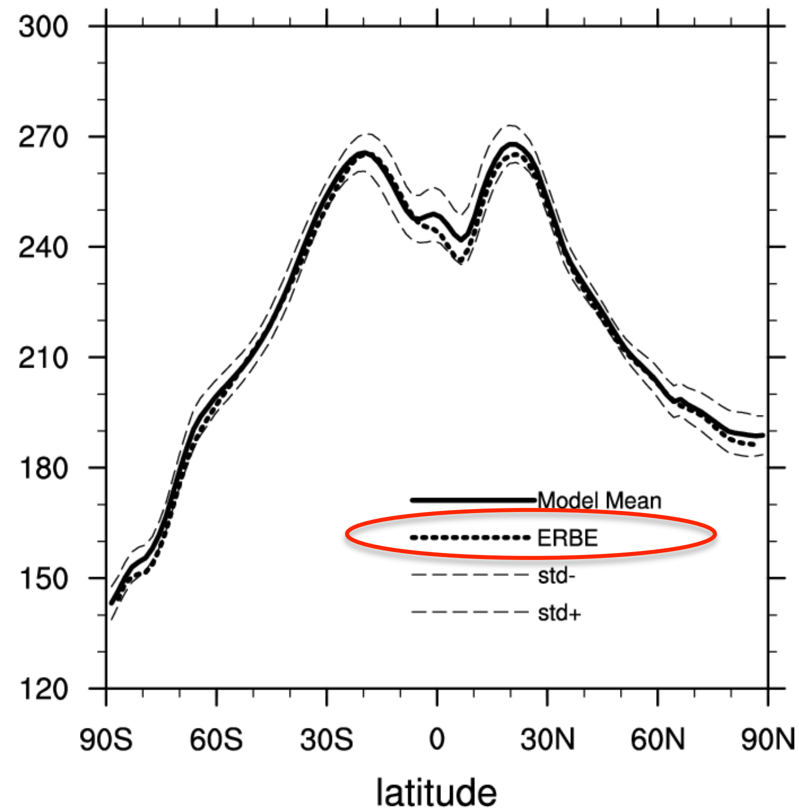

- Contiguous cloudy layers generally maximally overlapped
- Non-contiguous layers randomly overlapped; function of de-correlation length-scale

# Clouds in GCMs

## State of the Art from CMIP3

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

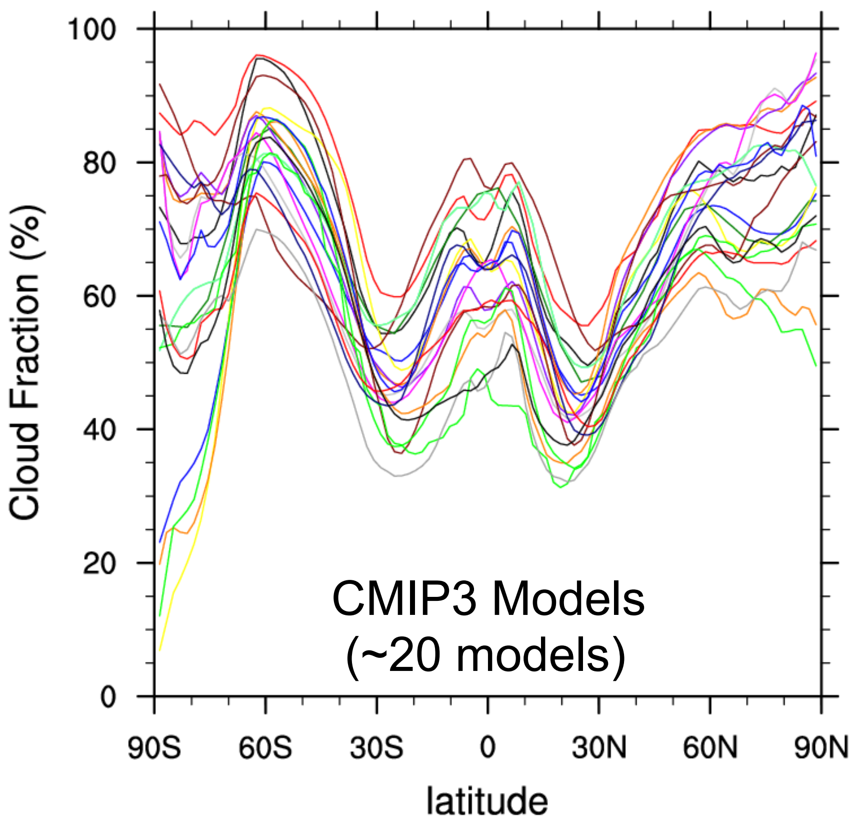


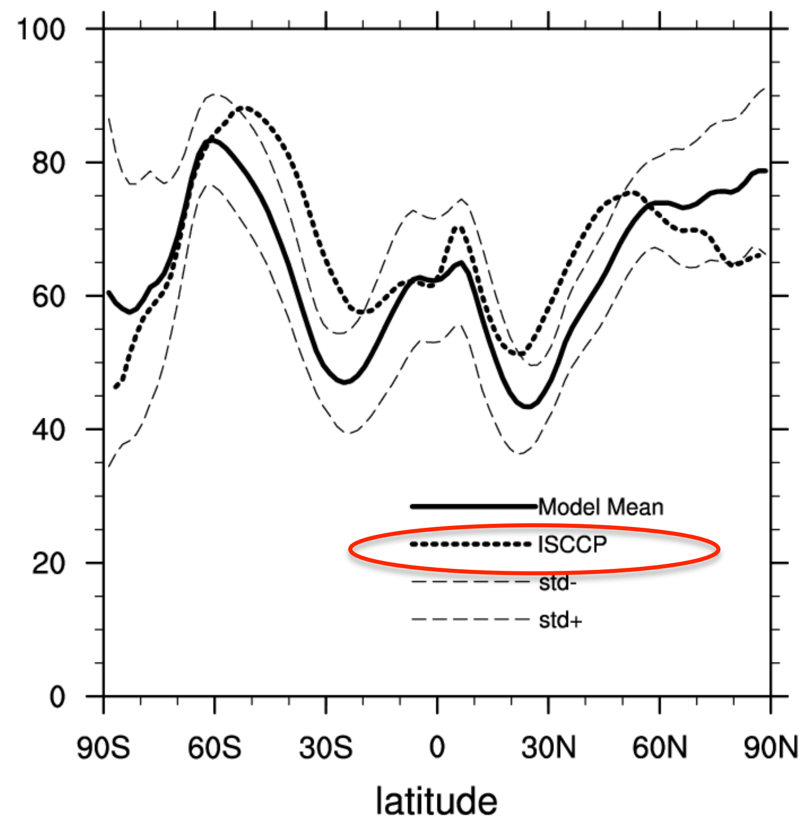



# Clouds in GCMs

## State of the Art from CMIP3

Total Cloud Fraction
(Annual, 1990-1999)

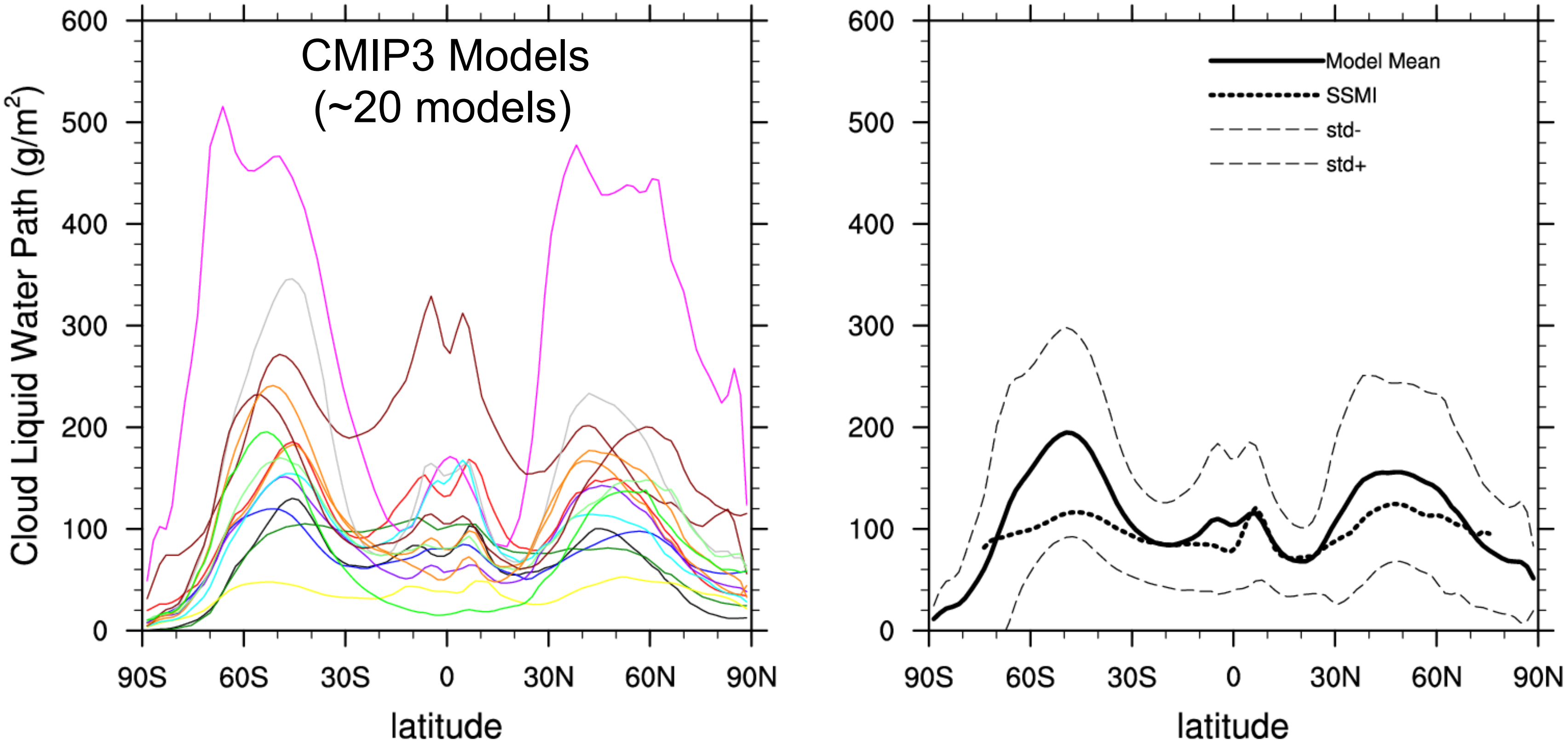


# Structural Clouds in GCMs

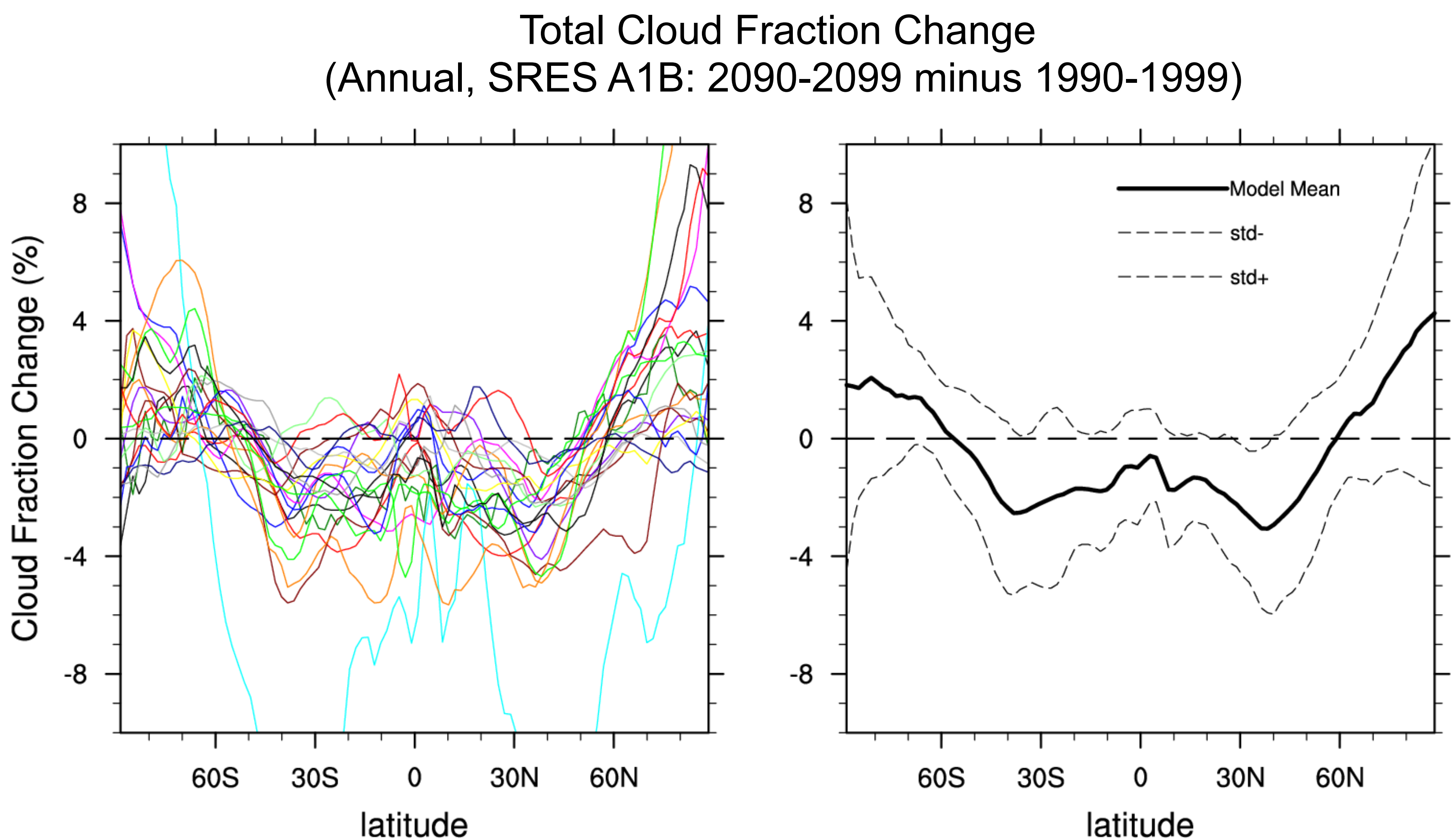
## State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)



# Future Clouds in GCMs

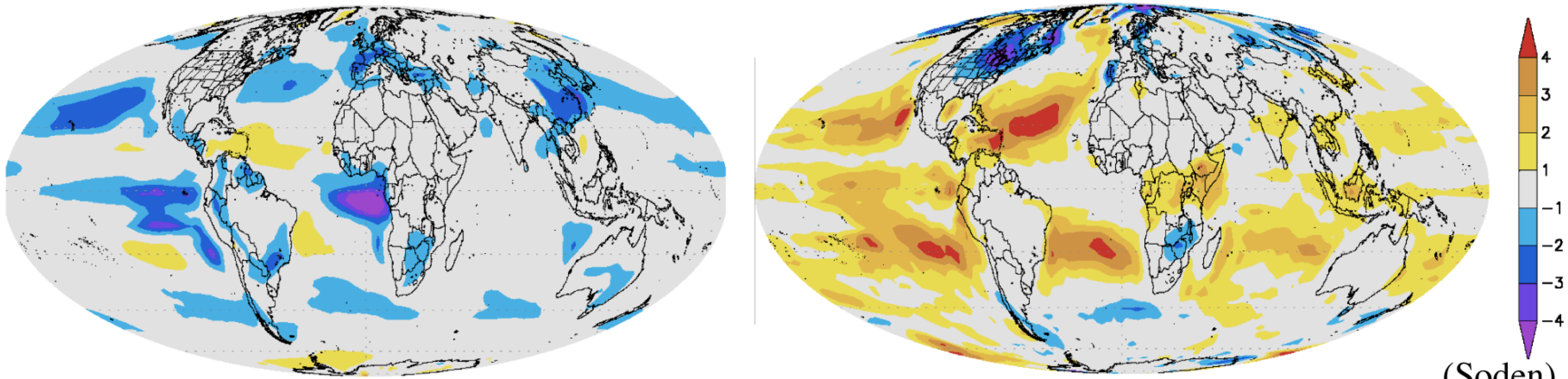
## State of the Art from CMIP3 – response to climate change



# Climate Sensitivity

## What happens to clouds when we double $CO_2$?

GFDL Model **+4.2K** NCAR Model **+1.8K**

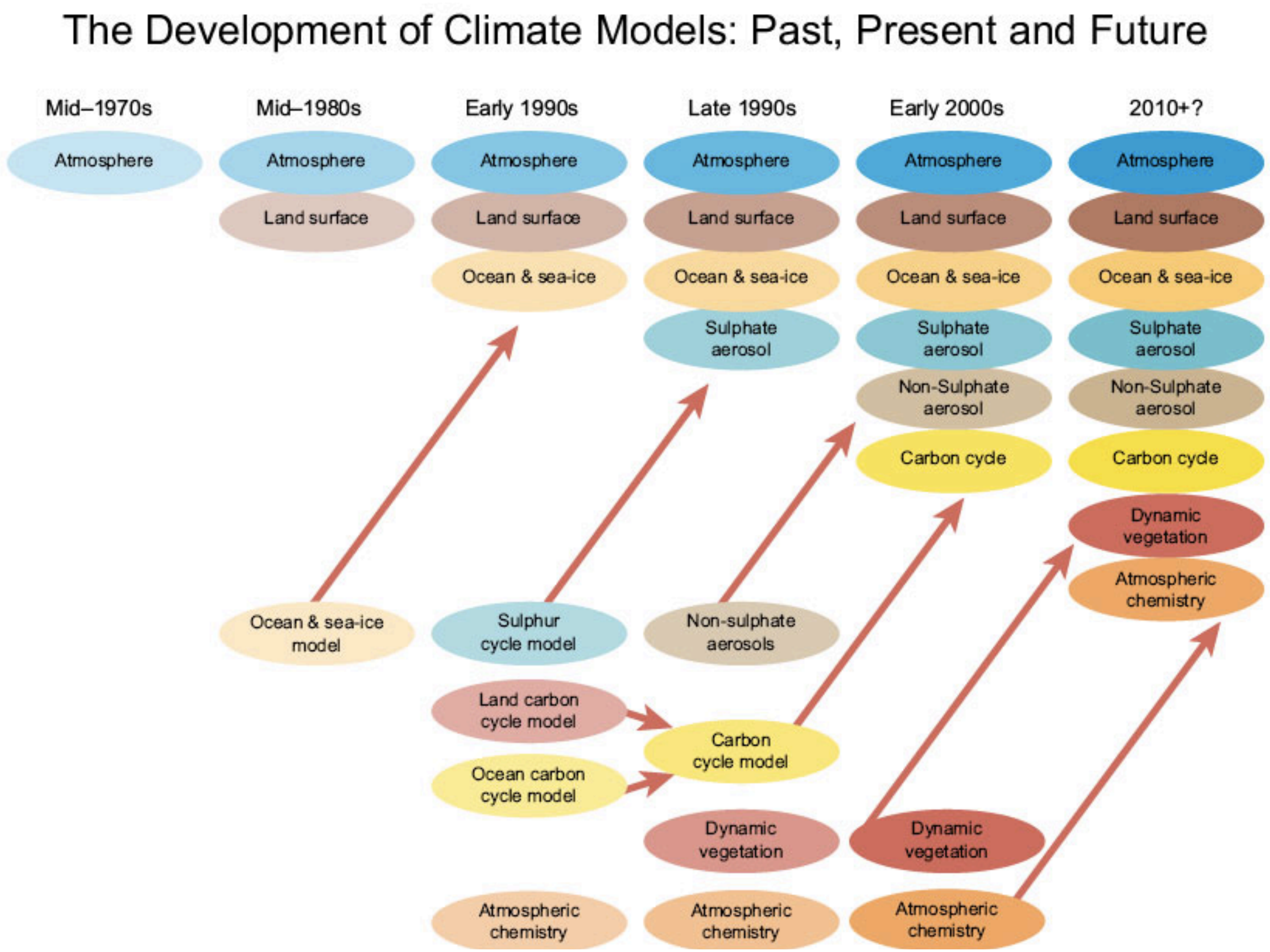



(Soden)

Change in low cloud amount (%)

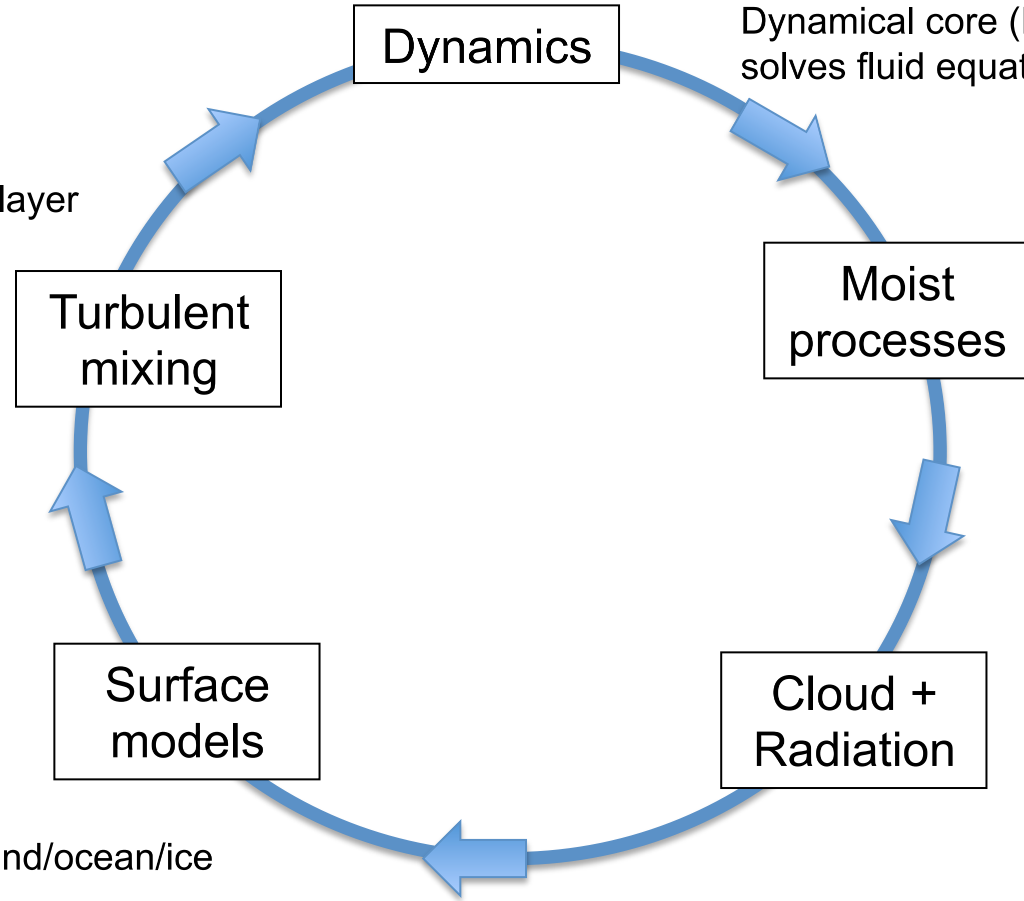
- Significant range in **low-cloud sensitivity** (low and high end of models)
- Cloud regimens are largely **oceanic stratocumulus** (difficult to model)
- Implied temperatures change is due to (higher/lower) solar radiation reaching the ground because of **clouds feedbacks.**

# More Processes=more feedbacks



# Older CAM workflow

## Up to CAM4




Dynamical core (Eulerian, Finite volume) solves fluid equations on resolved scales

- Deep convection
- Shallow Convection
- Large-scale condensation

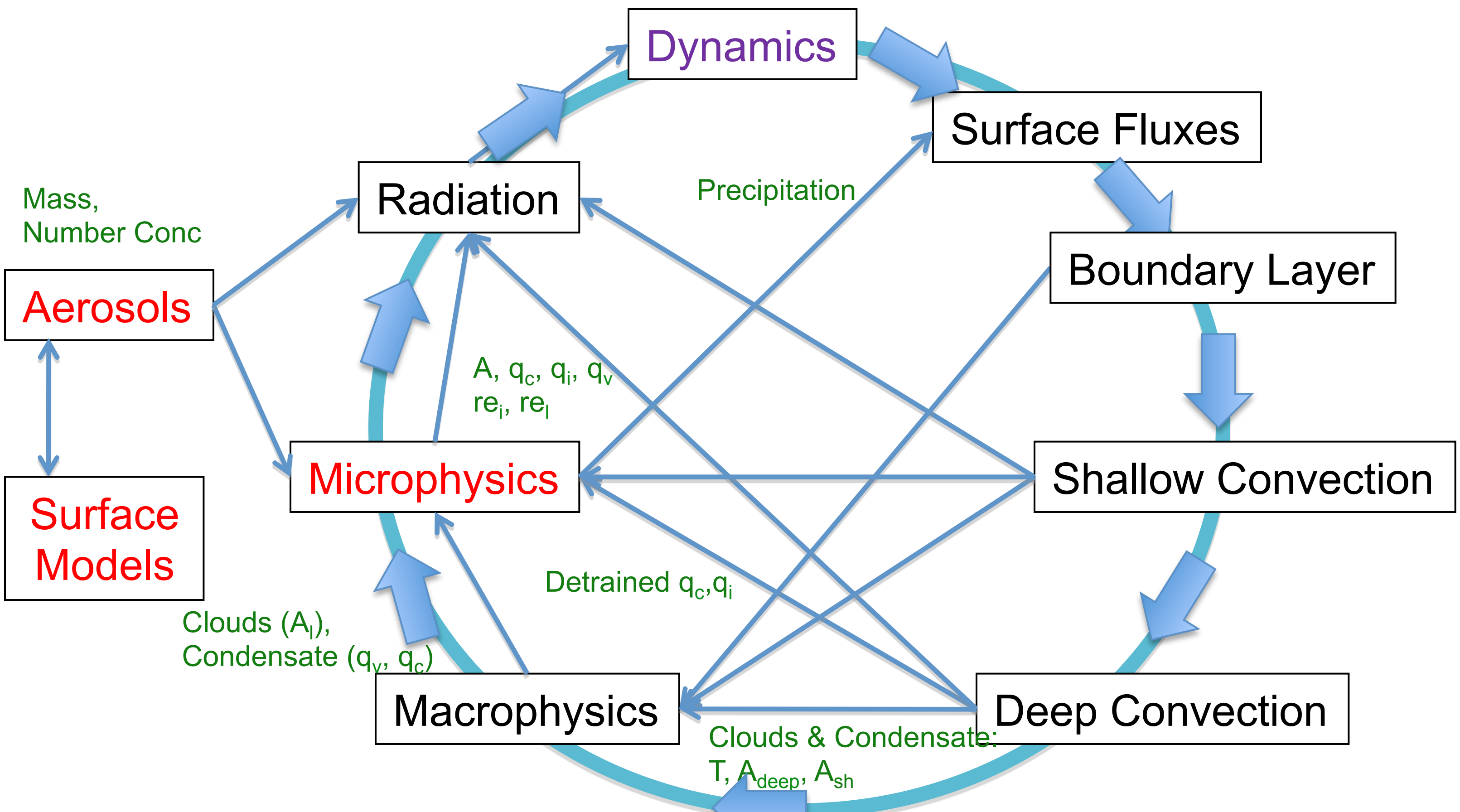
- Macrophysics
- Microphysics
- Radiation

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

- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag

# New CAM workflow

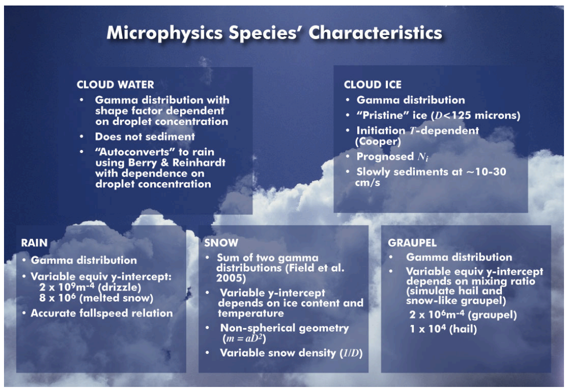
## Community Atmosphere Model (CAM) Version 5

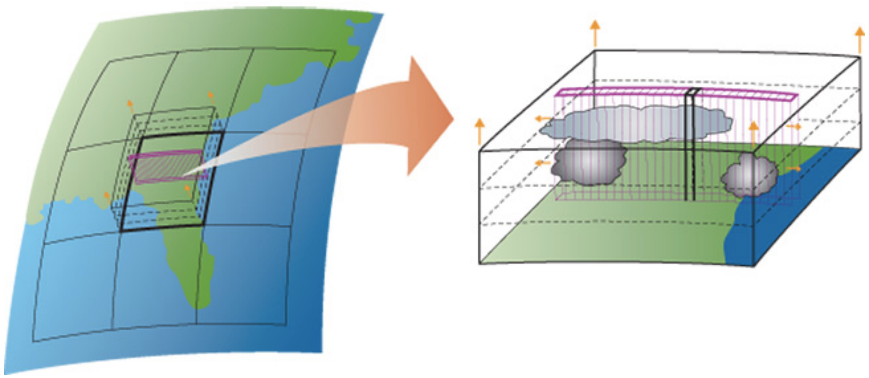



A = cloud fraction, q=$H_2O$, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor

# Model physics: The future

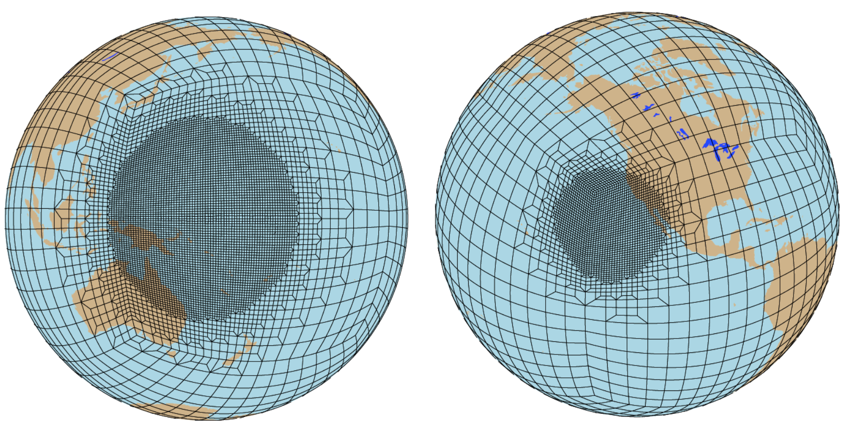
- 1. How to operate in varying grid scale environments
- 2. Advanced representation of processes.



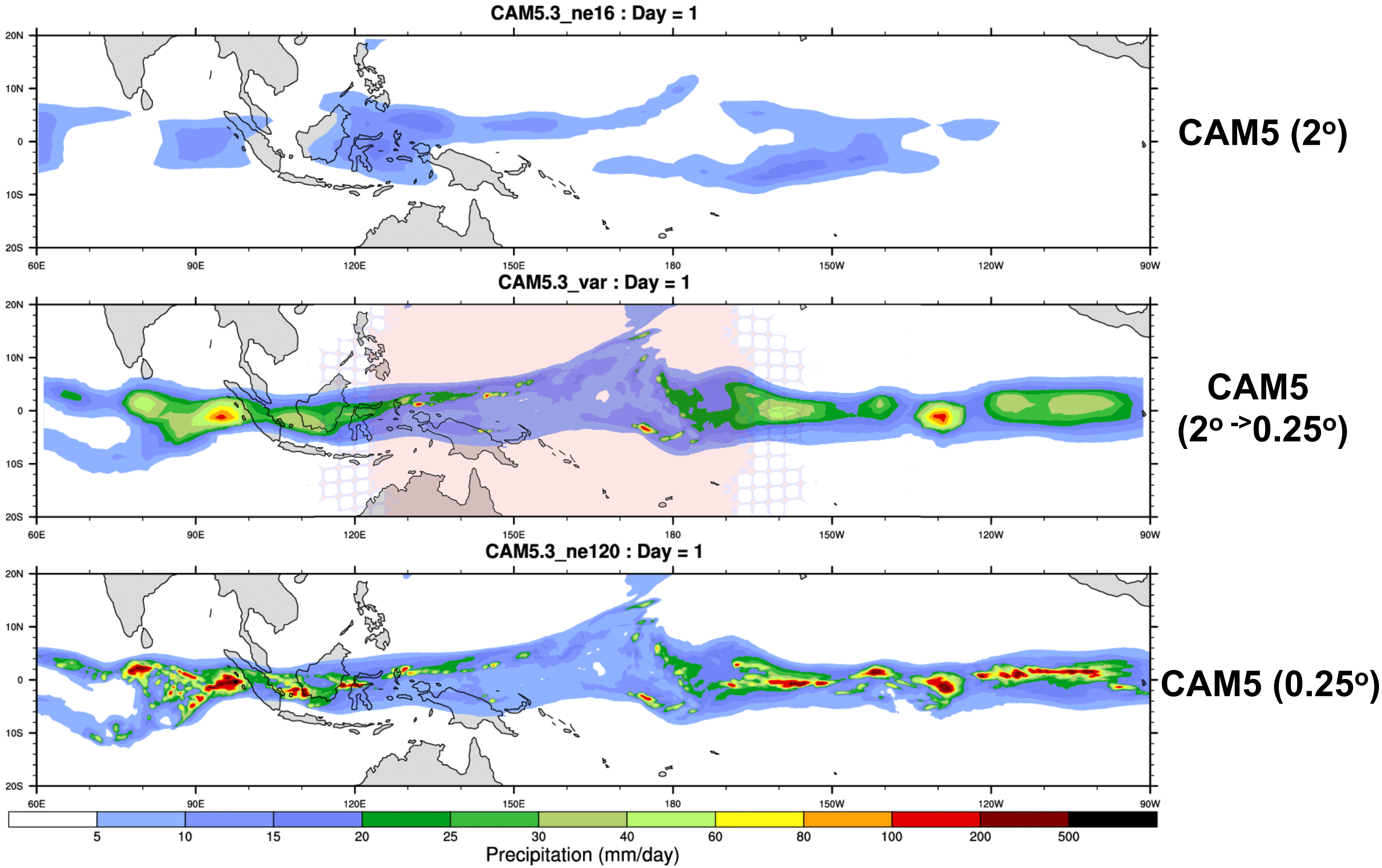
**New** and **more complex** processes

Cloud **super-parameterization**



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

# Precipitation Response to Mesh Refinement



# 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**