# Atmospheric Modeling II:

## Physics in the Community Atmosphere Model (CAM)

CESM Tutorial

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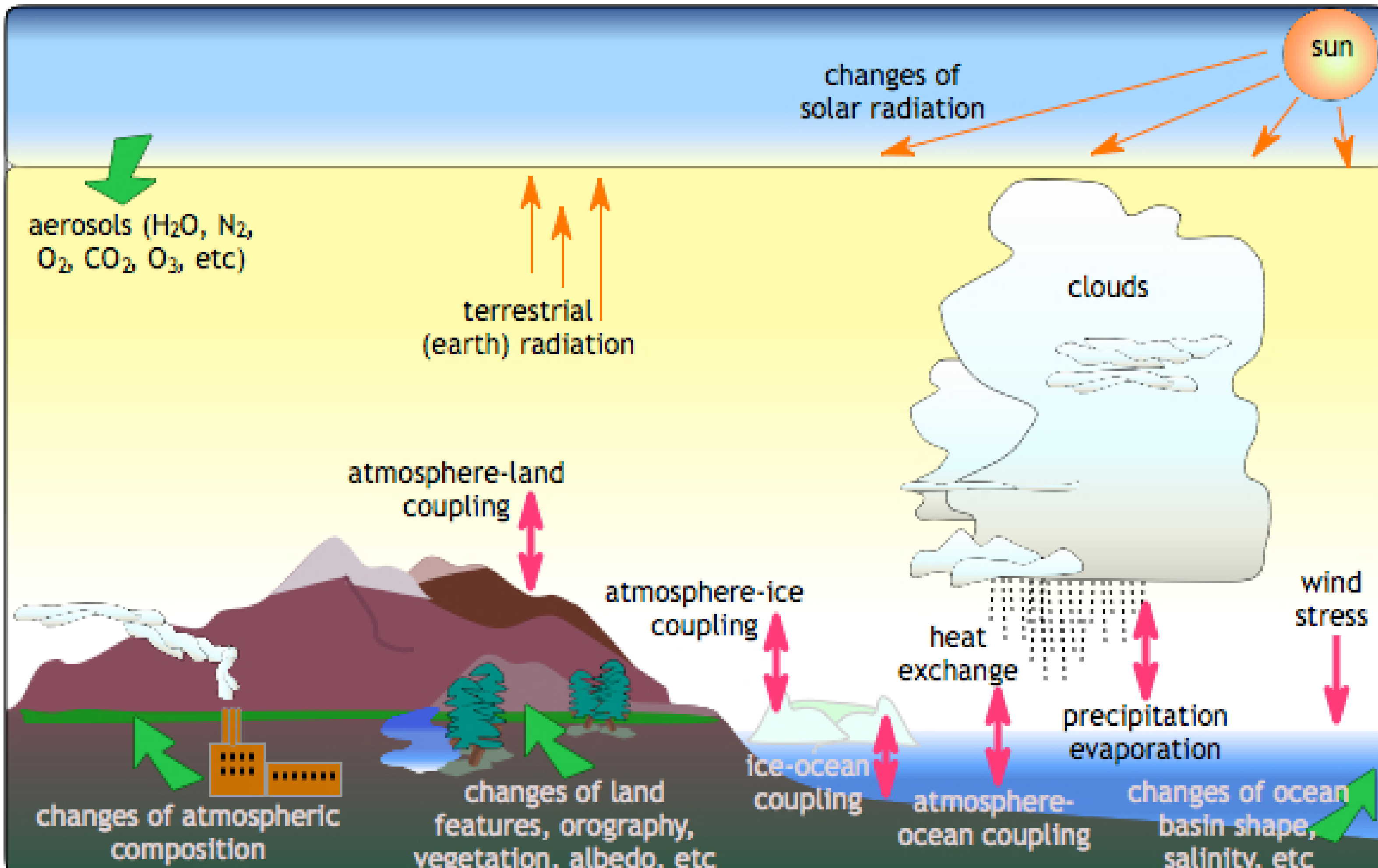
# Outline

- Physical processes in an atmospheric GCM
- Distinguishing GCMs from other models (scales)
- Concept of ‘Parameterization’
- Physics representations
  - Clouds (different types), cloud fraction and microphysics
  - Radiation
  - Boundary layers, surface fluxes and gravity waves
- Process interactions
- CAM4 (CCSM4) v. CAM5 (CESM1 option) physics
- Forcings and Feedbacks

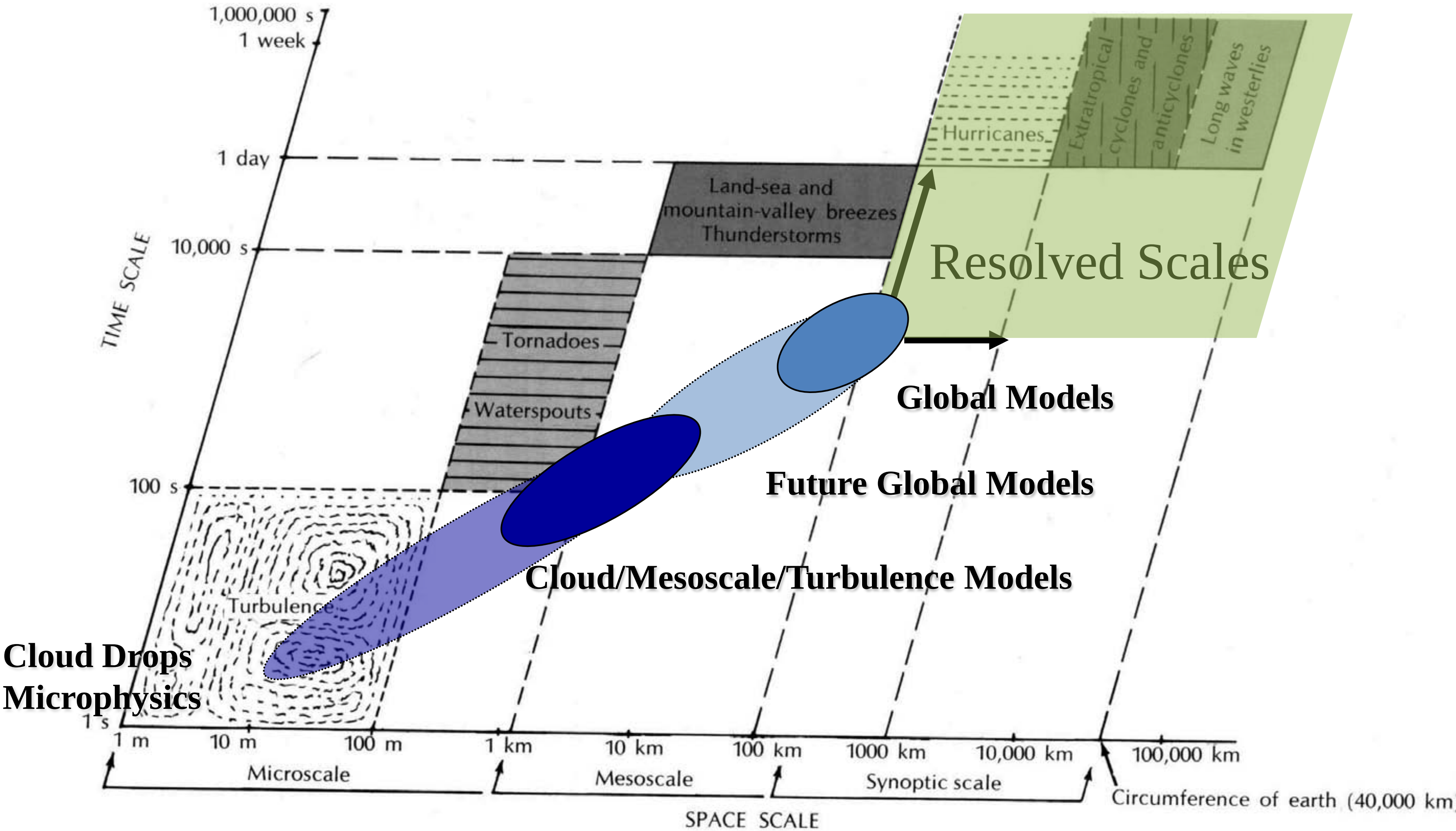
# Physics Phenomena

## Process and process interaction



# 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"**

# Effect of Physics on the Model

## What do we need to consider?

To close the forcing terms of the governing equations ($F_V$ $F_T$ $F_{QV,QL,QI}$), need to incorporate the effects of physical processes on scales below resolved scale

- Momentum (horizontal velocity) $F_V$
  - Turbulence: Transport, generation, and dissipation of momentum
  - Cloud –scale transport (updrafts/downdrafts)
  - Drag (surface roughness, mountain stress, gravity waves)
- 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
- Other continuity equations for other tracers, $F_{tracers}$
  - Includes chemistry and aerosols
  - Wet deposition, scavenging, etc

# Parameterization

## Some definitions

*"The representation, in a dynamic model, of physical effects in terms of admittedly oversimplified parameters, rather than realistically requiring such effects to be consequences of the dynamics of the system. "*

*"…refers to the method of replacing processes that are too small-scale or complex to be physically represented in the model by a simplified process. This can be contrasted with other processes—e.g., large-scale flow of the atmosphere—that are explicitly resolved within the models. "*

"…to express in terms of parameters."

These "parameters" are of course the grid-mean quantities of the model u, v, w, T, Ps, $q_v$, $q_L$, $q_I$ (including derived quantities)

'Diffusivity'

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

Unresolved 'sub-grid'

Resolved 'grid-scale'

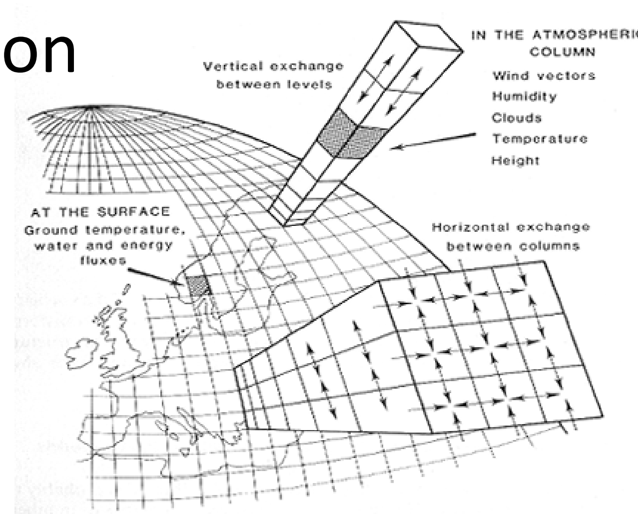
# What is a ‘Parameterization’?

- 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

# Parameterizations

## Characteristics and Requirements

1. Plane parallel approximation
2. Mass, momentum and Energy (Moist Static Energy) conserving (limiters and fixers)
3. Retains *reasonable* atmospheric state
4. Reproducibility: the same configuration should produce the same answer




Notes:

-Can still have stochastic elements

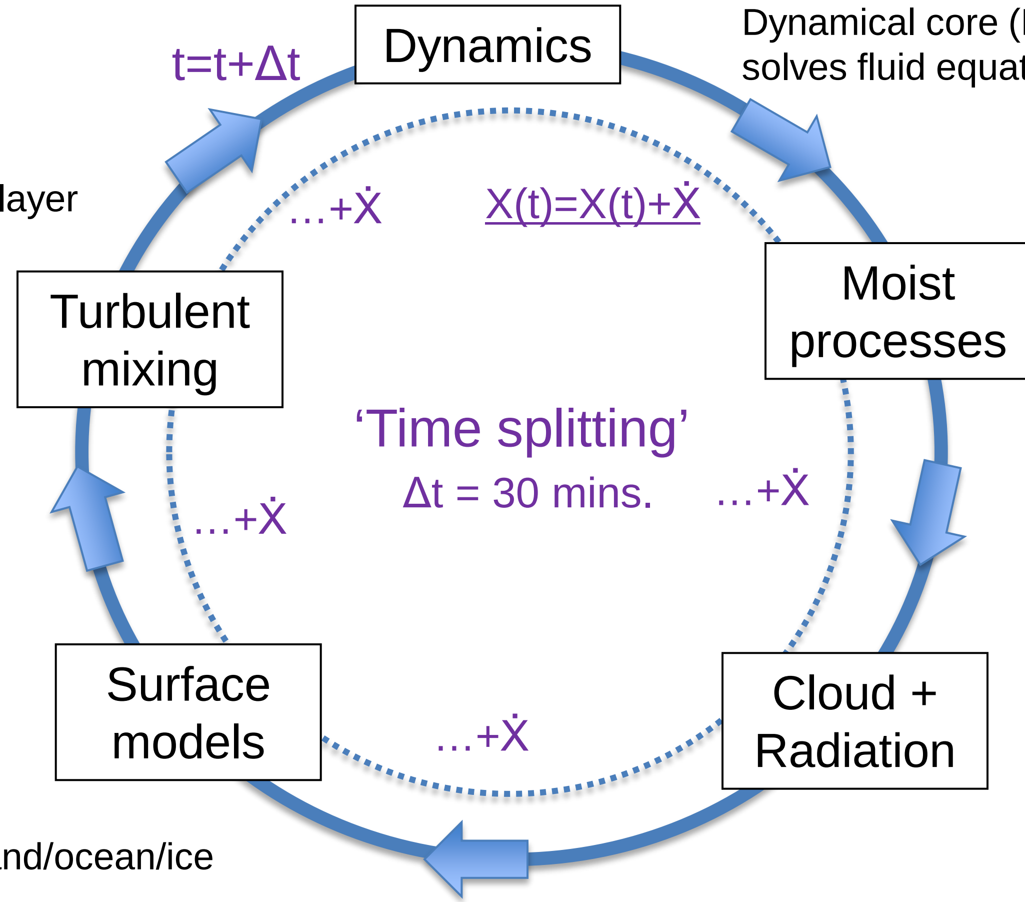
(same seeds for random number generators)

# CAM workflow

## up to CAM4 (CCSM4)

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

- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag




- 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)

Forecast (e.g., short time-step models) more likely **process split**

# Clouds

# Clouds

## Multiple Categories

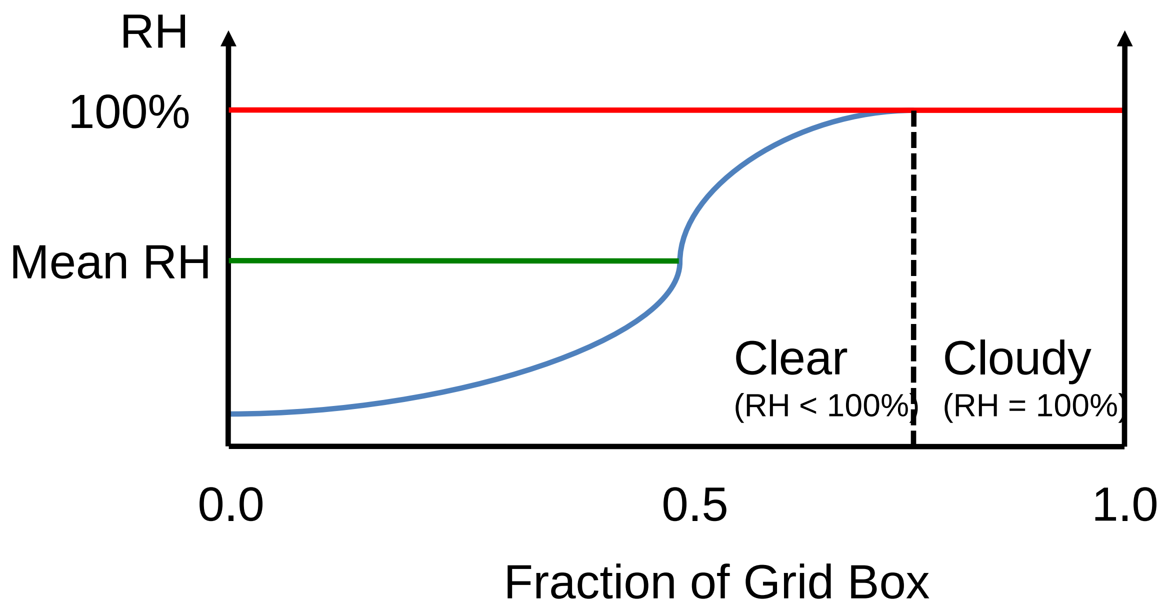
- Stratiform (large-scale) clouds
  - Responds to large-scale saturation fraction, RH (parameterized)
  - Coupled to presence of condensate (microphysics, advection)
- Shallow convection clouds
  - Symmetric turbulence in lower troposphere
  - Non precipitating (mostly)
  - Responds to surface forcing
- Deep convection clouds
  - Asymmetric turbulence
  - Penetrating convection (surface -> tropopause)
  - Precipitating
  - Responds to surface forcing and conditional instability

# Stratiform Clouds

## Sub-Grid Humidity and Clouds

Liquid clouds form when RH = 100% ($q=q_{sat}$)

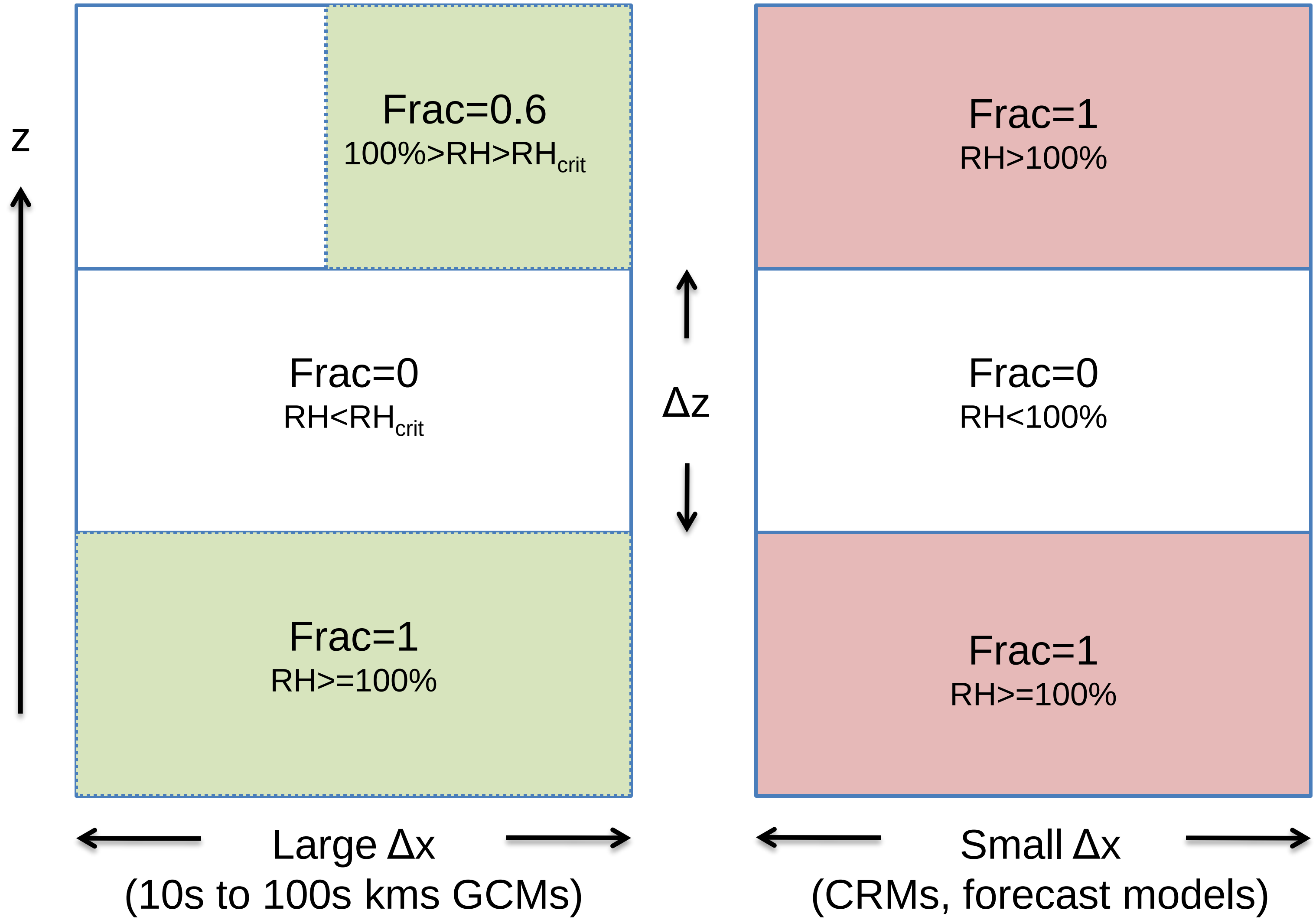
But if there is variation in RH in space, some clouds will form before *mean* RH = 100%




Assumed Cumulative Distribution function of Humidity in a grid box with sub-grid variation

# The Cloud Fraction Challenge

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



# Shallow and Deep Convection

## Exploiting conservation properties

### Common properties

Parameterize consequences of vertical displacements of air parcels

Thermodynamic conservation properties (adiabatic when sub saturated)

*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

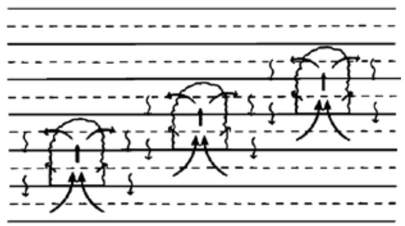
Large cloud radius small entrainment

# Shallow and Deep Convection

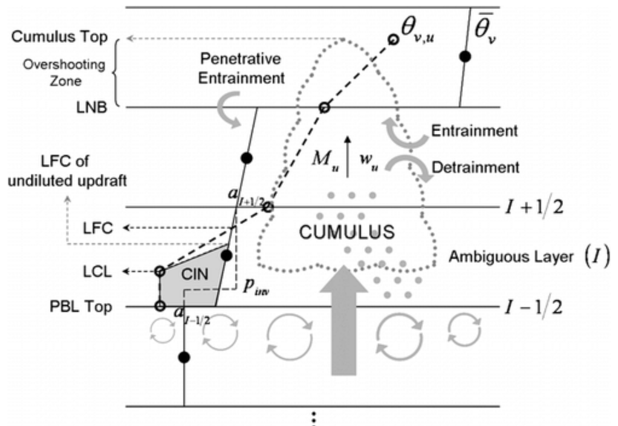
## Closure: How much and when?

### Shallow

Local conditional instability CAM4



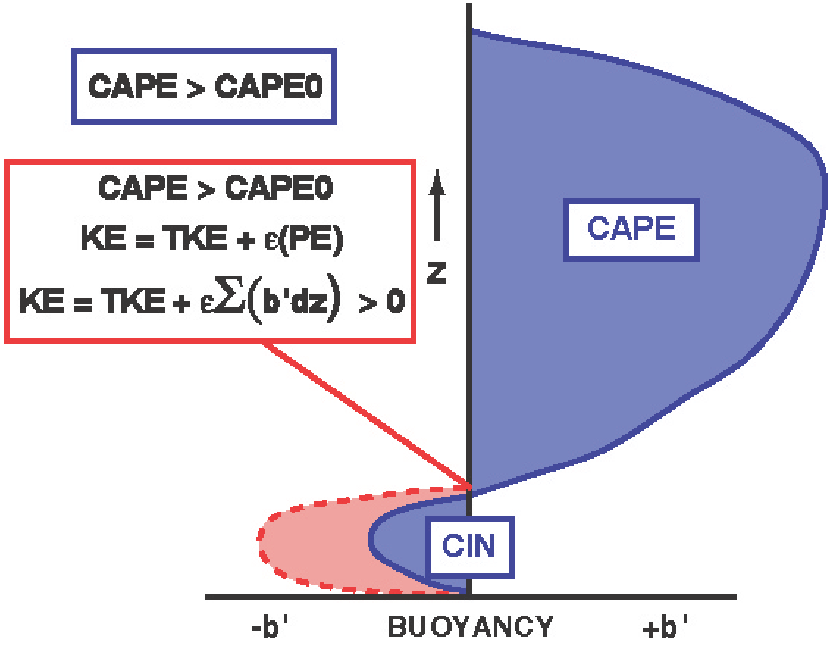
Convective inhibition and turbulent kinetic energy (TKE) CAM5




### 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

# Different types of Microphysics

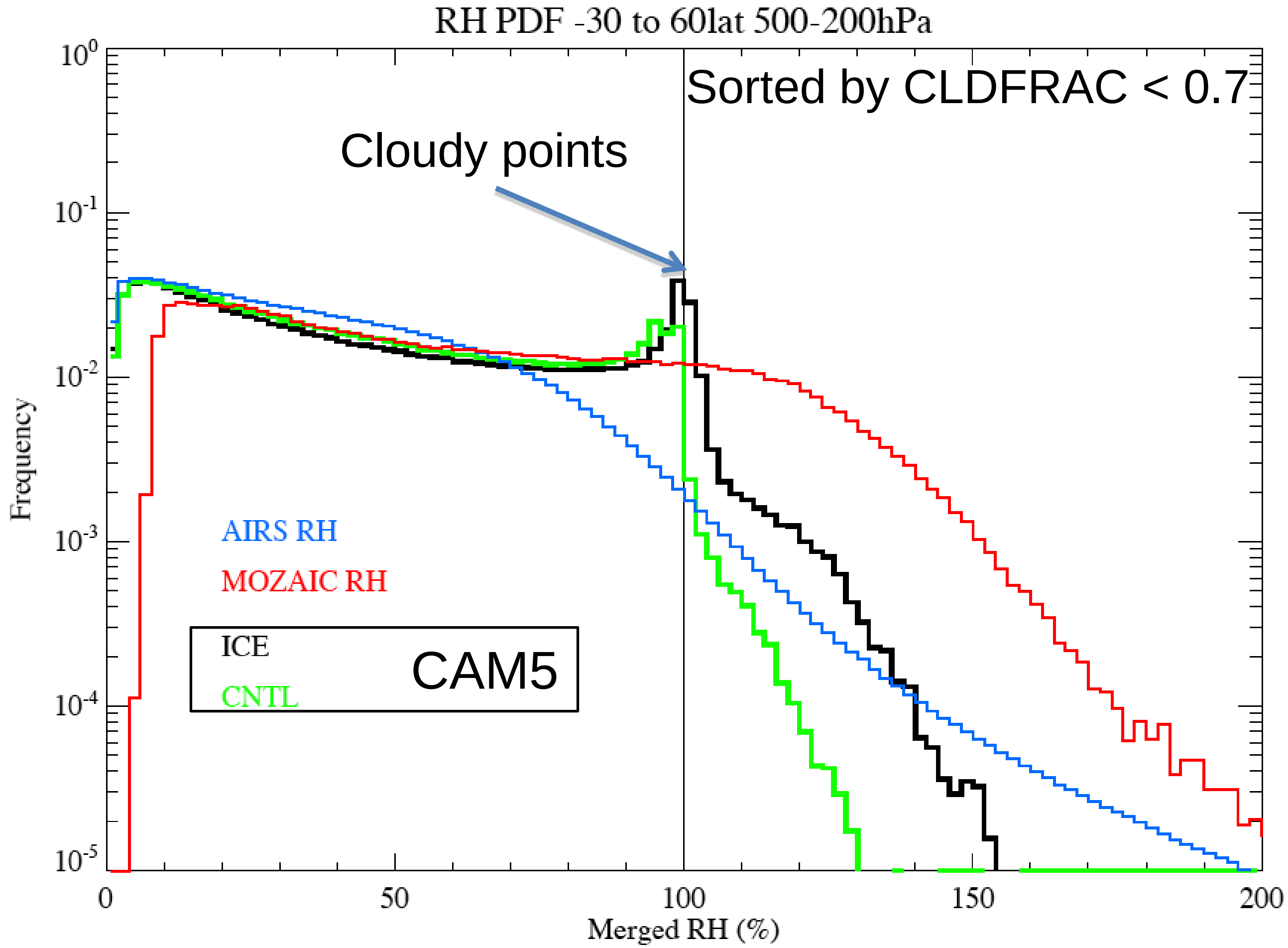
- Bulk Microphysics (CAM4)
  - Mass based only (2 species: liquid and ice)
  - Bulk transformations and processes
  - Specified sizes or size distributions
- Modal Microphysics (CAM5)
  - Use an analytic representation of the size distribution and carry around moments of the distribution
  - First moment = mass; 2nd moment = number
  - Size distribution reconstructed from an assumed shape.
  - Advantage: represent sizes consistently with computational efficiency

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

- Bin Microphysics
  - Multiple size bins (many constituents) with a mass in each. Explicit representation of size distribution
  - Transformations depend on mass and number

# Ice Supersaturation in CAM5

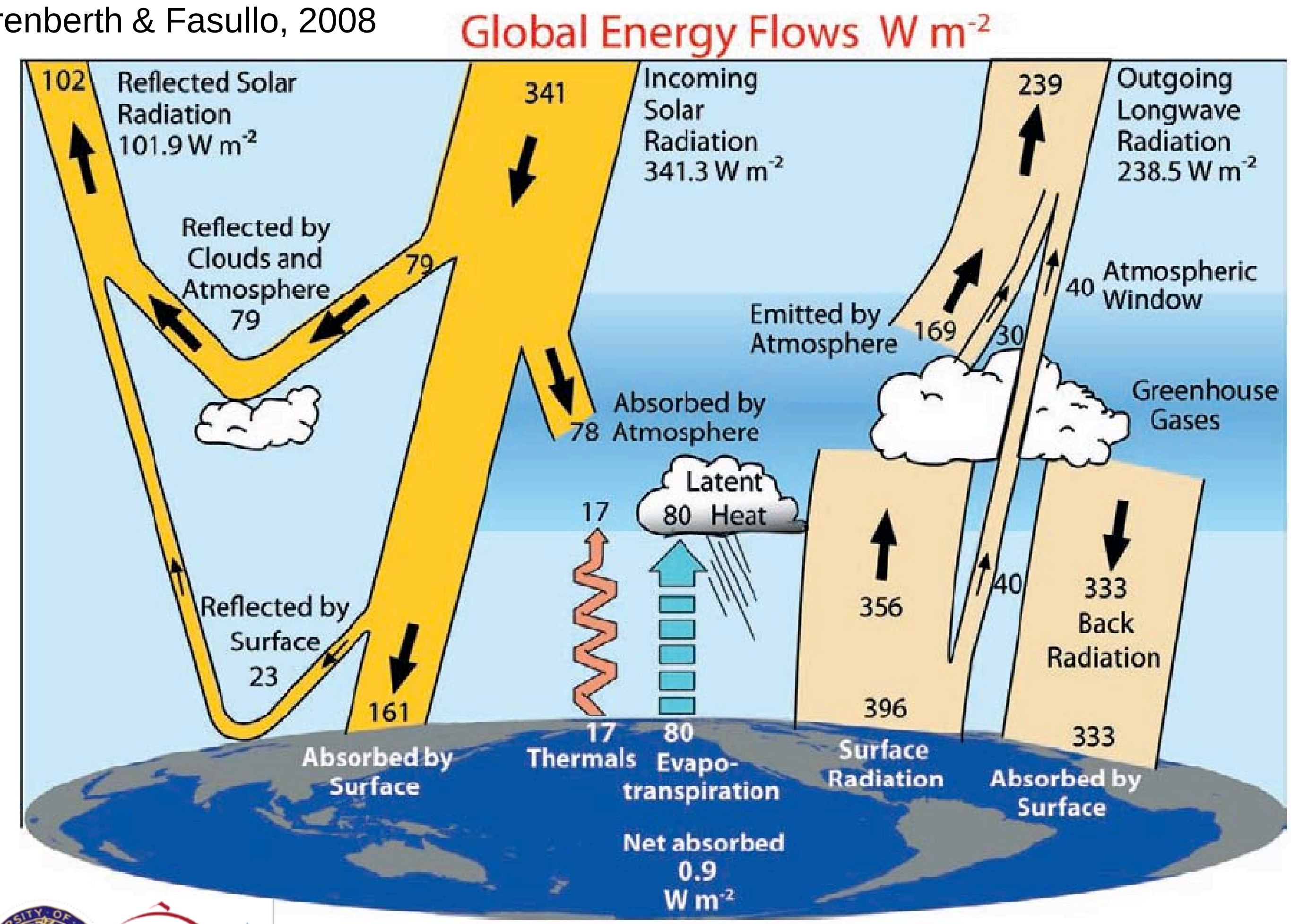
## Not allowed in CAM4



# Radiation

## The Earth's Energy Budget

Trenberth & Fasullo, 2008



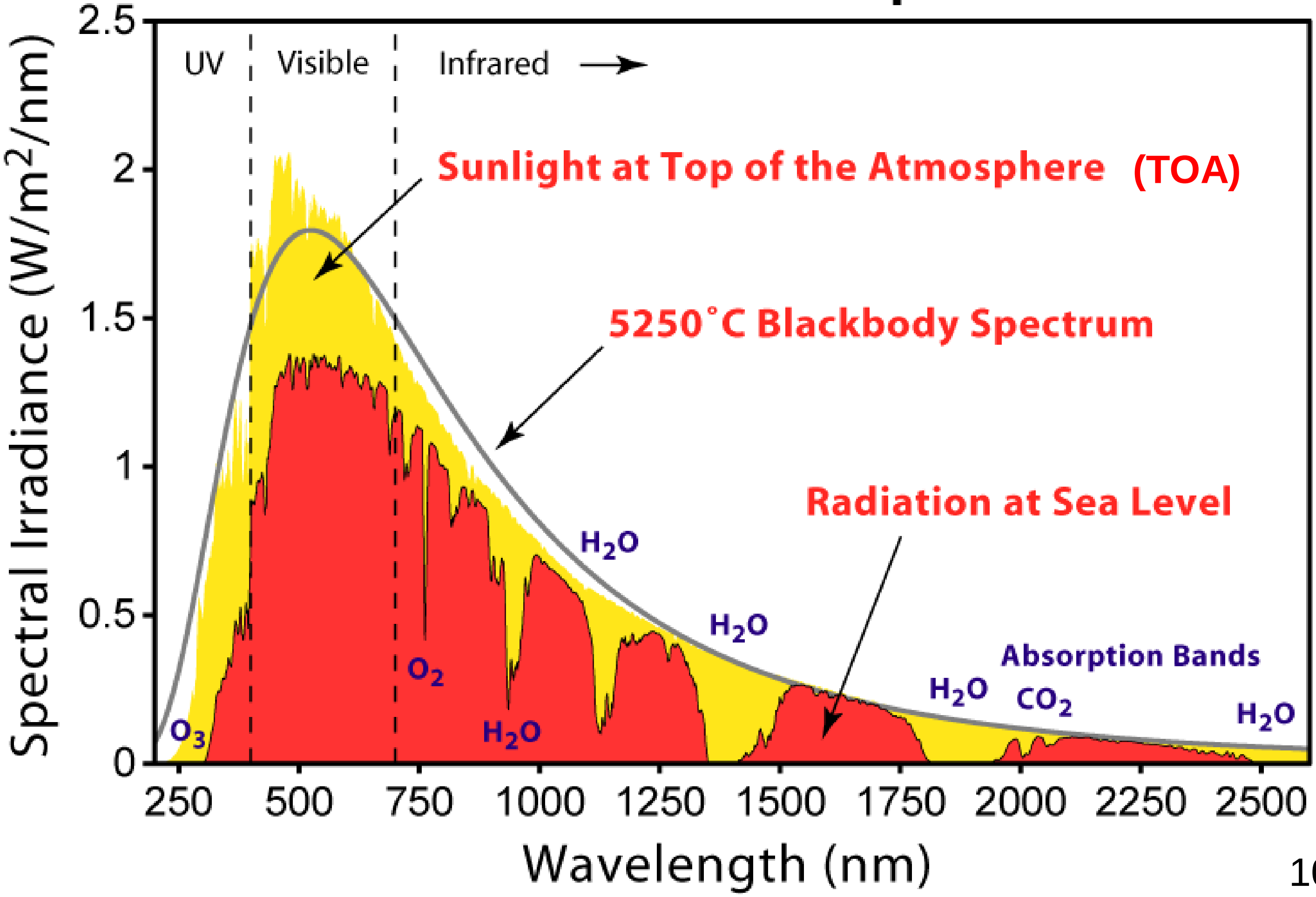

| Gas | SW Absorption ($Wm^{-2}$) |
|---|---|
| $CO_2$ | 1 |
| $O_2$ | 2 |
| $O_3$ | 14 |
| $H_2O$ | 43 |

Thanks to: Bill Collins, Berkeley & LBL

# Goals of GCM Radiative 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

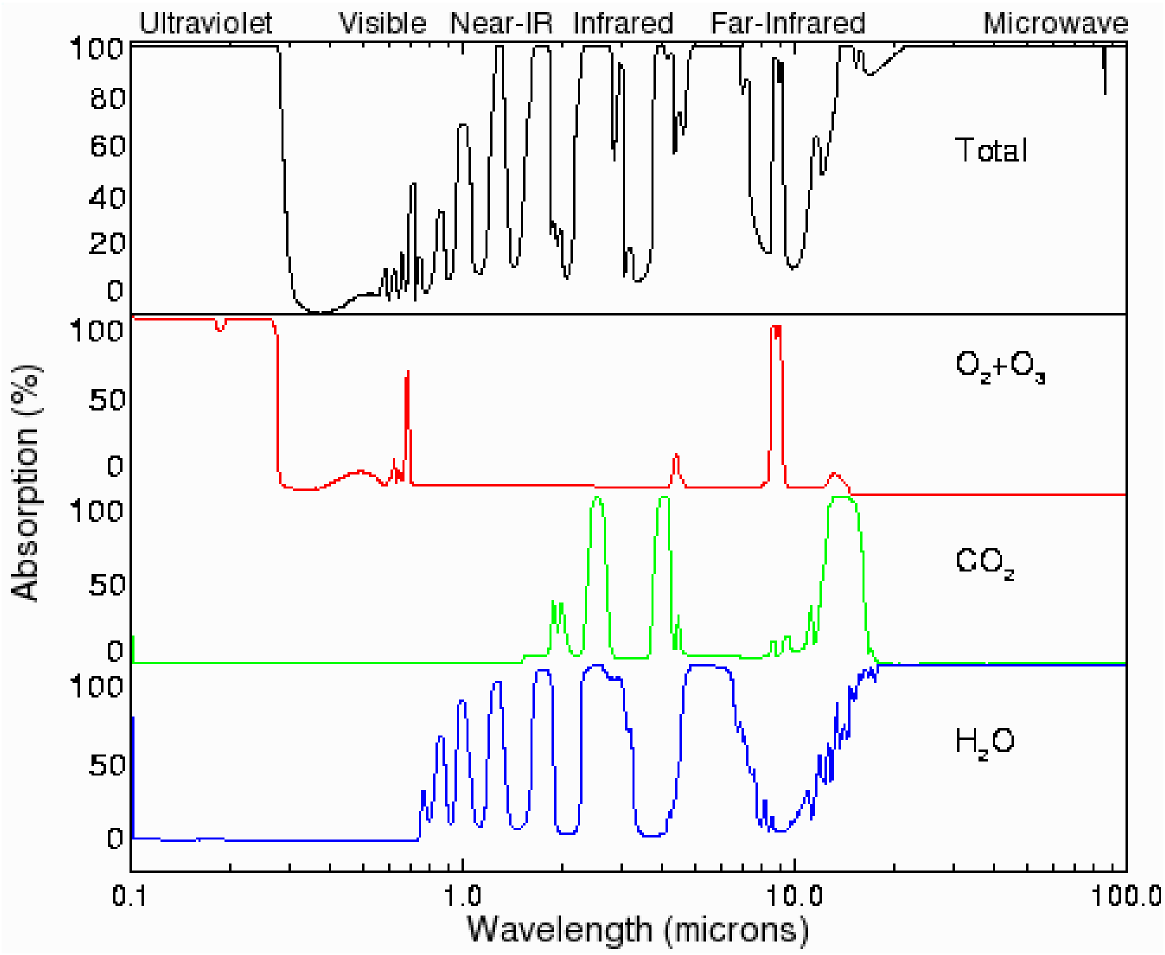



1000nm = 1μm

Input at TOA, Radiation at surface

From: 'Sunlight', Wikipedia

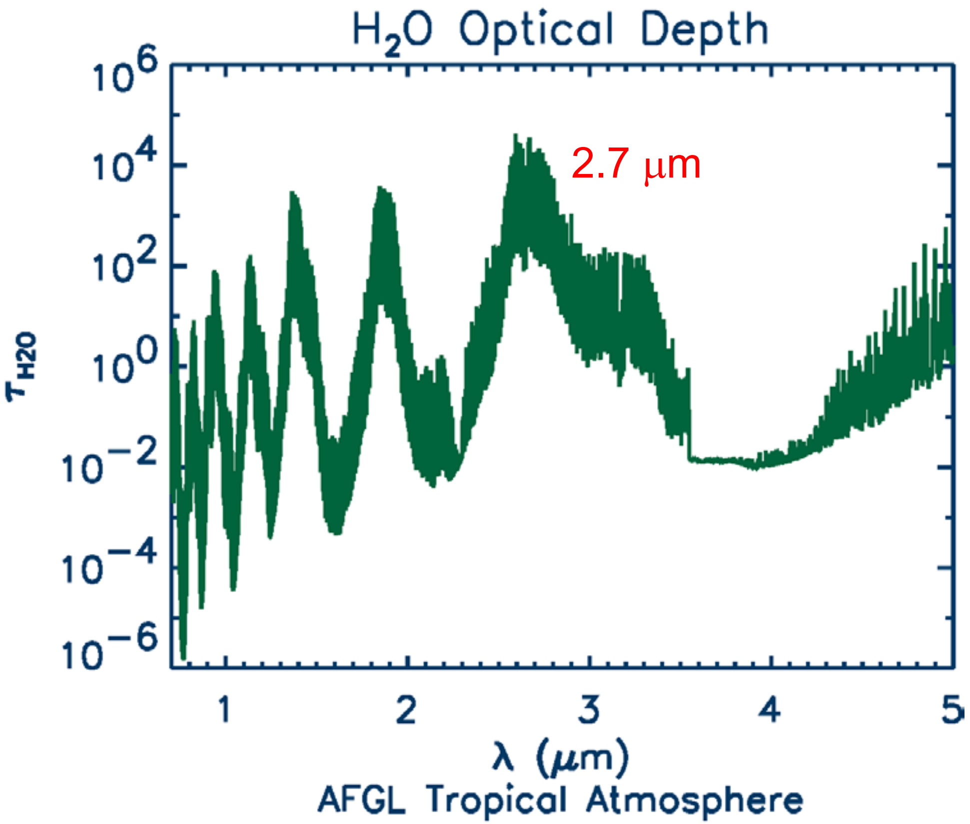
# IR absorption




1000nm = 1μm

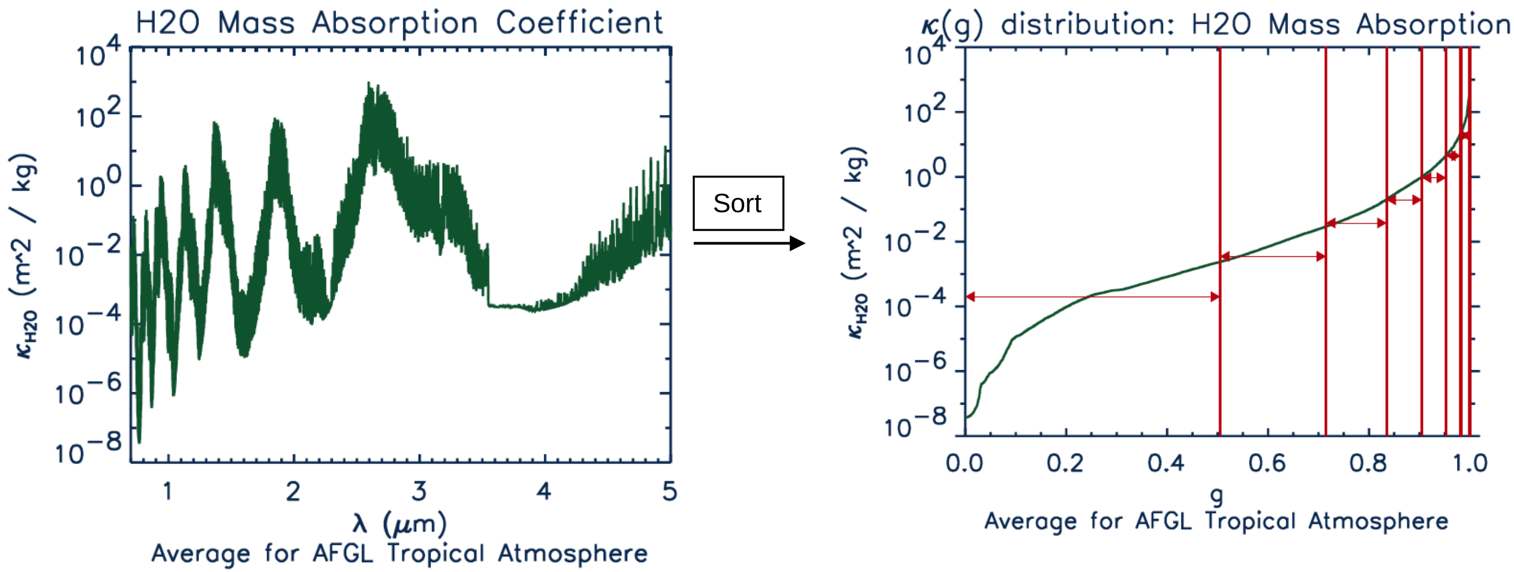
# Challenge of radiative parameterization

Solar & infrared spectra variations in extinction, optical depth, and heating rates of ≥12 orders of magnitude at different wavelengths!




Collins et al, 2006

# k-distribution Band Models




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

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

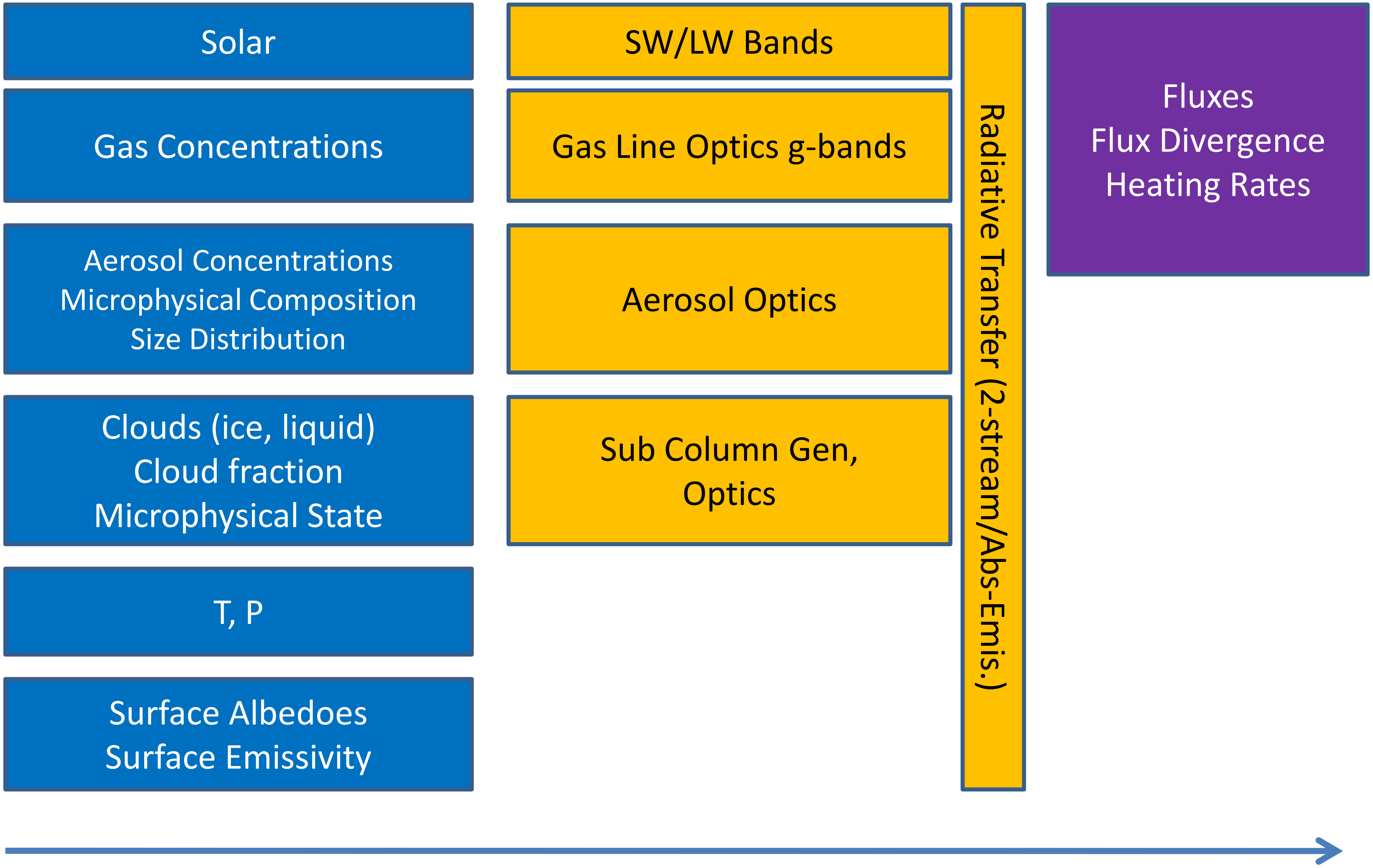
- In the k-distribution band model, the absorption coefficients are sorted by magnitude.
- The transmission integral should be much easier to approximate in this sorted form.
- Yet classical approximation methods may not be suitable.

- Are there physically and mathematically optimal methods for approximation?

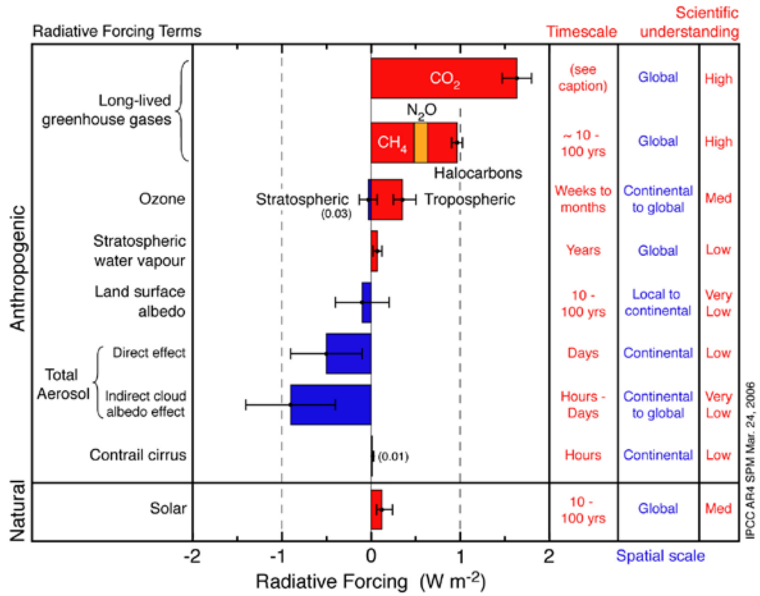
# CAM Radiation Code

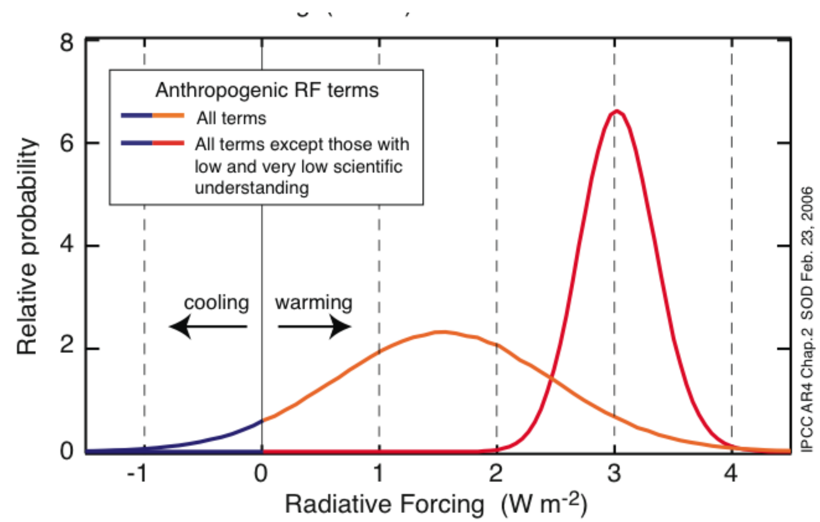
- Radiation code is expensive (~50% of total) even when calculated once every hour
- CAM4: ‘CAMRT’
  - Collins et al (2003, 2006)
- CAM5: ‘RRTMG’ (14 SW, 16 LW bands)
  - Rapid Radiative Transfer Model for GCM’s
  - Iacono et al (2008)
  - Correlated K-code, more traceable to obs (RRTM)
  - Validated against line-by-line models
  - New radiation interface (flexible)

# Radiative Inputs and Outputs



# Historical Radiative Forcing




IPCC AR4, 2007

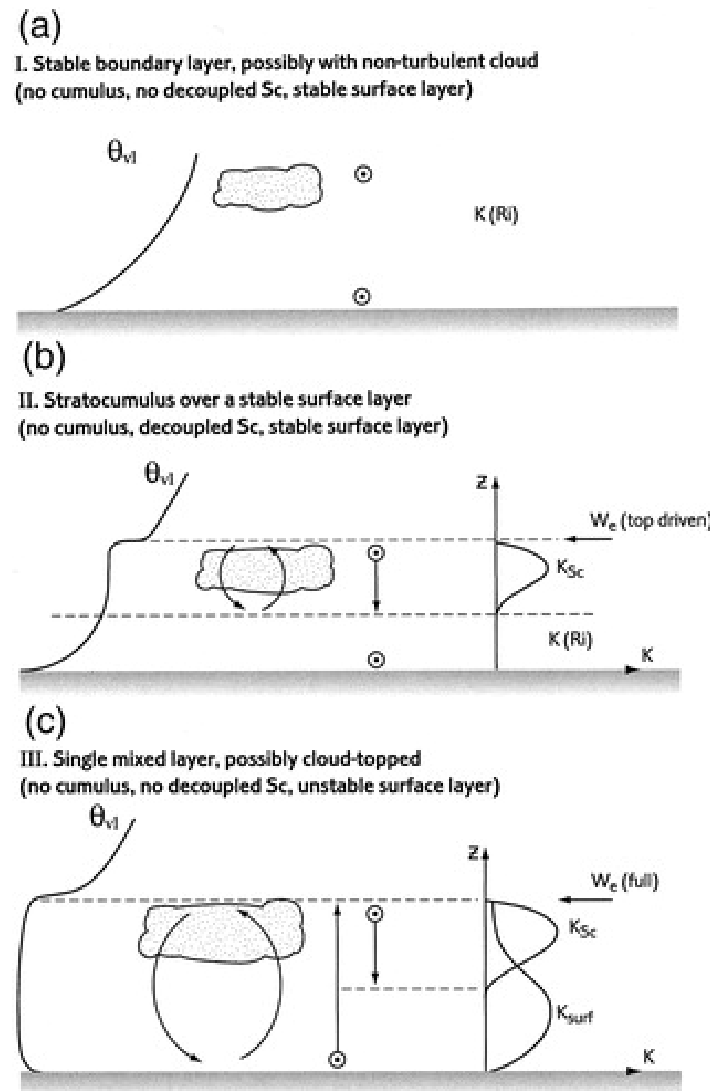
**Radiative forcing** is an "externally imposed perturbation in the radiative energy budget of the Earth's climate system." (IPCC TAR)

- Models should simulate this forcing as accurately as possible
- Probability that historical forcing > 0 is very likely (90%+).
- Confidence in aerosol forcing estimates is higher than in the TAR..

# Planetary Boundary Layer (PBL)

## Regime dependent representations

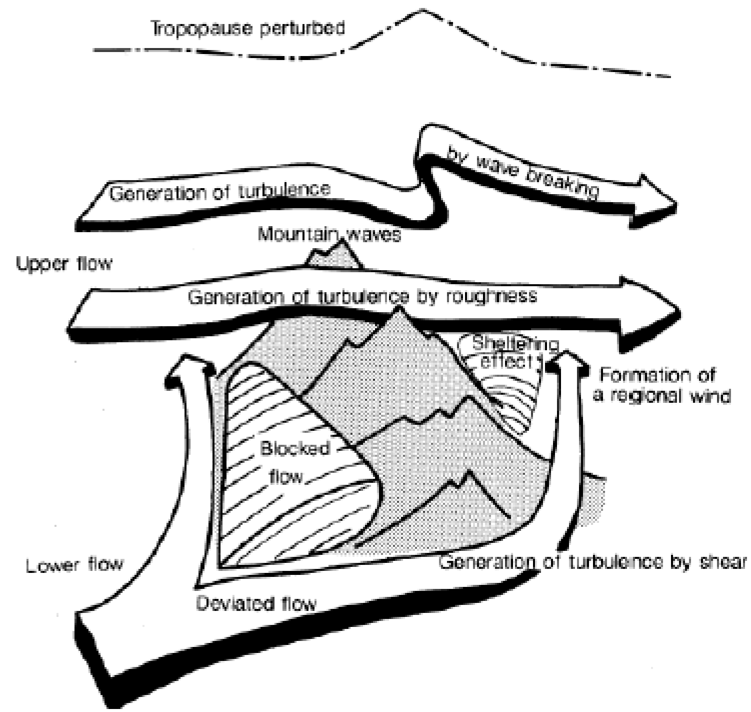
- Vital for near-surface environment (humidity, temperature, chemistry)
- Exploit thermodynamic conservation (liquid virtual potential temperature $\theta_{vl}$)
- Conserved for rapidly well mixed PBL
- Not conserved for stable PBL
- Critical determinant is the presence of turbulence
- Richardson number $\mathrm{Ri} = \frac{g\beta}{(\partial u/\partial z)^2},$
- <<1, flow becomes turbulent
- <u>CAM4:</u> Gradient Ri # + non-local transport (Holtslag and Boville)
- <u>CAM5:</u> TKE-based Moist turbulence (park and Bretherton)



# Gravity Waves and Mountain Stresses

## Sub-grid scale dynamical forcings

- Gravity Wave Drag
  - Determines flow affect 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

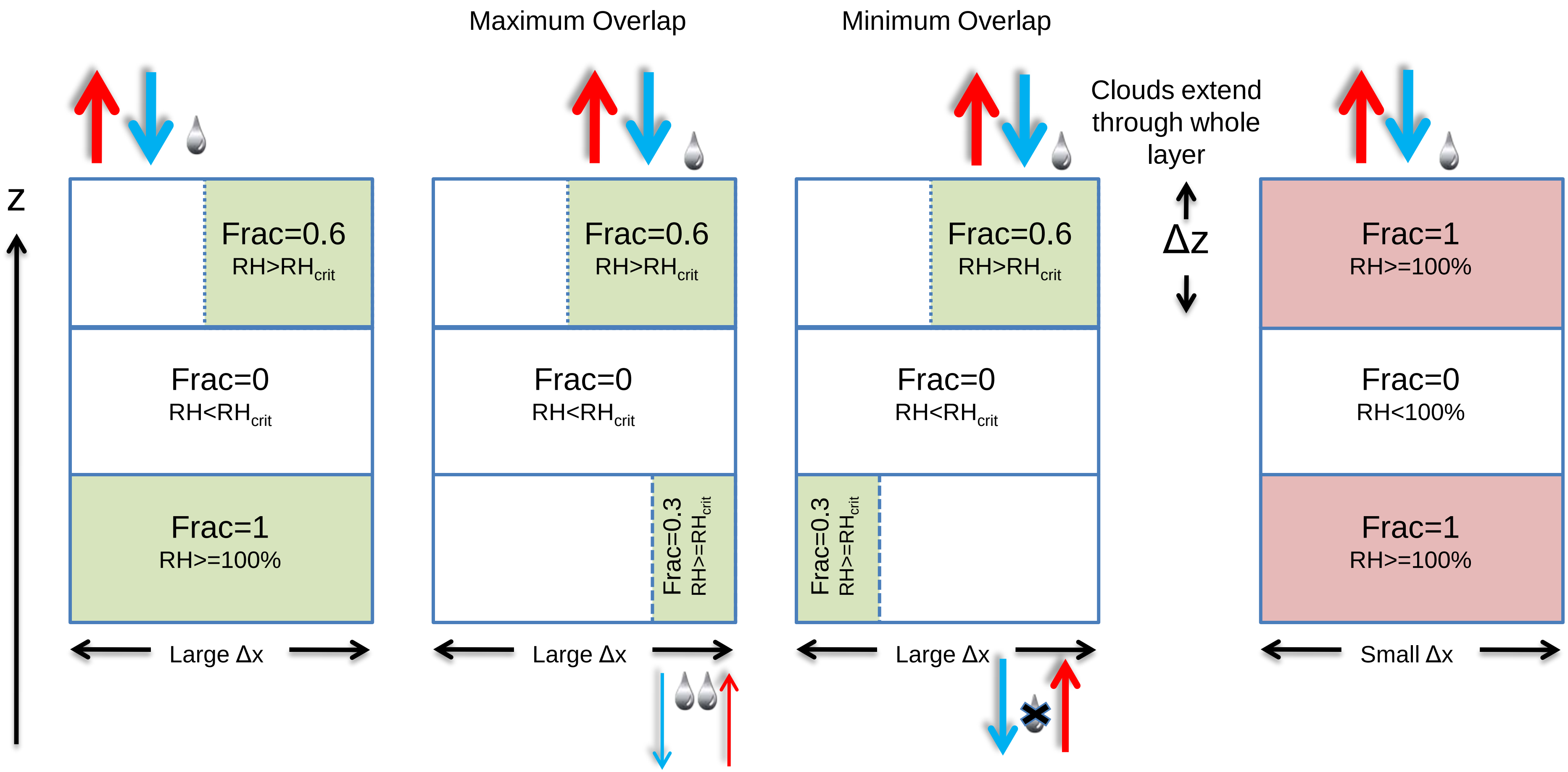
# Parameterization Interactions

## 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

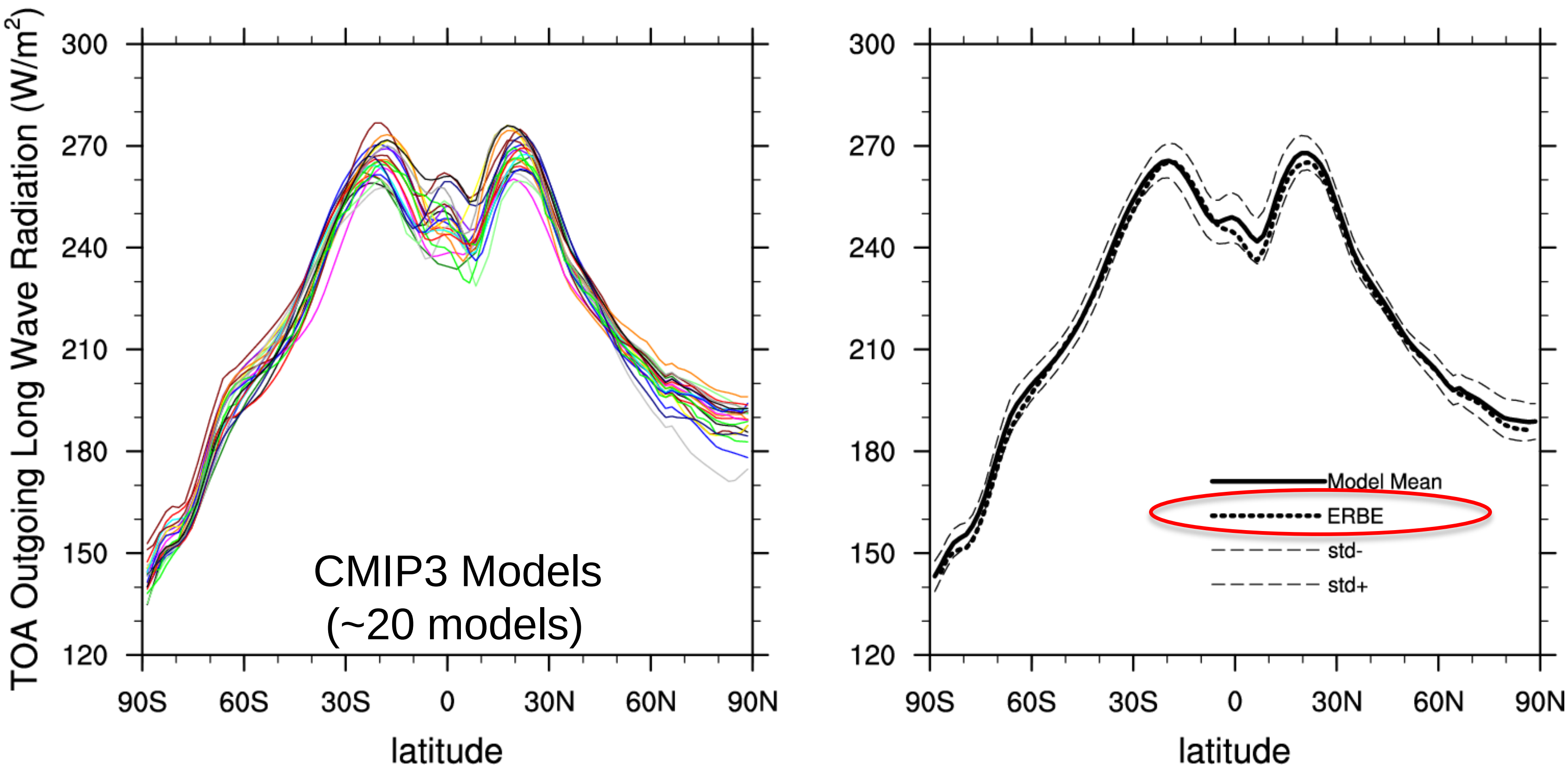



•Contiguous cloudy layers generally maximally overlapped

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

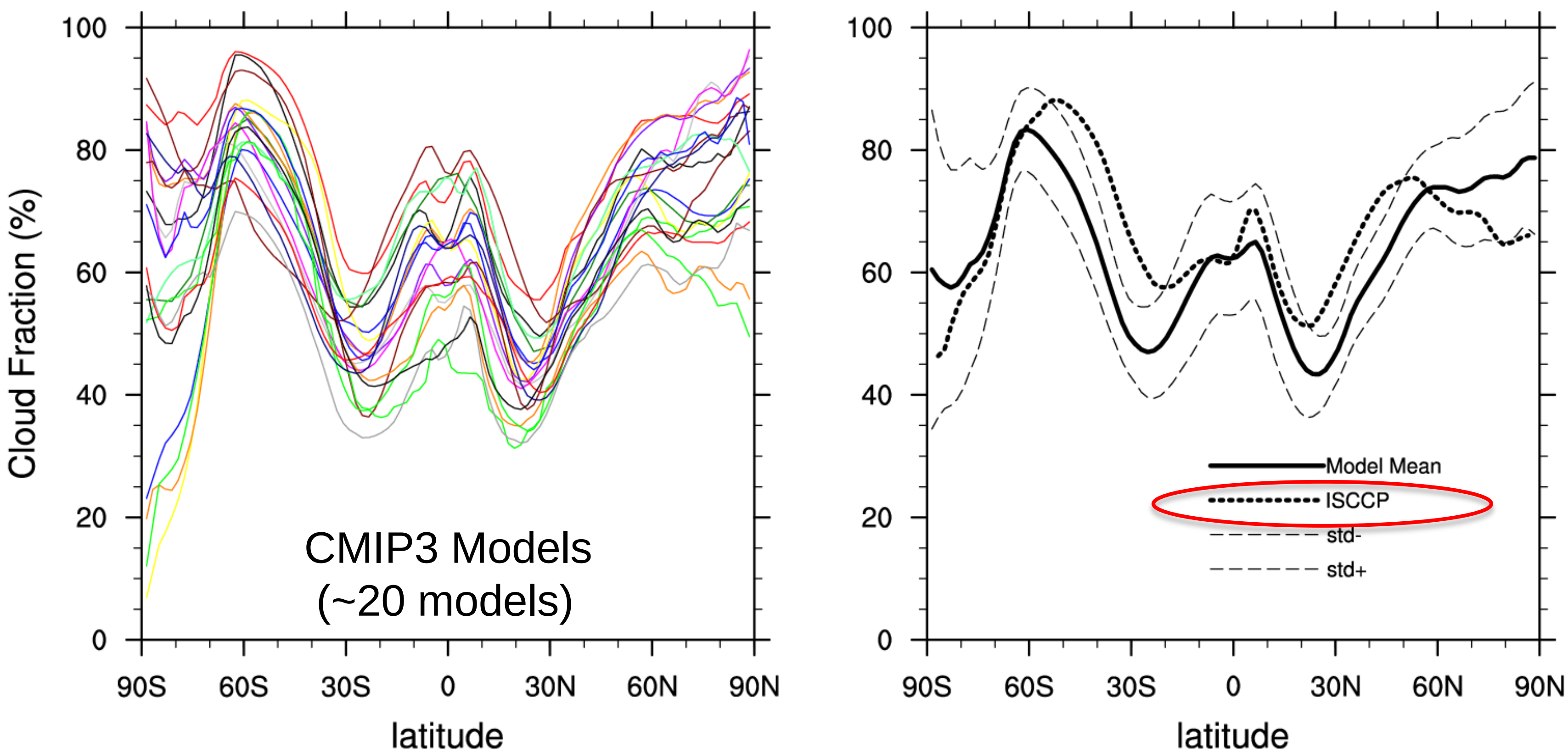
# Clouds in GCMs
## State of the Art from CMIP3

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



# Clouds in GCMs
## State of the Art from CMIP3

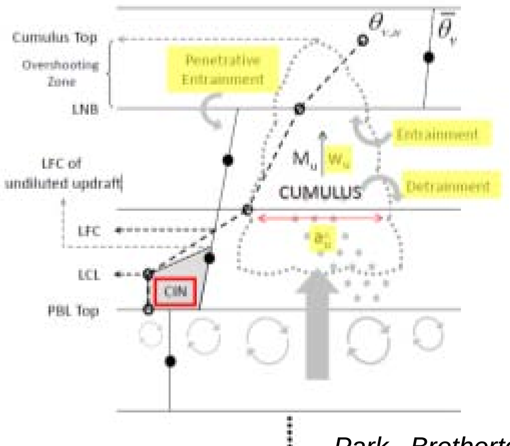
Total Cloud Fraction
(Annual, 1990-1999)



# CAM5: Physics Changes

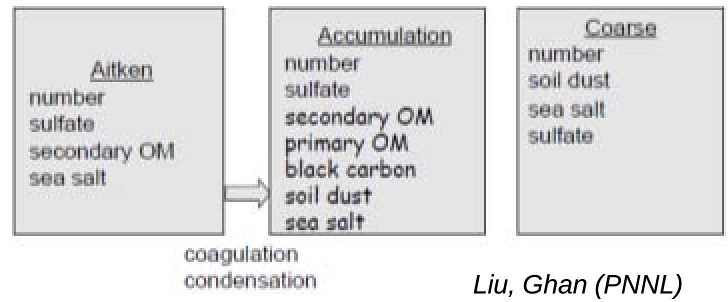
## Cloud-aerosol interaction focus -> community efforts

*UW PBL and shallow cumulus*



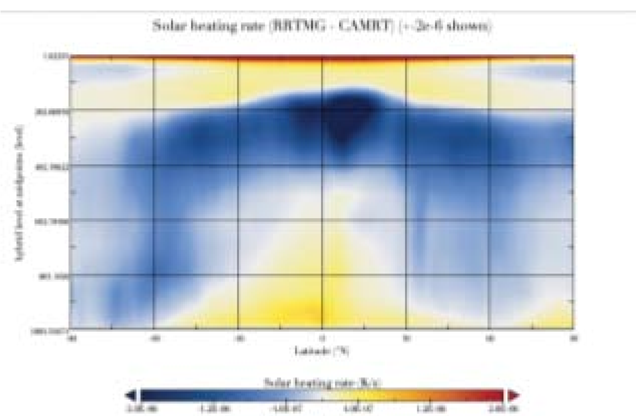

*Park , Bretherton (UW)*

*3-mode Modal Aerosol Model (MAM)*



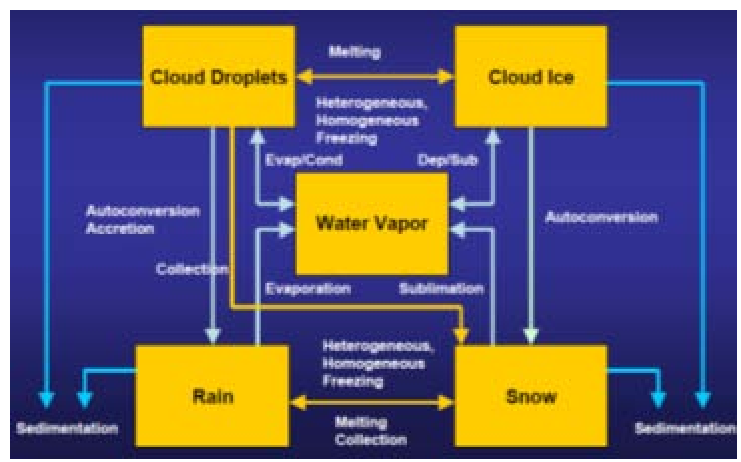

*Liu, Ghan (PNNL)*

*Rapid Radiative Transfer Model (RRTM)*




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

*2-moment microphysics + ice cloud*



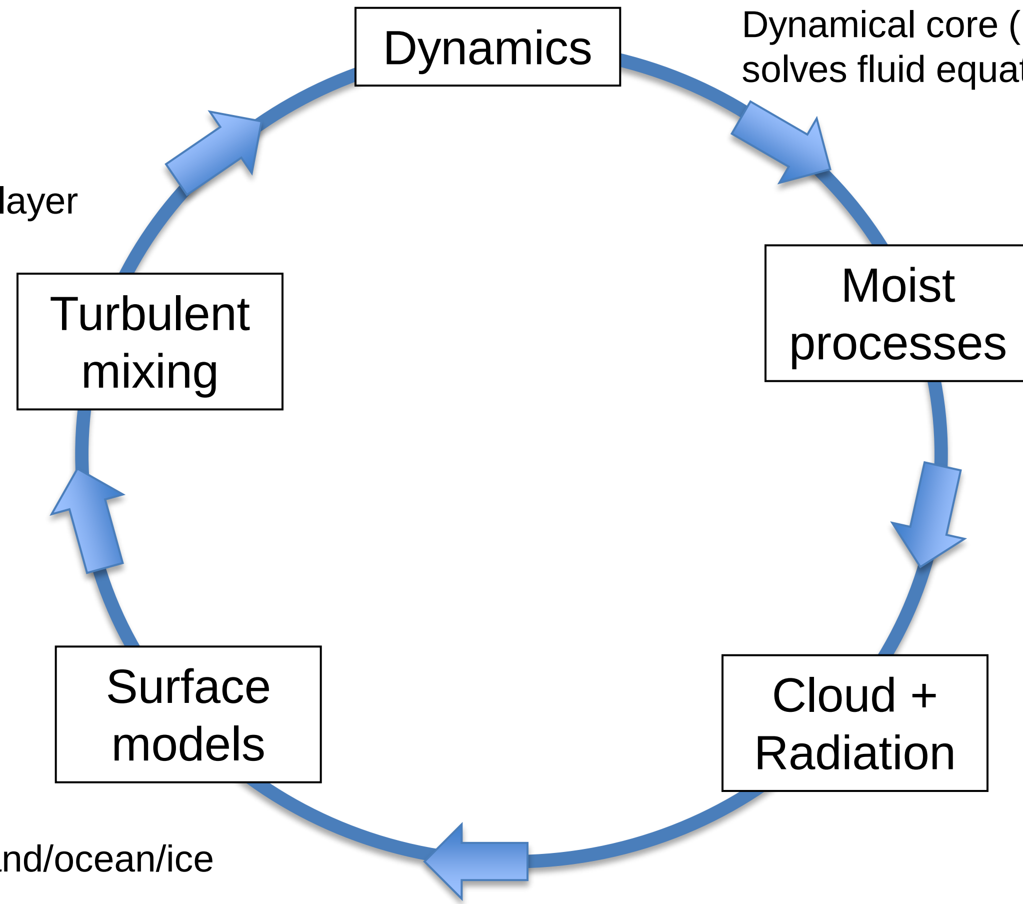

*Morrison, Gettleman (NCAR)*

# Older CAM workflow

## Up to CAM4

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

- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag



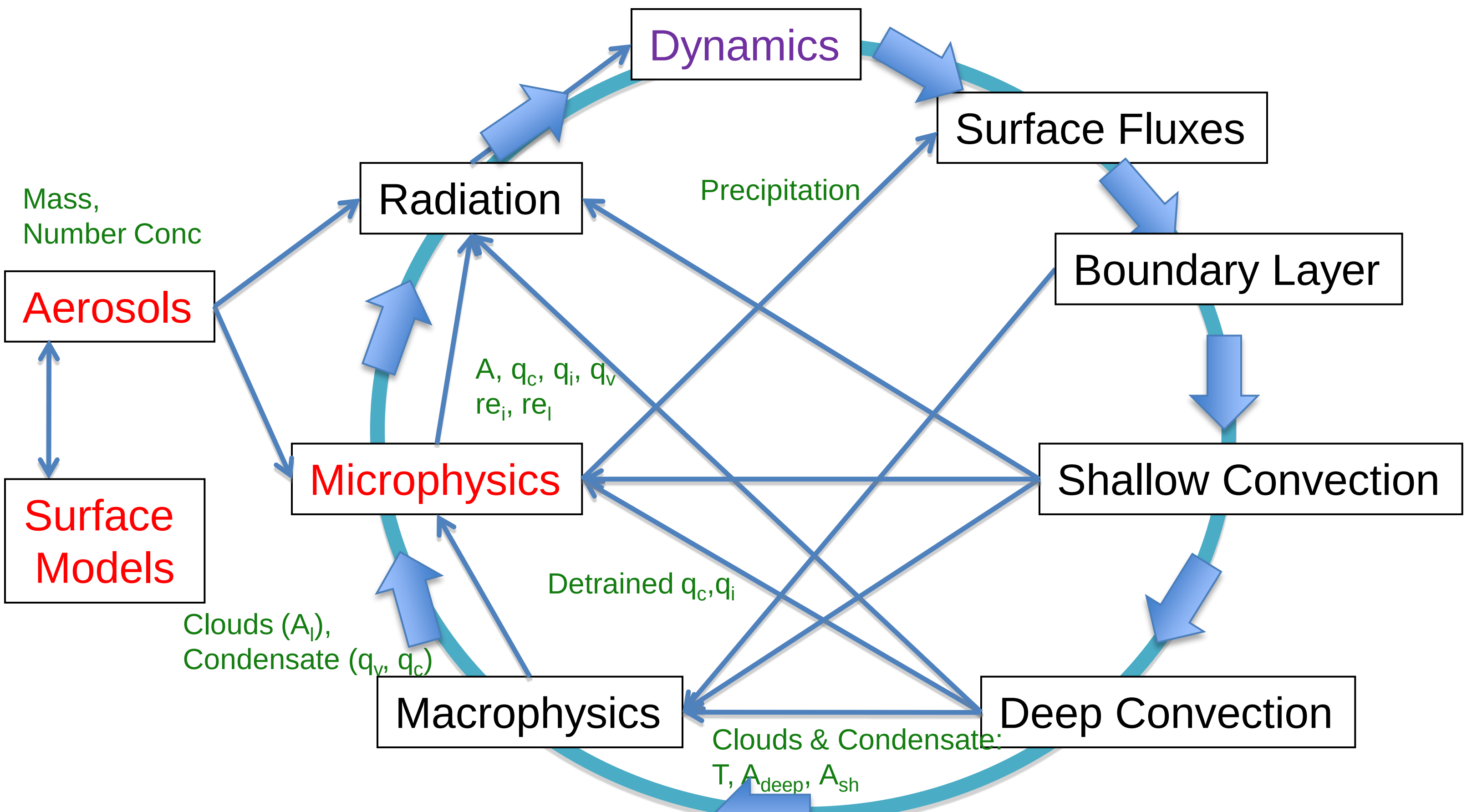

- Deep convection
- Shallow Convection
- Large-scale condensation

- Macrophysics
- Microphysics
- Radiation

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

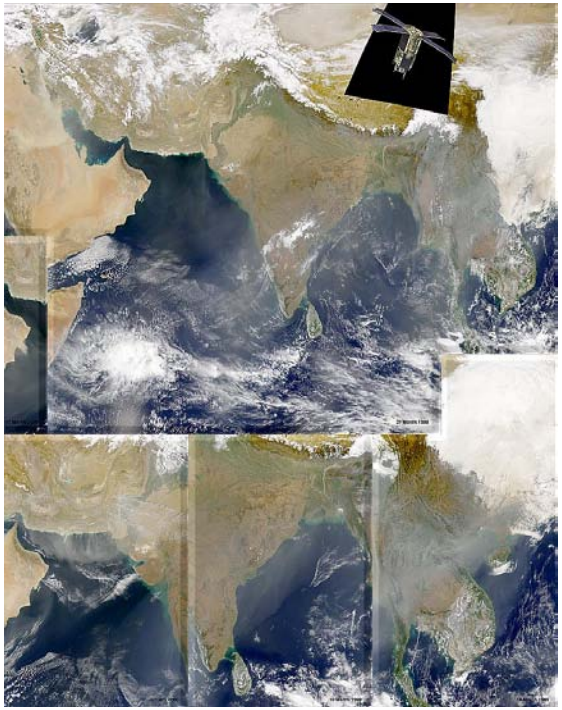
# New CAM workflow

## Community Atmosphere Model (CAM) Version 5



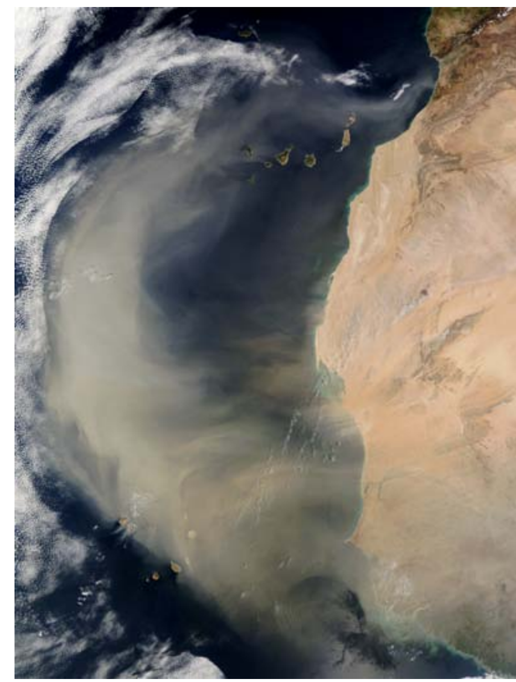

A = cloud fraction, $q=H_2O$, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor

# Natural and anthropogenic aerosols



India, March 2000

California, October 2003

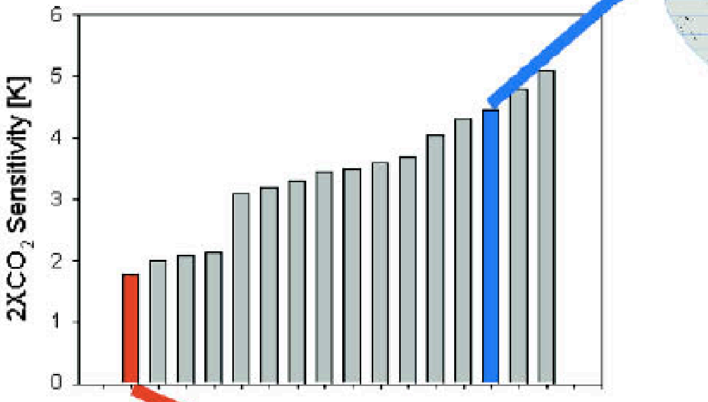


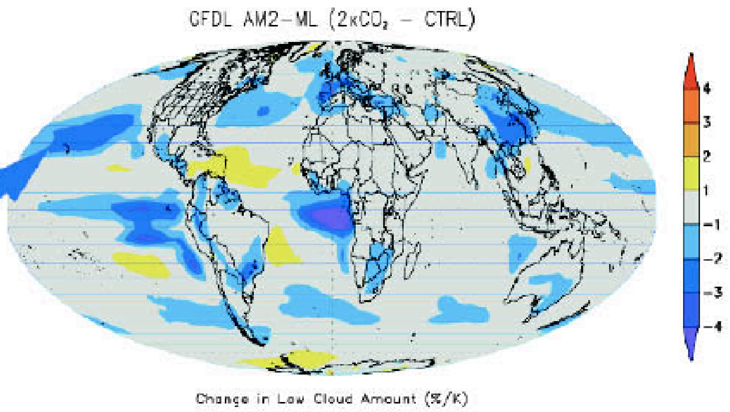
Africa, March 2003

# Cloud Feedbacks

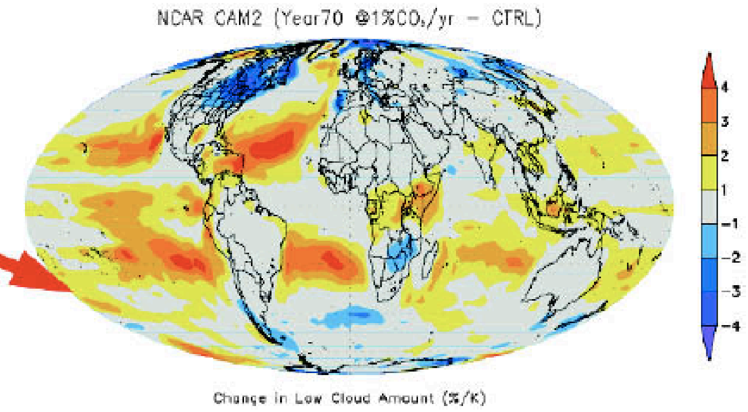
- Different between different models
- Provides spread in projections
- Due to parameterizations

$T_s$ Response to doubling $CO_2$




Difference in cloud fraction with climate change




Stephens, 2005

# Summary

- GCMs physics=unresolved processes=parameterization
- Parameterization = approximating reality
  - Starts from and maintains physical constraints
  - Tries to represent effects of smaller 'sub-grid' scales
- Fundamental constraints (mass & energy conservation) are our friends
- 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)