

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

CESM Tutorial

Rich Neale, NCAR

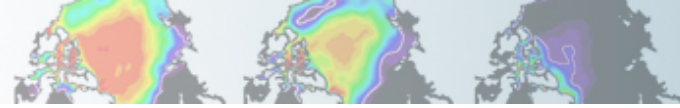
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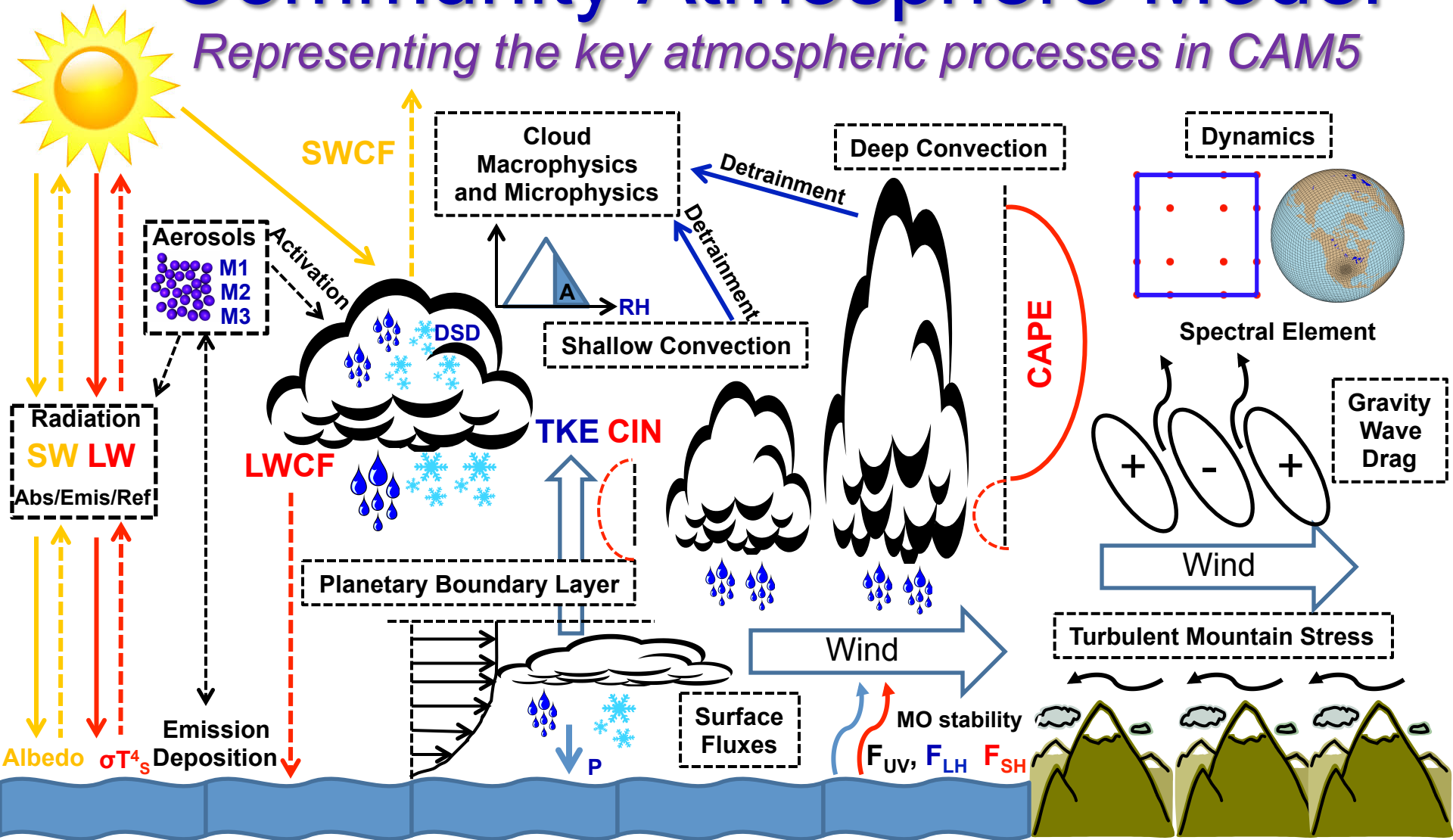


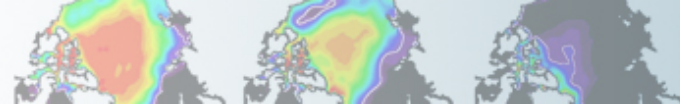
Outline

- 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

Community Atmosphere Model

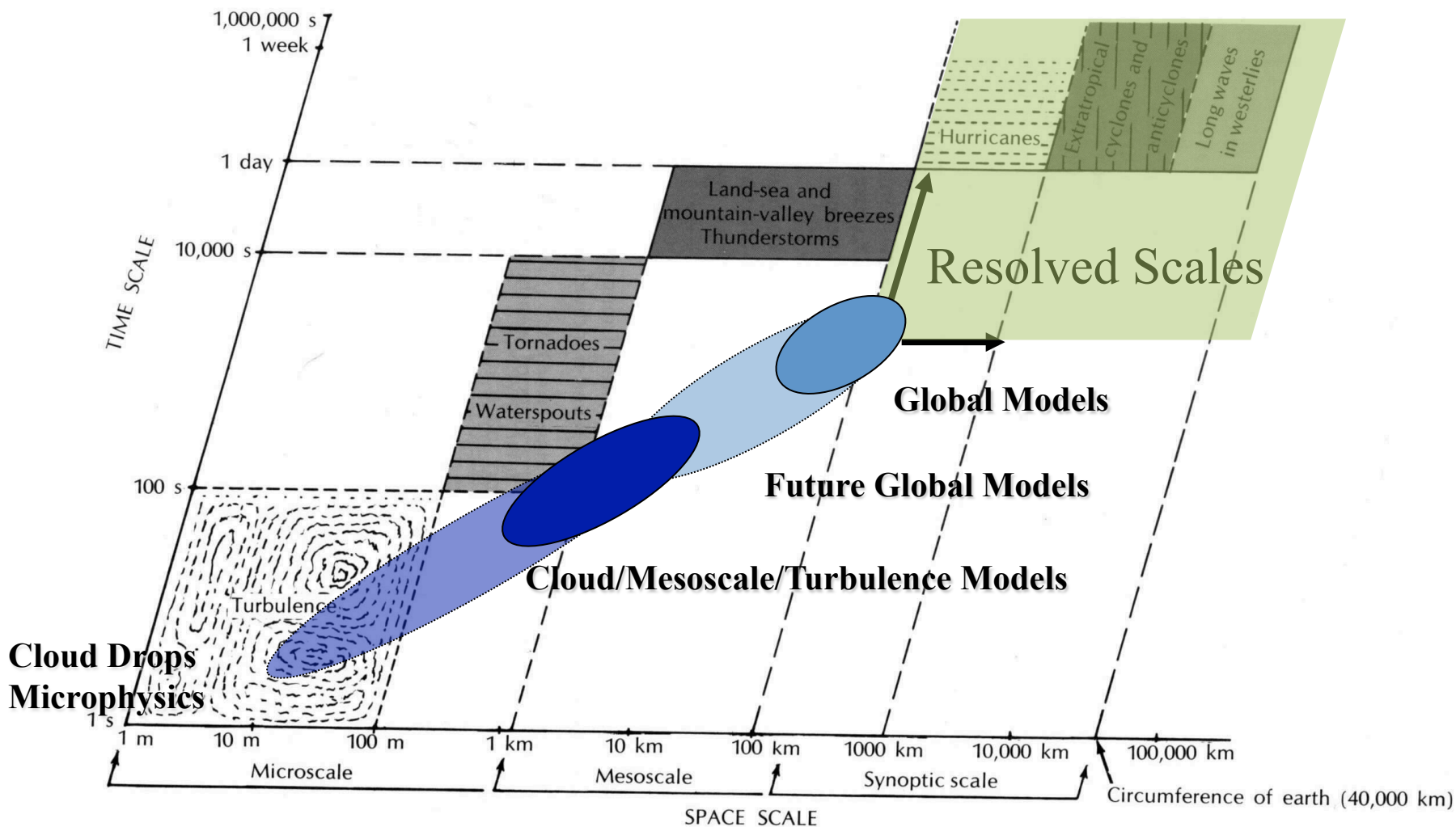
Representing the key atmospheric processes in CAM5

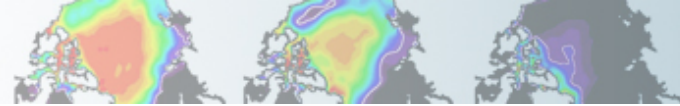




Scales of Atmospheric Processes

Determines the formulation of the model





Hydrostatic Primitive Equations

Where do we put the physics?

Horizontal scales \gg vertical scales

Vertical acceleration \ll gravity

$$d\bar{\mathbf{V}}/dt + f\mathbf{k} \times \bar{\mathbf{V}} + \nabla\bar{\phi} = \mathbf{F}, \quad \mathbf{F}_V \quad (\text{horizontal momentum})$$

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

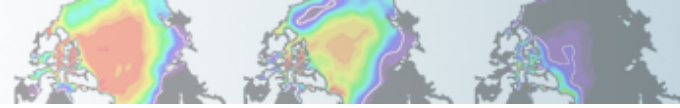
$$\nabla \cdot \bar{\mathbf{V}} + \partial\bar{\omega}/\partial p = 0, \quad (\text{mass continuity})$$

$$\partial\bar{\phi}/\partial p + R\bar{T}/p = 0, \quad (\text{hydrostatic equilibrium})$$

$$d\bar{q}/dt = S_q, \quad \mathbf{F}_{QV}, \mathbf{F}_{QL}, \mathbf{F}_{QI} \quad (\text{water vapor mass continuity})$$

Harmless looking terms \mathbf{F} , Q , and $S_q \implies$ “physics”

(Peter Lauritzen (NCAR) talked about the dynamics yesterday)

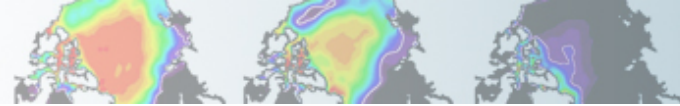


Effect of Physics on the Model

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
 - Turbulence



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. ”

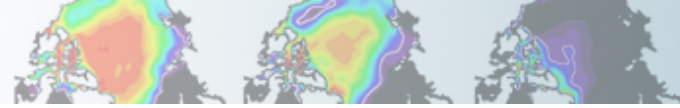
“...to express in terms of parameters.”

These “parameters” are of course the grid-mean quantities of the model $u, v, w, T, P_s, q_v, q_L, q_i$ (including derived quantities)

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

Diagram illustrating the relationship between unresolved and resolved quantities in a parameterization scheme:

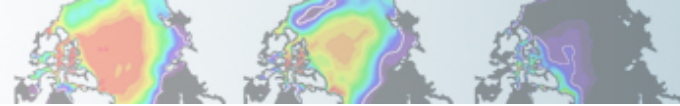
- The term $\overline{w'\chi'}$ is labeled as “Unresolved ‘sub-grid’”.
- The term $-K_\chi \frac{\partial \chi}{\partial z}$ is labeled as “Resolved ‘grid-scale’”.
- The coefficient K_χ is labeled as “‘Diffusivity’”.



What is a 'Parameterization'?

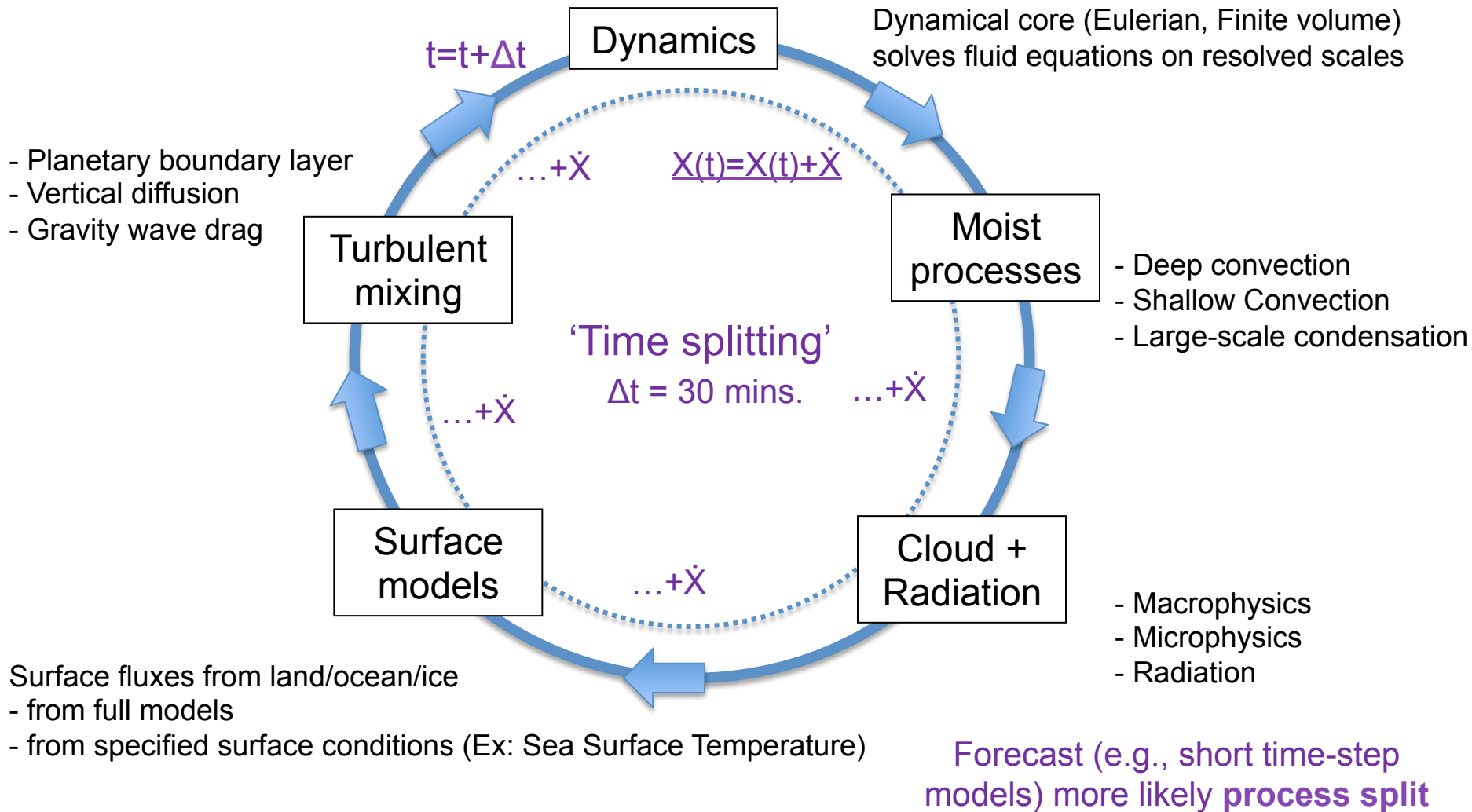


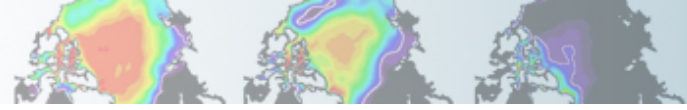
- Usually based on
 - Basic physics (conservation laws of thermodynamics)
 - Empirical formulations from observations
- In many cases: no explicit formulation based on first principles is possible at the level of detail desired. Why?
 - Non-linearities & interactions at 'sub-grid' scale
 - Often coupled with observational uncertainty
 - Insufficient information in the grid-scale parameters



CAM workflow

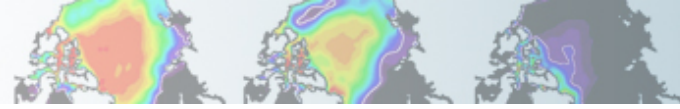
up to CAM4 (CCSM4)





Clouds

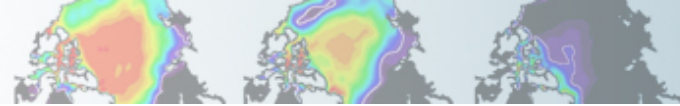




Clouds

Multiple Categories

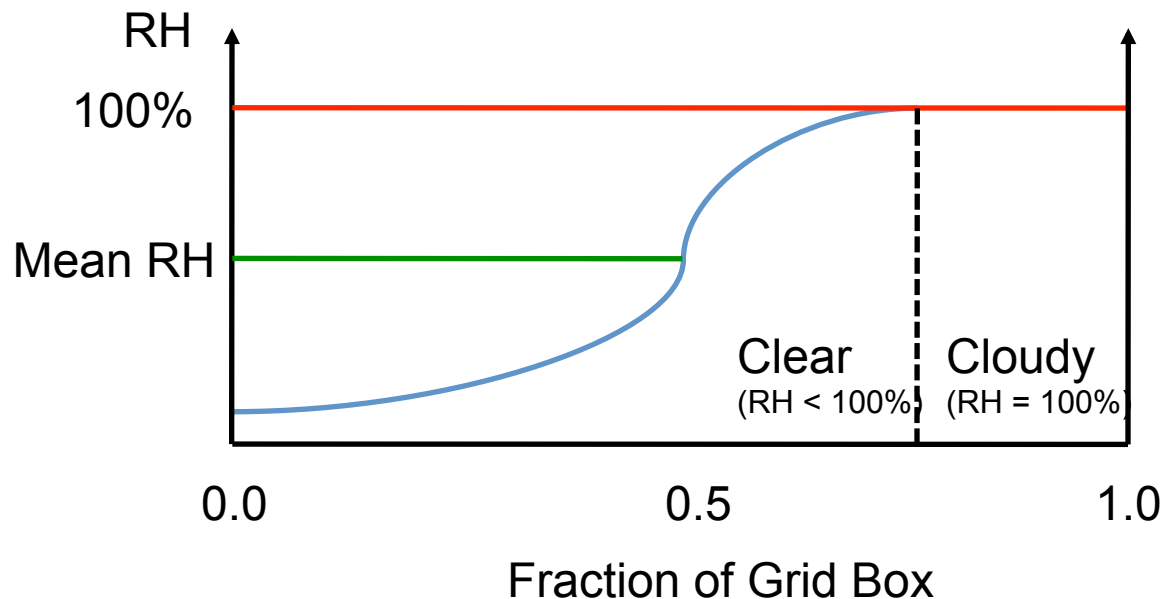
- **Stratiform (large-scale) clouds**
 - Responds to large-scale saturation fraction, RH (parameterized)
 - Coupled to presence of condensate (microphysics, advection)
- **Shallow convection clouds**
 - Symmetric turbulence in lower troposphere
 - Non precipitating (mostly)
 - Responds to surface forcing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



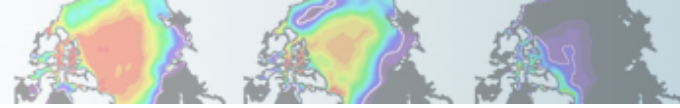
Stratiform Clouds

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* $RH = 100\%$
- ✓ RH_{crit} 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

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)

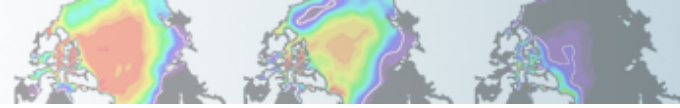
Parcels become unstable (buoyancy >0)

Deep heating

Latent heating and precipitation

Generally a sink of water vapor

Large cloud radius small entrainment

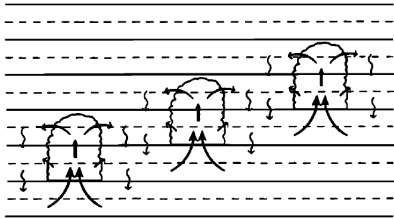


Shallow and Deep Convection

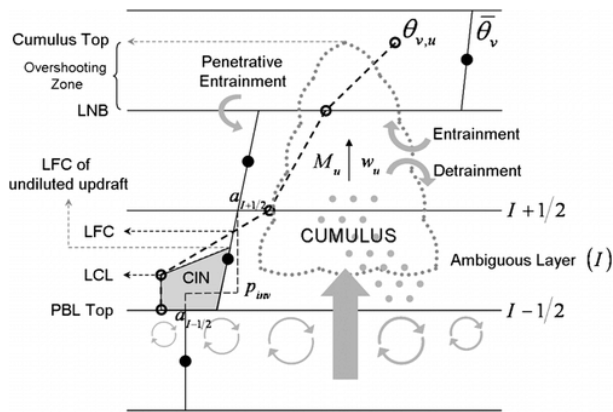
Closure: How much and when?

Shallow

Local conditional instability **CAM4**



Convective inhibition and turbulent kinetic energy (TKE) **CAM5**

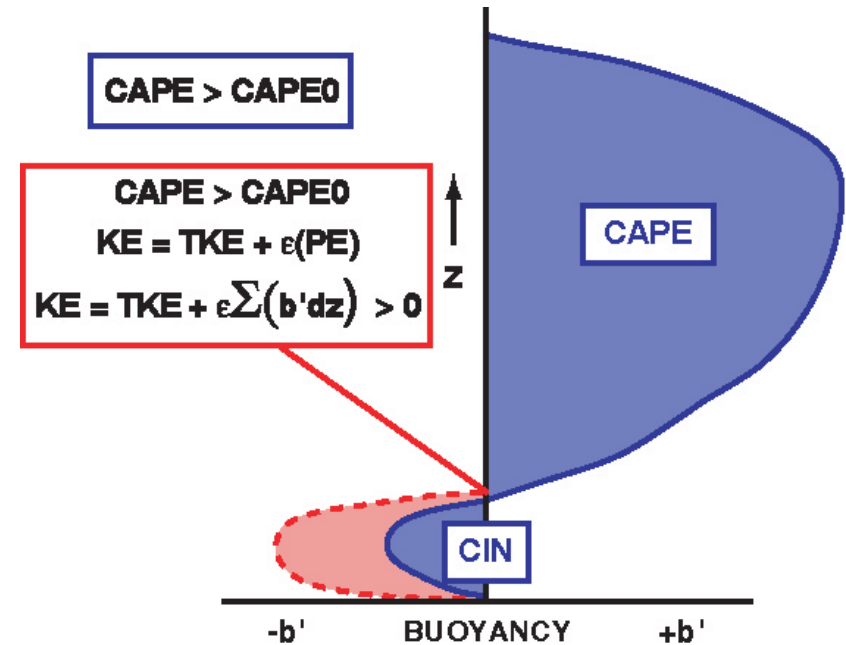


Deep

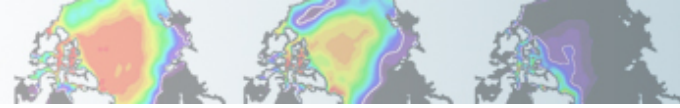
Convective Available Potential Energy (CAPE) **CAM4 and CAM5**

$$CAPE > CAPE_{\text{trigger}}$$

Timescale=1 hour

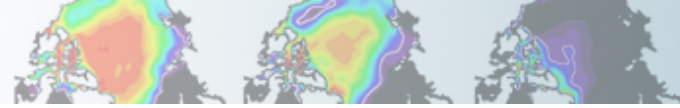


Shallow and deep convection and stratiform cloud fractions combined for radiation



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

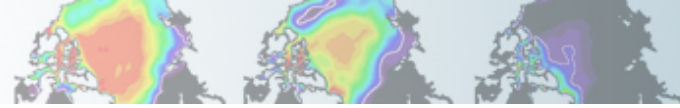


Different types of Microphysics

- 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

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

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

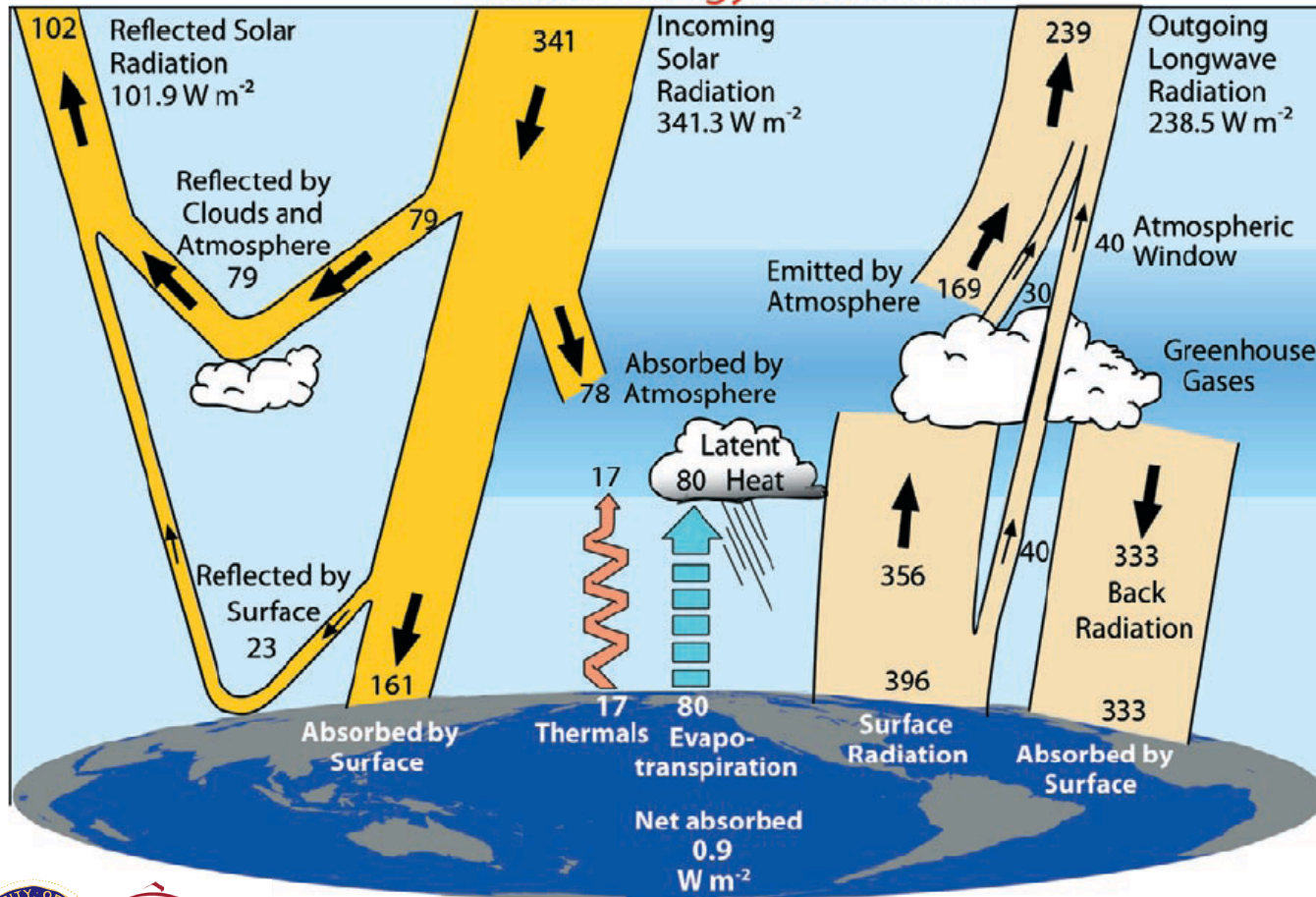


Radiation

The Earth's Energy Budget

Trenberth & Fasullo, 2008

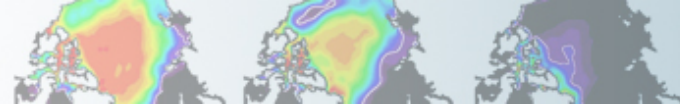
Global Energy Flows $W m^{-2}$



Gas	SW Absorption (Wm^{-2})
CO ₂	1
O ₂	2
O ₃	14
H ₂ O	43

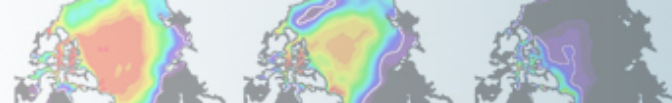


Thanks to: Bill Collins, Berkeley & LBL

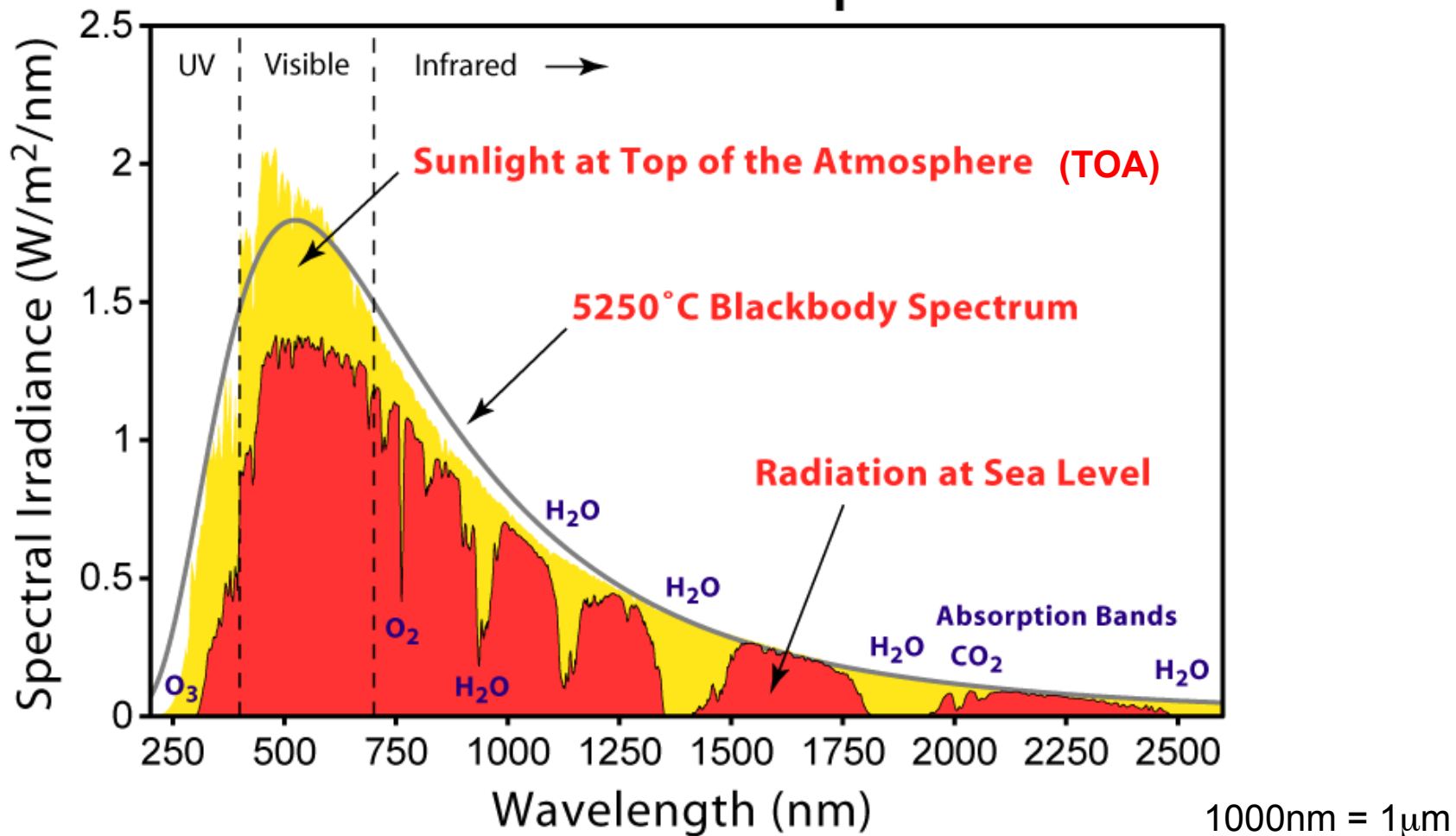


Goals of GCM Radiative Codes

- 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

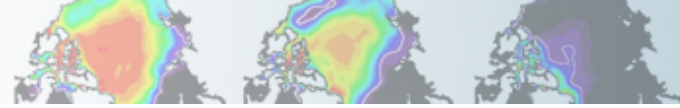


Solar Radiation Spectrum

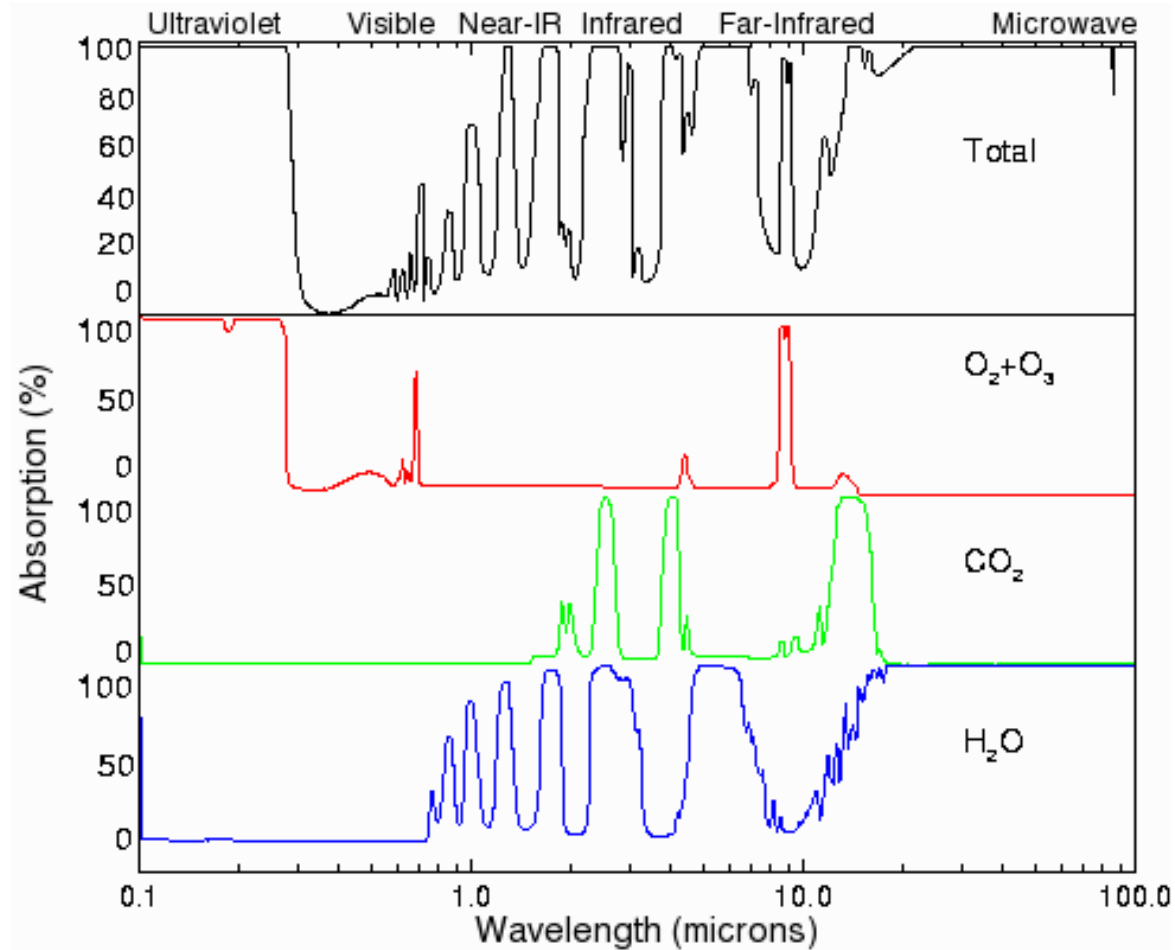


Input at TOA, Radiation at surface

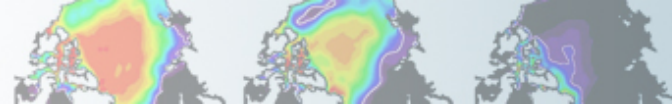
From: 'Sunlight', Wikipedia



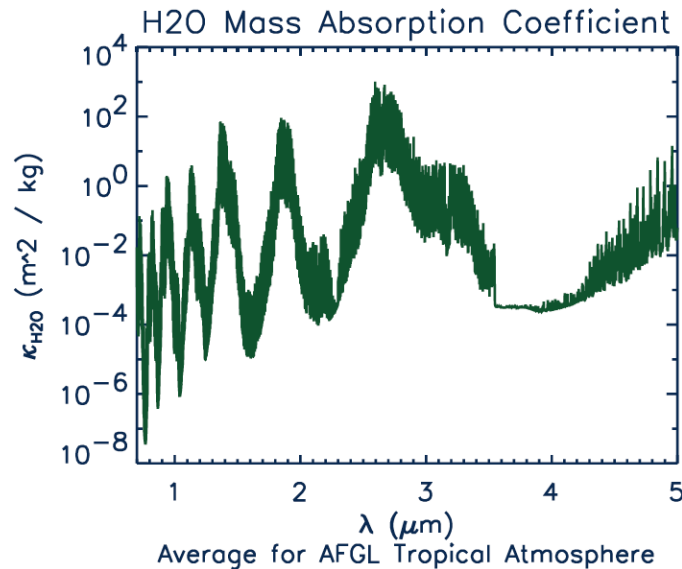
IR absorption



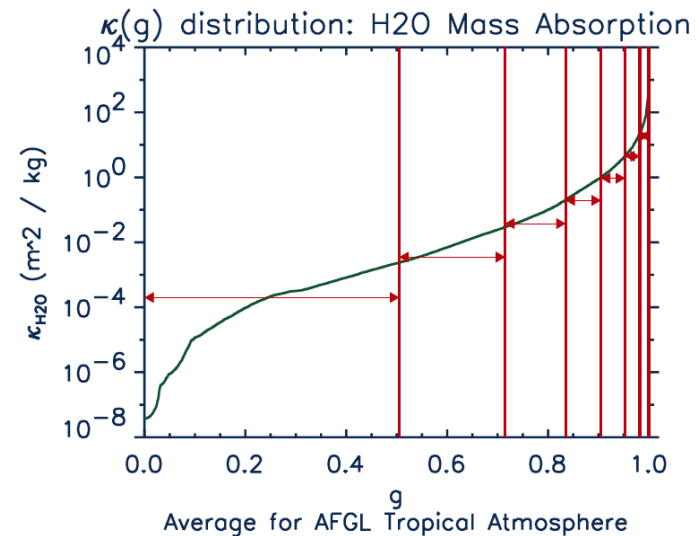
1000nm = 1 μ m



k-distribution Band Models



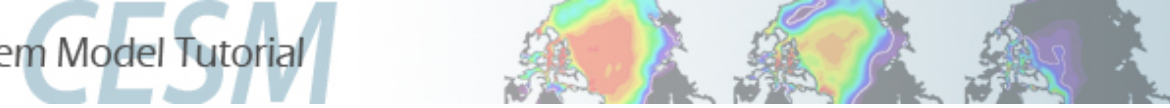
Sort



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

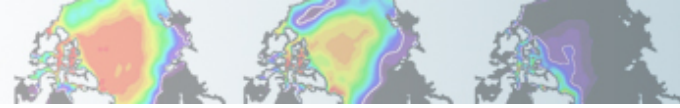
$$T(u) \hat{T}(u) \approx \sum_{i=1}^N \exp[-\hat{\kappa}_i u] \delta g_i dg$$

- 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 couple of hours
- 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)



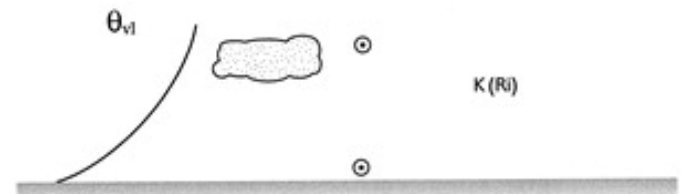
Planetary Boundary Layer (PBL)

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
$$Ri = \frac{g\beta}{(\partial u / \partial z)^2},$$
- $\ll 1$, flow becomes turbulent
- CAM4: Gradient Ri # + non-local transport (Holtslag and Boville, 1993)
- CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)

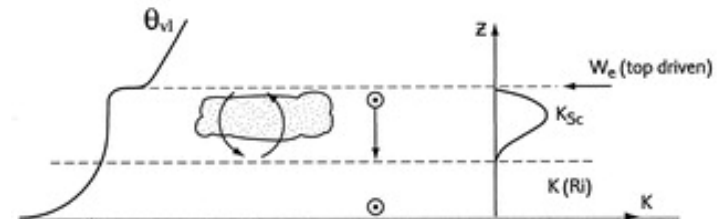
(a)

I. Stable boundary layer, possibly with non-turbulent cloud (no cumulus, no decoupled Sc, stable surface layer)



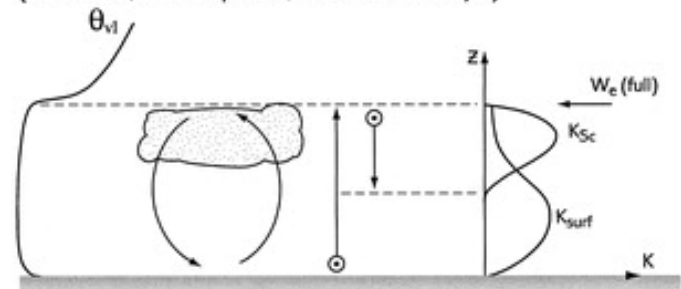
(b)

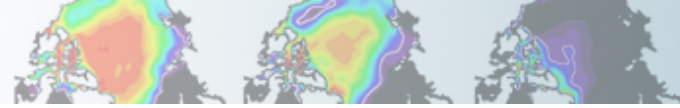
II. Stratocumulus over a stable surface layer (no cumulus, decoupled Sc, stable surface layer)



(c)

III. Single mixed layer, possibly cloud-topped (no cumulus, no decoupled Sc, unstable surface layer)

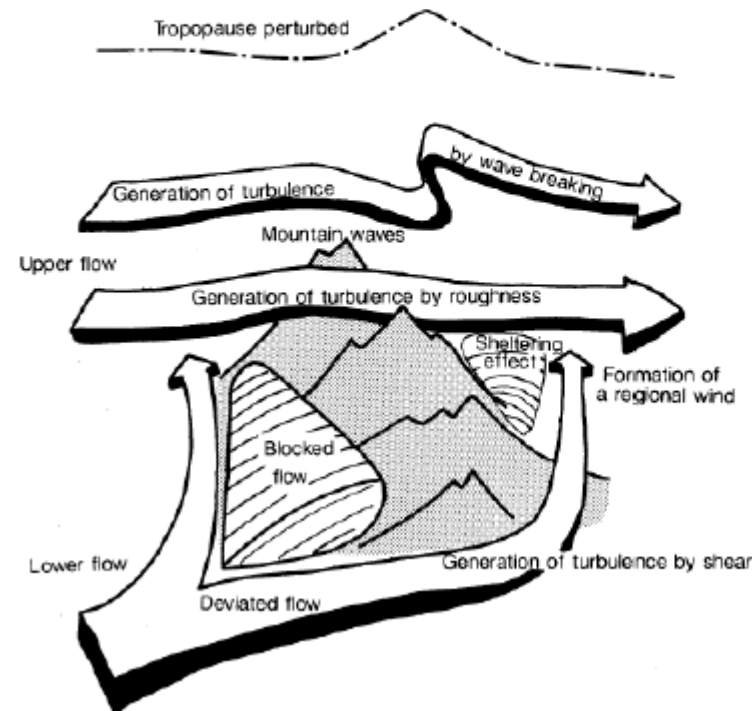


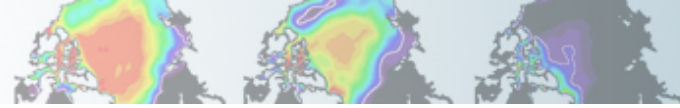


Gravity Waves and Mountain Stresses

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

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

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

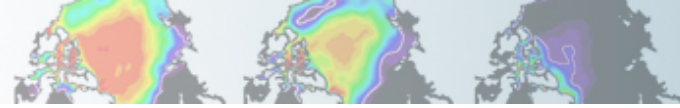
Specific Heat

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

Latent heat
(evaporation)

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

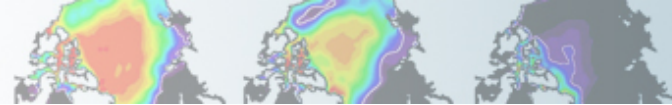
- Resistances r_{ax} based on
 - Monin-Obhukov similarity theory



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

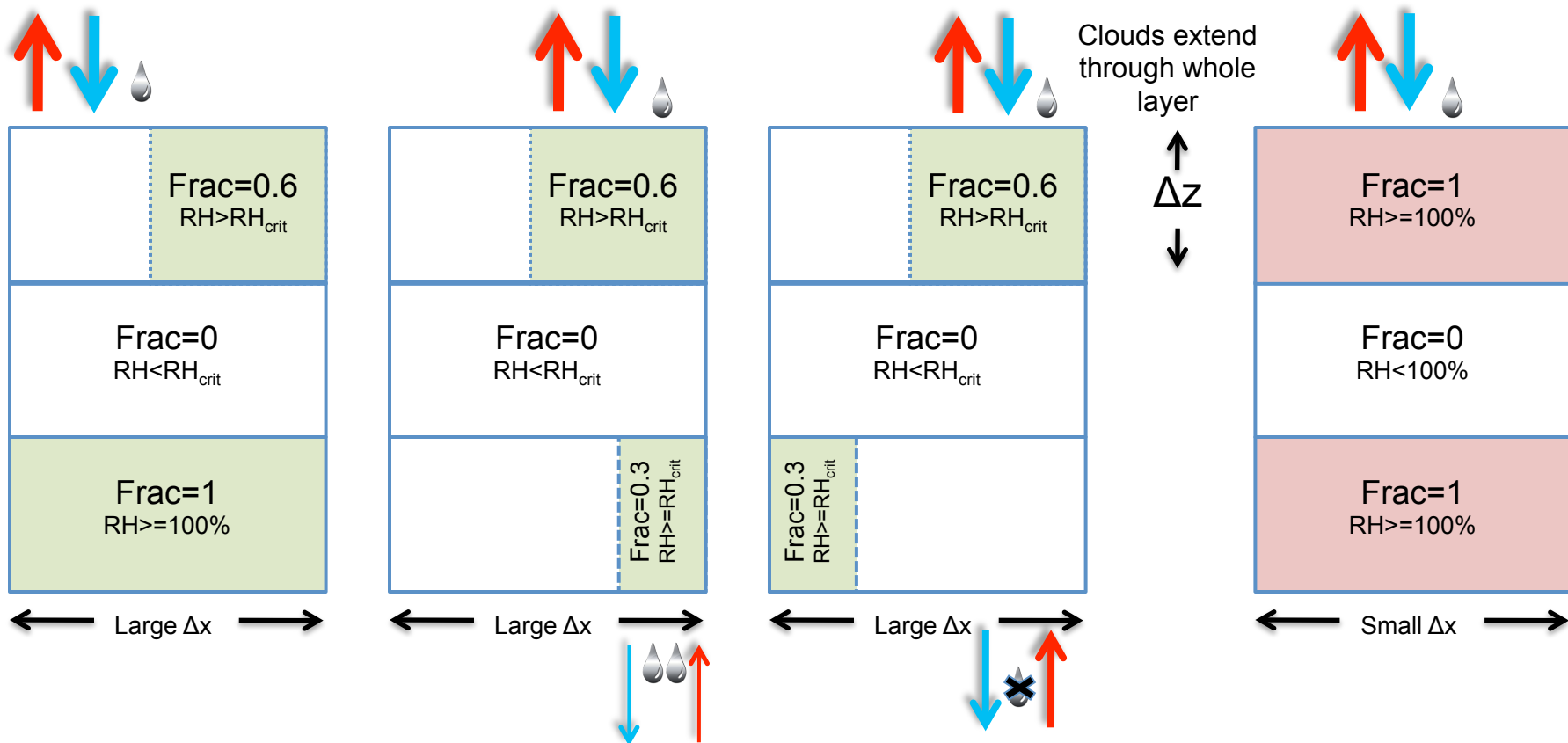


The Cloud Overlap Challenge

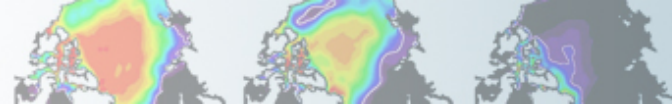
Radiation and micro/macro-physics impact

Maximum Overlap

Minimum Overlap



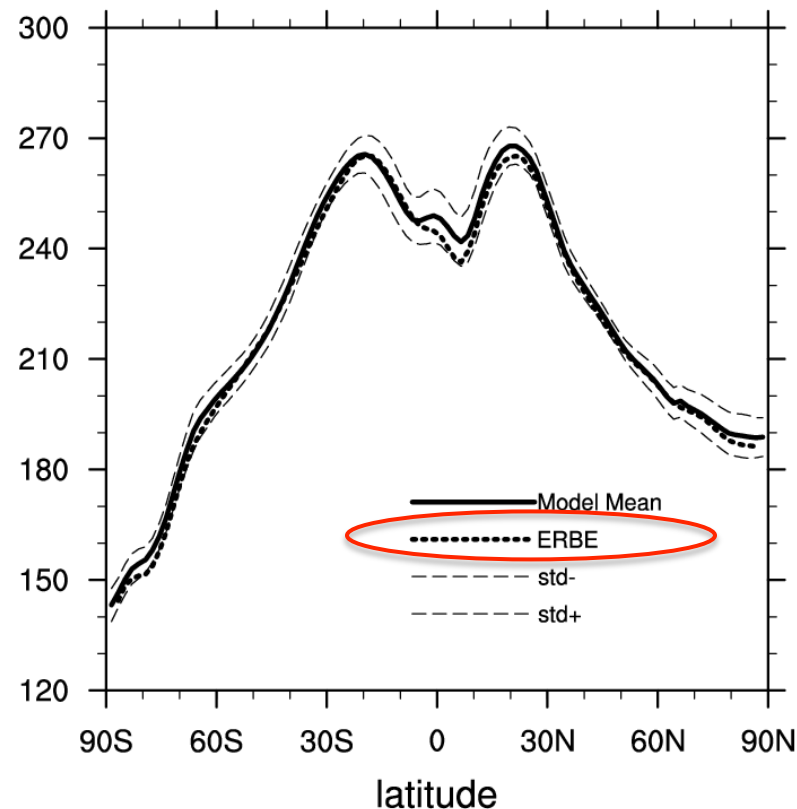
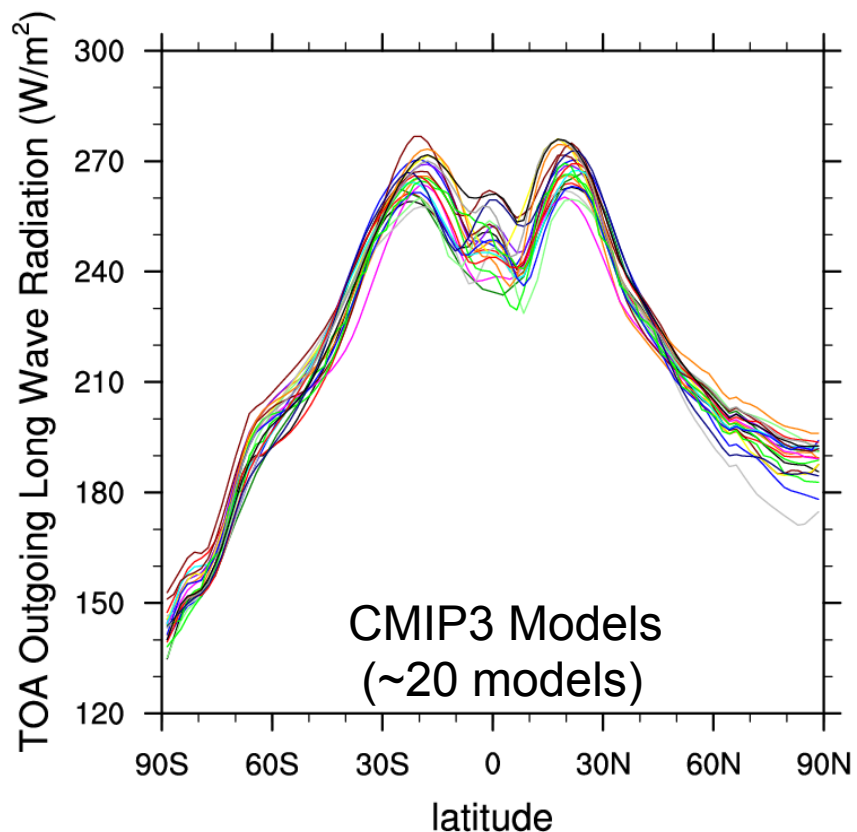
- Contiguous cloudy layers generally maximally overlapped
- Non-contiguous layers randomly overlapped; function of de-correlation length-scale

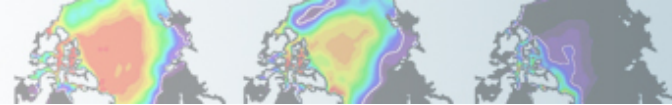


Clouds in GCMs

State of the Art from CMIP3

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

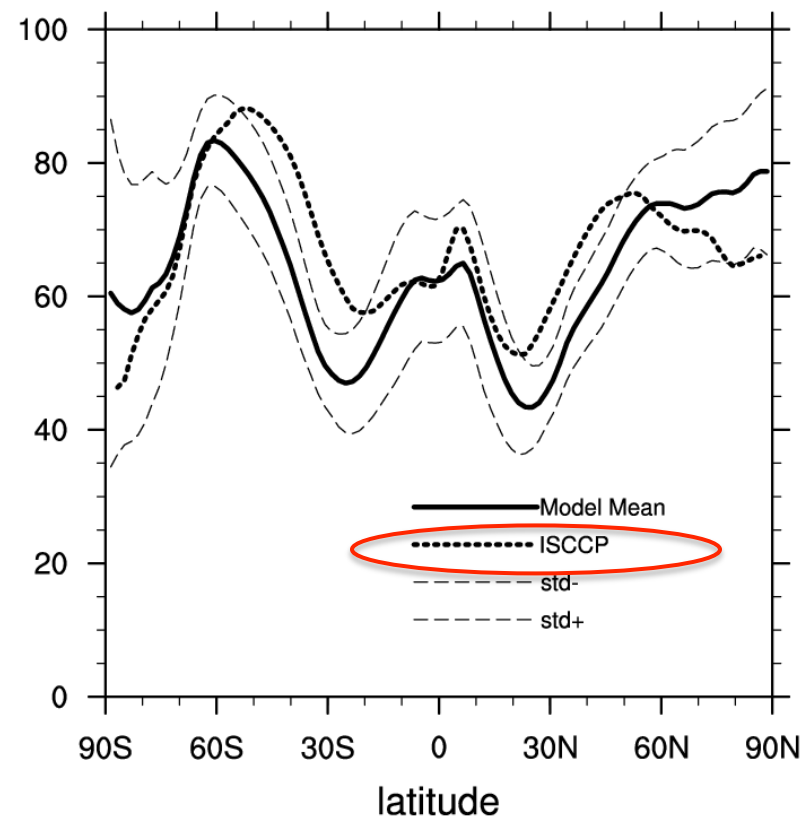
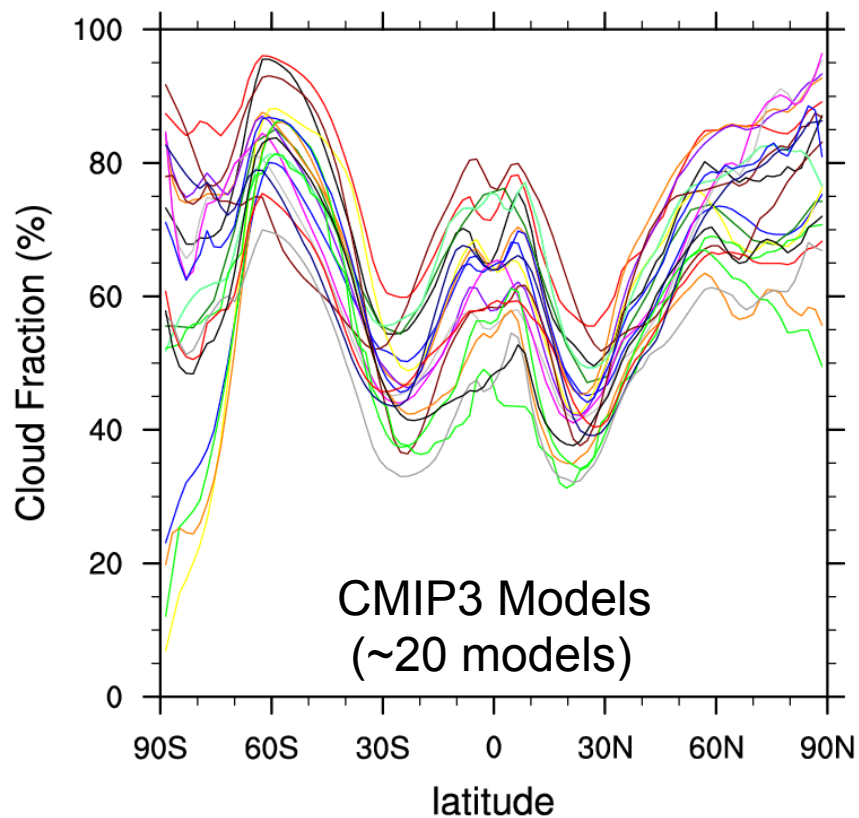


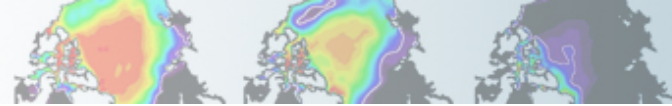


Clouds in GCMs

State of the Art from CMIP3

Total Cloud Fraction
(Annual, 1990-1999)

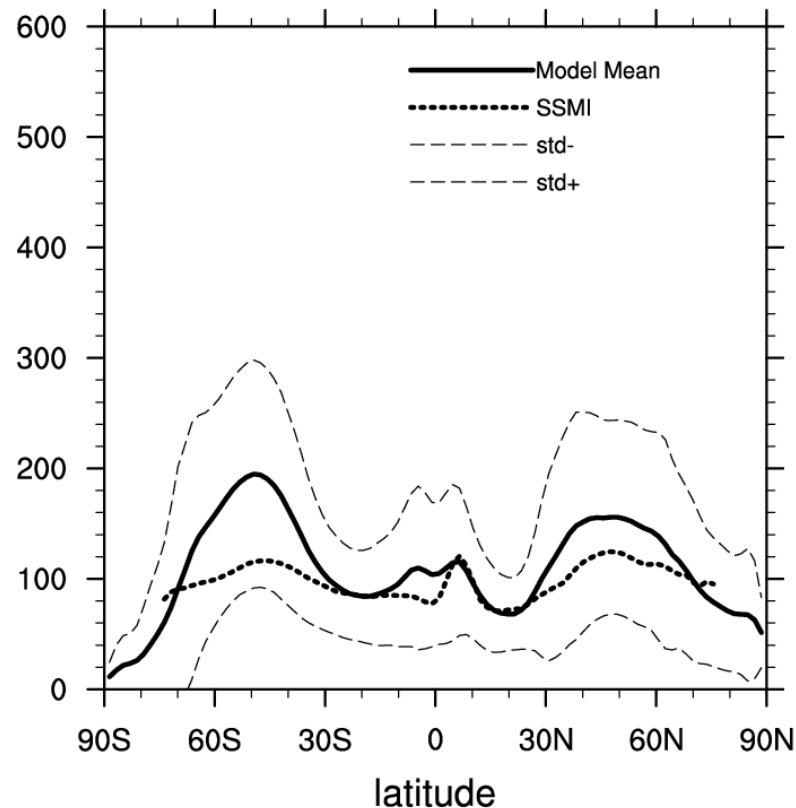
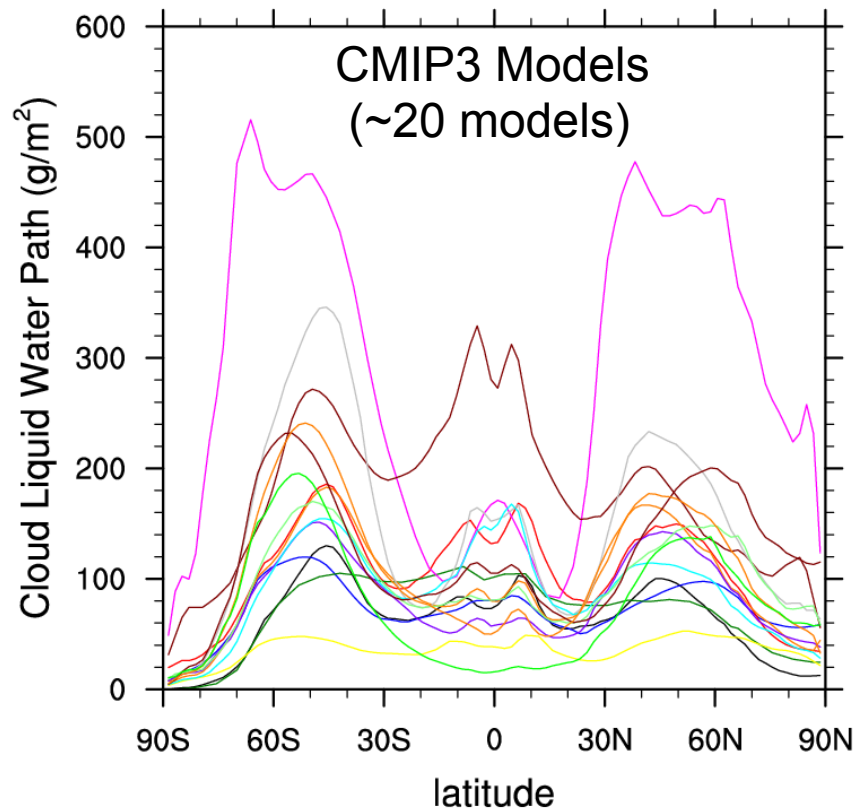


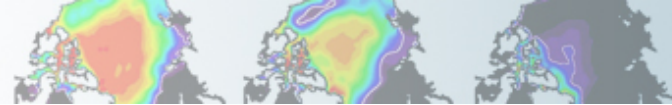


Structural Clouds in GCMs

State of the Art from CMIP3

Liquid Water Path
(Annual, 1990-1999)

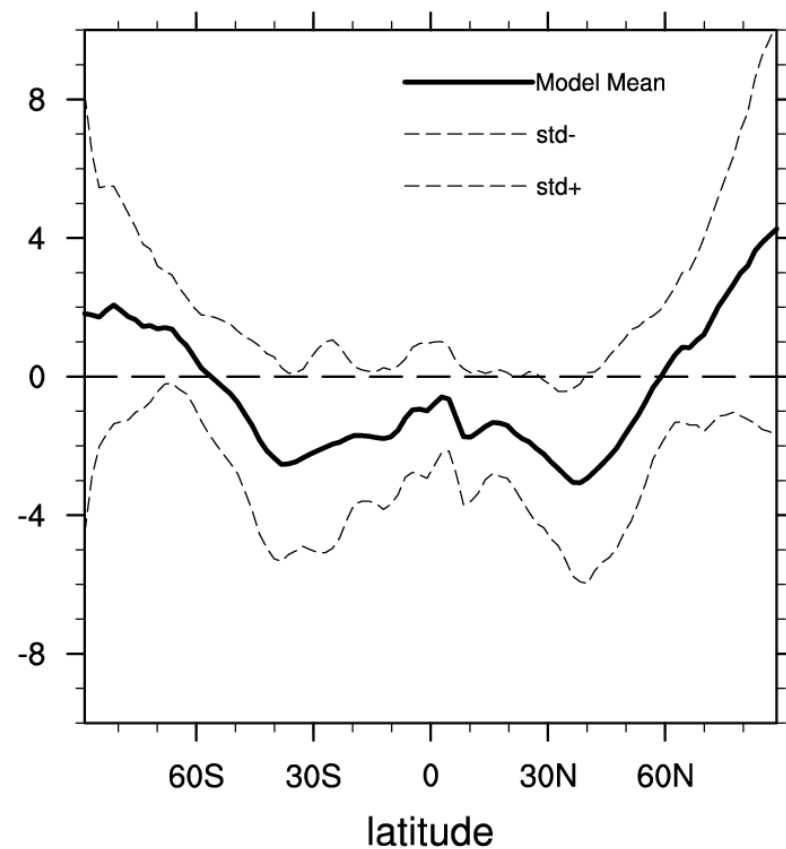
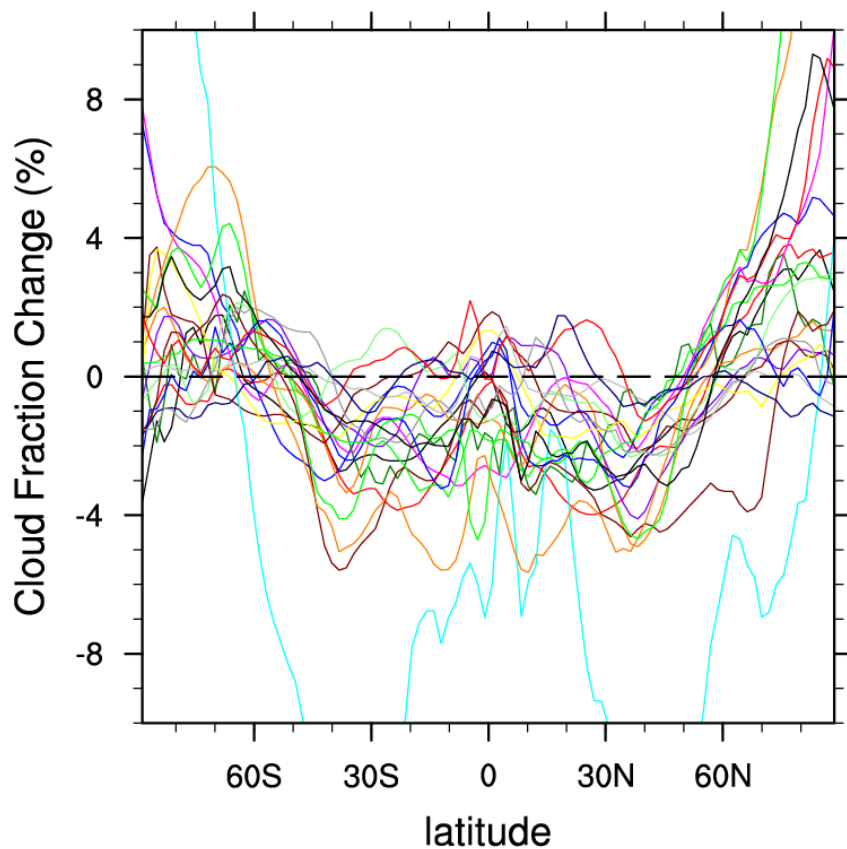


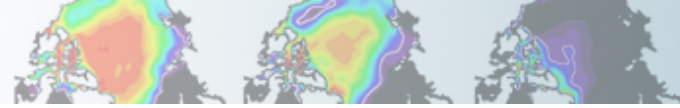


Future Clouds in GCMs

State of the Art from CMIP3 – response to climate change

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

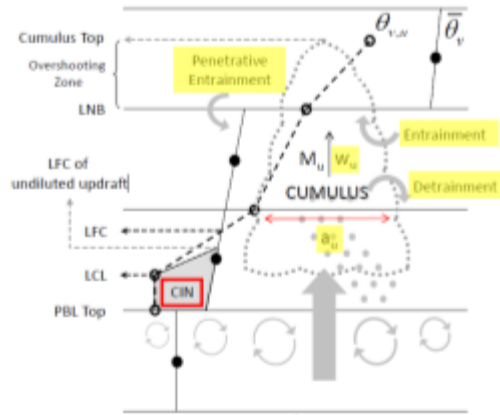




CAM5: Physics Changes

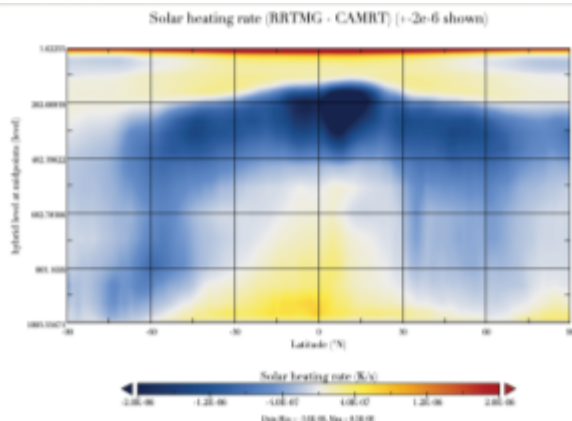
Cloud-aerosol interaction focus -> community efforts

UW PBL and shallow cumulus



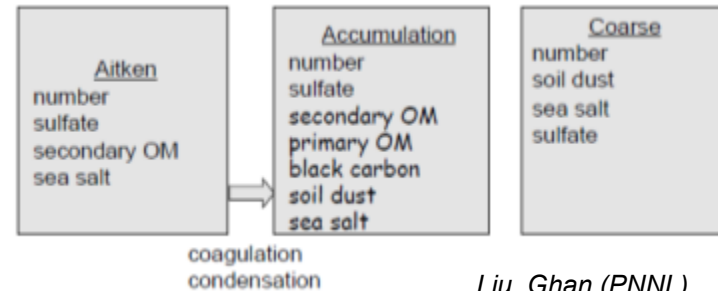
Park, Bretherton (UW)

Rapid Radiative Transfer Model (RRTM)



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

3-mode Modal Aerosol Model (MAM)

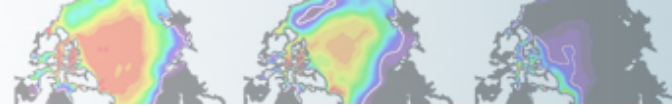


Liu, Ghan (PNNL)

2-moment microphysics + ice cloud

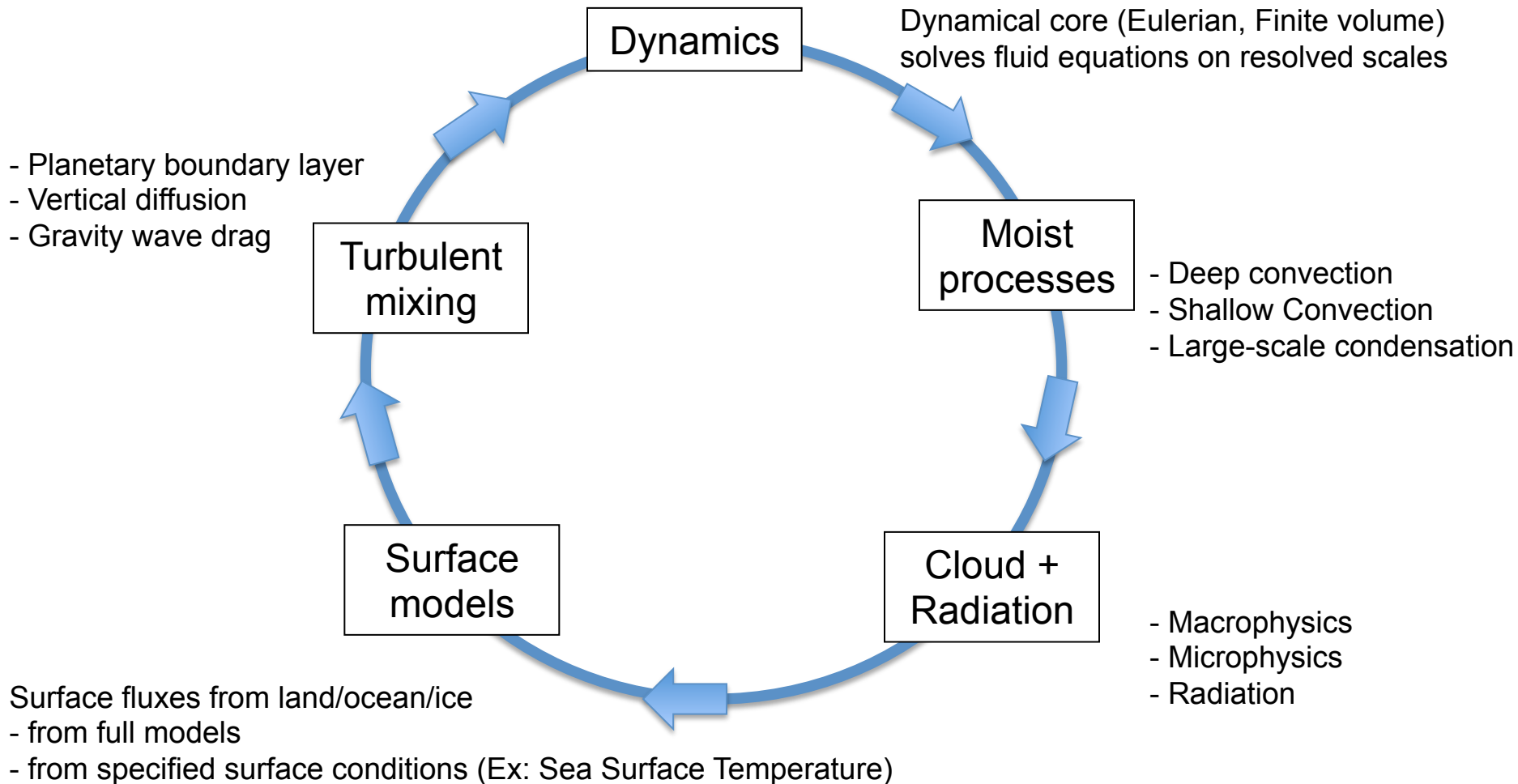


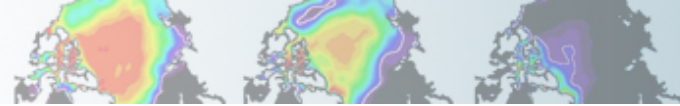
Morrison, Gettleman (NCAR)



Older CAM workflow

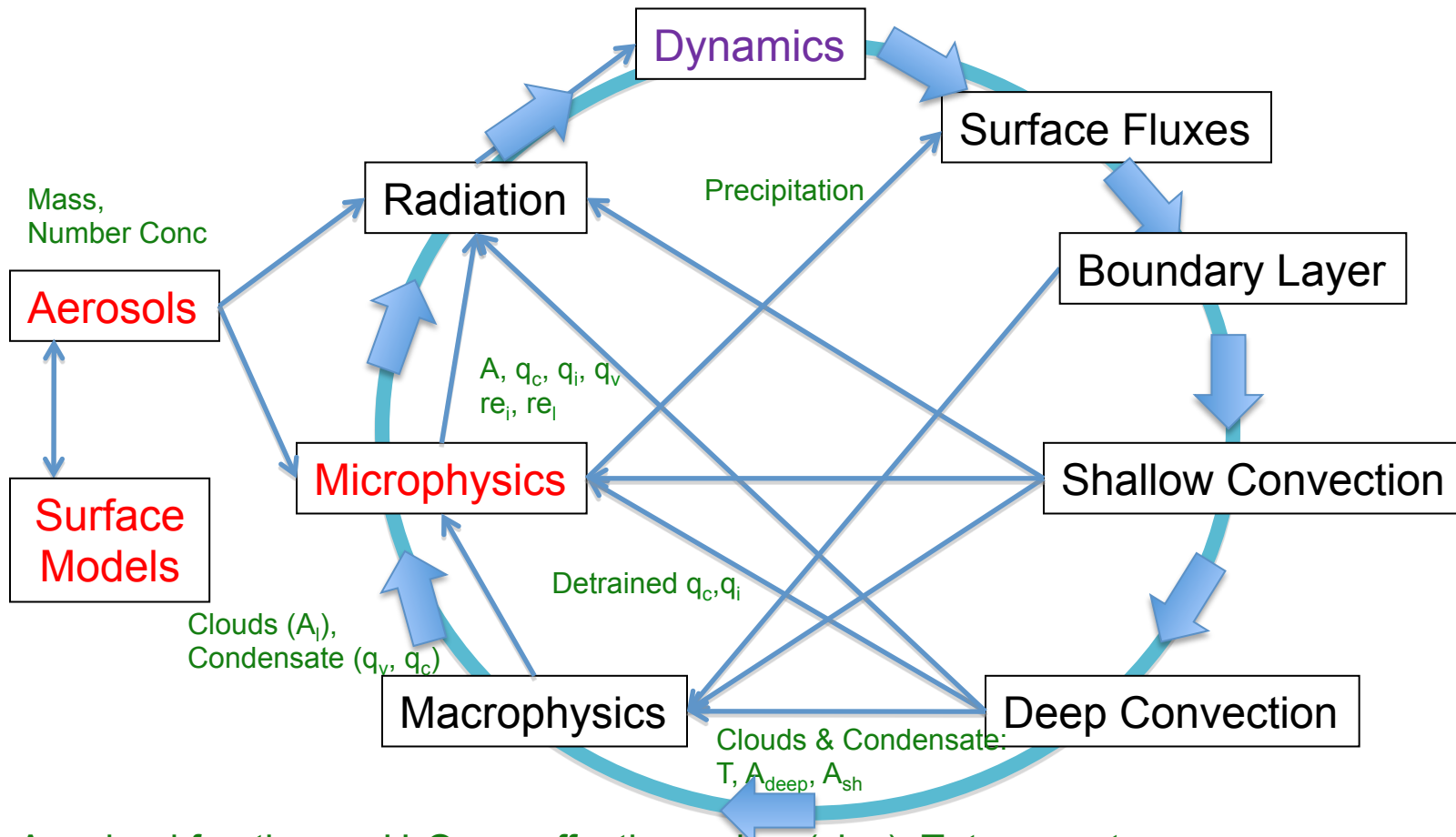
Up to CAM4



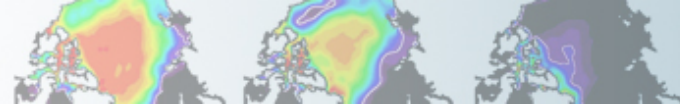


New CAM workflow

Community Atmosphere Model (CAM) Version 5

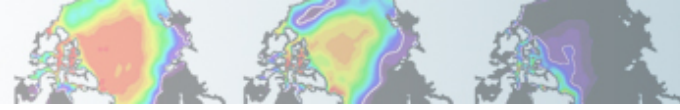


A = cloud fraction, q =H₂O, re =effective radius (size), T =temperature
 (i)ce, (l)iquid, (v)apor



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)
- Future parameterizations aim to be process **scale-aware** and model **grid-scale independent**



Questions?