Atmospheric Modeling II:

Physics in the Community Atmosphere Model (CAM)

CESM Tutorial

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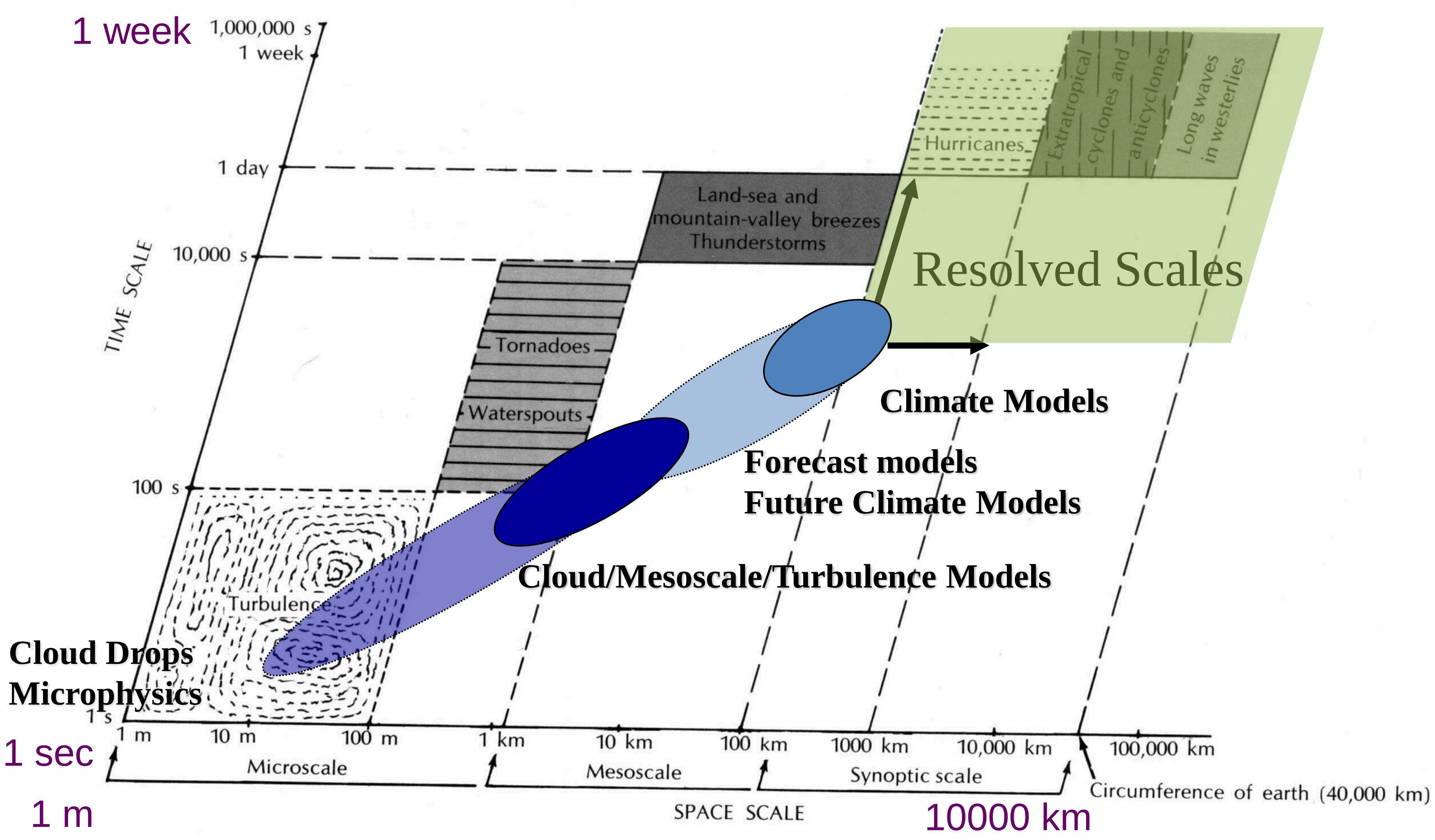
Outline

- **Physical processes** in an atmosphere GCM
- Distinguishing GCMs from other models (scales)
- Concept of **'Parameterization'** of sub-grid processes
- Physics representations (CESM)
  - **Clouds** (different types) and microphysics
  - Radiation
  - Boundary layers, surface fluxes and gravity waves
  - Unified turbulence methodology (CESM2)
- **Process interactions**
- Model **complexity**, **sensitivity** and **climate feedbacks**

Scales of Atmospheric Processes

Determines the formulation of the model



Equations of Motion

Where do we put the physics (with the dynamics)?

Horizontal scales >> vertical scales

Vertical acceleration << gravity

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

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

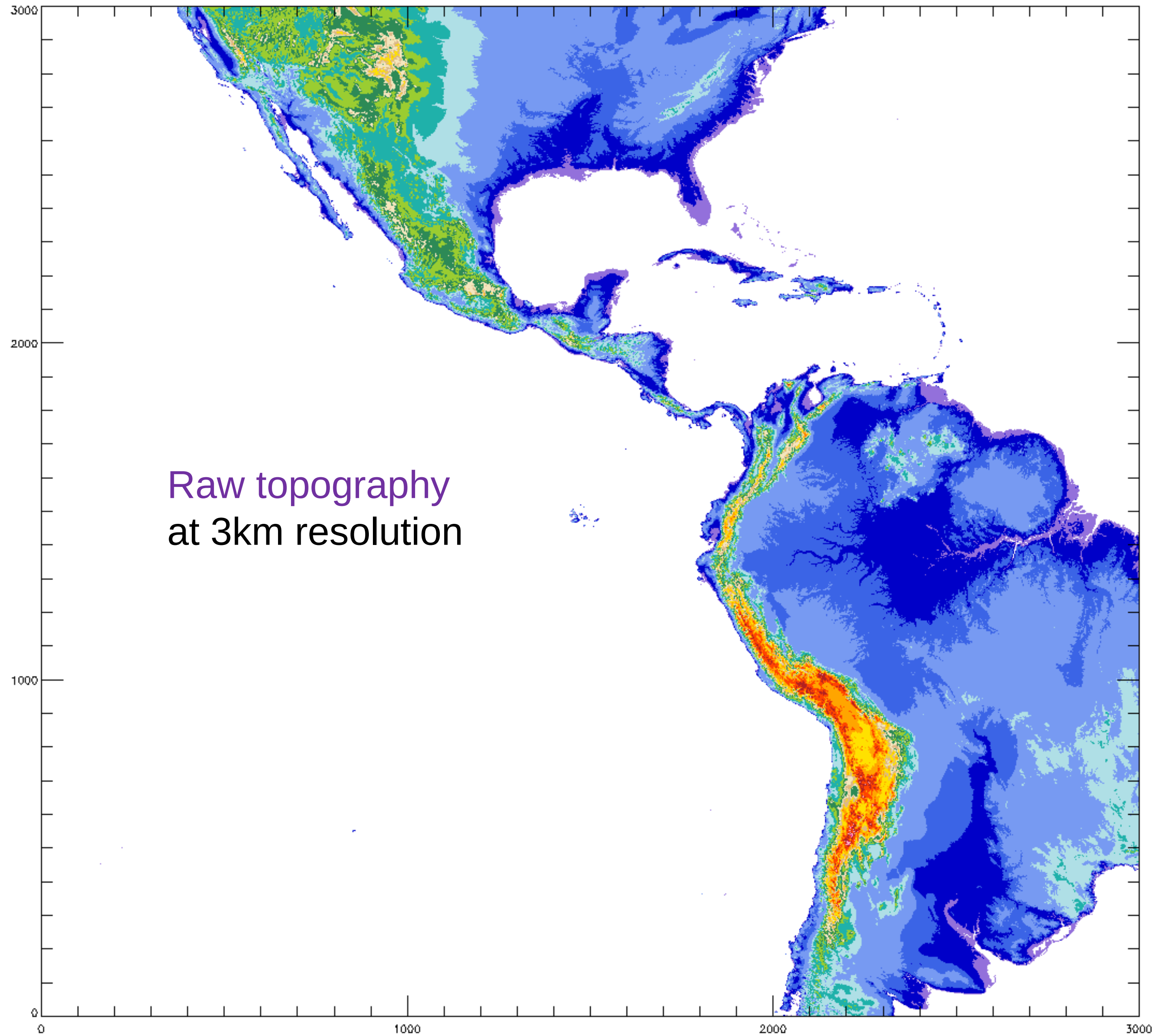
$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \quad \textit{(mass continuity)}$$

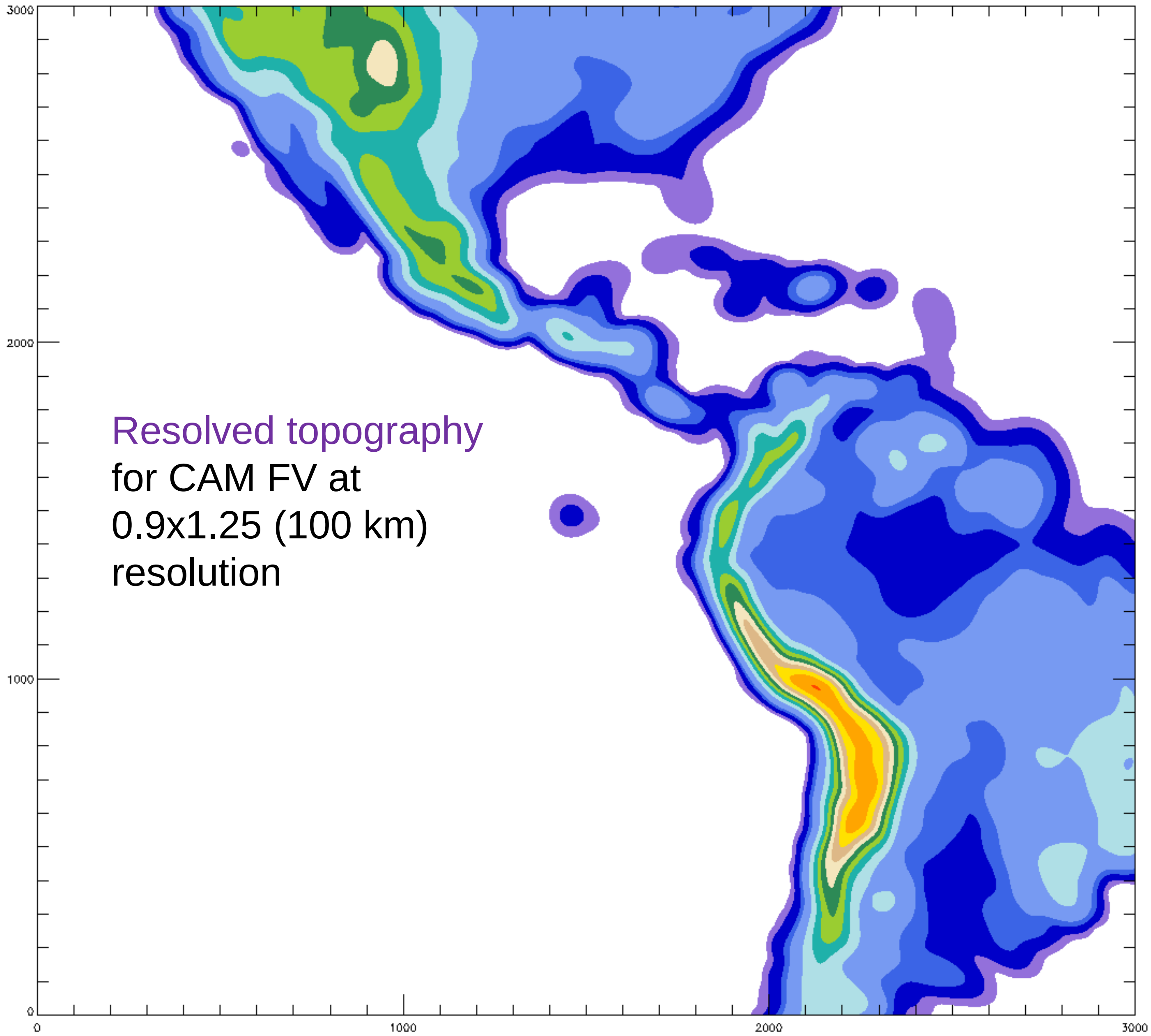
$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \quad \textit{(hydrostatic equilibrium)}$$

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

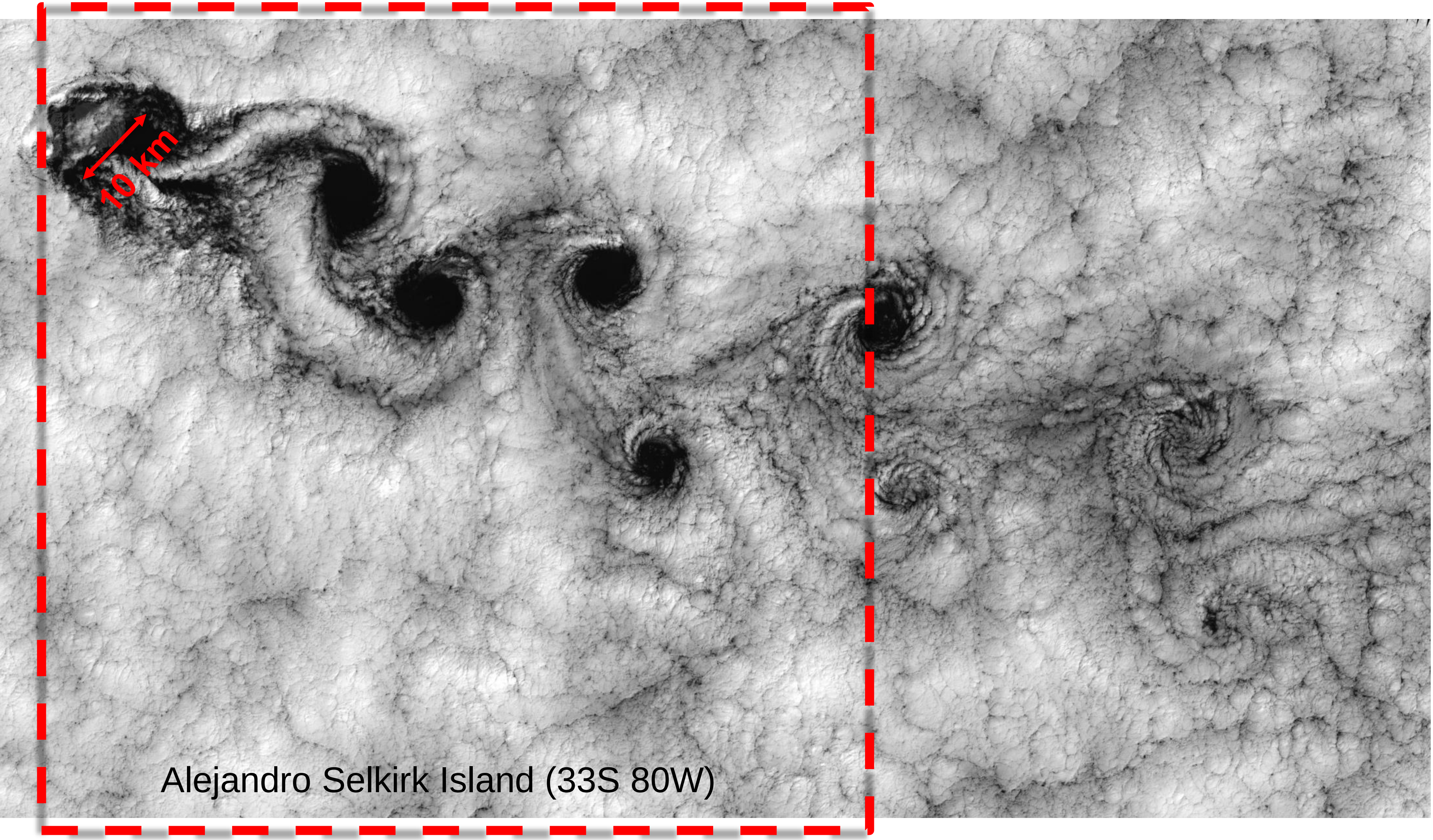
+transport

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

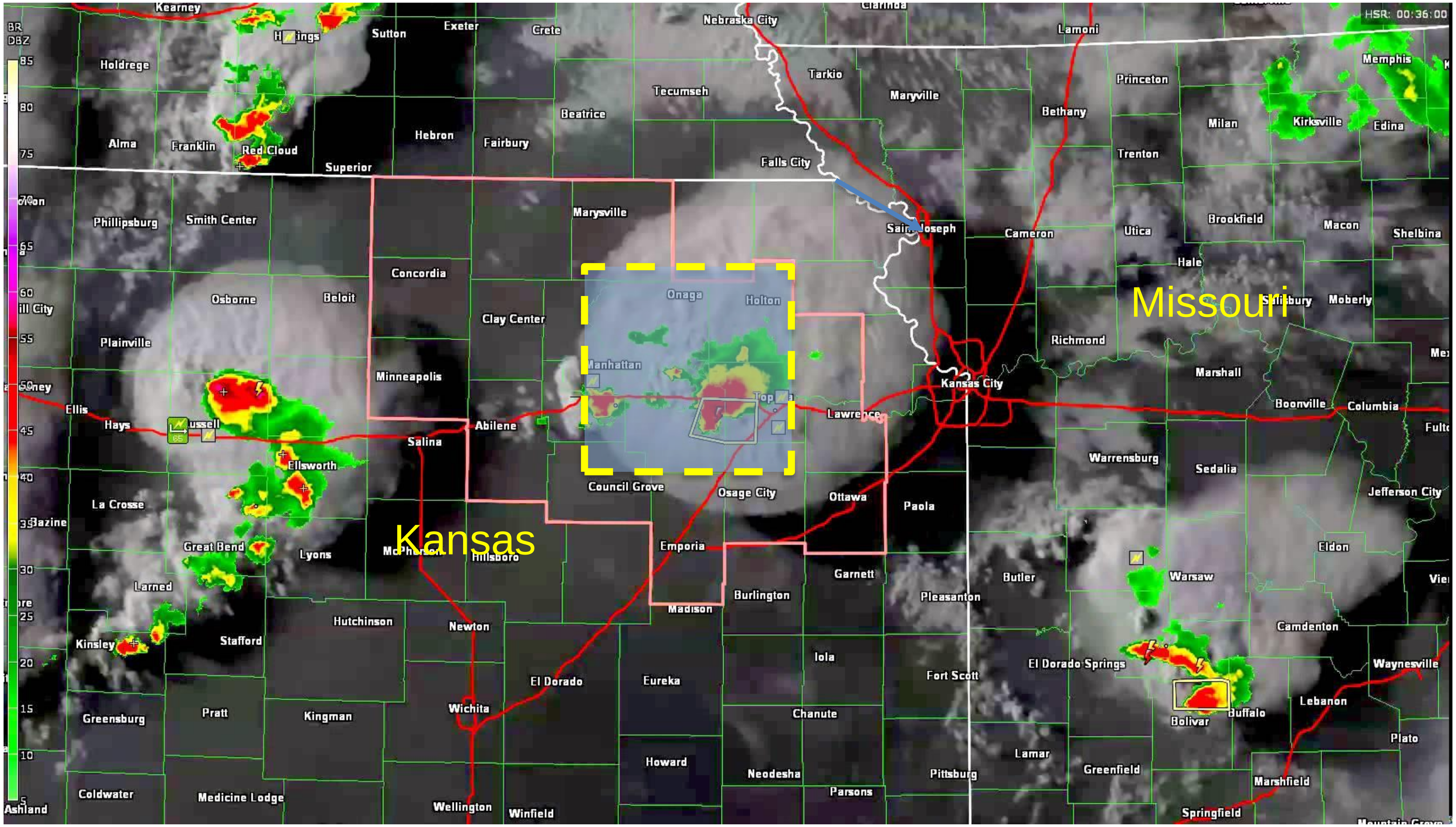

Raw topography
at 3km resolution
3000
2000
1000
0
0
1000
2000
3000


Resolved topography
for CAM FV at
0.9x1.25 (100 km)
resolution
3000
2000
1000
0
0
1000
2000
3000

Boundary Layer Clouds



Deep Convection



July 15, 2015

What is a 'Parameterization'?

- Represent impact of sub-grid scale unresolved processes on resolved scale
- 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

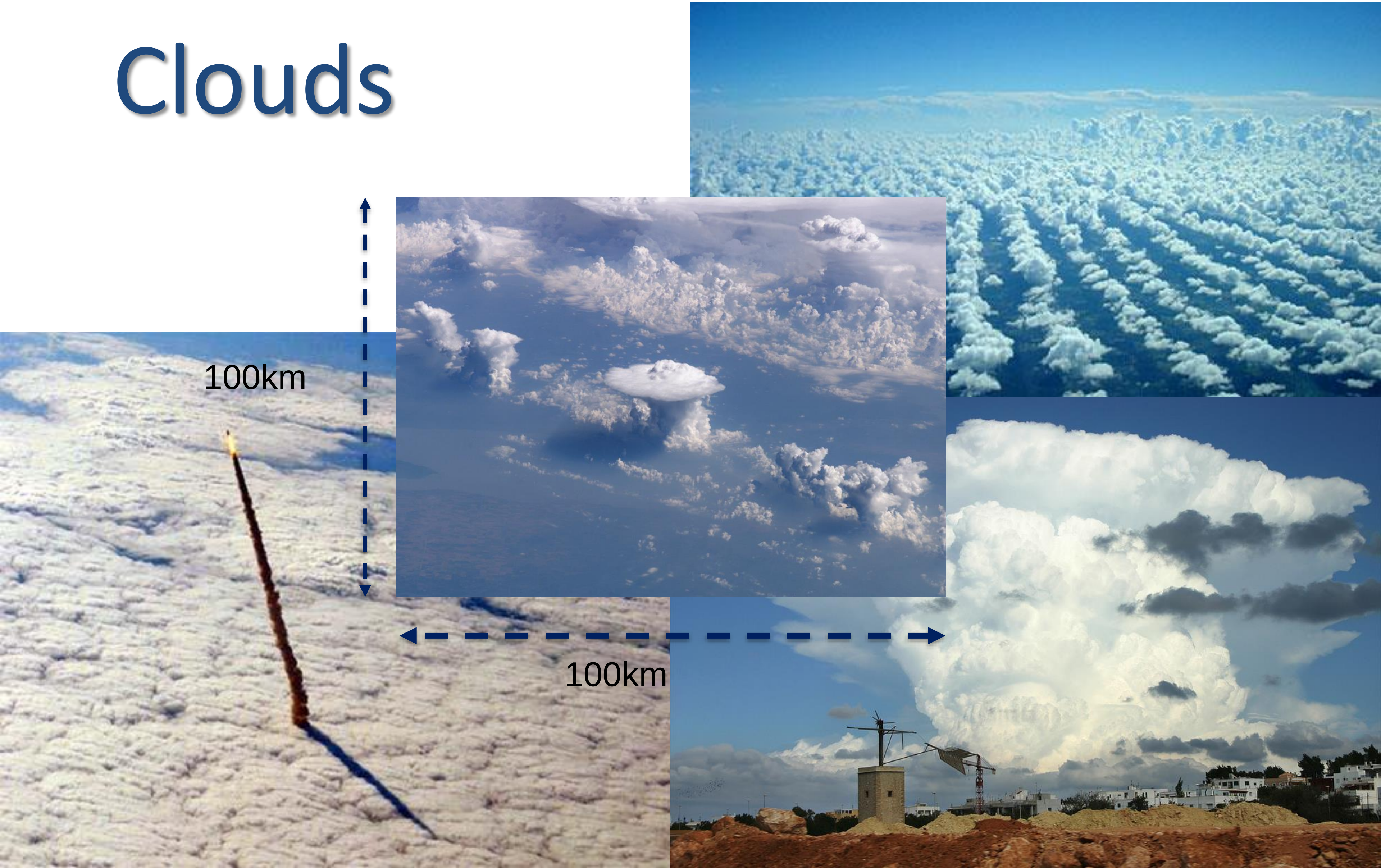
'Diffusivity'

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

Unresolved 'sub-grid'

Resolved 'grid-scale'

Clouds



Clouds

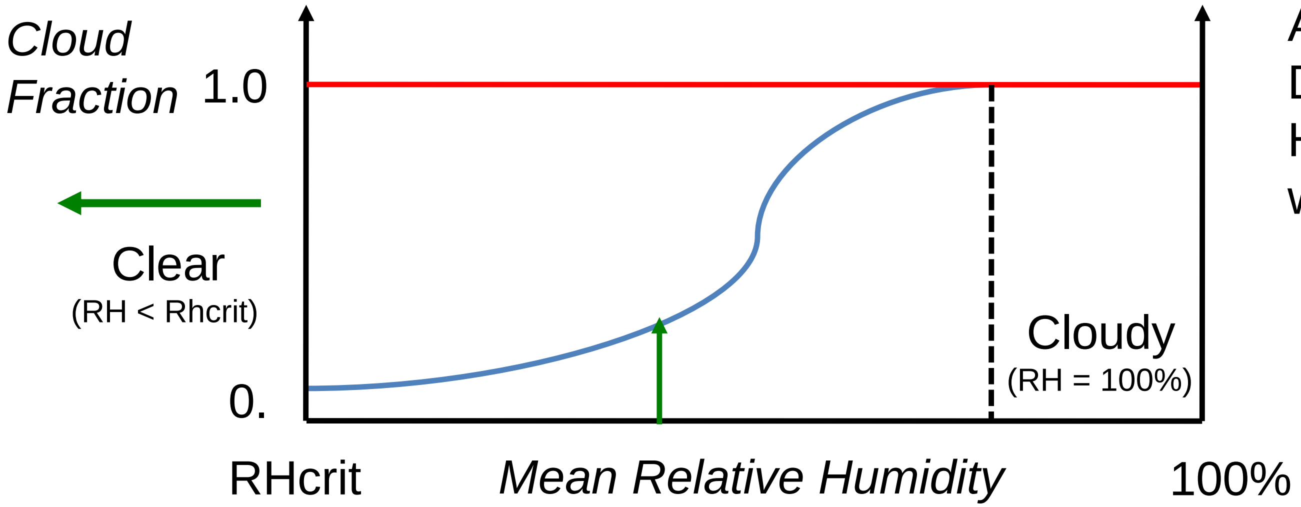
Multiple Categories

- **Stratiform (large-scale) clouds**
- **Shallow convection clouds**
- **Deep convection clouds**

Stratiform Clouds (macrophysics)

Sub-Grid Humidity and Clouds (different from high res)

- ✓ Liquid clouds form when relative humidity = 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



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

Shallow and Deep Convection

Exploiting conservation properties

<u>Common properties</u>

Parameterize consequences of vertical displacements of air parcels

<u>Unsaturated</u>: Parcels follow a dry adiabat (conserve **dry static energy**)

<u>Saturated</u>: Parcels follow a moist adiabat (conserve **moist static energy**)

<u>Shallow (10s-100s m) - local</u>

Parcels remain stable (buoyancy<0)

Shallow cooling mainly

Some latent heating and precipitation

Generally a source of water vapor

Small cloud radius large entrainment

<u>Deep (100s m-10s km) – non-local</u>

Parcels become unstable (buoyancy>0)

Deep heating

Latent heating and precipitation

Generally a sink of water vapor

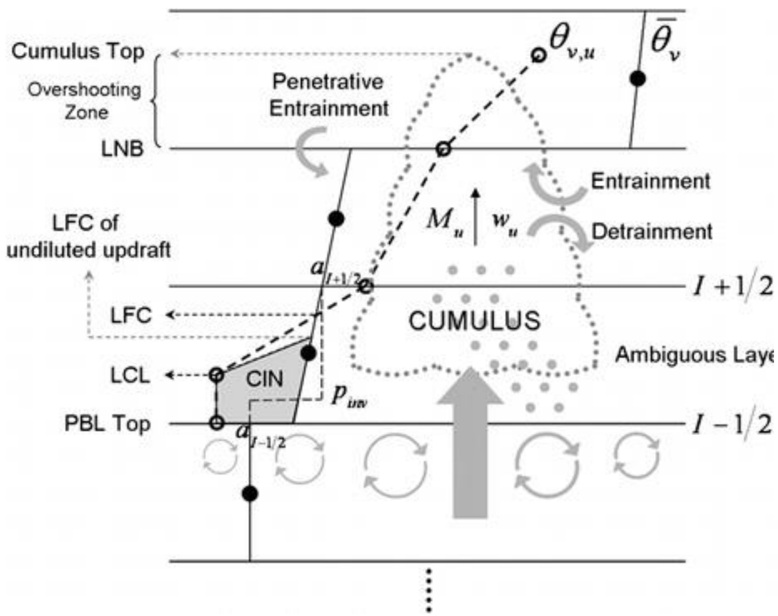
Large cloud radius small entrainment

Shallow and Deep Convection

Closure: How much and when?

Shallow

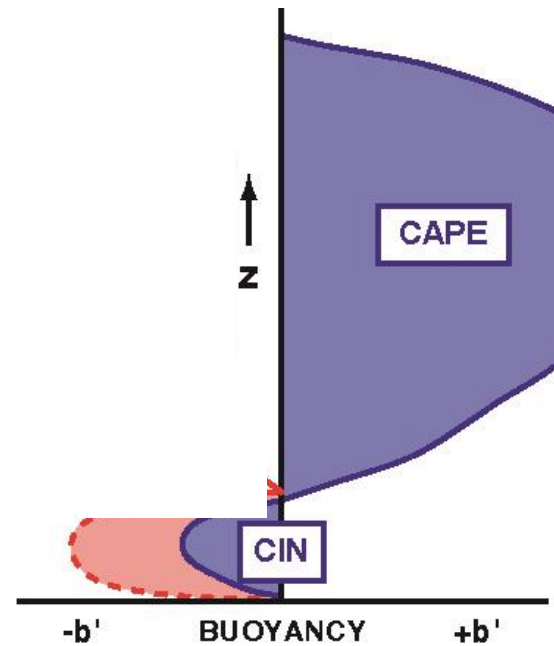
Convective inhibition (CIN) and turbulent kinetic energy (TKE) CAM5



Deep

Convective Available Potential Energy (CAPE) CAM4/CAM5/CAM6

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



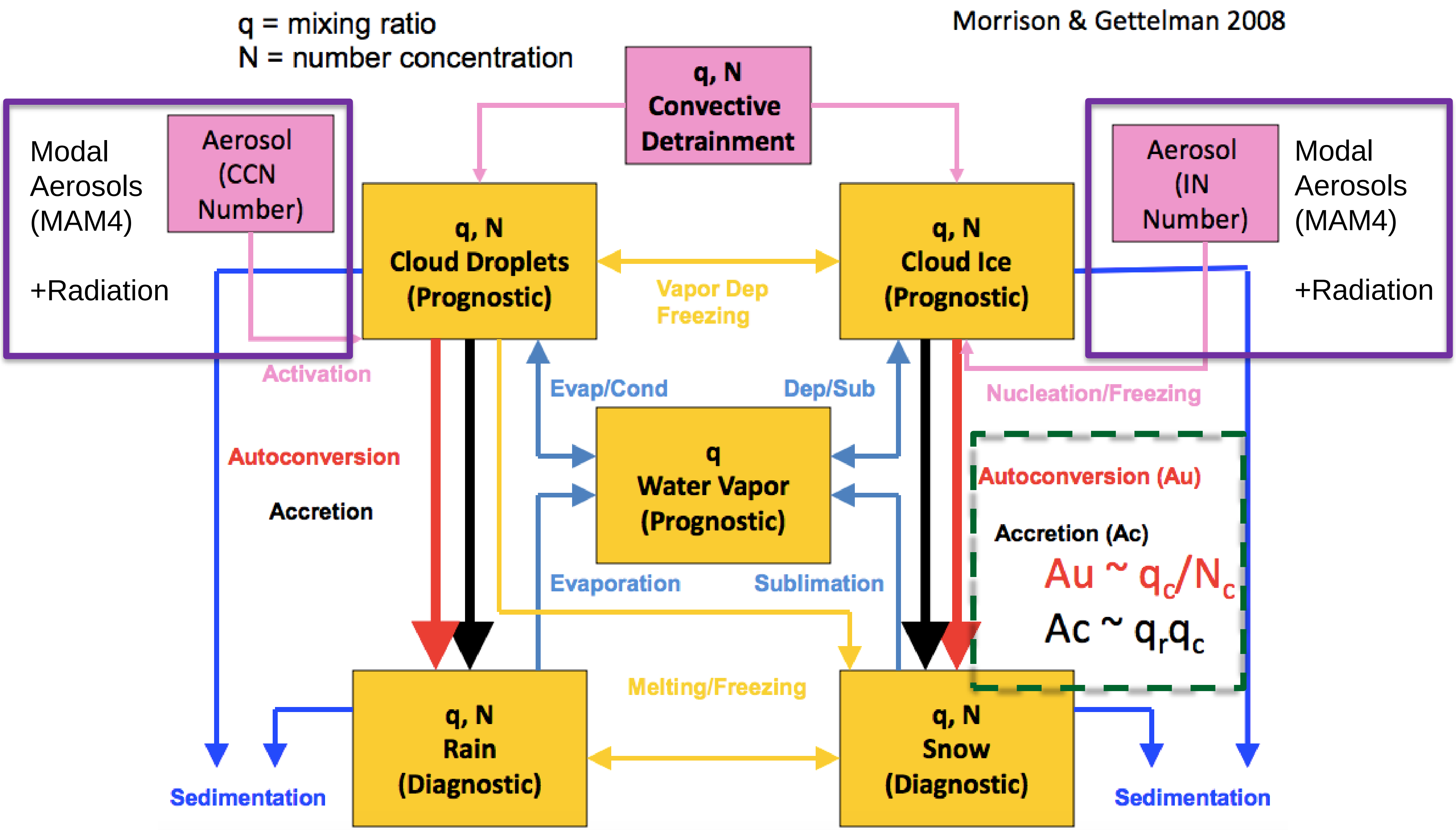
Shallow and deep convection and stratiform cloud fractions combined for radiation

Cloud Microphysics

- **Condensed phase water processes (mm scale)**
  - 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 *very* simplified
  - Formulations currently being implemented into convection

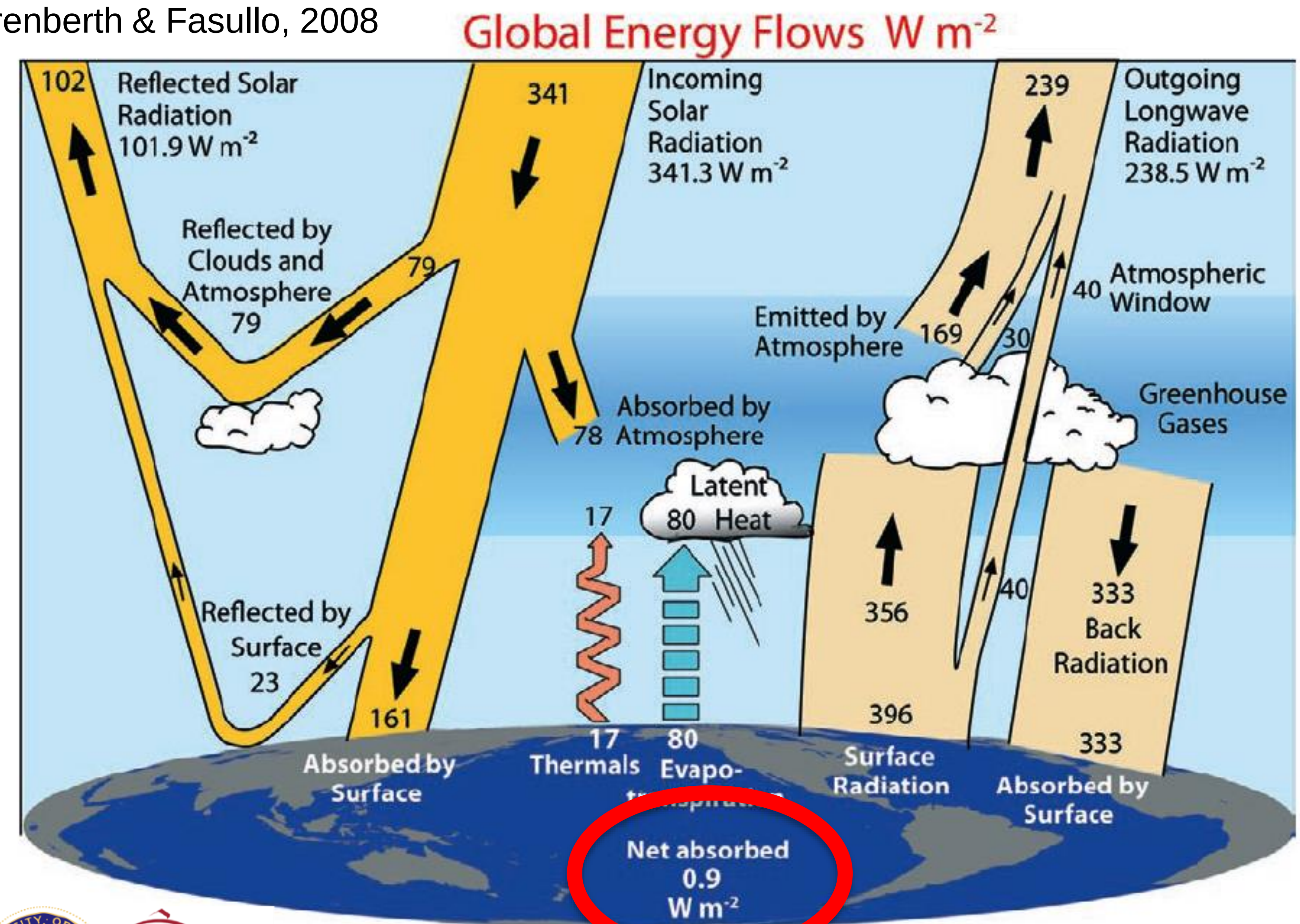
CAM Microphysics



Radiation

The Earth's Energy Budget

Trenberth & Fasullo, 2008



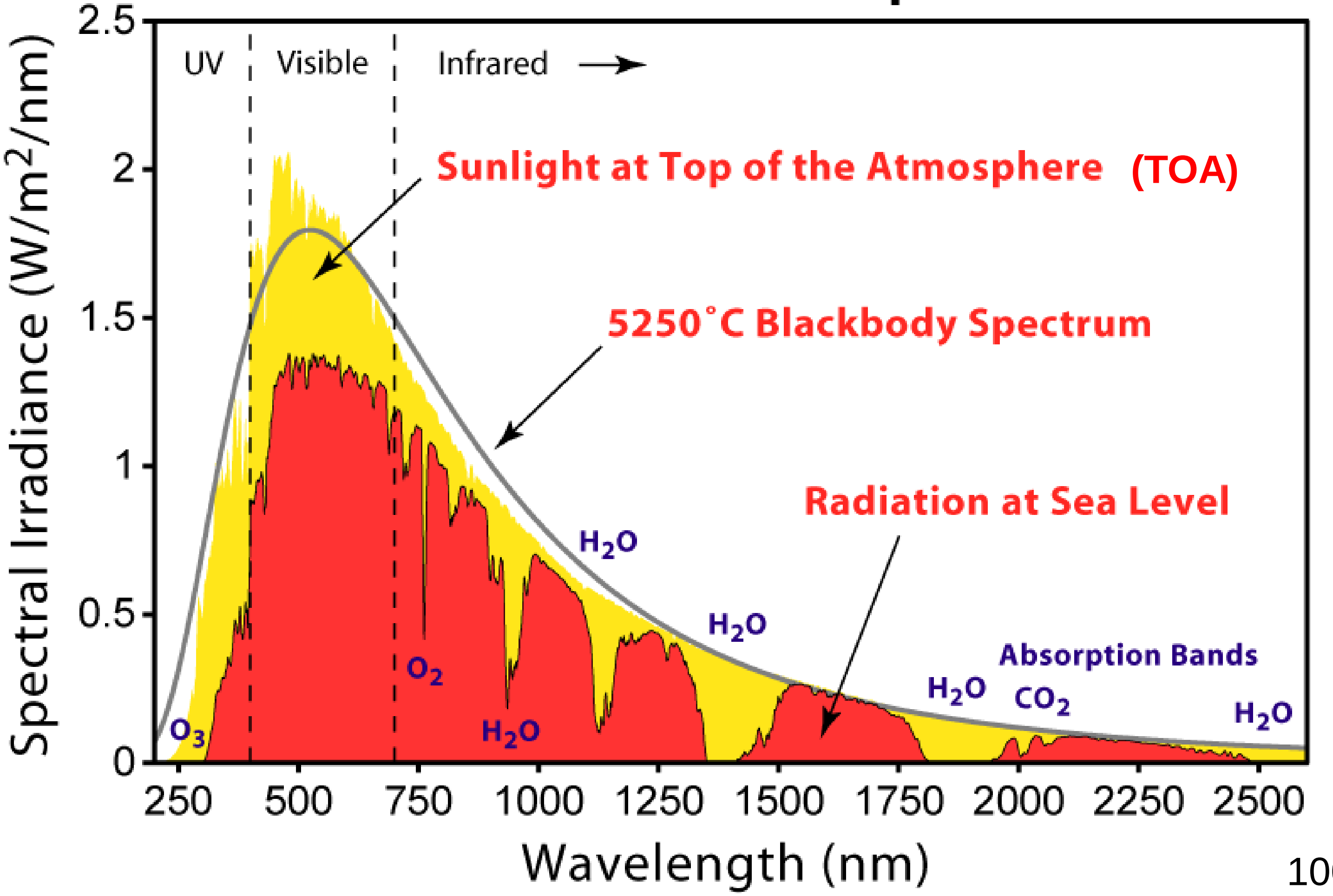
Gas	SW Absorption (Wm^{-2})
CO_2	1
O_2	2
O_3	14
H_2O	43

+Condensed species: Clouds & Aerosols

Not Important for ~weeks forecast!

Bill Collins, Berkeley & LBL

Solar Radiation Spectrum

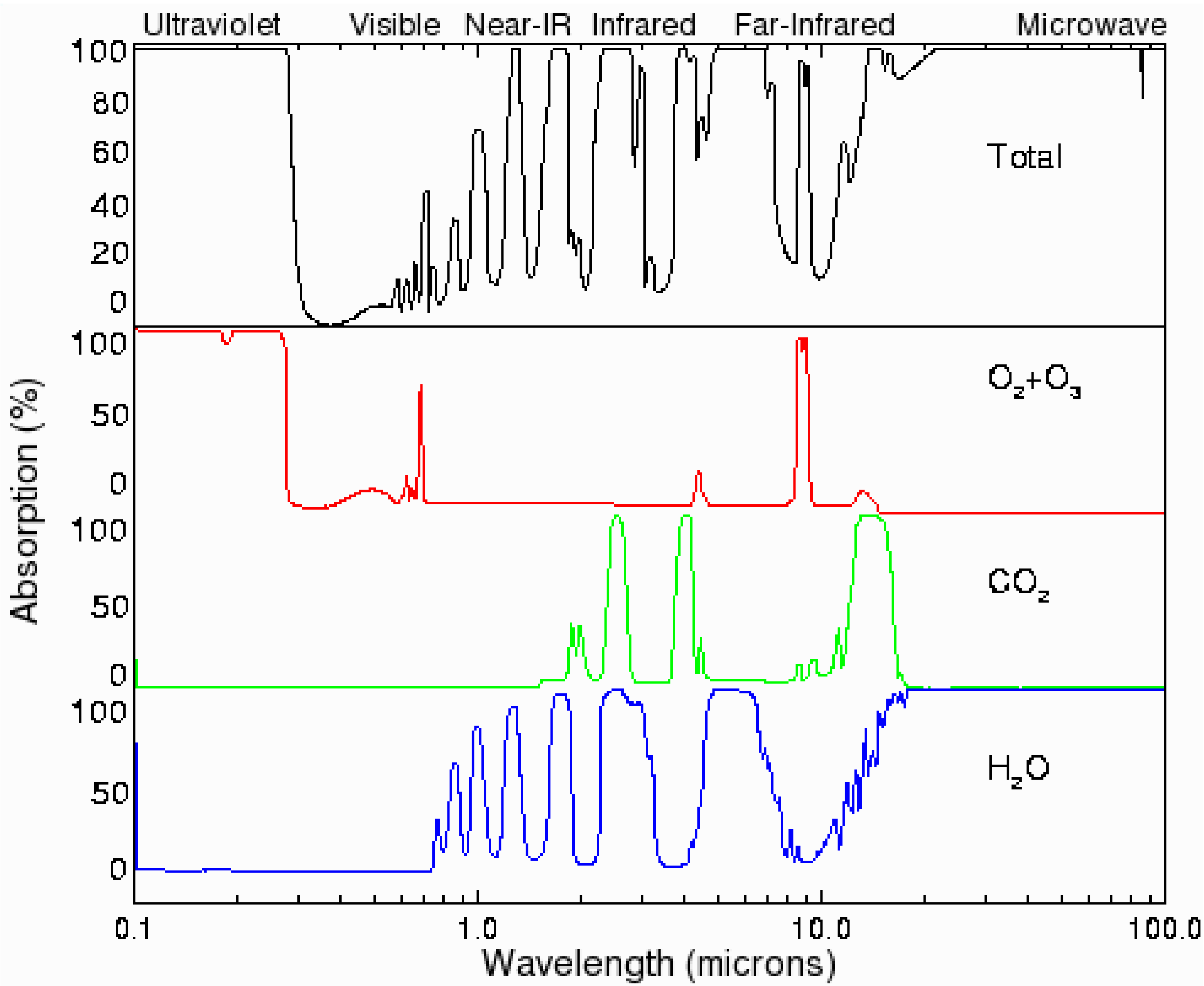


1000nm = 1μm

Input at TOA, Radiation at surface

From: ‘Sunlight’, Wikipedia

IR absorption



"Greenhouse Gases"
"Absorption Windows"

1000nm = 1μm

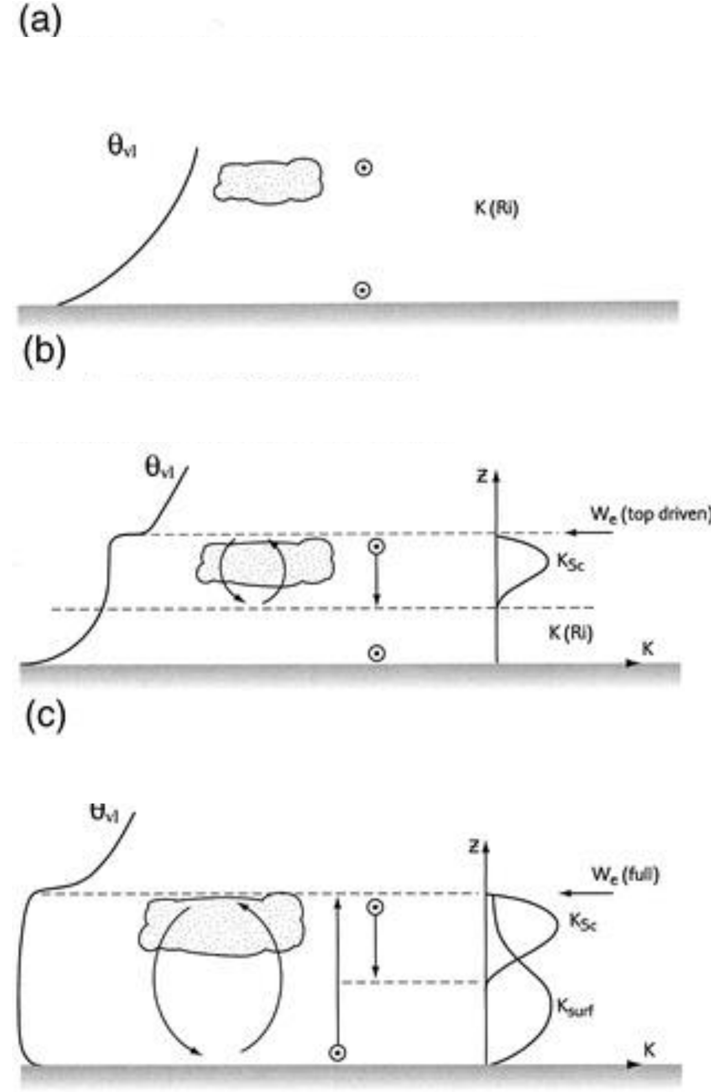
Planetary Boundary Layer (PBL)

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
- Critical determinant is the presence of turbulence
- **Richardson number**
- <<1, flow becomes turbulent

$$Ri = \frac{g\beta}{(\partial u/\partial z)^2},$$

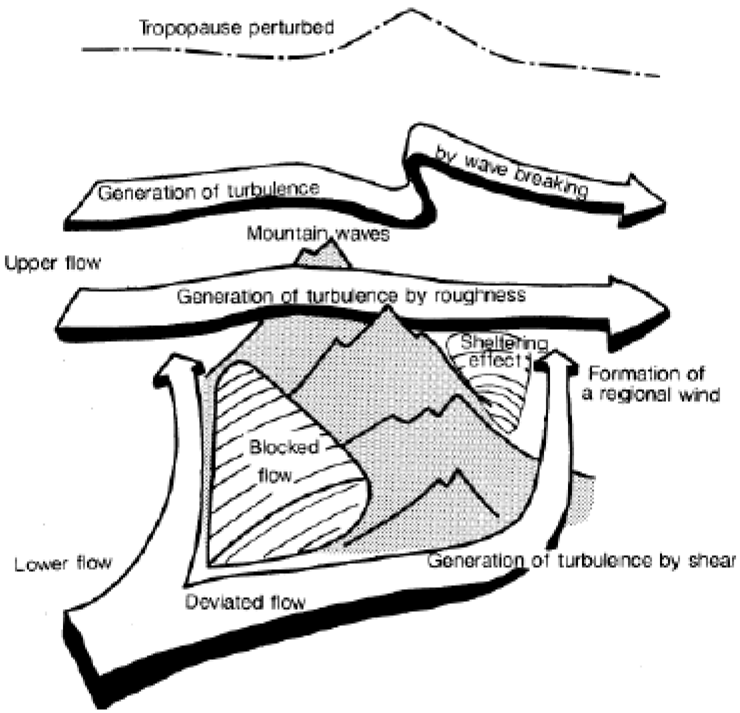
- CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)



Gravity Waves and Mountain Stresses

Sub-grid scale dynamical forcing

- **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

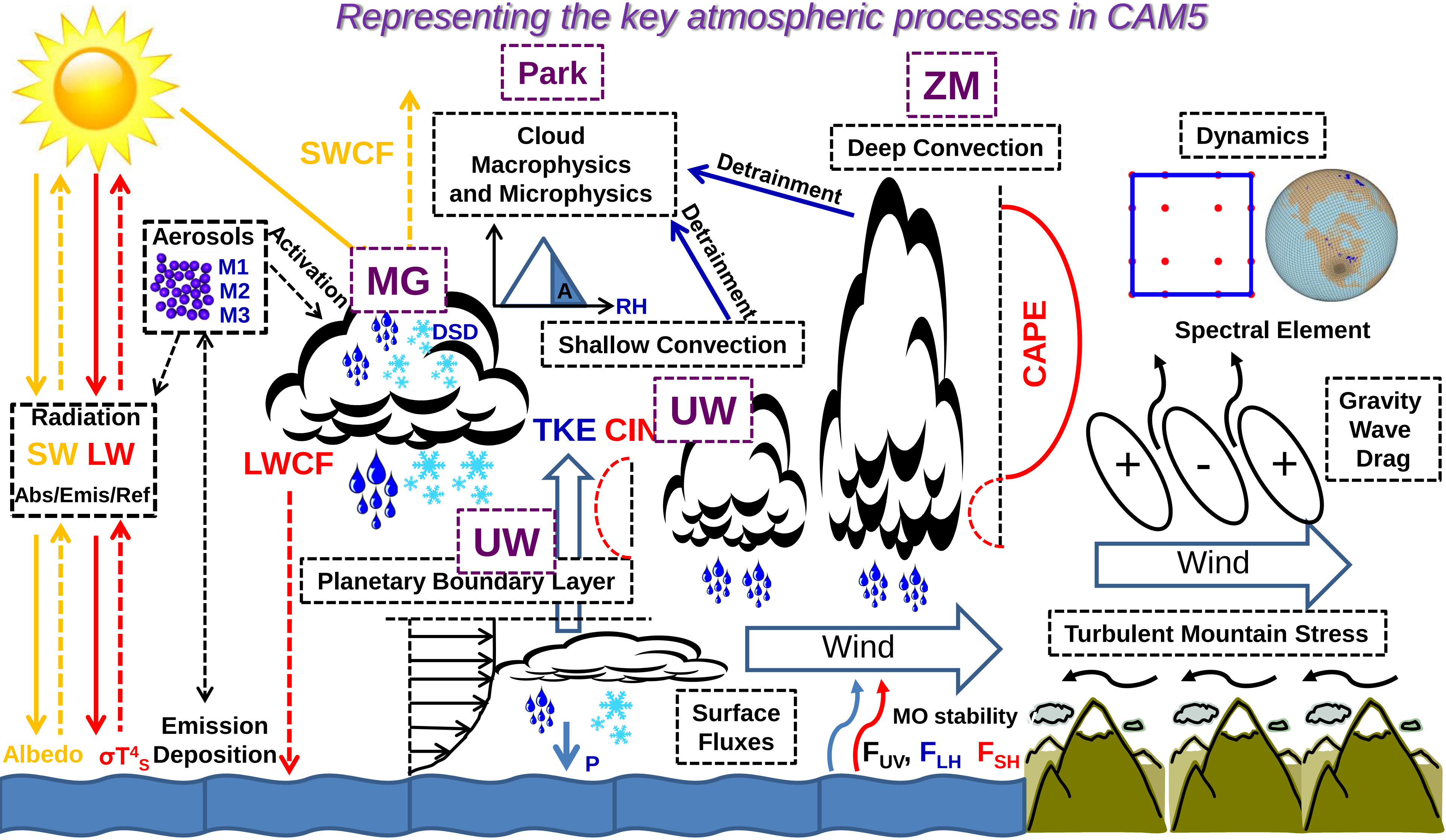


- **Turbulent mountain stress**
  - Local near-surface stress on flow
  - Roughness length < scales < grid-scale
  - Impacts mid/high-latitude flow (CAM5)

- More difficult to parameterize than thermodynamic impacts (conservation?)

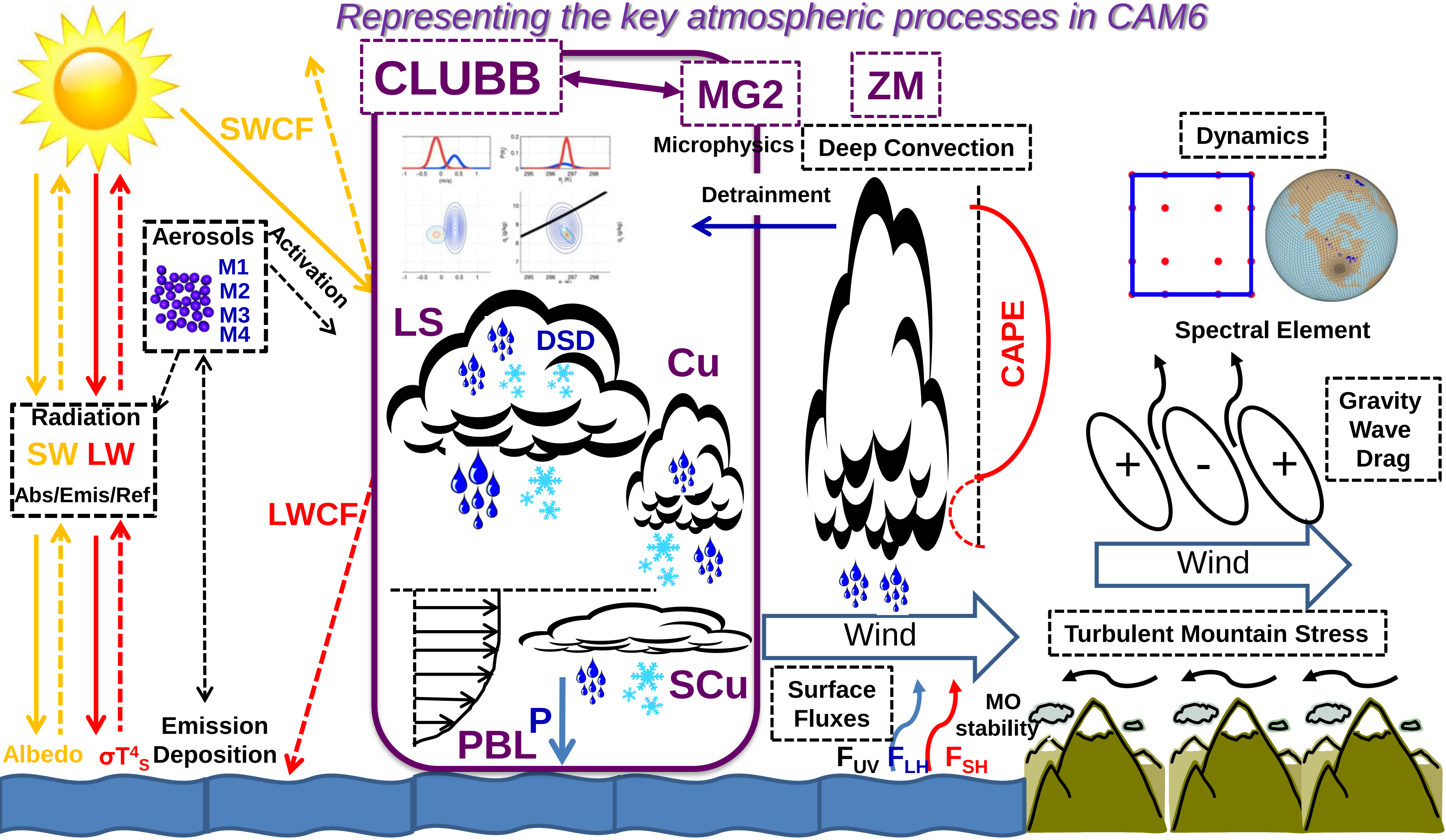
Community Atmosphere Model

Representing the key atmospheric processes in CAM5



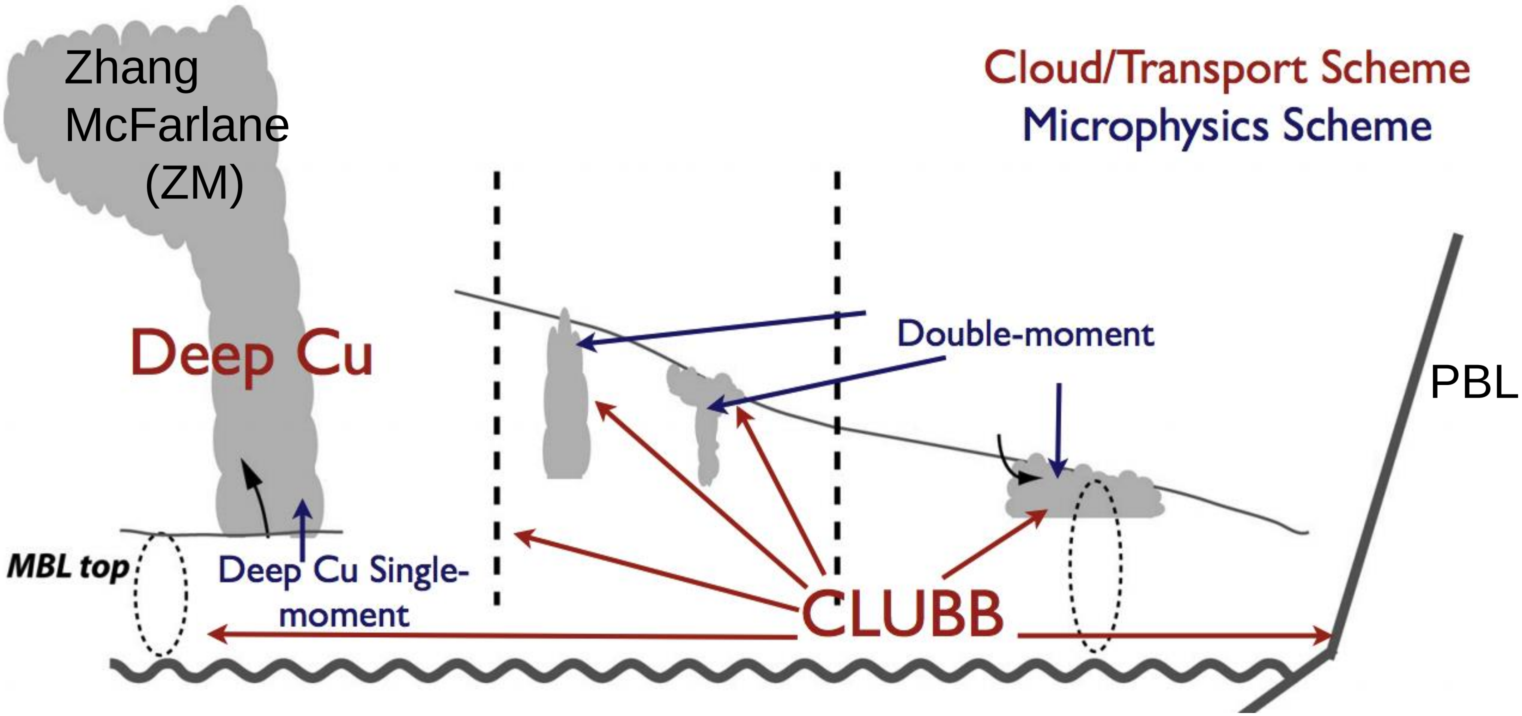
Community Atmosphere Model

Representing the key atmospheric processes in CAM6



CLUBB: Cloud Layers Unified By Binormals (CAM6)

Golaz 2002b, J. Atmos. Sci.

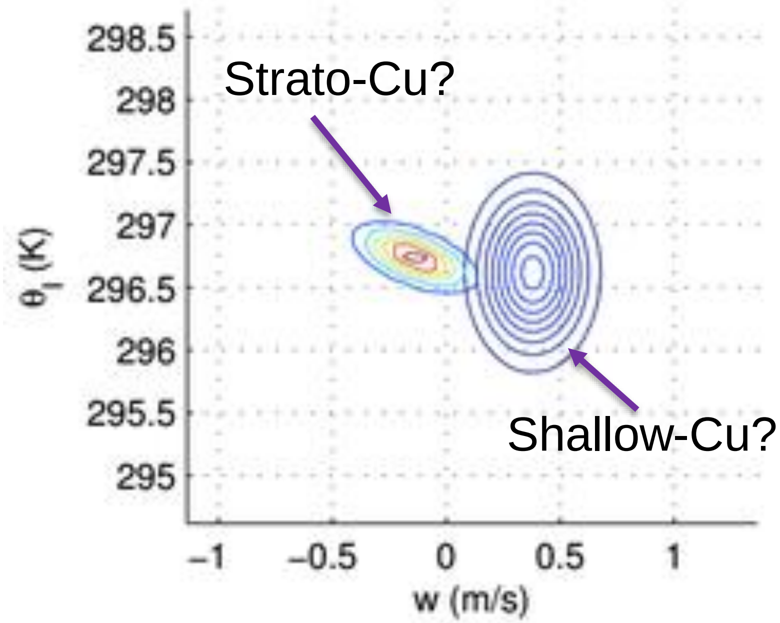


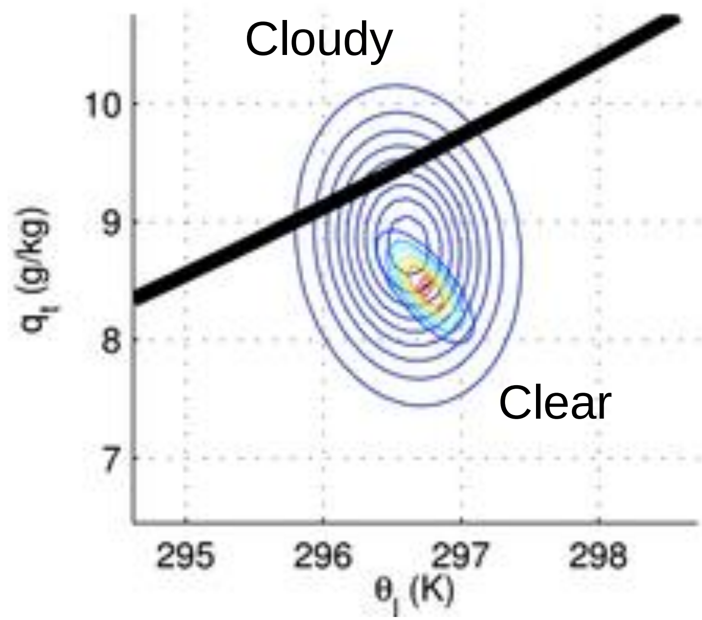
- Unifies moist and dry turbulence (except deep convection – CAM6)
- ’Seamless’ representation; no specific case adjustments
- Unifies microphysics (across cloud types)
- High order closures (1 third order, 6 second order, 3 first order-means)

CLUBB: Cloud Layers Unified By Binormals (CAM6)

Golaz 2002b, J. Atmos. Sci.

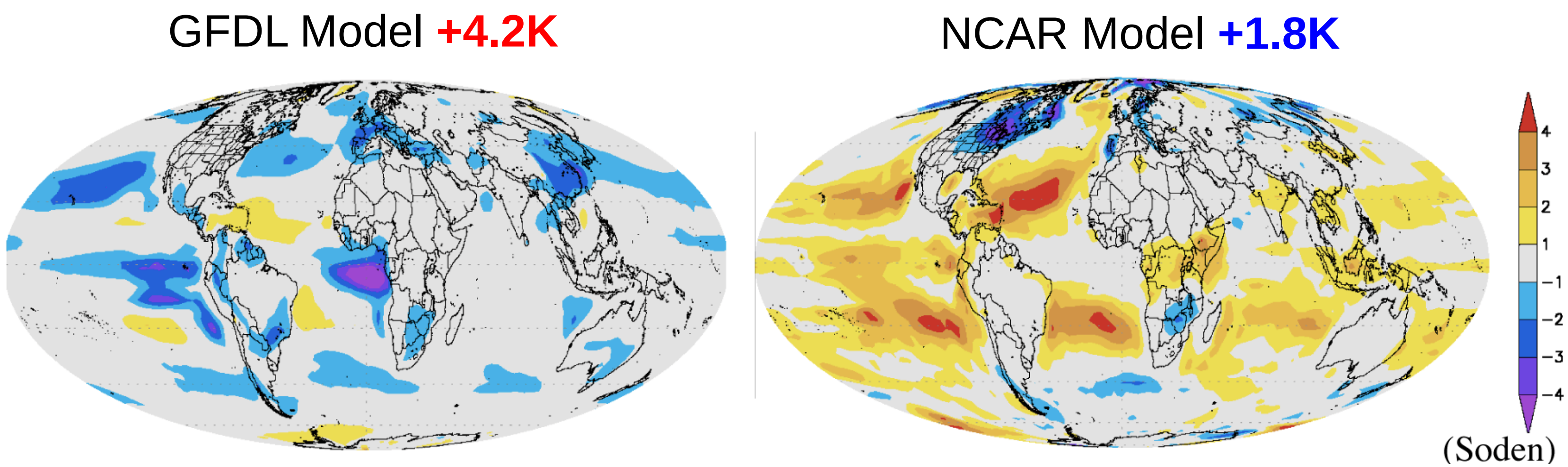
– Predict joint PDFs of vertical velocity, temperature and moisture
– Assume double Gaussians can reflect a number of cloudy regimes
– Predict **grid box means** and **higher-order moments**
– Transport, generate, and dissipate mean moments (w'^2,w□θ_L□, $\omega' q_L'$)





Climate Sensitivity

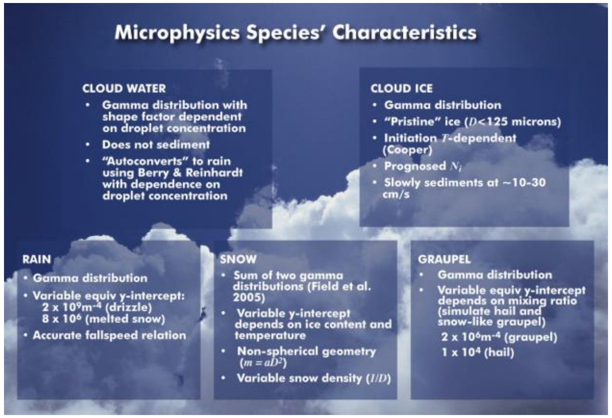
What happens to clouds when we double CO_2?

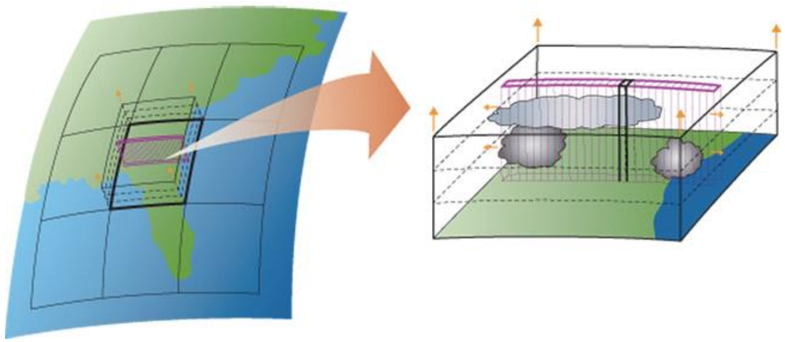


Change in low cloud amount (%)

- 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.**

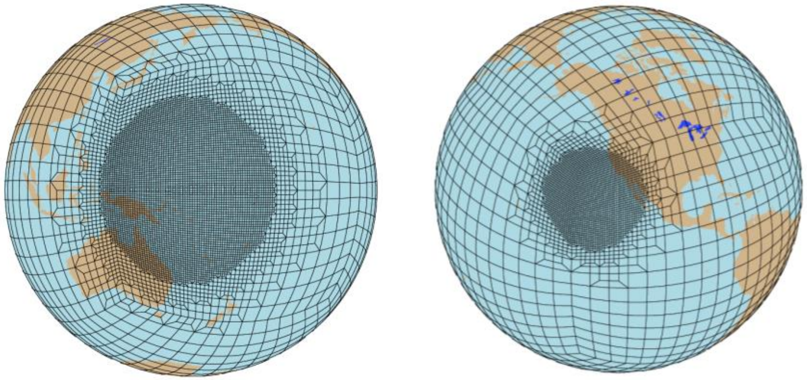
Model physics: The future

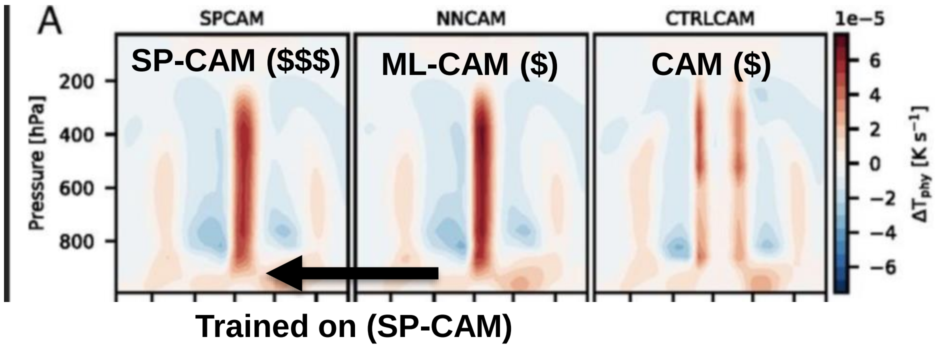




New and **more complex** processes

Cloud **super-parameterization**





Regional grid and **scale-aware** physics

Machine Learning (ML)

[Rasp et al., (2018)](https://doi.org/10.1073/pnas.1810286115)
https://doi.org/10.1073/pnas.1810286115

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?