Atmospheric Modeling II:
Physics

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CESM Tutorial Aug 8, 2022

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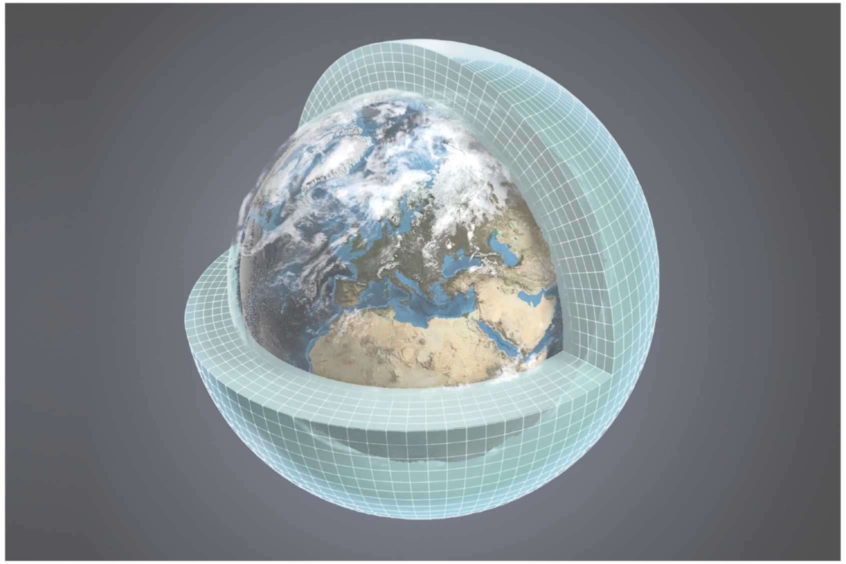
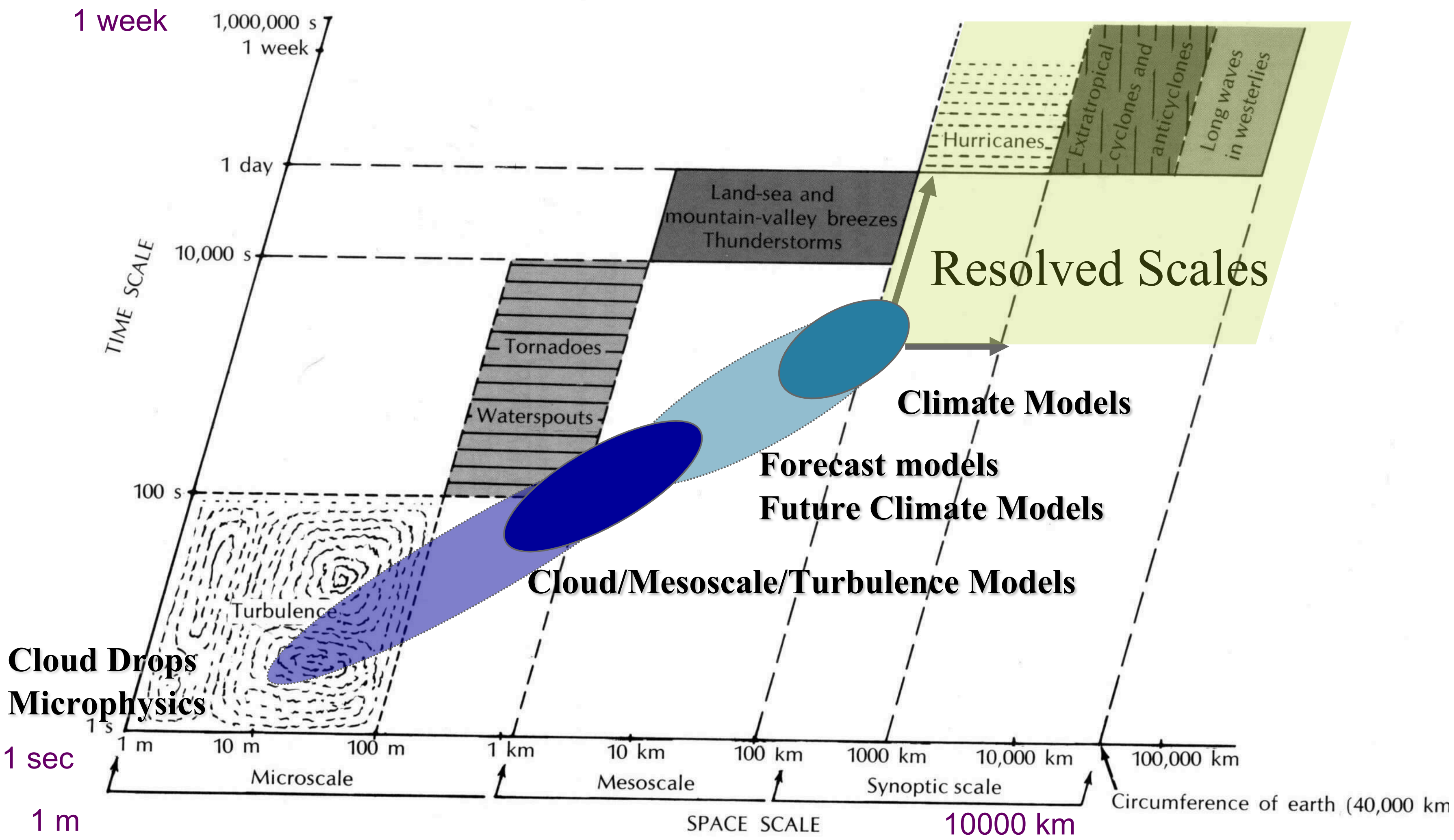
Outline

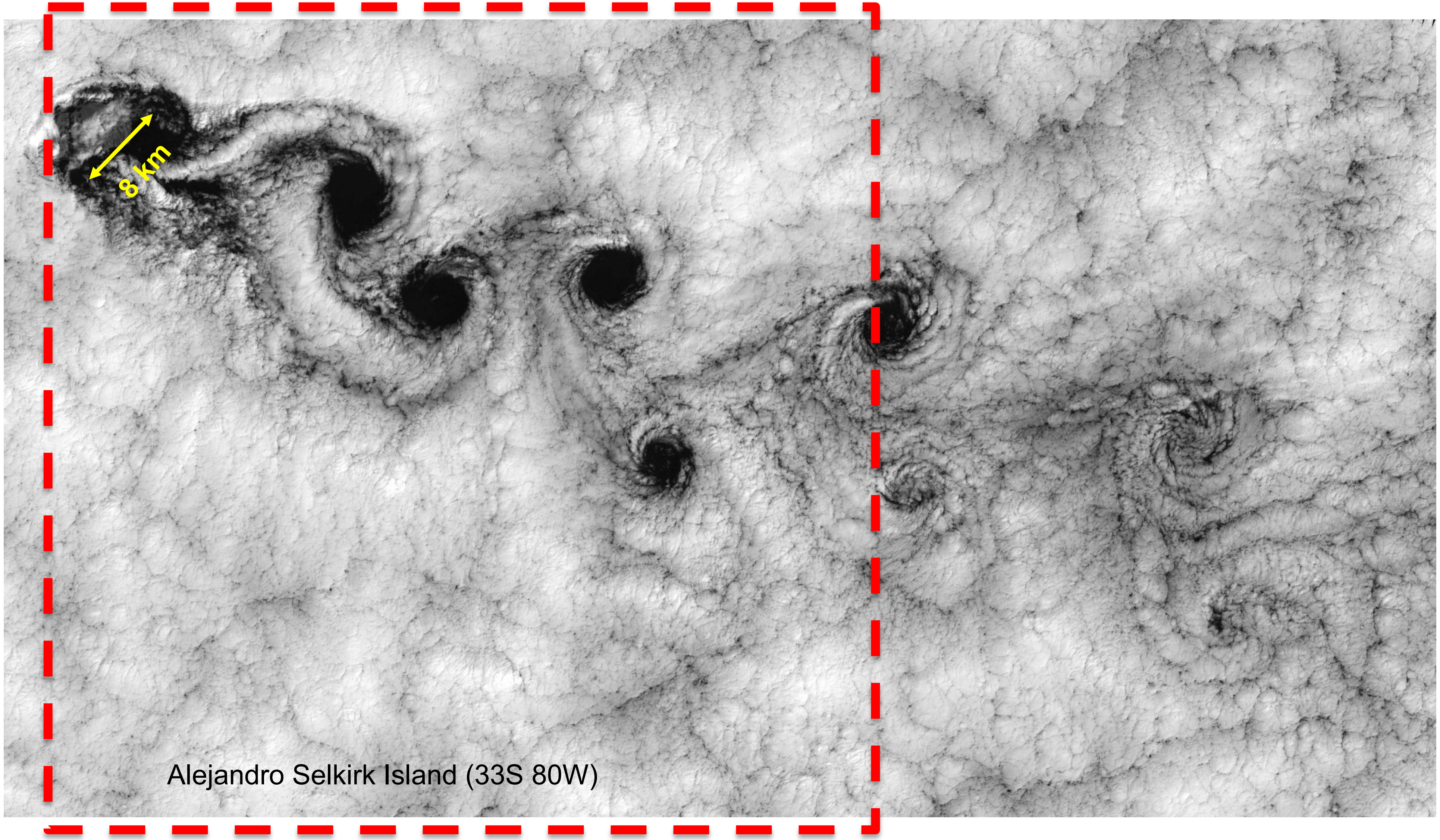
- Physical processes in an atmosphere GCM
- Distinguishing GCMs from other models (scales)
- Concept of 'Parameterization' of sub-grid processes
- Physics representations (CESM)
  - Clouds (different types) and microphysics
  - Radiation
  - Boundary layers, surface fluxes and gravity waves
  - Unified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



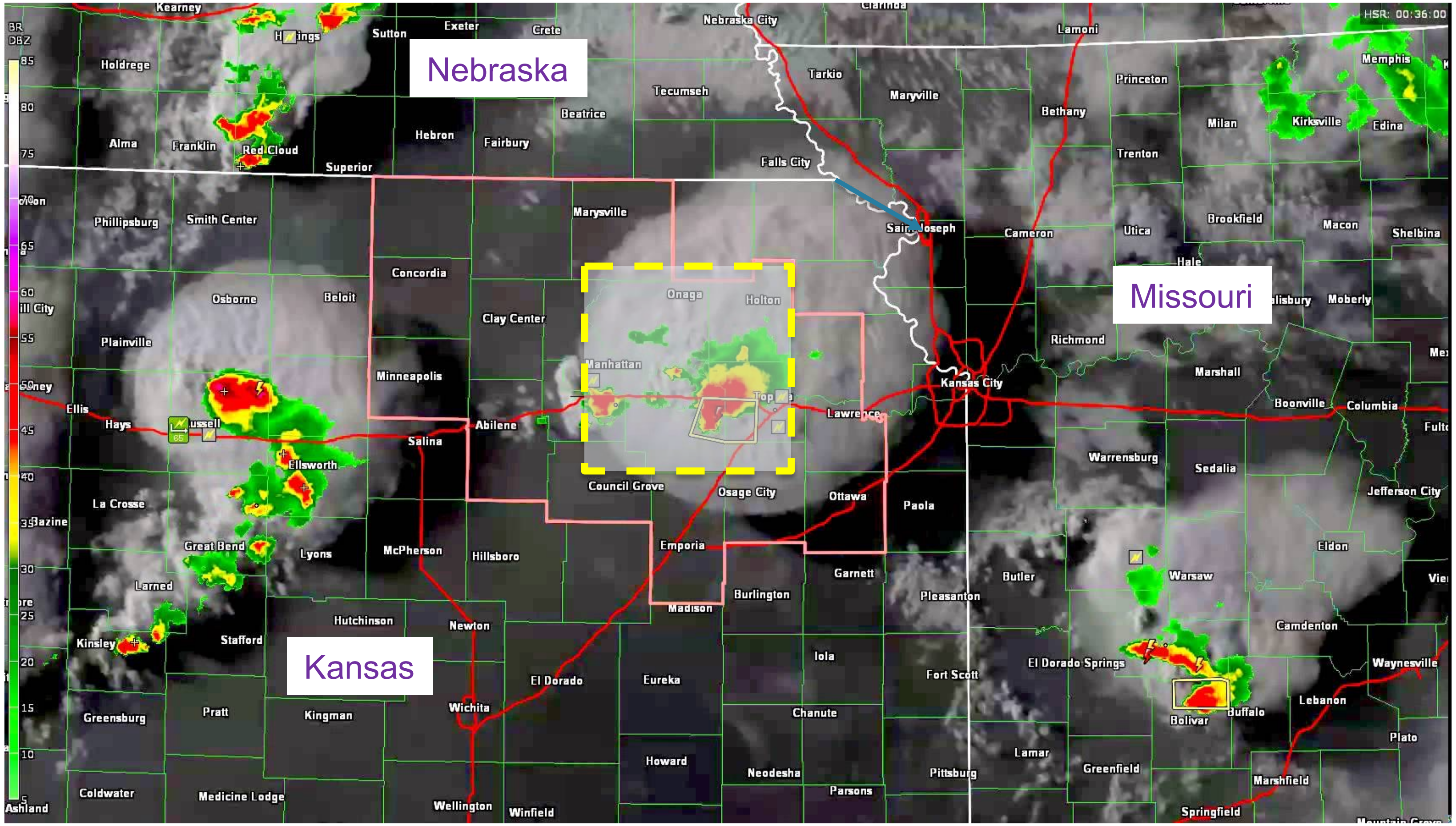
Scales of Atmospheric Processes



Boundary Layer Cloud Scales

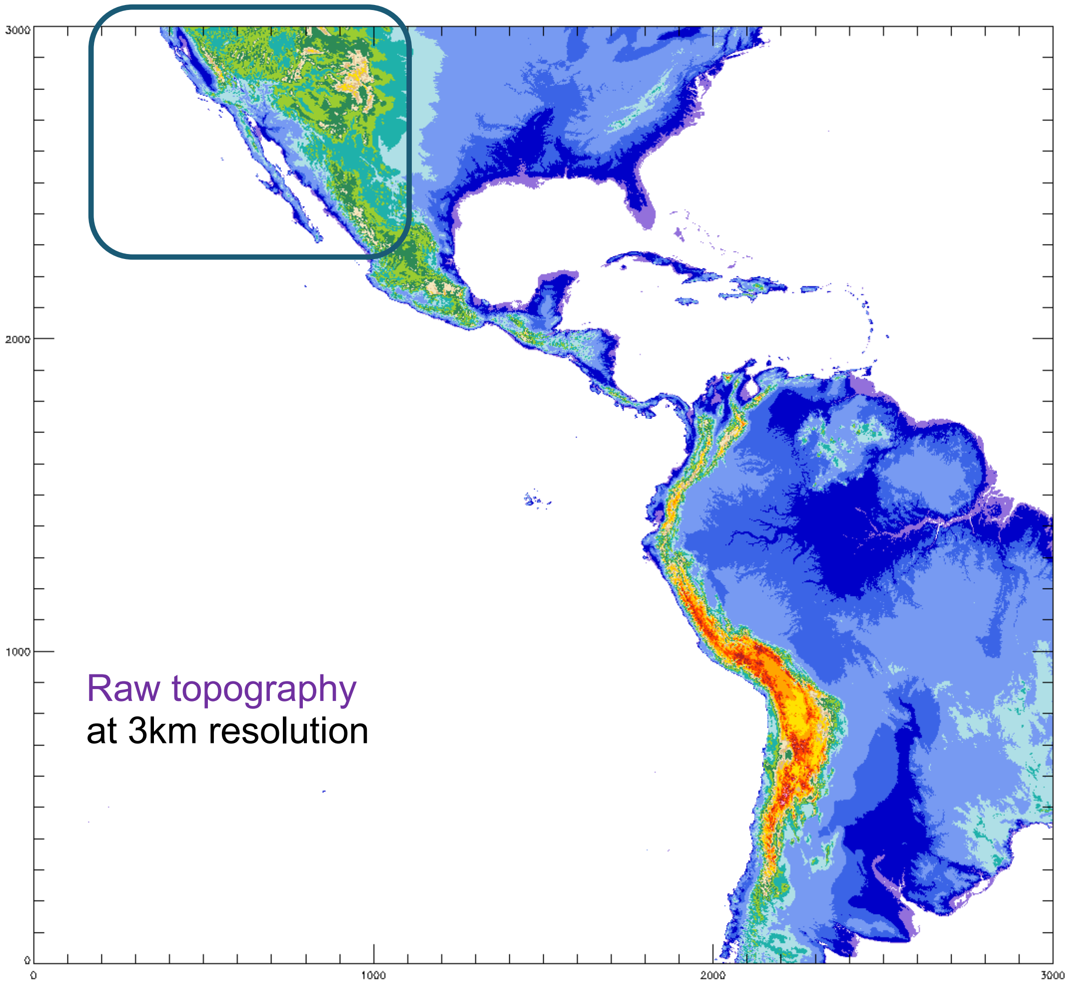


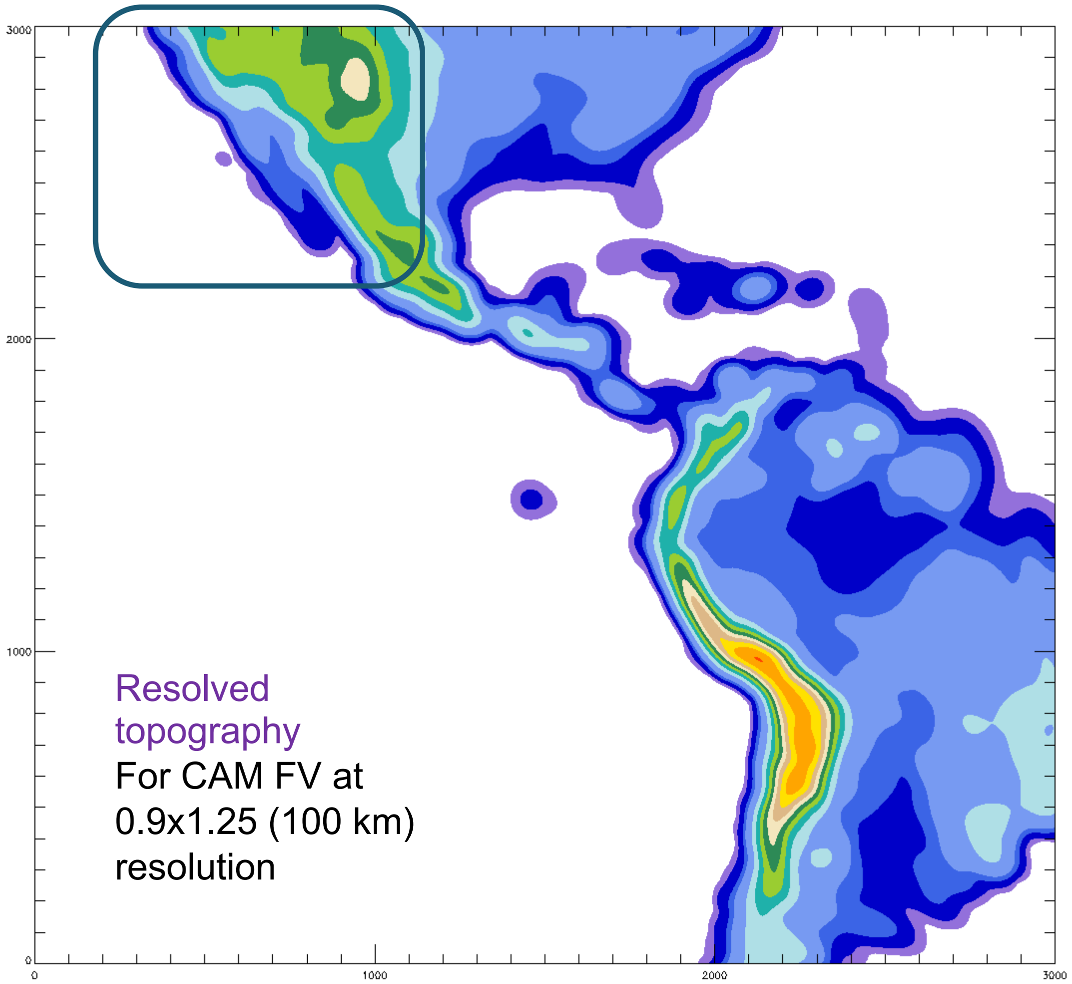
Storm Scales



July 15, 2015

Orographic Forcing Scales





What is a 'Parameterization'?

Represent impact of sub-grid scale unresolved processes on resolved scale (with dynamics)

- 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

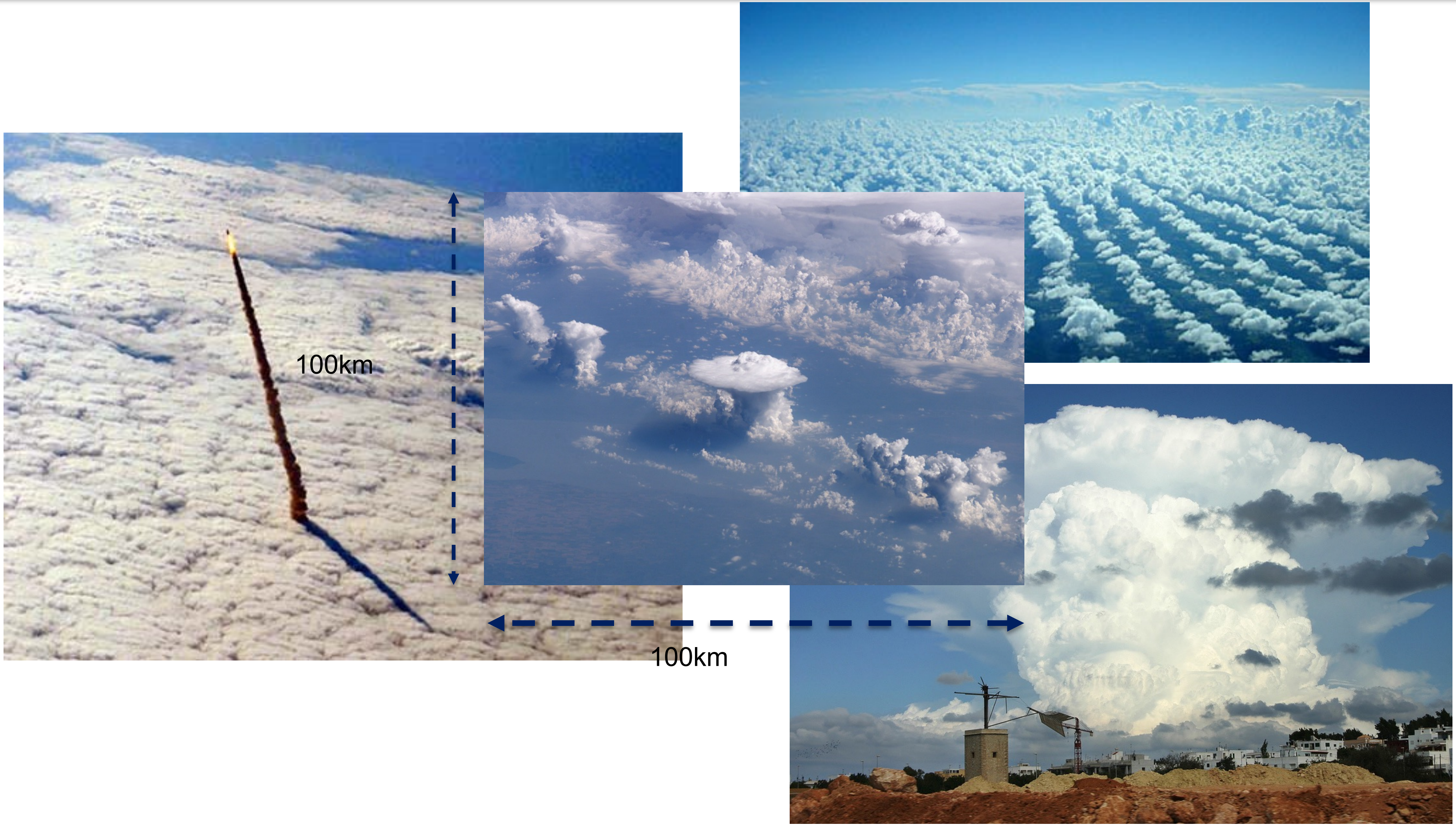
'Diffusivity'

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

Unresolved 'sub-grid'

Resolved 'grid-scale'

Clouds

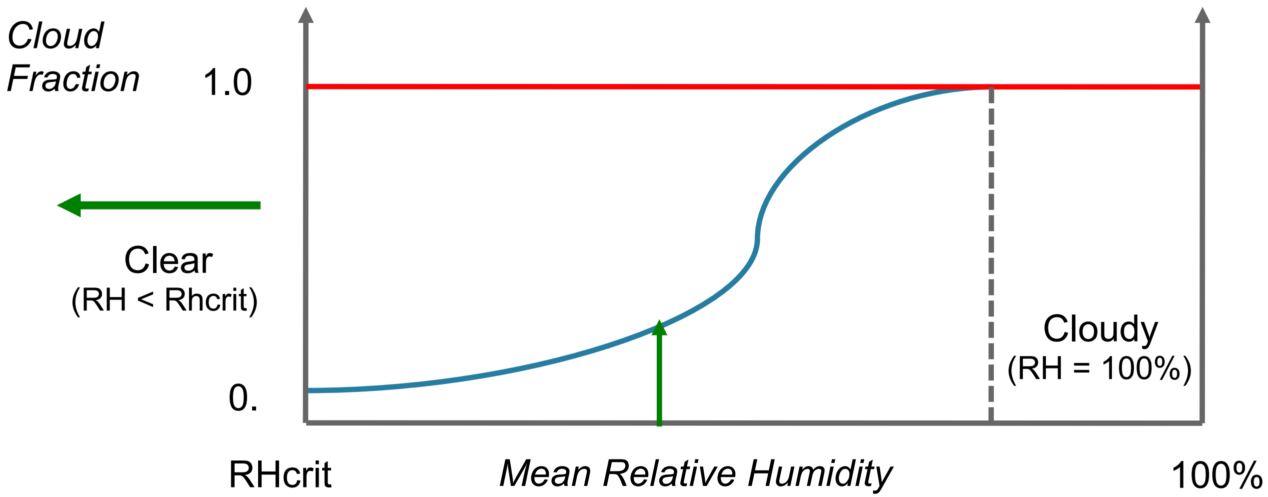


Cloud Categories

- Stratiform (large-scale/resolved) clouds
- Shallow convection clouds
- Deep convection clouds

Stratiform Clouds (macrophysics)

- ✓ 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 Common Conservation 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) - local

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) – non-local

Parcels become unstable (buoyancy>0)

Deep heating

Latent heating and precipitation

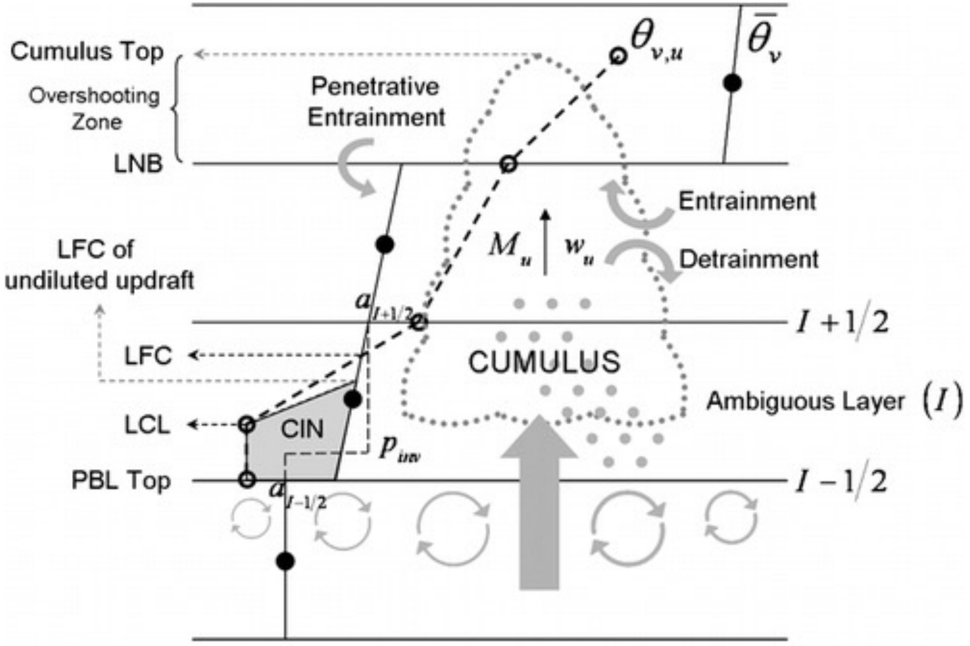
Generally a sink of water vapor

Large cloud radius small entrainment

Shallow and Deep Convection

Shallow

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



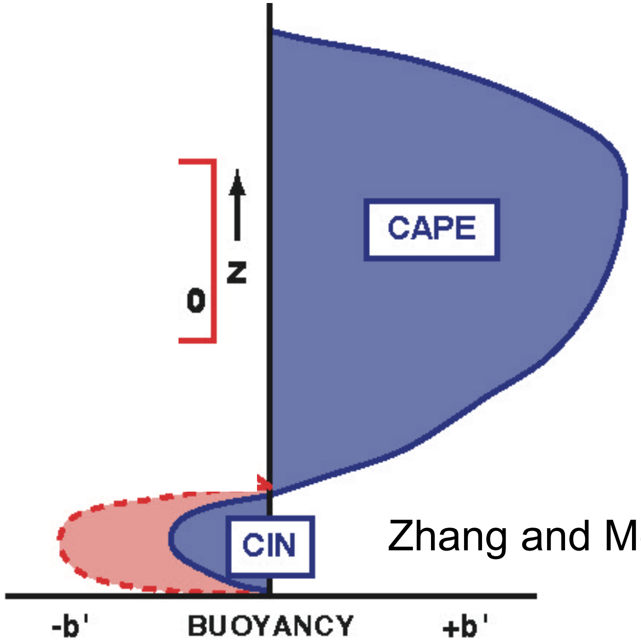
Park and Bretherton (2009)

Deep

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

$CAPE > CAPE_{trigger}$

Timescale=1 hour

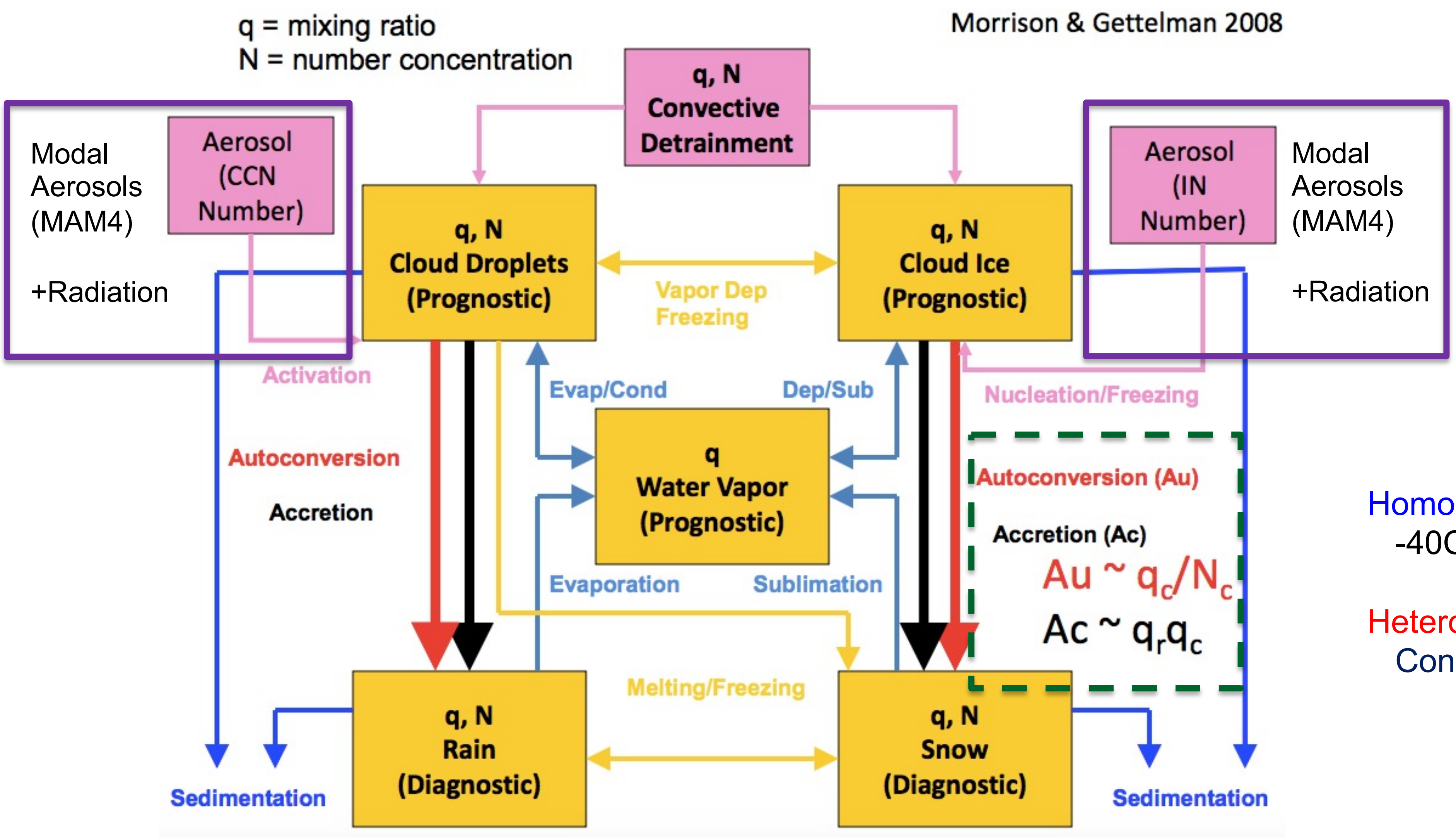


Zhang and McFarlane (1995)

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 separate and *very* simplified

CAM Microphysics

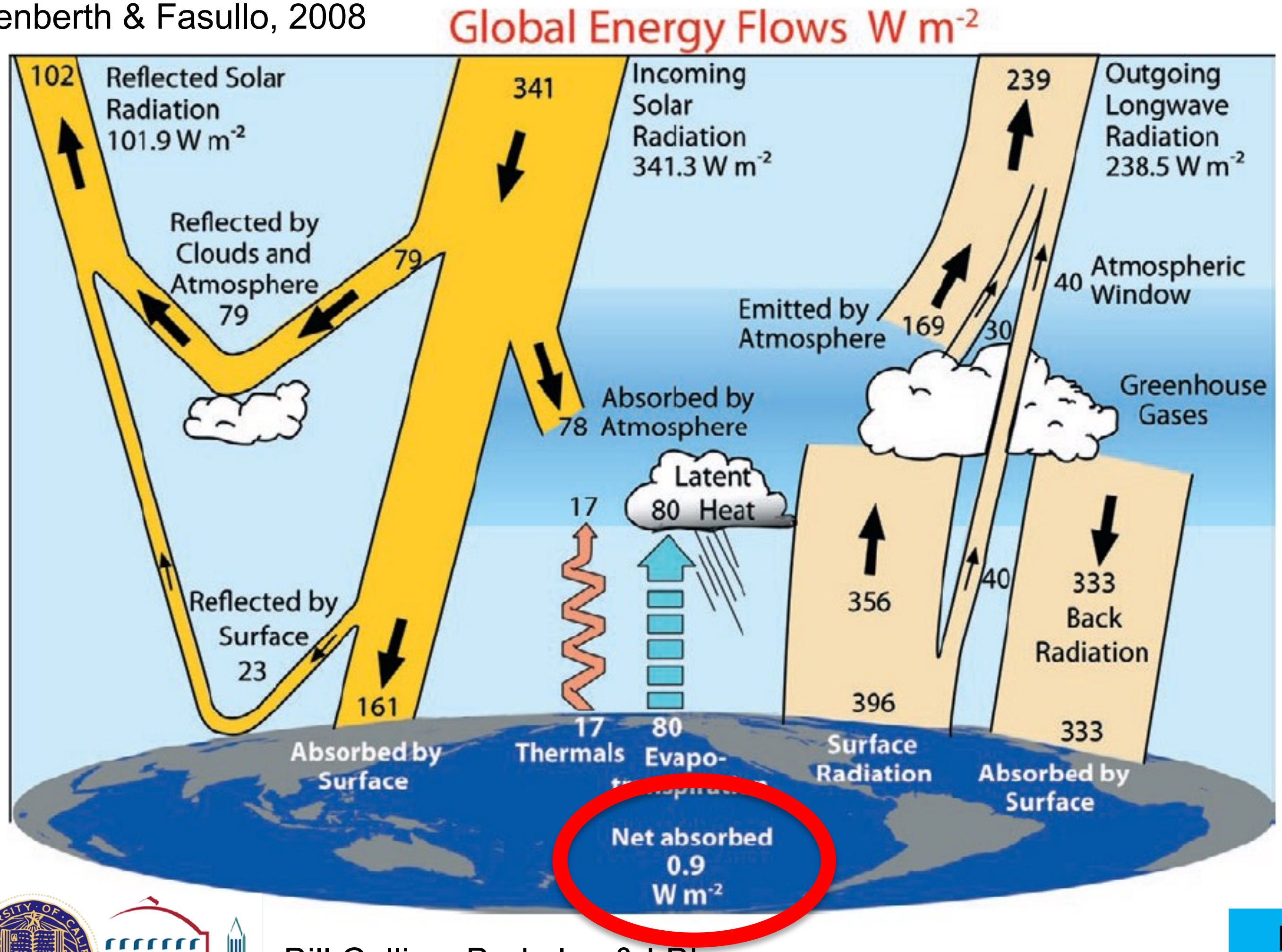


Homogeneous nucleation
-40C, supersaturation

Heterogenous nucleation
Condensation nuclei, saturation

Radiation and the The Earth's Energy Budget

Trenberth & Fasullo, 2008



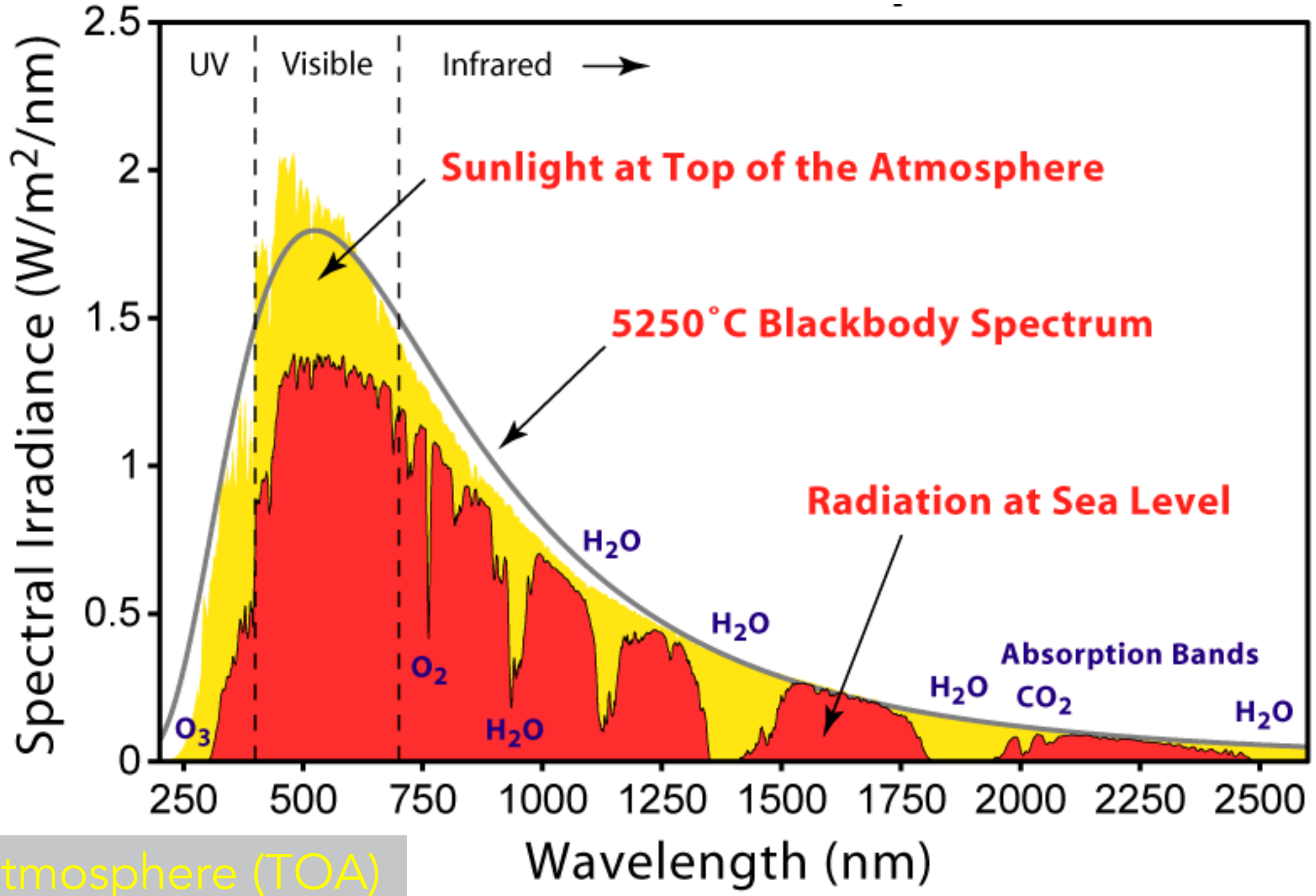
Bill Collins, Berkeley & LBL

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!

Solar Radiation Spectrum (short wave)

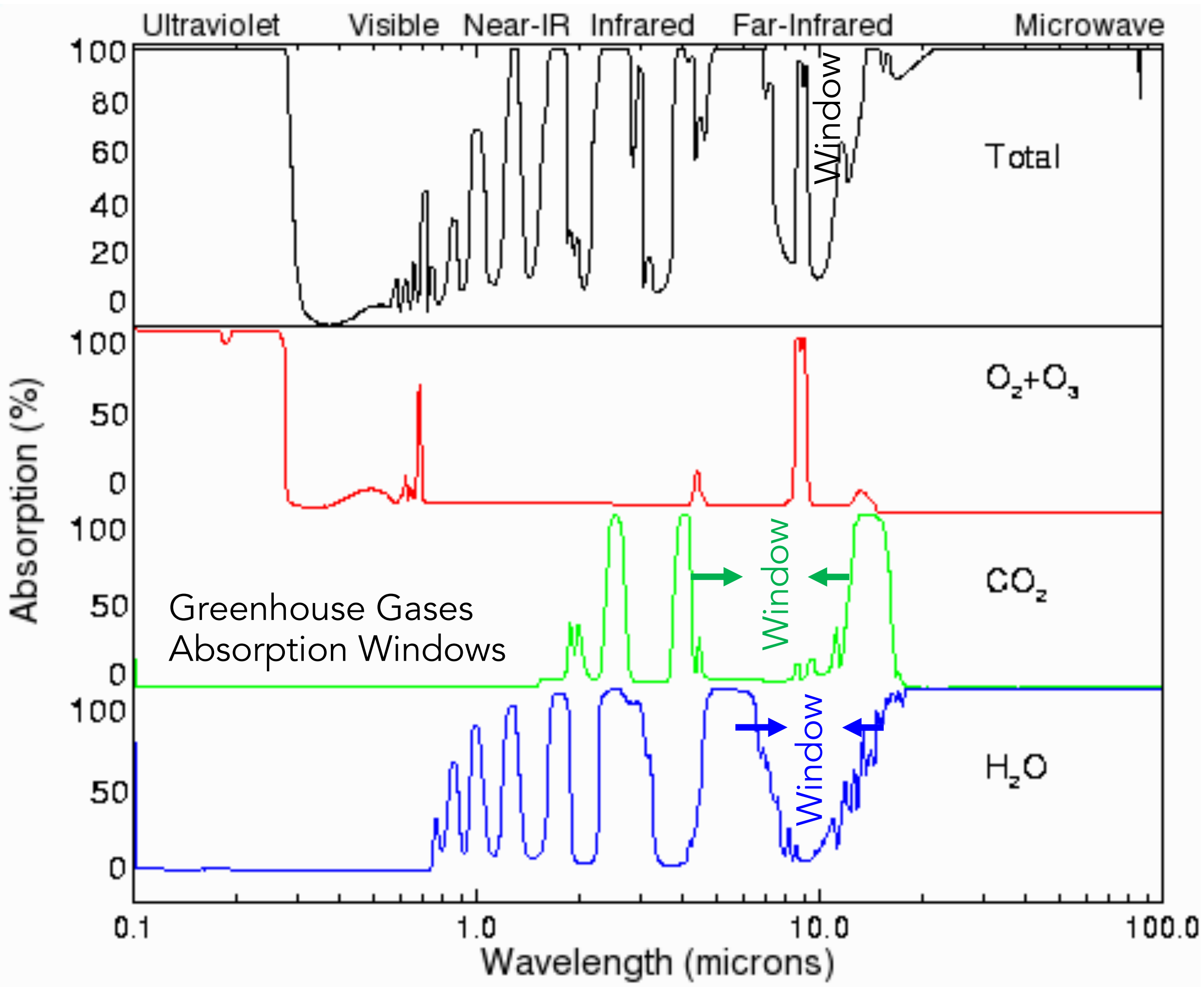


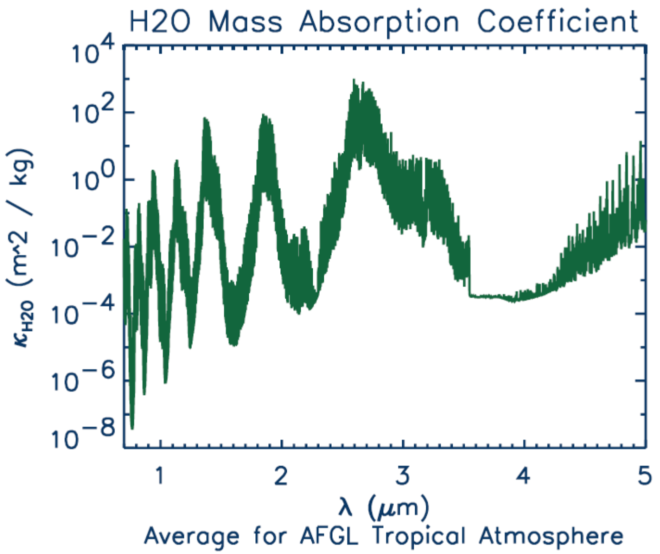
Input at Top of Atmosphere (TOA)
Radiation at surface

1000nm = 1μm

From: ‘Sunlight’, Wikipedia

Infrared absorption (long wave)



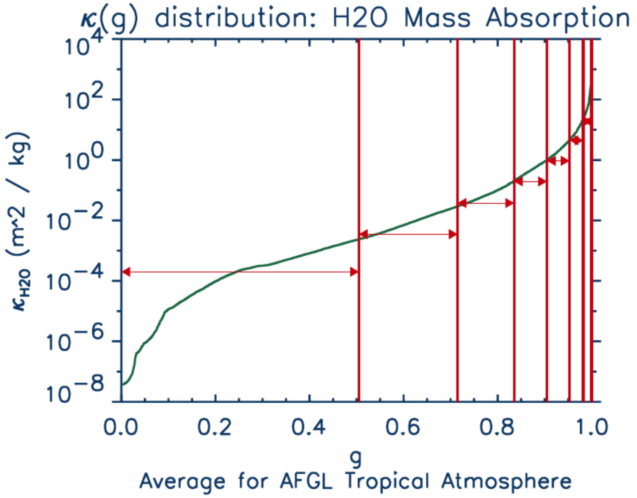


Line-by-line calculations

Very expensive/slow, accurate

Rapid Radiative Transport Model (RRTM)

Iacono et al. 2000



k-distribution band model, sort absorption coefficients by magnitude

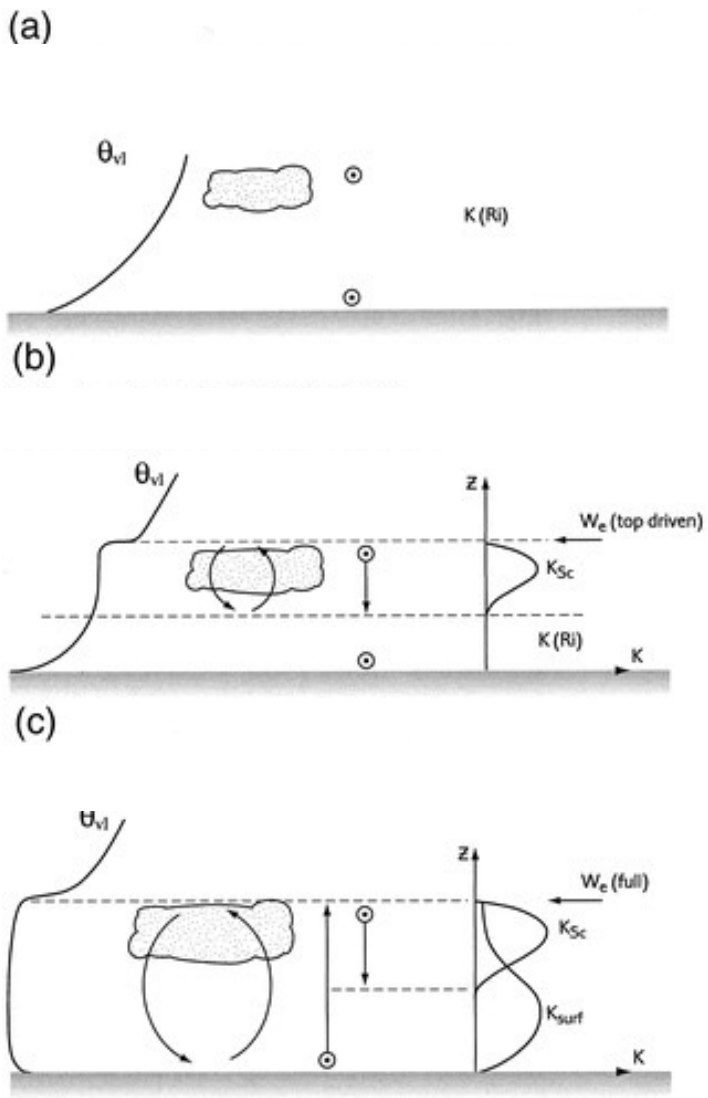
Cheaper/fast, less accurate

Planetary Boundary Layer (PBL)

- 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

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

- CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)
- CAM6: 3 slides time

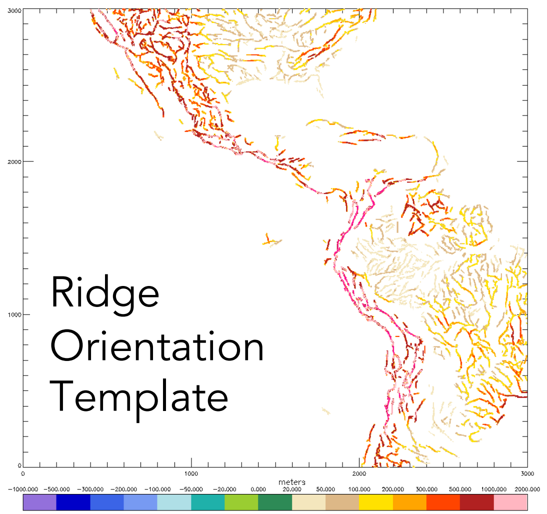


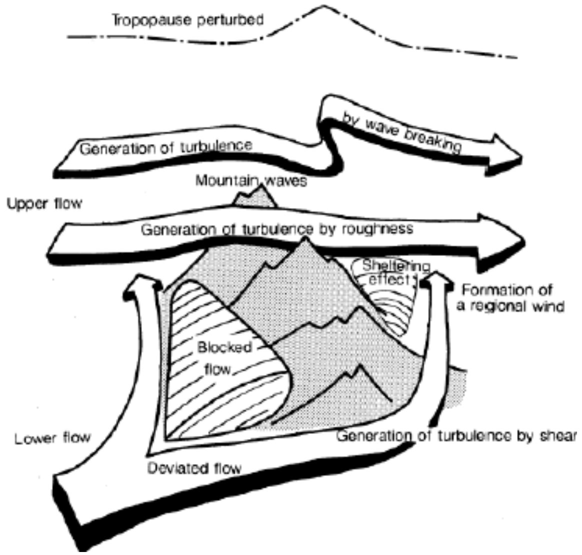
Gravity Waves and Mountain Stresses

- Gravity Wave Drag
  - Determines flow effect of upward propagating (sub-grid scale) gravity waves that break and add momentum/turbulence
  - Generated by surface orography (mountains), deep convection, frontals systems
  - Greatest impacts above tropopause (WACCM)

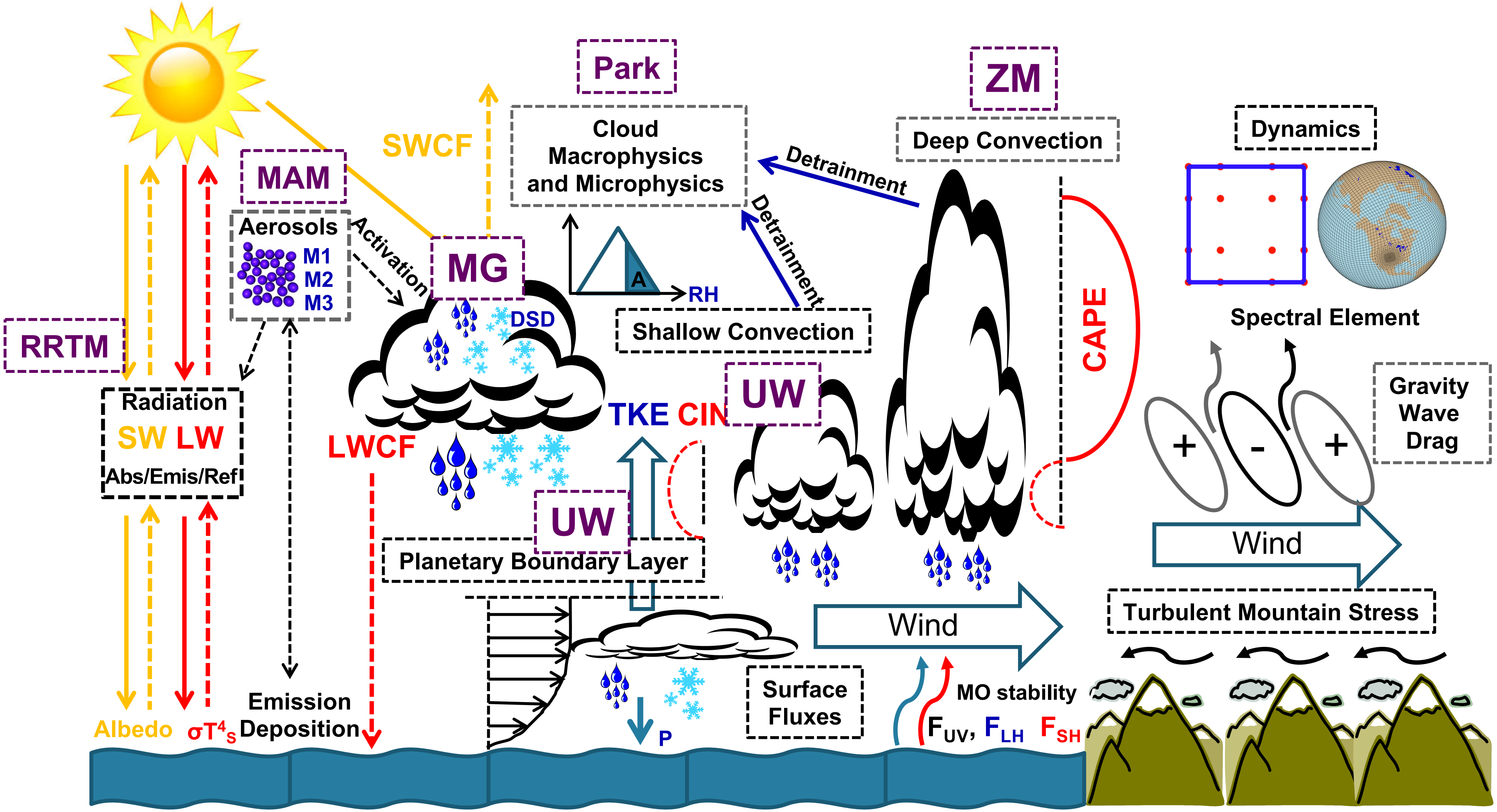
- Turbulent mountain stress
  - Local near-surface stress on flow based on stability
  - Roughness length < scales < grid-scale
  - Impacts mid/high-latitude flow
  - Applied over physical based height scales (Beljaars et al 2004)

More difficult to parameterize than thermodynamic impacts (conservation?)

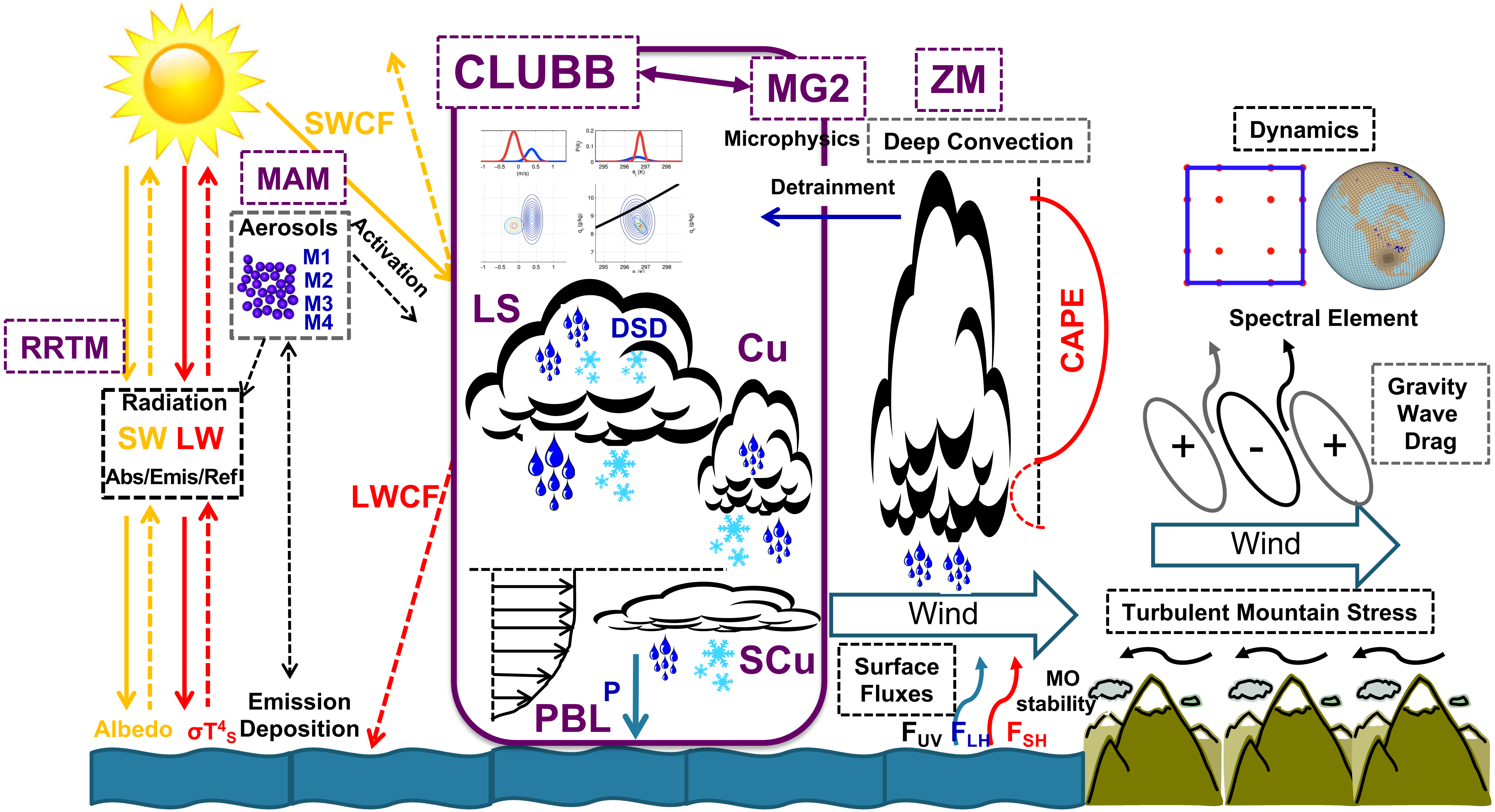




Community Atmosphere Model (CAM5)

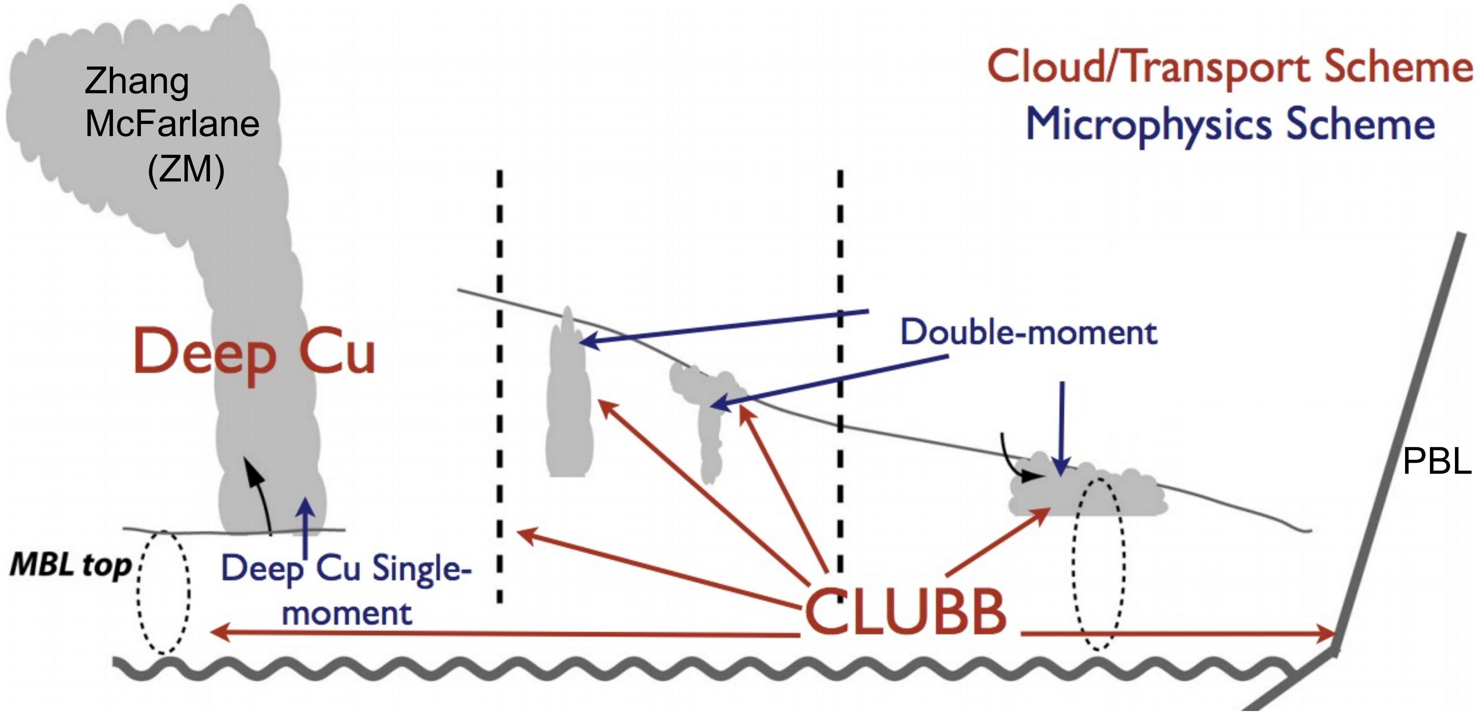


Community Atmosphere Model (CAM6)



CLUBB: Cloud Layers Unified By Binormals

Golaz 2002b, J. Atmos. Sci.



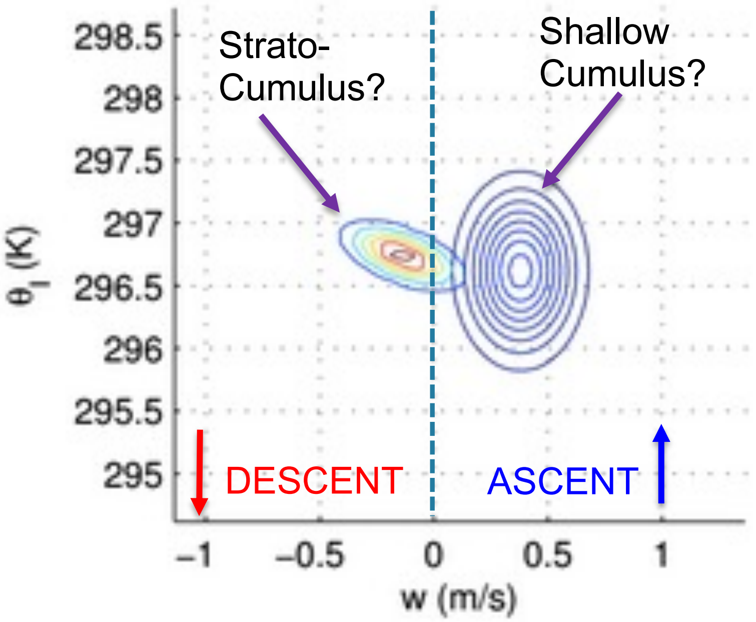
- Unifies moist and dry turbulence (except deep convection – CAM6)
- 'Seamless' representation; no specific case adjustments
- Unifies microphysics (across cloud types)
- High order closures (1 third order, 6 second order, 3 first order-means)

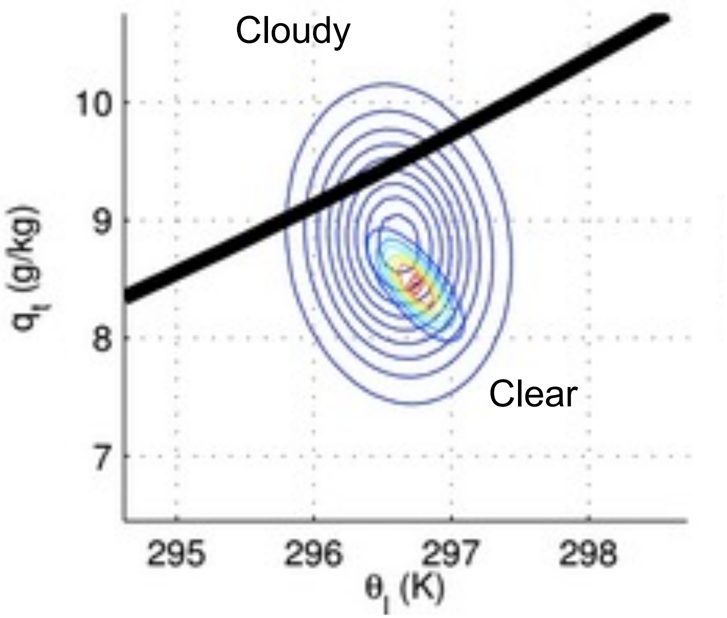
CLUBB: Cloud Layers Unified By Binormals

- 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, $w'q_L'$, $w'q_L'$)

$$\frac{\partial \overline{w'\theta_l'}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{w'\theta_l'}}{\partial z}}_{ma} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2\theta_l'}}{\partial z}}_{ta} \underbrace{-\overline{w'^2}\frac{\partial \overline{\theta_l}}{\partial z}}_{tp} \underbrace{-\overline{w'\theta_l'}\frac{\partial \overline{w}}{\partial z}}_{ac} + \underbrace{\frac{g}{\theta_{vs}}\overline{\theta_l'\theta_v'}}_{bp}$$
$$\underbrace{-\frac{C_6}{\tau}\overline{w'\theta_l'}}_{pr1} \underbrace{+C_7\overline{w'\theta_l'}\frac{\partial \overline{w}}{\partial z}}_{pr2} \underbrace{-C_7\frac{g}{\theta_{vs}}\overline{\theta_l'\theta_v'}}_{pr3}$$

Vertical Heat Flux
Vertical Advection
Turbulence transport
Buoyancy production
Dissipation
Pressure related terms

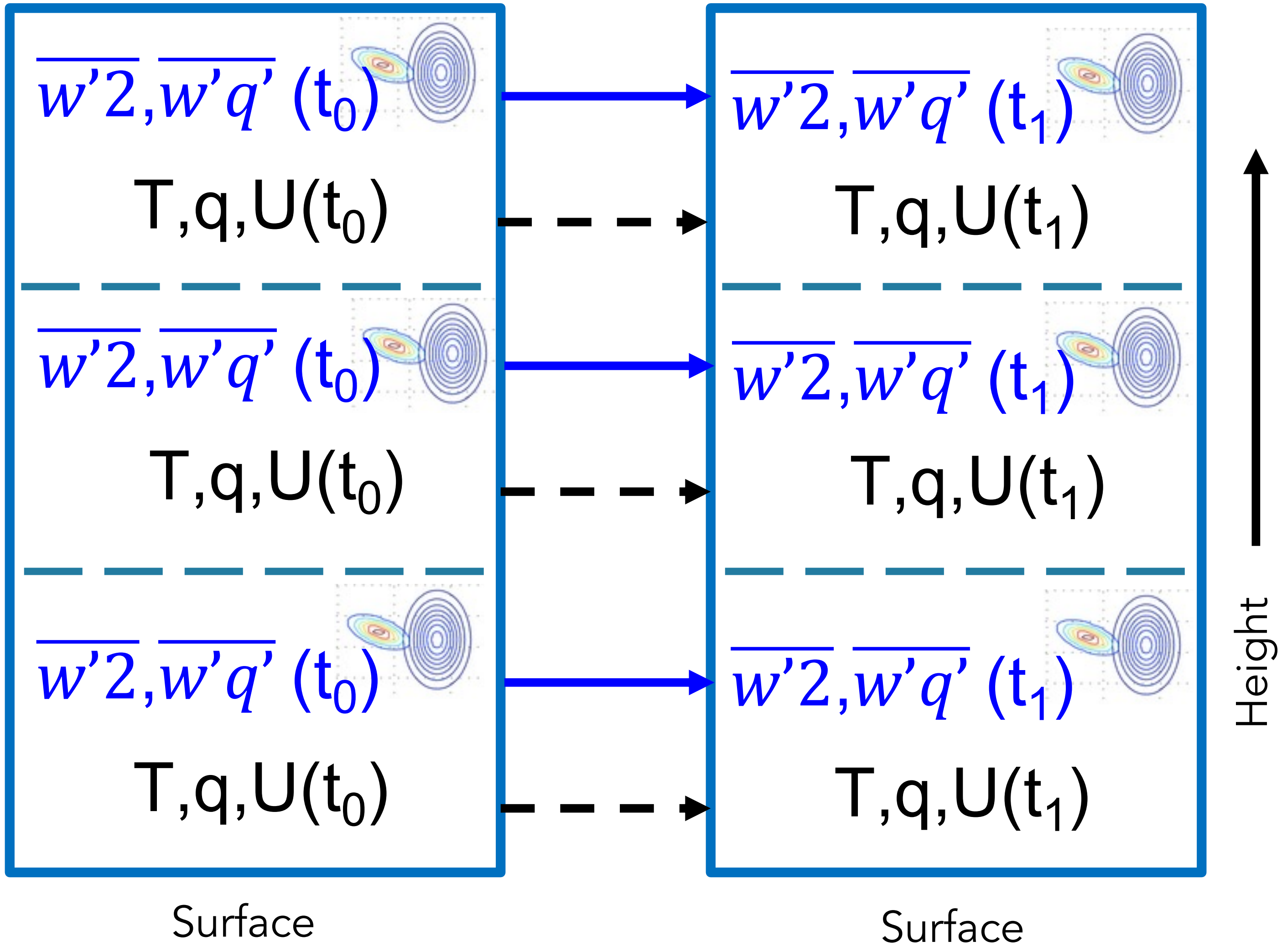




NCAR | UCAR

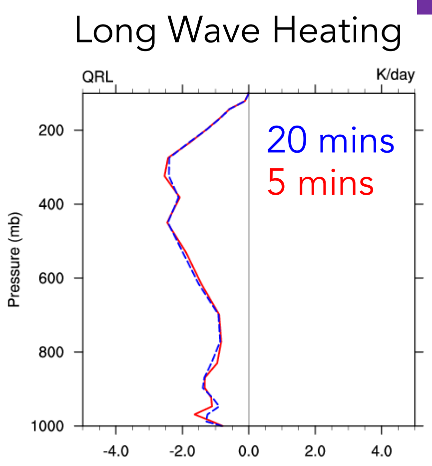
CLUBB: A New Approach

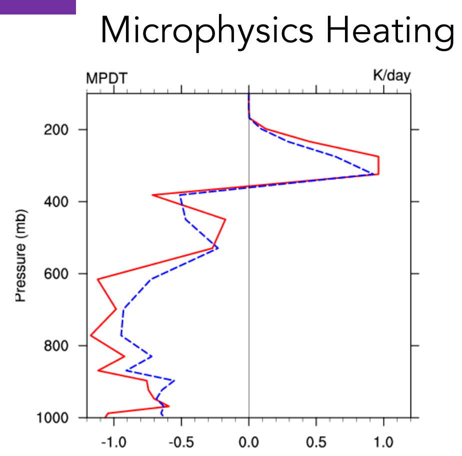
- Conventionally mean 'prognostic' state variables are calculated
- They are retained over each time step
- CLUBB calculates higher order 2nd/3rd moments
- These are advanced across time steps
- Requires sub-cycling with microphysics
- Allows information from surface heterogeneity to be considered



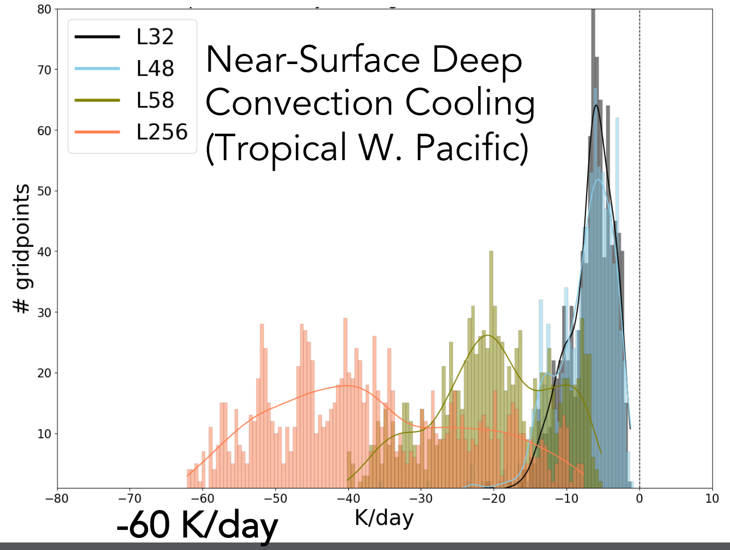
Process Interactions: Resolution Sensitivity

Time



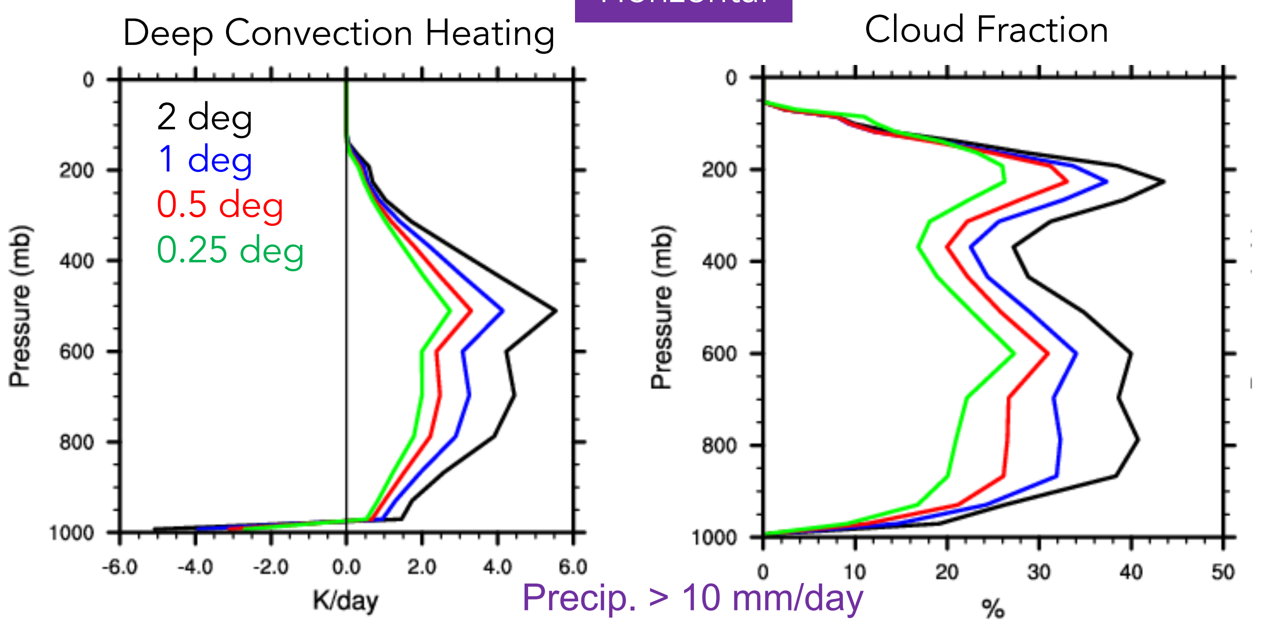


Vertical



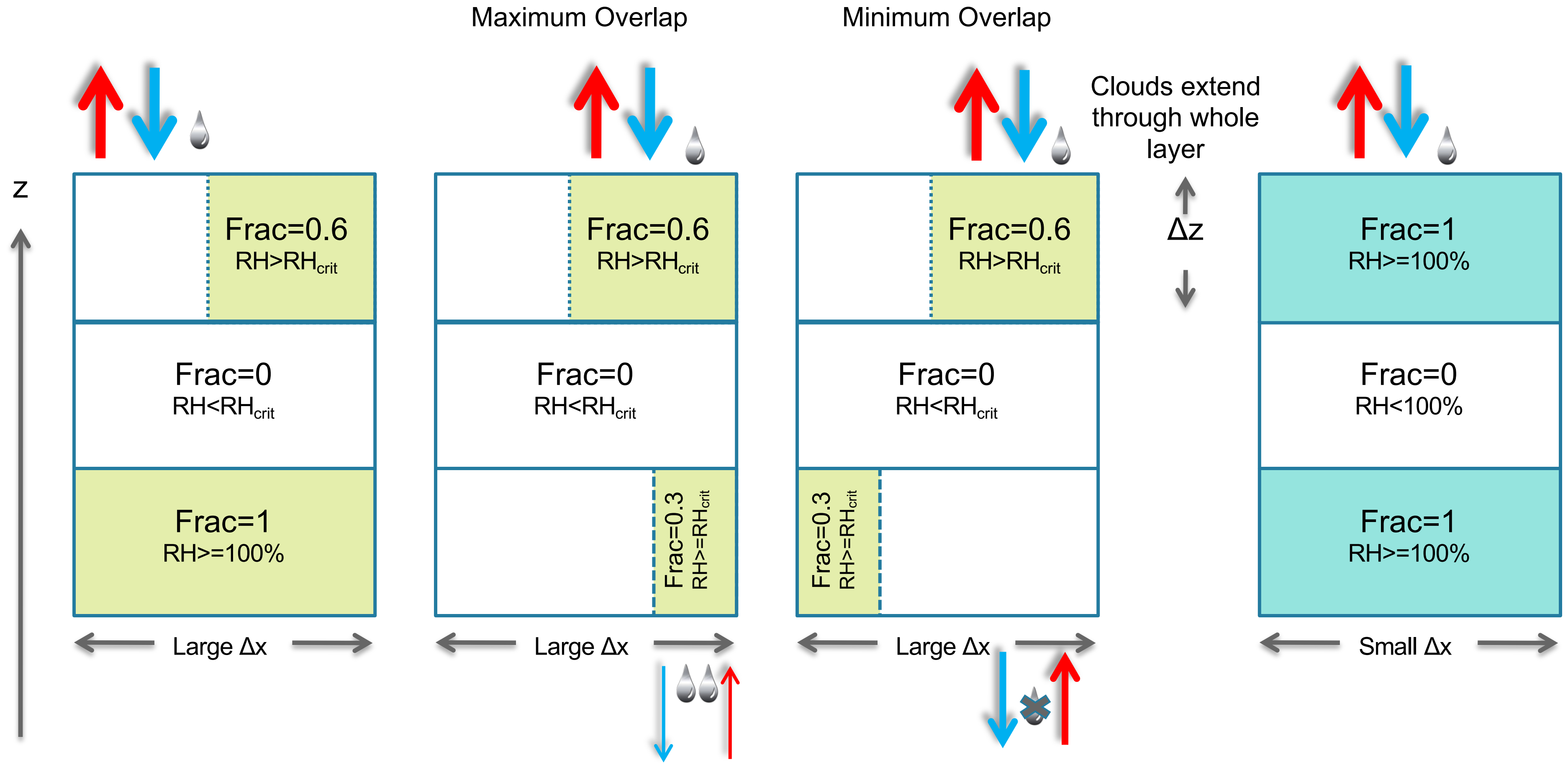
- Different vertical, horizontal and time resolutions
- Significant sensitivity to resolution can exist
- Greatest in cloud-related fields
- Impacts on radiation -> energy imbalance
- Separate 'tunings' required
- Strive for scale-aware parameterizations

Horizontal



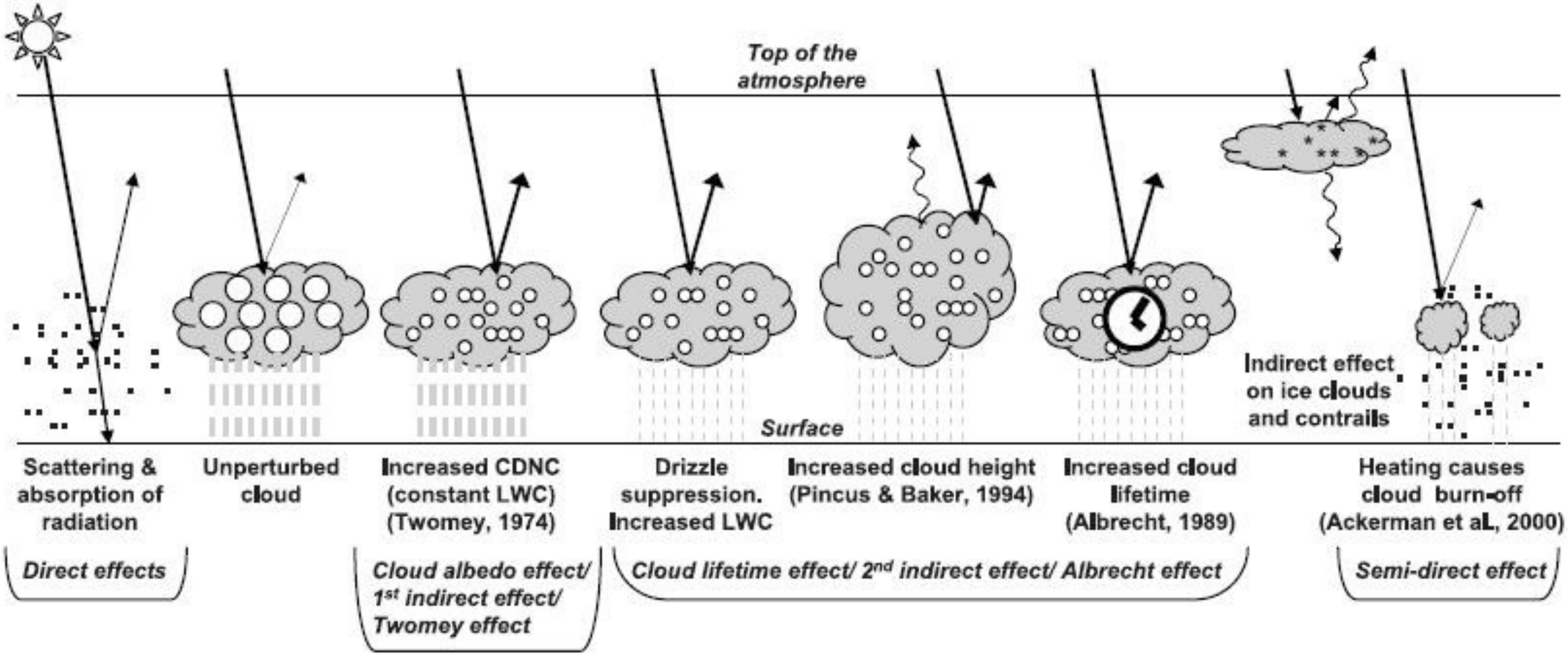
Process Interactions: The Cloud Overlap Challenge

Radiation and micro/macro-physics impact



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

Process Interactions: Cloud, Aerosol, Radiation

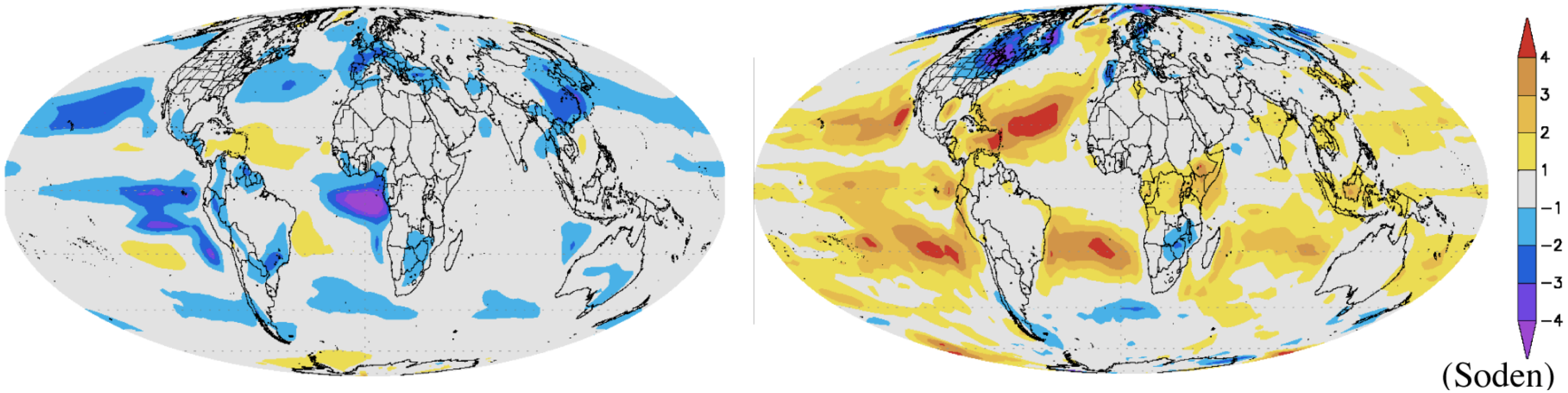


IPCC, AR4

Process Interaction: Climate Sensitivity

What happens to clouds when we double CO2 (CMIP3)?

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 temperature change is due to (higher/lower) solar radiation reaching the ground because of clouds feedbacks.

The CAM family

Model	CCM2/3 CSM1	CAM2 CCSM2	CAM3 CCSM3	CAM4 CCSM4	CAM5 CESM1	CAM6 CESM2	CAM7 CESM3
Release	June 1998	May 2002	June 2004	Apr 2010	June 2011	June 2017	End 2023
PBL	HB	HB	HB	HB	UW	CLUBB	CLUBB
Shallow conv.	Hack	Hack	Hack	Hack	UW	CLUBB	CLUBB
Deep conv.	ZM	ZM	ZM	ZM_mod1	ZM_mod1	ZM_mod2	CLUBB-MF
Microphysics	RK	RK	RK	RK	MG1	MG2	PUMAS
Macrophysics	Sundqvist	Zhang	Zhang	Zhang	Park	CLUBB	CLUBB
Radiation	Briegleb	Briegleb	CAMRT	CAMRT	RRTMG	RRTMG	RRTMGP
Aerosols	Uniform	Uniform	BAM	BAM	MAM3	MAM4	MAM5
Dynamics	Spectral	Spectral	Spectral	FV	FV	FV	SE
Levels	18	26	26	26	30	32	58/93
Horiz. res	T42 (2.8°)	T42 (2.8°)	T85 (1°)	0.9°x1.25°	0.9°x1.25°	0.9°x1.25°	0.9x1.25
Land/Ocn	LSM/NCOM	CLM2/POP	CLM3/POP	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM

Climate Models

- Few options
- Slow turnover of physics
- Evaluated as a single 'best suite' for climatological skill globally

Weather Models

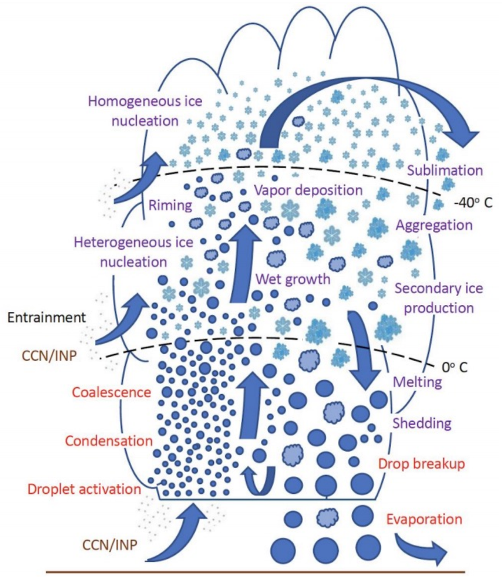
- Many options
- Rapid turnover of physics
- Evaluated as multiple 'best suites' for forecast skill regionally

https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_v4/v4.4/users_guide_chap5.html#Phys

= New/major update parameterization/dynamics

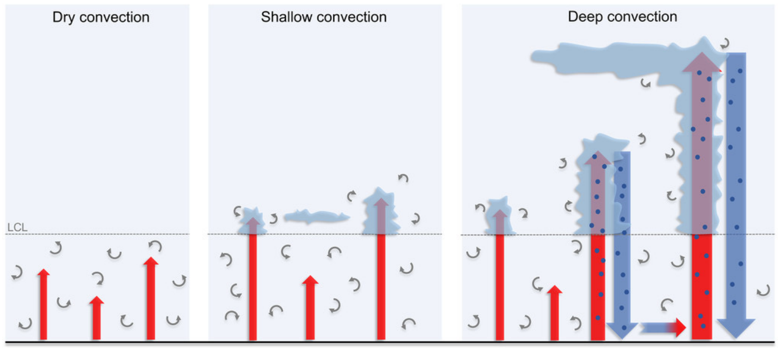
MG – Morrison Gettelman
UW – U. Washington
CLUBB - Cloud Layers Unified By Binormals
ZM – Zhang-McFarlane
HB – Holtslag-Boville
RRTM – Rapid Radiative Transfer Model
MAM – Model Aerosol Model
RK – Rasch-Kristienson

Model physics: Alternatives and The future

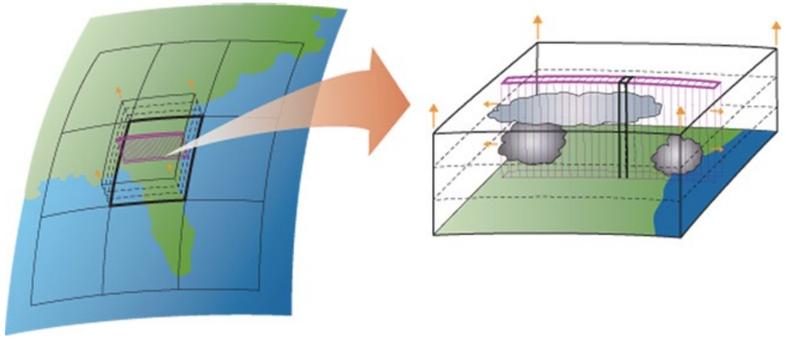


More comprehensive processes

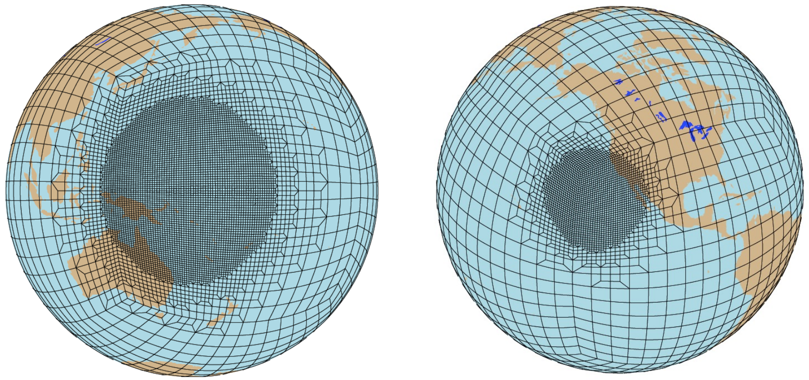
CLUBB --> CLUBB-MF



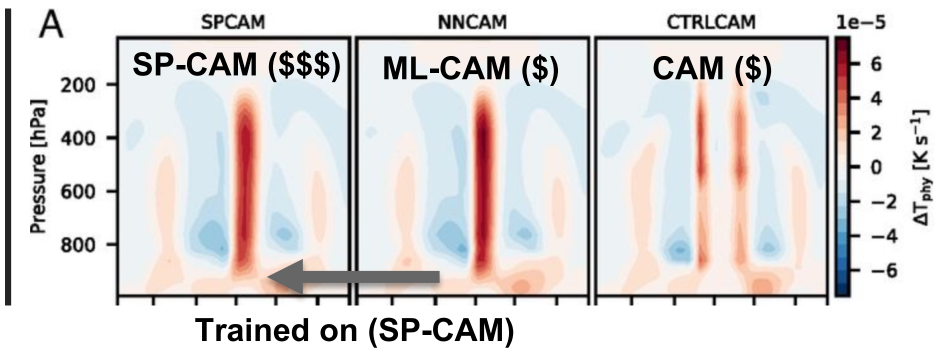
More consistent and continuous processes



Cloud super-parameterization



Regional grid and scale-aware physics

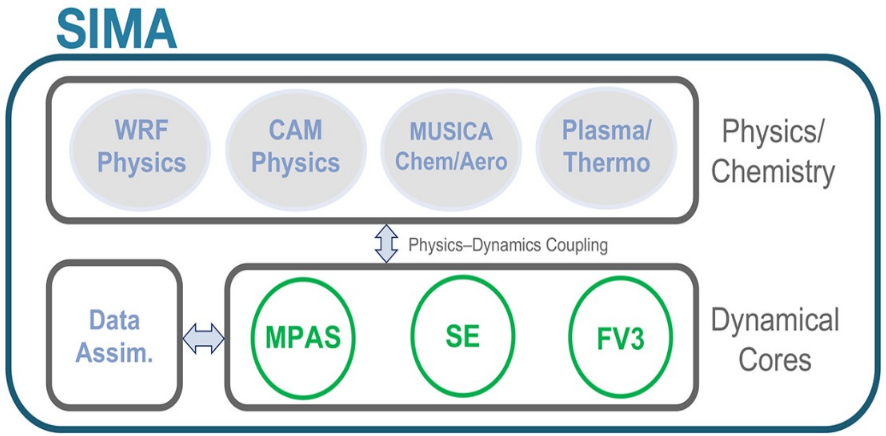


Machine Learning (ML) and Emulators

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

SIMA: Common Modeling Framework

SIMA is a unified community atmospheric modeling framework, for use in an Earth System Model (ESM). SIMA enables diverse configurations of an atmosphere model inside of an ESM for applications spanning minutes to centuries and cloud to global scales, including atmospheric forecasts and projections of the atmospheric state and composition from the surface into the thermosphere. LEARN MORE ›



https://sima.ucar.edu/

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 (CLUBB)
- Future parameterizations aim to be process scale-aware and continuous

Questions?

Thanks!

Equations of Motion

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

Resolved 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"