Atmospheric Modeling II:

Physics (parameterizations)

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CESM Tutorial: Aug 10, 2023

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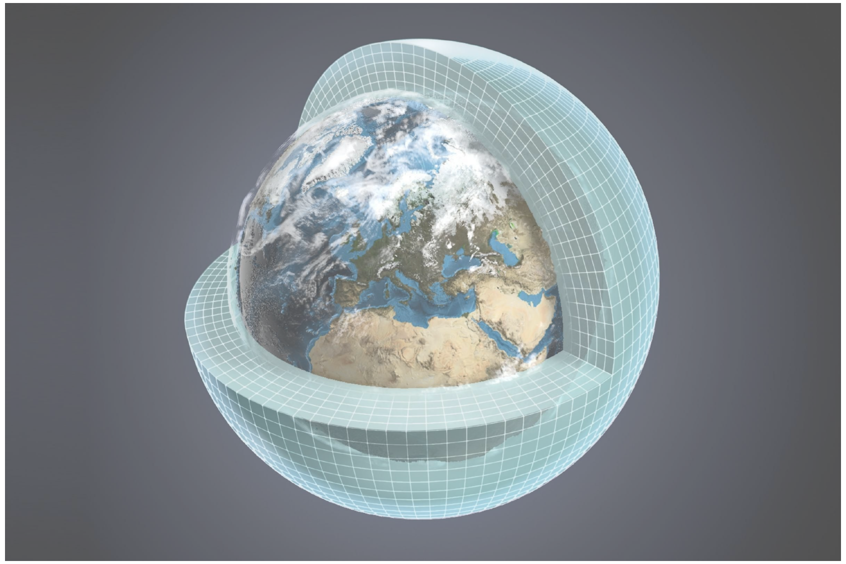
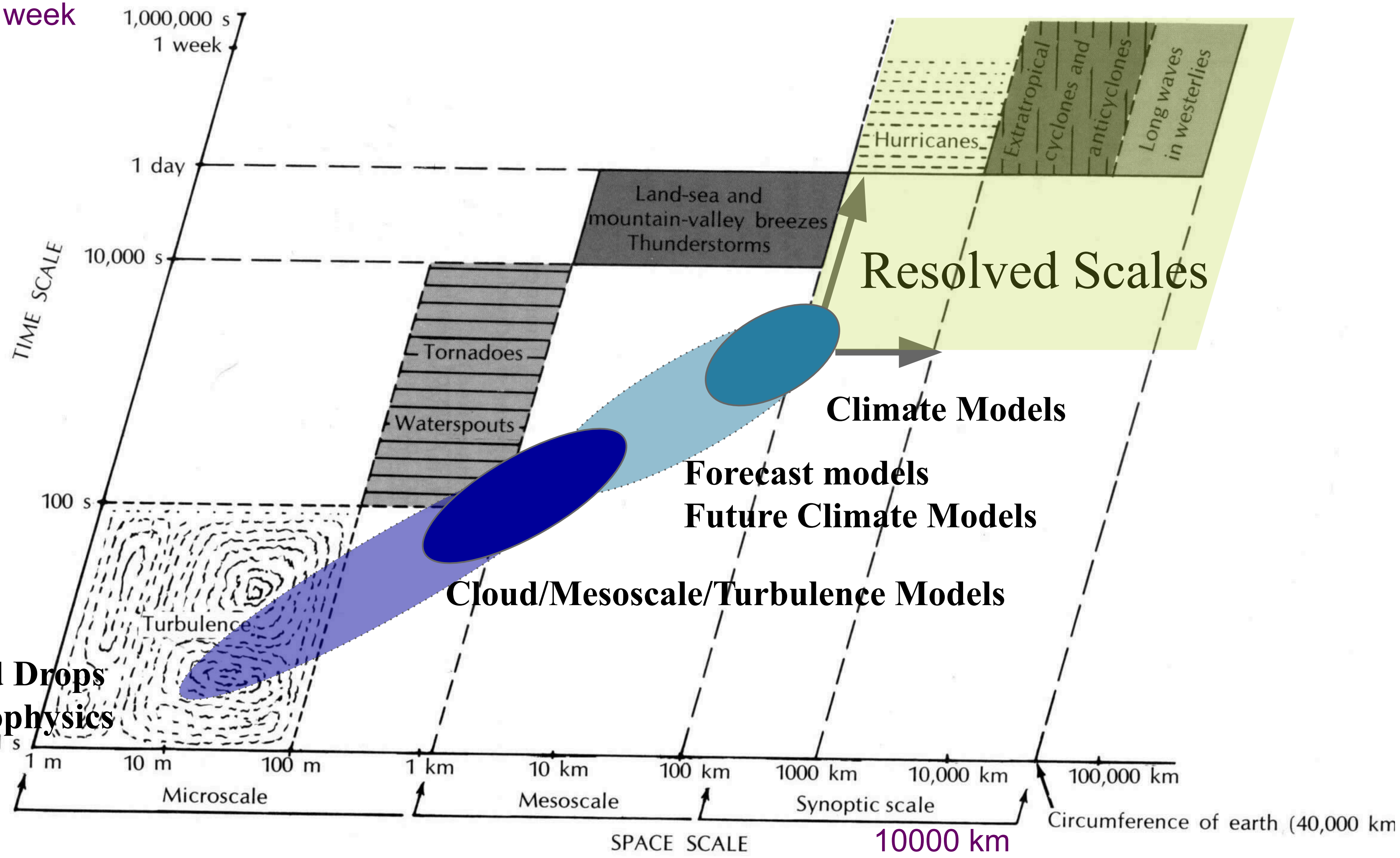
Outline

- Physical processes in an atmosphere GCM
- Distinguishing GCMs from other models (scales)
- Concept of Parameterization of sub-grid processes
- Physics representations (CESM)
    - Condensation clouds 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



1 week

Resolved Scales

Climate Models

Forecast models
Future Climate Models

Cloud/Mesoscale/Turbulence Models

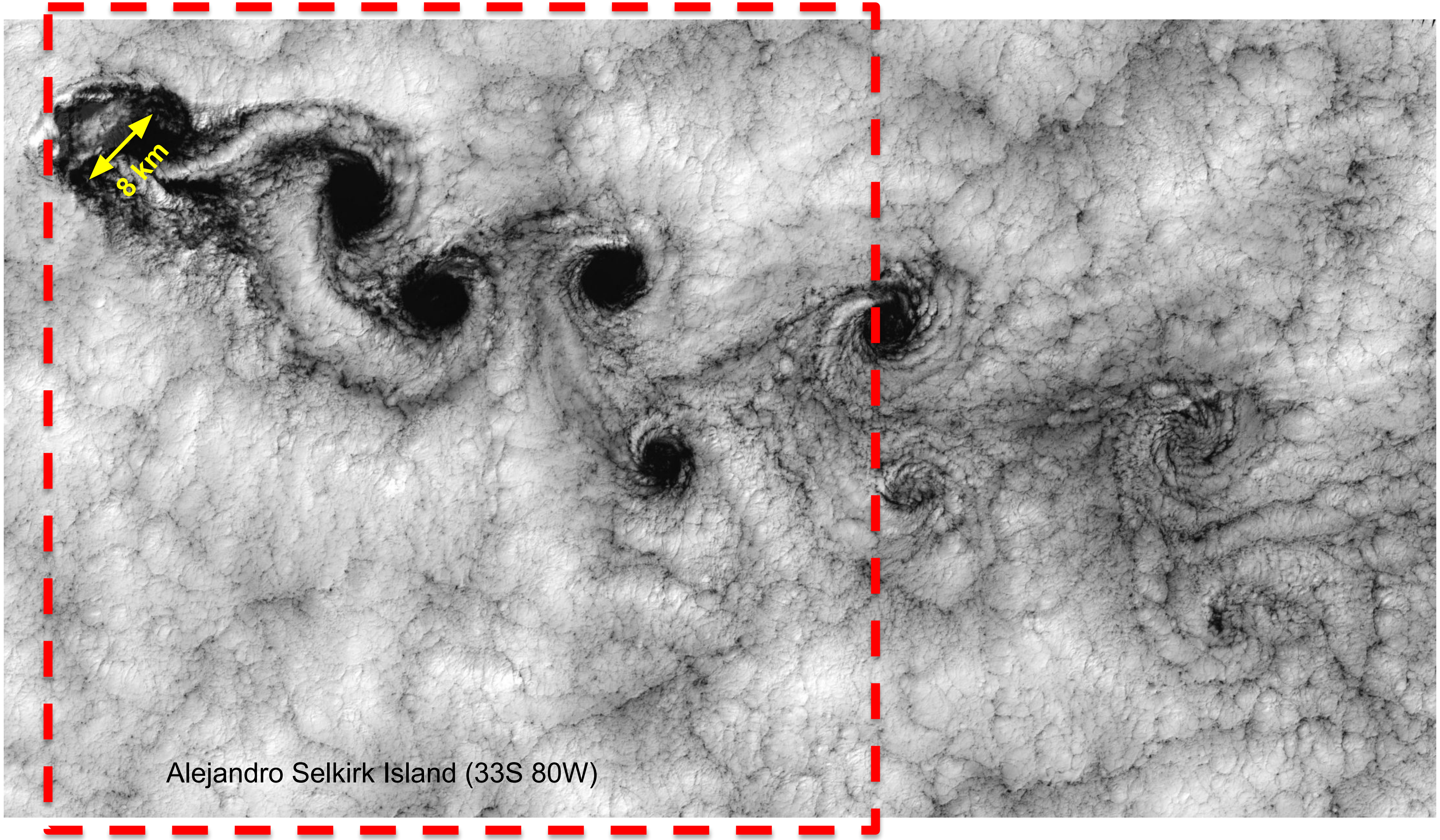
Cloud Drops
Microphysics

1 sec

1 m

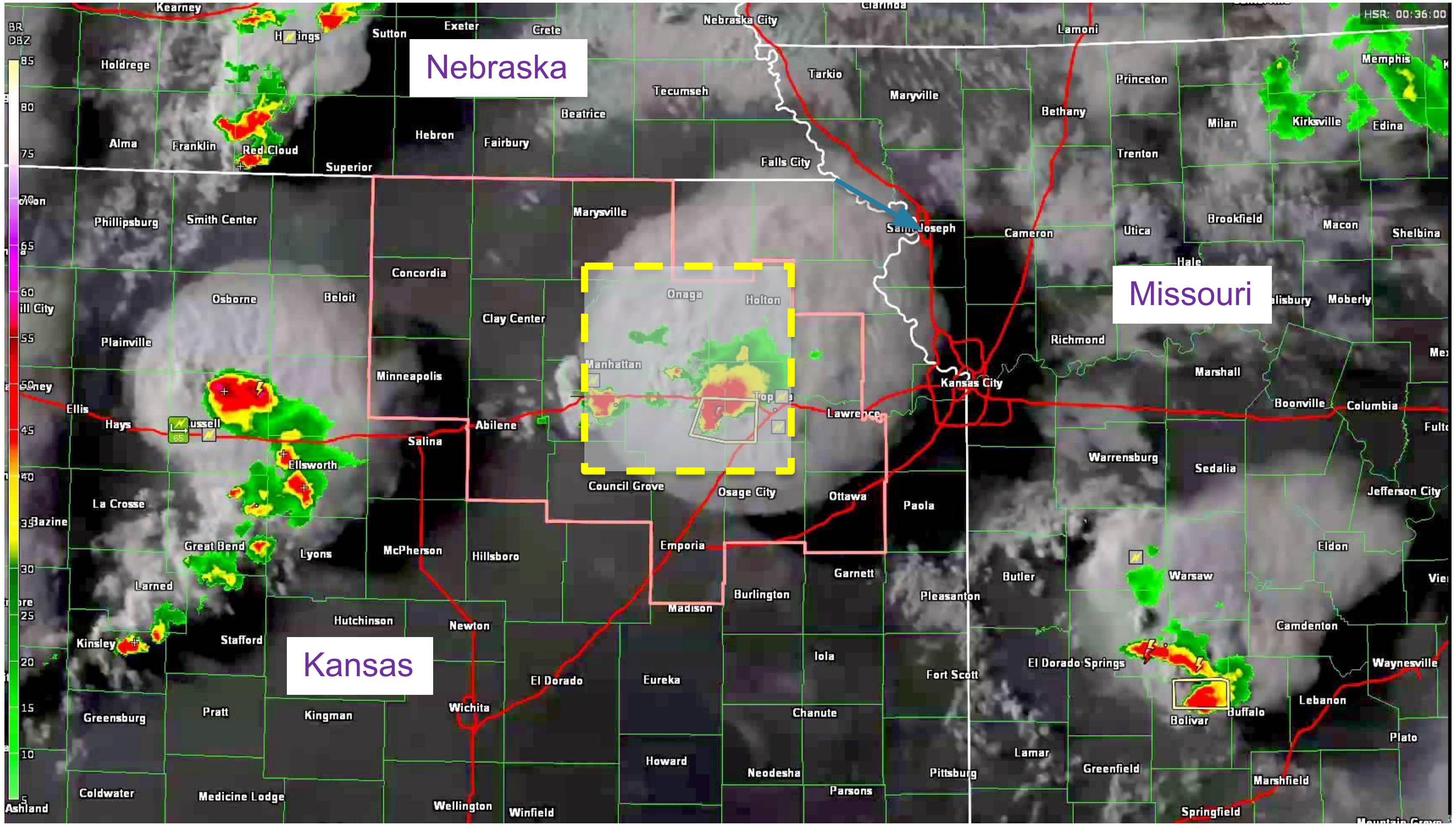
10000 km

Boundary Layer Cloud Scales



Alejandro Selkirk Island (33S 80W)

Storm Scales



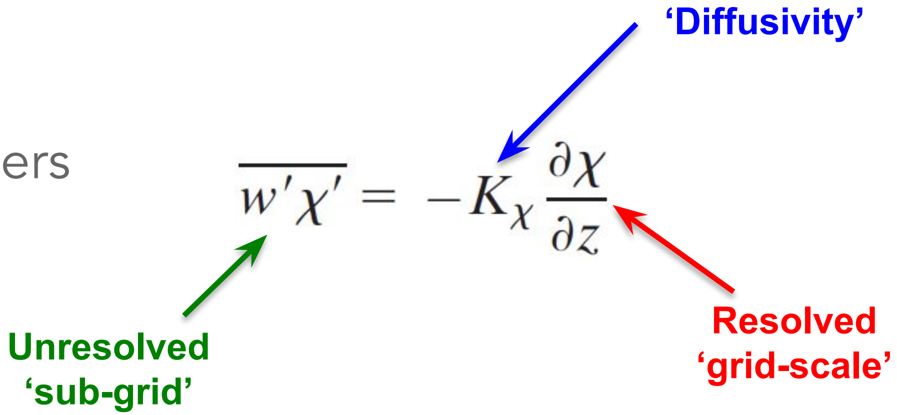
July 15, 2015

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



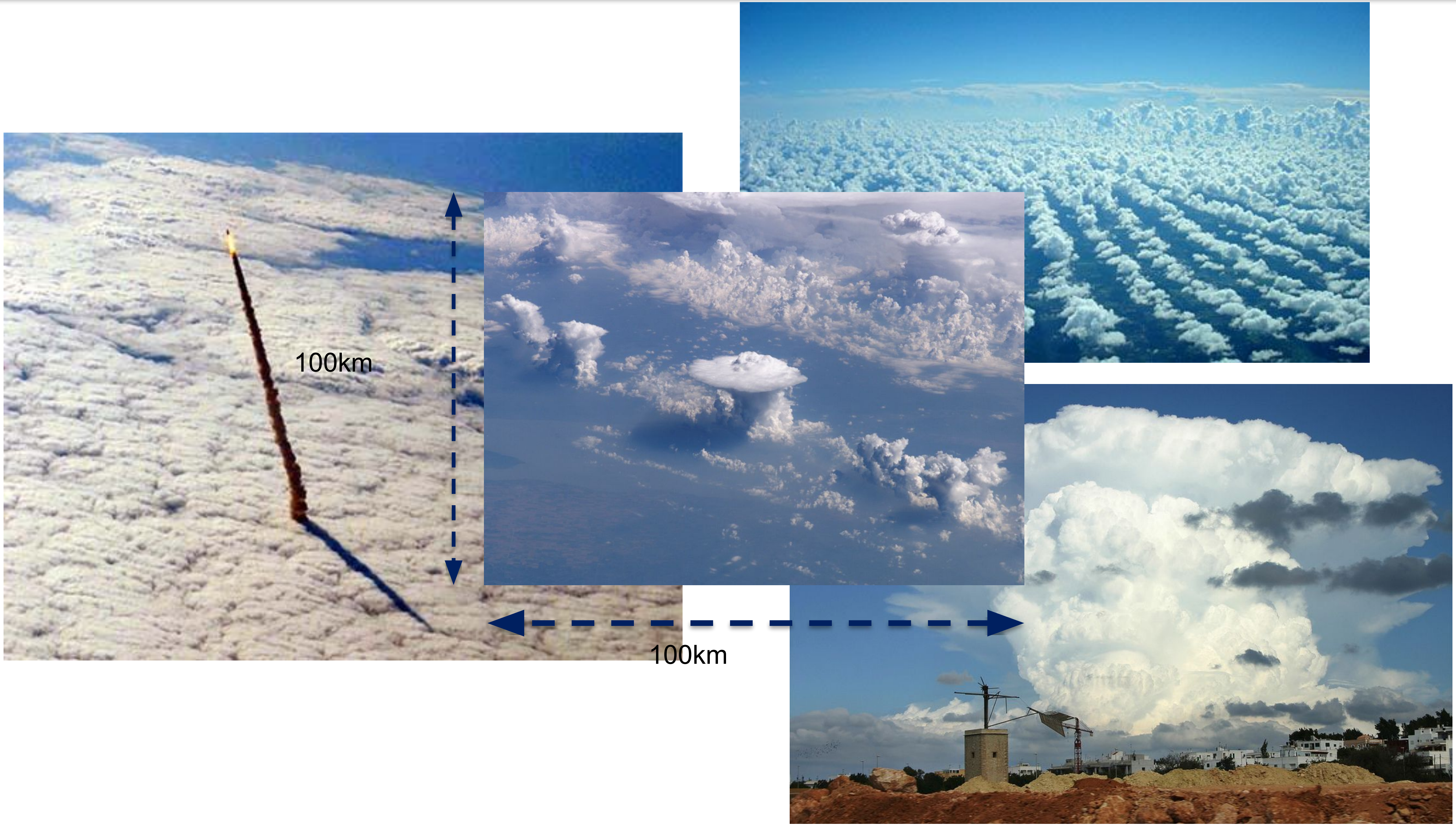
‘Diffusivity’

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

Unresolved ‘sub-grid’

Resolved ‘grid-scale’

Clouds, clouds, clouds

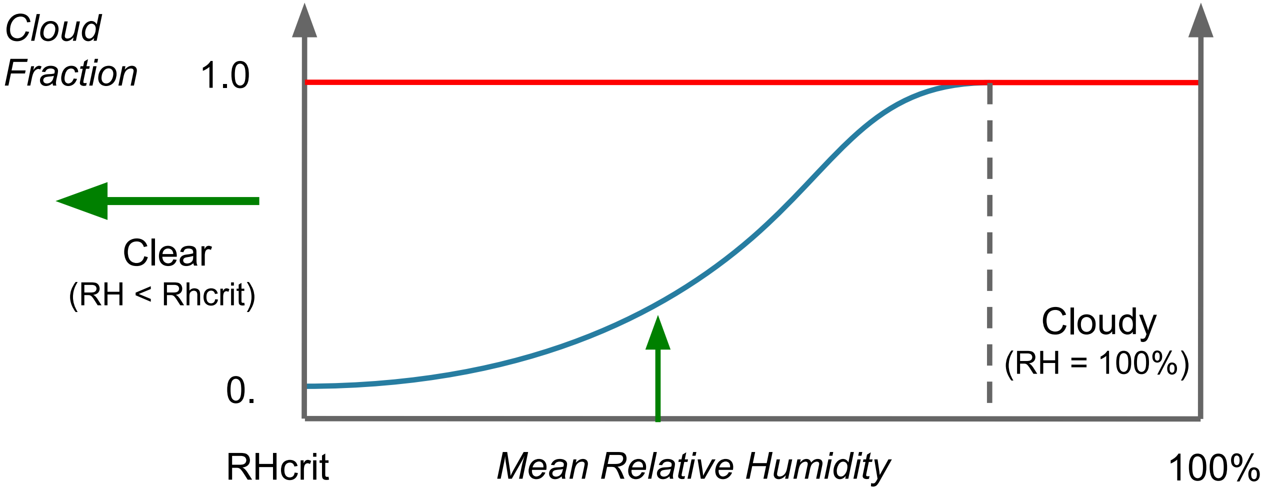


Cloud Categories

- 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 - CAM5



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

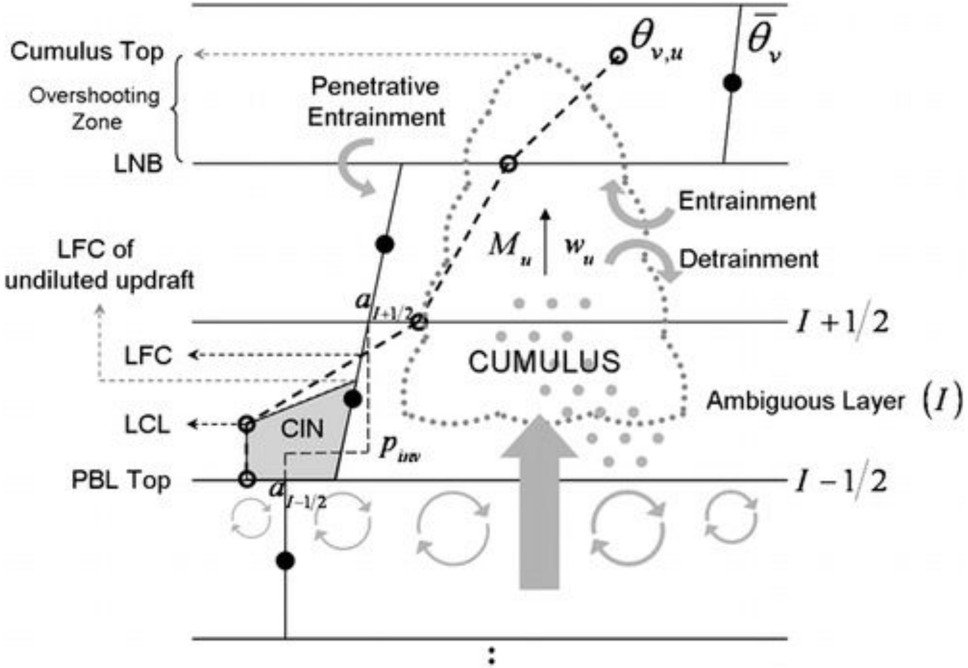
Deep (100s m-10s km) – non-local

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, CAM6 later

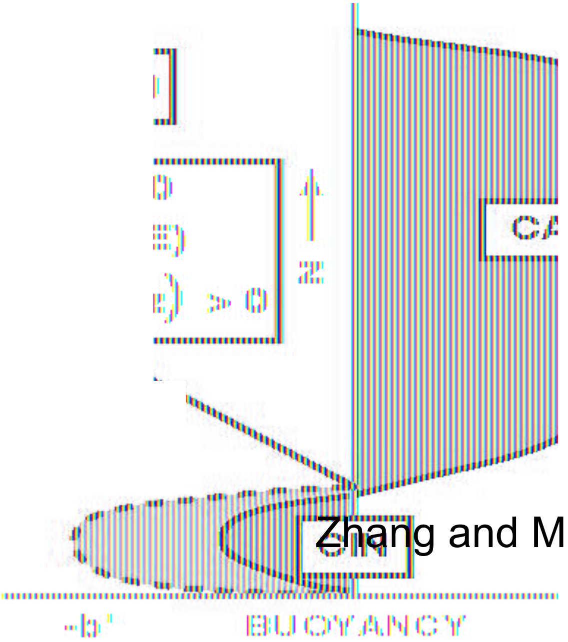


Park and Bretherton (2009)

Deep

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

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



Zhang and McFarlane (1995)

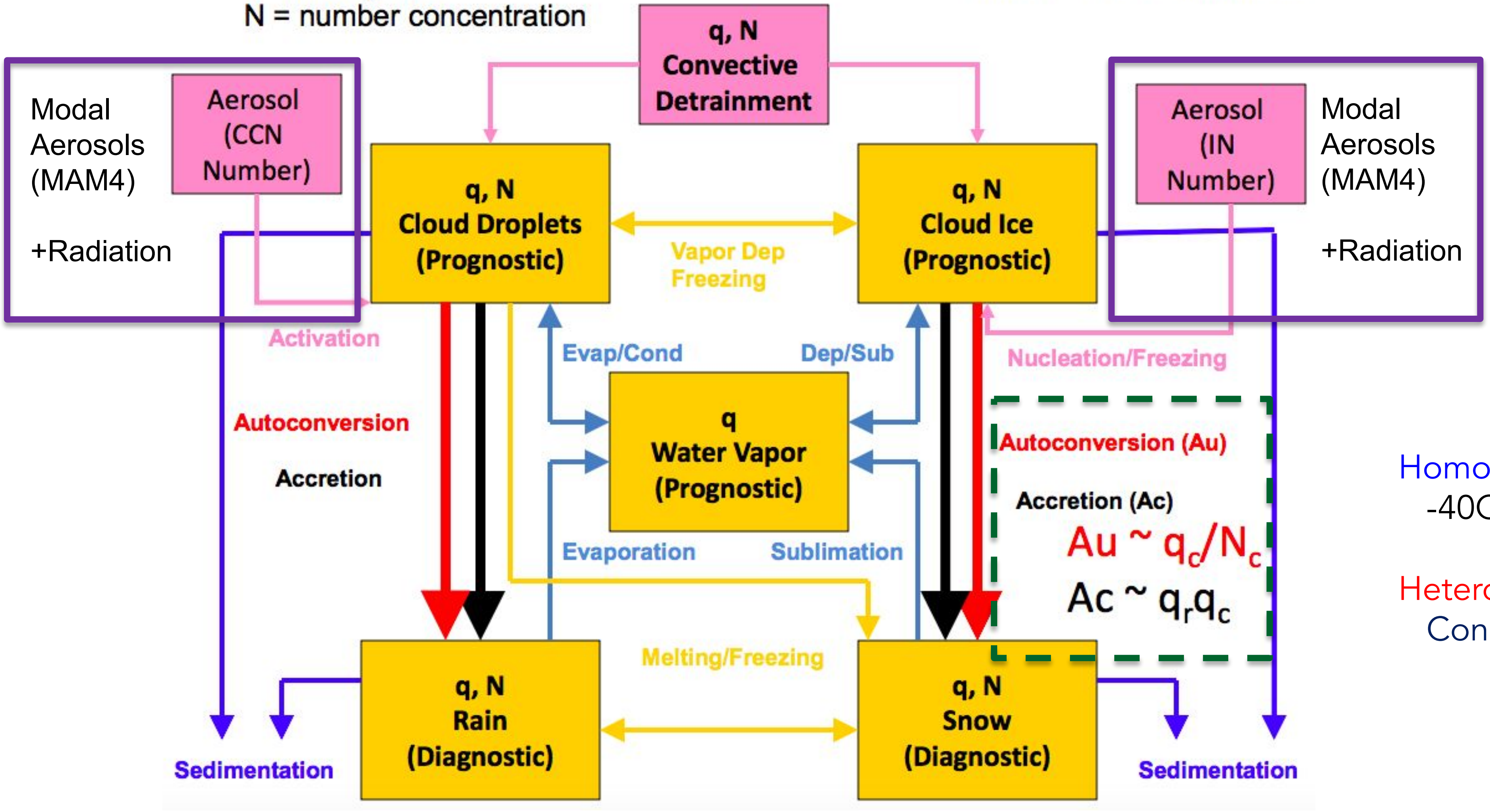
Cloud Microphysics

- 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

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008



q, N
Convective Detrainment

Modal Aerosols (MAM4)

+Radiation

Aerosol (CCN Number)

q, N
Cloud Droplets
(Prognostic)

Vapor Dep
Freezing

q, N
Cloud Ice
(Prognostic)

Aerosol (IN Number)

Modal Aerosols (MAM4)

+Radiation

Activation

Evap/Cond

Dep/Sub

Nucleation/Freezing

Autoconversion

Accretion

q
Water Vapor
(Prognostic)

Autoconversion (Au)

Accretion (Ac)

$Au \sim q_c/N_c$

$Ac \sim q_r q_c$

Evaporation

Sublimation

Melting/Freezing

q, N
Rain
(Diagnostic)

q, N
Snow
(Diagnostic)

Sedimentation

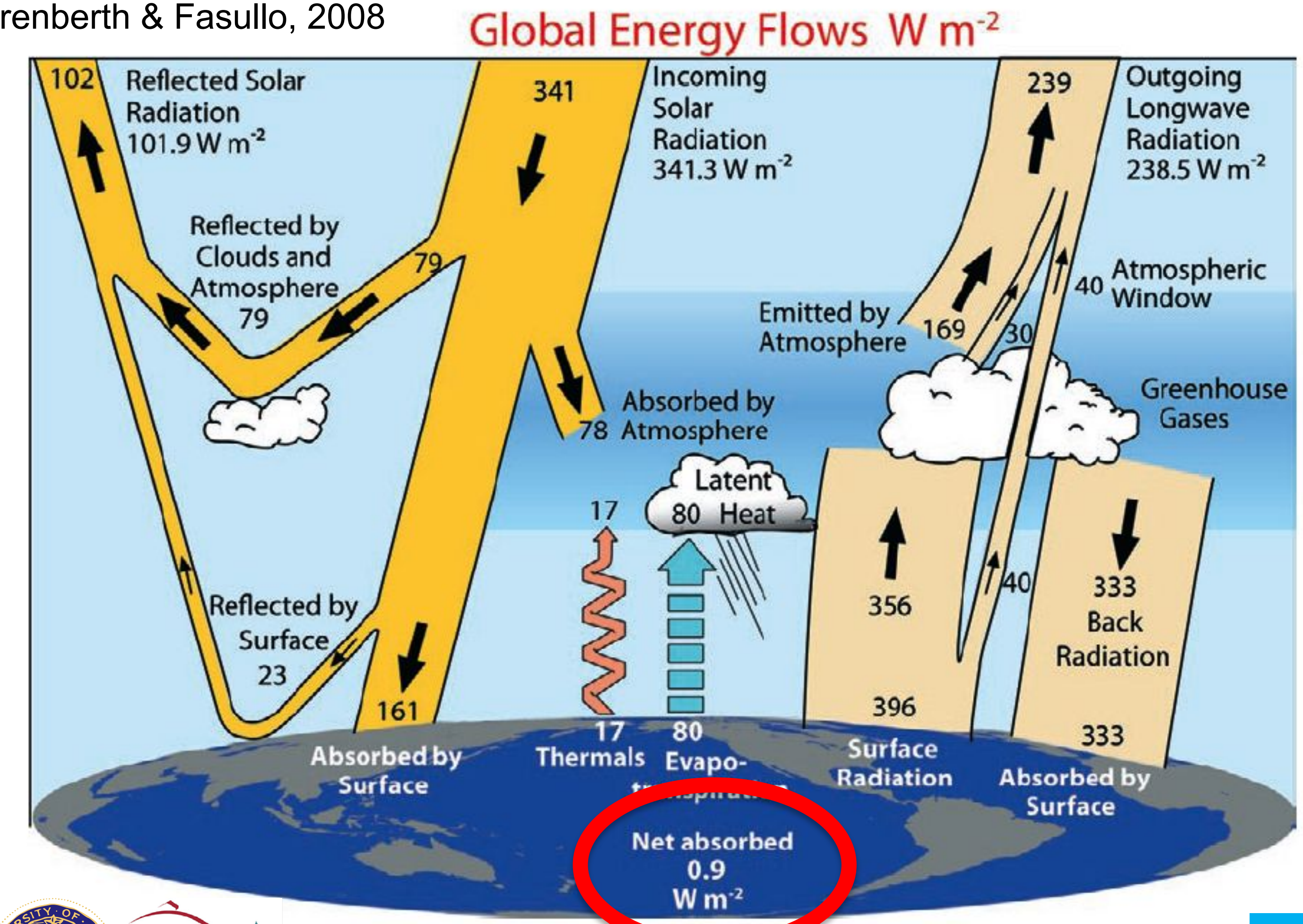
Sedimentation

Homogeneous nucleation
-40C, supersaturation

Heterogenous nucleation
Condensation nuclei, saturation

Radiation and the The Earth's Energy Budget

Trenberth & Fasullo, 2008



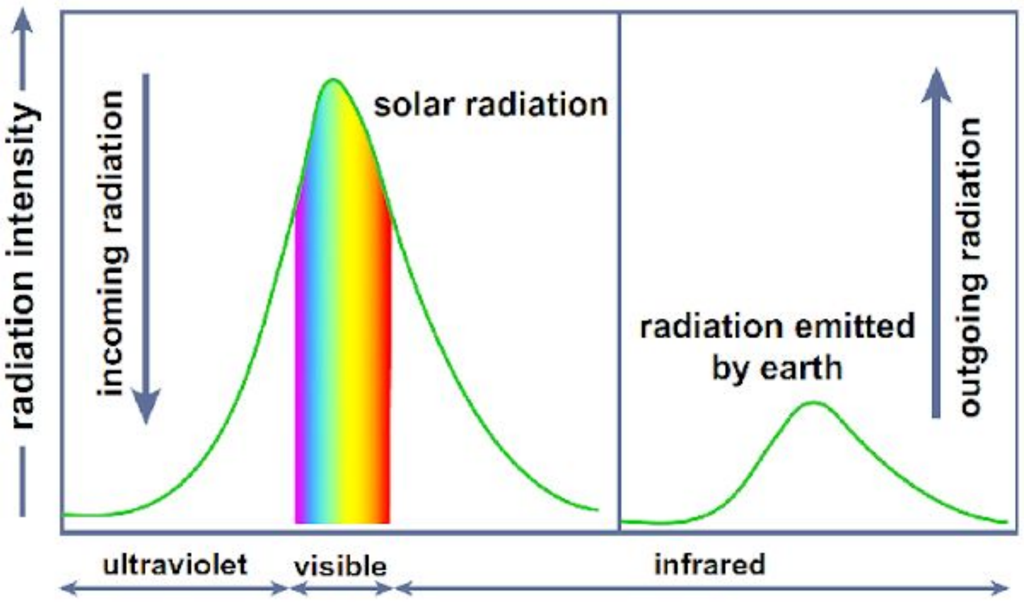
Bill Collins, Berkeley & LBL

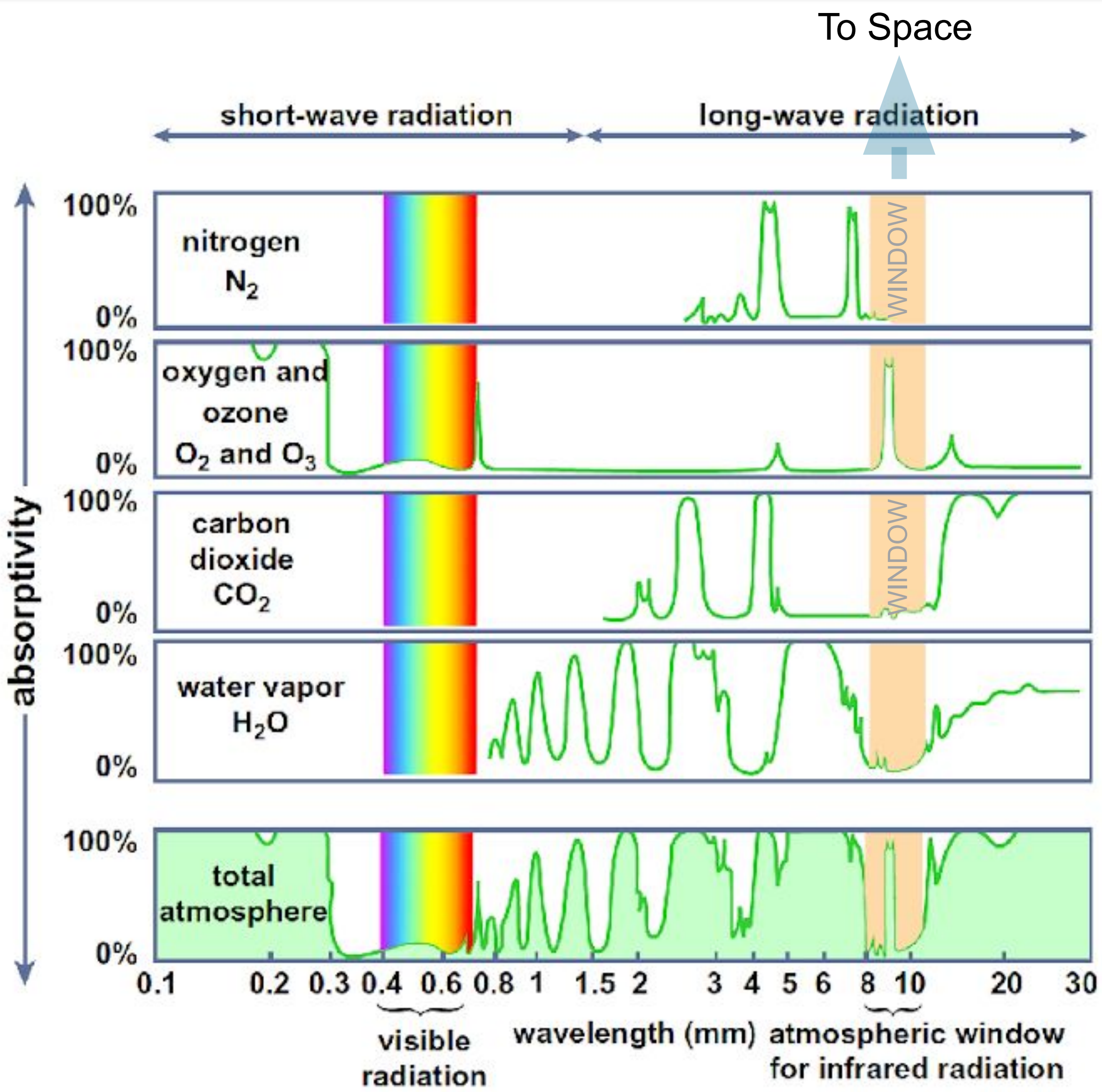
Gas	SW Absorption (Wm^{-2})
CO_2	1
O_2	2
O_3	14
H_2O	43

+Condensed species: Clouds & Aerosols

Not Important for ~weeks forecast!

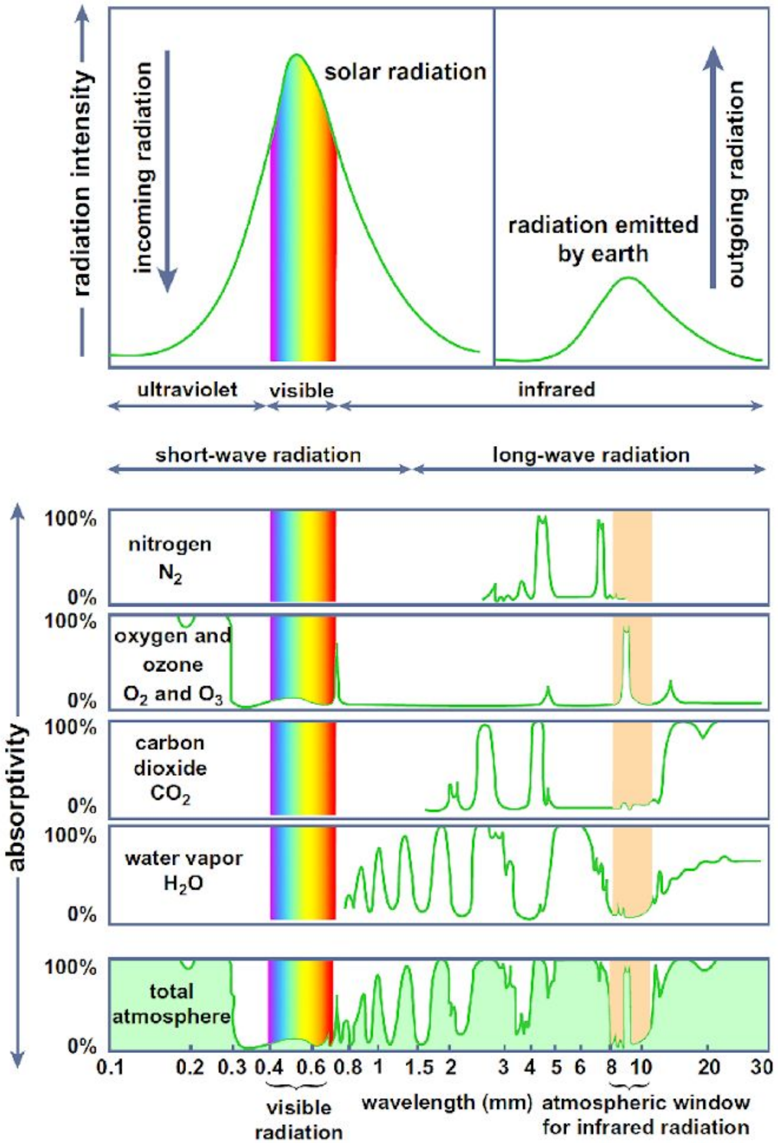
Atmospheric Radiation Absorption

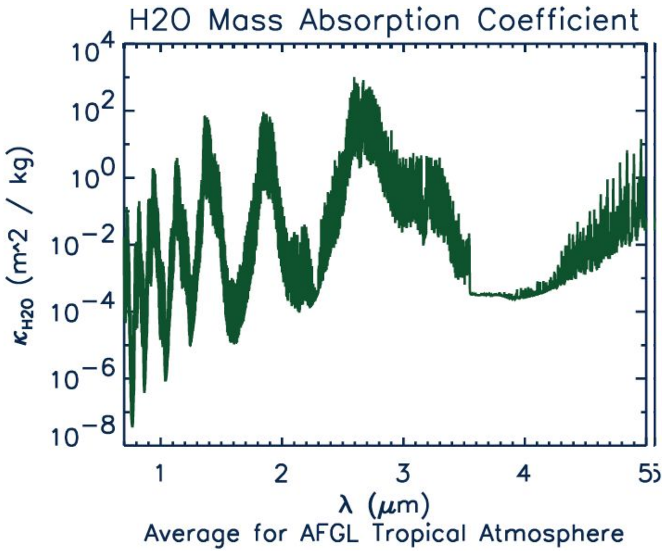


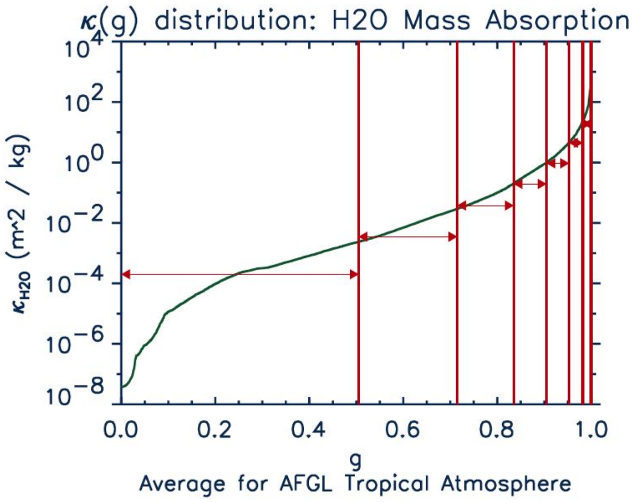


Need to capture for gaseous SW and LW absorption
Need to account for clouds
Need to account for aerosols

Radiation Approaches







Line-by-line calculations

Very expensive/slow, accurate

Rapid Radiative
Transport Model
(RRTM)
Iacono et al. 2000
CAM5/CAM6

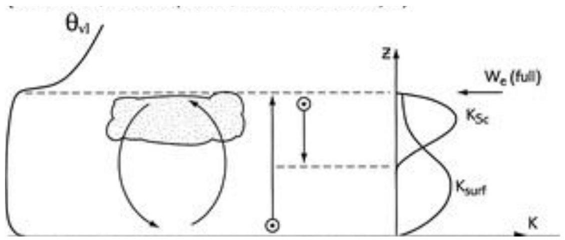
k-distribution band model, sort absorption coefficients by magnitude

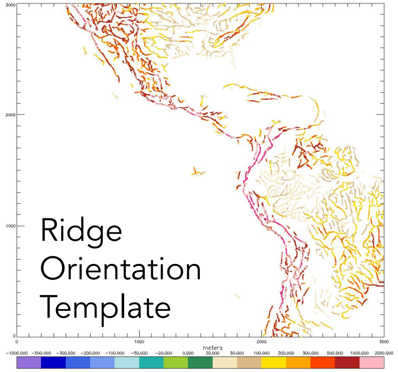
Cheaper/fast, less accurate

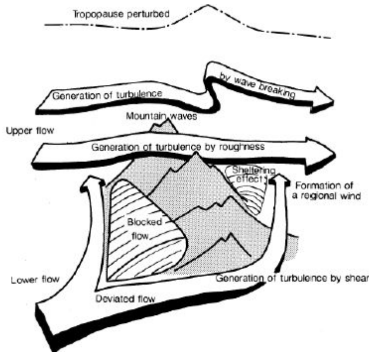
Gravity Waves and Mountain Stresses

- Boundary Layers
  - Richardson number based mixing
  - <<1, flow becomes turbulent
  - CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)
  - CAM6: Different: 3 slides time
- Gravity Wave Drag
  - Generated by surface orography (mountains), deep convection, frontals systems
  - Greatest impacts above tropopause (WACCM – later presentation)
- Turbulent mountain stress
  - Local near-surface stress on flow based on stability
  - Impacts mid/high-latitude flow
  - Applied over physical based height scales (Beljaars et al 2004)

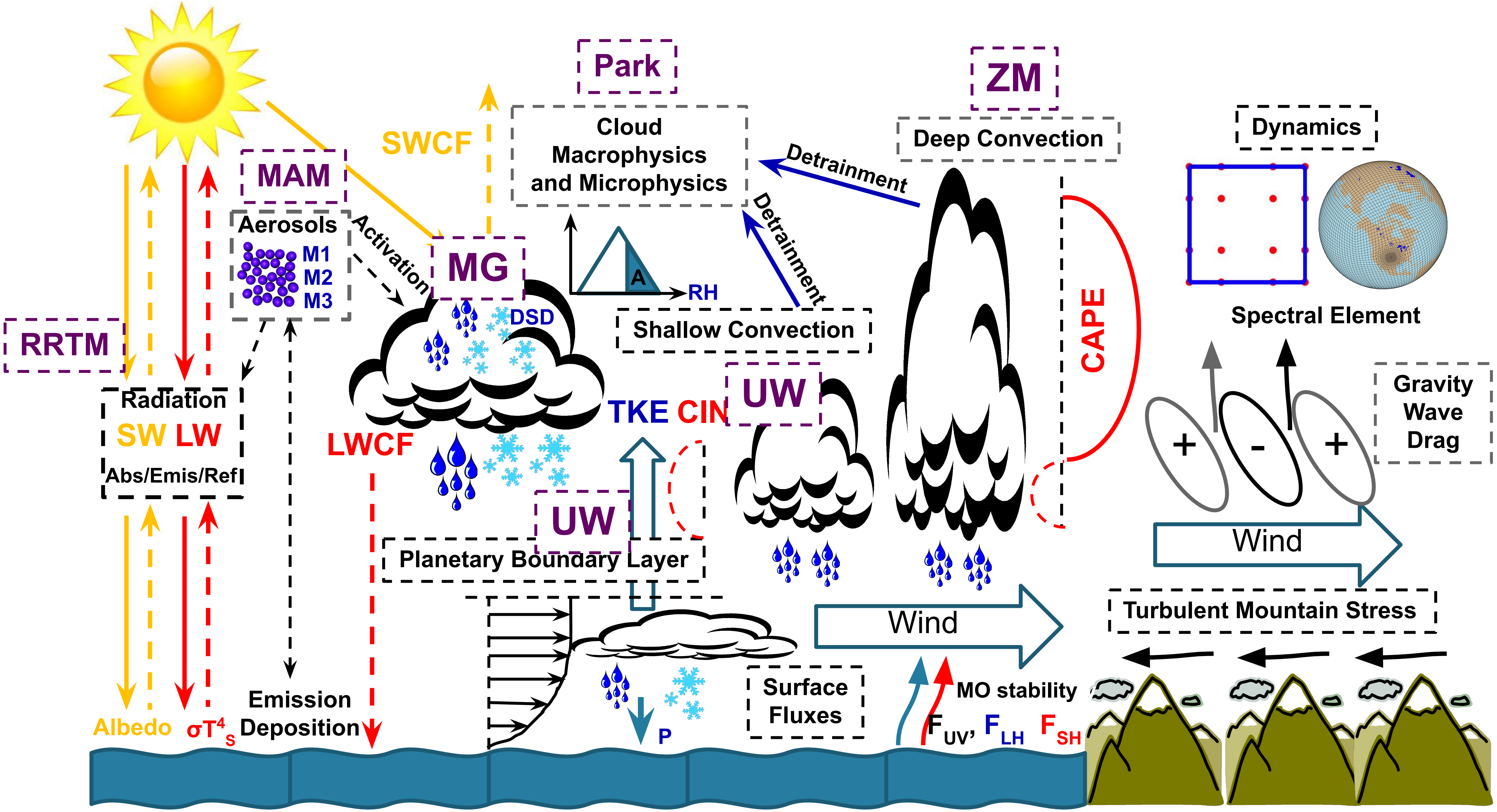
More difficult to parameterize than thermodynamic impacts (conservation?)



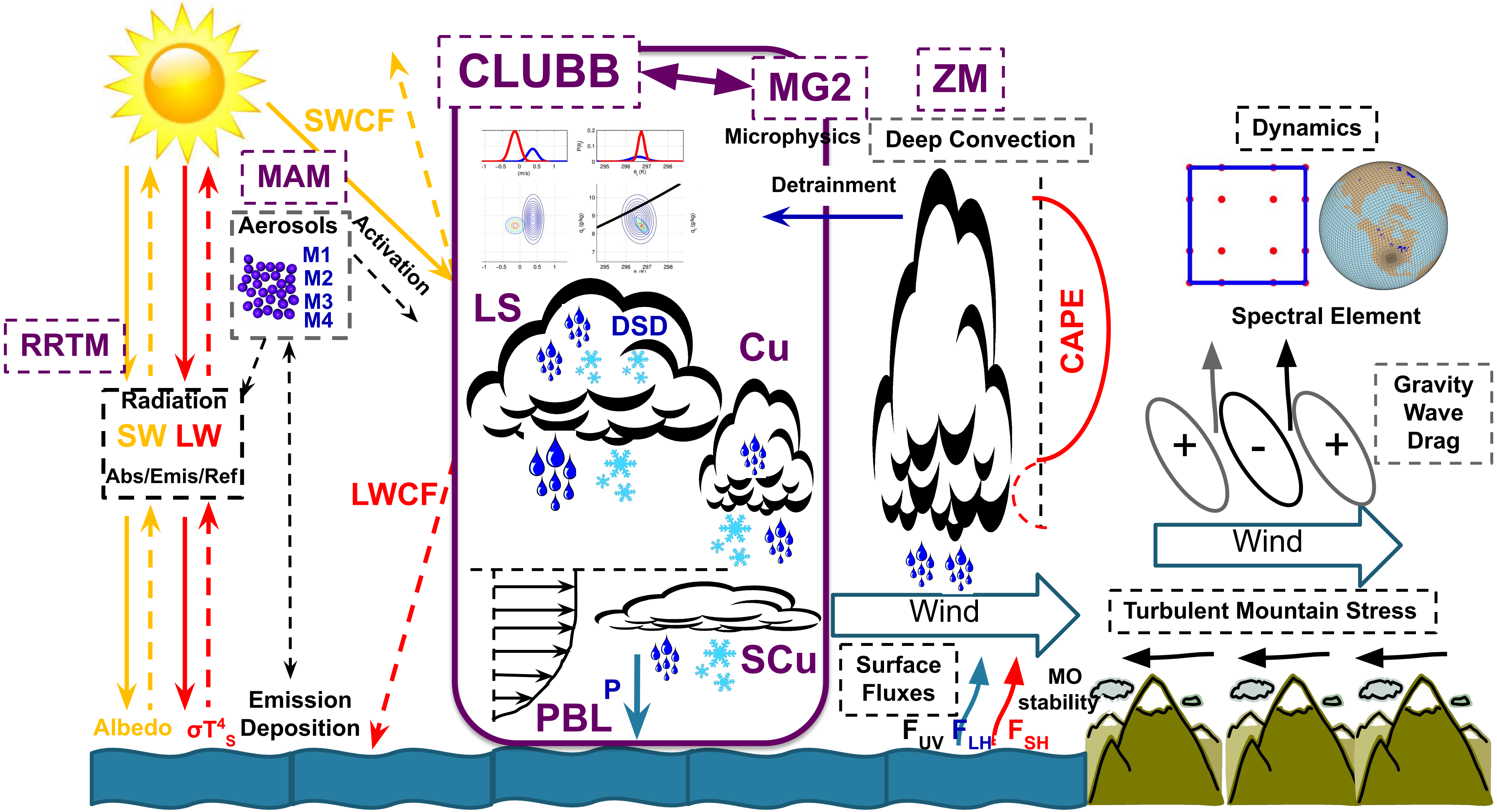

Ridge Orientation Template



Community Atmosphere Model (CAM5)

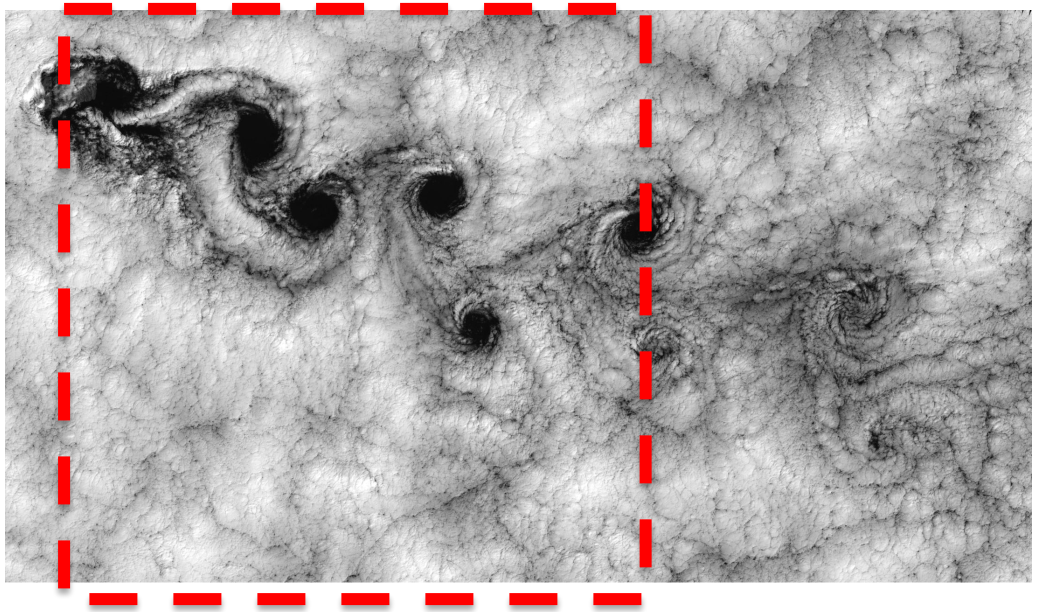


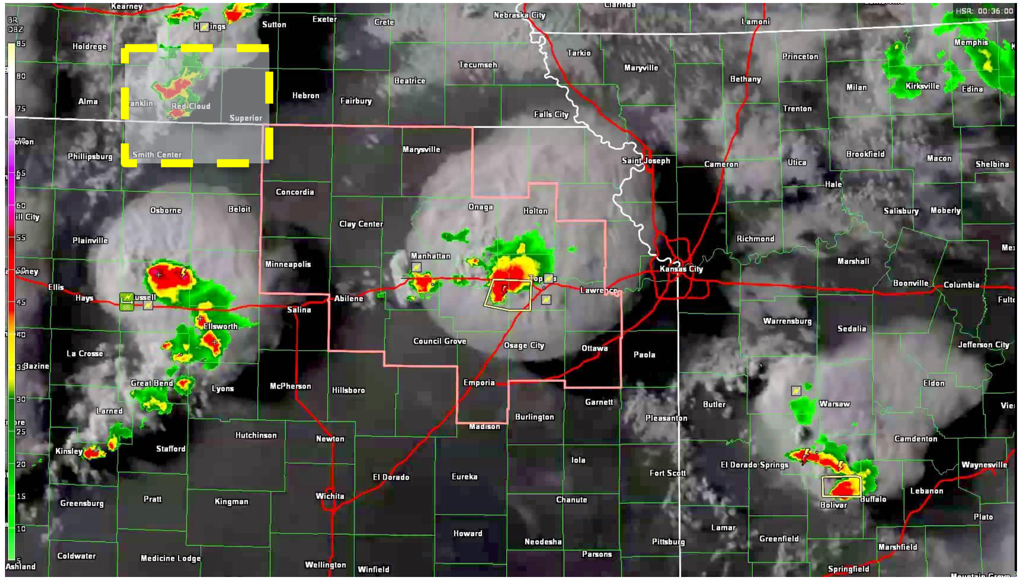
Community Atmosphere Model (CAM6)



Explicitly Representing Variability

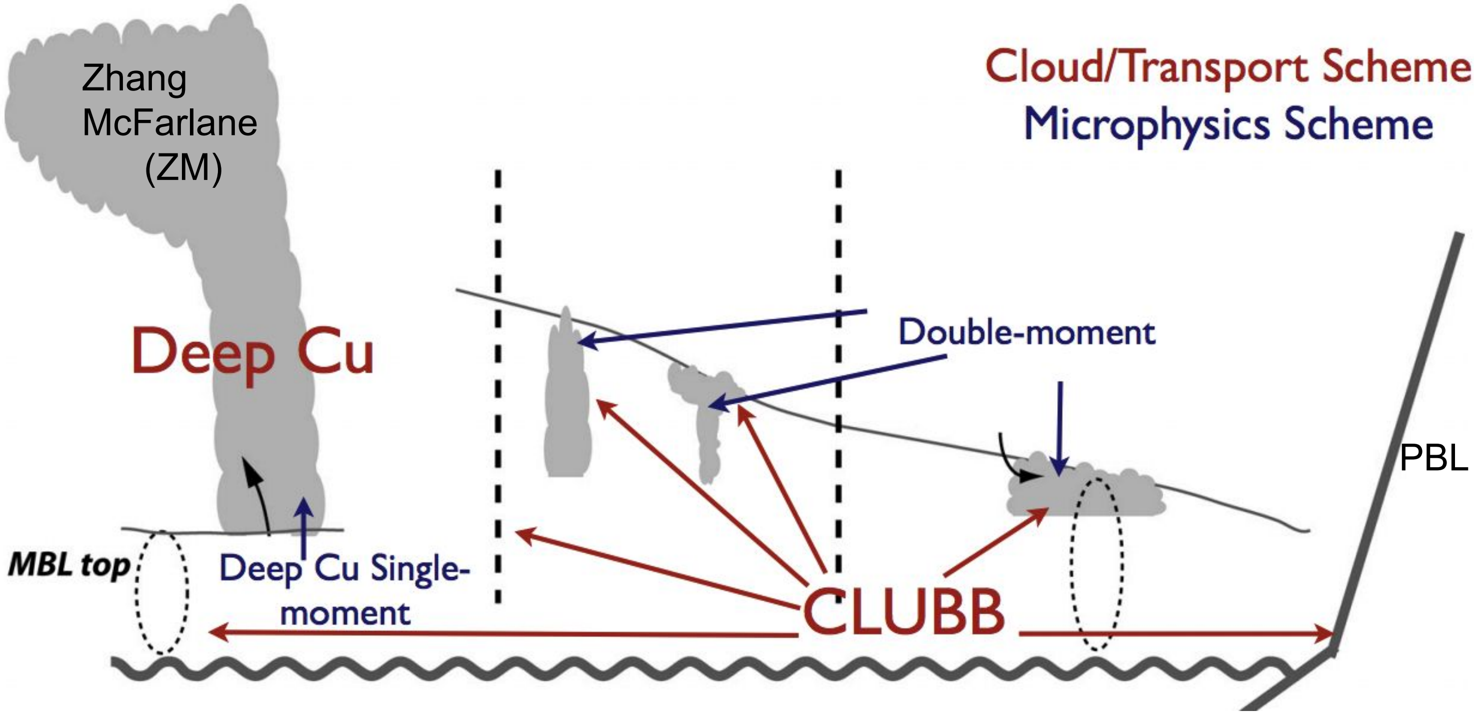
Can we represent continuous variability (water, temperature, momentum) in a parameterization?





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

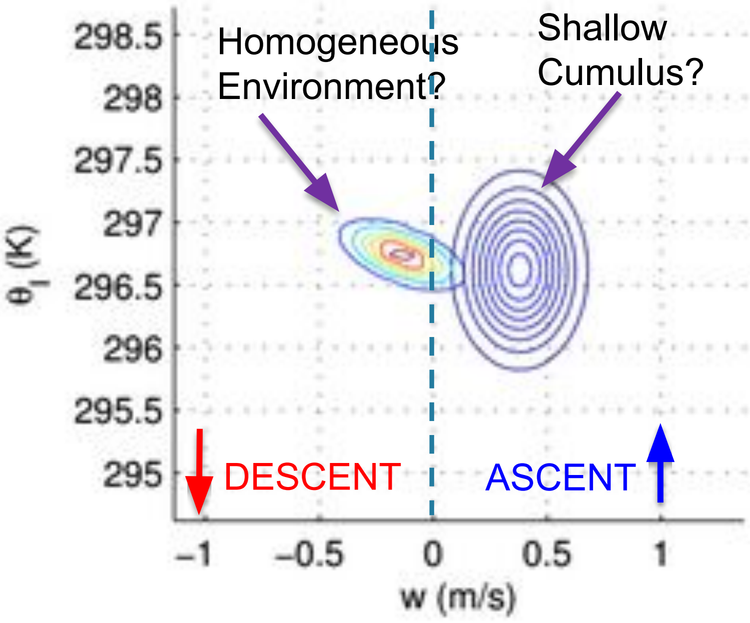
- Predict joint PDFs of vertical velocity, temperature and moisture
- Assume double Gaussians can reflect a number of cloudy regimes
- Predict grid box means and higher-order moments
- Transport, generate, and dissipate mean moments (w'^2,$w'q_L'$, $w'q_L'$)

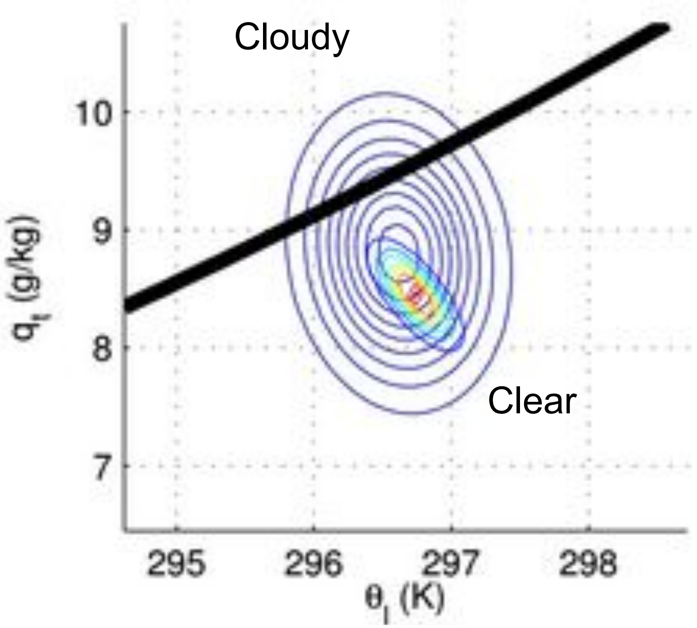
$$\frac{\partial \overline{w'\theta_l'}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{w'\theta_l'}}{\partial z}}_{ma} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^2\theta_l'}}{\partial z}}_{ta} \underbrace{-\overline{w'^2}\frac{\partial \overline{\theta_l}}{\partial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

$$\underbrace{-\frac{C_6}{\tau}\overline{w'\theta_l'}}_{pr1} \underbrace{+C_7\overline{w'\theta_l'}\frac{\partial \overline{w}}{\partial z}}_{pr2} \underbrace{-C_7\frac{g}{\theta_{vs}}\overline{\theta_l'\theta_v'}}_{pr3}$$

Vertical Heat Flux

Vertical Advection
Turbulence transport
Buoyancy production
Dissipation
Pressure related terms





Process Interaction: Climate Sensitivity

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

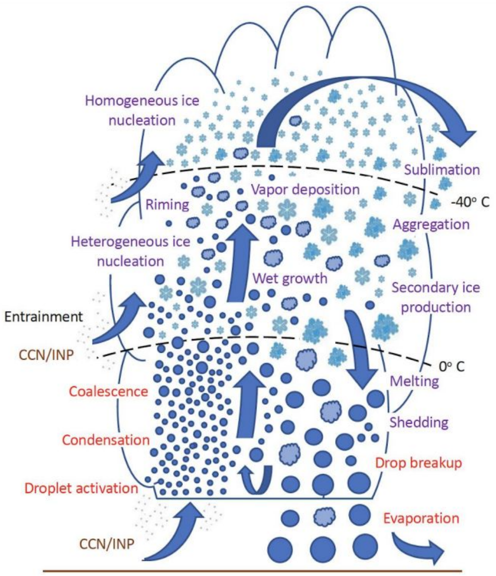
GFDL Model **+4.2K**

NCAR Model **+1.8K**

Change in low cloud amount (%)

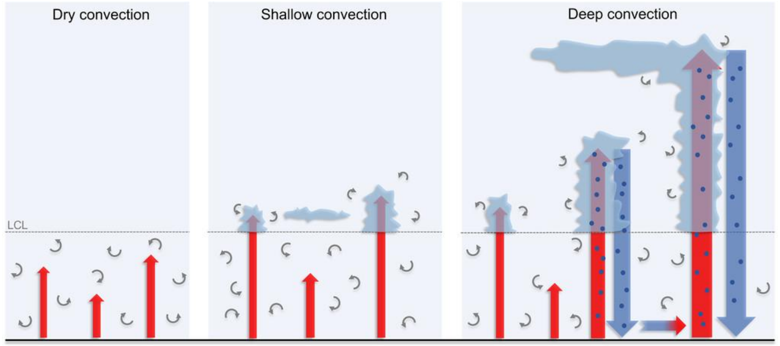
- Significant range in low-cloud sensitivity (low and high end of models)
- Cloud regimens are largely oceanic stratocumulus (difficult to model)
- Implied temperature change is due to (higher/lower) solar radiation reaching the ground because of clouds feedbacks.

Model physics: Alternatives and The future

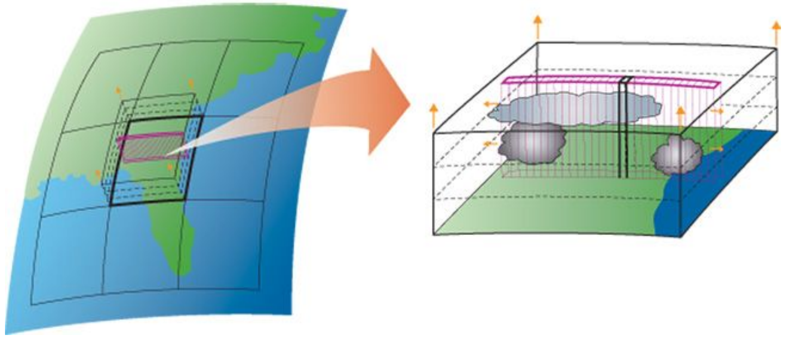


More comprehensive processes

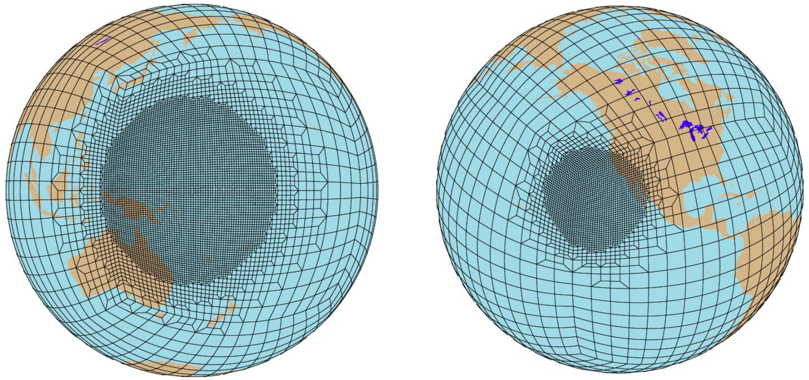
CLUBB --> CLUBB-MF



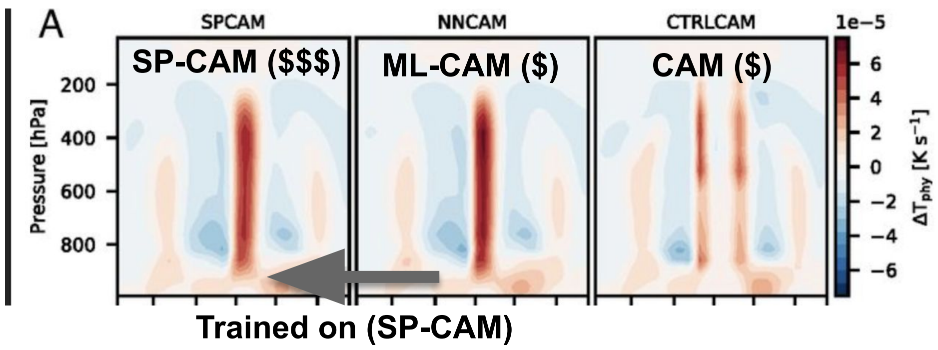
More consistent and continuous processes



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

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

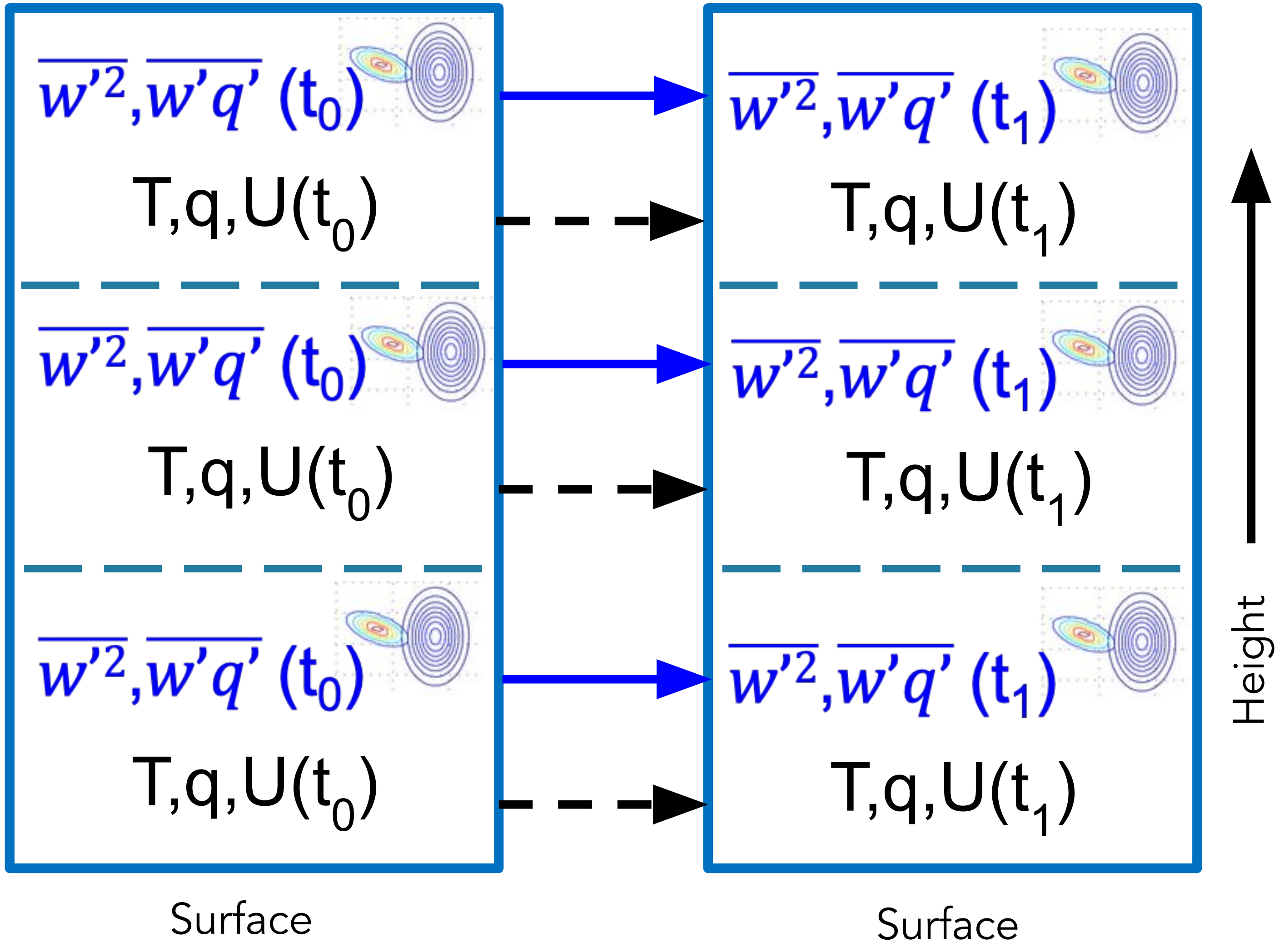
- CESM physics increasingly complex and comprehensive (CLUBB)
- Future parameterizations aim to be process scale-aware and continuous

Questions?

Thanks!

CLUBB: A New Approach

- Conventionally only 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



$\overline{w'^2},\overline{w'q'}\ (t_0)$

$T,q,U(t_0)$

$\overline{w'^2},\overline{w'q'}\ (t_0)$

$T,q,U(t_0)$

$\overline{w'^2},\overline{w'q'}\ (t_0)$

$T,q,U(t_0)$

Surface

$\overline{w'^2},\overline{w'q'}\ (t_1)$

$T,q,U(t_1)$

$\overline{w'^2},\overline{w'q'}\ (t_1)$

$T,q,U(t_1)$

$\overline{w'^2},\overline{w'q'}\ (t_1)$

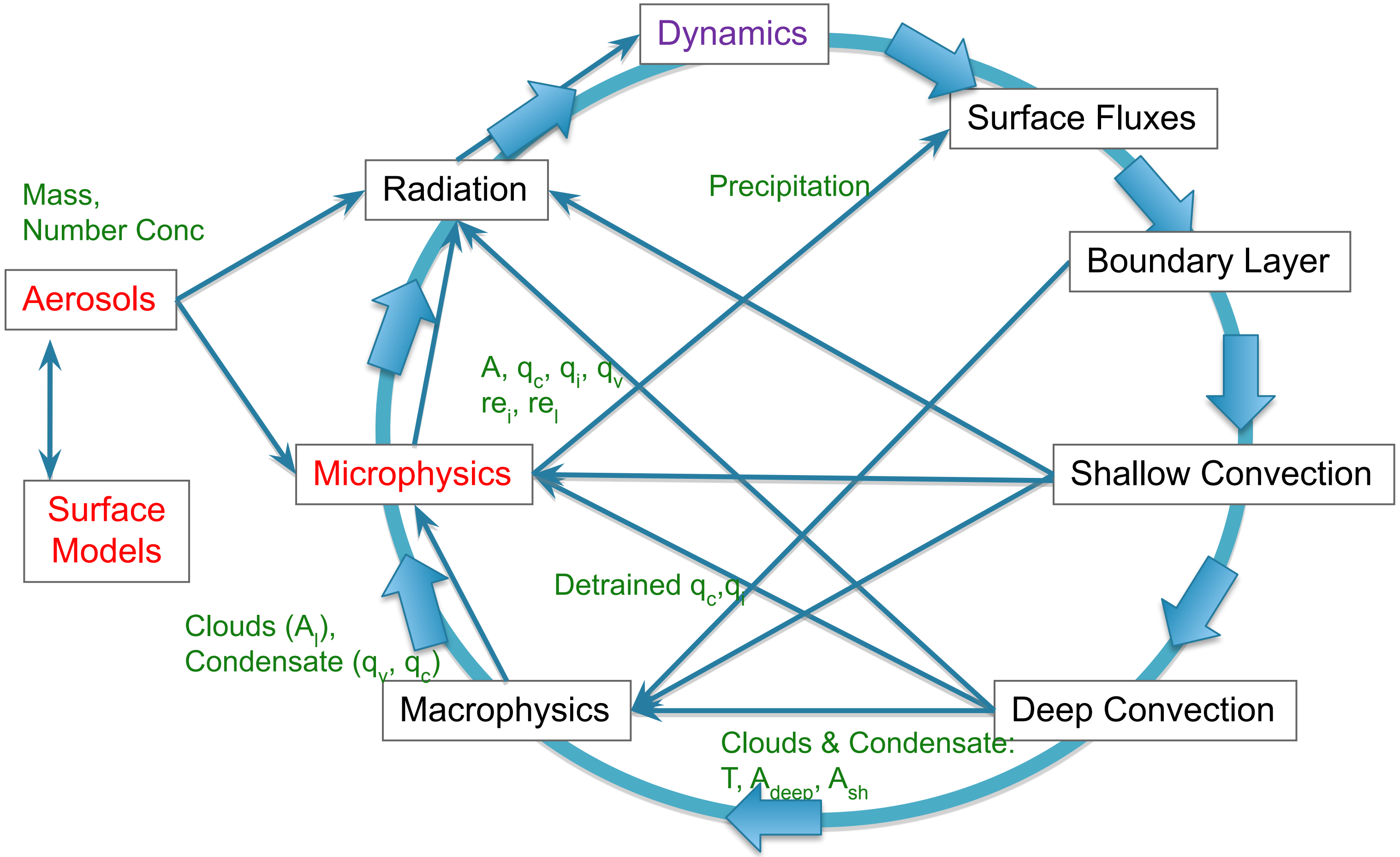
$T,q,U(t_1)$

Surface

Height

Timestep Loop

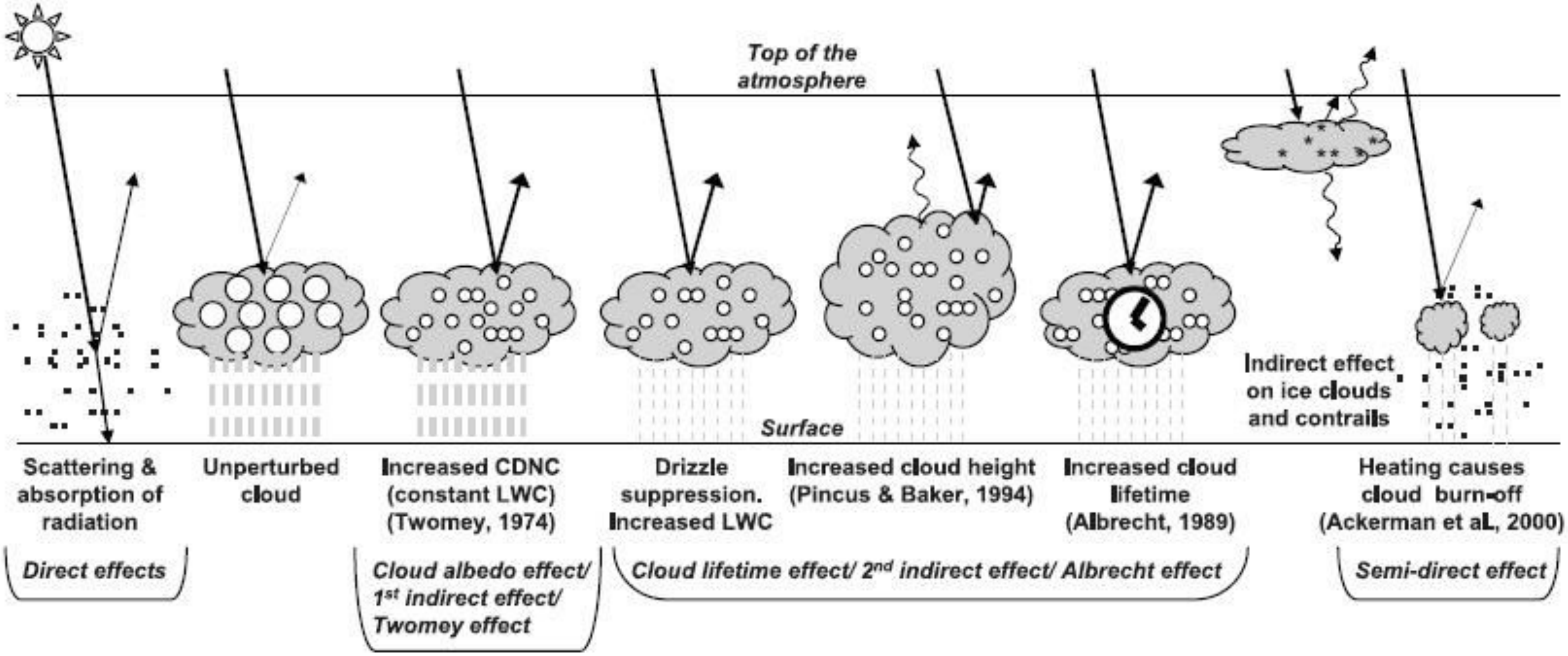
Community Atmosphere Model (CAM) Version 5



A = cloud fraction
$q=H_2O$
re=effective radius (size)
T=temperature

(i)ce, (l)iquid, (v)apor

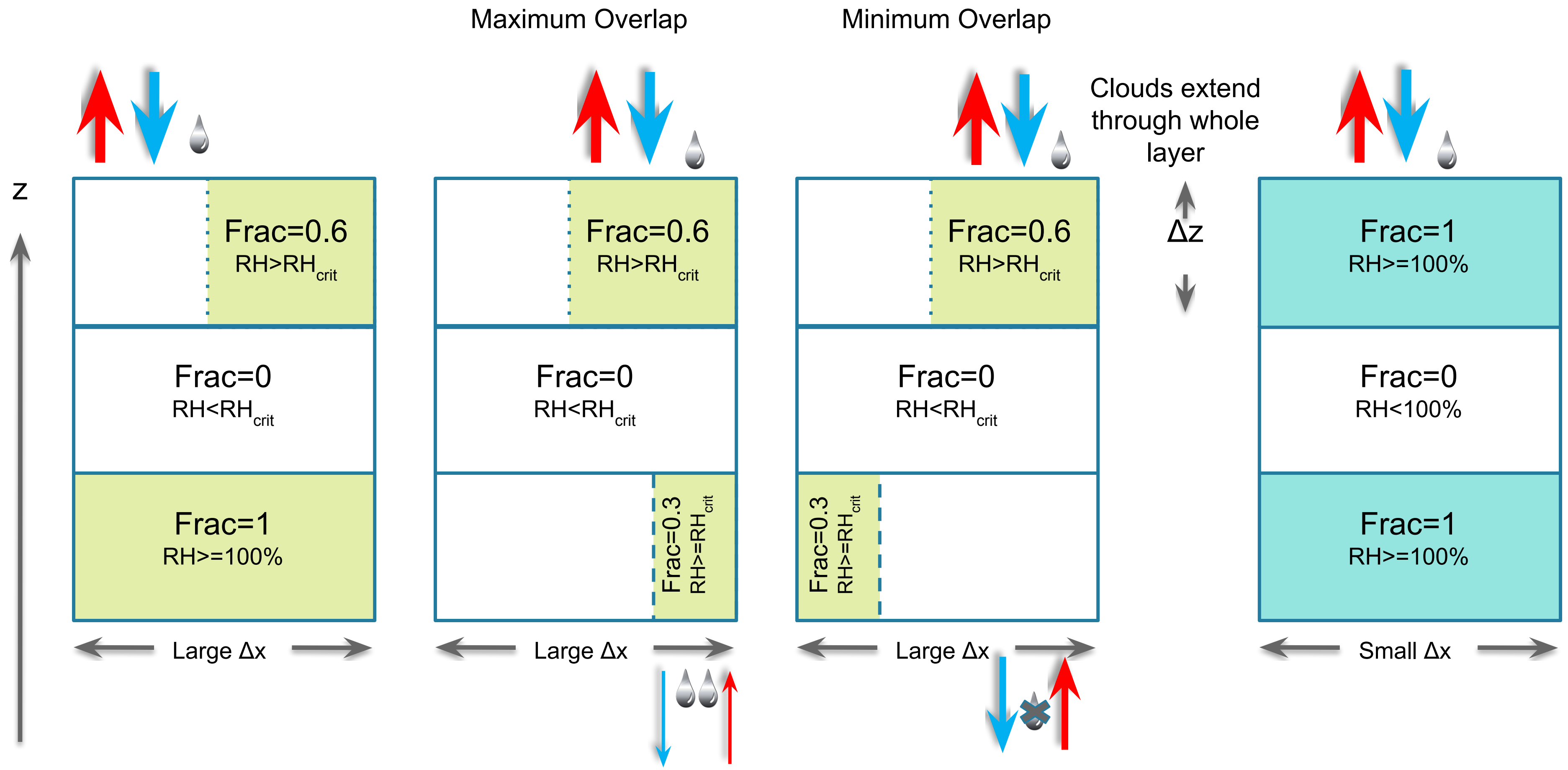
Process Interactions: Cloud, Aerosol, Radiation



IPCC, AR4

Process Interactions: The Cloud Overlap Challenge

Radiation and micro/macro-physics impact



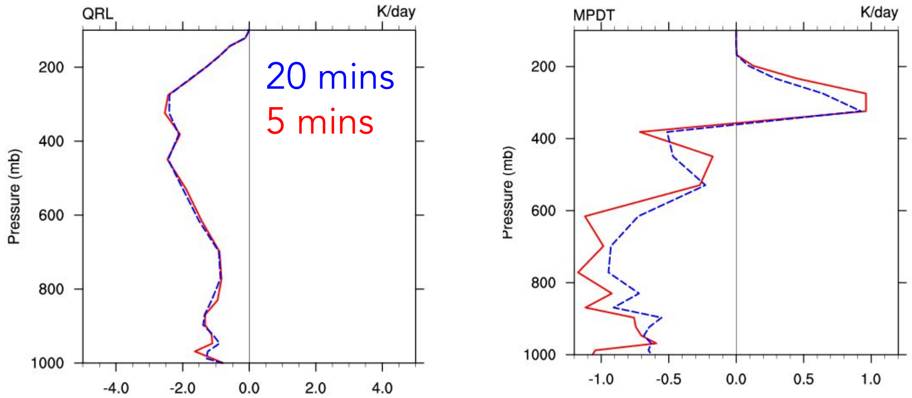
- Contiguous cloudy layers generally maximally overlapped
- Non-contiguous layers randomly overlapped; function of de-correlation length-scale

Process Interactions: Resolution Sensitivity

Time

Long Wave Heating

Microphysics Heating

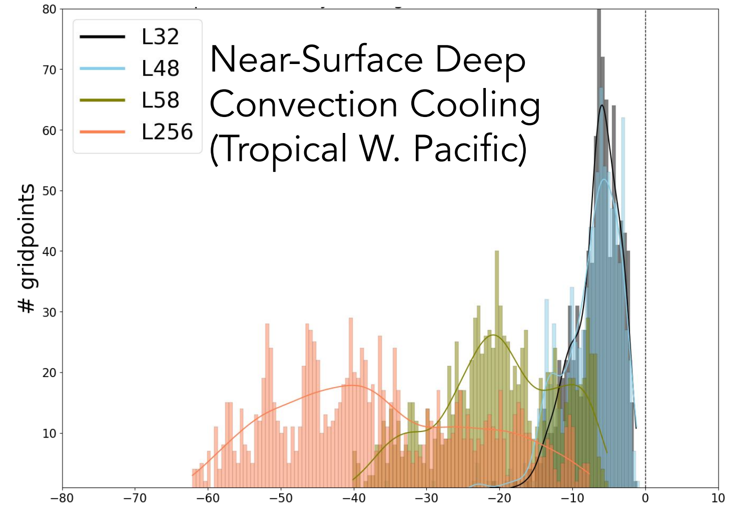


20 mins

5 mins

- 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

Vertical



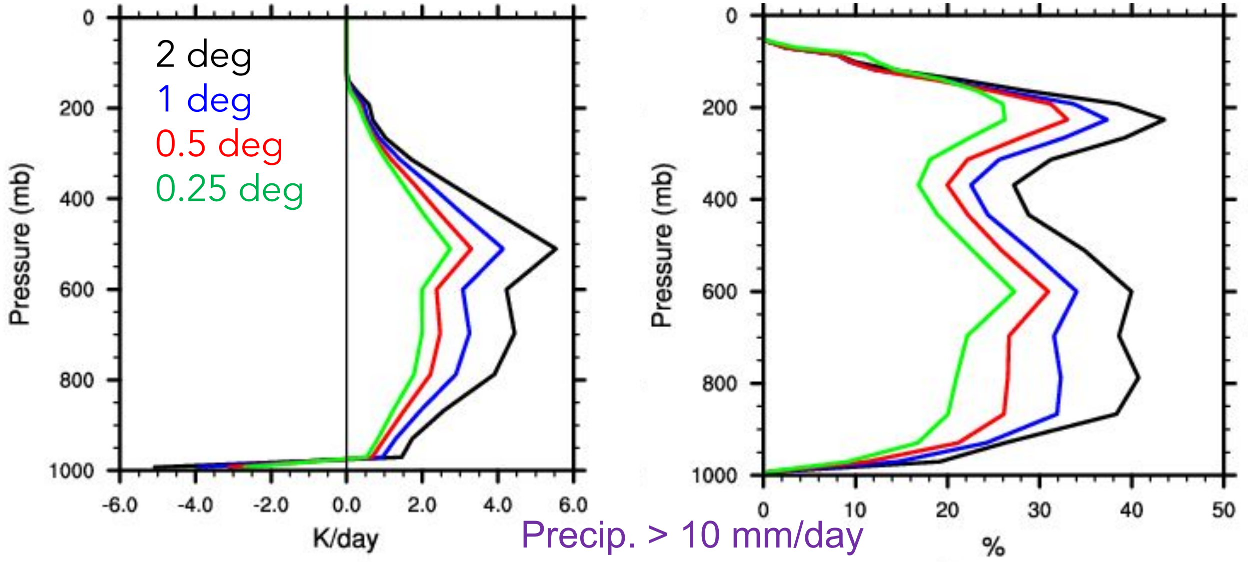
Near-Surface Deep Convection Cooling (Tropical W. Pacific)

-60 K/day

Horizontal

Deep Convection Heating

Cloud Fraction



2 deg

1 deg

0.5 deg

0.25 deg

Precip. > 10 mm/day

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							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

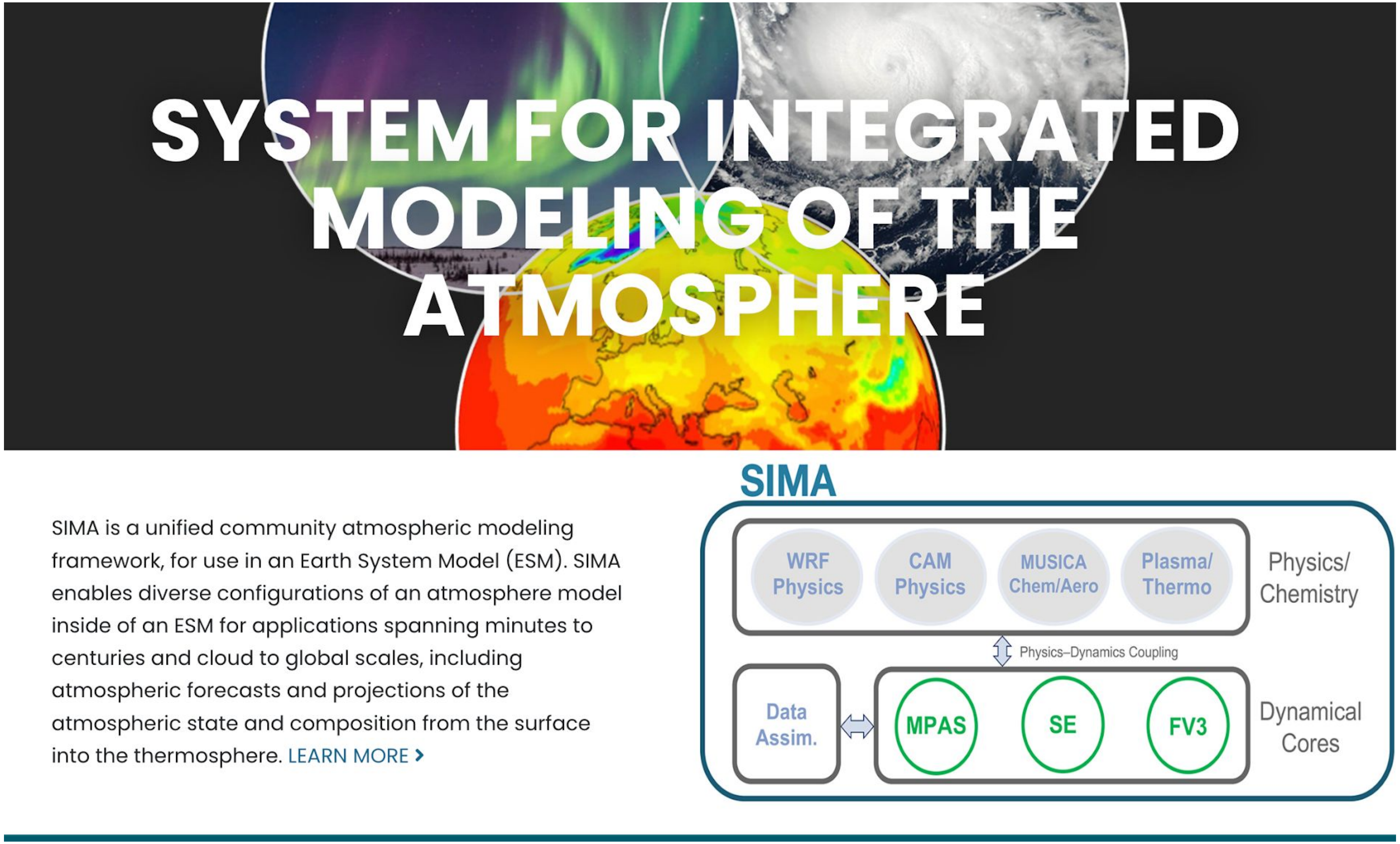
- Many options
- Rapid turnover of physics
- Evaluated as multiple 'best suites' for forecast skill regionally

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

SIMA: Common Modeling Framework



SYSTEM FOR INTEGRATED MODELING OF THE ATMOSPHERE

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/