Cloud Microphysics Across Scales for Weather and Climate

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Thanks to: H. Morrison, G. Thompson

Outline

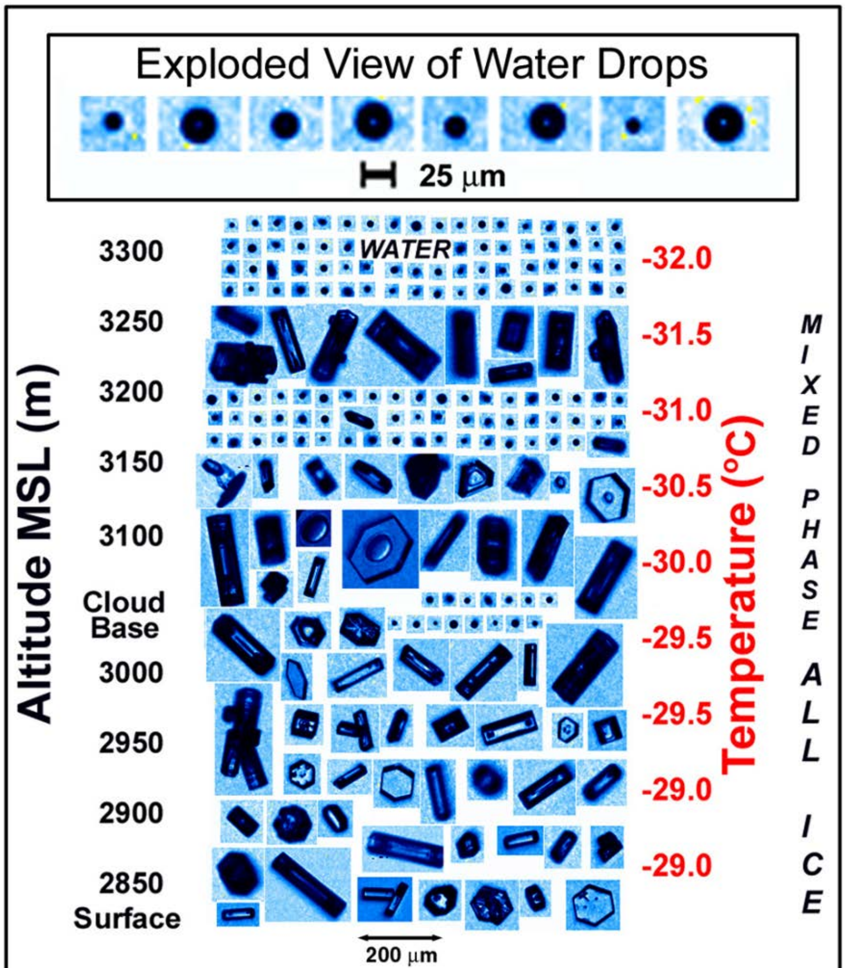
- Definition
- Motivation: cloud microphysics is critical for weather and climate
- How we simulate microphysics
- MG2 Scheme in CESM
- Latest advancements in Microphysics
- Summary

What is Cloud Microphysics?

- Define the evolution of the condensed water phases (liquid and ice)
- Includes:
  - phase determination
  - Distribution of drop and crystal sizes
  - Evolution of these species
- Inputs
  - Atmospheric State (humidity)
  - Cloud macrophysics (large scale condensation)
  - Dynamics (vertical velocity)
- Outputs
  - Definitions and tendencies for condensed phase.

Motivation: 12 orders of Magnitude

10^{-6}m → 10^{6}m



Lawson & Gettelman, PNAS (2014)

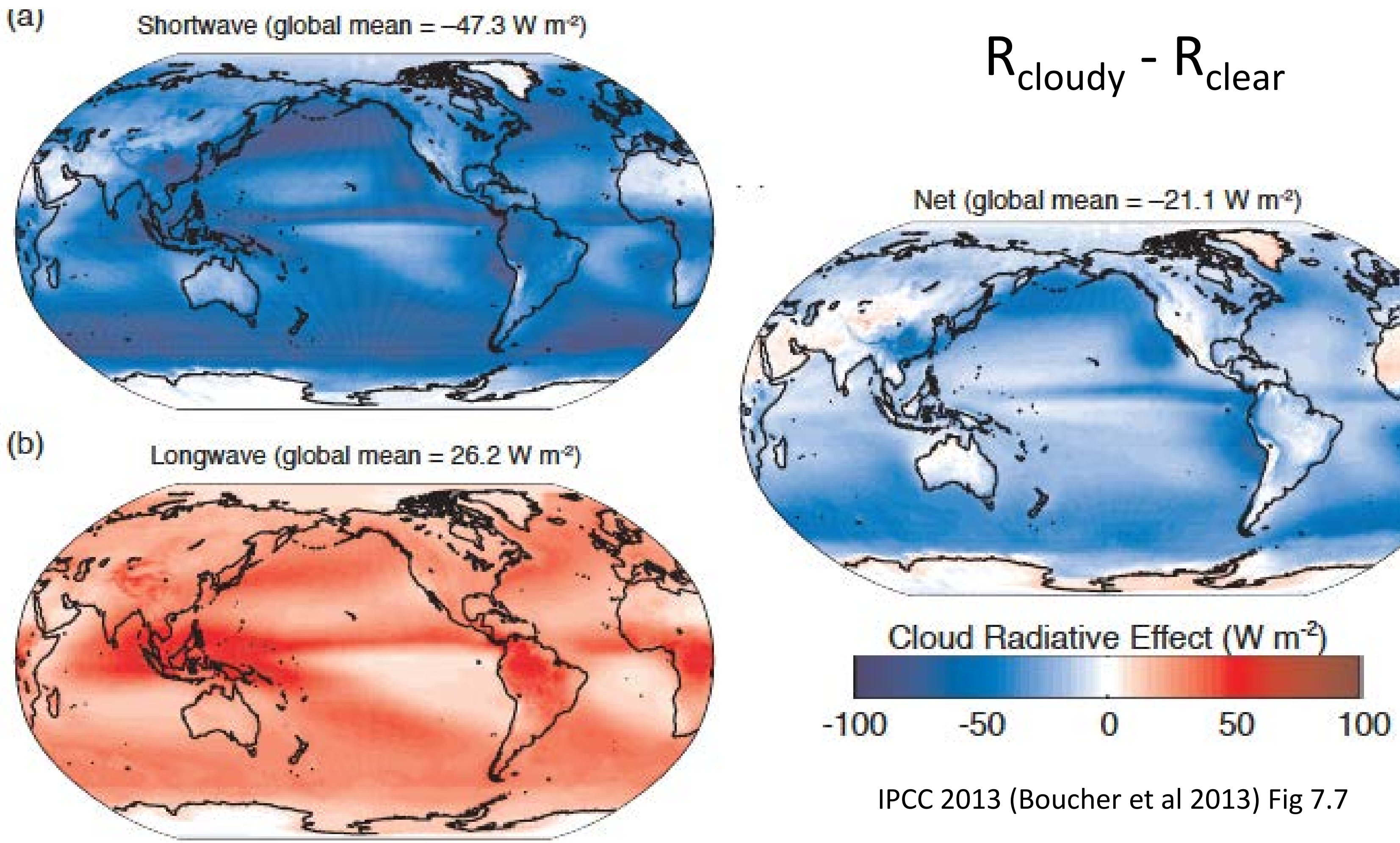
← $1.2\text{x}10^{7}$m →

Microphysics and Weather

- Clouds are responsible for most severe weather
  - Tornadoes, Thunderstorms, Hail, Tropical Cyclones
- Many of these events & impacts are sensitive to microphysics
  - Latent heat
  - Condensate loading
  - Surface precipitation

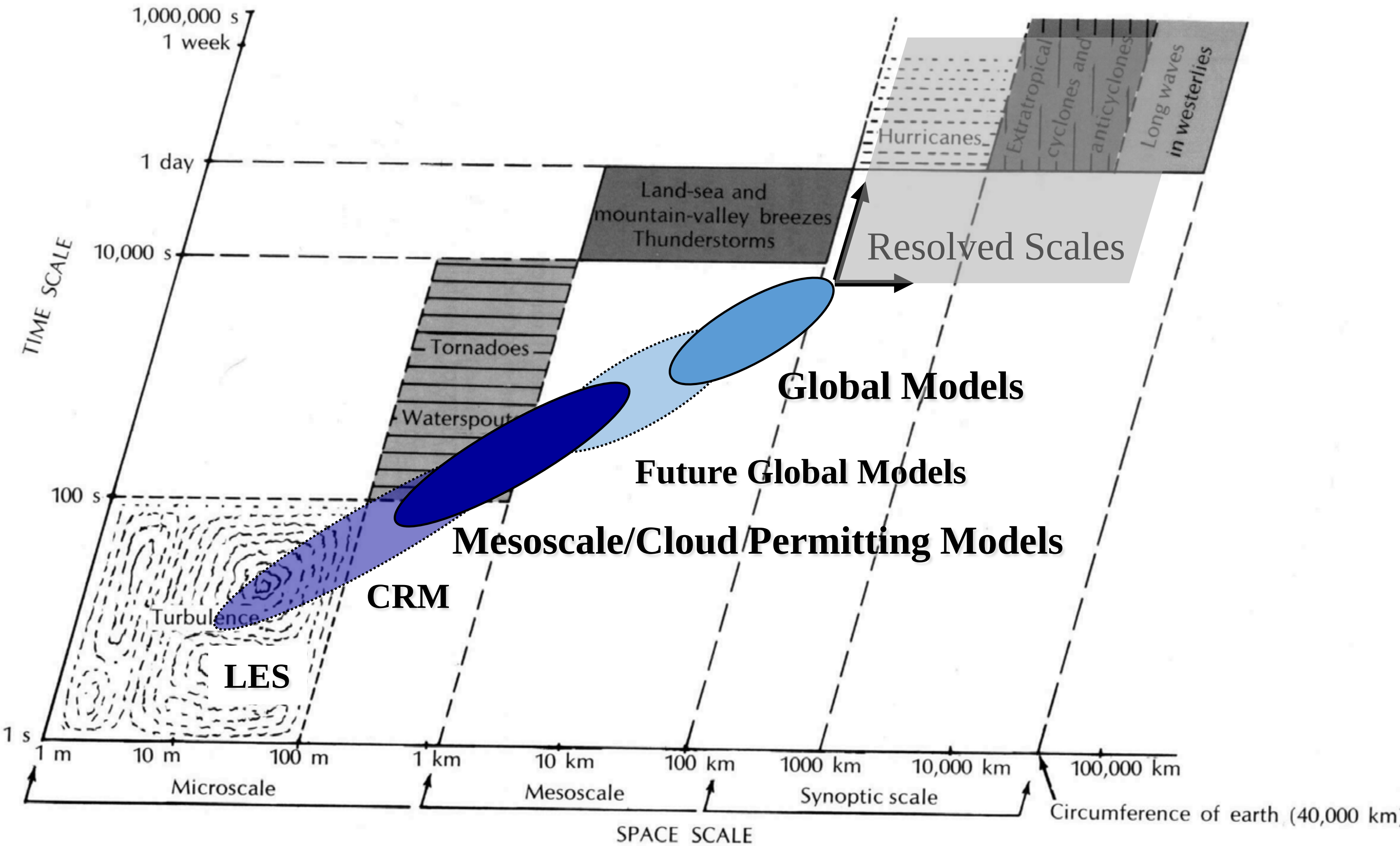
Microphysics and Climate:
Cloud Radiative Effects are Large

$R_{cloudy} - R_{clear}$



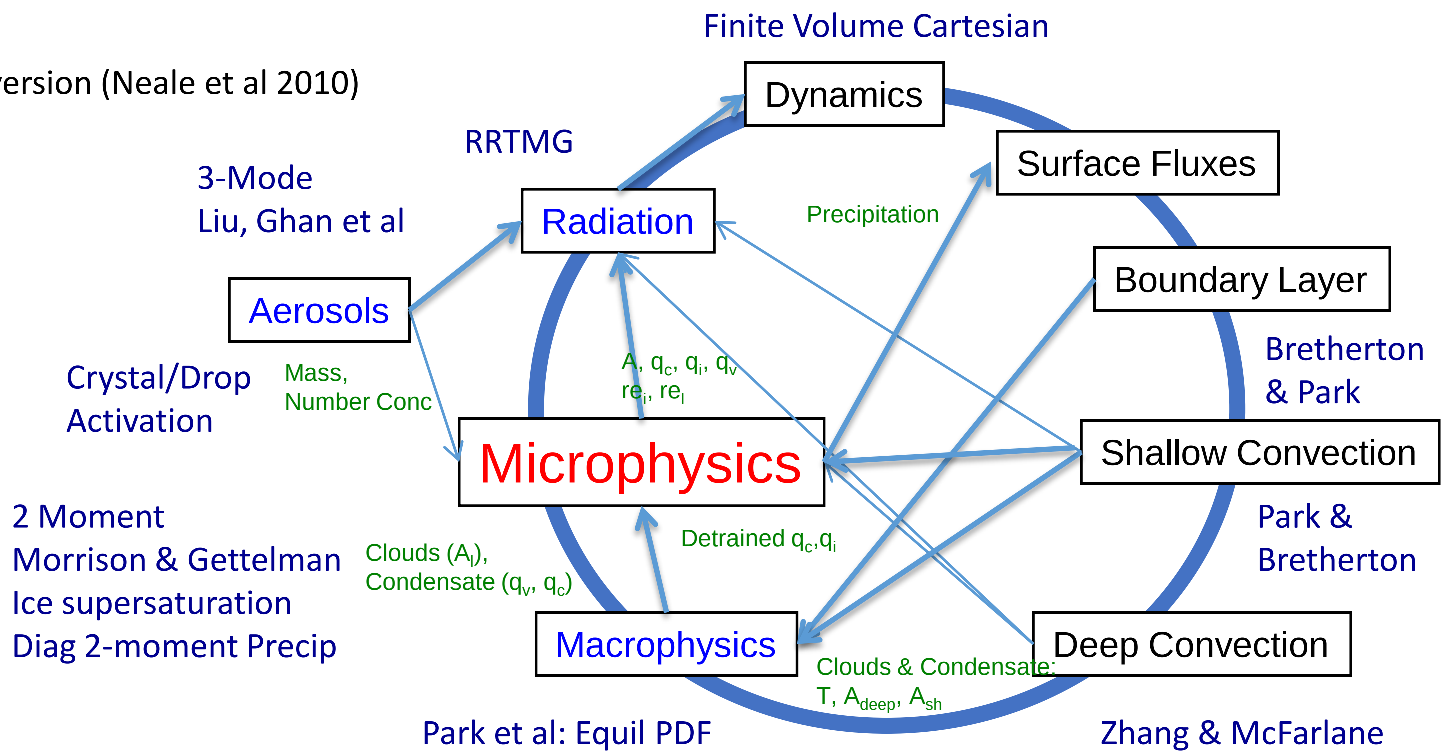
IPCC 2013 (Boucher et al 2013) Fig 7.7

Scales of Atmospheric Processes



Simulating Cloud Microphysics

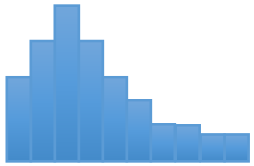
CAM5: IPCC AR5 version (Neale et al 2010)



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

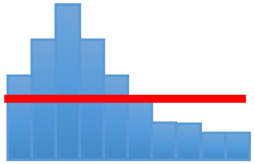
Types of Microphysical Schemes

- ‘Explicit’ or Bin Microphysics



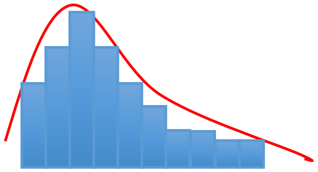
Represent the number of particles in each size ‘bin’
One species(number) for each mass bin
Computationally expensive, but ‘direct’

- Bulk Microphysics



Represent the total mass and number
Computationally efficient
Approximate processes

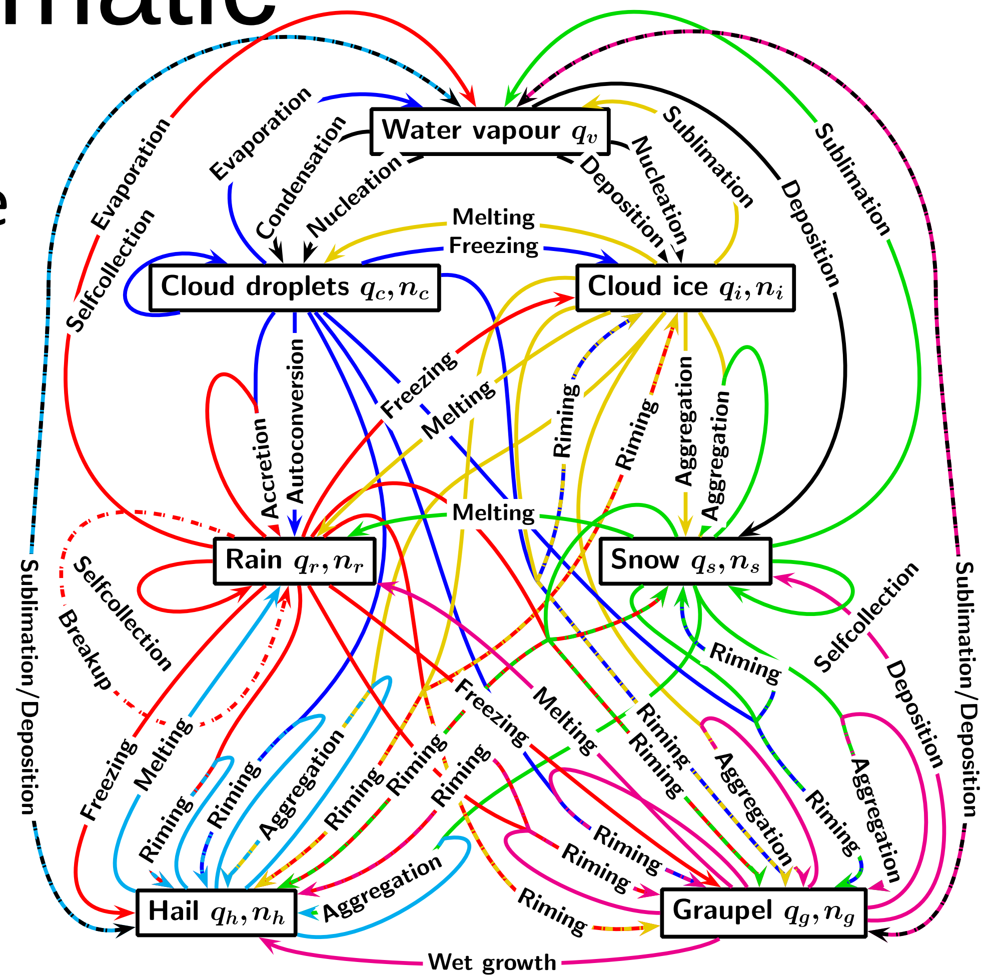
- Bulk Moment based microphysics



Represent the size distribution with a function
Have a distribution for different ‘Classes’
(Liquid, Ice, Mixed Phase)
Hybrid: functional form makes complexity possible

Ultimate Schematic

- 6 class, 2 moment scheme
- Seifert and Behang 2001
- Processes
  - Maybe a matrix better?
- Break down by processes



Seifert, Personal Communication

Cloud Microphysics: Representing 4 ‘classes’

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008

q, N
Cloud Droplets
(Prognostic)

q, N
Cloud Ice
(Prognostic)

q
Water Vapor
(Prognostic)

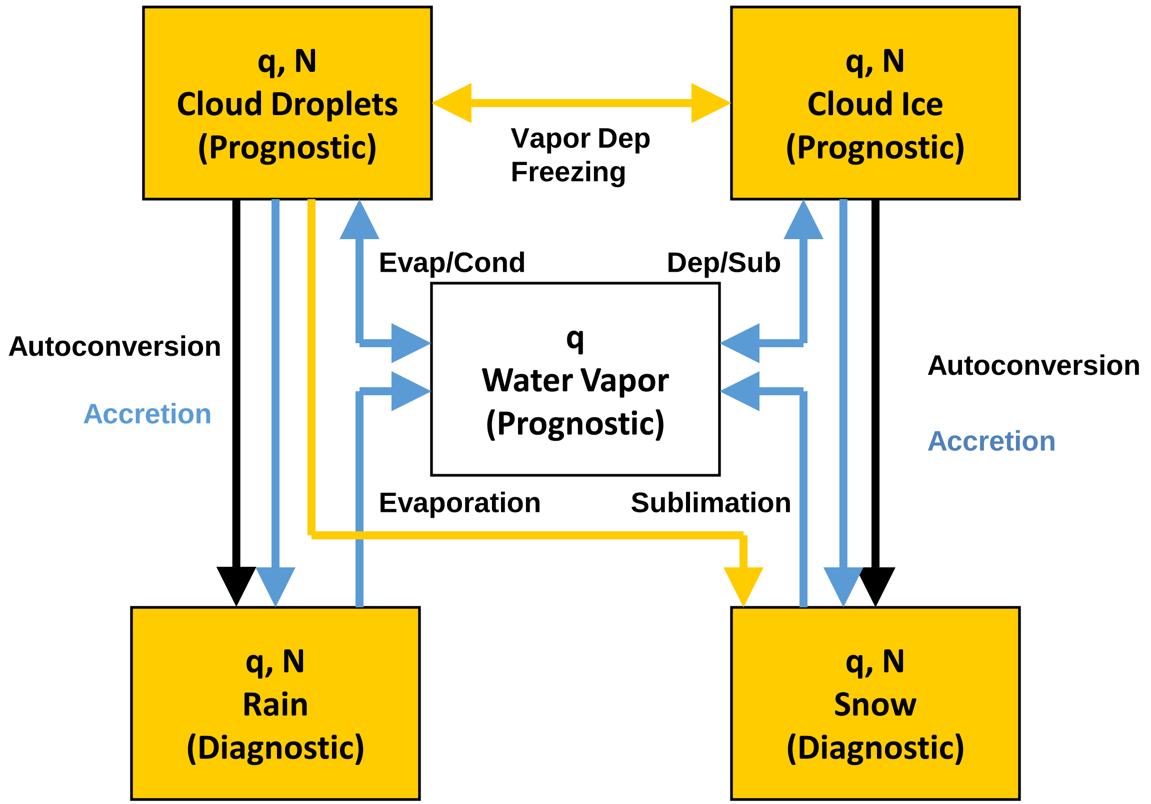
q, N
Rain
(Diagnostic)

q, N
Snow
(Diagnostic)

Transformations Between Classes

q = mixing ratio
N = number concentration

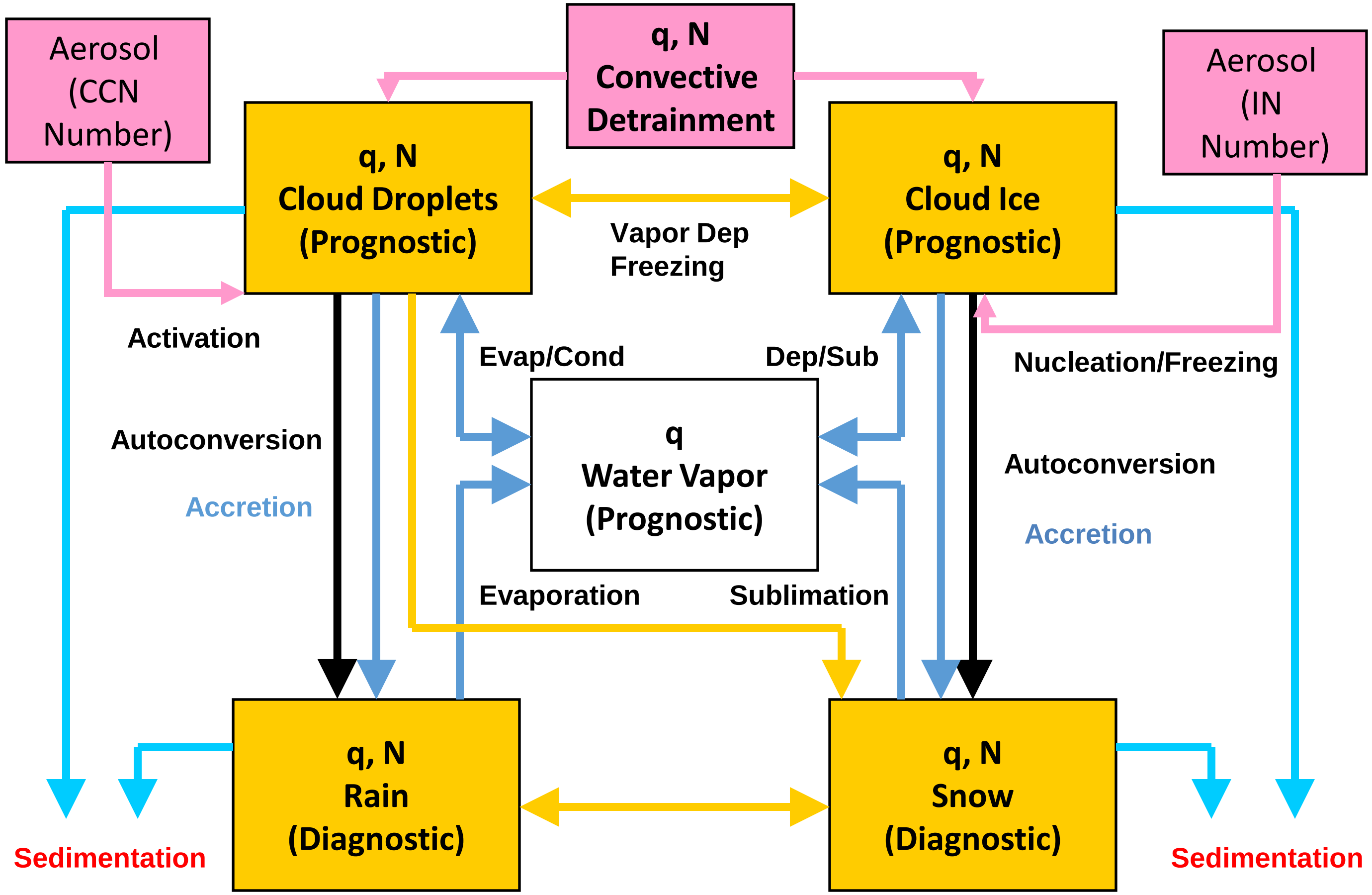
Morrison & Gettelman 2008



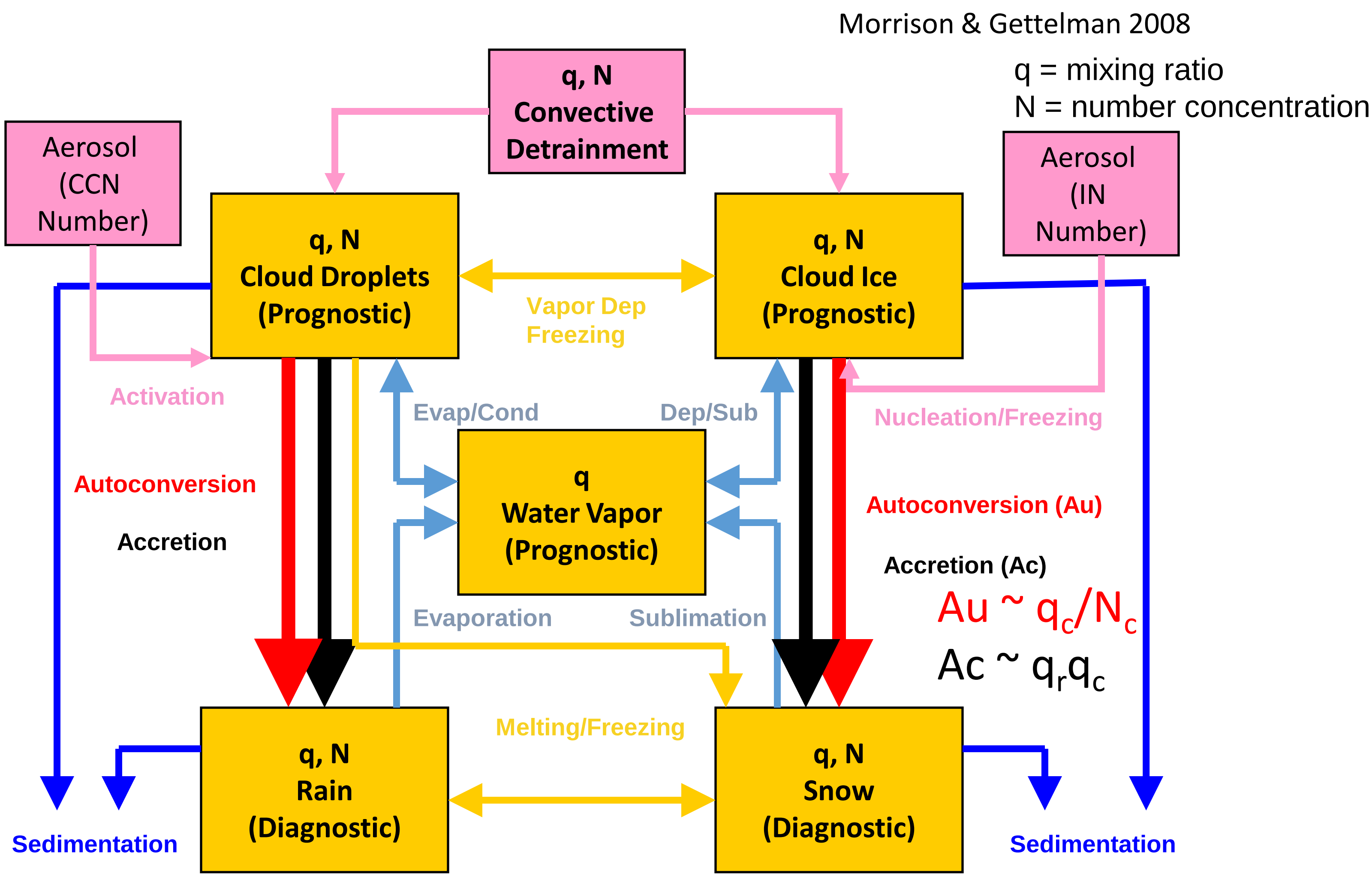
Sources & Sinks: Aerosols

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008



Important Processes



Key MG2 Features

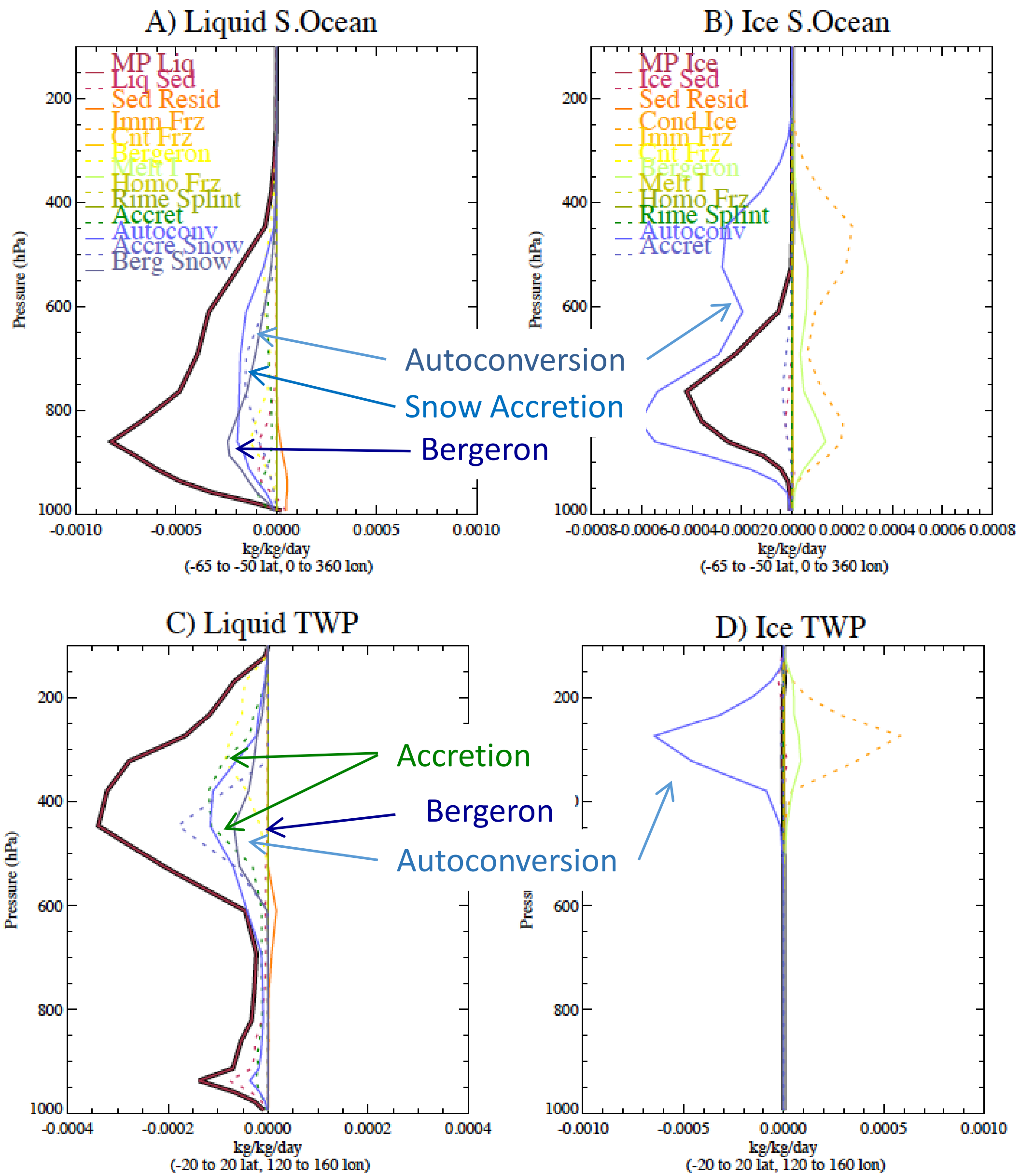
- Based on Morrison et al 2005 mesoscale scheme
- Bulk 2-moment (gamma functions)
- Prognostic Precipitation
- Conservative
- Aerosol aware (or not)
- Ice supersaturation (condensation closure on liquid, ice nucleation)
- Include sub-grid variance (or not)
- Modular: process rates are subroutines
  - Easy to modify
  - Flexible (model-agnostic), open source
- Efficient: Optimized by professionals

Microphysical Process Rates

S. Ocean

Autoconversion and Accretion are critical

Bergeron process is also important for cold clouds



Tropical W. Pacific

Auto-conversion (Ac) & Accretion (Kc)

Khairoutdinov & Kogan 2000: regressions from LES experiments with explicit bin model

Ac = $$\left(\frac{\partial q_r}{\partial t}\right)_{\text{auto}} = 1350 q_c^{2.47} N_c^{-1.79}, \qquad (29)$$

Kc= $$\left(\frac{\partial q_r}{\partial t}\right)_{\text{accr}} = 67 (q_c q_r)^{1.15}. \qquad (33)$$

- Auto-conversion an inverse function of drop number
- Accretion is a mass only function

Balance of these processes (sinks) controls mass and size of cloud drops

Problem: sub-grid varaibility

Autoconversion and Accretion

- If cloud water has sub-grid variability, then the process rate will not be constant.
- Autoconversion/accretion: depends on co-variance of cloud & rain water
- Assuming a distribution (log-normal) a power law $M=ax^b$ can be integrated over to get a grid box mean M

$$\bar{M} = \int ax^b P(x)dx = E[v_x, b]a\bar{x}^b$$

$$E[v_x, b] = \left(1 + \frac{1}{v_x}\right)^{\frac{b^2-b}{2}}$$

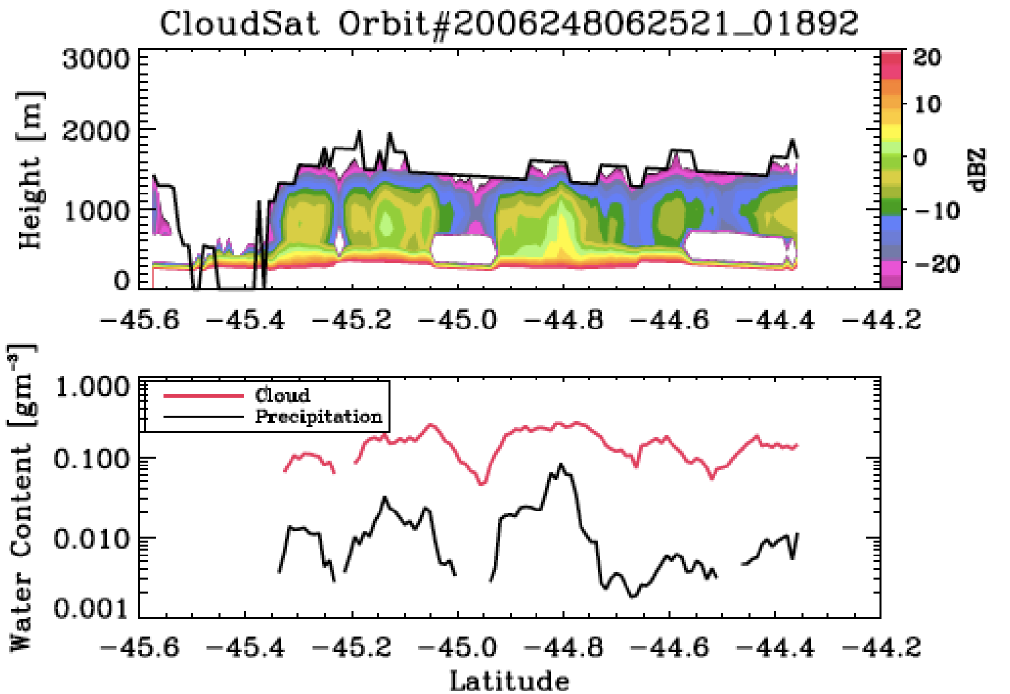
E = Enhancement factor

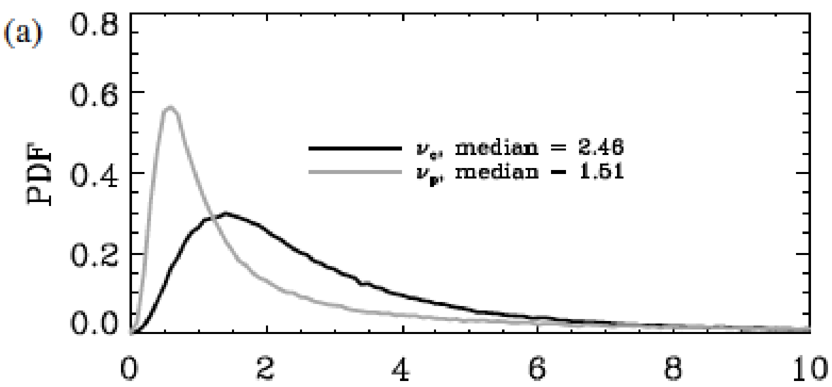
and v_x is the normalized variance $v_x = x^2/\sigma^2$

E.g.: Morrison and Gettelman 2008, Lebsock et al 2013

Observing co-variance

- Can be observed from satellites (CloudSat)
- Calculate variance, mean and normalized variance (*ν*) or homogeneity
- Yields observational estimate of Ac & Au enhancement factors.





Lebsock et al 2013

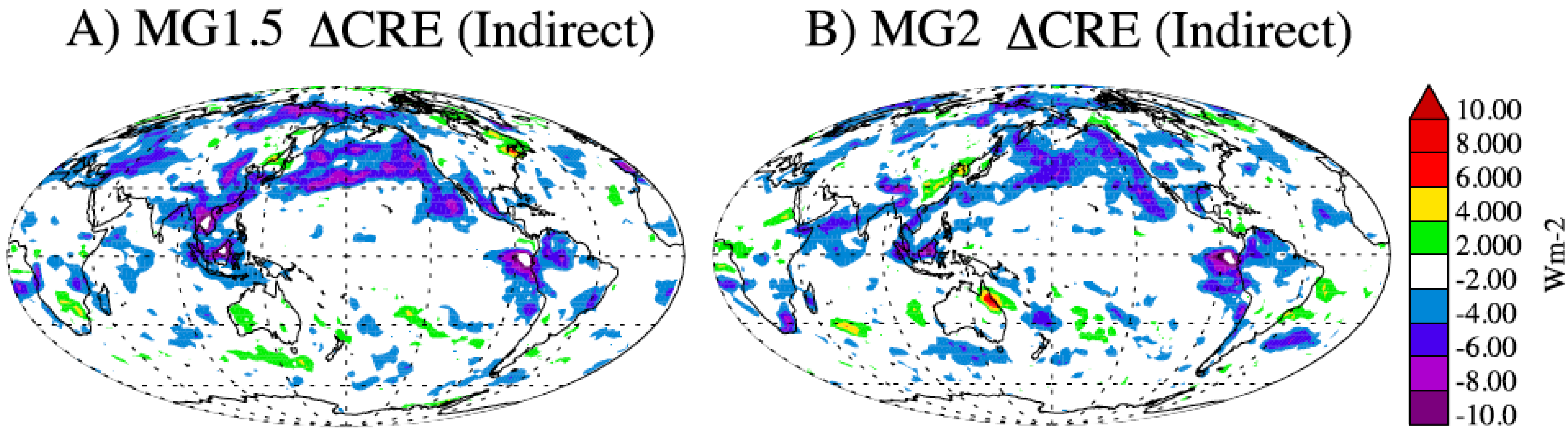
Note: parameterizations like CLUBB can determine this relative variance.

Morrison Gettelman Advancements

- MG1: Morrison & Gettelman 2008 (CESM1, CAM5)
  - Morrison et al 2005 scheme
  - Added sub-grid scale variance
  - Coupling to activation (aerosols)
- MG2: Gettelman & Morrison 2015 (CESM2, CAM6)
  - Prognostic precipitation
  - Sub-stepping and sub-column capable
- MG3: (in Prep)
  - Adds graupel/hail (one more mixed phase hydrometeor)

MG2 Prognostic Precipitation

Reduces Indirect Effect



-1.2 Wm^{-2}

-0.9 Wm^{-2}

Gettelman et al 2015, J. Climate

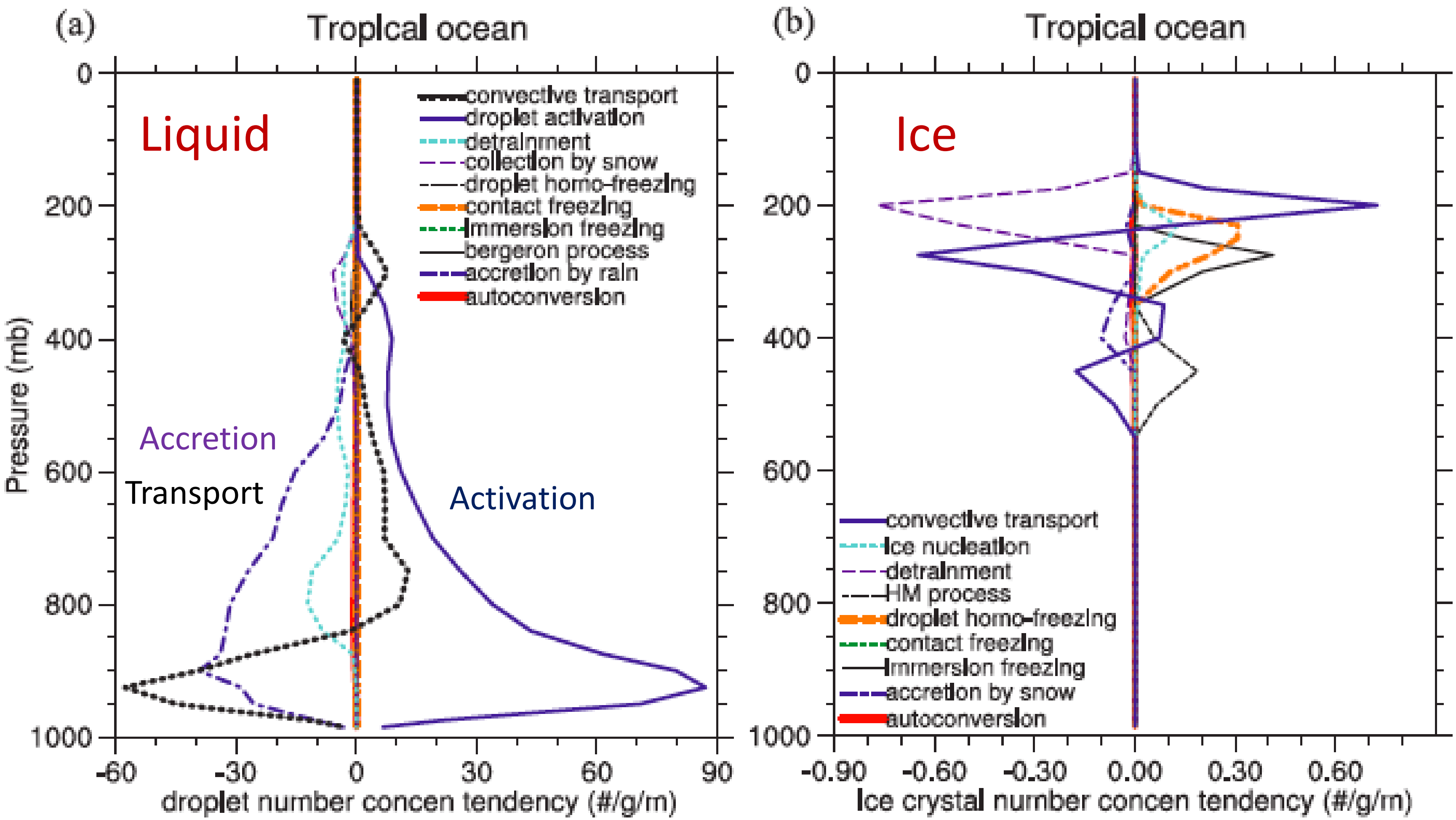
Next Steps for Global Models

- Double Moment (M2005)
- Aerosol Aware (MG)
- Prognostic Precipitation (MG2)
- Convective Microphysics
- Sub-columns
- Unified Snow/Ice/Mixed phase

Convective microphysics
A version of MG scheme in Deep Convection

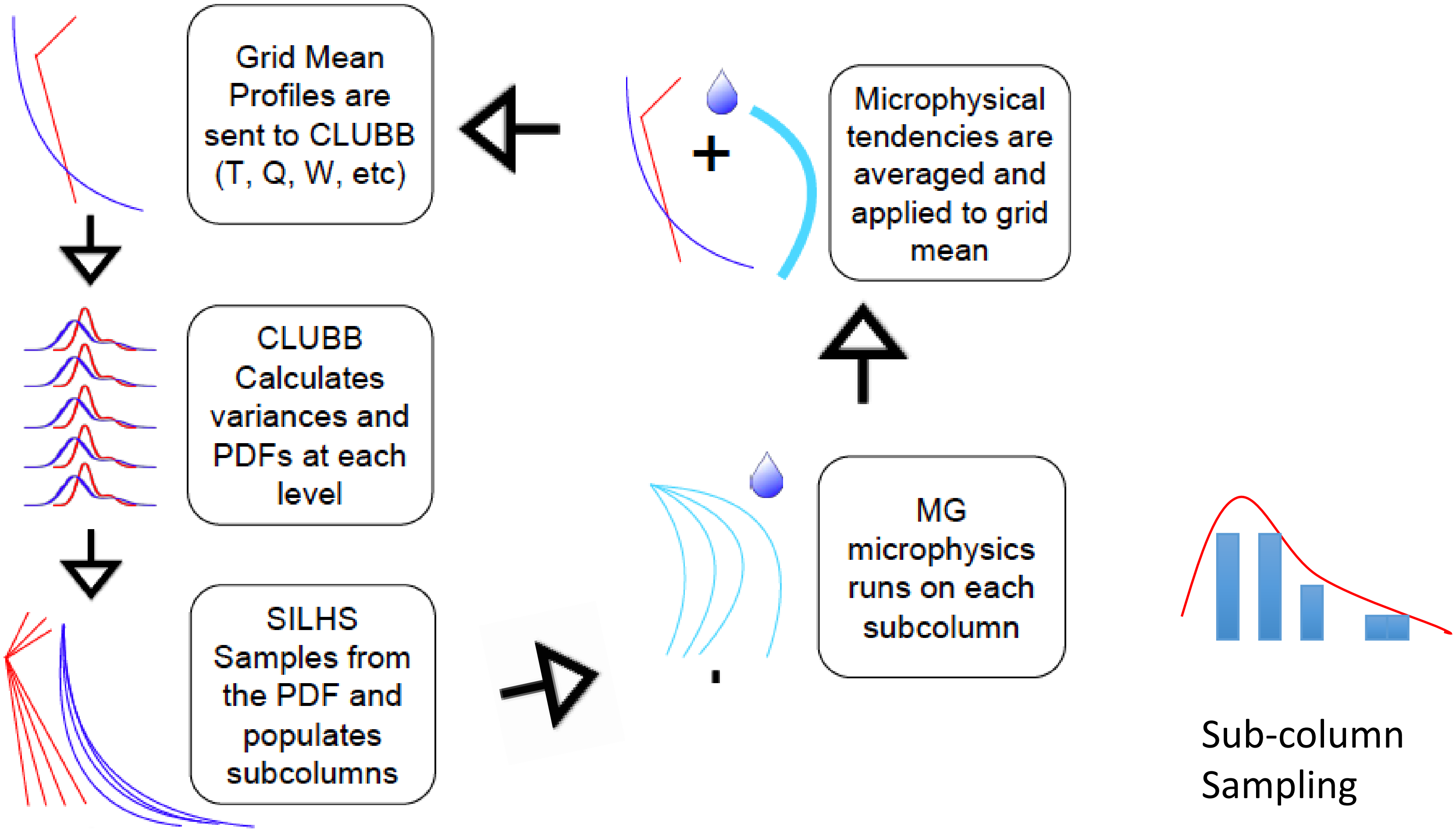
Goal: represent microphysics the same in all clouds

Song et al 2012



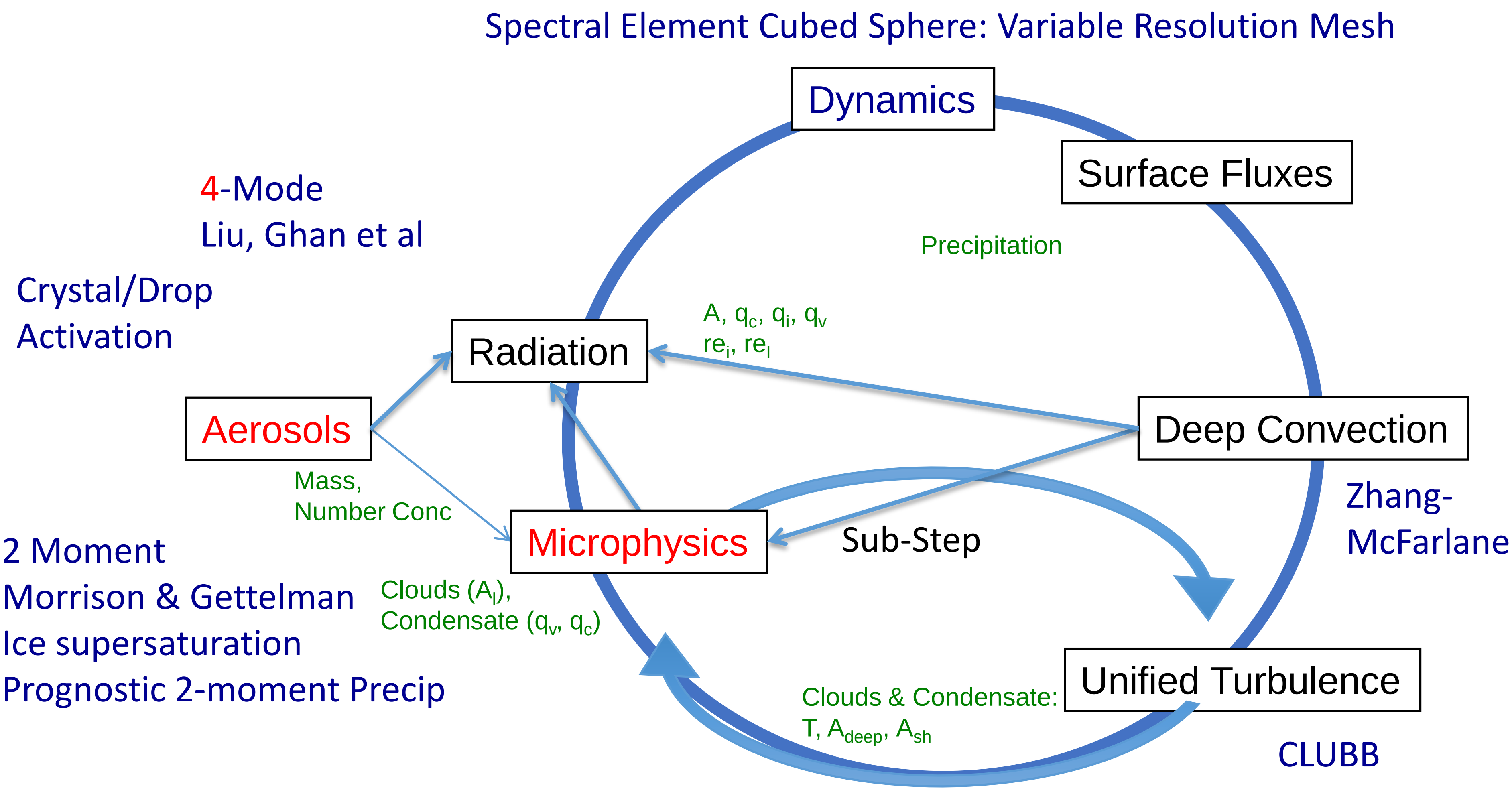
Advancements: Sub-columns

Statistically Sample Sub-Grid Variability: non-linear process rates



Thayer-Calder et al 2015, Larson et al 2005

Community Atmosphere Model (CAM6)



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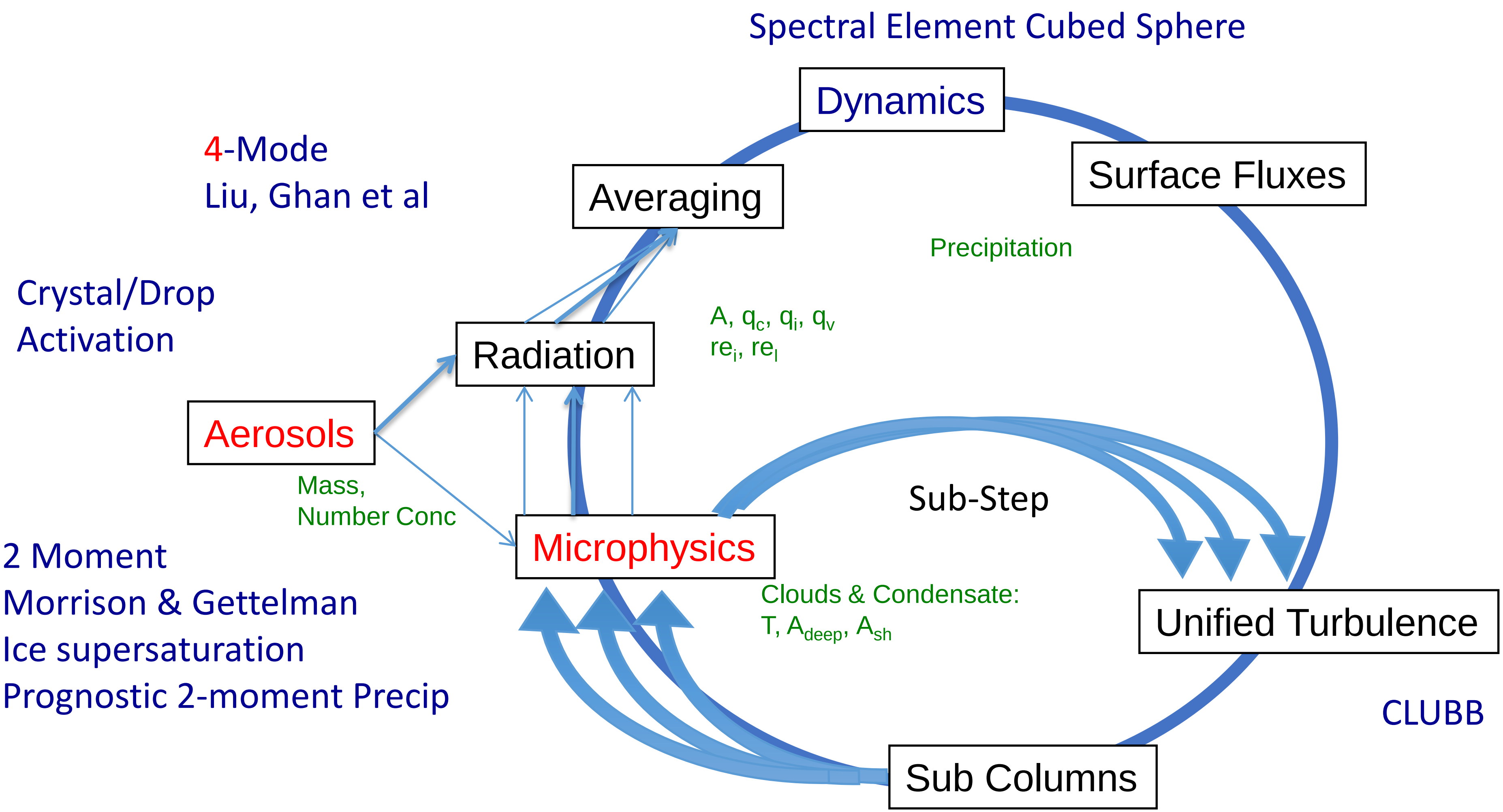
Community Atmosphere Model (CAM6)

Now in development: Sub-columns across parameterizations



A = cloud fraction, $q=H_2O$, re=effective radius (size), T=temperature
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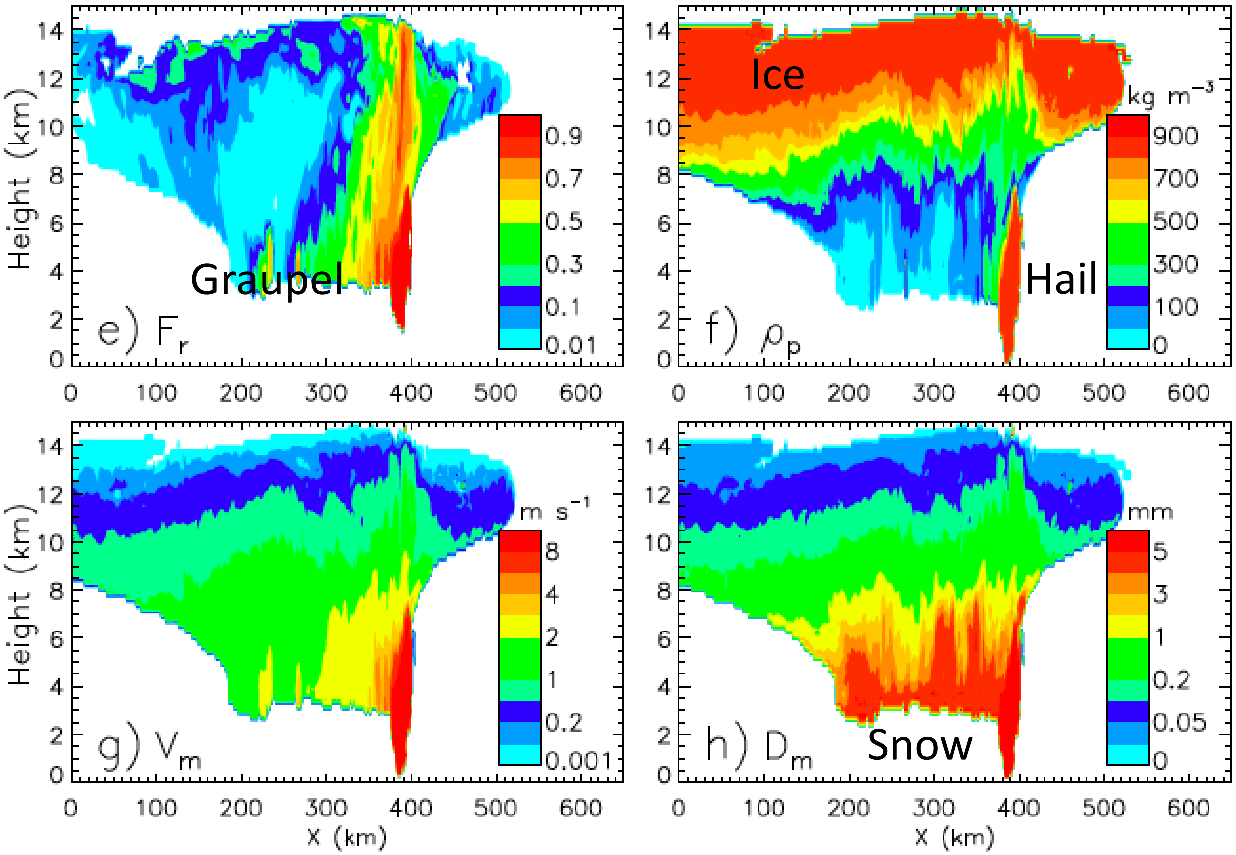
Advancements: Unified Ice

Rimed Fraction Density



Fall Speed Size

Unify ‘Ice’, ‘Snow’ and ‘Graupel’ into one hydrometeor class. Define multiple properties: Mass, Number/Size, M-D (density), Rimed Fraction (F)

Predict a range of properties with no artificial conversion terms.

Morrison & Milibrant 2015, Eidhammer et al 2016, Xi et al (in prep)

Summary/Conclusions

- Cloud microphysics is critical for weather and climate scales
- Current global model treatments similar to mesoscale treatments
- Bulk schemes are very effective
- Working towards scale insensitive microphysics
  - Use for variable mesh simulations
- Advancements: ‘Unified Microphysics across scales’
  - Hail/Graupel
  - Use in convective schemes
  - Unified snow/ice
- Try to include sub-grid variance
  - Analytical (if possible)
  - Sub-columns (if not)
- MG scheme is open source for testing, further development
  - Optimized
  - Flexible: designed to work across scales (stability for large scale, detailed processes for small scale)
  - Works in different models (flexible sub-grid and aerosol ’awareness’)