U.S. DEPARTMENT OF ENERGY
Office of Science

Pacific Northwest NATIONAL LABORATORY

Cloud Microphysics

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BATTELLE

Outline

Motivation/
Introductory Concepts

1. Motivation: Cloud Microphysics in Weather and Climate
2. What is cloud microphysics? How does it work?
3. Resolved and Unresolved scales
4. Cloud *macro*-physics: coupling to the large scale
5. Types of cloud microphysical schemes

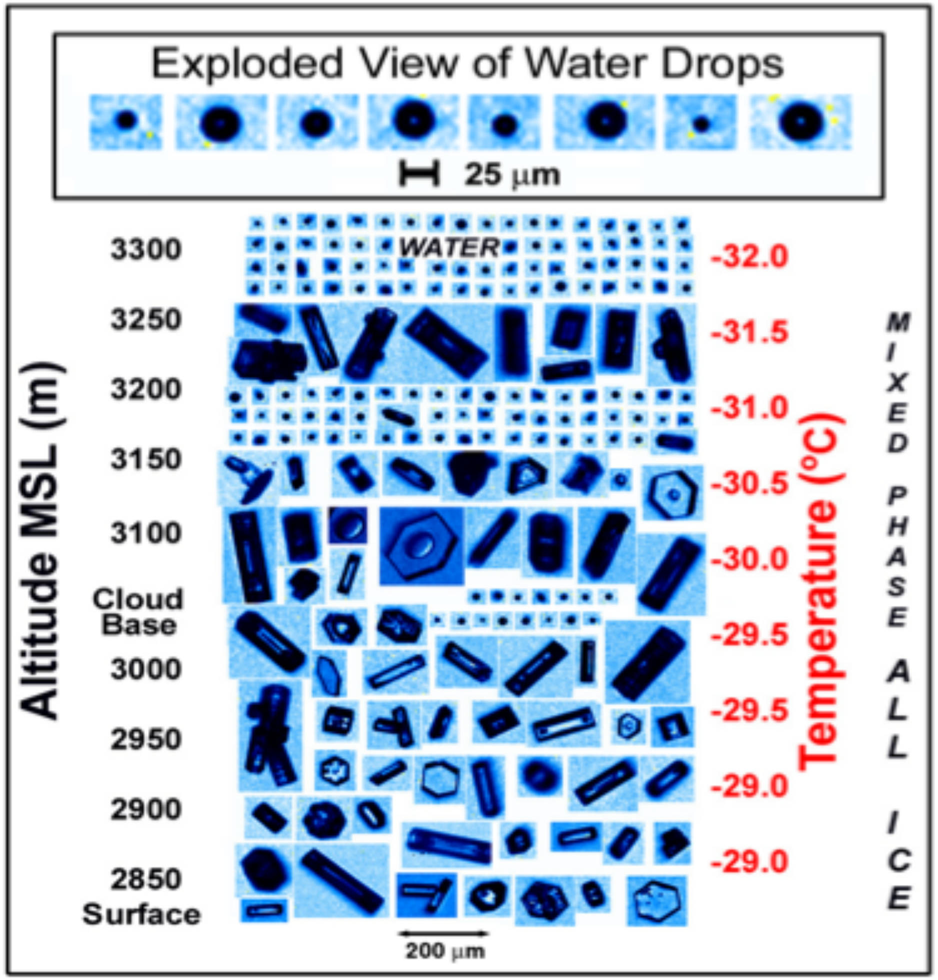
Details of common
Climate Model
Schemes, Evaluation

6. Description of Morrison-Gettelman/PUMAS scheme
7. Important processes and interactions
8. Some Numerical Considerations
9. Evaluation with observations

Coupling and New
Approaches

10. Coupling to Aerosols (and Radiation)
11. Other Aspects: Convection & Machine Learning
12. Summary: Uncertainties and Frontiers

1. Motivation, Spanning Scales 10^{-6}m → 10^{6}m

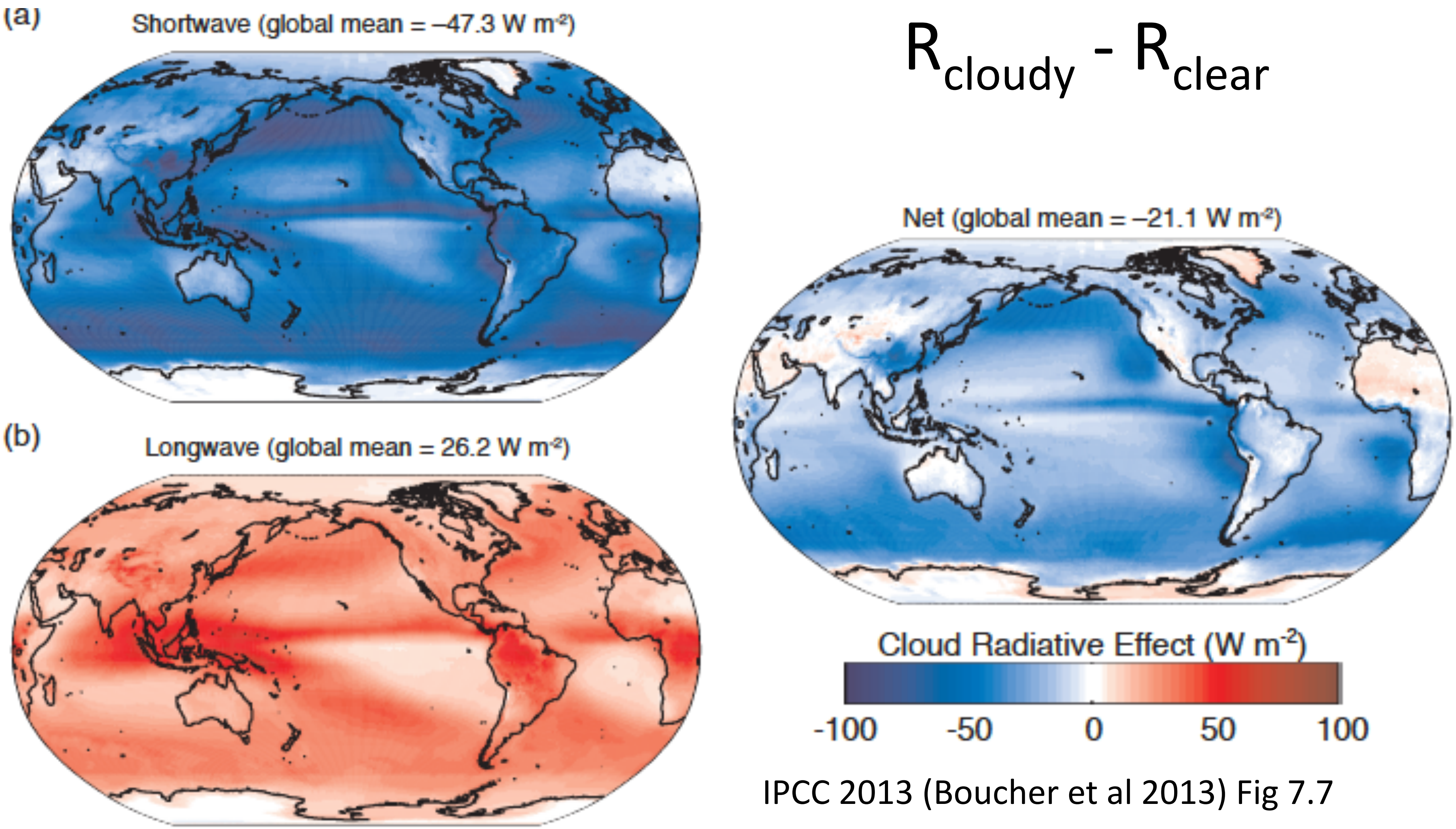


Lawson & Gettelman, PNAS (2014)

← 1.2×10^{7}m →

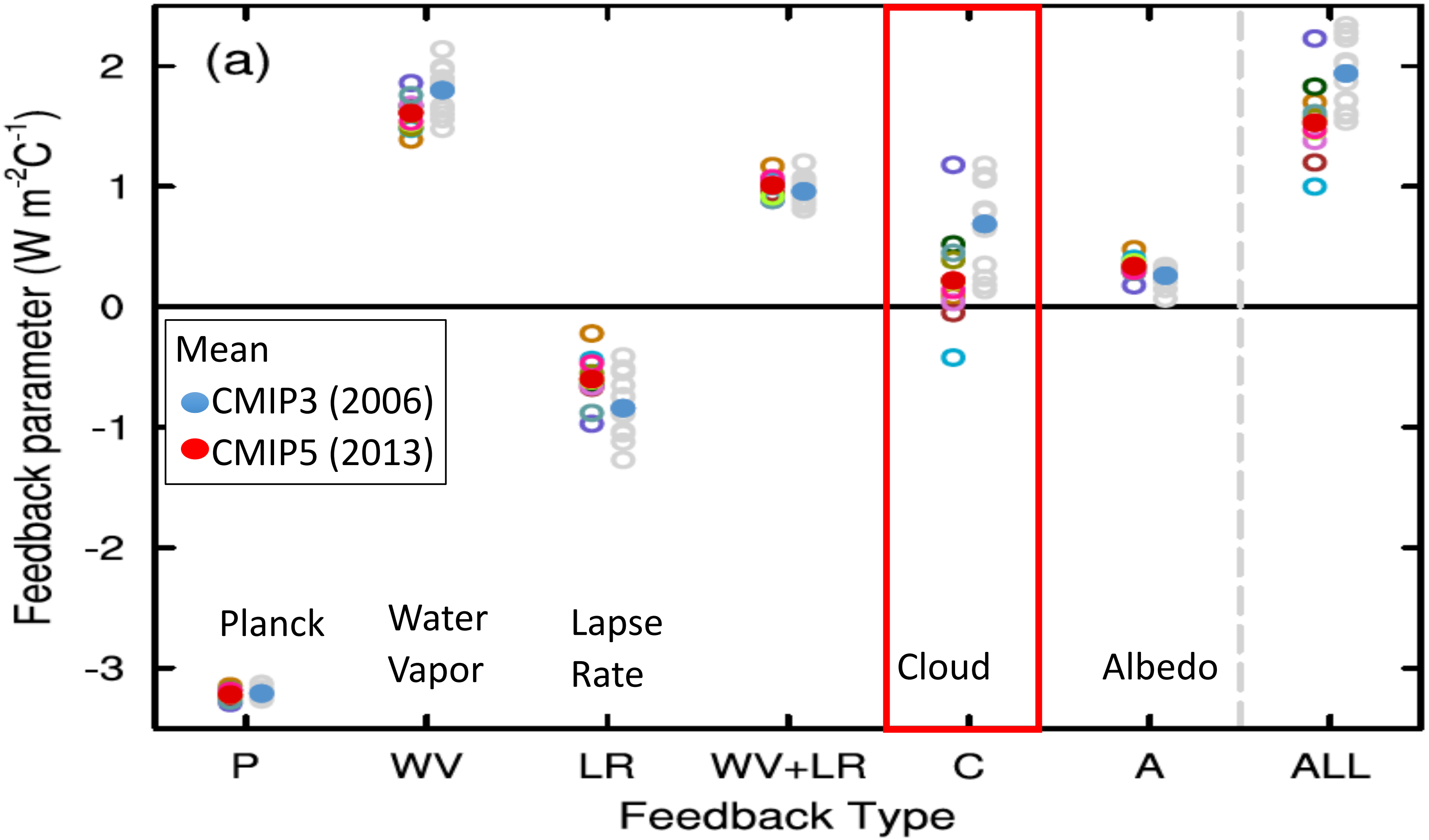
Cloud Radiative Effects are Large

$R_{cloudy} - R_{clear}$



IPCC 2013 (Boucher et al 2013) Fig 7.7

Clouds = Largest Uncertainty in Climate Feedbacks



Planck $\varepsilon = \sigma T^4$ (-)

Water Vapor
+T & RH=C → +H2O (+)

Lapse Rate (-

Albedo (snow, ice)
+T → less snow, ice
-T → more snow, ice (+)

Clouds: Complicated (+)

IPCC, 2013 (Ch 9, Hartmann et al 2013) Fig 9.43

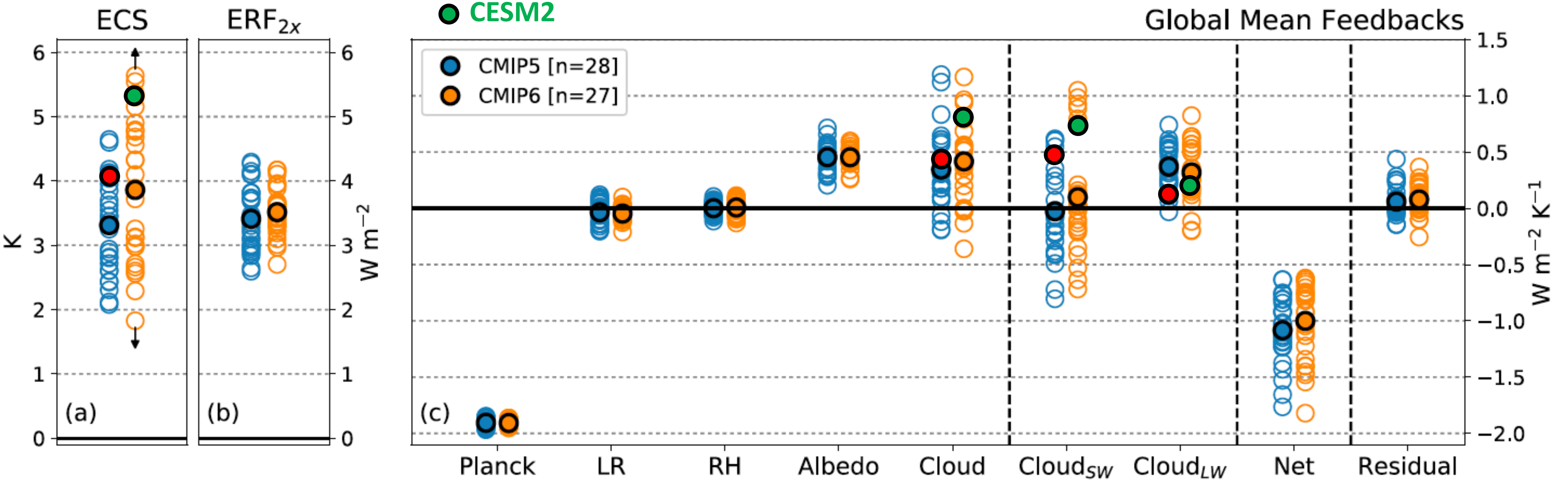
Climate Feedbacks

Equilibrium Climate Sensitivity (ECS) Uncertainty: *It's all about cloud feedback*

CESM1= 4.1K

CESM2= 5.3K

CESM2



(σT4)

Lapse Rate

RH Change

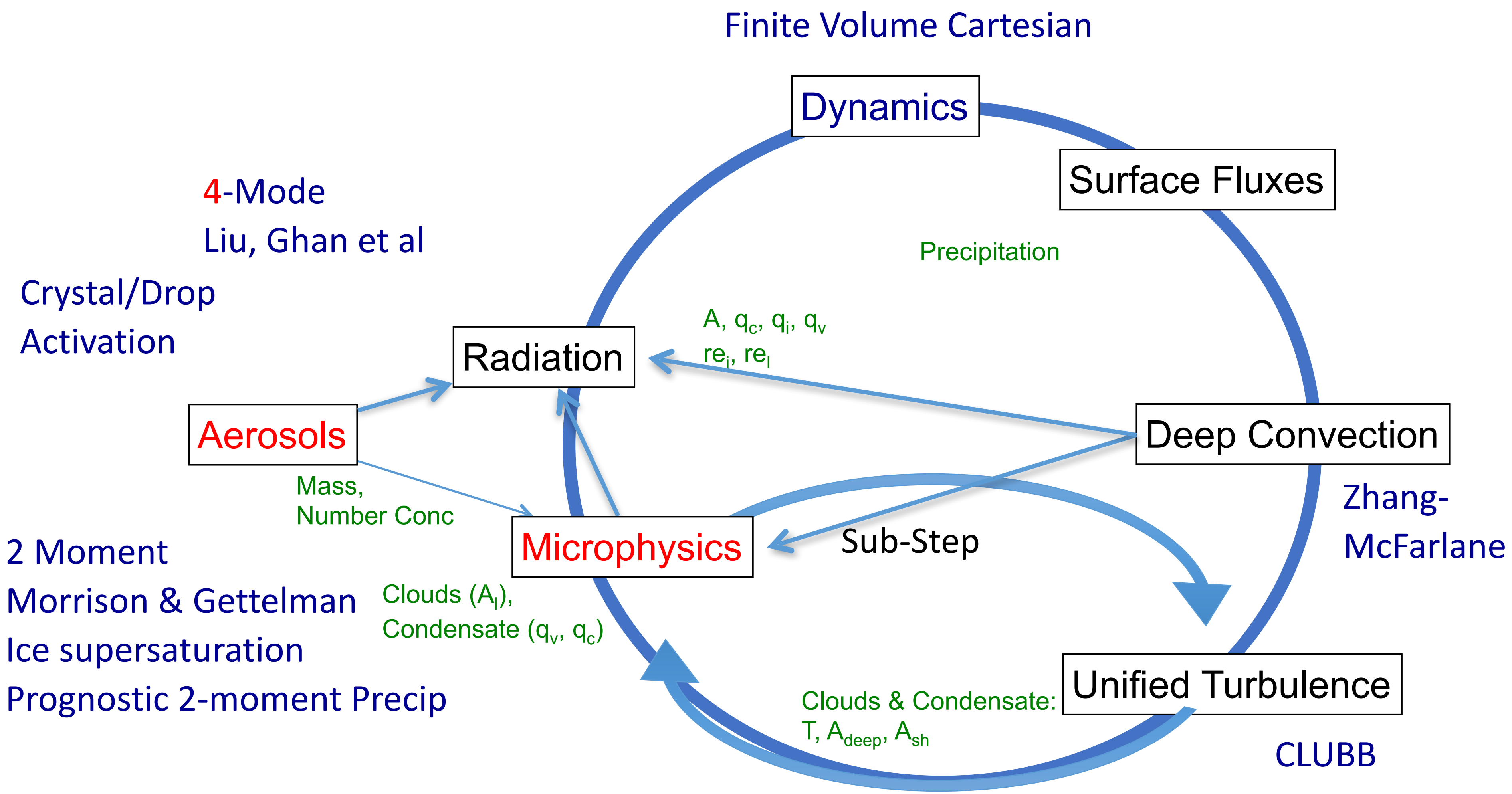
Zelinka et al 2020, GRL

Cloud Microphysics Kills!

- Clouds are responsible for most severe weather
  - Tornadoes, Thunderstorms, Hail, Tropical Cyclones
- Critical cloud processes depend on microphysics (latent heat release, cold pools, freezing, electrification)

2. What is Cloud Microphysics?

Community Atmosphere Model (CAM6/7)



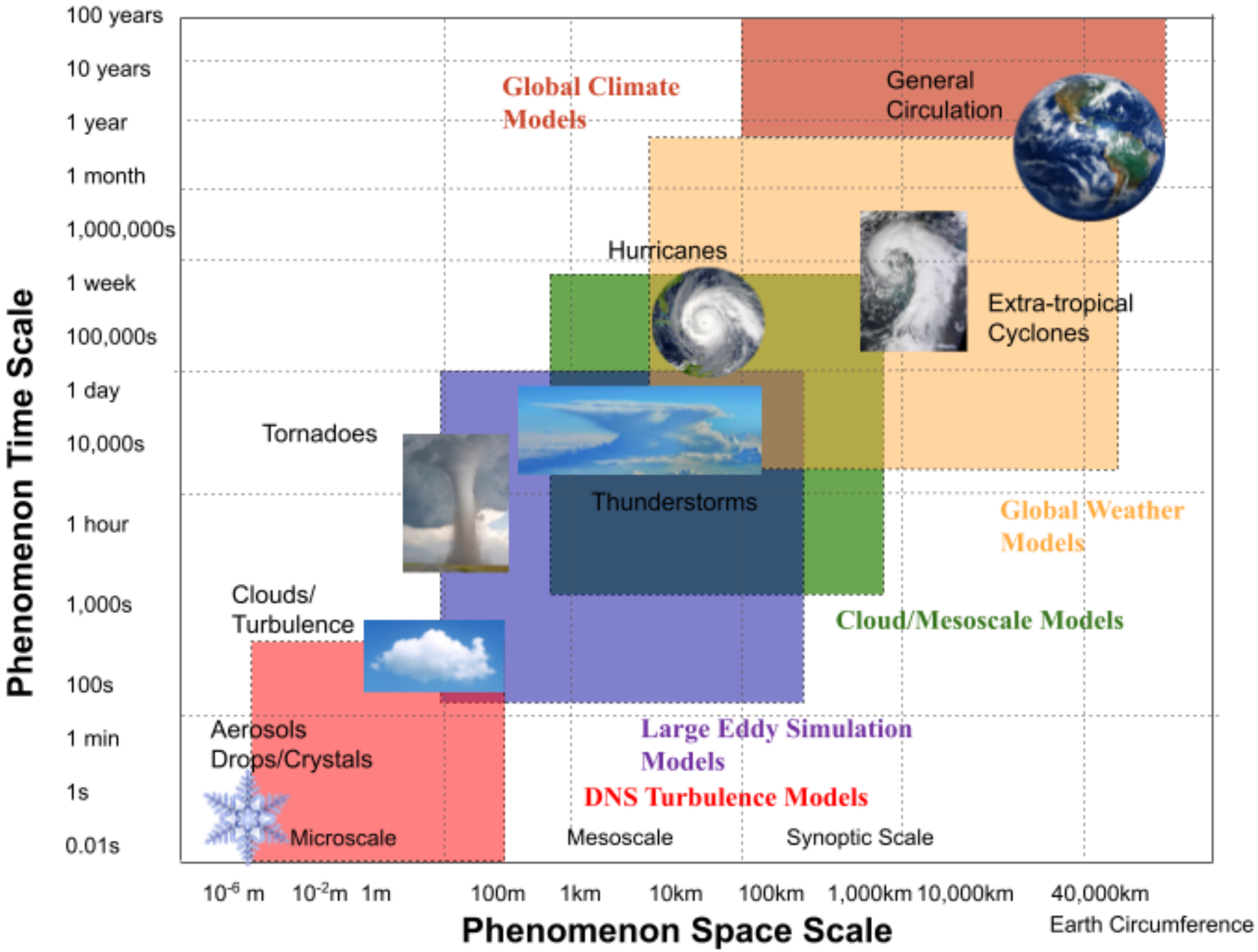
A = cloud fraction, q=H_2O, re=effective radius (size), T=temperature

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

Essence of Cloud Microphysics

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

3. Scales of Atmospheric Processes



Scales and parameterization

- OK: If processes have a large separation from the grid scale
  - Statistical (empirical) treatments often work: can represent small scale uniquely with state of large scale
- Problems: When the scales get close together
  - Example: representation of moist convection, or cloud dynamics in general
  - Convective equilibrium is a large scale process
- Key issue: proper representation of sub-grid variability

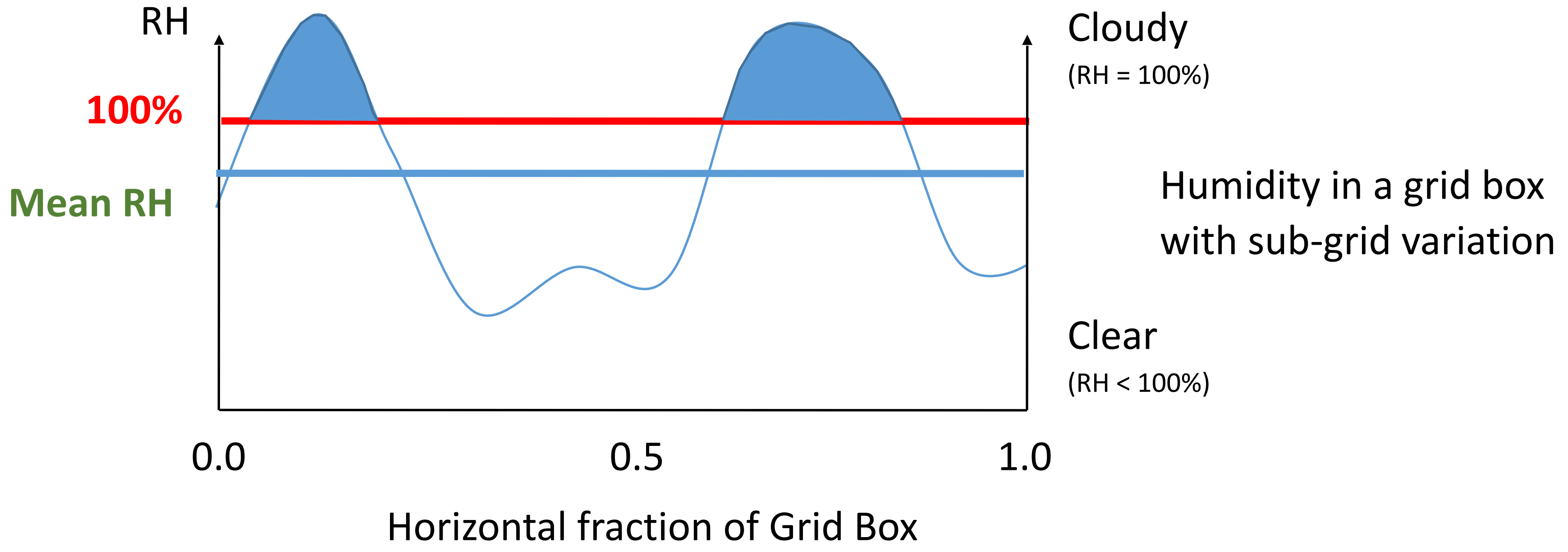
4. Cloud ‘Macrophysics’ & Sub-Grid Variability

- Generalized way to deal with small scales
- Not all processes assume uniform grid cell state
- Some processes are highly non-linear, so ‘sub-grid’ variability is assumed
- Cloud Macrophysics = condensation of water
  - Simple if all scales resolved
  - Need to deal with sub-grid variability for most applications.
  - Used by microphysics and radiation

Sub-Grid Humidity and Clouds

Liquid clouds form when RH = 100% ($q>e_{sat}$)

But if there is variation in RH in space, some clouds will form before *mean* RH = 100%



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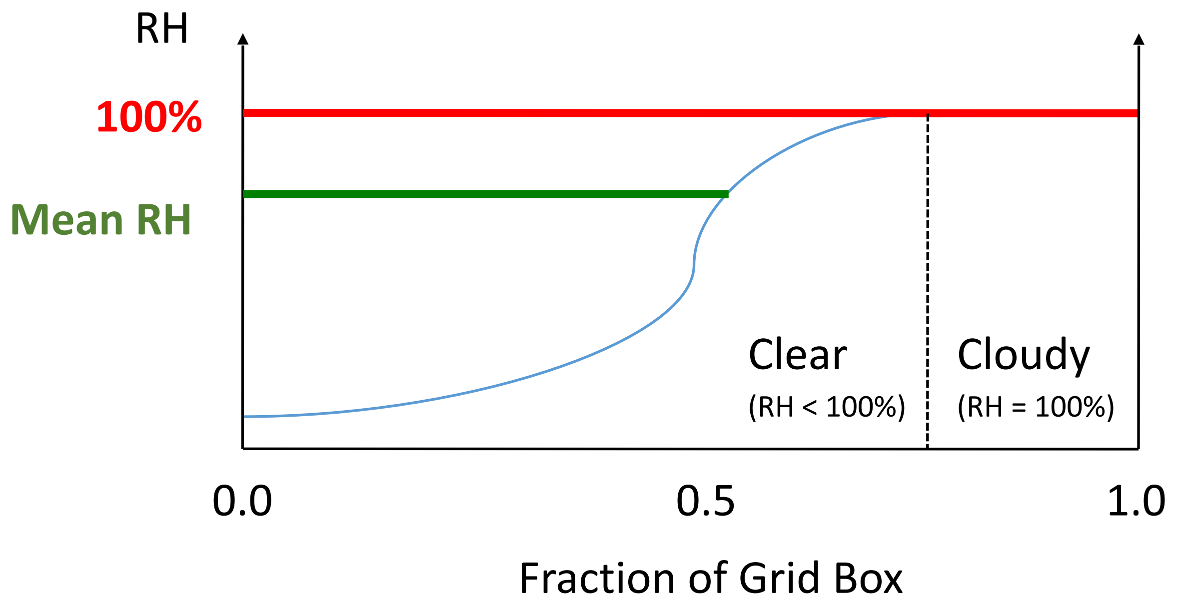


Assumed Cumulative Distribution function of Humidity in a grid box with sub-grid variation

‘Sub-Grid’ in different scale models

What is resolved at different scales?

- Global Scale (15-400km)
  - Example: Resolve ‘synoptic’ systems and the general circulation
- Regional/Mesoscale (0.5-20km)
  - Better resolution of orography, ‘permit’ deep convection at scales < ~5km
- ‘LES’ scale (10m – 200m)
  - Resolve convection, ‘permit turbulence’ at 100m or less
- Turbulence (5-50m)
  - Microphysics is still ‘sub-grid’ scale, resolve almost all motions

’Gray Zone’ = process is too big to describe statistically, too small to resolve completely

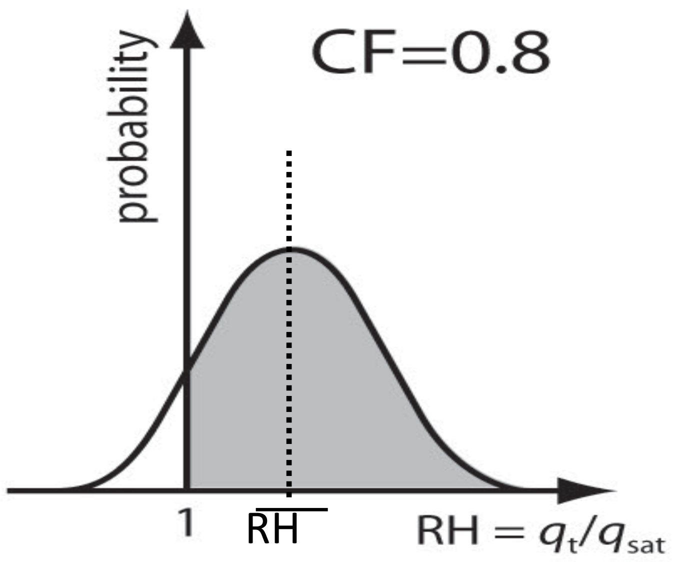
Cloud Macrophysical Approaches

- LES: ‘explicit’
  - The atmosphere is not significantly supersaturated w.r.t. liquid (ever)
  - Still parameterizations for ice processes (ice supersaturation)
- Fractional Cloudiness
  - Clouds form before grid reaches 100% supersaturation
  - Analytic distributions: Box or Triangular PDF
- Complex treatments: PDFs schemes
  - Multivariate PDFs or Higher Order Closure
  - Predict higher order moments of multivariate PDL of θ_l & w

Dynamics-Based PDFs for Cloud Parameterization: Motivation

- Moisture-based PDFs (widely used to represent cloud cover in GCMs) are not linked to dynamics of cloud formation and dissipation

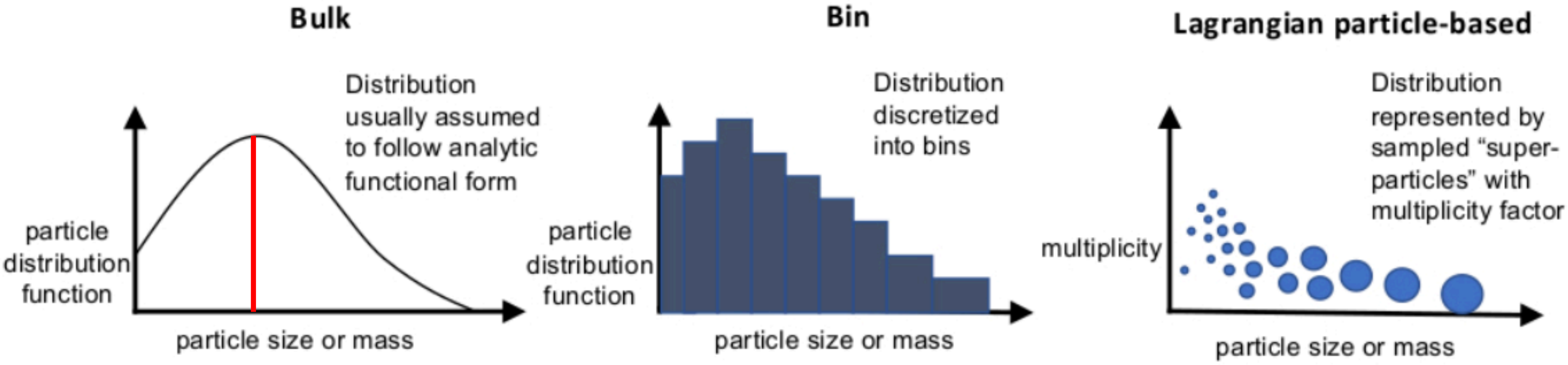
- Key cloud processes (drop activation, entrainment, and precip. Formation) are closely linked to vertical motions
- Need **joint distributions** of thermodynamics *and* dynamics (vertical motion)
- These are called Higher Order Closure (HOC) schemes (e.g. CLUBB, SHOC)



5. Types of Microphysical Schemes

Used in models at scales:

Global & Mesoscale models | Mesoscale /Large Eddy Simulations/Parcel | LES/Parcel



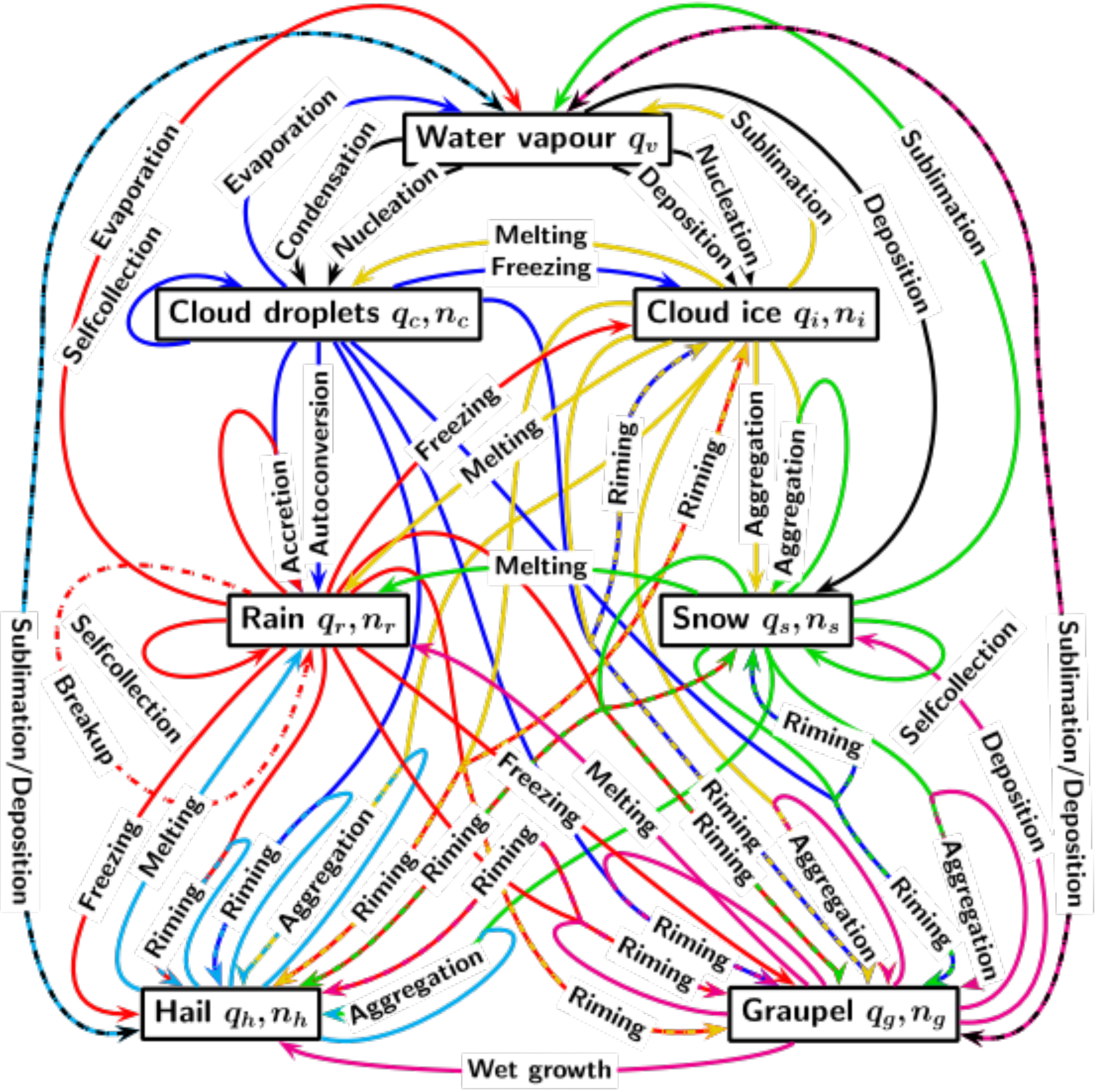
Two Moment = Prognostic Mass and Number

One Moment = Prognostic Mass, Diagnostic Number/Size

Figure: Morrison et al 2020, JAMES

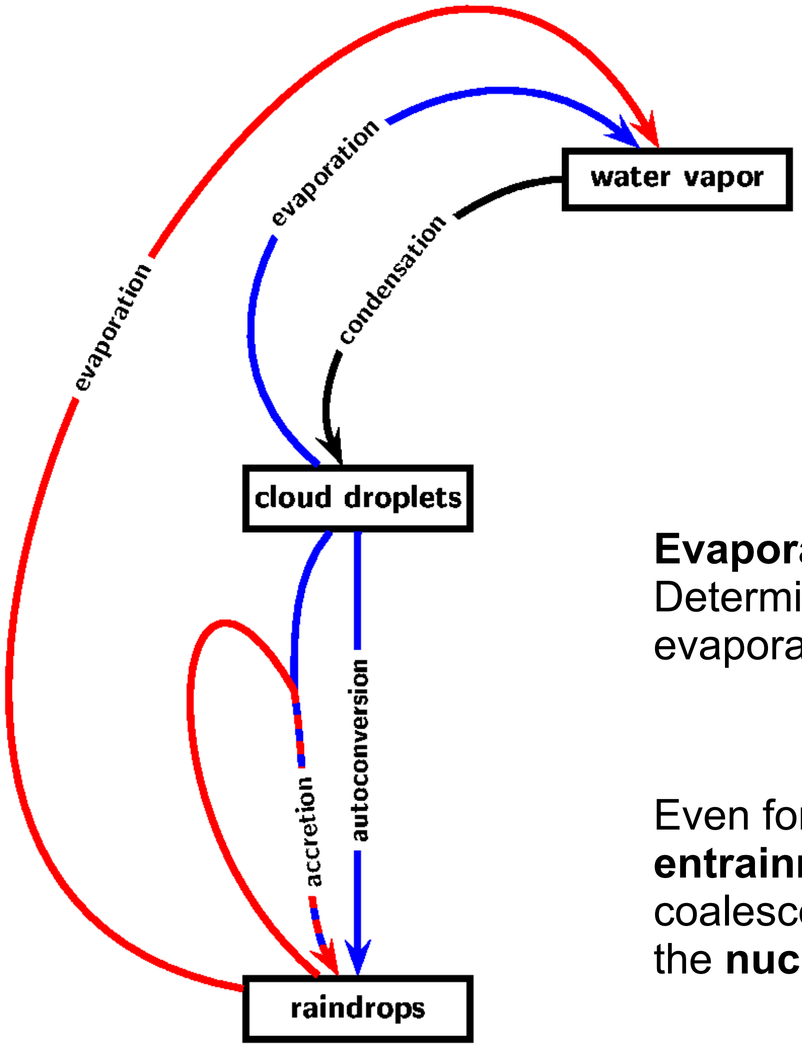
Ultimate Schematic

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



Seifert, Personal Communication

Cloud Microphysical Processes: Rain



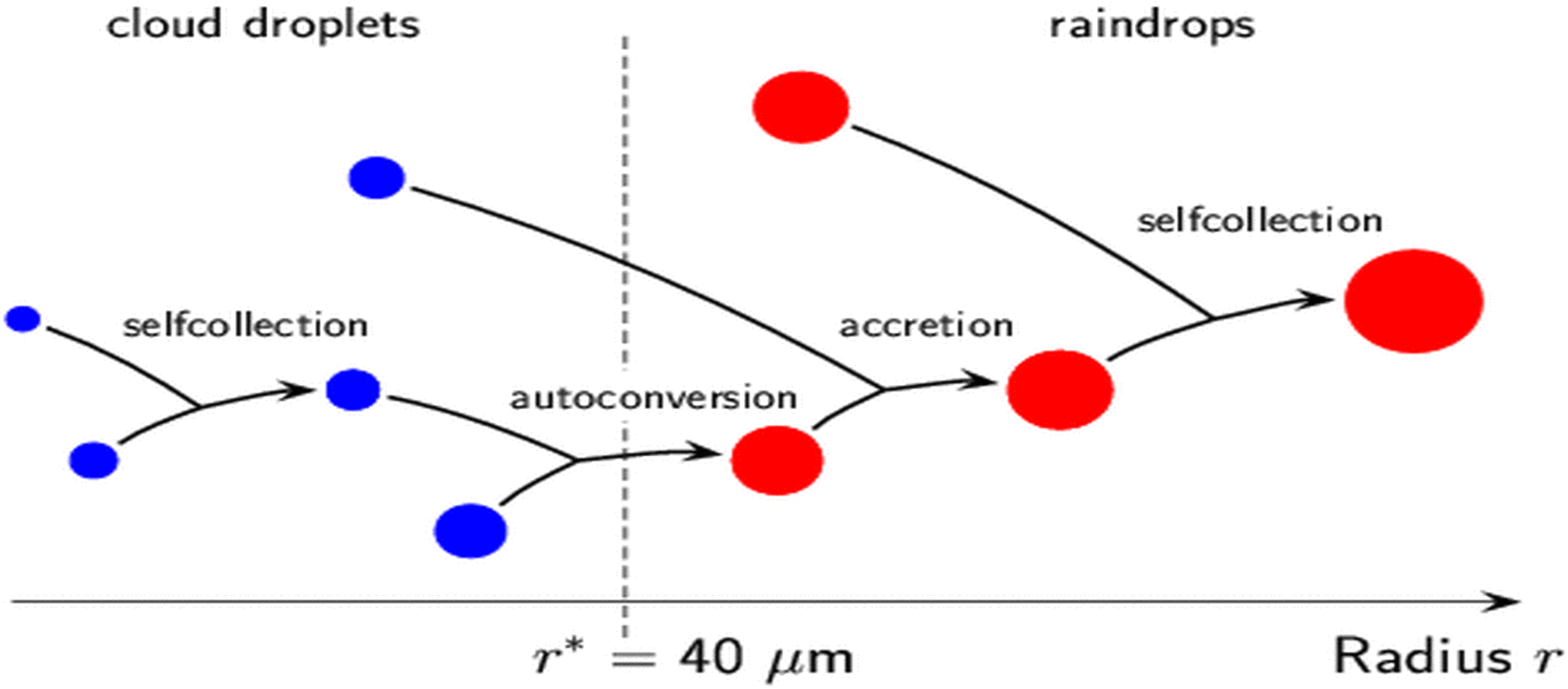
Evaporation and condensation of cloud droplets usually parameterized by saturation adjustment scheme.

Autoconversion is an artificial process introduced by the separation of cloud droplets and rain. Parameterization of the process is difficult and uncertain.

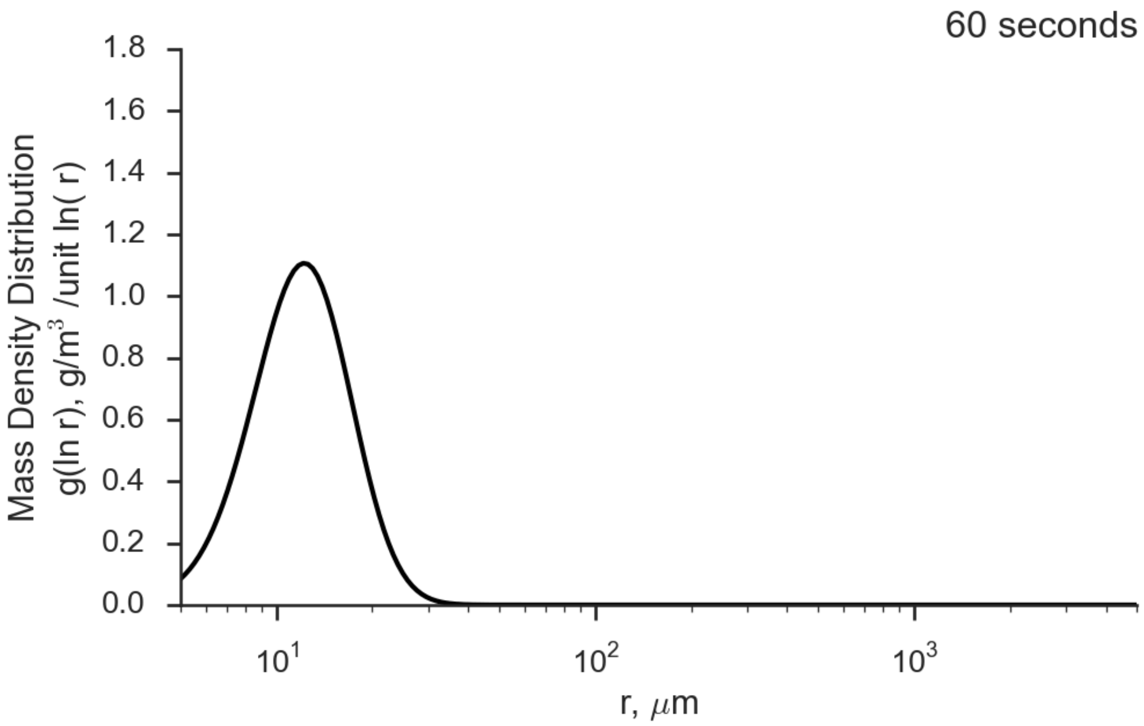
Evaporation of raindrops is very important in convective systems. Determines the strength of the cold pool. Parameterization difficult, since evaporation is very size dependent.

Even for the warm rain processes a lot of things are unknown: effects of **mixing / entrainment** on the cloud droplet distribution, effects of **turbulence** on coalescence, **coalescence efficiencies, collisional breakup** or the details of the **nucleation** process.

Collision-Coalescence Process



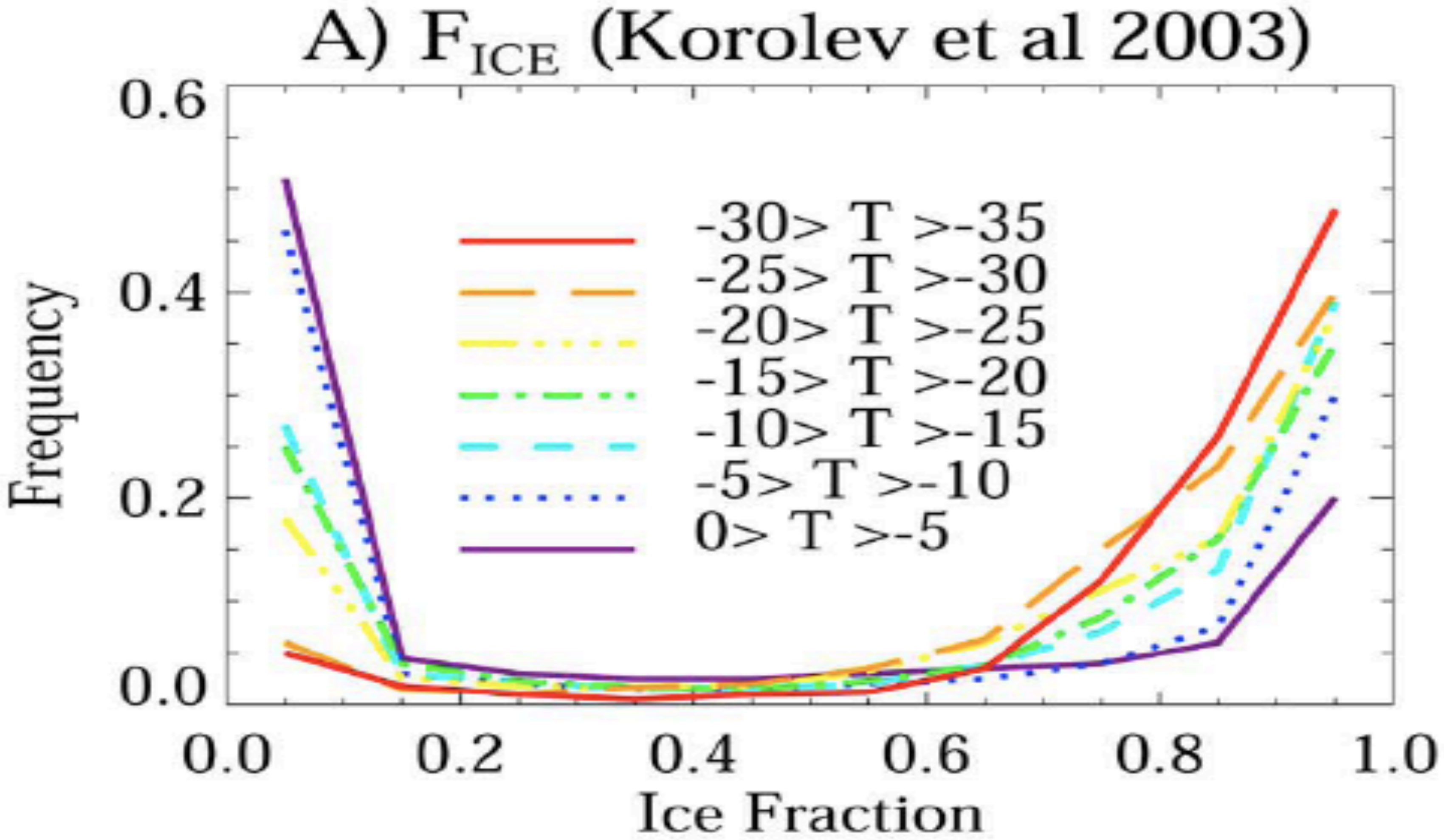
Detailed model of Rain Formation



Mixed (ice and vapor) Phase

- Ice saturation vapor pressure is lower
- Once ice forms it will preferentially take up vapor.
- Vapor deposition onto ice will occur (Bergeron-Findeisen process)
- This will cause evaporation of liquid water
- Key issue: how homogenous is a cloud? Key for mixed phase. In general: not well mixed

Mixed Phase: Ice



Dynamics

- Updraft strength is important for microphysics
  - Adiabatic cooling generates supersaturation
  - Rate affects particle growth and nucleation
- Cloud dynamics
  - Turbulence and mixing (moist or dry air)
  - Entrainment (especially important for convection)
- Microphysics feeds back on dynamics
  - Heating due to condensation/evaporation
  - Water (precipitation) changes pressure gradient

Key Cloud Properties

- Cloud Phase
- Particle size distribution
  - liquid drops are spheres
- Mass (Liquid water path)
- Allows calculation of optical depth
  - absorption and emission
- Precipitation
  - Also has a size distribution
- Process rates depend on size distribution

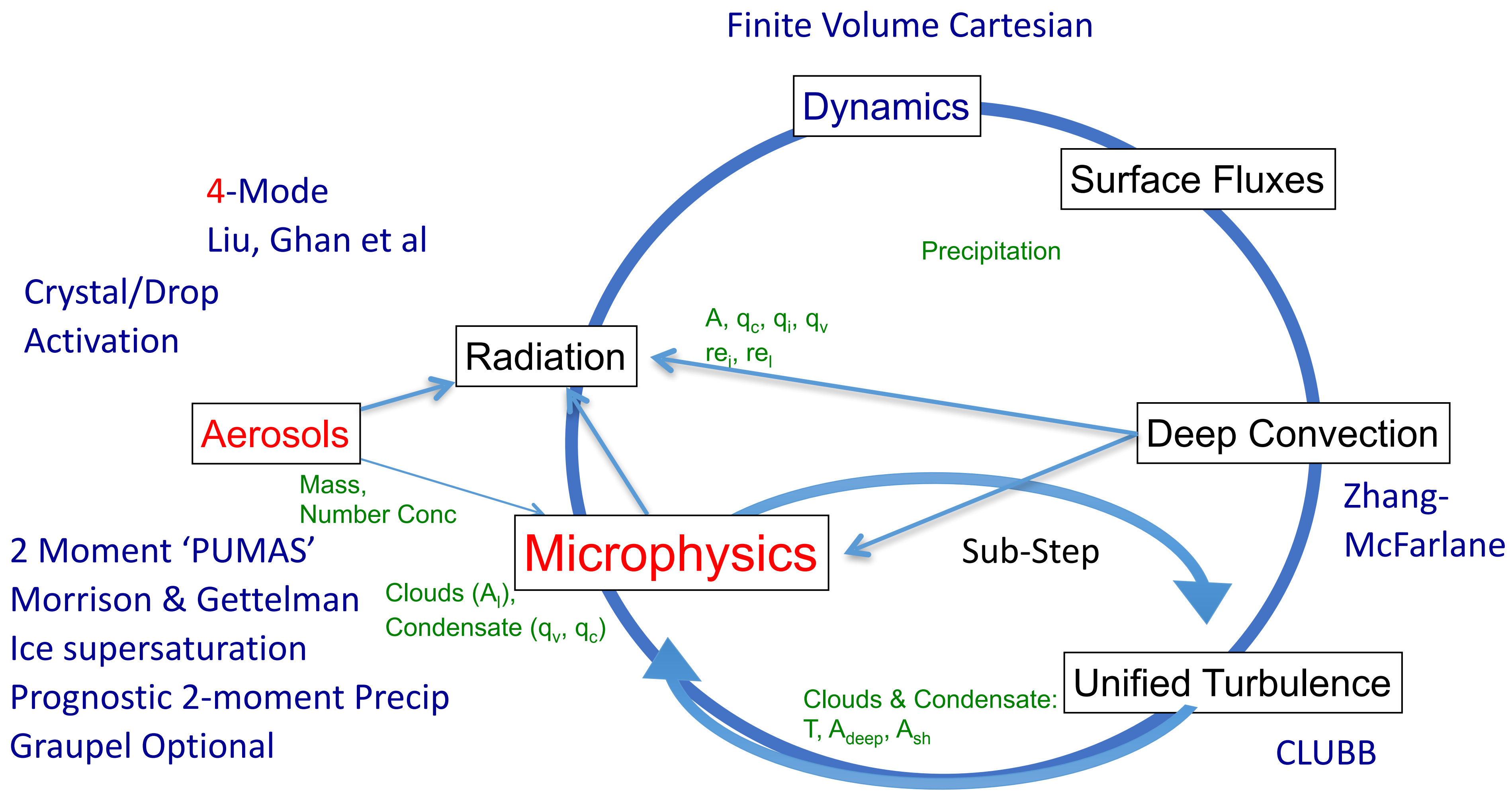
Summary

- Cloud processes governed by a series of processes related to transformation and evolution of water
- Goal for radiation and precip is drop size distribution
- Humidity is fundamental
- Dynamics is fundamental
- Tight coupling to local dynamics

6. Description of PUMAS Scheme

- Used in CAM6/7
- Derivative of Morrison et al 2005 WRF scheme
  - MG2 = identical to M2005 for liquid
  - MG3 = adds graupel/hail
  - PUMAS = new foundation and current development
- Bulk 2-Moment 4/5-class scheme
  - Mass and number
  - Liquid, Ice, Rain, Snow (Graupel)
  - Takes in state, activated number of aerosols
  - Prognostic rain, snow

Community Atmosphere Model (CAM6)



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

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008

Cloud Microphysics: Representing 4 ‘classes’

q, N
Cloud Droplets
(Prognostic)

q, N
Cloud Ice
(Prognostic)

q
Water Vapor
(Prognostic)

q, N
Rain
(Diagnostic)

q, N
Snow
(Diagnostic)

Size distributions and Classes

What does *q, N* mean?

Moments of a size distribution

0 = Number

3 = Mass (=6/(πρ$_w$)*M_3

6 = Reflectivity (radar) R ~ D^6

In MG/PUMAS: Gamma functions for each class:

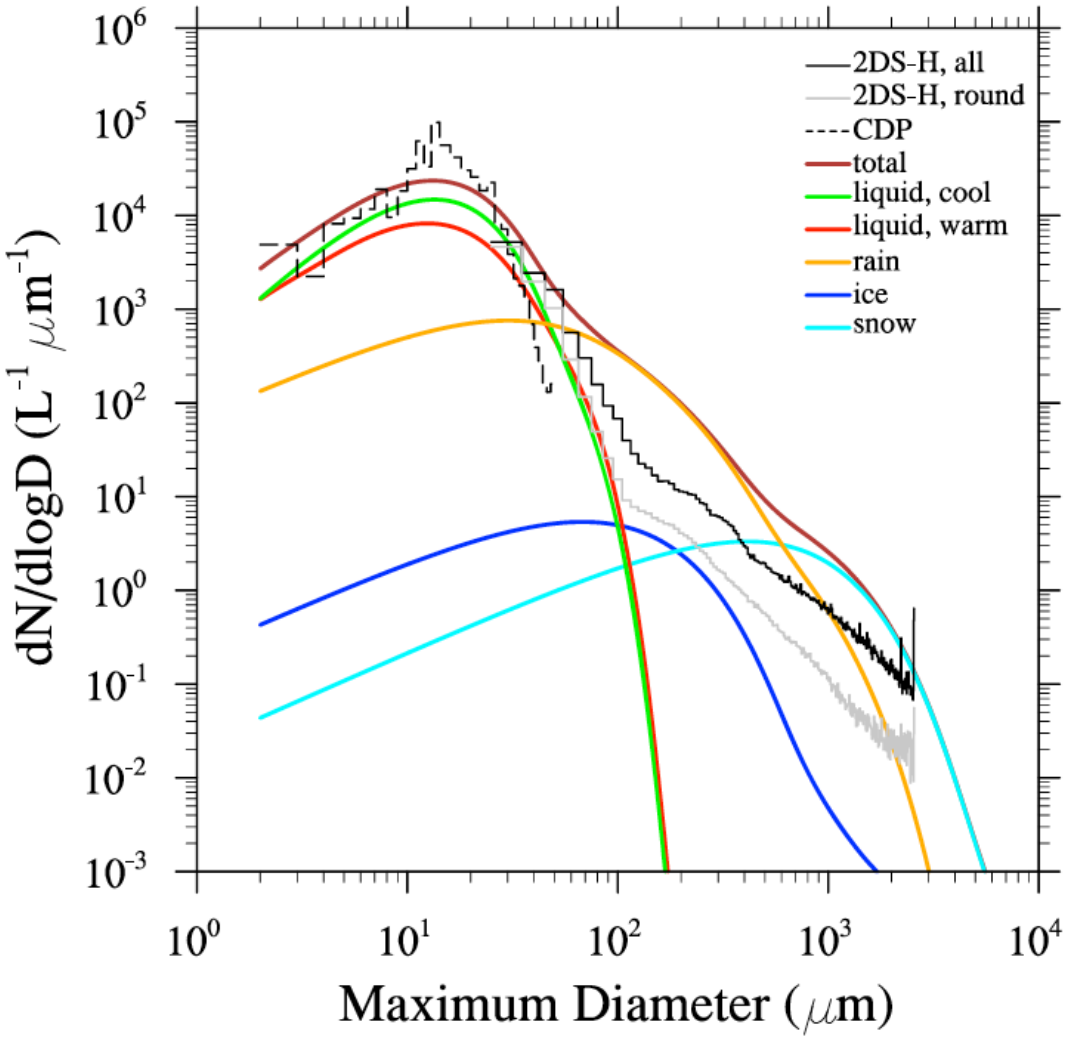
$$\phi(D) = N_0 D^{\mu} e^{-\lambda D}$$

D = diameter

N_0 = intercept

μ = shape, (~1/dispersion^2)

λ = slope

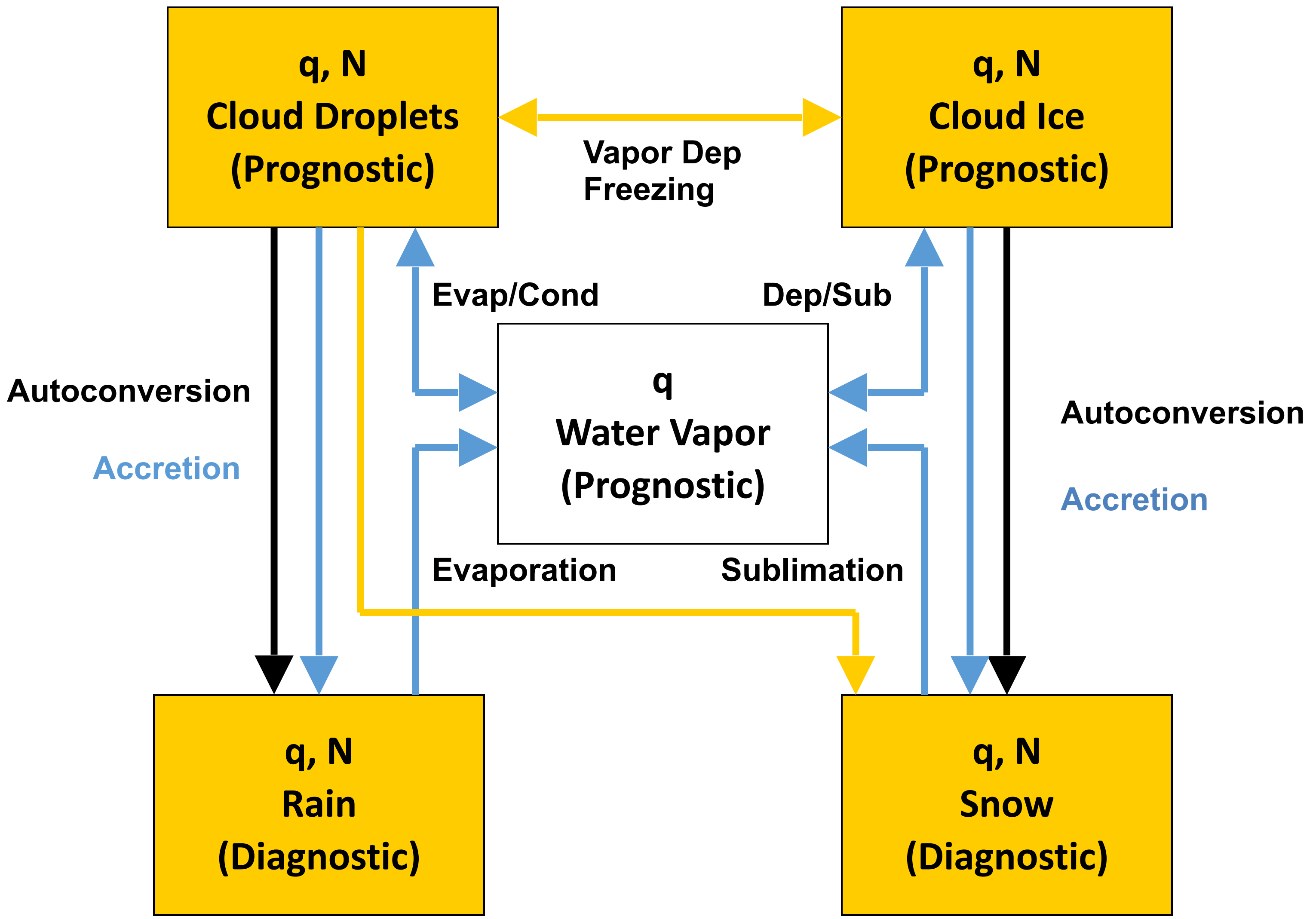


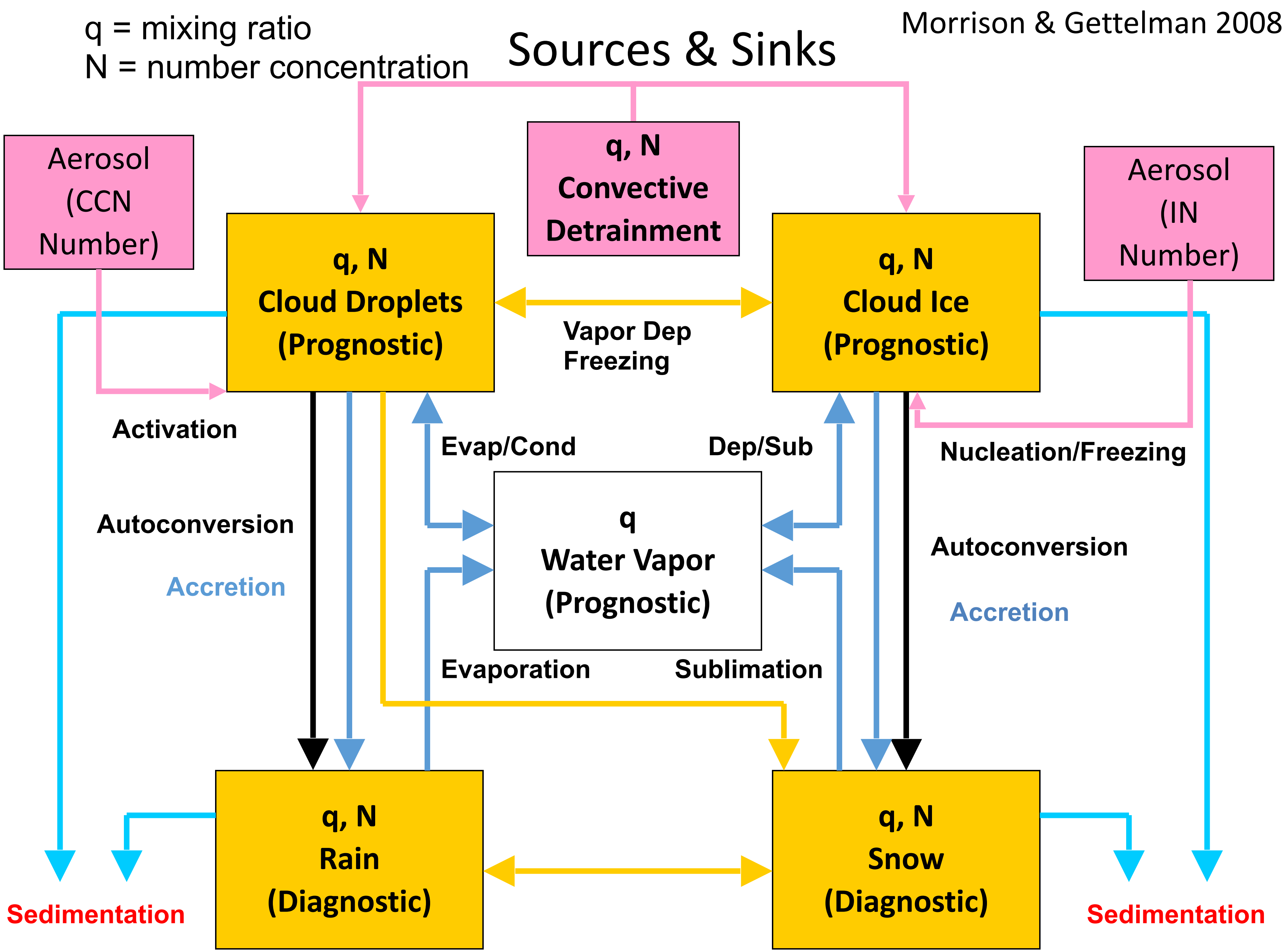
Different values/methods for each class. E.g. μ=0 for ice

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008

Transformations Between Classes

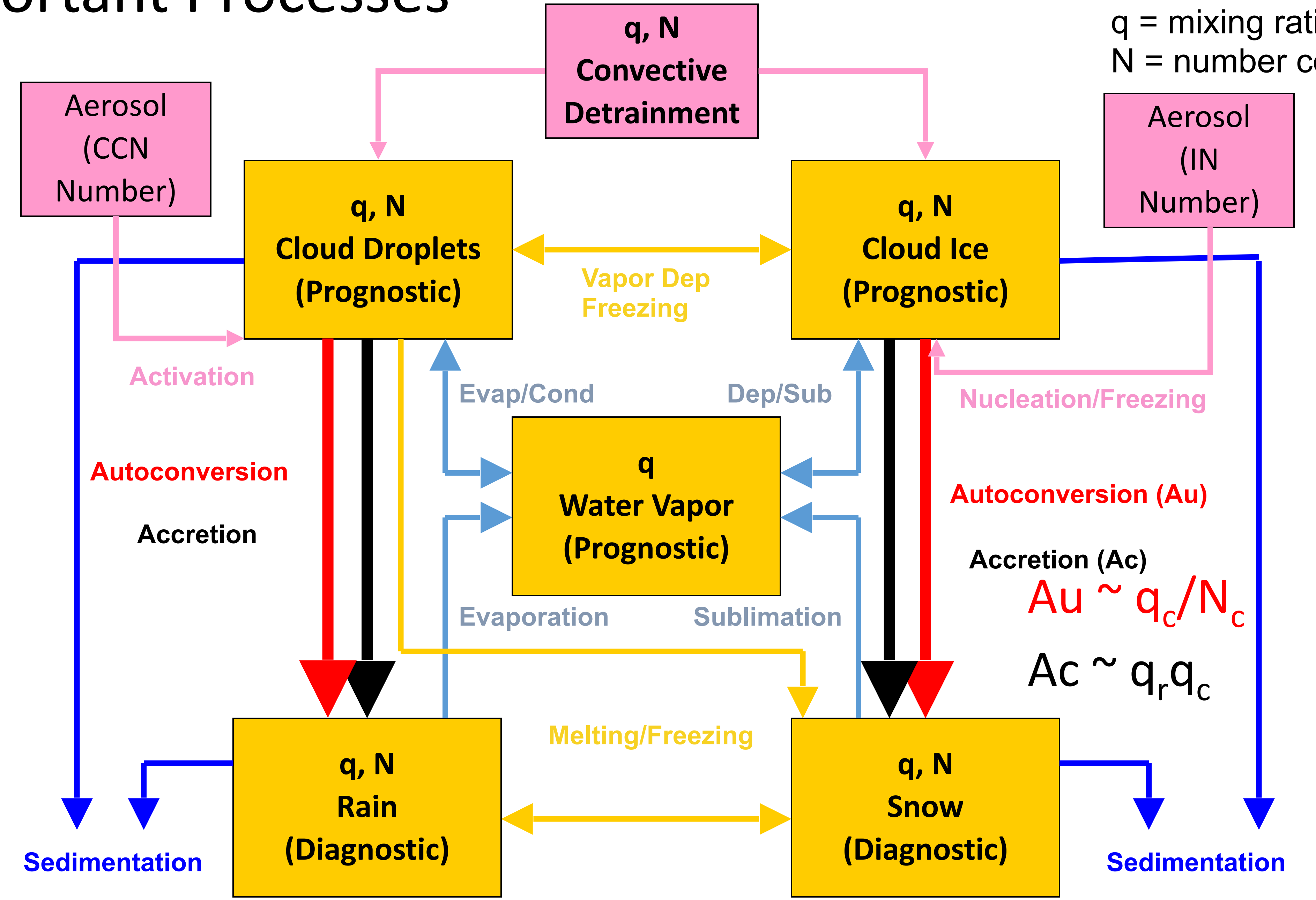



q = mixing ratio
N = number concentration
Sources & Sinks
Morrison & Gettelman 2008
Aerosol (CCN Number)
q, N Convective Detrainment
Aerosol (IN Number)
q, N Cloud Droplets (Prognostic)
q, N Cloud Ice (Prognostic)
Vapor Dep
Freezing
Activation
Evap/Cond
Dep/Sub
Nucleation/Freezing
q Water Vapor (Prognostic)
Autoconversion
Accretion
Autoconversion
Accretion
Evaporation
Sublimation
q, N Rain (Diagnostic)
q, N Snow (Diagnostic)
Sedimentation
Sedimentation

7. Important Processes

Morrison & Gettelman 2008

q = mixing ratio
N = number concentration



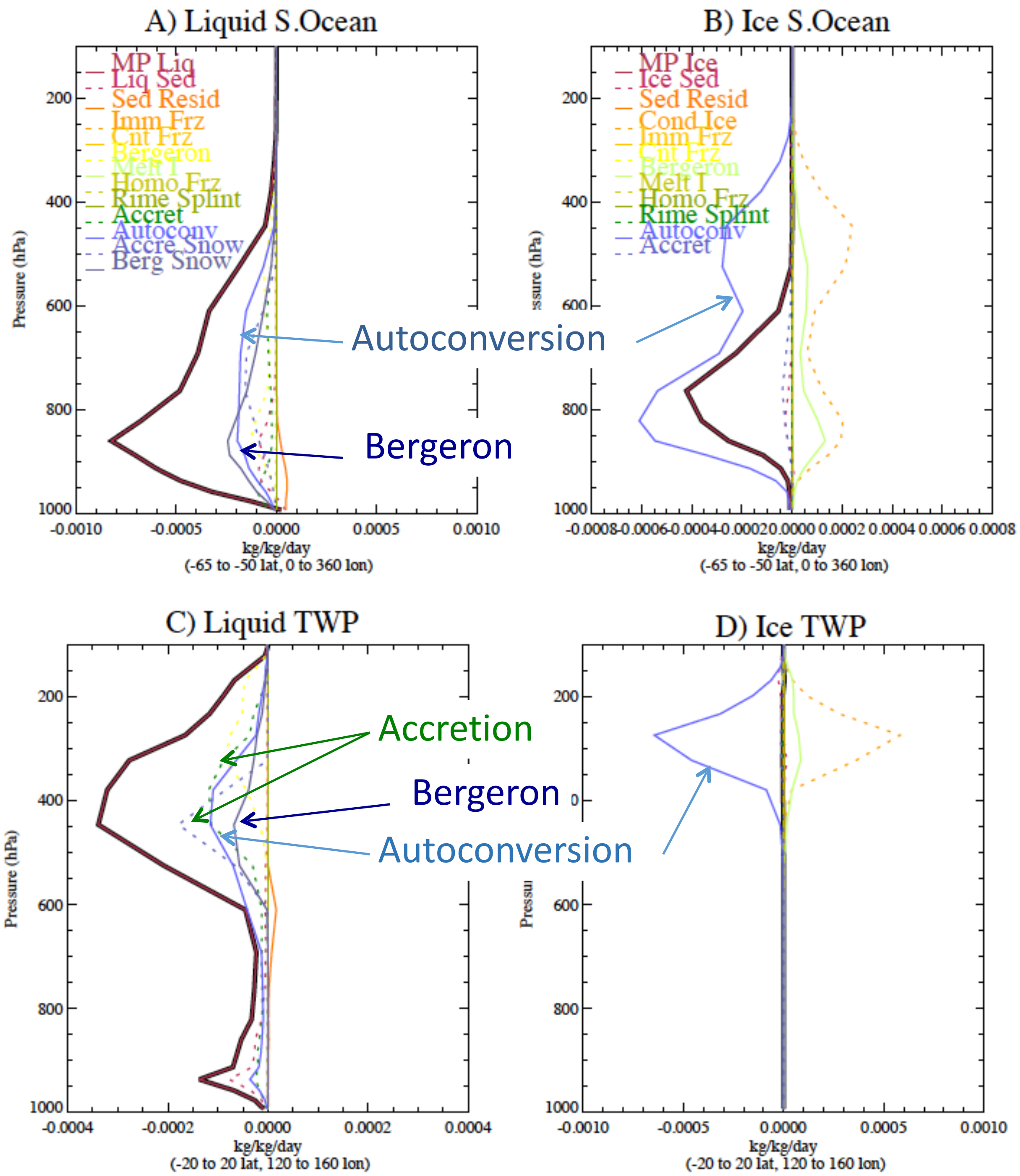
Microphysical Process Rates

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

Autoconversion and Accretion & Sub Grid

- 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

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

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

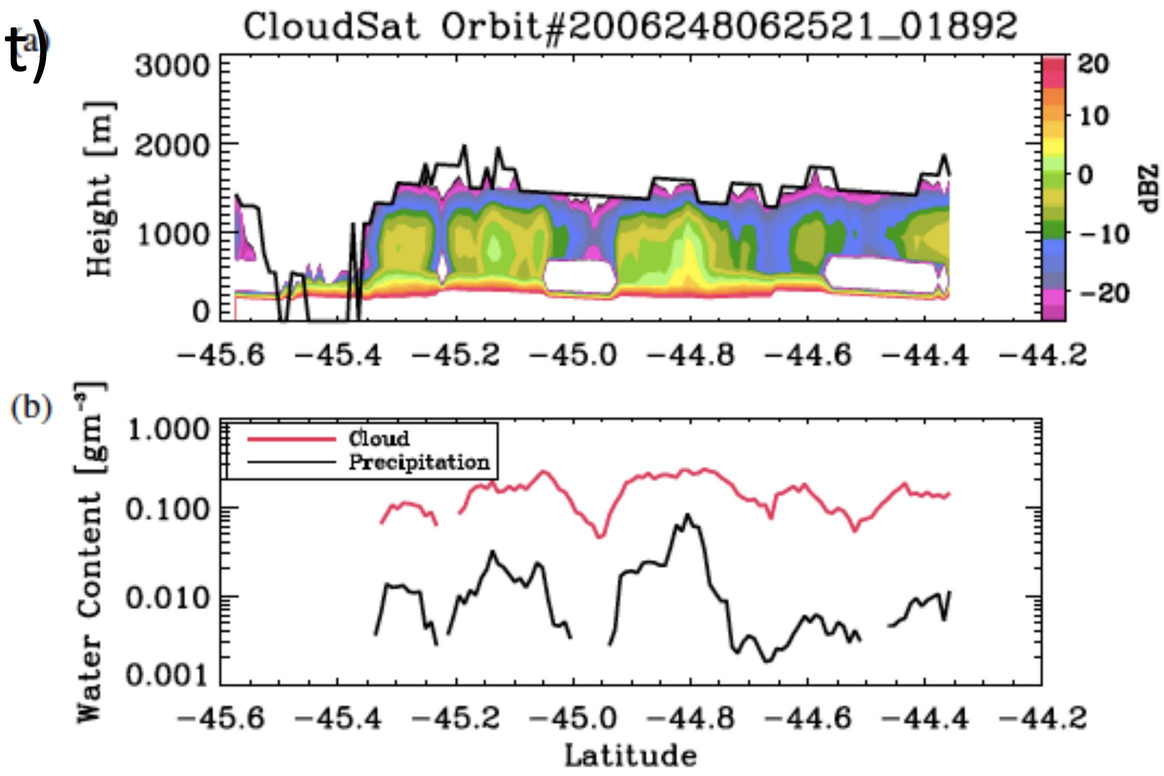
E = Enhancement factor

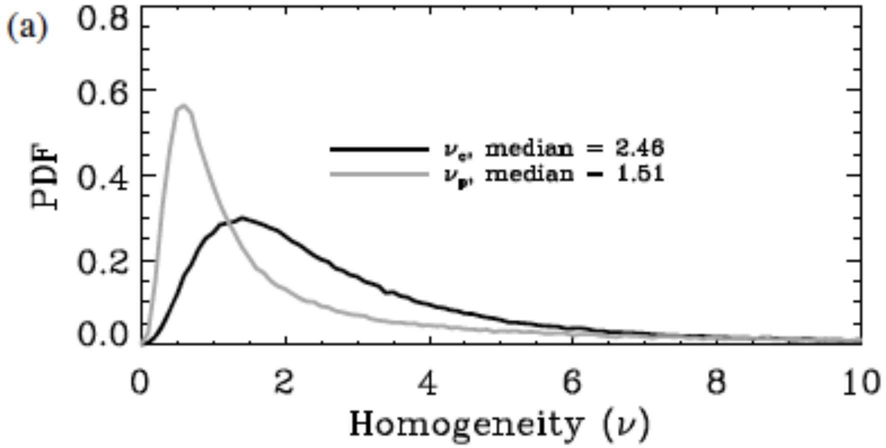
and v_x is the normalized variance $v_x = x^2/\sigma^2$

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

Observing co-variance of cloud and rain

- Observe cloud/rain from satellites (CloudSat)
- Calculate variance, mean and normalized variance (v) or homogeneity
- Yields observational estimate of Ac & Au enhancement factors.

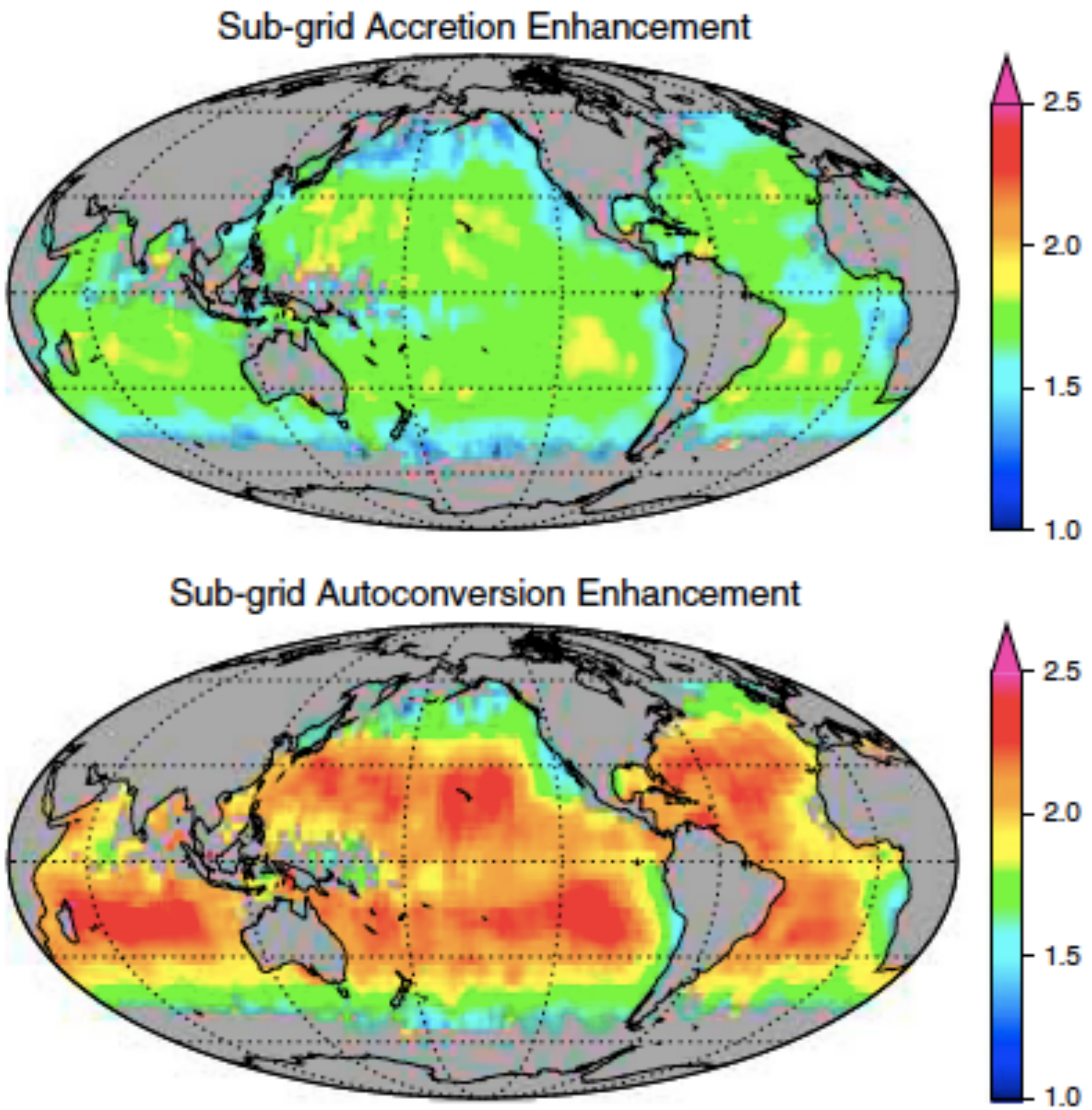




Lebsock et al 2013

Enhancement Factors

- More enhancement in drier regions, and regions with more variance
- Good example of observing higher order effects and sub-grid scale variability from Space
- Also an example of how to use observations to constrain microphysical process rates.



Lebsock et al 2013

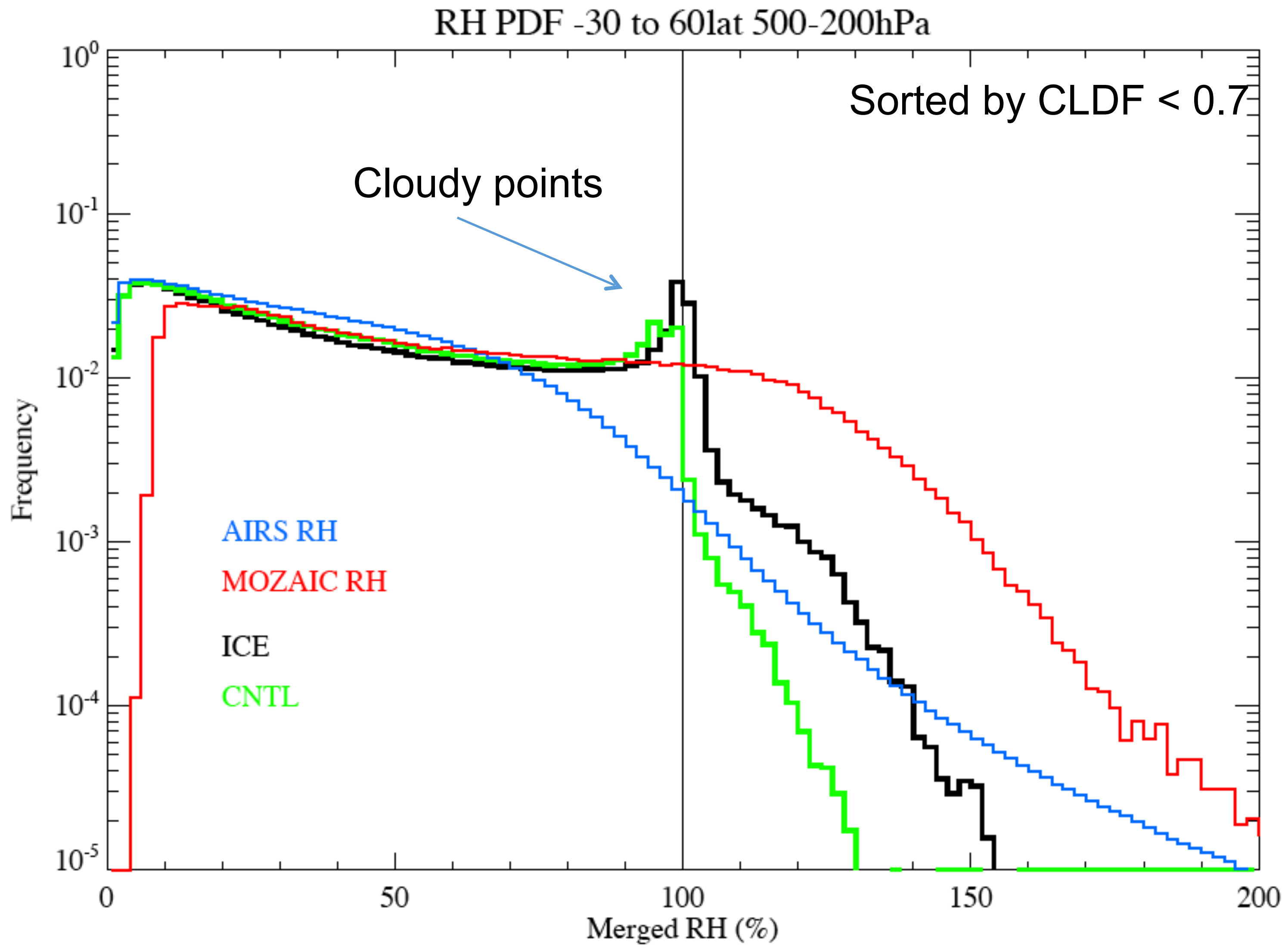
Ice Supersaturation

Observations show the upper troposphere is often supersaturated with respect to ice

Models usually close condensation on liquid and ice saturation.

Some models (e.g. CAM, MG) do not do this, require ice to form from ice nucleation

Allows ice supersaturation (‘ICE’) in figure

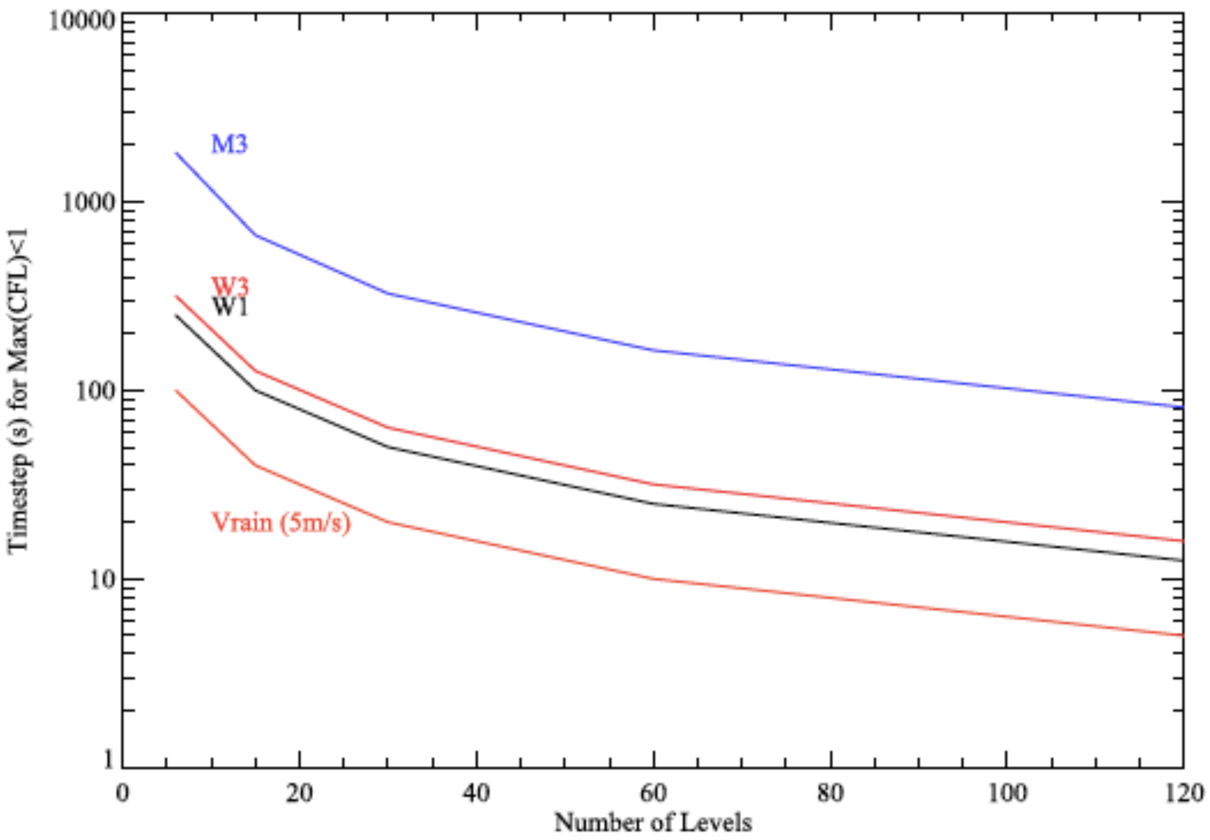


8. Numerical considerations: Sedimentation

- GCM timesteps are long (1800s)
  - If rain falls at 1-5 m/s, then in 1 timestep it crosses several levels
  - CFL problem for sedimentation

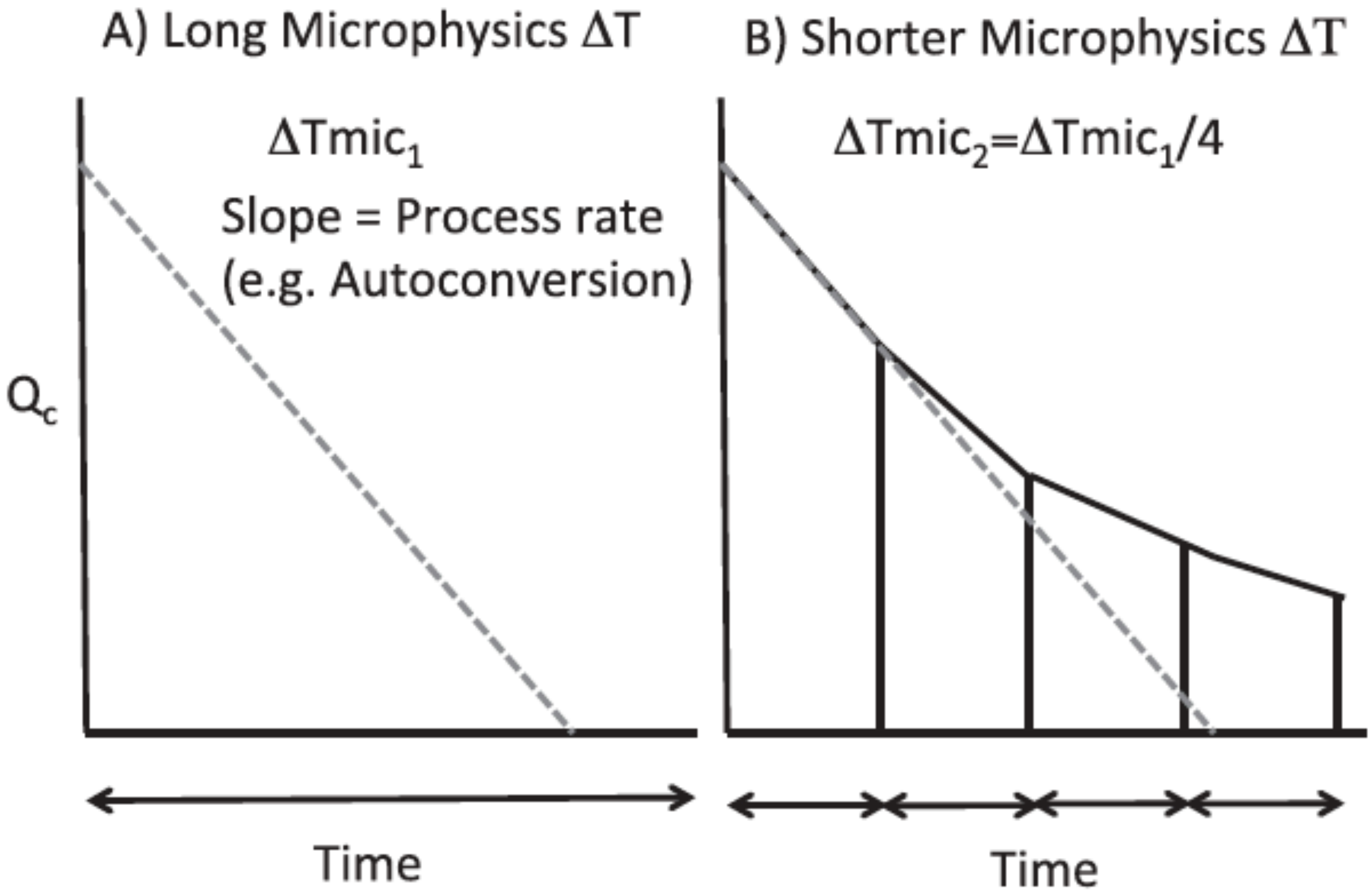
Figure: maximum timestep for satisfying CFL condition with different updraft speeds and fall speeds for rain (5m/s)

Control for this in microphysics (sub-steps)



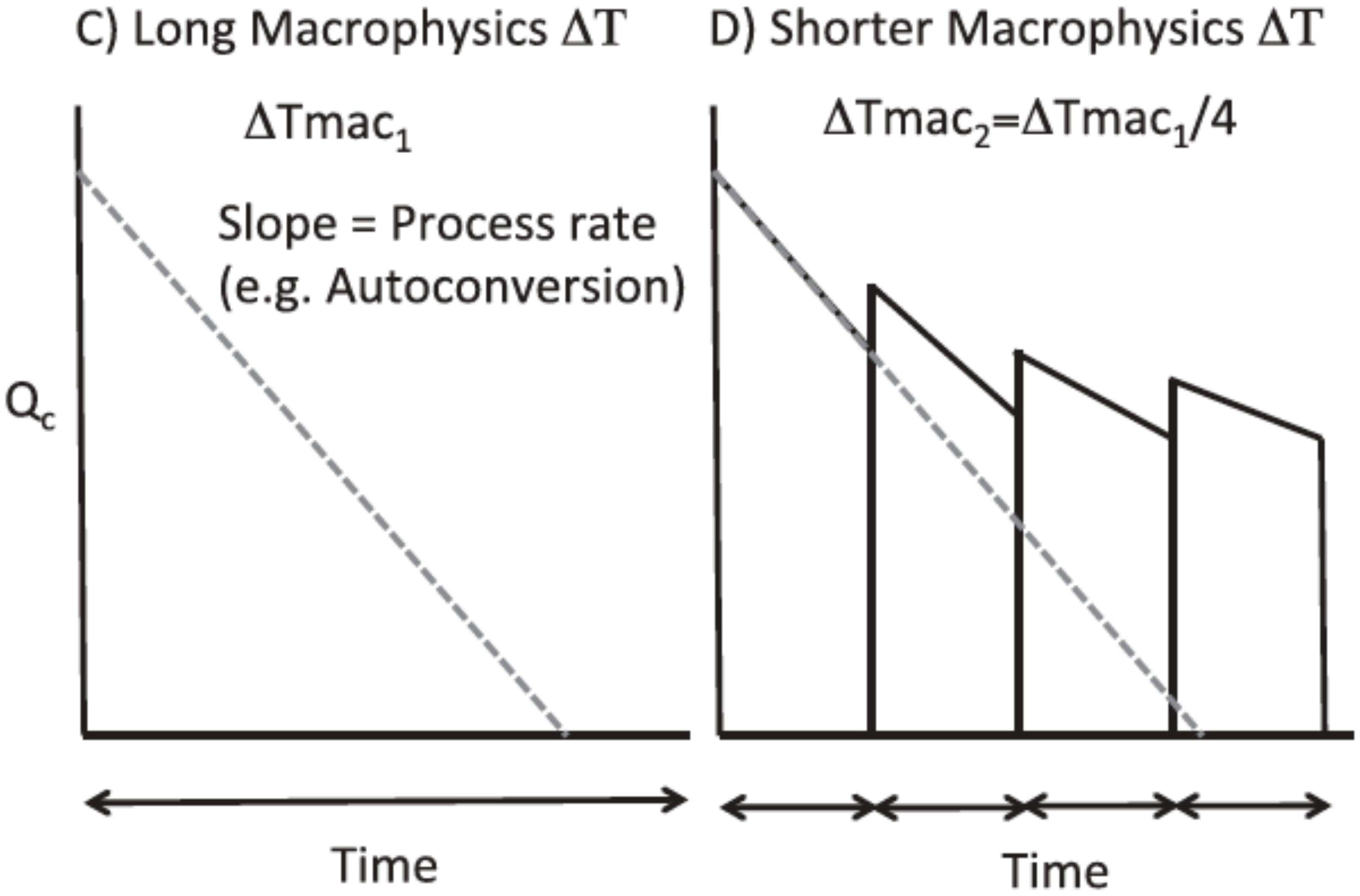
8. Numerical considerations: clipping

- Can also 'run out of water' with long timesteps
- Process rates are non-linear: lots of condensation means more autoconversion
- Shorter timesteps yield a different solution



8. Numerical considerations: coupling

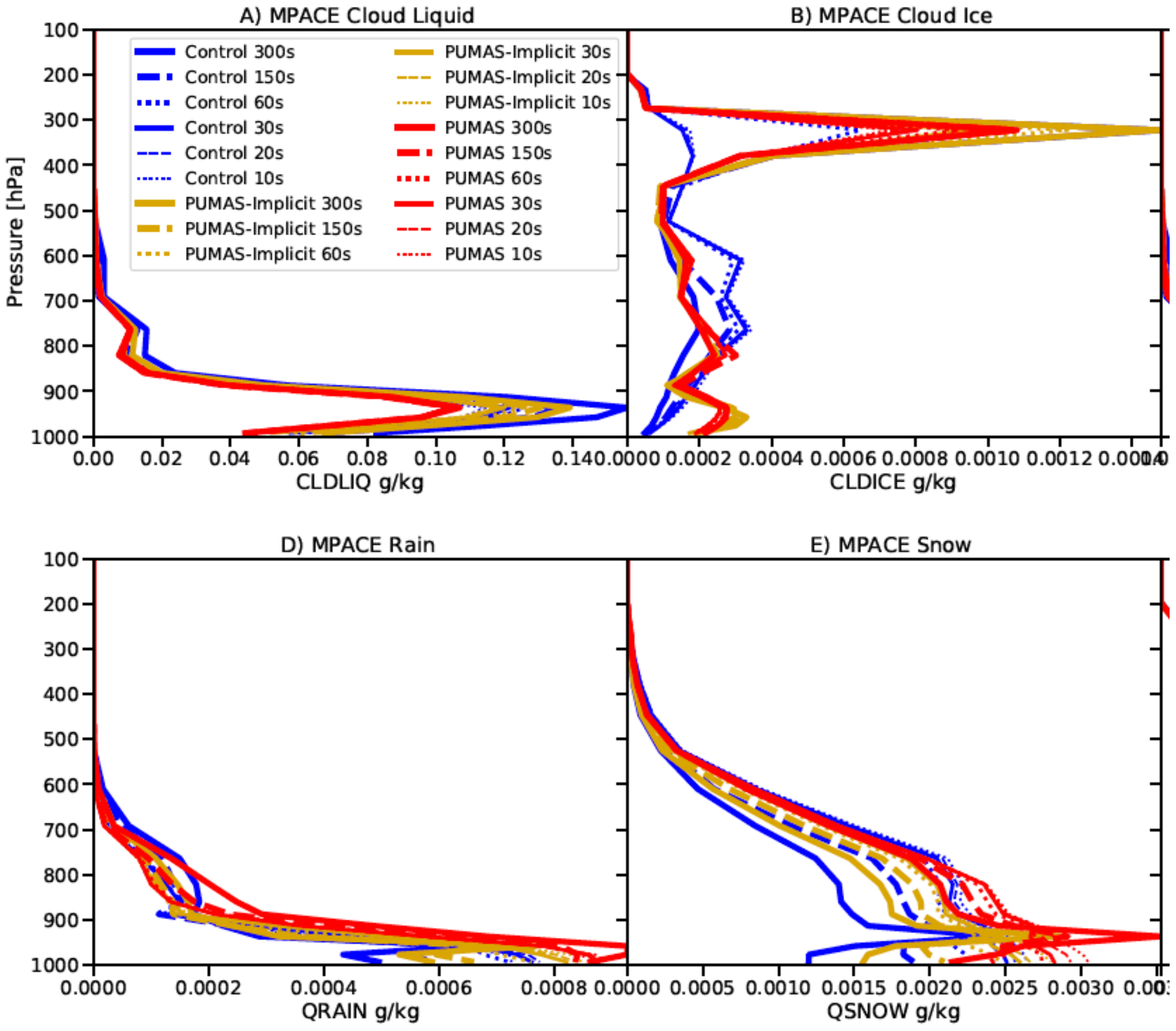
- Similar issues occur with condensation itself, and coupling with macrophysics



Alternatives: Implicit Sedimentation

Testing Numerics

- Explicit sedimentation iterates (substeps) to reduce the timestep for sedimentation
- Alternative is an implicit calculation. More diffusive, less accurate, but does not vary as much with timestep
- Latest versions include option for **implicit sedimentation**: less sensitive to timestep than **explicit sedimentation**



9. Evaluation with Observations

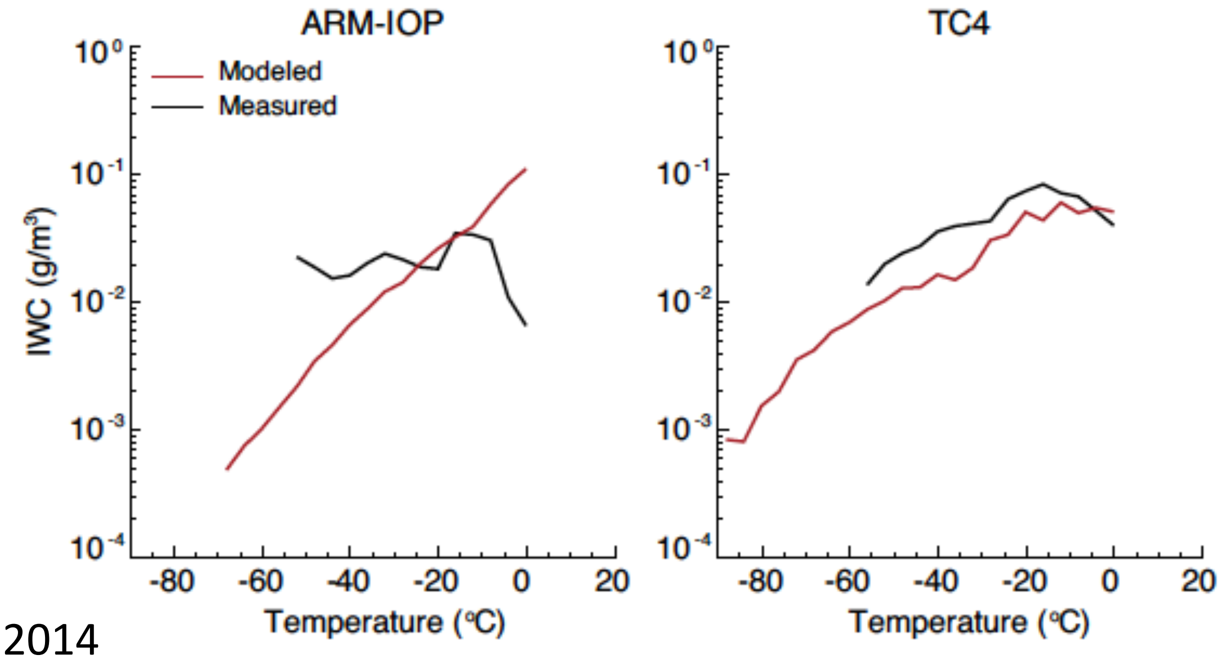
- Size distributions v. In-situ data
- Global Evaluations of Cloud Microphysics
  - Mostly satellite based. Still issues with Satellite date
- Local Evaluations of Cloud Microphysics (In Situ):
  - How to compare a global model to individual observations?
  - Climatology: Ice microphysics
  - Individual Flight comparisons (HIPPO)

Comparisons with observations

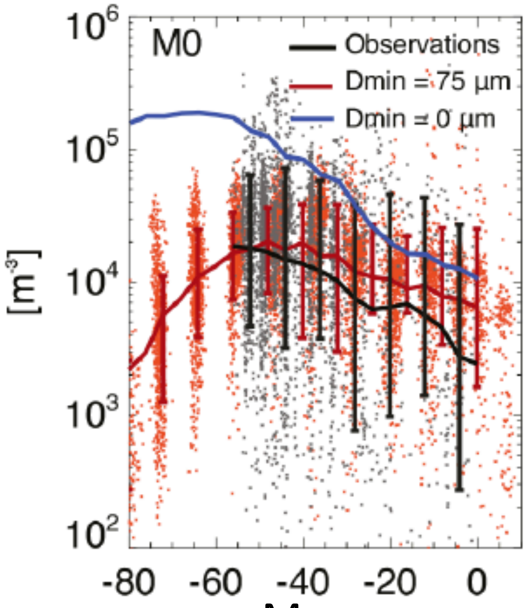
TC4 tropical observations of ice clouds v. temp

- Size distributions (Moments)
- Ice Water Content

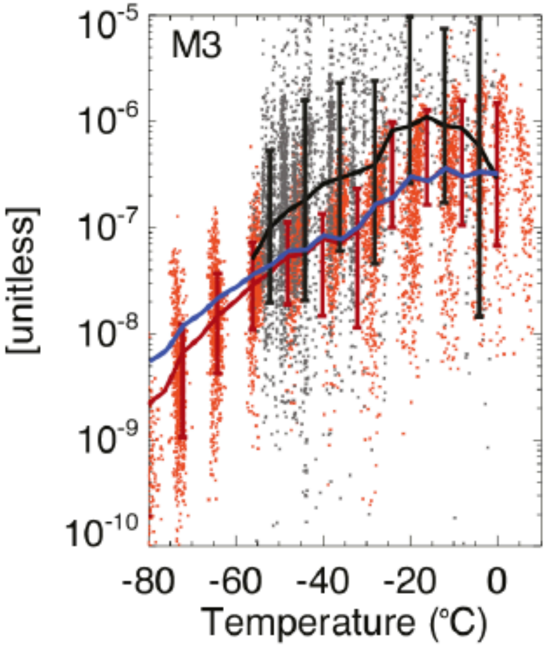
Ice Water Content



Number

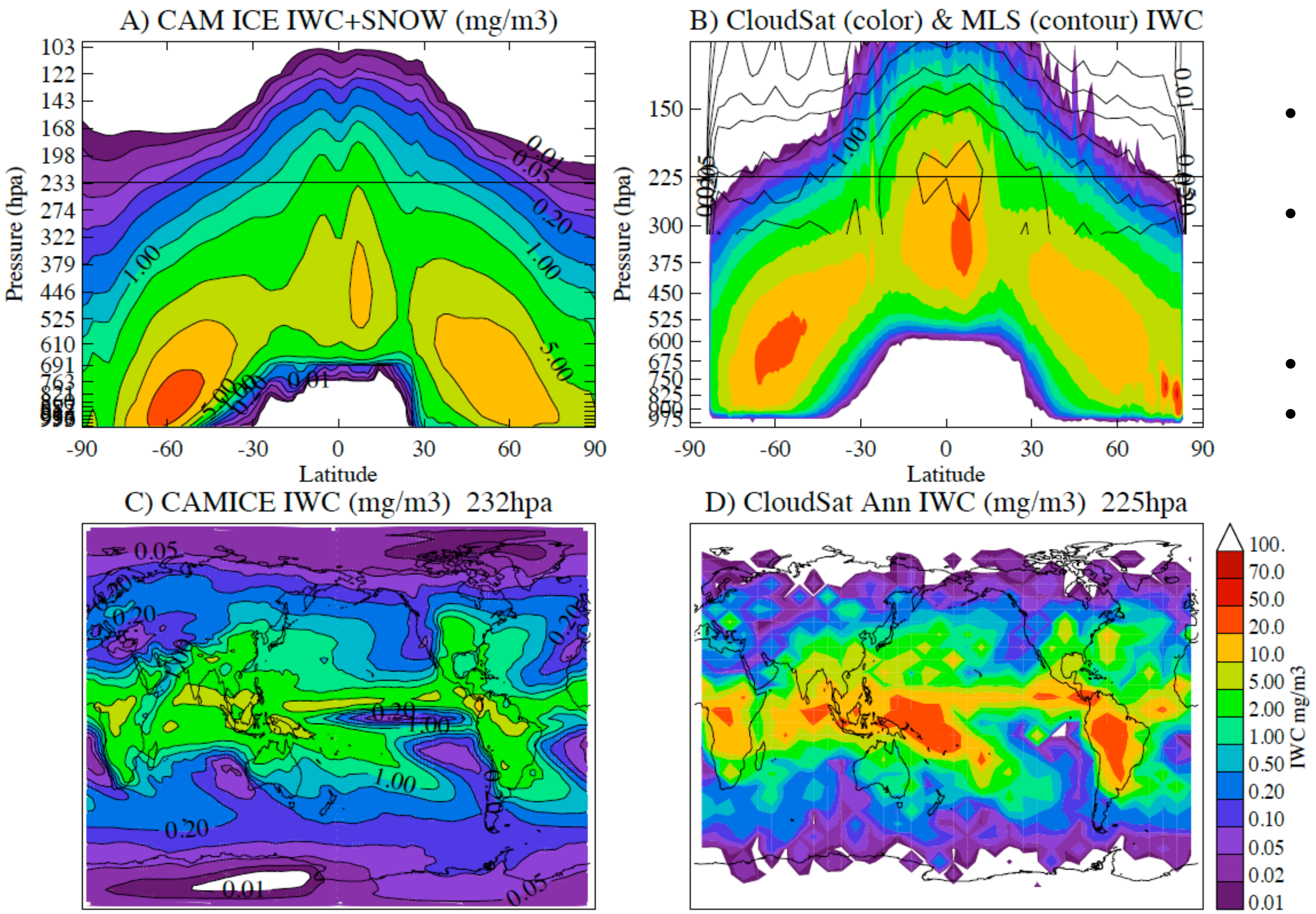


Mass



Eidhammer et al 2014

Evaluation v. Satellites (limited)

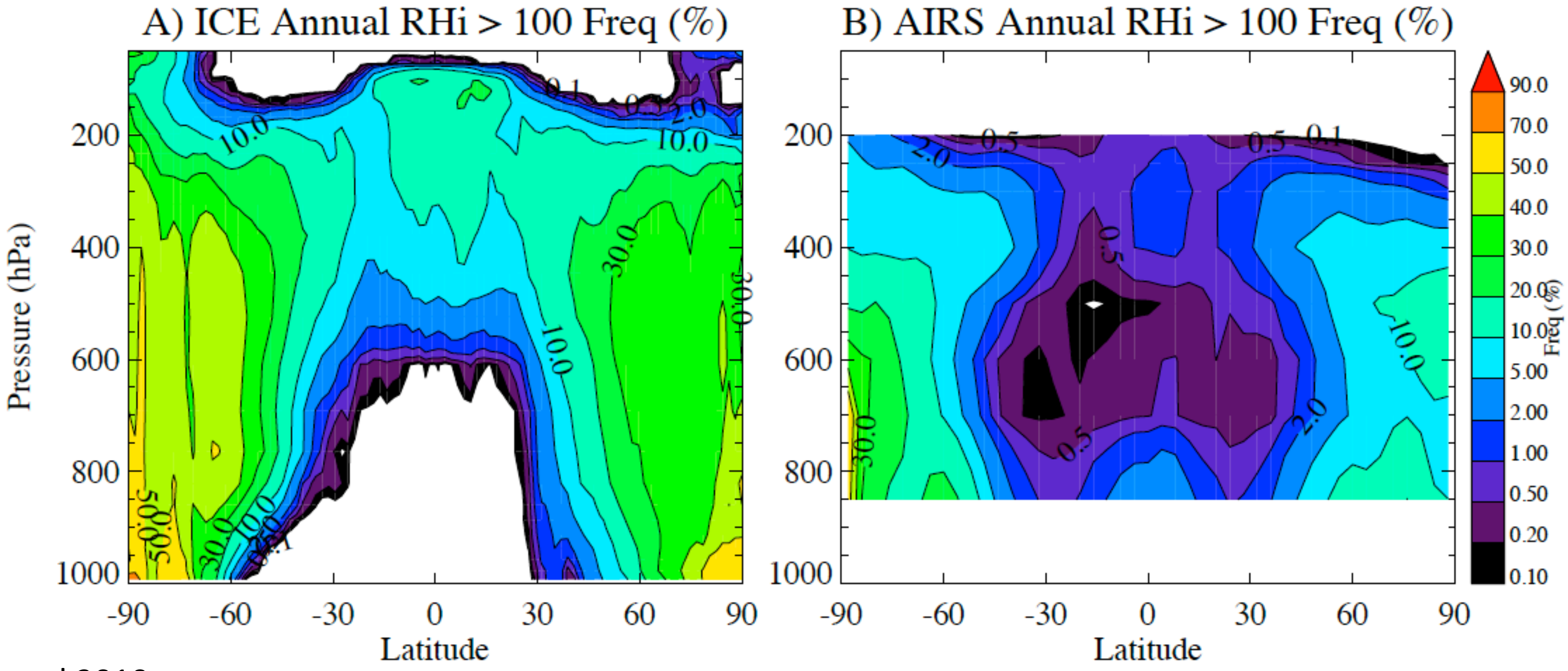


- Comparison between model and Observations
- Note that Observations of ice mass are highly uncertain (factors of 1.5-2 differences)
- Distribution and pattern is similar
- Most of 'mass' is in falling snow

Gettelman et al 2010

Ice Supersaturation Frequency

Unique measurements of T and Q from AIRS at high resolution (50km) yield RH

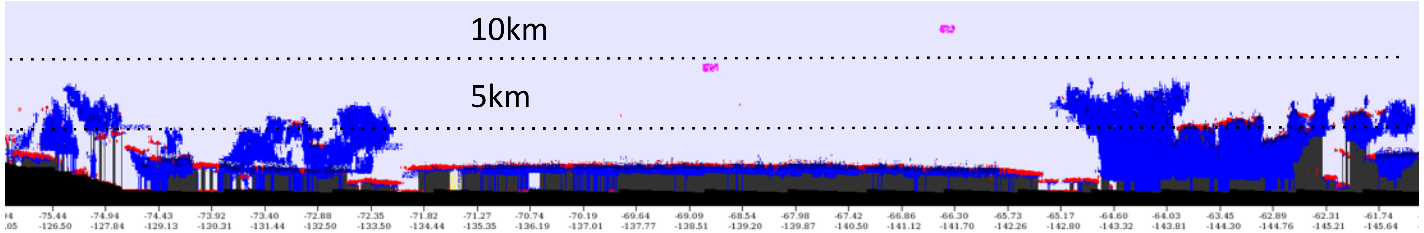


Gettelman et al 2010

Satellite Super-cooled Liquid

Another unique measurement: Co-located Radar and Lidar
Radar sensitive to size (sees large ice v. liquid) and solid ice shows up well on Lidar

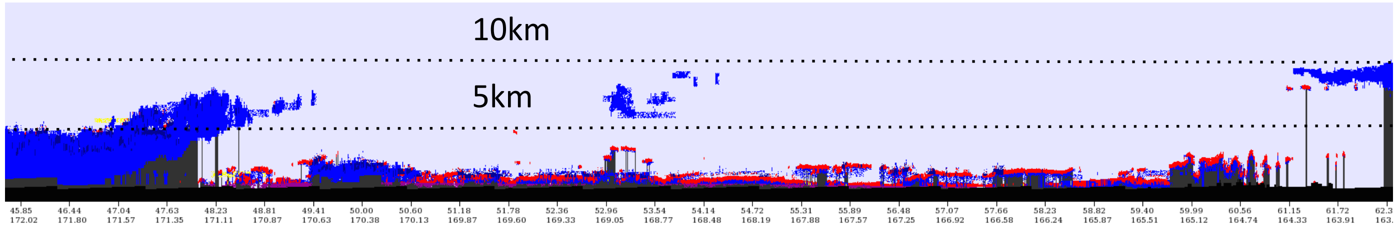
2013-01-01 S. Ocean (S. Of Pacific)



70S 61S

Liquid Ice Supercooled

2014-02-07 N. Pacific



45N 60N

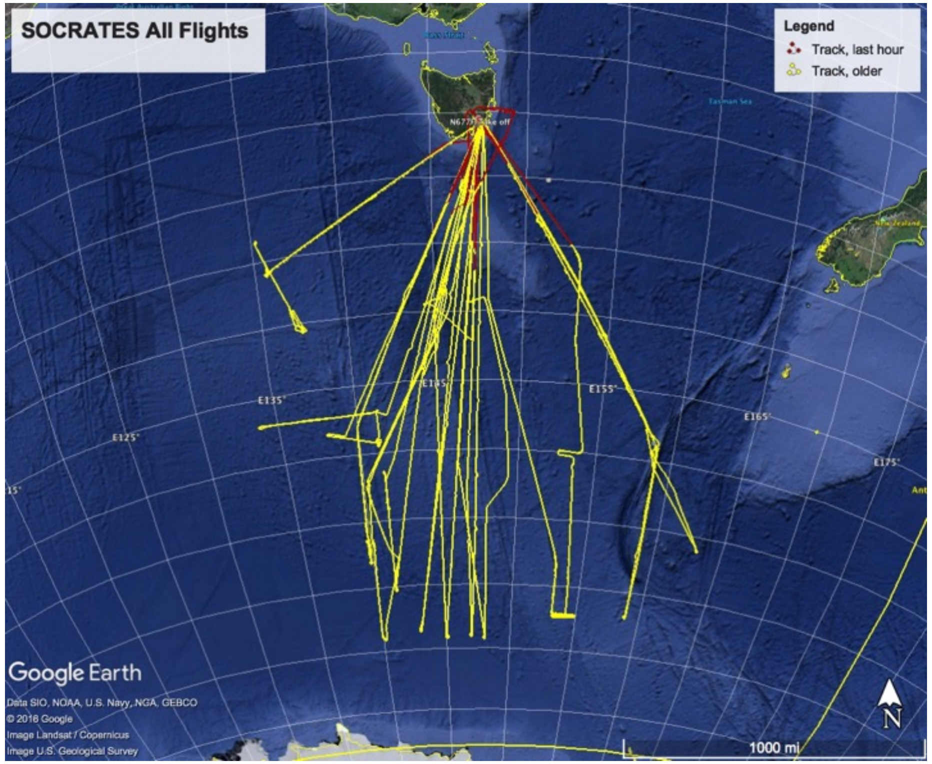
Most thin layers of super-cooled liquid over ice
Radar & Lidar (CloudSat + Calipso) product

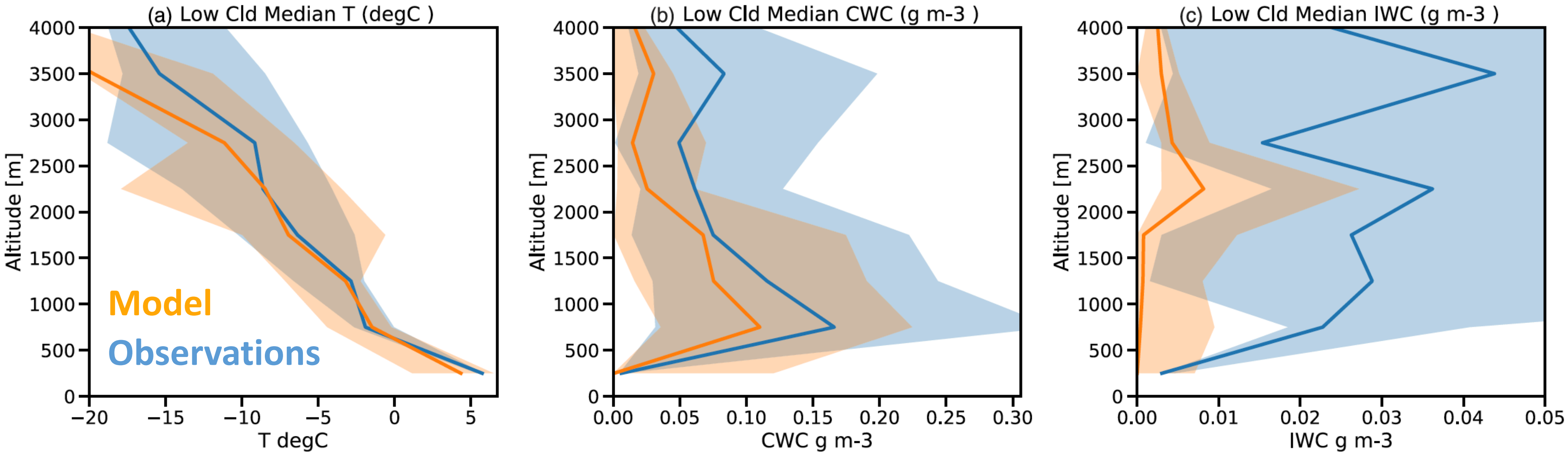
Cloud Phase

SOCRATES in-situ flights over the S. Ocean used to understand & improve models

CAM6: Too little ice. This contributes to high climate sensitivity.

Looking at modifications now



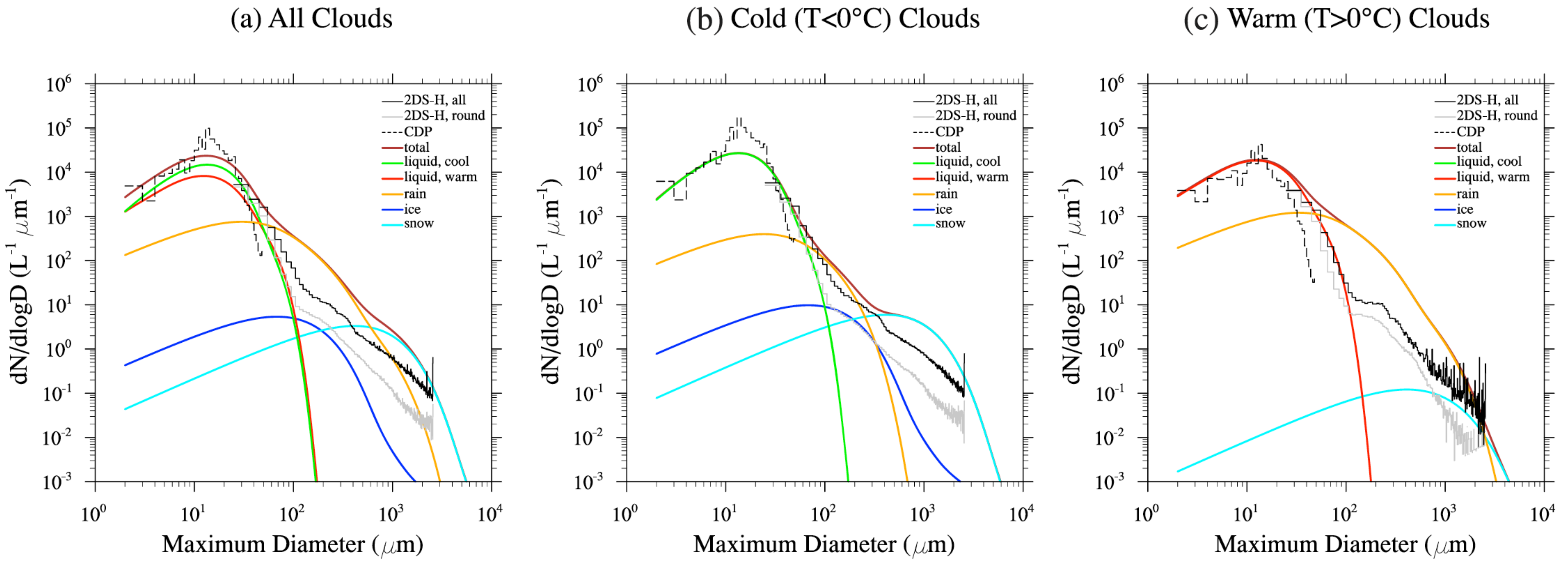


Gettelman et al 2020

Microphysics, Size distributions

Advanced GCMs/GSRMs can be compared directly to cloud microphysical size distributions (here from SOCRATES).

Comparison is GCM cloud microphysics along aircraft flight tracks with in-situ data

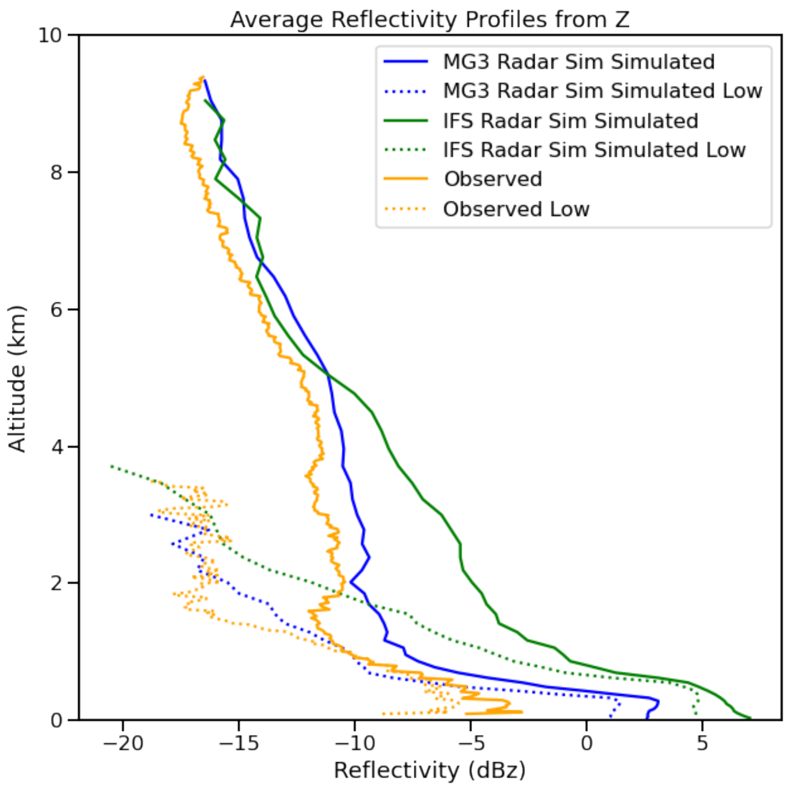


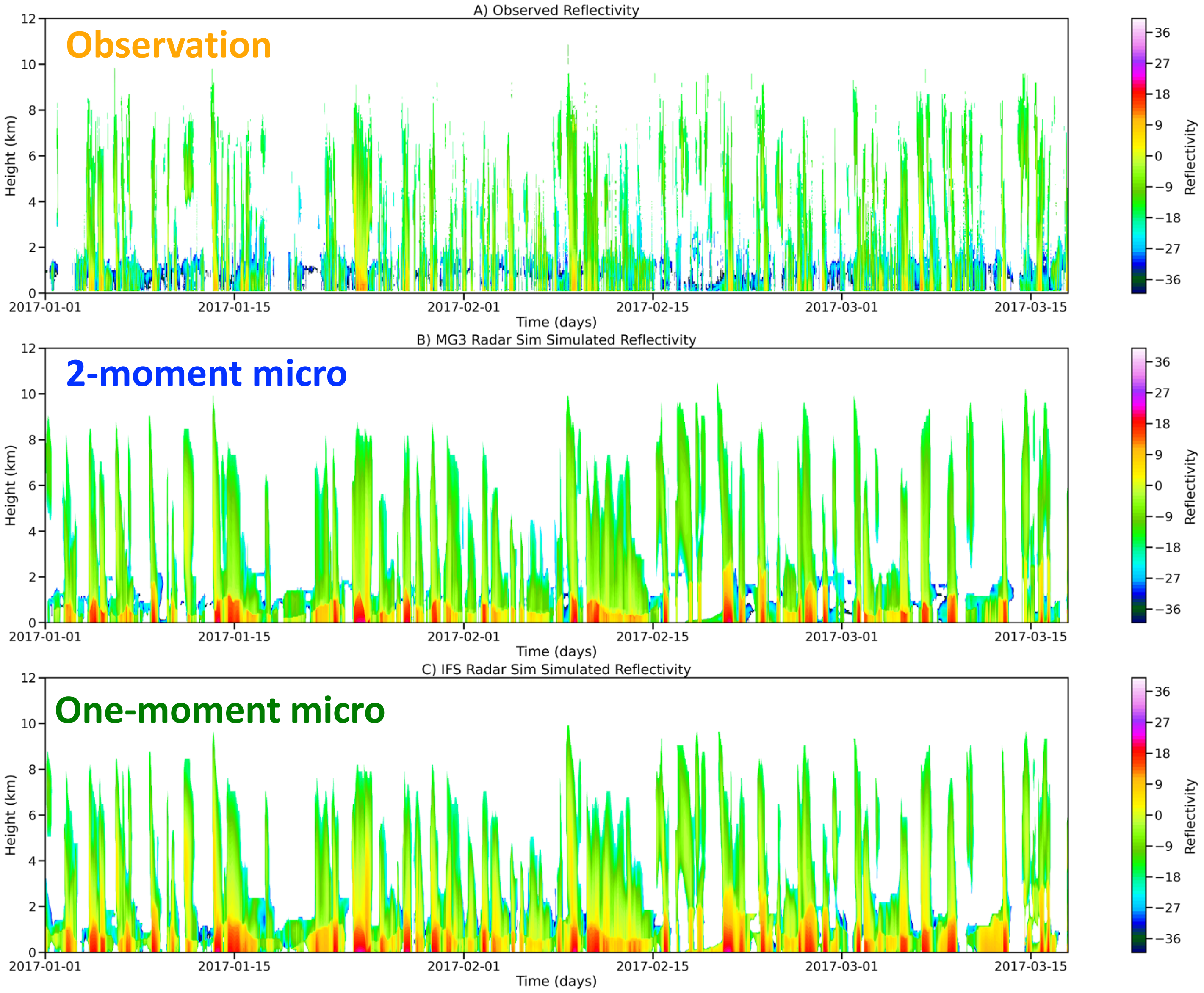
Note potential issue with too large rain sizes

Gettelman et al 2020

Microphysics: Comparing to Reflectivity

Comparisons over Macquarie Island in S. Ocean between a **precipitation radar** and single column simulations with **one-moment** and **2-moment** microphysics in the ECMWF-IFS SCM.





Gettelman, Forbes, Fielding, in Press GMD, 2024

10. Interactions with Aerosols

Clear sky in Beijing, Mon, Sept 19, 2006, 06:00 LT looking west

10. Interactions with Aerosols

Clear sky in Beijing, Thurs Sept 22,2016 ,06:00 LT looking west

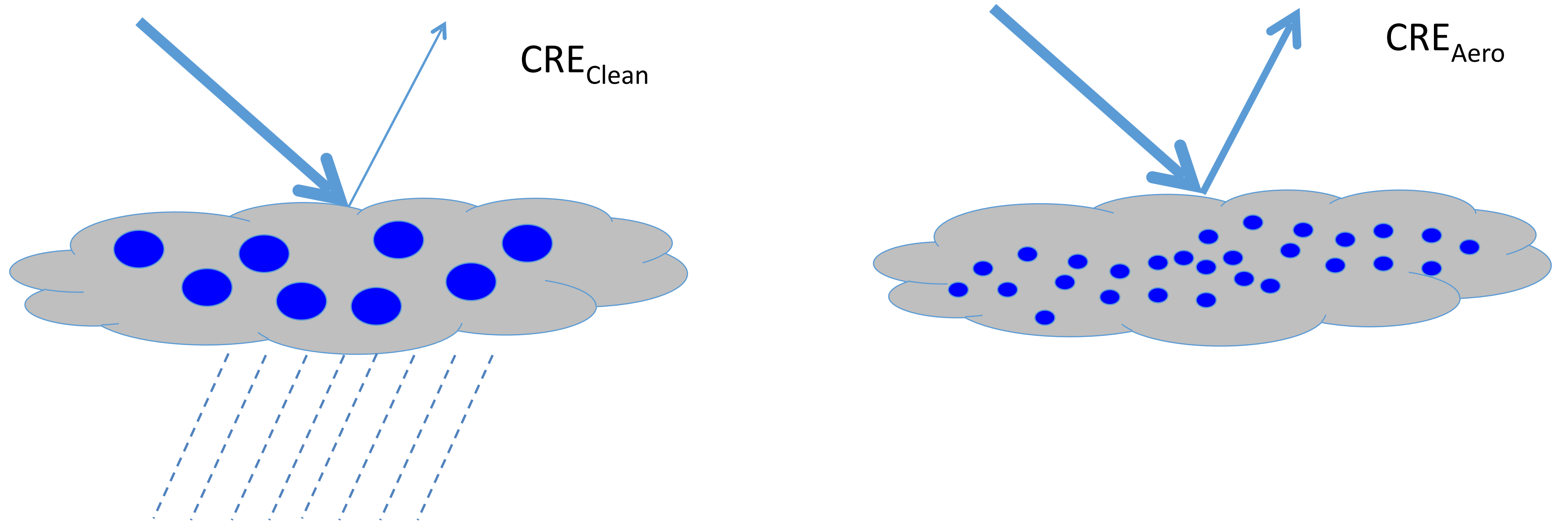
Microphysics is affected by aerosols

- Activation of aerosols control drop number
- Drop number impacts auto-conversion and accretion, radiation
- This affects precipitation, cloud lifetime and cloud water
- “Aerosol Cloud Interactions”
- Highly uncertain…

Aerosol Effects on Clouds

- Scattering & Absorption = Direct effects
  - Beijing picture
- Aerosol – Cloud – Interactions (ACI)

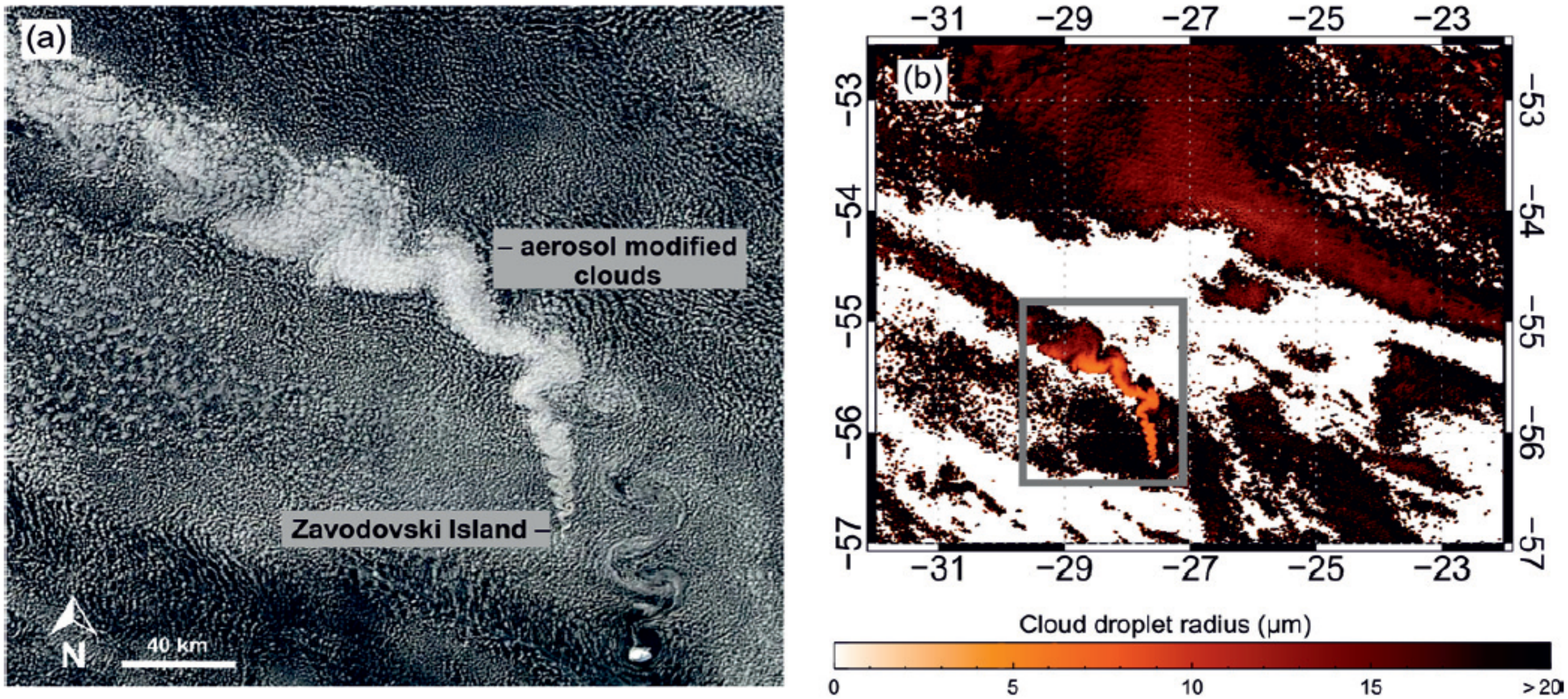
$$+\text{Aerosols} \rightarrow +\text{CCN} \rightarrow +N_c \rightarrow \Delta\text{CRE}$$



Net Cooling Effect: brighter clouds
Also: delay in precipitation. Longer lived Clouds?

‘Volcanic Tracks’

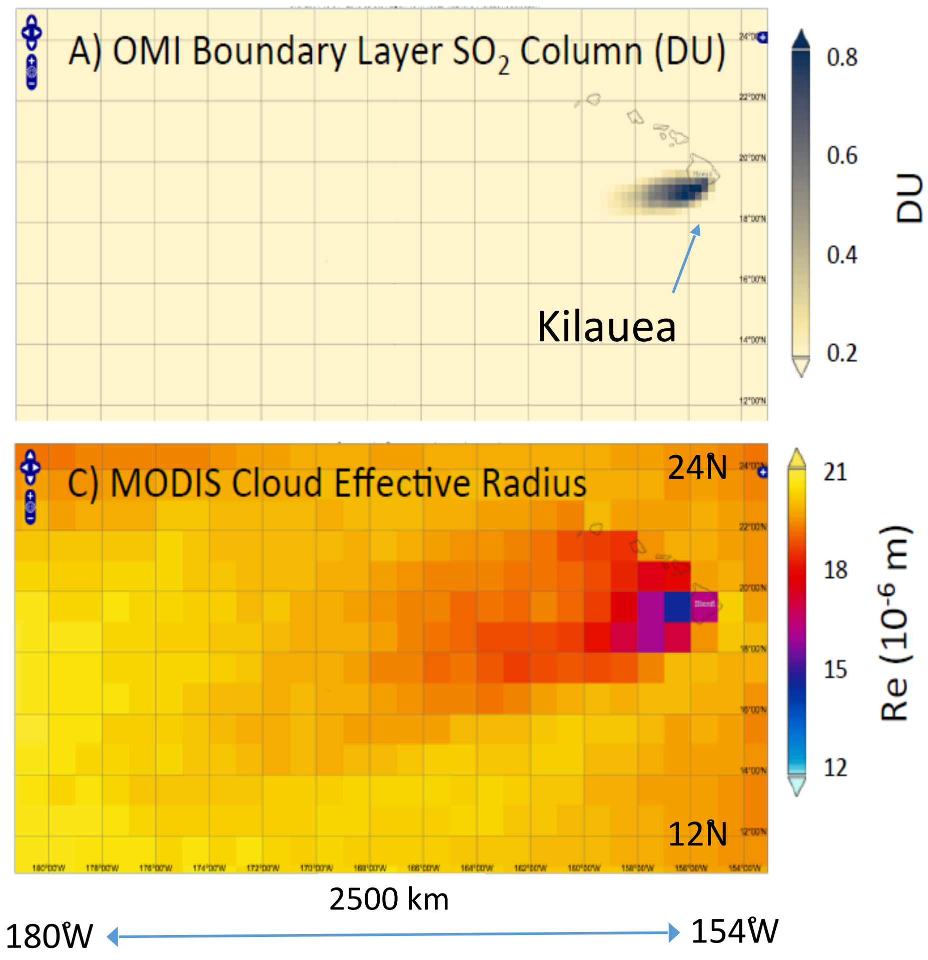
SO_2 emissions from Effusive Volcanoes Brighten Clouds

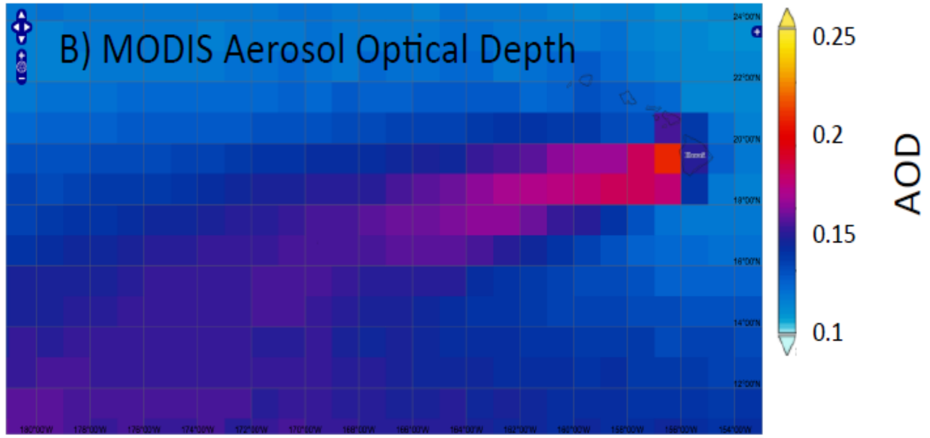


S. Sandwich Islands (Between S. America & Antarctica)

Schmidt et al 2012

‘Volcano Tracks’: Satellite Climatology



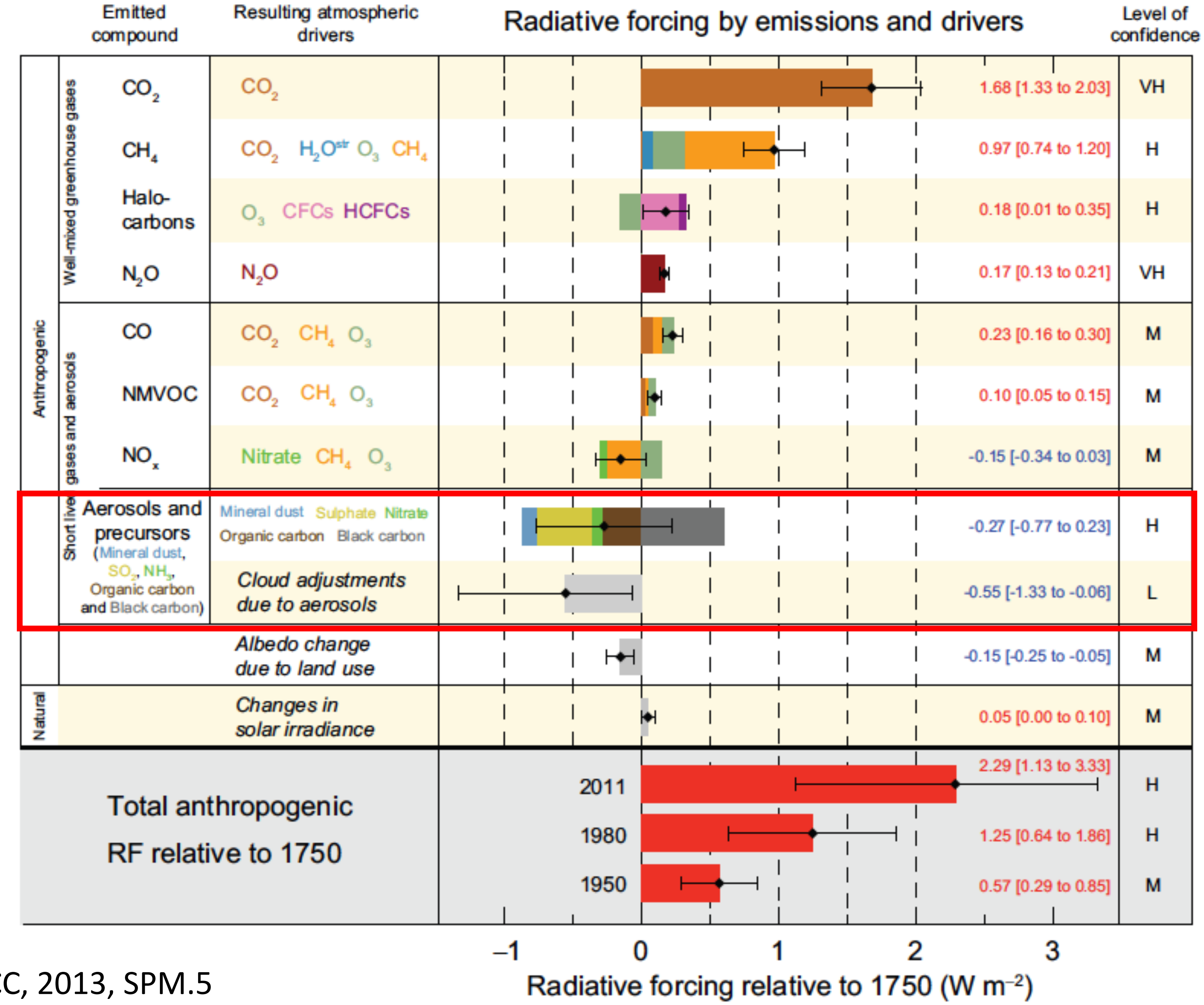


Satellite data for C. Pacific, 10 year climatology around the Hawaiian Islands

SO_2 is from Kilauea Volcano on Hawaii (Small-Griswold & Gettelman, in Prep)

Climate Forcing

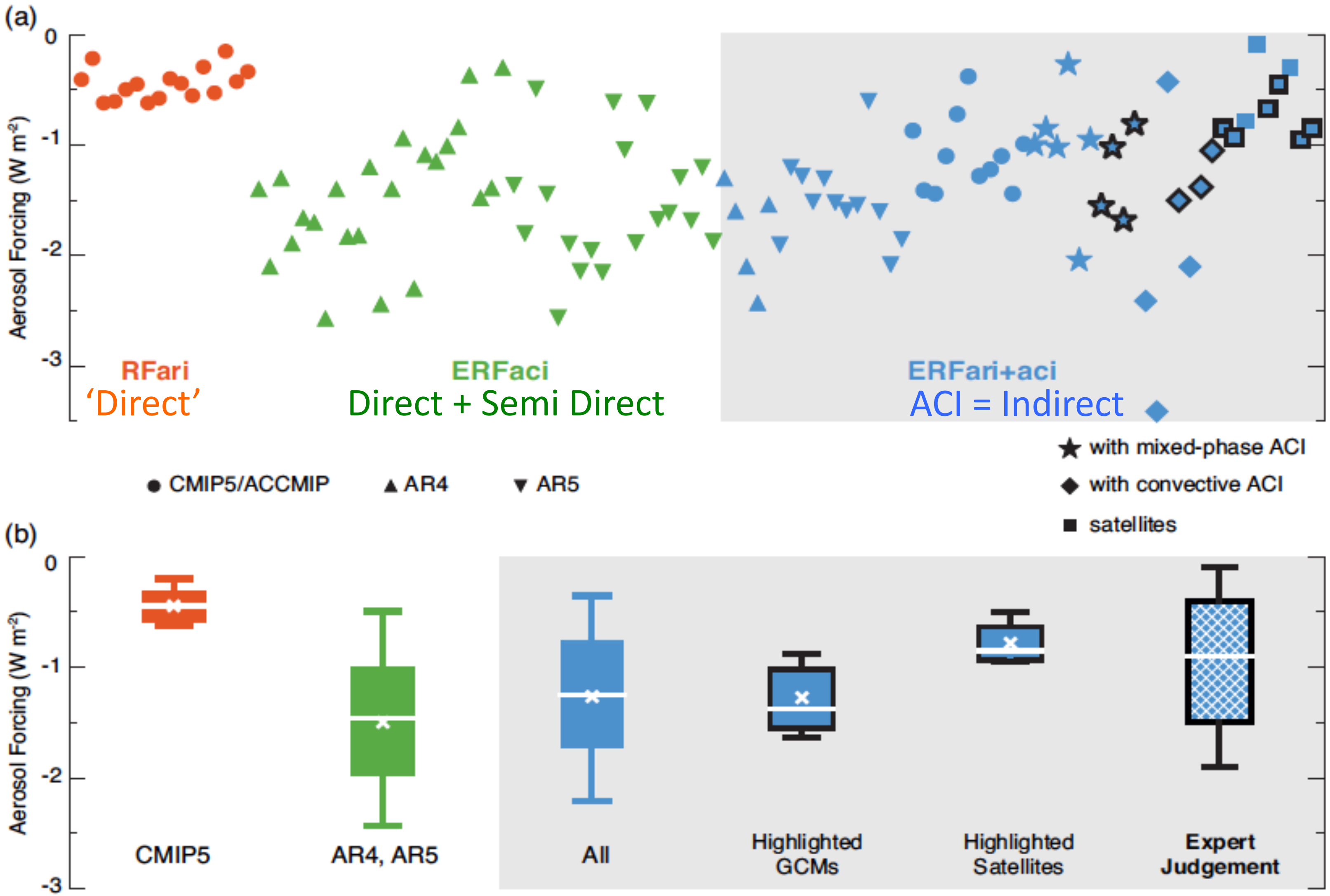
Aerosol Cloud interactions are the largest uncertainty ir Climate forcing



IPCC, 2013, SPM.5

Aerosol Effects: Present – Preindustrial Forcing

- Large uncertainties
- Difference between models and estimates from observations
- Models have a larger effect than observed
- Why? Either:
    - Obs are incorrect
    - Microphysics is missing something
- What is missing? ‘buffering’: e.g. evaporation feedbacks?



Boucher et al 2013, Figure 7.19

10. Interactions with Radiation: Liquid

- Cloud Radiative Effects related to Albedo

$$A = C\frac{\tau}{\beta+\tau} + (1-C)A_b,$$

- Albedo depends on optical depth (τ) and cloud cover/fraction (C). β = constant
- τ a non-unique function of size and mass

$$\tau = \alpha N_c^{1/3} L_c^{5/6}, \qquad \alpha = 0.19.$$

Seifert et al 2015, JGR

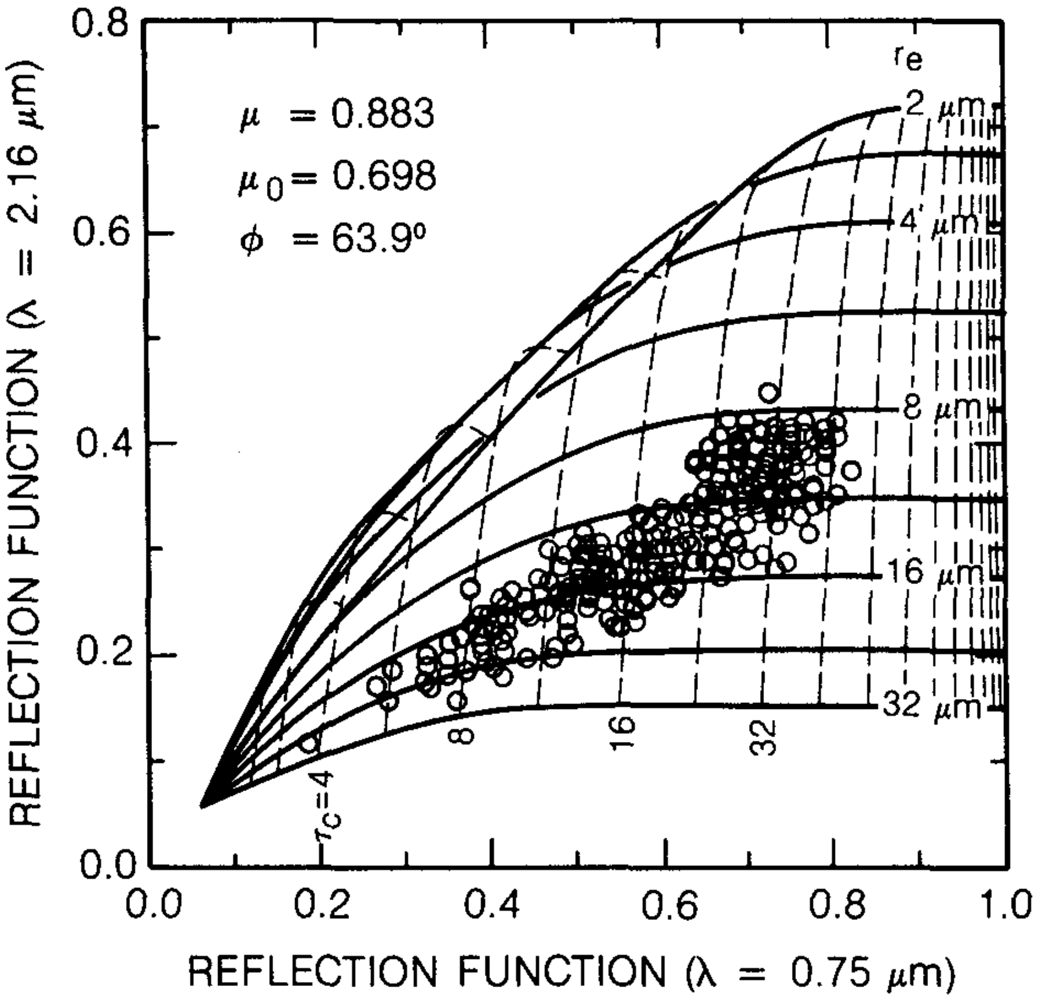
- Droplets well constrained (CAM6: self-consistent)
- Note: significant implications for OBSERVING cloud microphysics

Aside: observing cloud microphysics

- Satellites observe τ in some wavelength (even active sensors)
- τ is a non-unique function of N (or r_e), LWP

$$\tau = \alpha N_c^{1/3} L_c^{5/6}$$

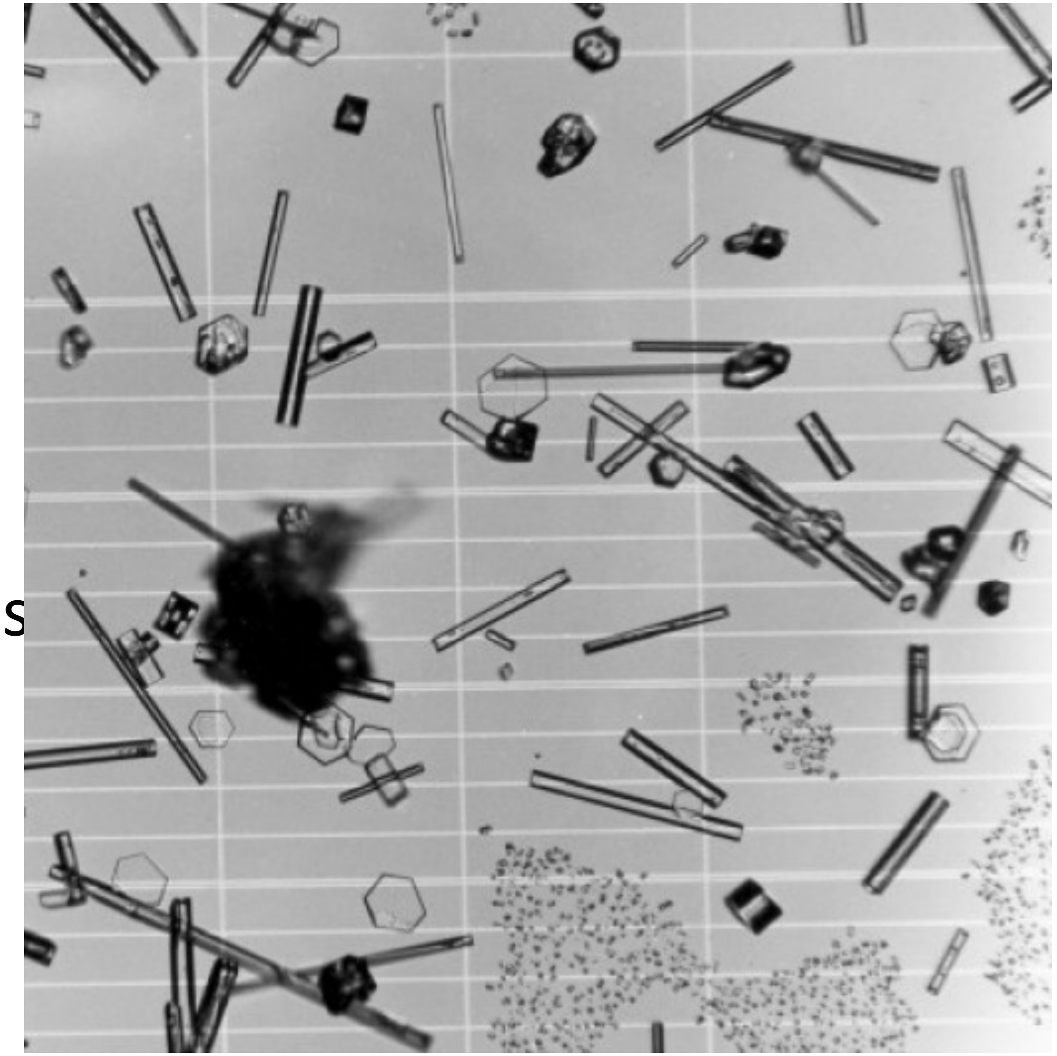
- To determine cloud microphyiscs (N, LWP), need to make an assumption (e.g. adiabatic)
- Better: IR more sensitive to r_e, microwave more sensitive to LWP
- Still large uncertainties (even for liquid)



Nakajima and King,, JAS, 1989

Interactions with Radiation: Ice

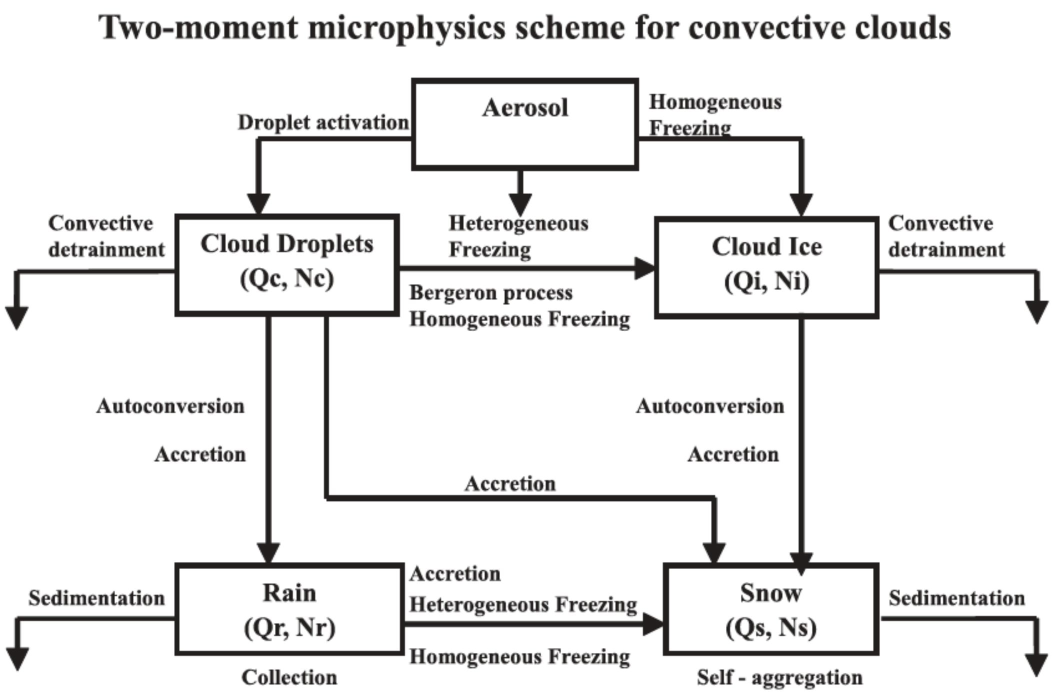
- Ice is more complicated
- It’s not spherical: different ‘habits’ have different optical properties
- Ice clouds are typically a collection of habits
- Impacts optics (absorption, scattering), als sedimentation



11. Latest Developments/Options

Microphysics in cumulus parameterization

- Large scale models also typically have a ‘convective’ or cumulus cloud parameterization.
- Usually diagnostic, estimate mass fluxes, precipitation and detrainment
- Can be used to estimate microphysical rates
- Methods: Convective mass fluxes supply the condensation. Calculation going upwards for condensation & activation. Then downward (same as stratiform)



Song and Zhang 2011,2012

Machine Learning the Warm Rain Process

Can we do the warm rain process better with Machine Learning?

Replace traditional GCM bulk rain formation with a bin model formulation for stochastic collection. This is too expensive for climate use. So emulate it with a neural network.

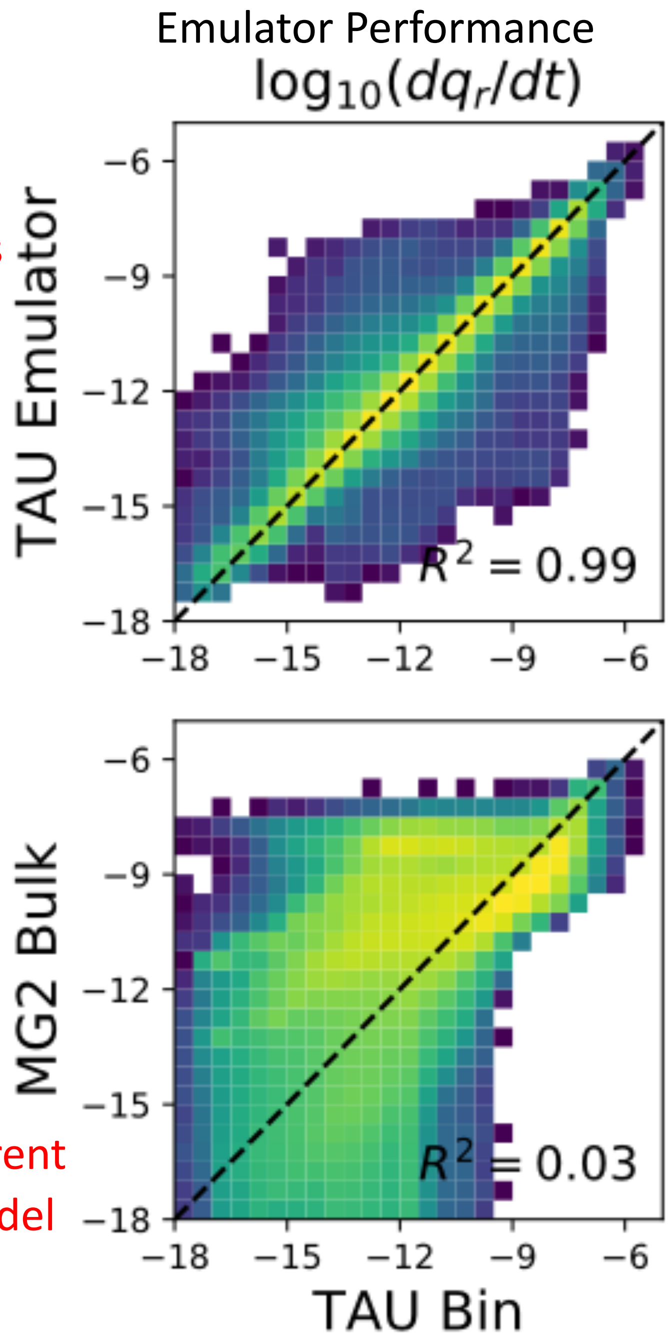
Results:

- We can change the answer in the model with the bin code.
- Very slow when using full treatment
- Recover speed and recover results with a neural network emulator (it works)
- Embedded NN in the microphysics: maintains conservation with series of checks

Gettelman et al 2021, JAMES

NN Emulator reproduces detailed code

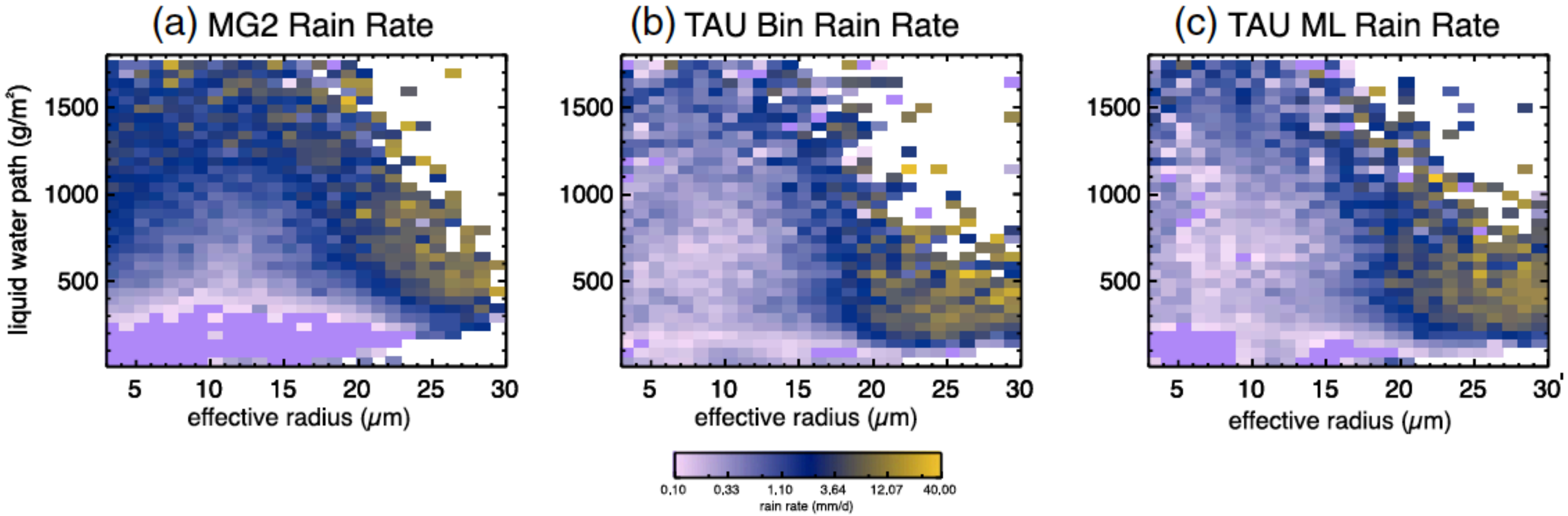
Bin code is Different than original model



Improving results with Machine Learning

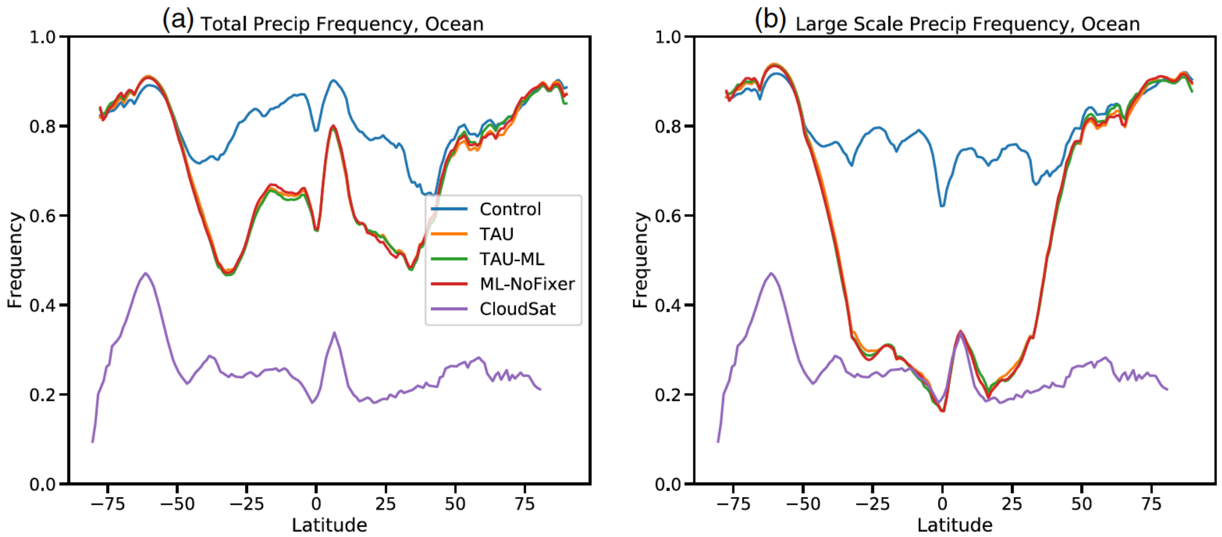
Replace autoconversion and accretion in a bulk scheme with stochastic collection with a bin scheme. Then emulate that with a neural network.

Reduces rain rate for small drop sizes but large LWP



Precipitation Frequency

Control v. **Observations** and
Bin precipitation and **ML Emulator.**
Using stochastic collection from a bin scheme improves large scale precipitation frequency in shallow clouds



Gettelman et al 2021, JAMES

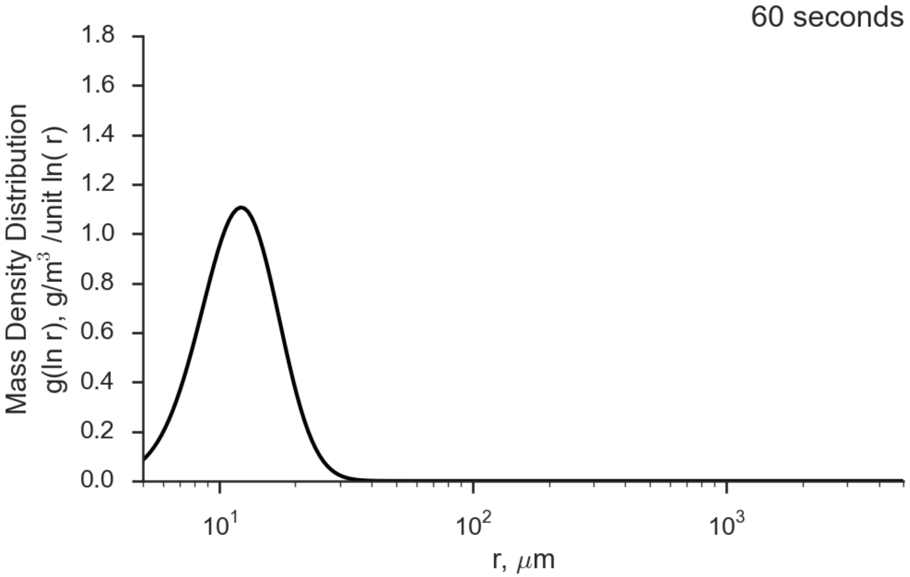
Alternatives: Unified Ice

Liquid and rain nearly ALWAYS form two distinct distributions

Not so for ice, so separation of ice and snow is a bit arbitrary

Several schemes have worked to unify ice and snow

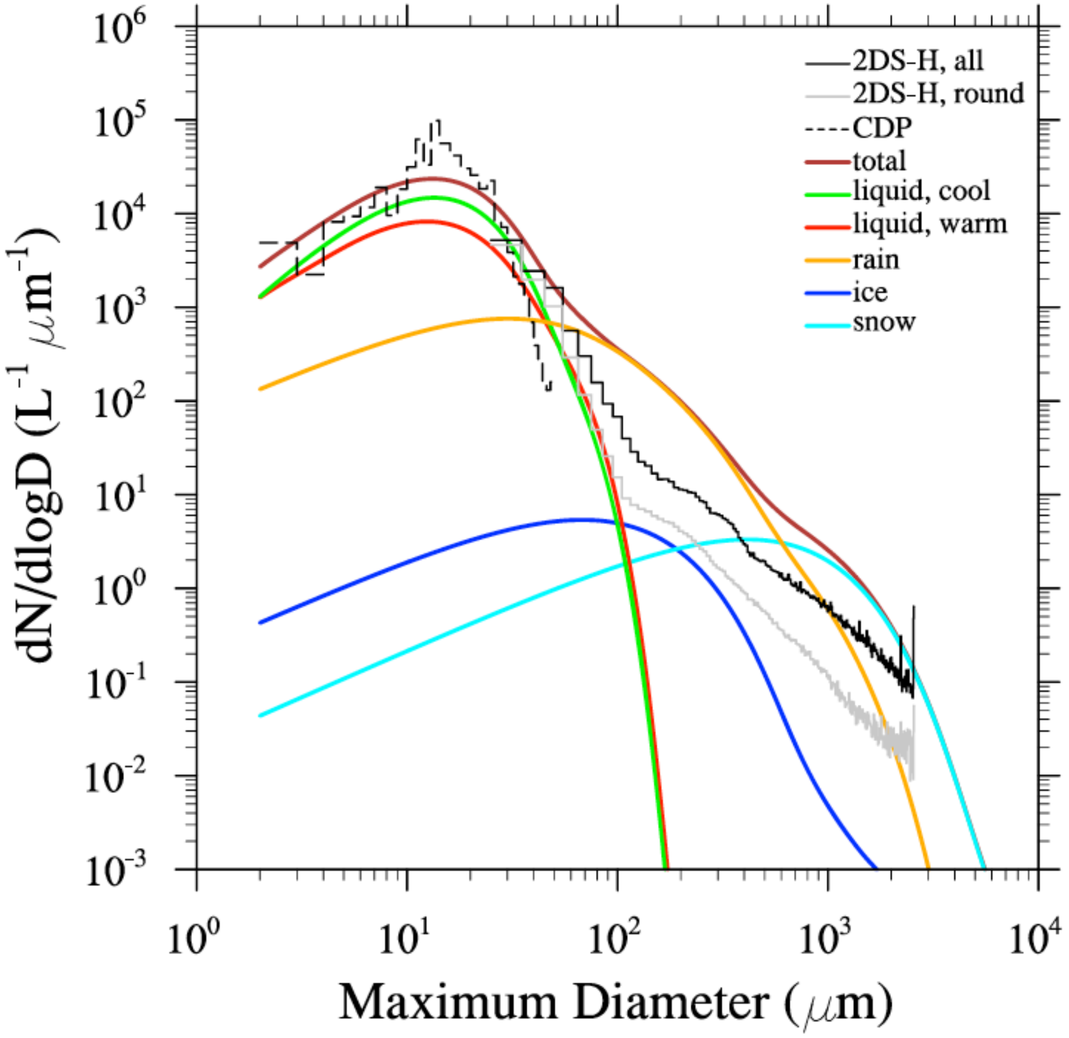
- Predicted Particle Properties (P3): Morrison & Milbrant (2015)
- MG: Eidhammer et al (2016)



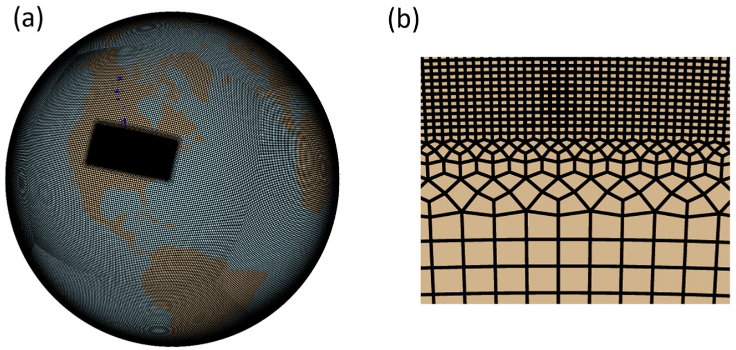
Alternatives: Learning the Functional Form (BOSS)

- Can prognose any moments of the size distribution
- Generalize as a series of conservation equations for moments AND generalize process rate equations
- Can then try to learn the relevant parame as a set of functions
- New warm rain scheme for this: Bayesian Observationally Constrained Statistical–Physical Scheme (BOSS)
  - Morrison, van Lier-Walqui et al (2020)

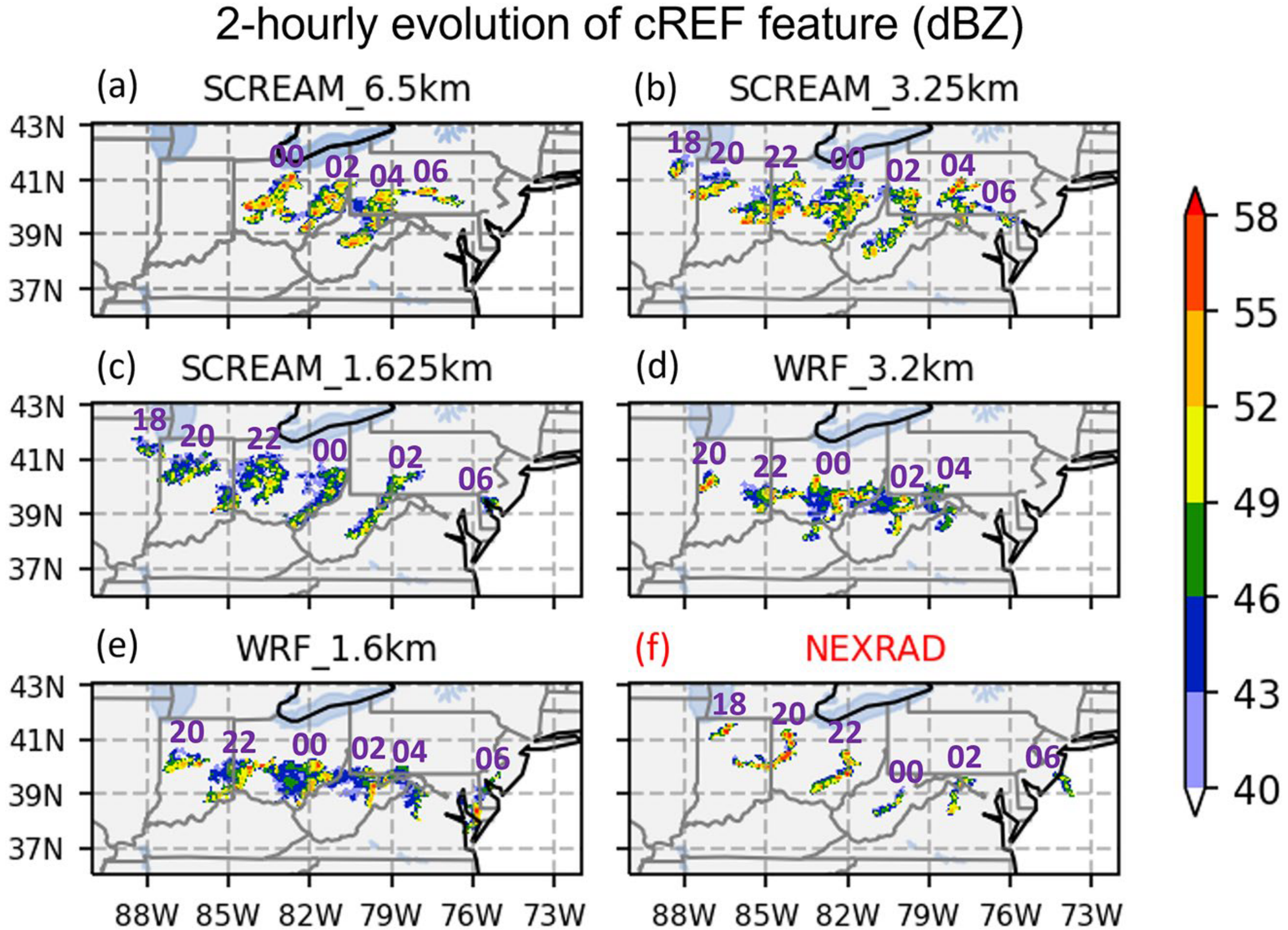
$$\phi(D) = N_0 D^{\mu} e^{-\lambda D}$$



Global Modeling to 1.6km…



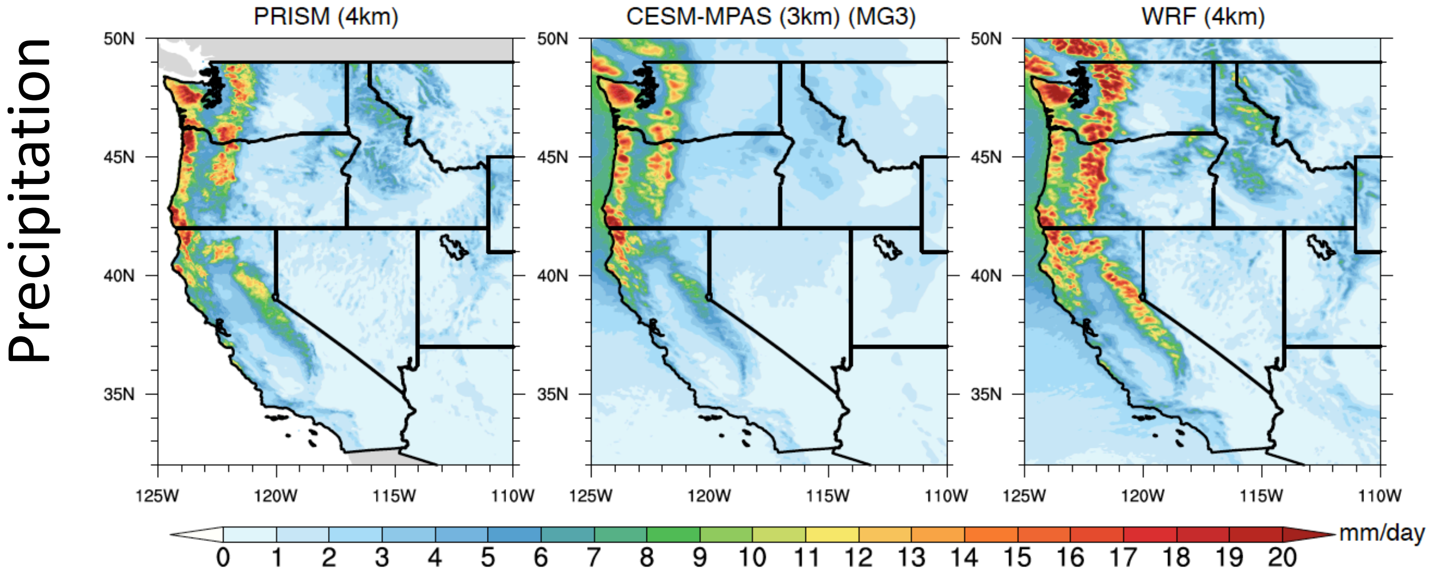
- Regionally Refined Global Model (SCREAM-E3SM)
- Evolution of a Mesoscale Convective Storm in the US
- WRF and SCREAM using 2-moment bulk microphysics with graupel/hail (P3)



Liu et al 2023, JAMES

Climate Extremes: Variable-Resolution (60→3 km)

- Global Model: CESM-MPAS: 3km regional, non-hydrostatic dynamics. (Earthworks Prototype)
- Regional climate model: WRF (CONUS) 4km (Rasmussen et al., 2021)



Wet-season (Nov-March) mean precipitation over western US (1999-2000)

W. USA Wet-season (Nov-Mar) precip (5yrs)

- CESM-MPAS results compare well to obs
- Smaller biases than WRF mesoscale model

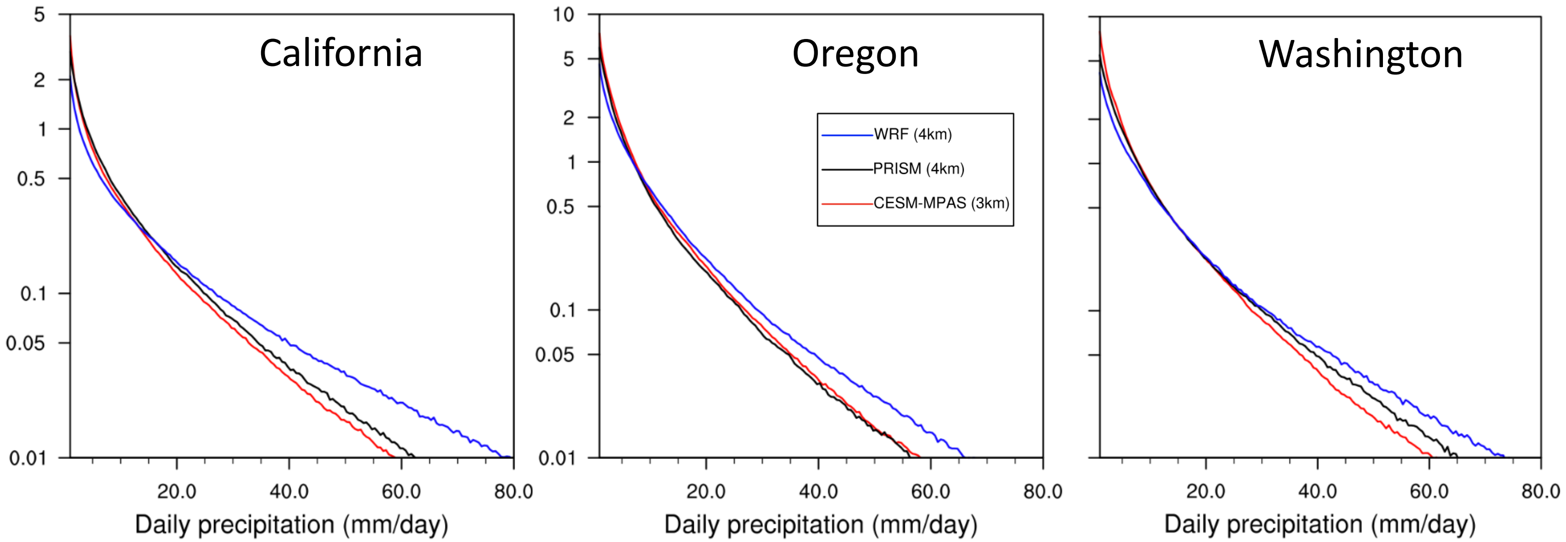
Daily precipitation Intensity PDF

4km Mesoscale Model (WRF)

3km Global Model (CESM)

4km Observations

CESM captures **observed PDF** better than **WRF**, especially for extreme precipitation



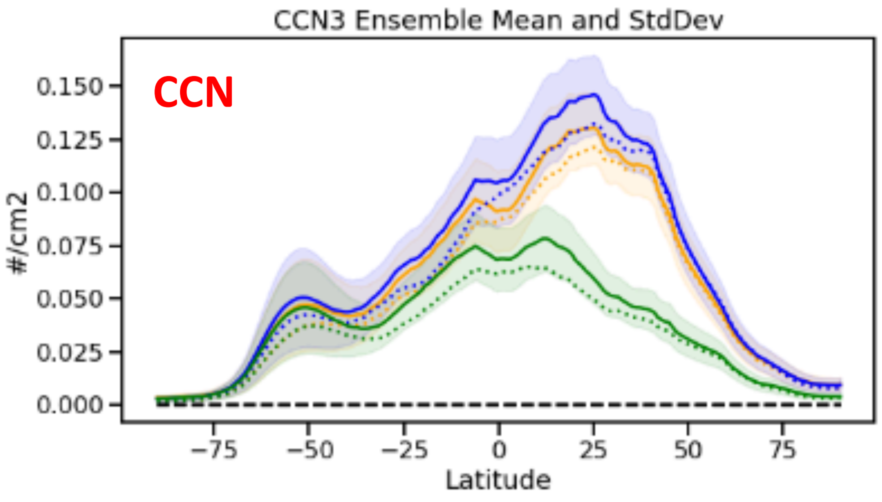
Huang et al 2022, GMD

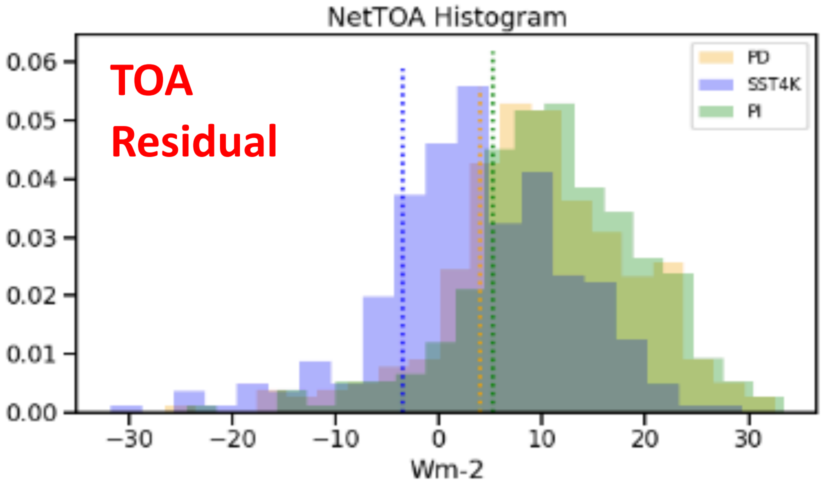
12. Uncertainty and Parameters

CAM6 Perturbed Parameter Ensemble

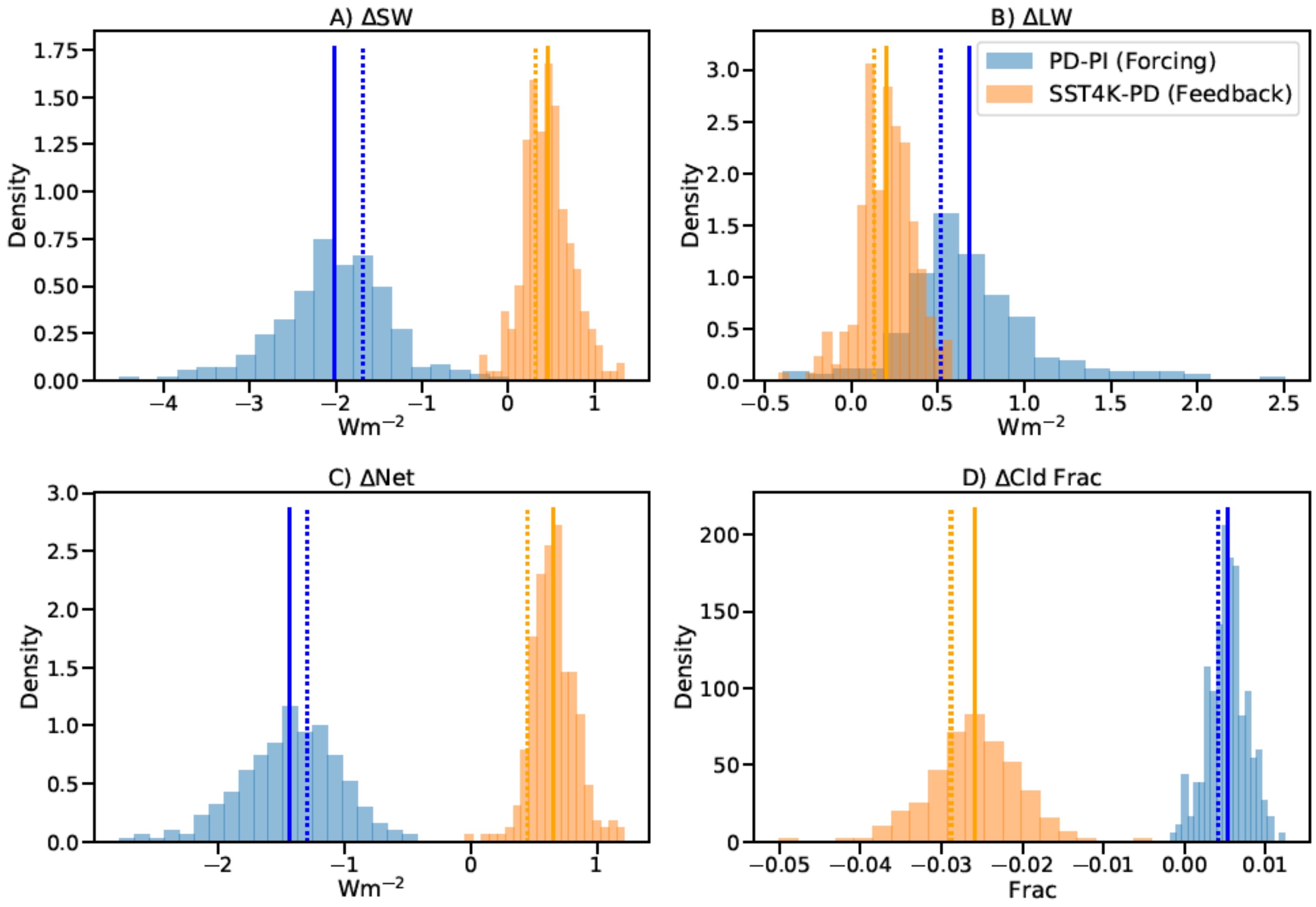
- 43 Parameters
  - Cloud Microphysics (11), Turbulence (11), Aerosols (9), Deep Convection (12)
- 263 parameter sets for simulations, selected using *Latin Hypercube Sampling*
- Three types of simulations (3 years): all fixed SST ('Climatological AMIP')
  - **PD:** Present Day forcing, SSTs
  - **PI:** Pre-Industrial (1850) Aerosol Emissions
  - **SST4K:** Present day with SST + 4K (Cess et al 1989)
- Data available (https://doi.org/10.26024/bzne-yf09)

PPE Spread





PPE Forcing and Feedback

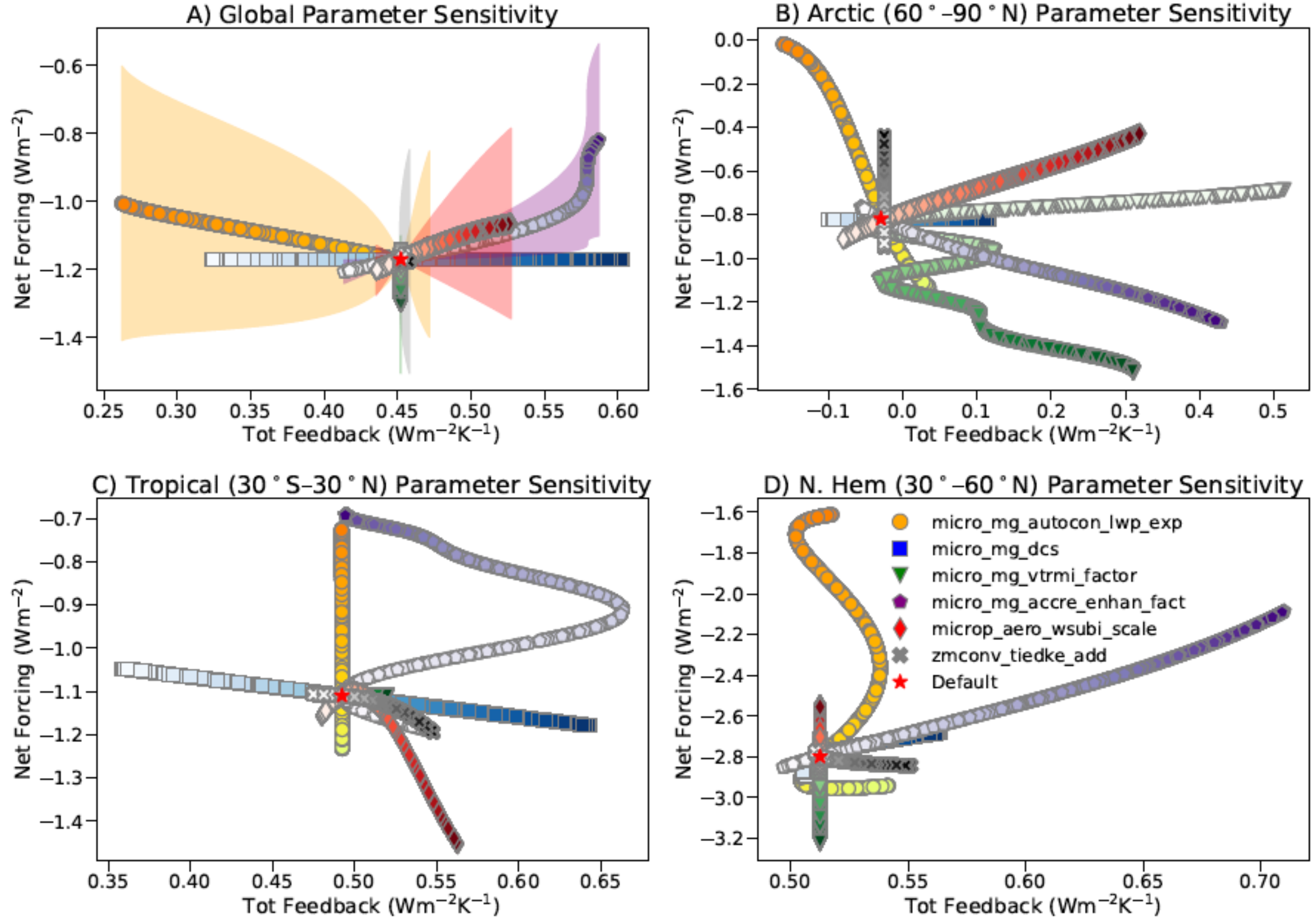


Forcing: Present day (PD) - Pre-industrial (PI) aerosol
Feedback: 4K SST - Present day (PD)

Gettelman 2024, JGR, in Review

Key Parameter Sensitivities: Using Gaussian Process Emulators

- Gaussian process emulators for forcing and feedback
- Global (A) and regional (B-D)
- Large uncertainties (1σ in A)
- Identify key parameters with correlations
- Key parameters mostly in the cloud microphysics (5/6)
  - Ice processes (2)
  - Rain formation (2)
  - Aerosol activation (1)
- Can also look at parameter relations to state parameters



Gettelman 2024, in Press JGR

Some Conclusions

- Cloud Microphysics is critical for weather and climate prediction
- Microphysics describes what happens to condensed phase in clouds
- Inputs from state, condensation (macrophysics/turbulence), aerosols
- Output is precipitation, detailed size distributions (for radiation code)
- PUMAS is a bulk 2-moment scheme (mass, number)
- Coupled to an aerosol activation scheme so aerosols affect cloud drop number concentrations
- Future of cloud microphysical parameterization
  - Focus on ice/snow, mixed phase, precipitation formation
  - Machine learning will be used in new ways, emulation, parameter optimization
  - Turbulence-cloud interactions are important