Condensation & Cloud Microphysics 1

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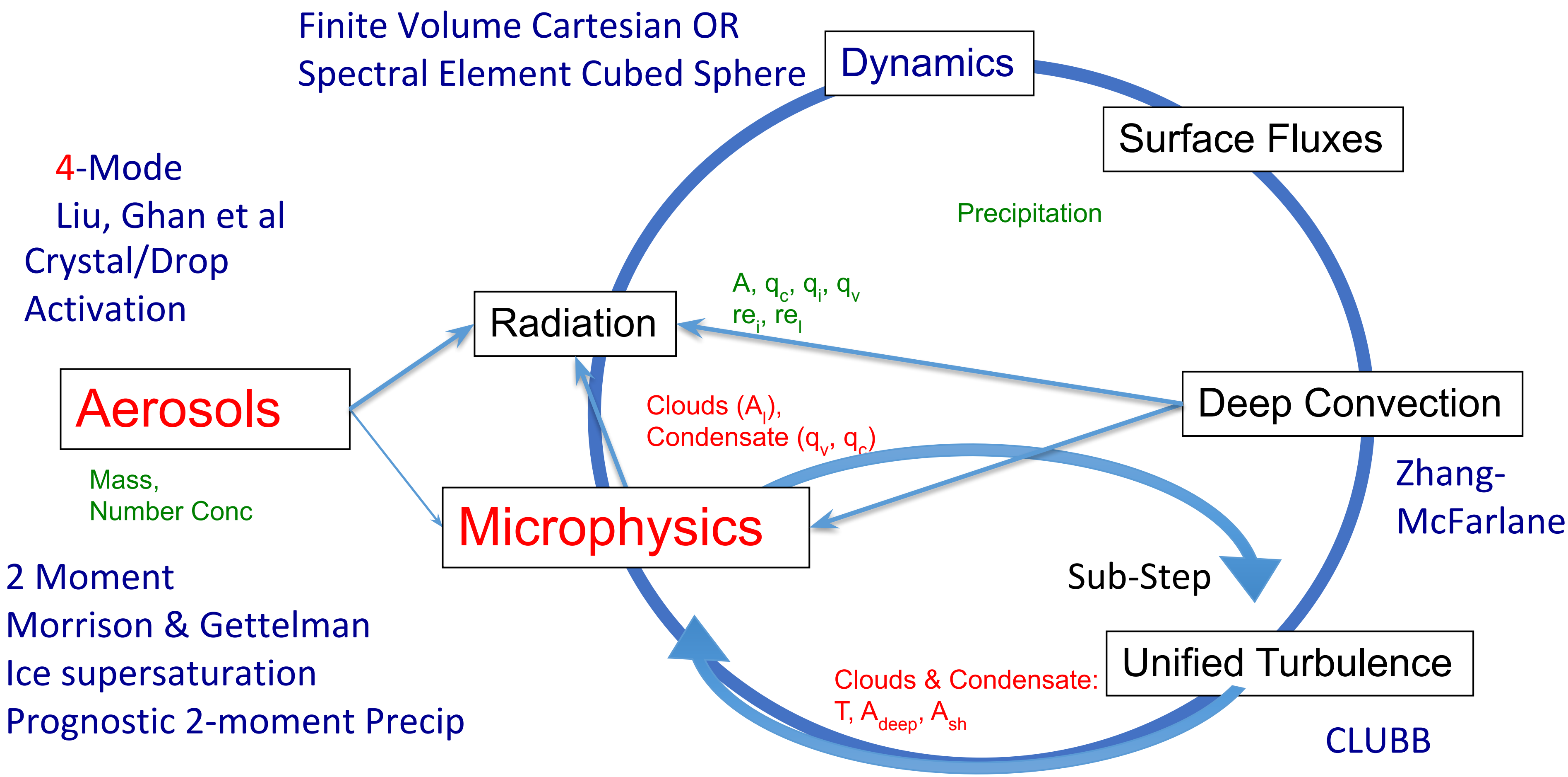
Outline

- Motivation: Cloud Microphysics in Weather and Climate
- Cloud MACROphysics and Condensation across scales
- What is cloud microphysics? How does it work in CESM?
  - Types of cloud microphysical schemes
  - Description of Morrison-Gettelman scheme
  - Important processes and interactions
  - Numerical Considerations
  - Evaluation with observations
- Summary: Uncertainties and Frontiers

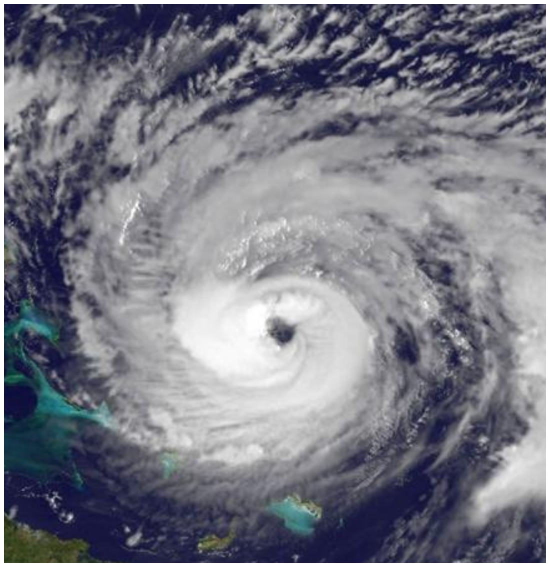
Lecture Scope

Community Atmosphere Model (CAM6): Moist Physics + Dynamics



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

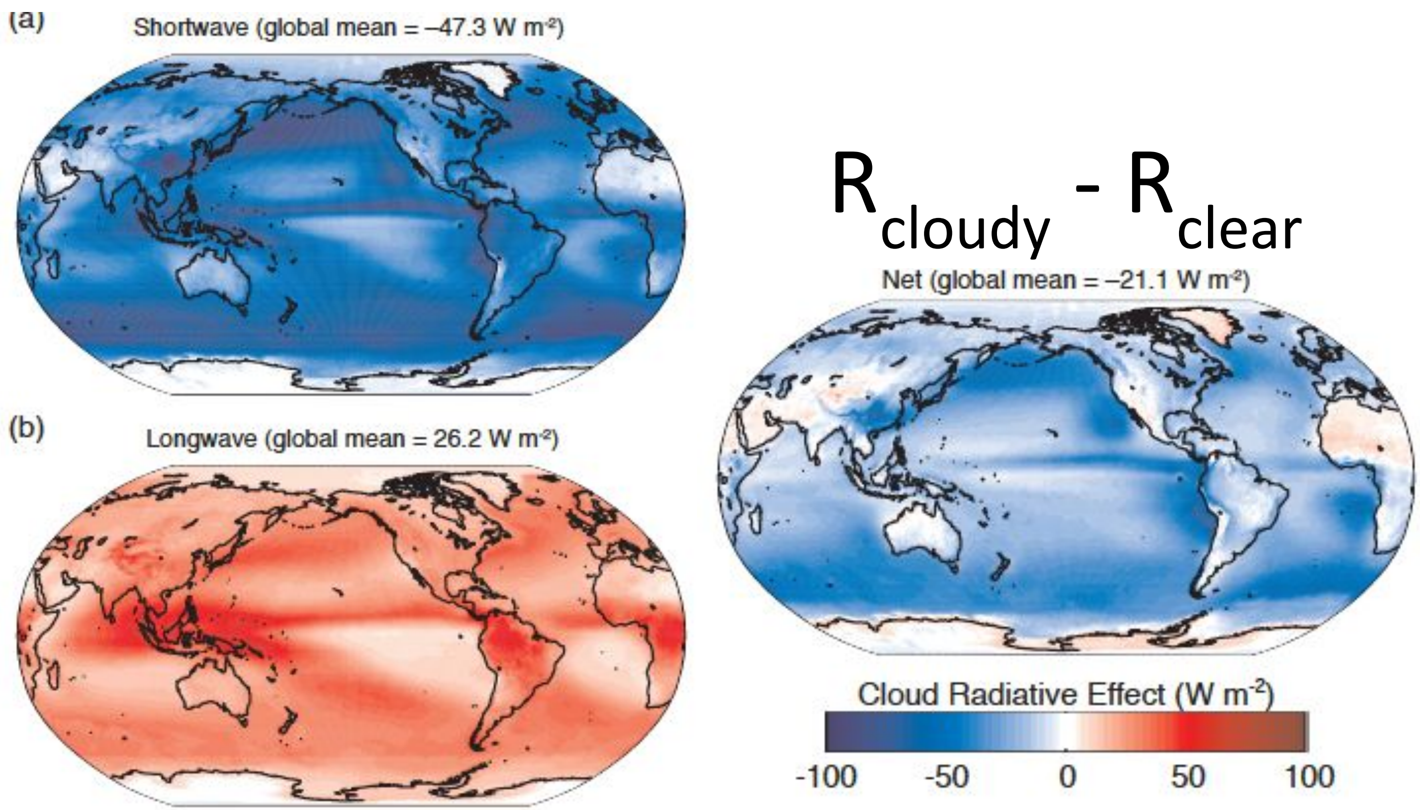
Cloud Microphysics Kills!



Clouds and Weather

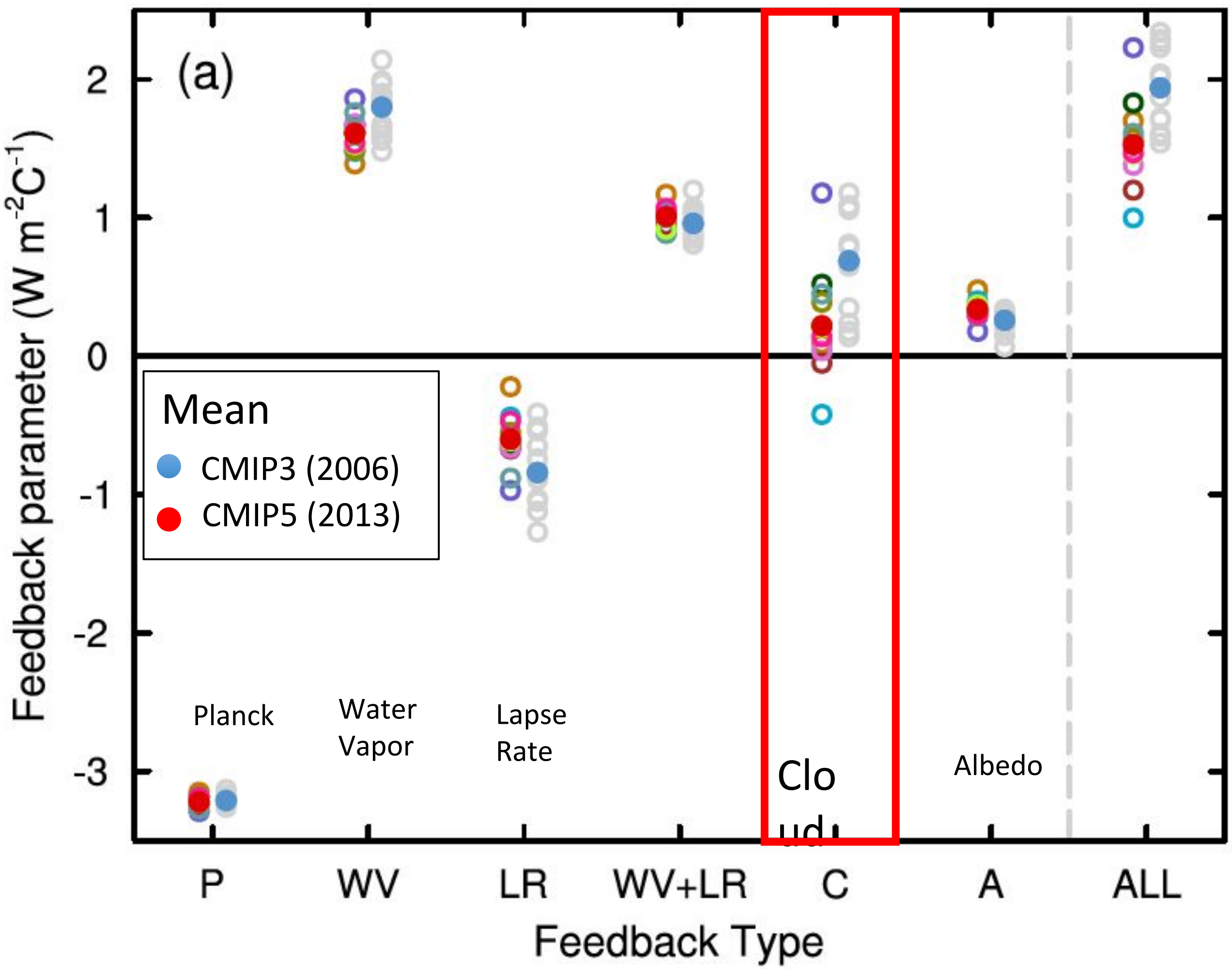
- Clouds are responsible for most severe weather
  - Tornadoes, Thunderstorms, Hail, Tropical Cyclones
- Critical processes depend on cloud microphysics (Thunderstorms, Hail, even Tornadoes)

Cloud Radiative Effects are Large



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 (+)

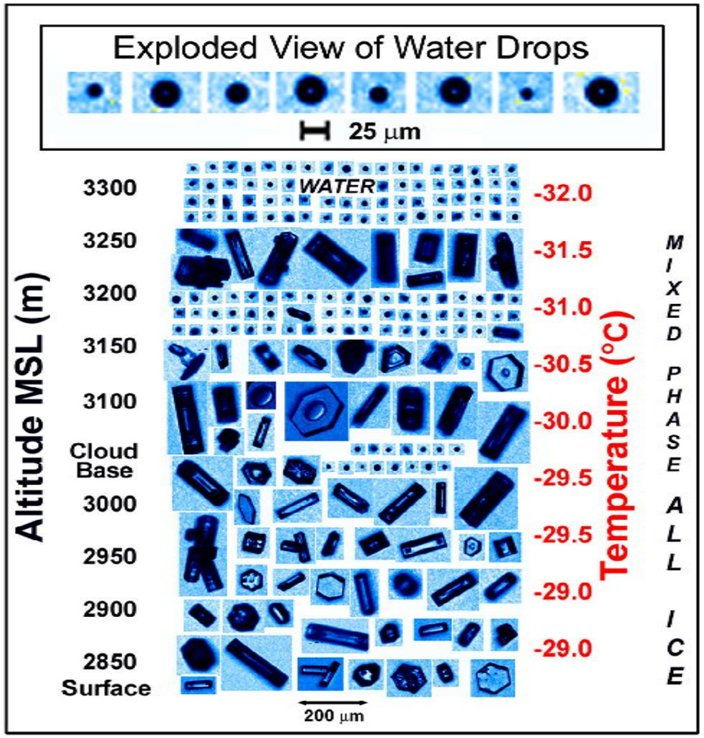
Lapse Rate (-)

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

Clouds: Complicated (+)

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

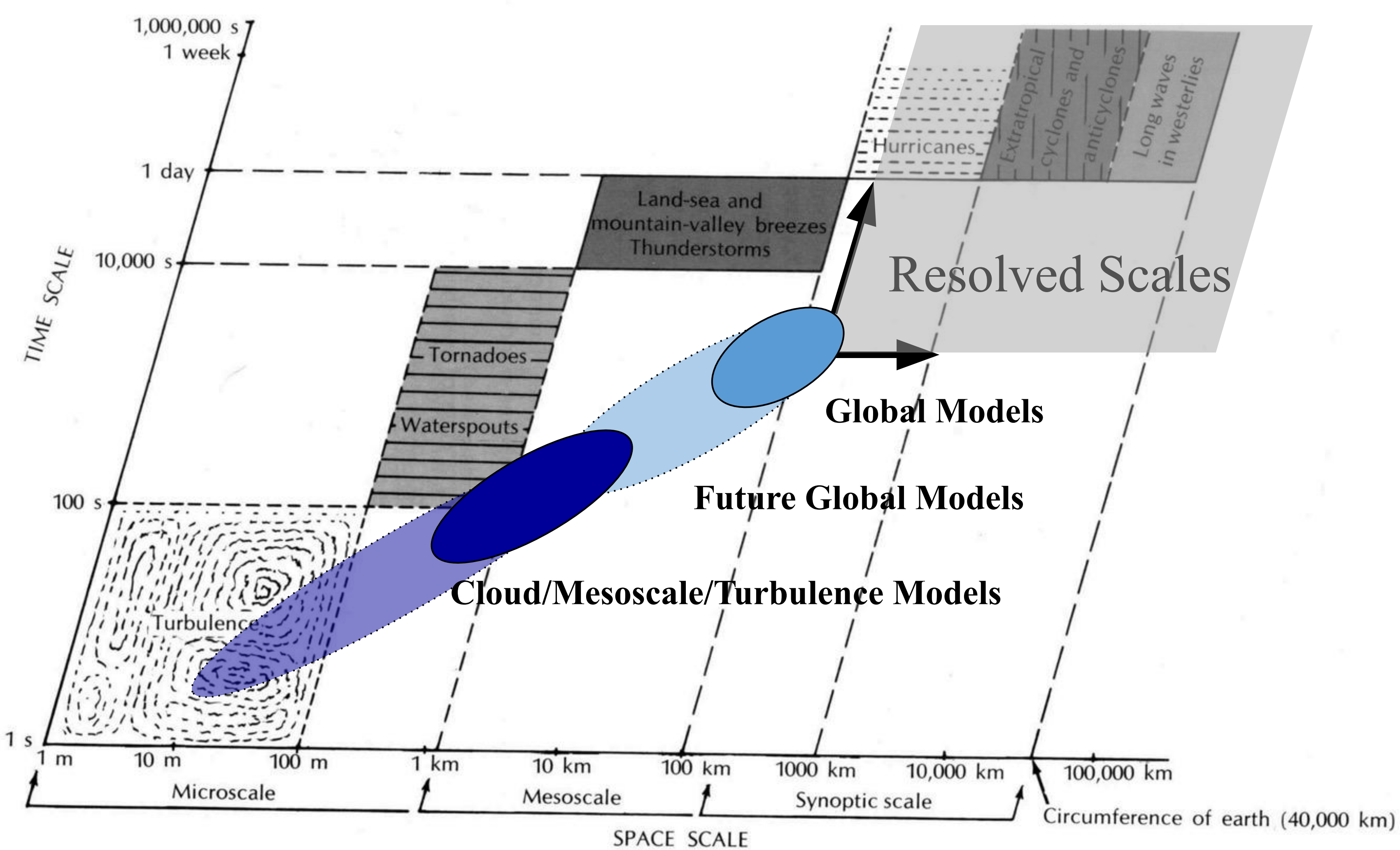
Spanning Scales
10^{-6}m --> 10^{6}m



Lawson & Gettelman, PNAS (2014)

$1.2x10^{7}$m

Scales of Atmospheric Processes



Scales and parameterization

- OK: processes separated from the grid scale
  - Statistical (empirical) treatments often work: 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

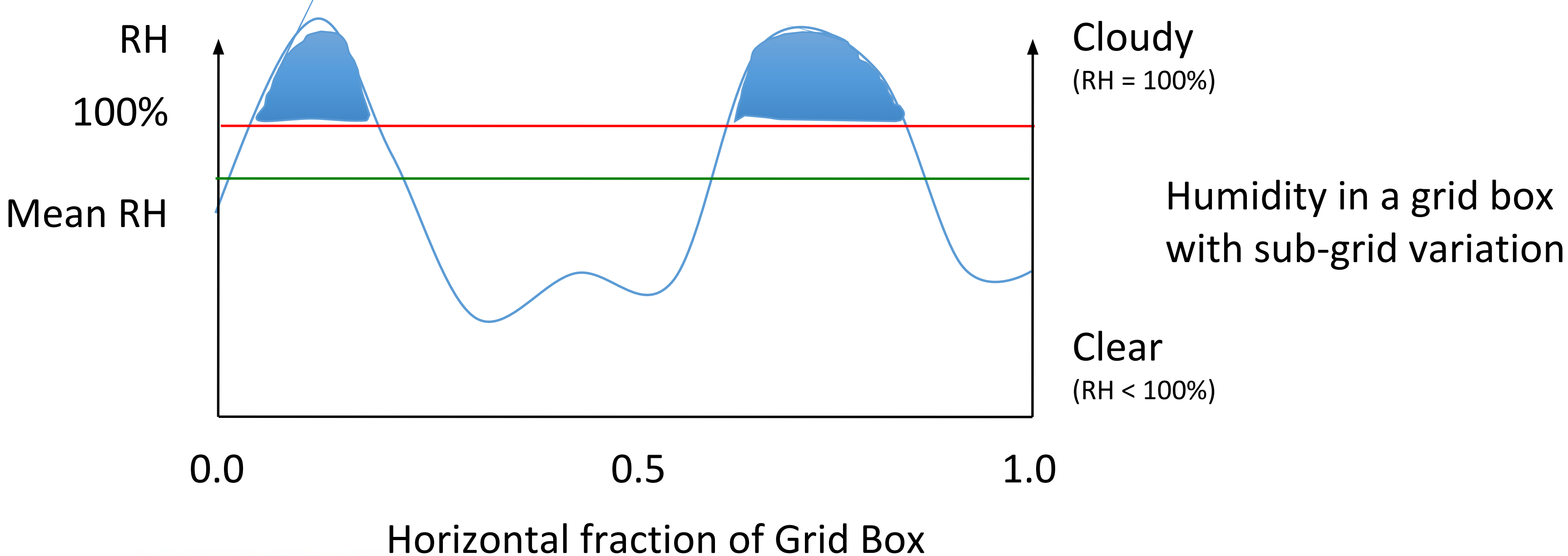
Cloud ‘Macrophysics’ & Sub-Grid Variability

- 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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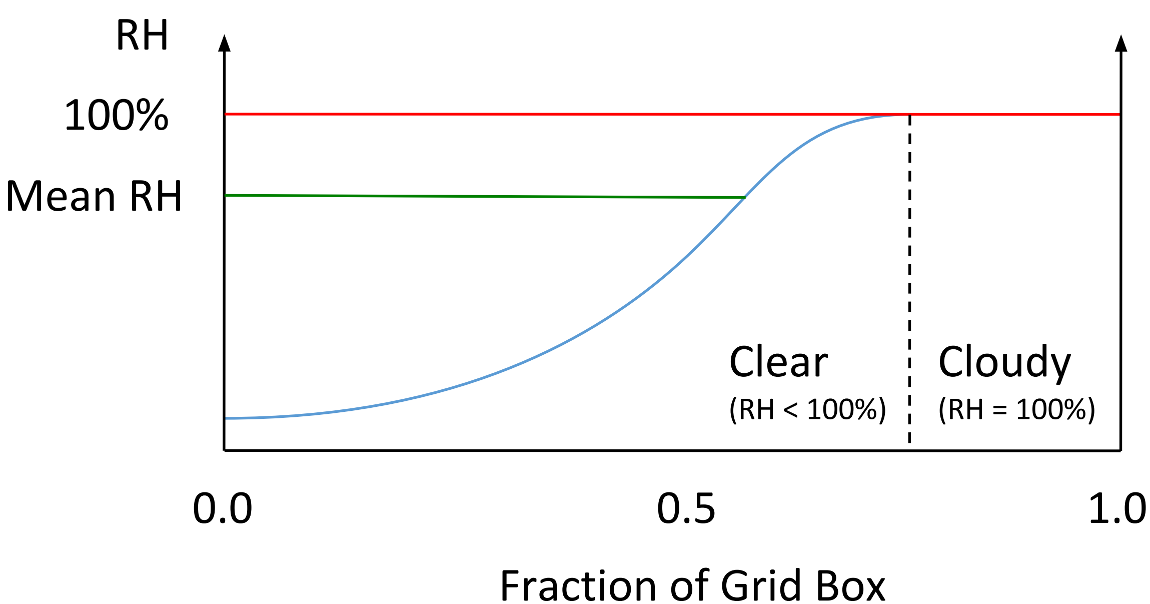
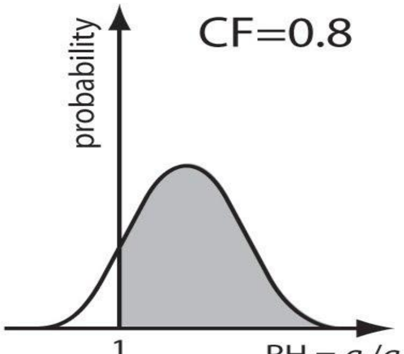


Assumed Cumulative Distribution function of Humidity in a grid box with sub-grid variation

Another way of looking at the PDF



‘Sub-Grid’ in different scale models

What is resolved at different scales?

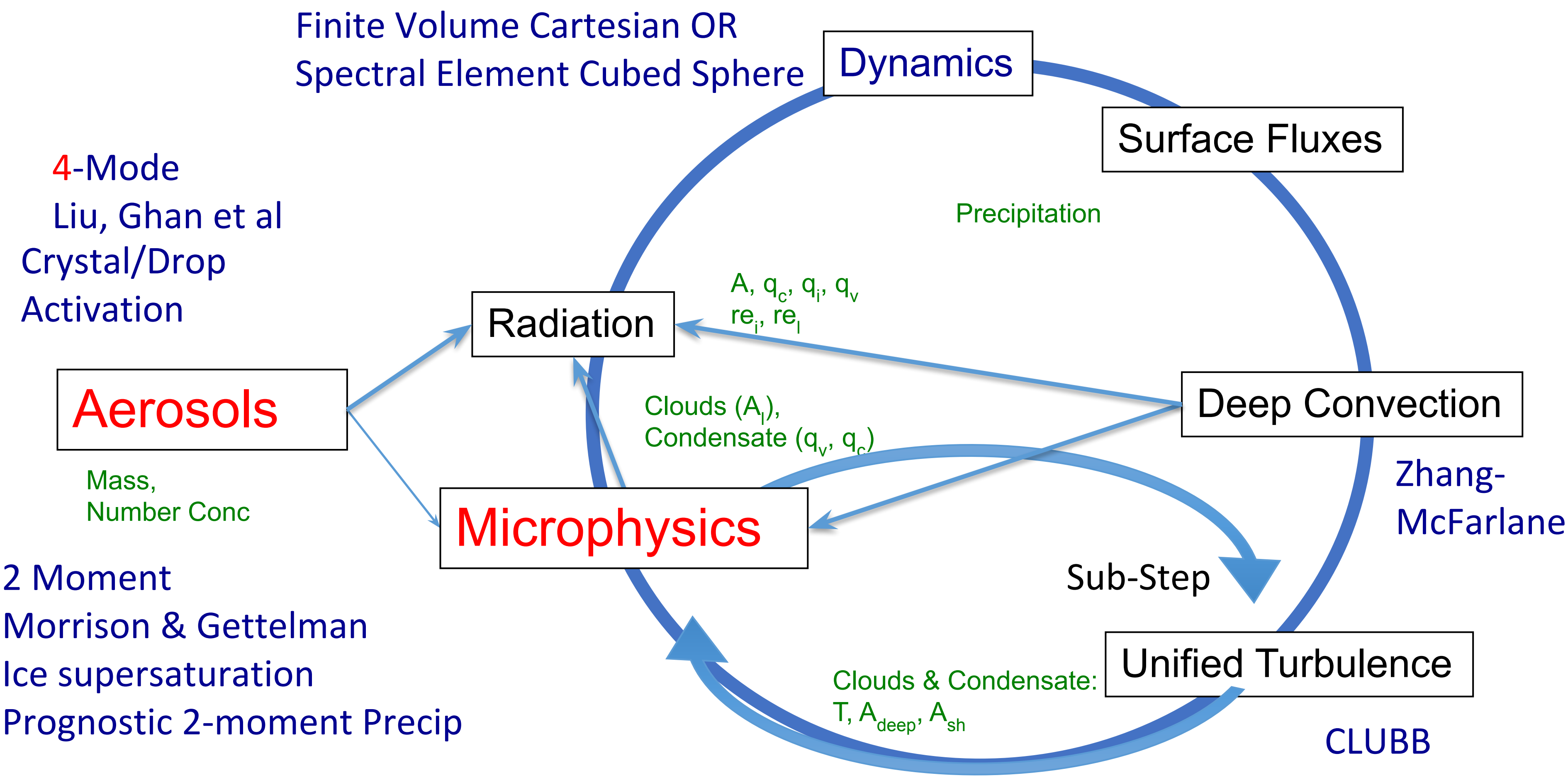
- Global Scale (15-400km)
  - Example: Resolve ‘synoptic’ systems and the general circulation
- Regional/Mesoscale (0.5-20km)
- ‘LES’ scale (10m – 200m)
- Turbulence (1-50m)

Cloud Macrophysical Approaches

- Explicit: Grid scale macrophysics (up to 3-5km!)
  - 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: PDF schemes
  - Multivariate PDFs or Higher Order Closure (e.g. CLUBB)
  - Predict higher order moments (multivariate PDF) of θ_l & w

What is Cloud Microphysics?

Community Atmosphere Model (CAM6): Moist Physics + Dynamics



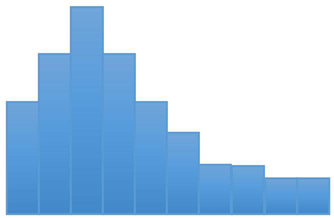
A = cloud fraction, q=H_2O, re=effective radius (size), T=temperature (i)ce, (l)iquid, (v)apor

Essence of Cloud Microphysics

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

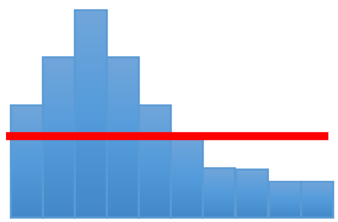
Types of Microphysical Schemes

- ‘Explicit’ or Bin Microphysics



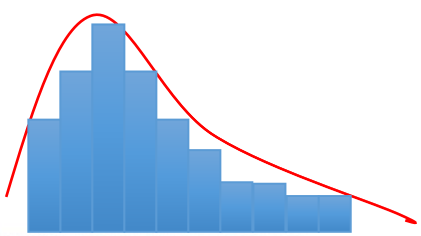
Represent the number of particles in each size ‘bin’
One species(number) for each mass bin
Computationally expensive, but ‘direct’

- Bulk Microphysics



Represent the total mass and number
Computationally efficient
Approximate processes

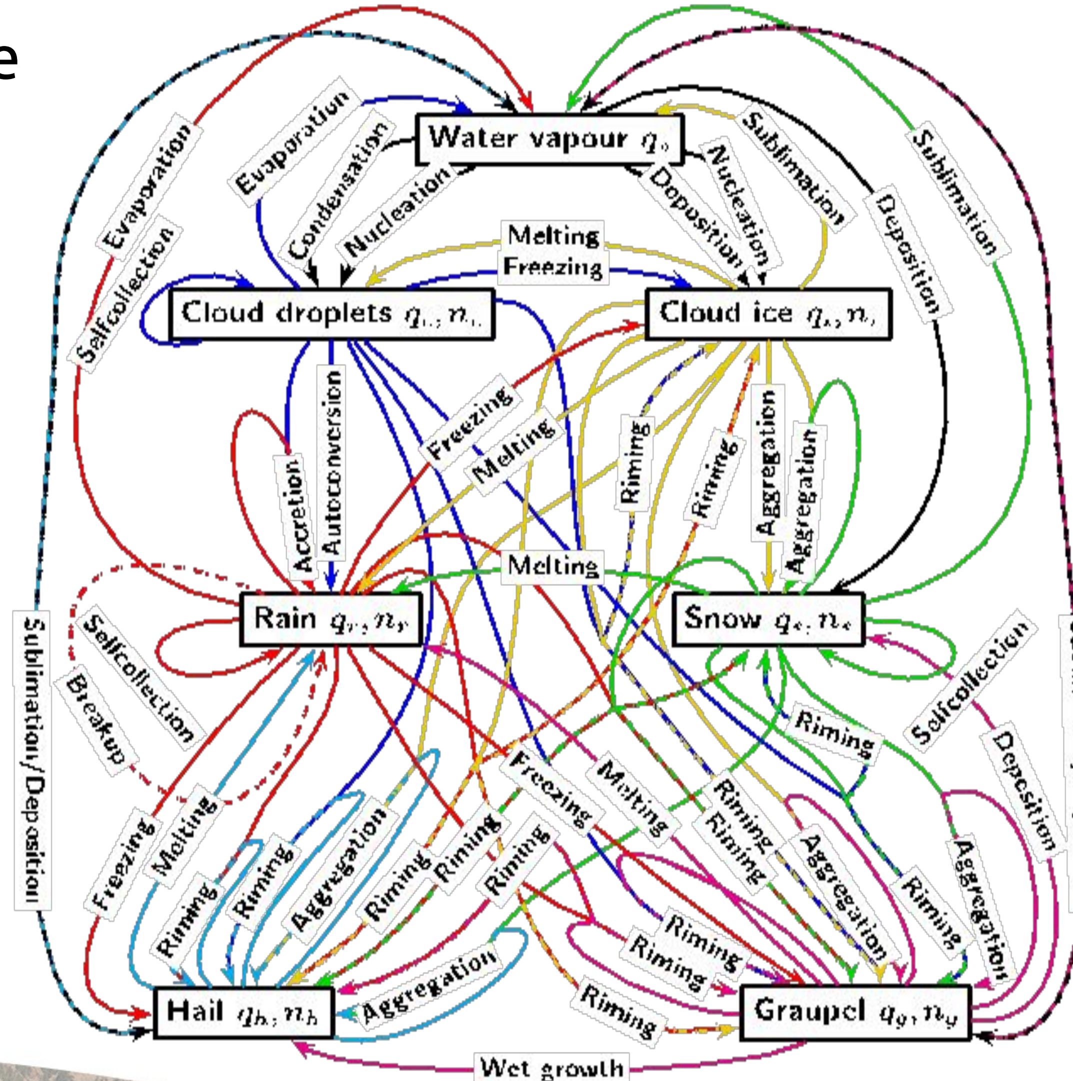
- Bulk Moment based microphysics



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

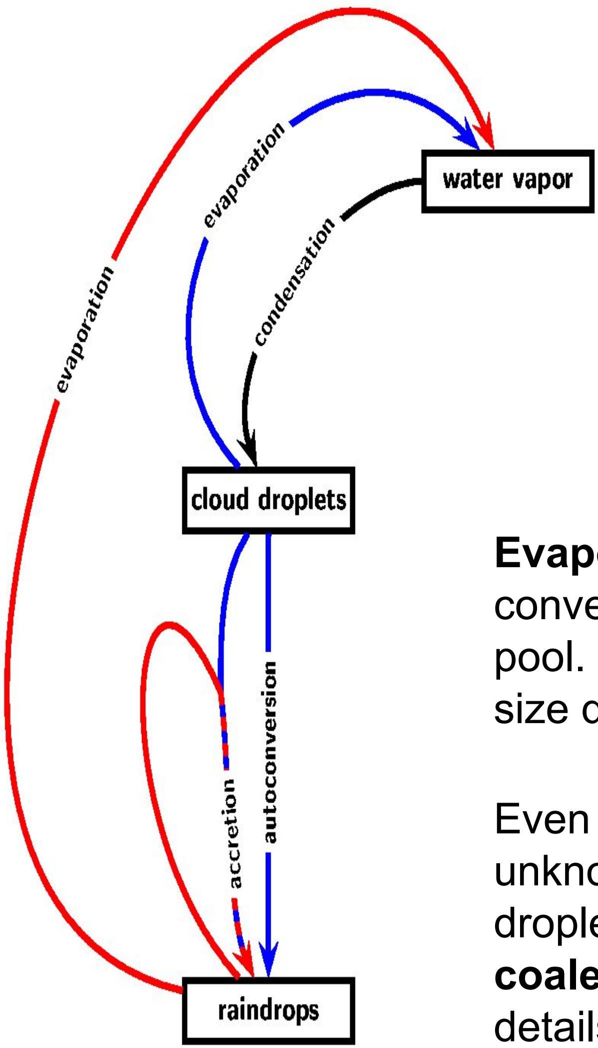
Ultimate Schematic

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



Seifert, Personal Communication

Cloud Microphysical Processes: Rain



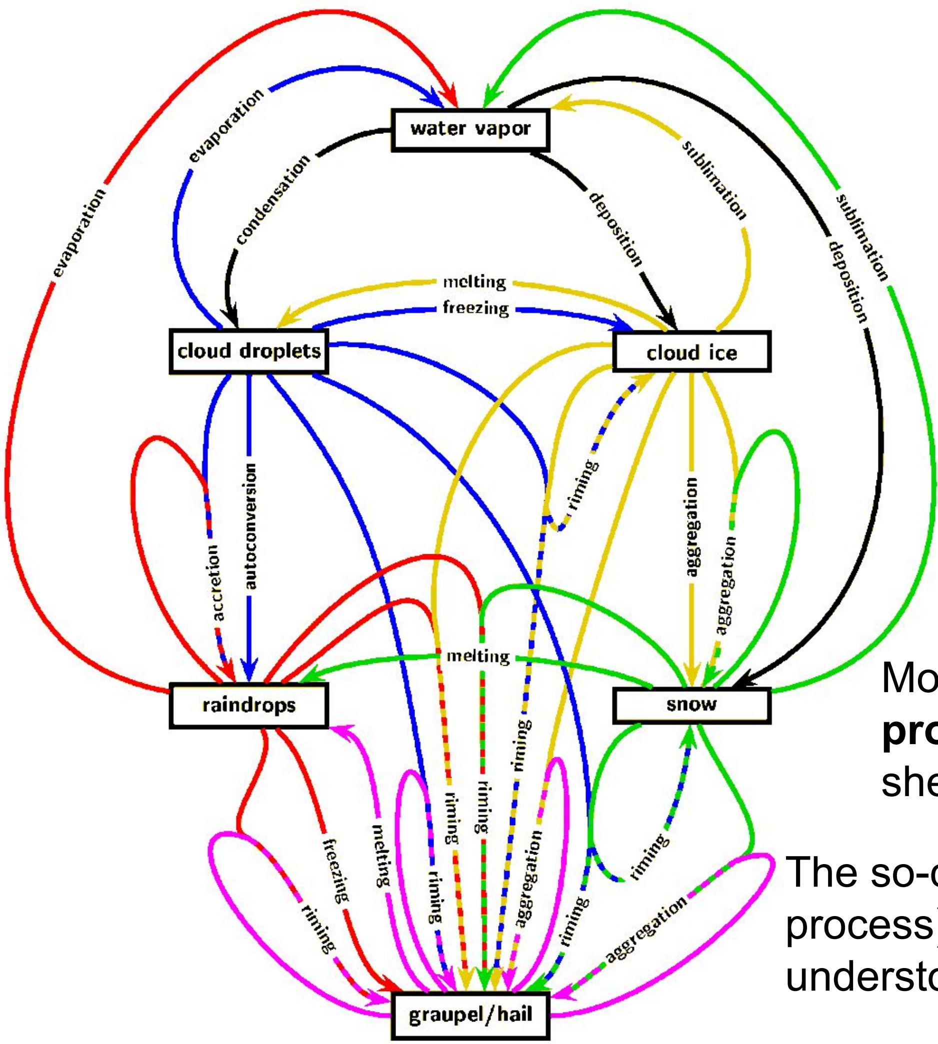
Evaporation and condensation of cloud droplets usually parameterized by saturation adjustment scheme.

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.

Cloud Microphysical Process Interactions



Conversion processes, (e.g. snow to graupel conversion by riming), are difficult to parameterize but important in convective clouds.

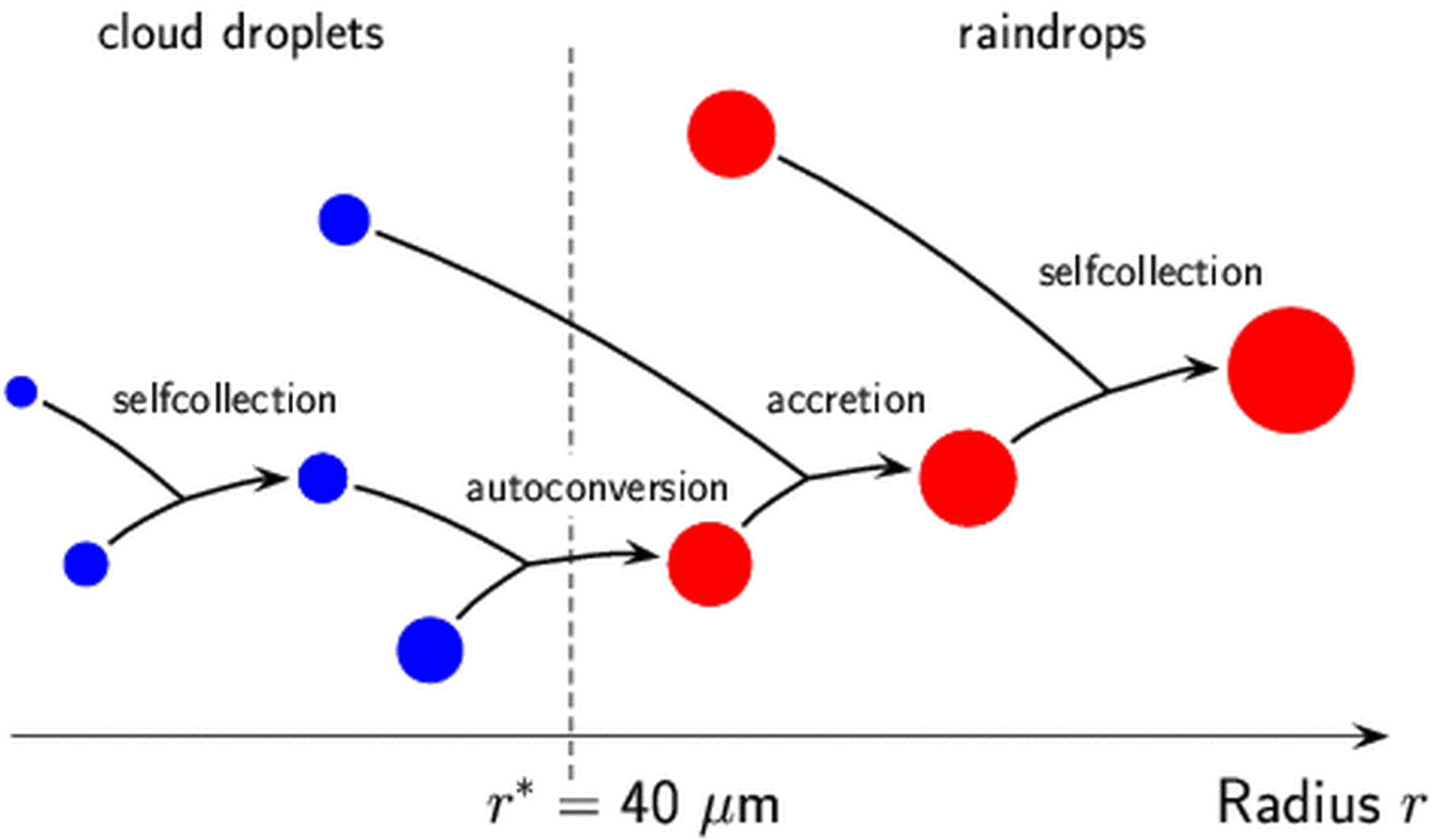
For frozen phases (snow, ice, graupel) particle properties like **particle density** and **fall speeds** are important parameters. Density may vary.

Aggregation processes assume certain collision and sticking efficiencies, which are not well known.

Most schemes do not include detailed **hail processes** like wet growth, partial melting or shedding

The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood

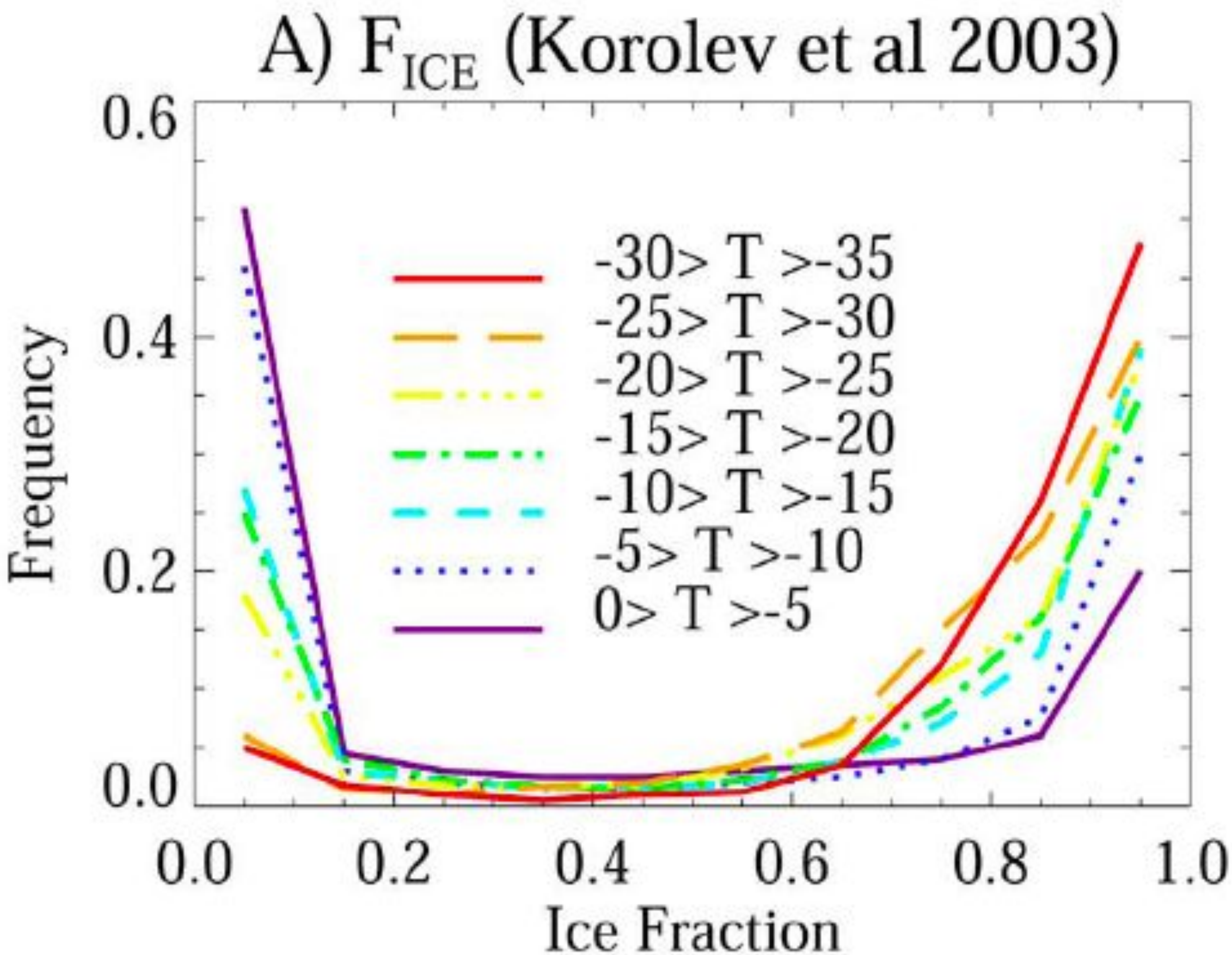
Collision-Coalescence Processes



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 homogeneous is a cloud? Key for mixed phase. In general: not well mixed

Mixed Phase: Ice

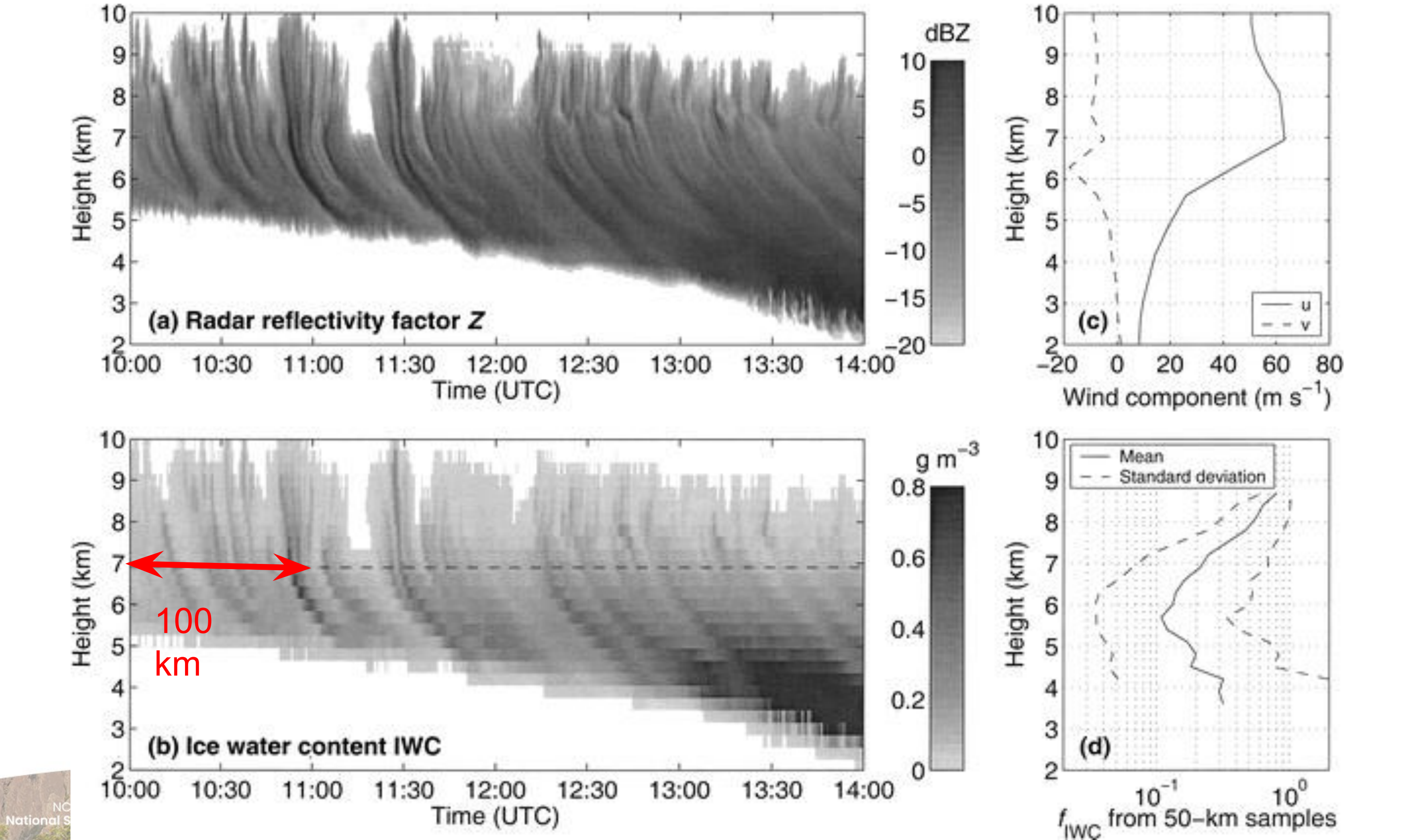


Constraints

- Clouds are inhomogeneous
  - Particles feel surrounding humidity
- What is the variance above the ‘micro’ scale?
- Condensation and other transformations depend on state, depend on small scale variance
- In the atmosphere: updrafts produce rapid adiabatic cooling that leads to condensation

Cloud Inhomogeneity

Hogan and Illingworth, 2003, JAS



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

- Particle size distribution
  - liquid drops are spheres
- Mass (Liquid water path)
- Allows calculation of optical depth
  - absorbtion 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

Condensation & Cloud Microphysics 2: CAM6 Microphysics

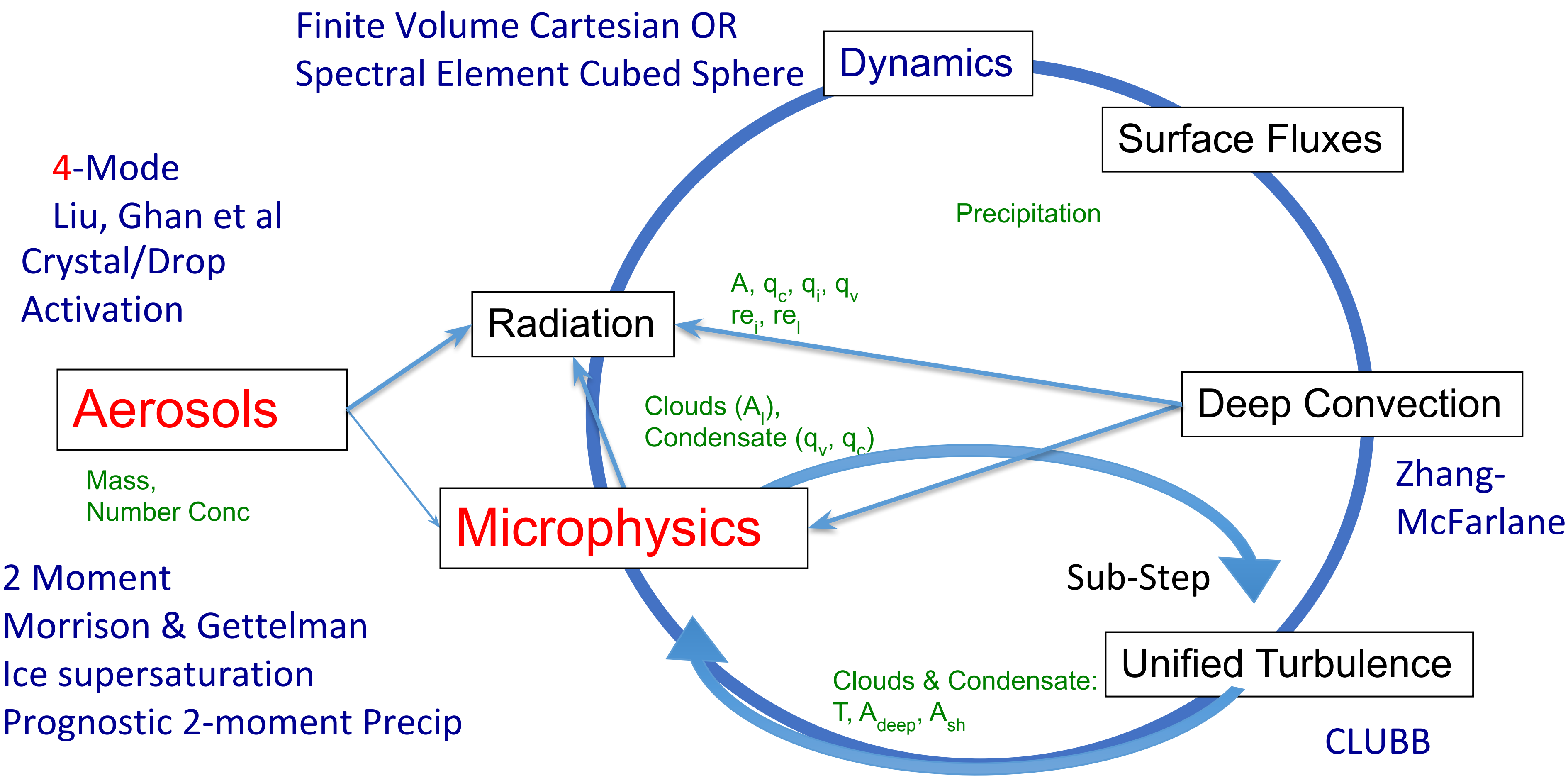
Andrew Gettelman, Hugh Morrison

National Center for Atmospheric Research

Description of CAM6 Microphysics

- Gettelman and Morrison 2015 (MG2)
- Derivative of Morrison et al 2005 WRF scheme
  - MG2 = identical to M2005 for liquid
- Bulk 2-Moment 4-class scheme
  - Mass and number
  - Liquid, Ice, Rain, Snow
  - 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)

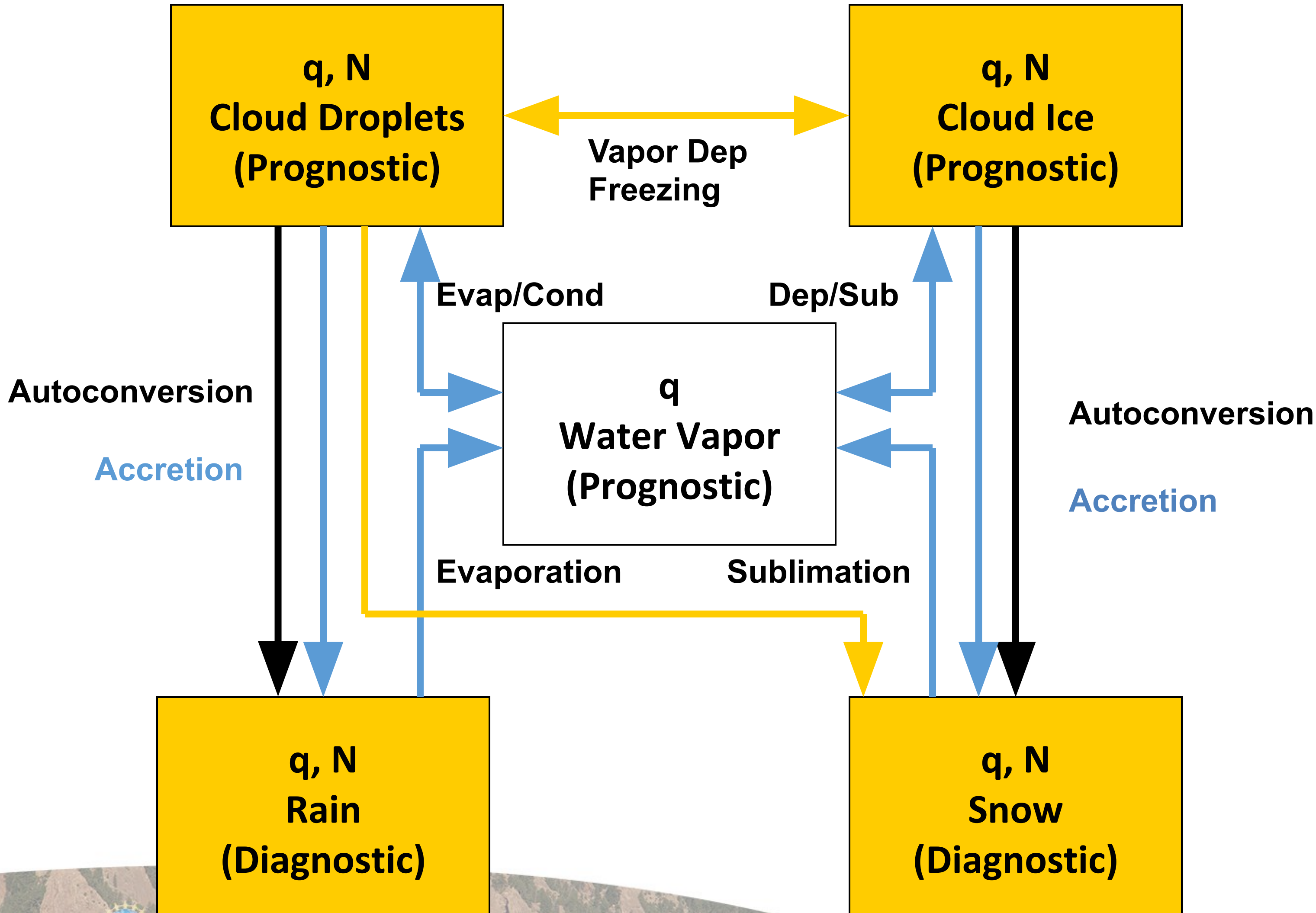
q, N
Rain
(Diagnostic)

q, N
Snow
(Diagnostic)

q = mixing ratio
N = number concentration

Morrison & Gettelman 2008

Transformations Between Classes

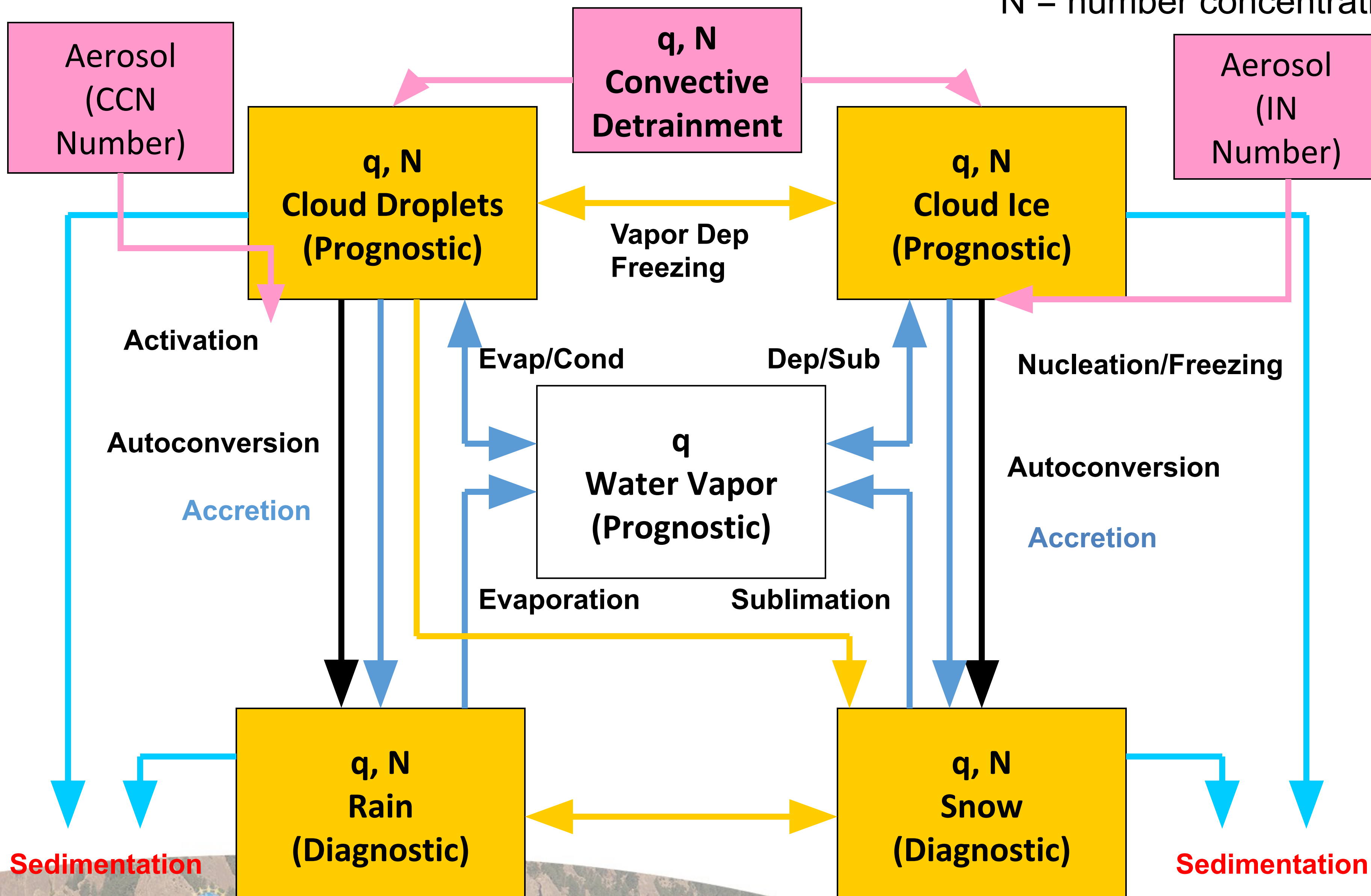


q = mixing ratio
N = number concentration

Sources & Sinks

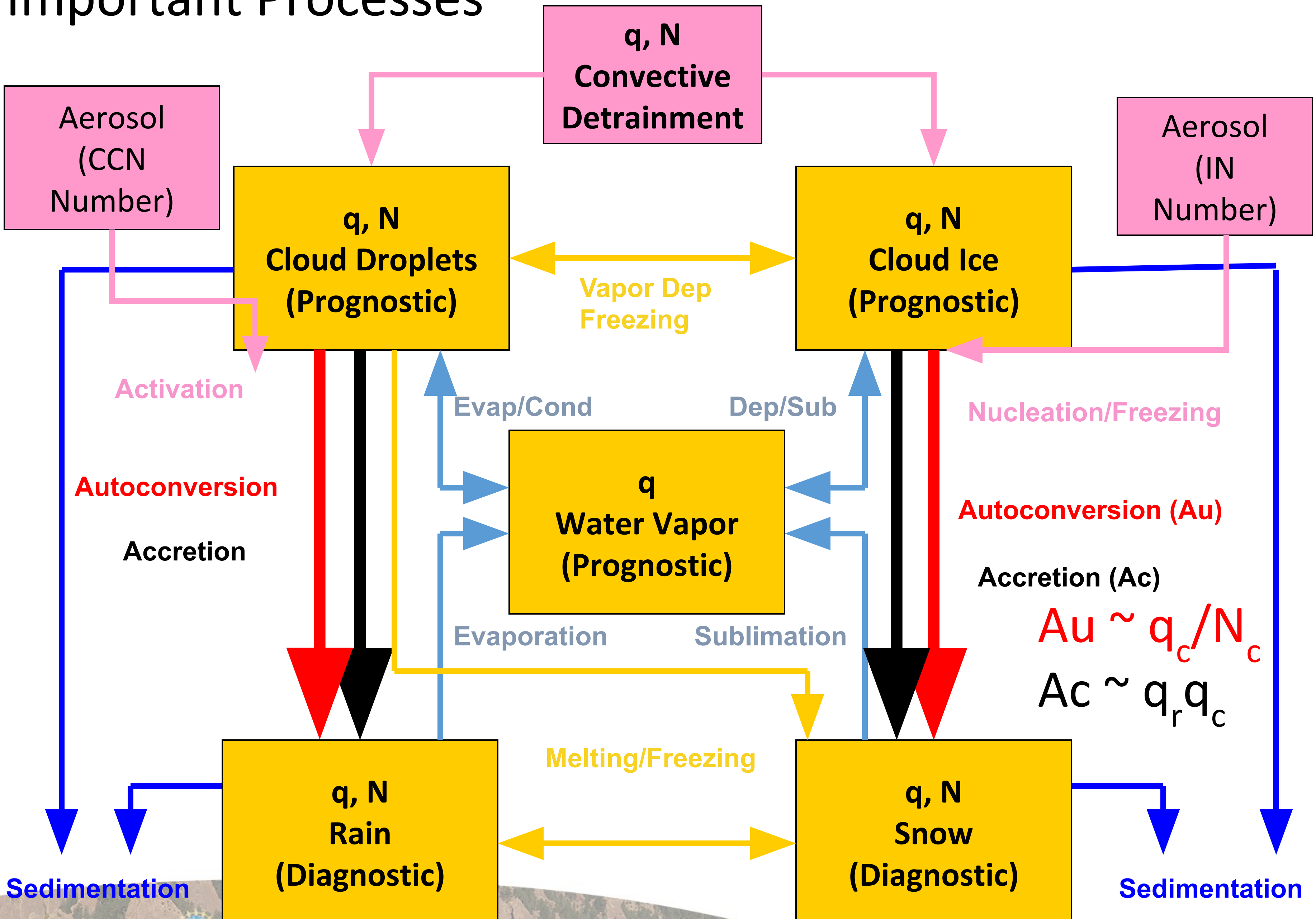
Morrison & Gettelman 2008

q = mixing ratio
N = number concentration



Important Processes

Morrison & Gettelman 2008

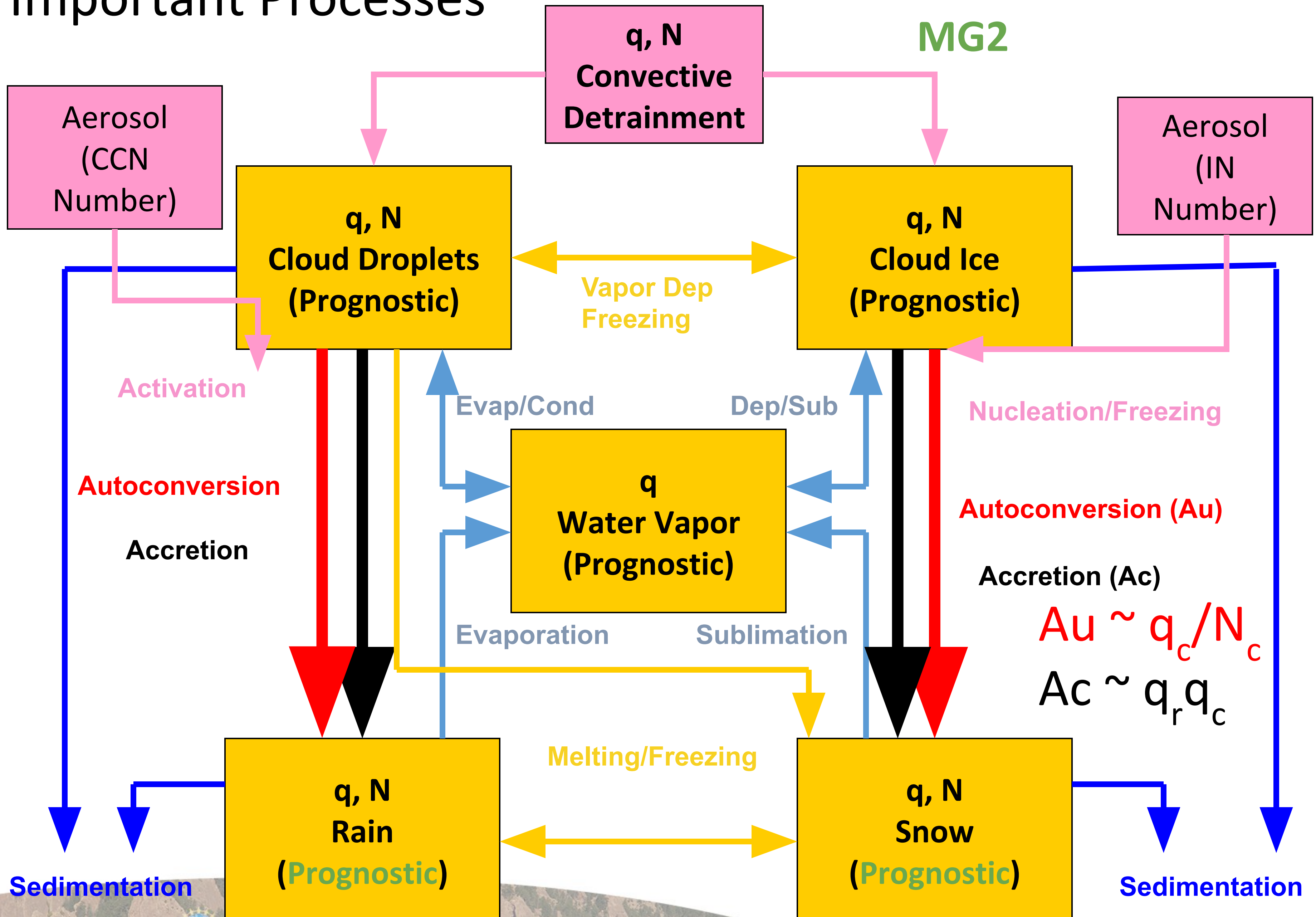


$Au \sim q_c/N_c$

$Ac \sim q_r q_c$

Important Processes

Morrison & Gettelman 2015



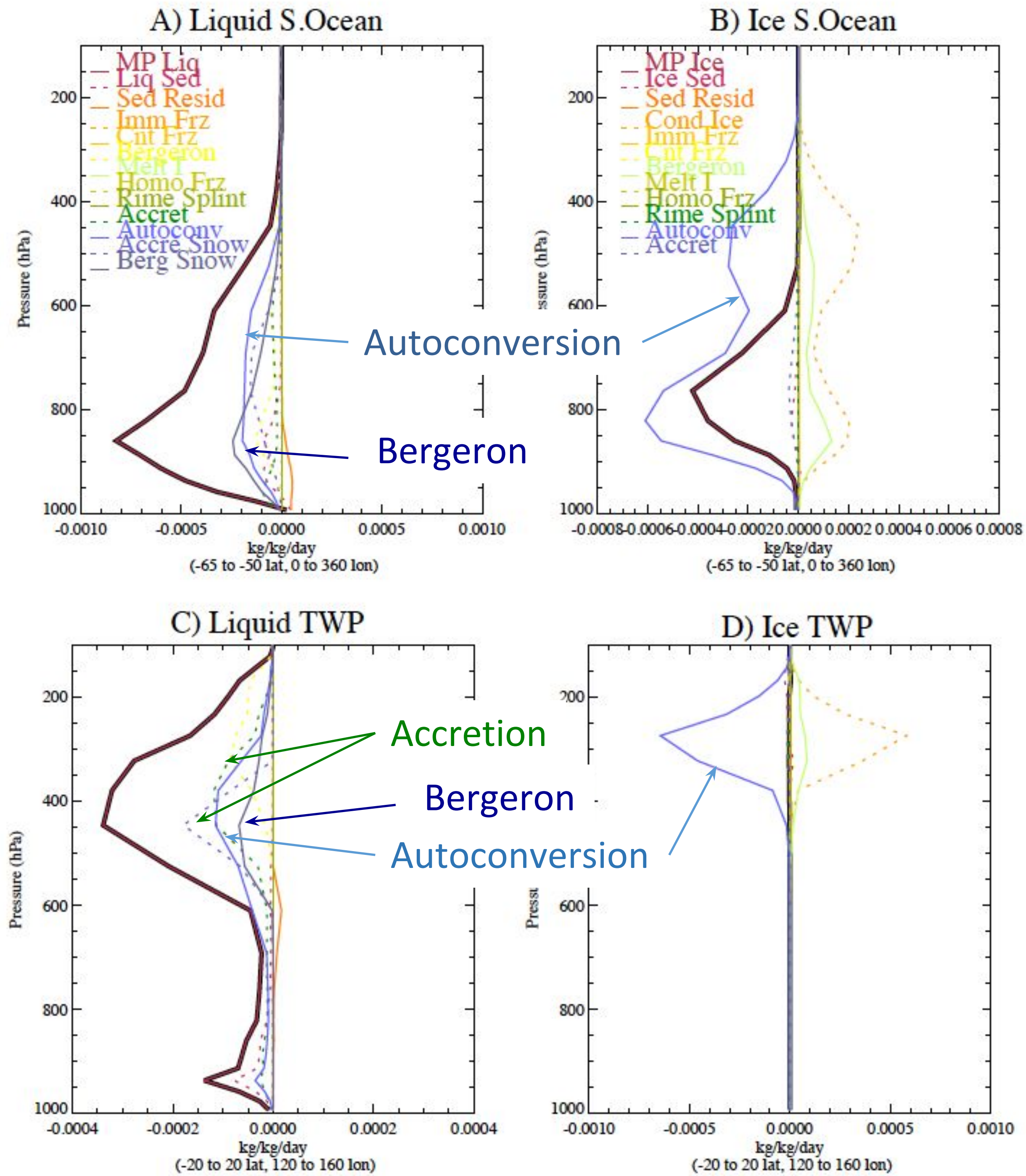
Microphysical Process Rates

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

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

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

- 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, process rates not constant
- Au/Acc 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

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

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

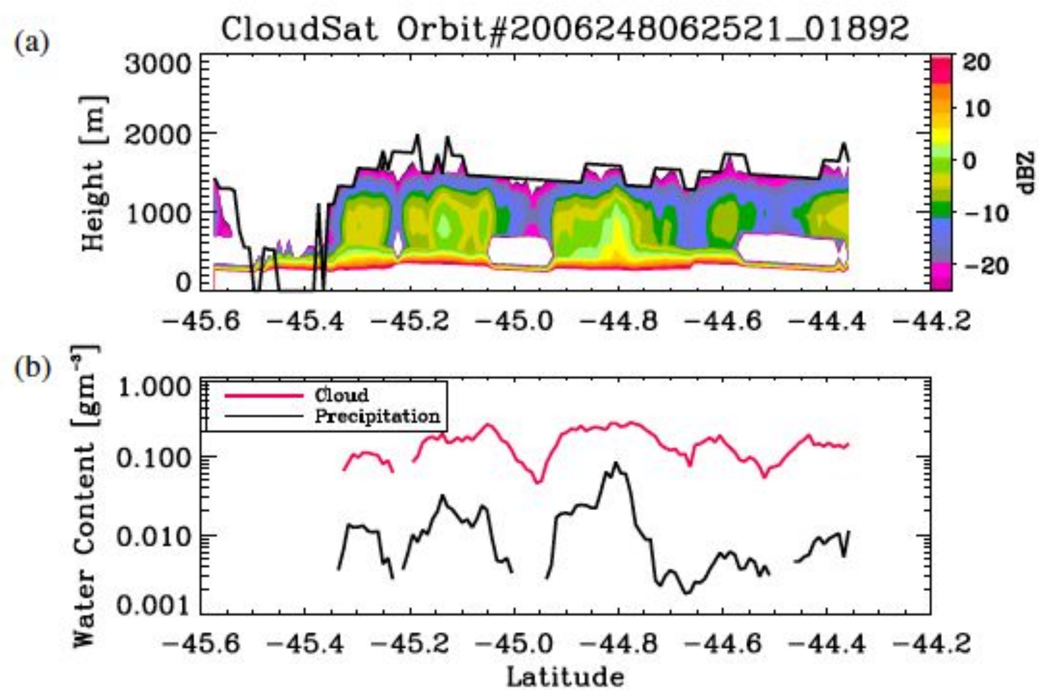
E = Enhancement factor

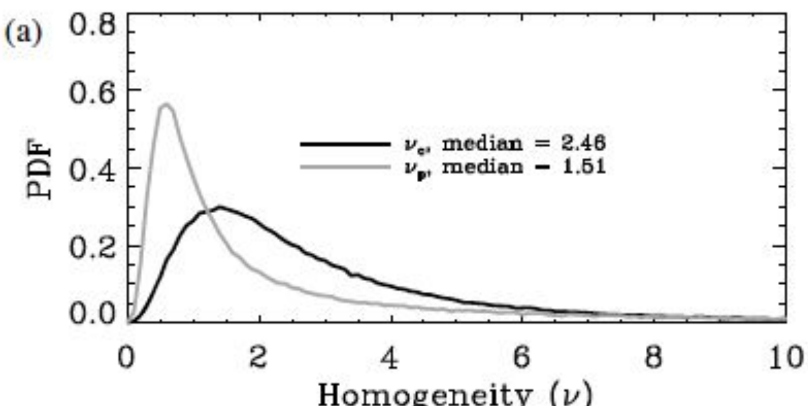
and v_x is the normalized variance $v_x = x^2/\sigma^2$

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

Observing co-variance of cloud & rain

- Observe cloud/rain from satellites (CloudSat)
- Calculate variance, mean and normalized variance (v) or homogenaiety



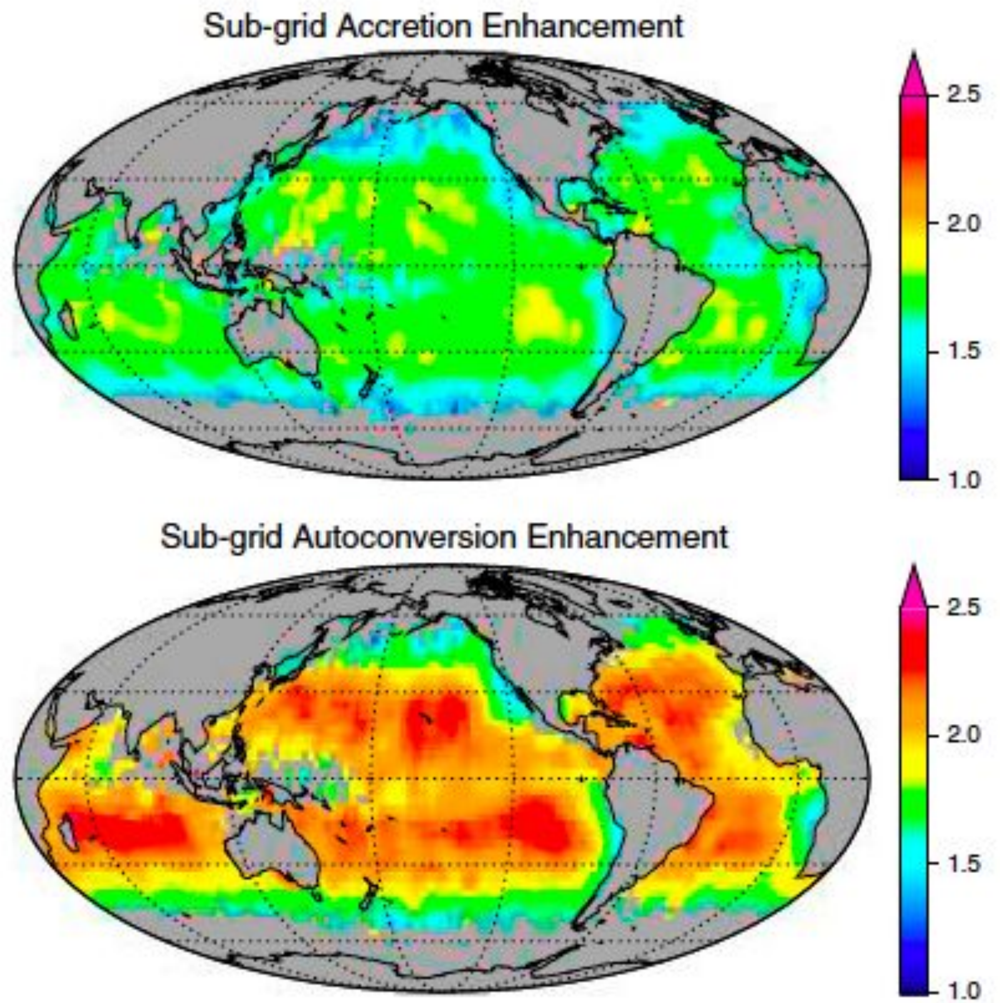


- Yields observational estimate of Ac & Au enhancement factors

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

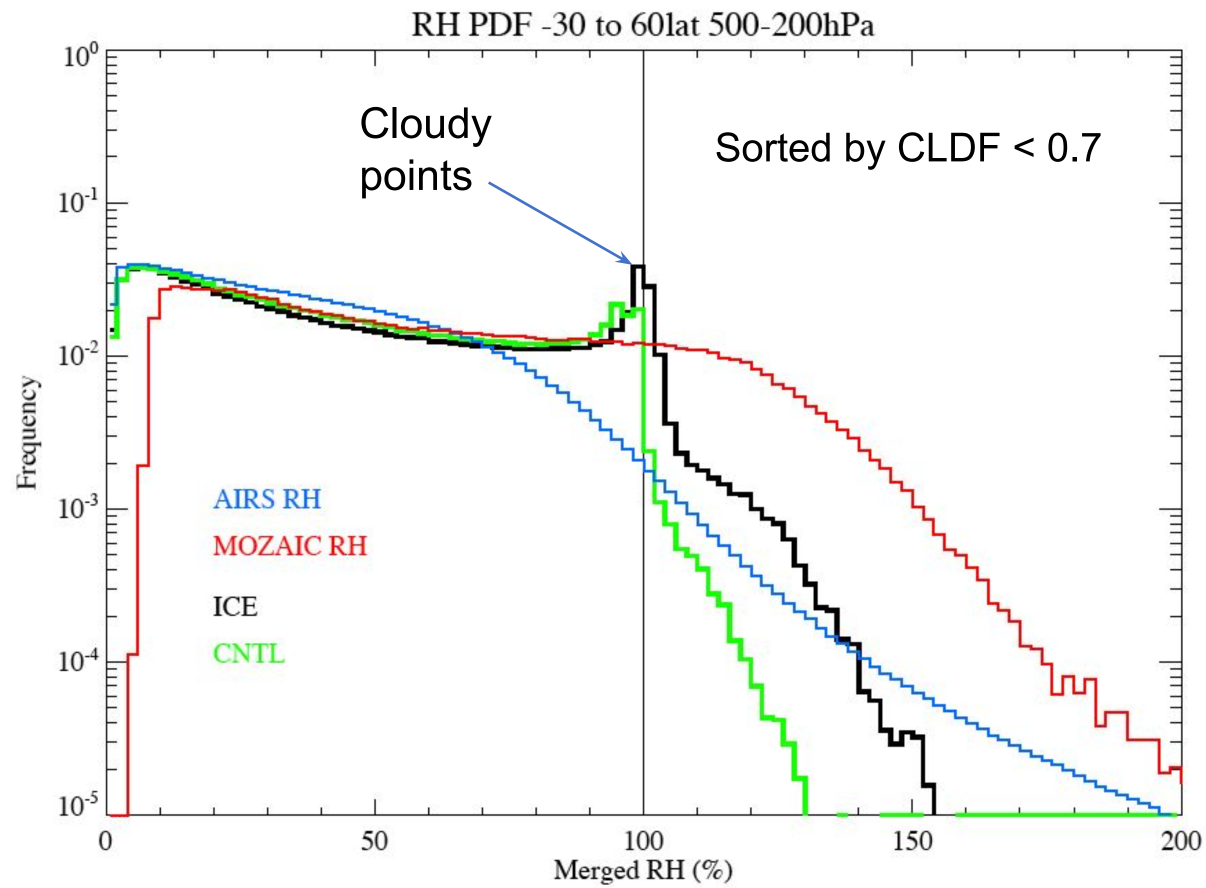
Ice Supersaturation

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')



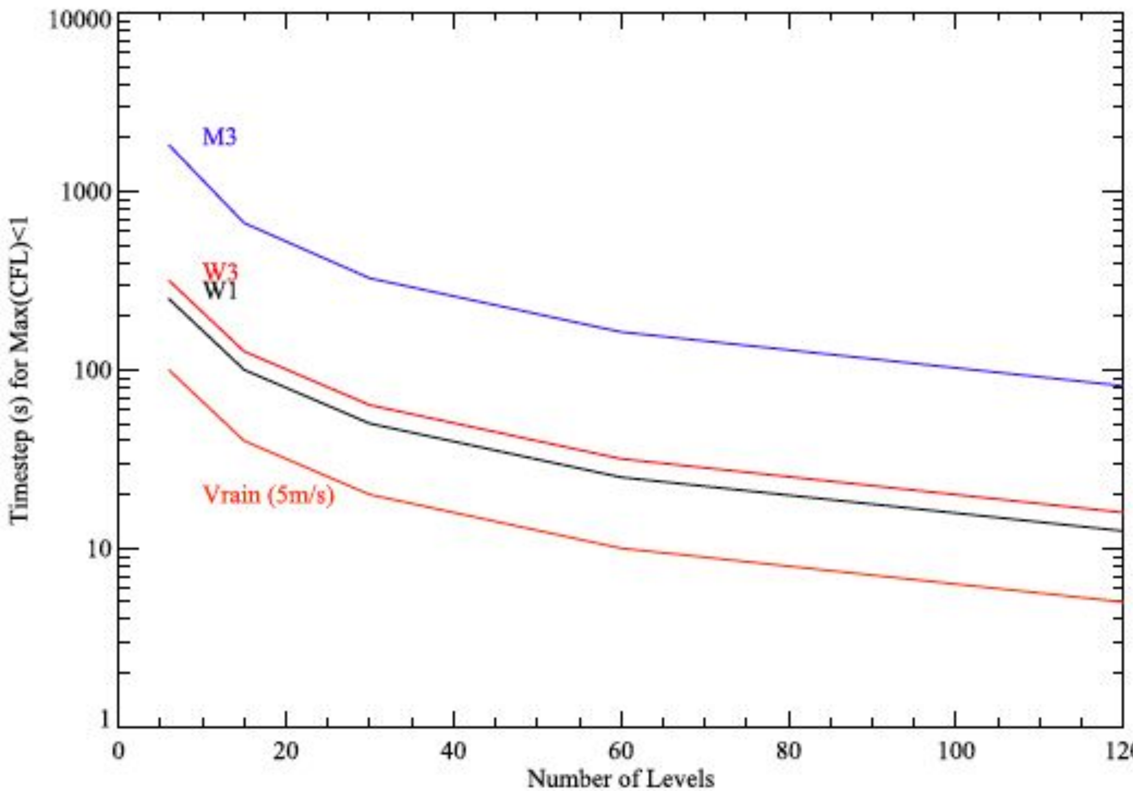
Numerical considerations: Sedimentation

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

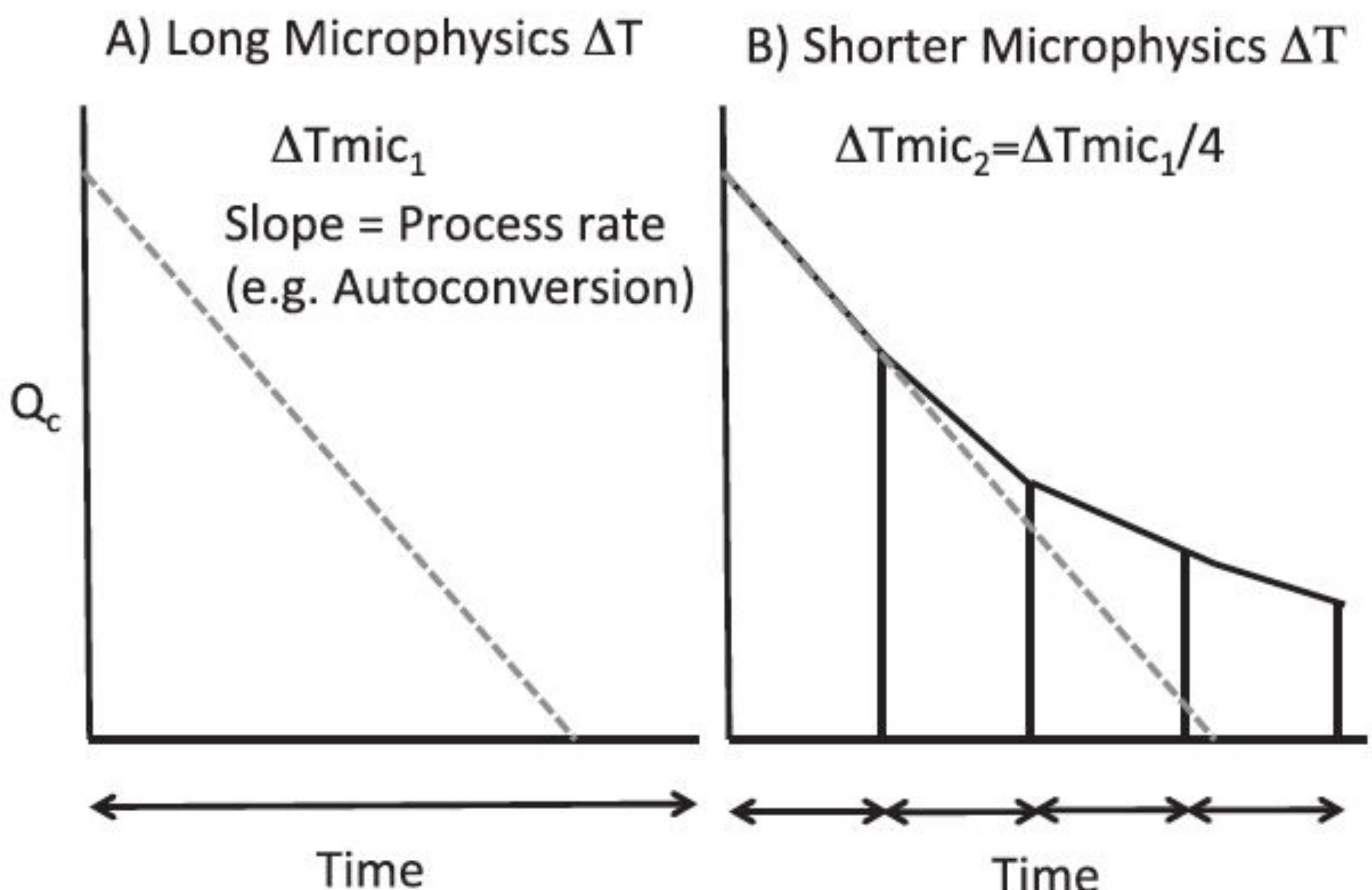
Figure: maximum timestep for satisfying CFL condition with different updraft speeds and fall speeds for rain (5m/s)

Control for this in microphysics (sub-steps)



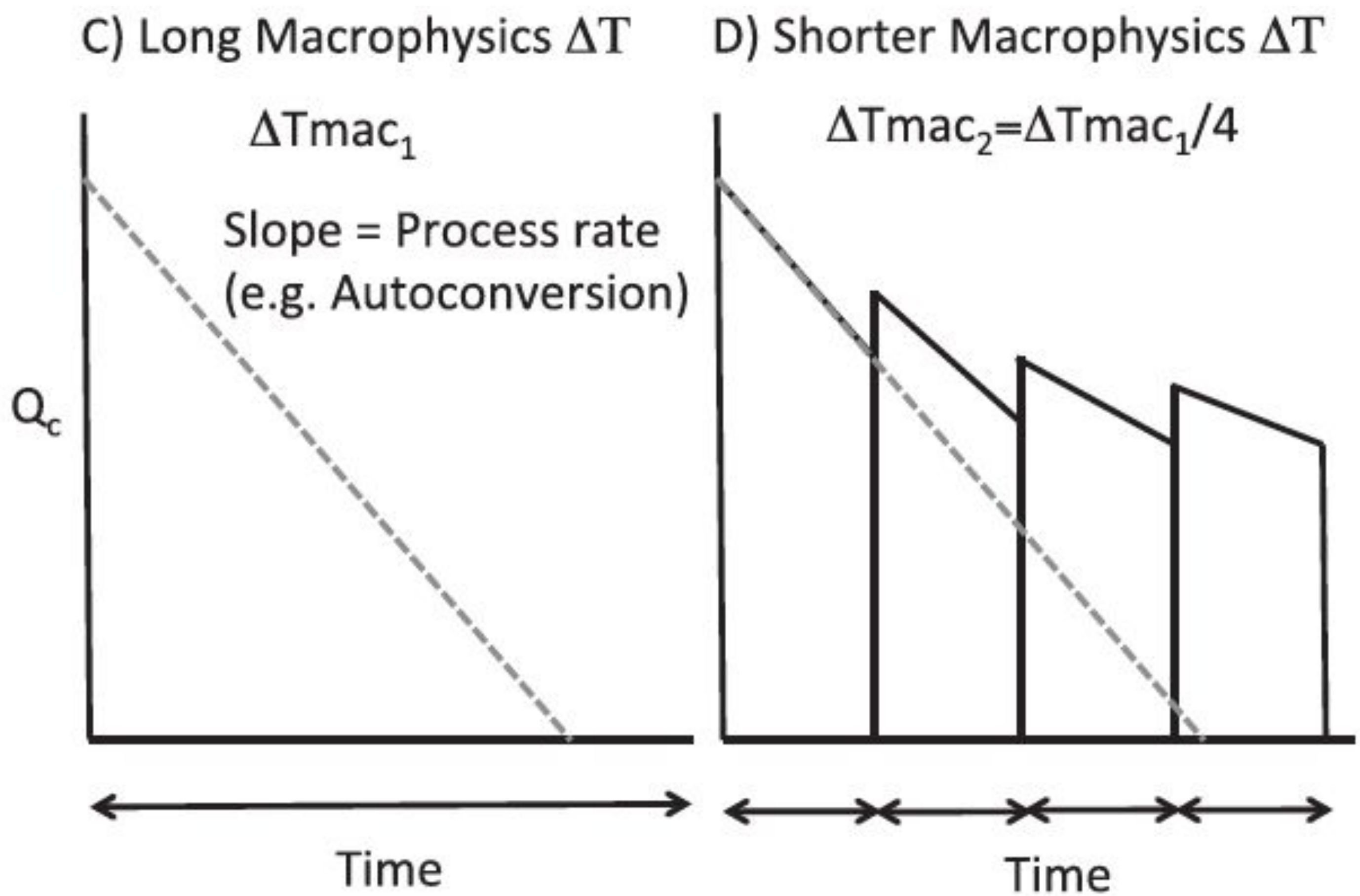
Numerical considerations: clipping

- 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



Numerical considerations: coupling

Similar issues occur with condensation itself, and coupling with macrophysics

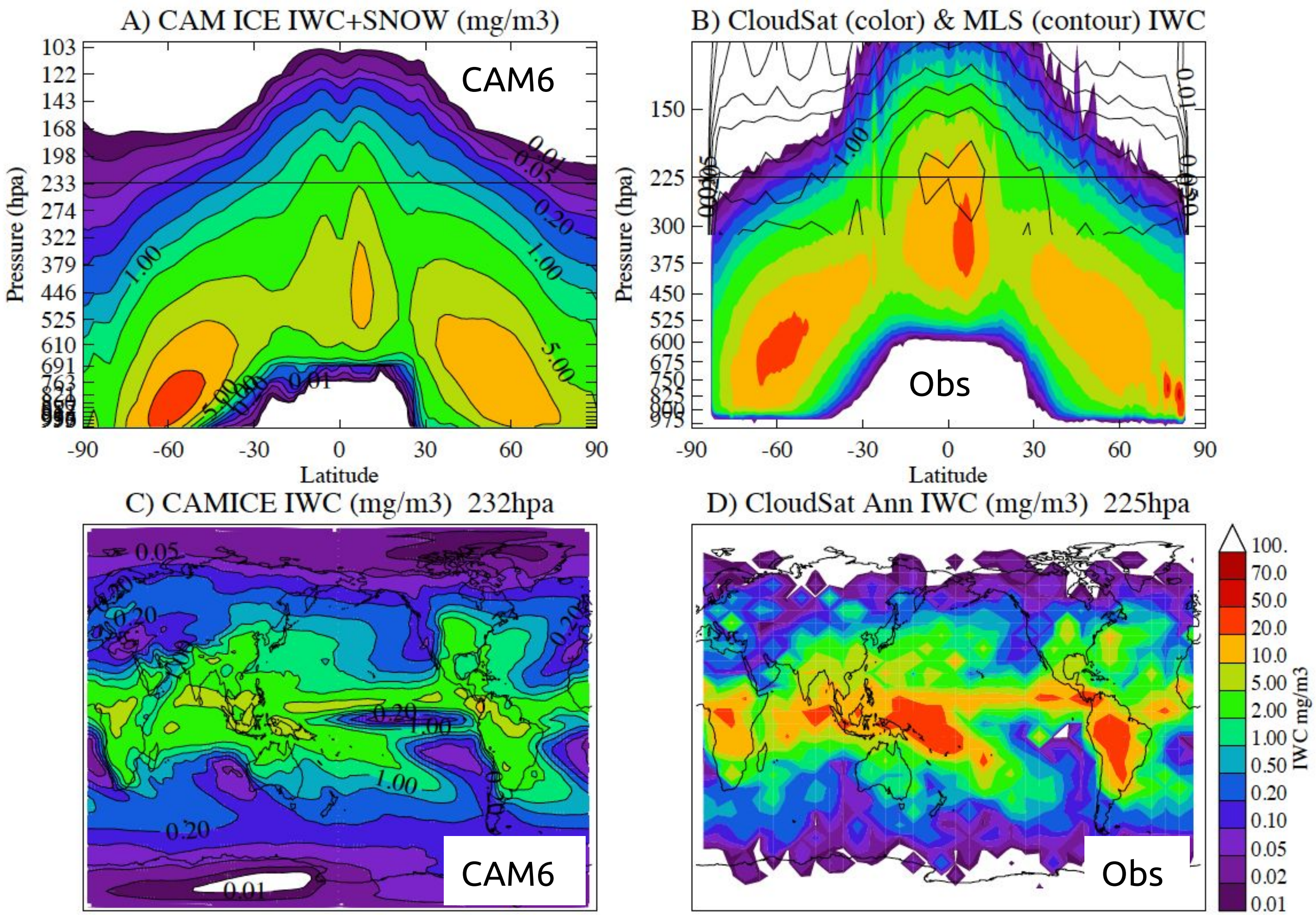


Evaluation with Observations

- 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)

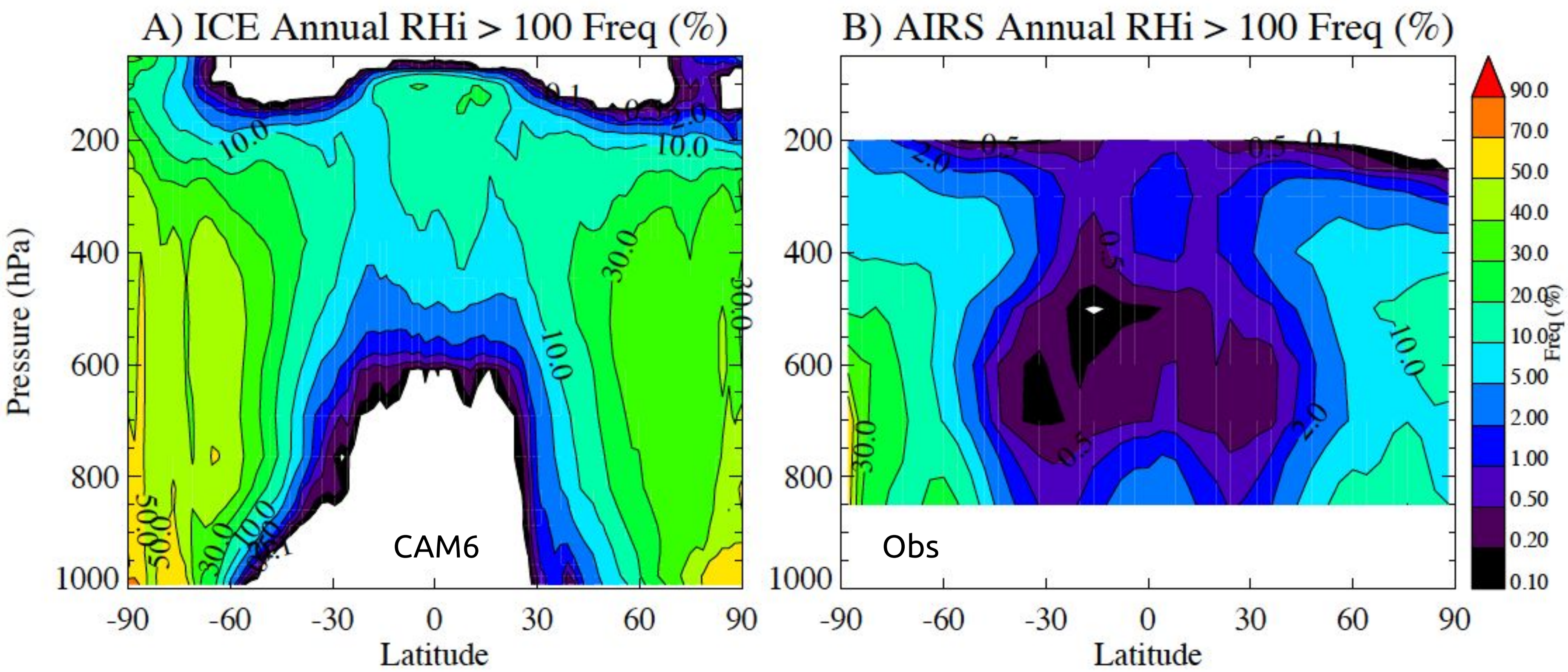
Evaluation v. Satellites

- 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



Ice Supersaturation Frequency

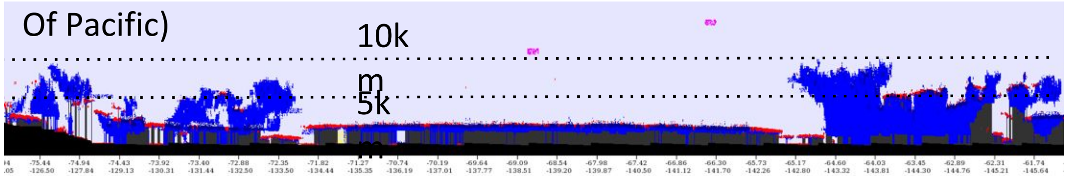
Neasurements of T and Q from AIRS at high resolution (50km) yield RH



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

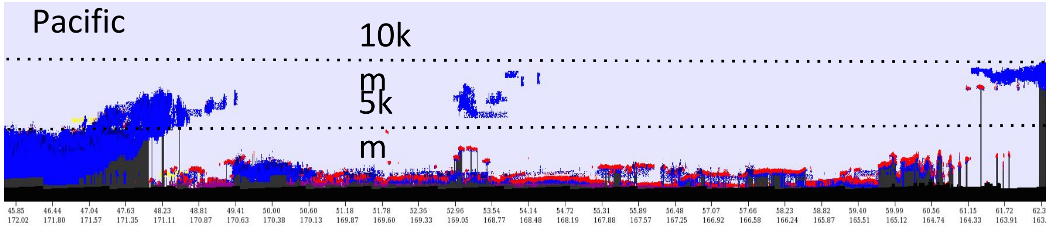
Liquid

Ice

Supercooled

61S

2014-02-07 N. Pacific



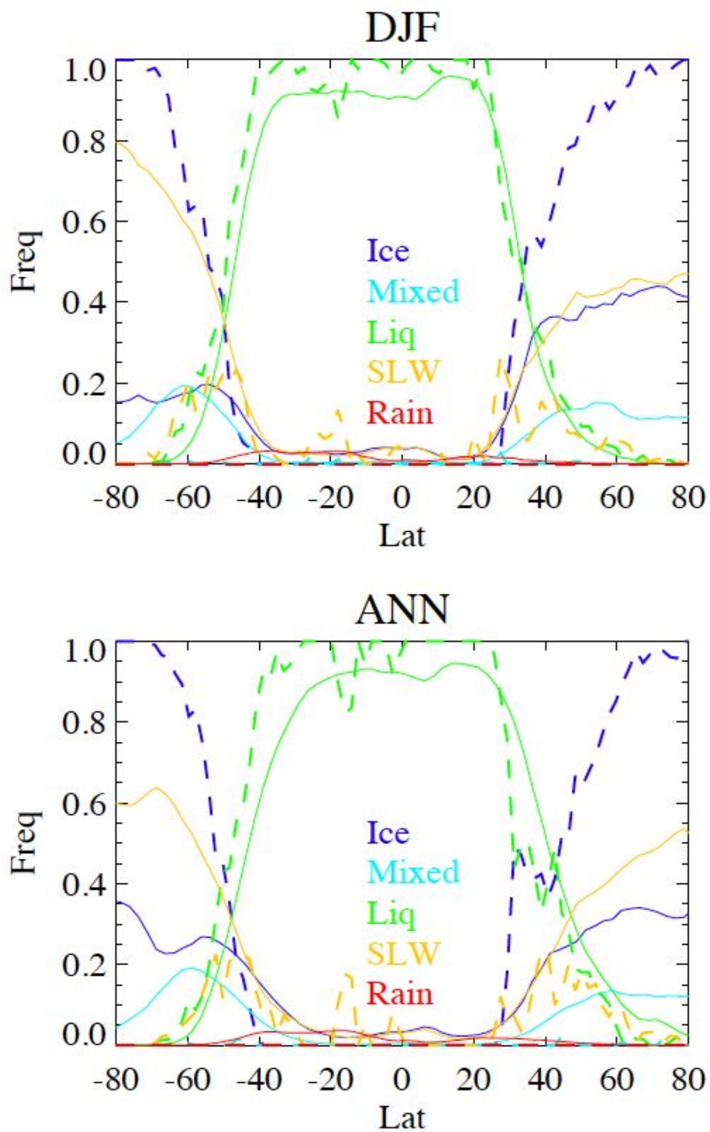
45 N

60 N

Most thin layers of super-cooled liquid over ice

Radar & Lidar (CloudSat + Calipso)

Supercooled liquid



Frequency of occurrence of different hydrometeors at cloud top.

Solid = Satellite observations. (DARDAR)

Dashed = CAM5.4 (Climate Model)

Getting some super-cooled liquid water (SLW), not quite enough

Liquid looks good (too much Ice)

Aerosols & Clouds

Andrew Gettelman
National Center for Atmospheric Research
Thanks to Jerome Fast, PNNL

Interactions with Aerosols

Clear sky in Beijing, Mon, Sept 19, 2016,06:00 LT looking west

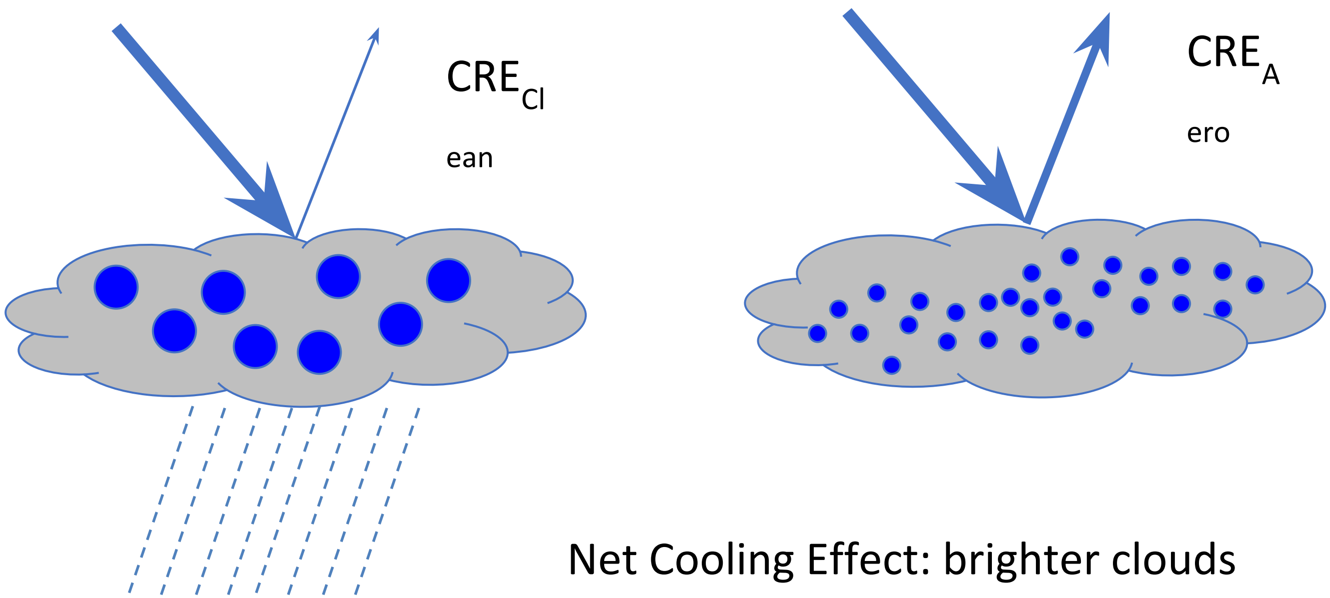
Interactions with Aerosols

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

Aerosol Cloud Interactions

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

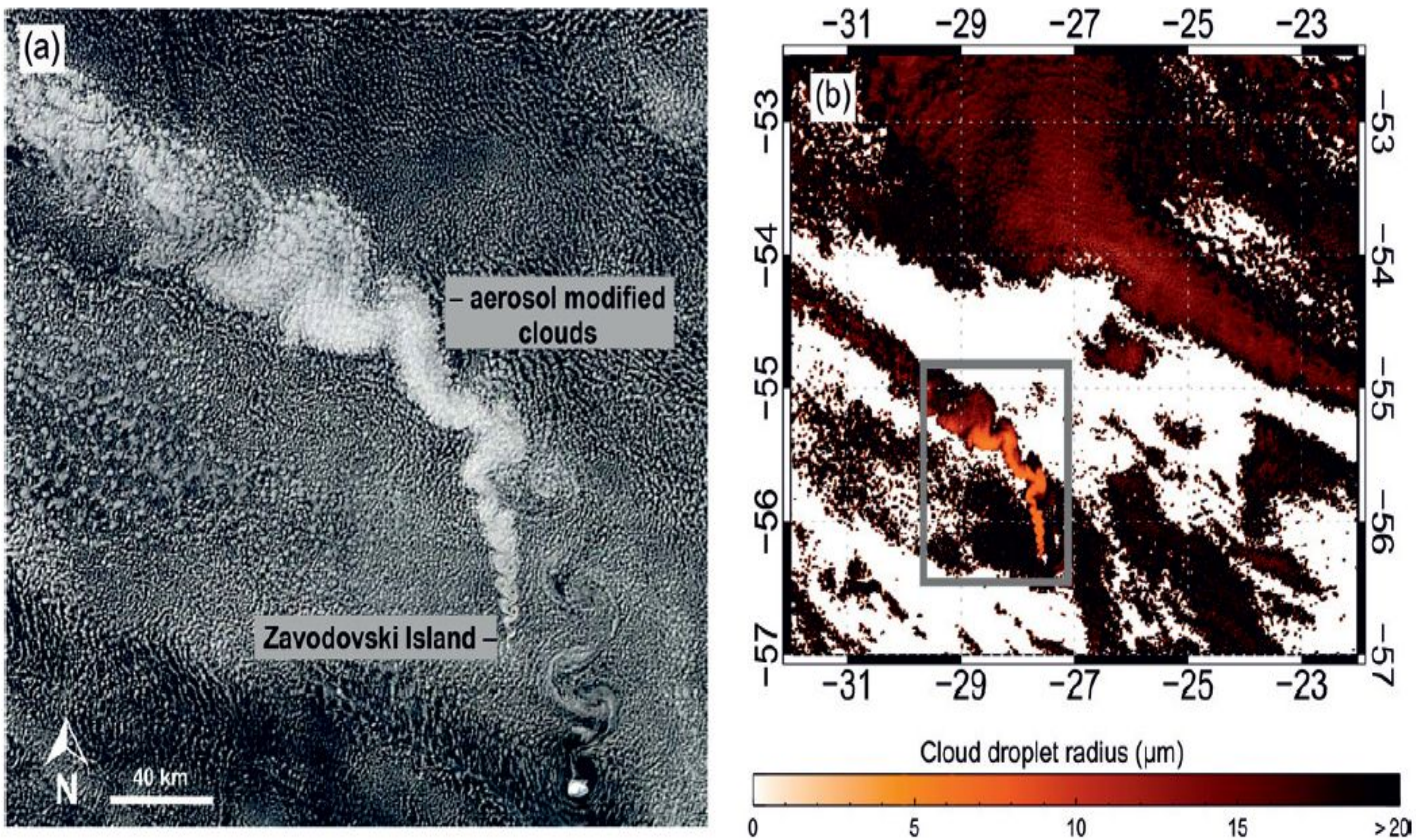
$$+\text{Aerosols} \dashrightarrow +\text{CCN} \dashrightarrow +N_c \dashrightarrow \Delta\text{CRE}$$



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)

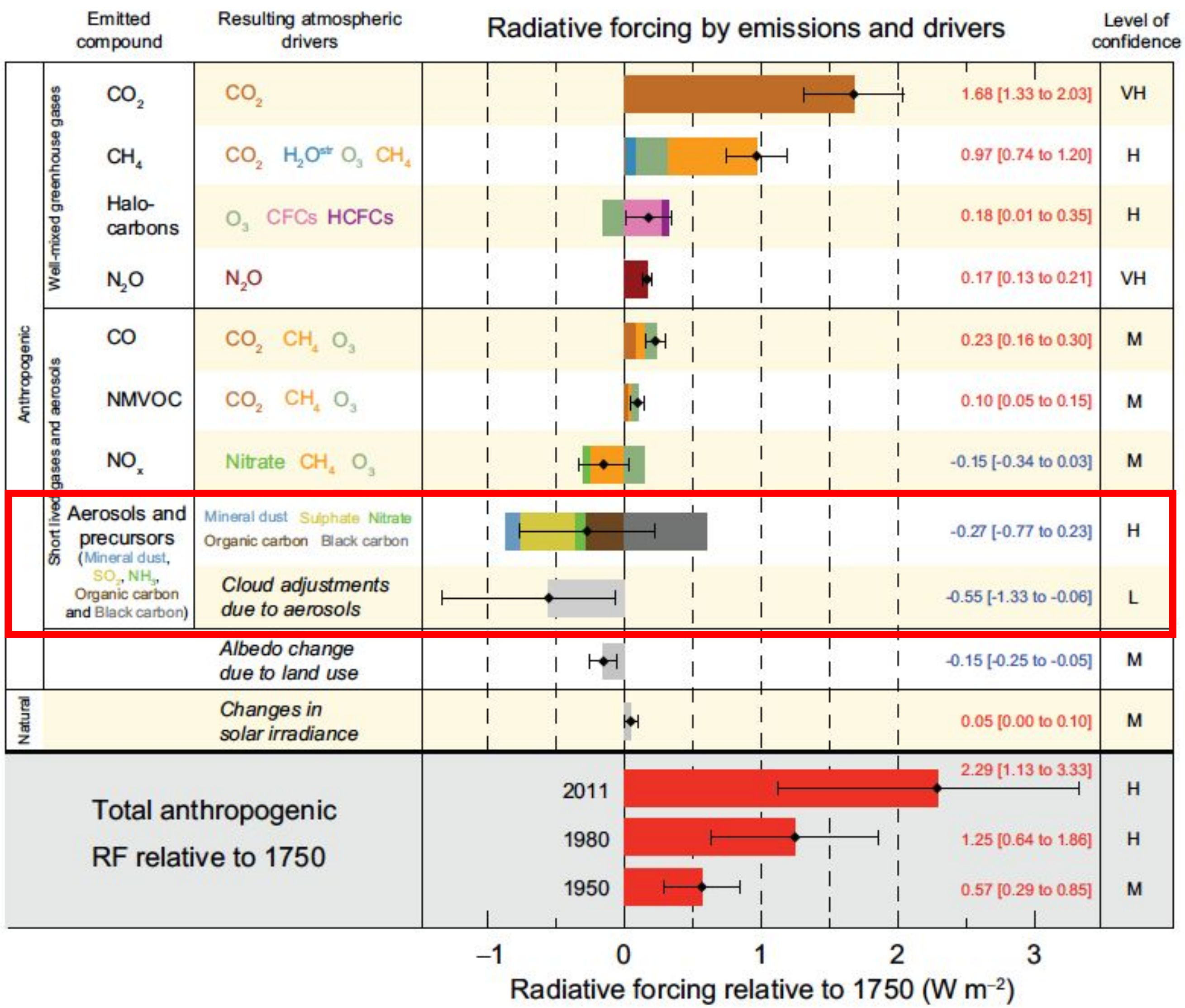
Schmidt et al 2012

Microphysics affected by aerosols

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

Climate Forcing

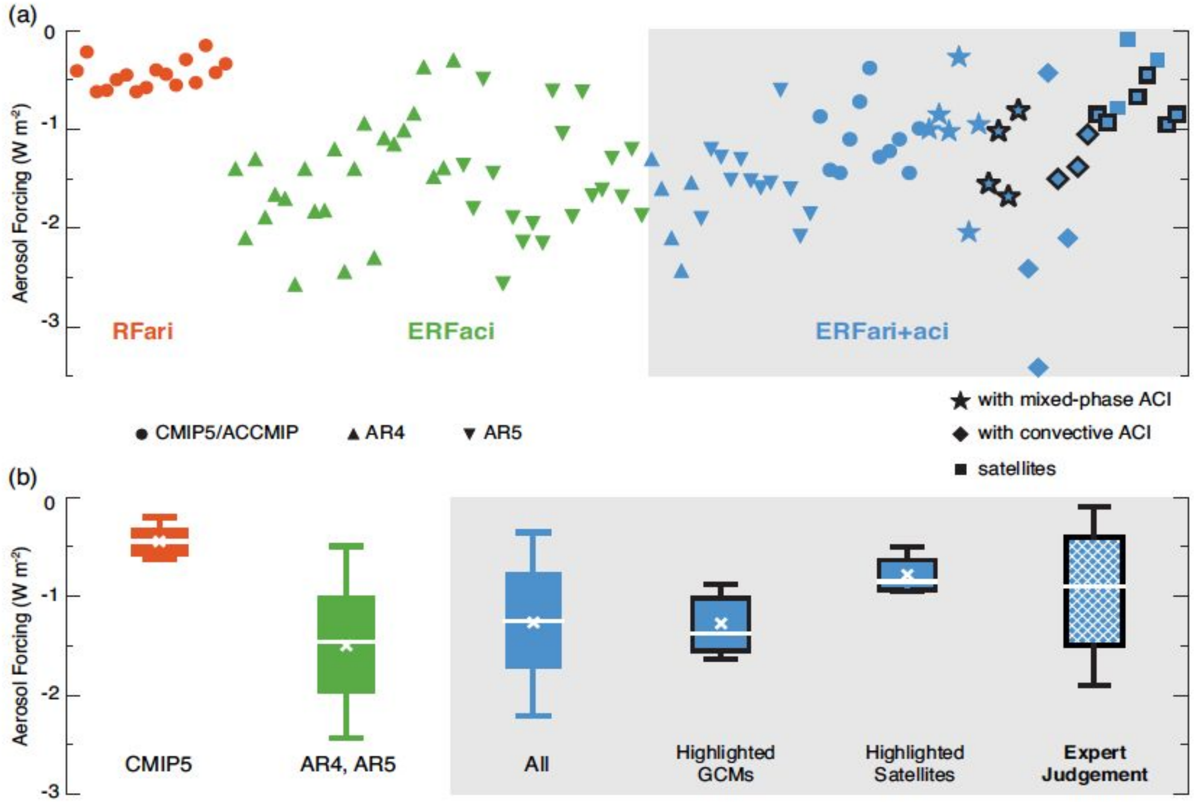
Aerosol Cloud Interactions are the largest uncertainty in Climate forcing



IPCC, 2013, SPM.5

Aerosol Forcing: Present – Preindustrial

- Large uncertainties
- Difference between models and observations
- Models have a larger effect than observed
- Why? Either:
  - Obs are incorrect
  - Microphysics is missing something
- Obs are 'different': new work shows more agreement
- What is missing? 'buffering': e.g. evaporation feedbacks?



Boucher et al 2013, Figure 7.19

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

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

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

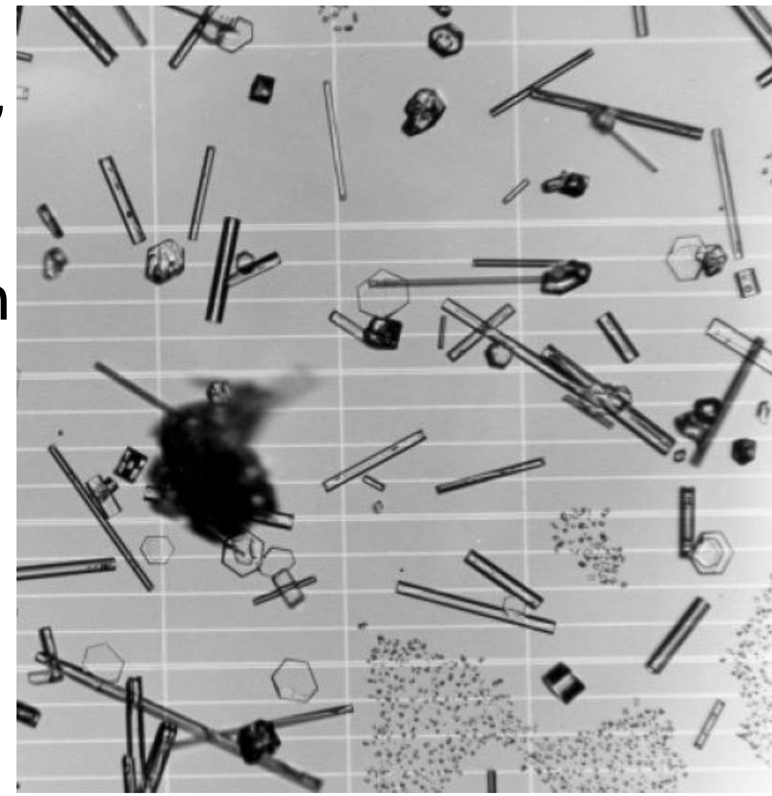
Seifert et al 2015, JGR

Aside: observing cloud microphysics

- Satellites observe τ in some wavelength
  (even active sensors)
- τ is a non-unique function of N, LWP. $\tau = \alpha N_c^{1/3} L_c^{5/6}$
- To determine cloud microphyiscs (N, LWP), need to make an assumption.
- Better: IR more sensitive to N, microwave more sensitive to LWP
- Still large uncertainties (even for liquid)

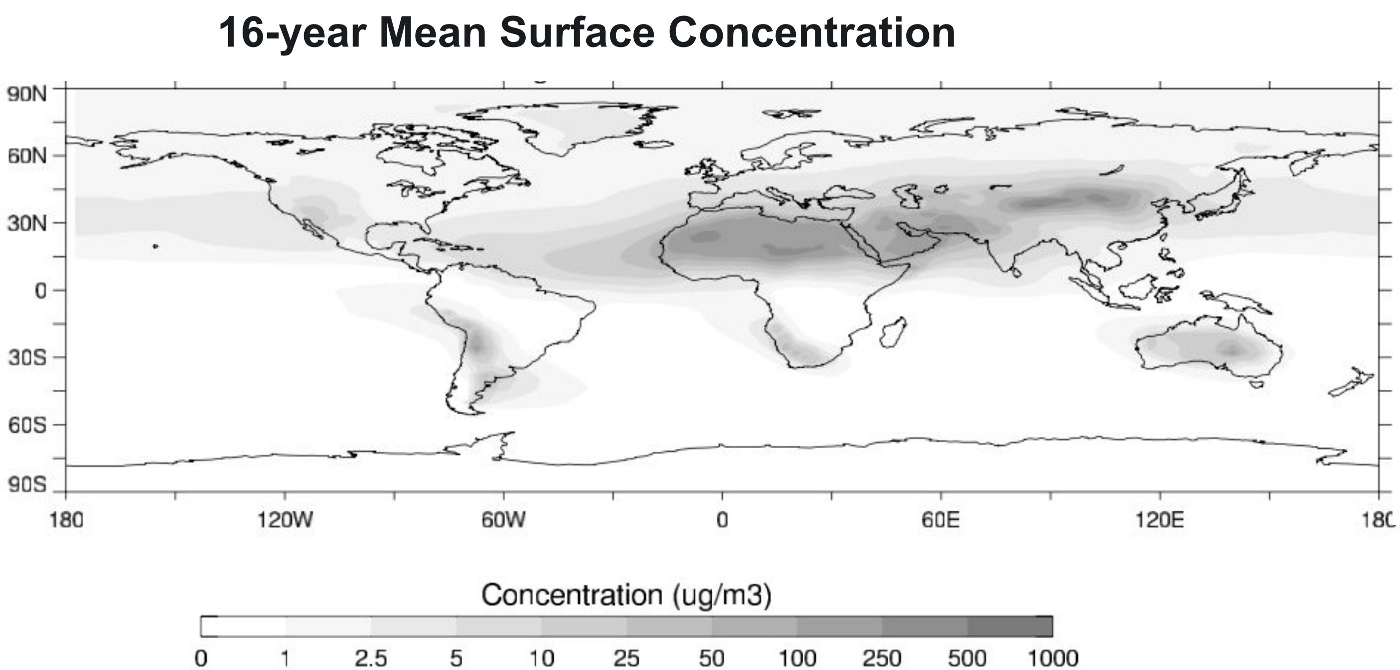
Interactions with Radiation: Ice

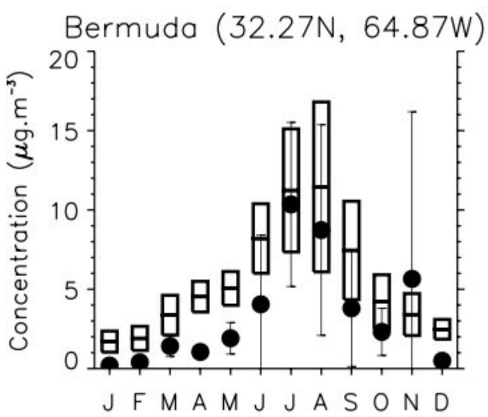
- Ice is more complicated
- It's not spherical: different 'habits' have different optical properties
- Ice clouds are typically a collection of habits
- Impacts optics (absorption, scattering), also sedimentation



Bulk Approach

- Only total mass of aerosol compounds are represented
- No information on particle number or size – assume size distribution for radiative transfer and response of cloud properties to aerosols
- Most numerically efficient of all the approaches (fewest number of species to keep track of)

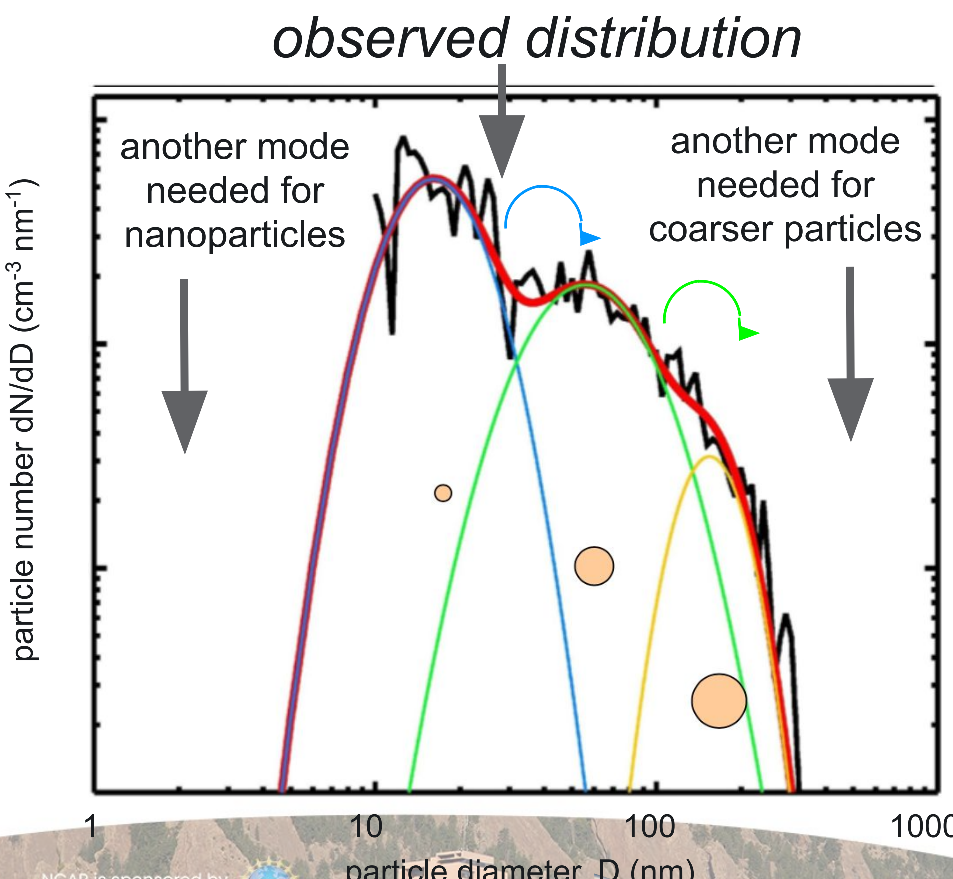




from Ginoux et al. EMS, 2004

Modal Approach

- Represents the size by a discrete number of log-normal distributions
- Number of modes usually hard-coded into the model
- Modes smoother than observed distributions
- Numerical efficient – suitable for AQ and climate models



Example: MAM in CESM

Liu et al. GMD, 2016

4 modes by default

$$\frac{dN}{dD} = \frac{dN}{dD} + \frac{dN}{dD} + \frac{dN}{dD}$$

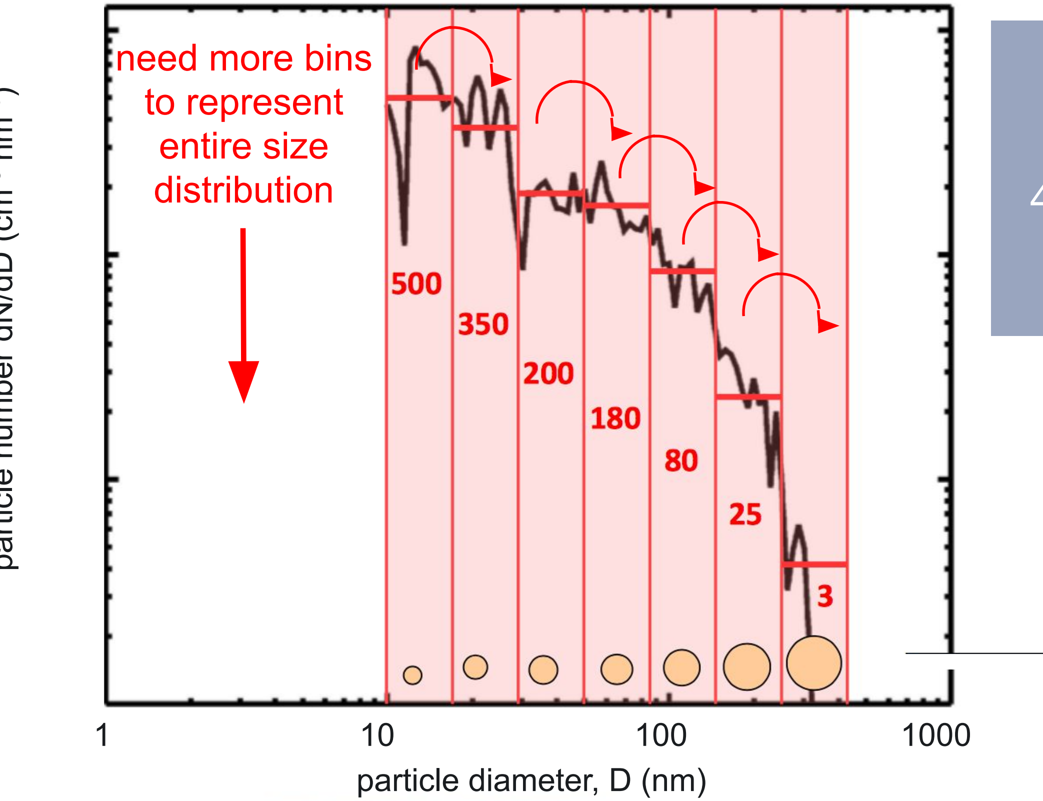
$\frac{dN}{dD} \rightarrow N = 8195\ cm^{-3}$, $\mu = 18.22\ nm$, $\sigma = 1.42$ — **Aiken mode**

$\frac{dN}{dD} \rightarrow N = 12732\ cm^{-3}$, $\mu = 68.44\ nm$, $\sigma = 1.57$ — **Accumulation mode**

$\frac{dN}{dD} \rightarrow N = 3140\ cm^{-3}$, $\mu = 164.41\ nm$, $\sigma = 1.28$ — **Coarse mode**

Sectional Approach

- Represents the size distribution by a discrete number of size bins
- More flexible than modal approach – better represents size
- Need a large number of bins to represent observed distributions
- Numerical more expensive - suitable for AQ models and research studies



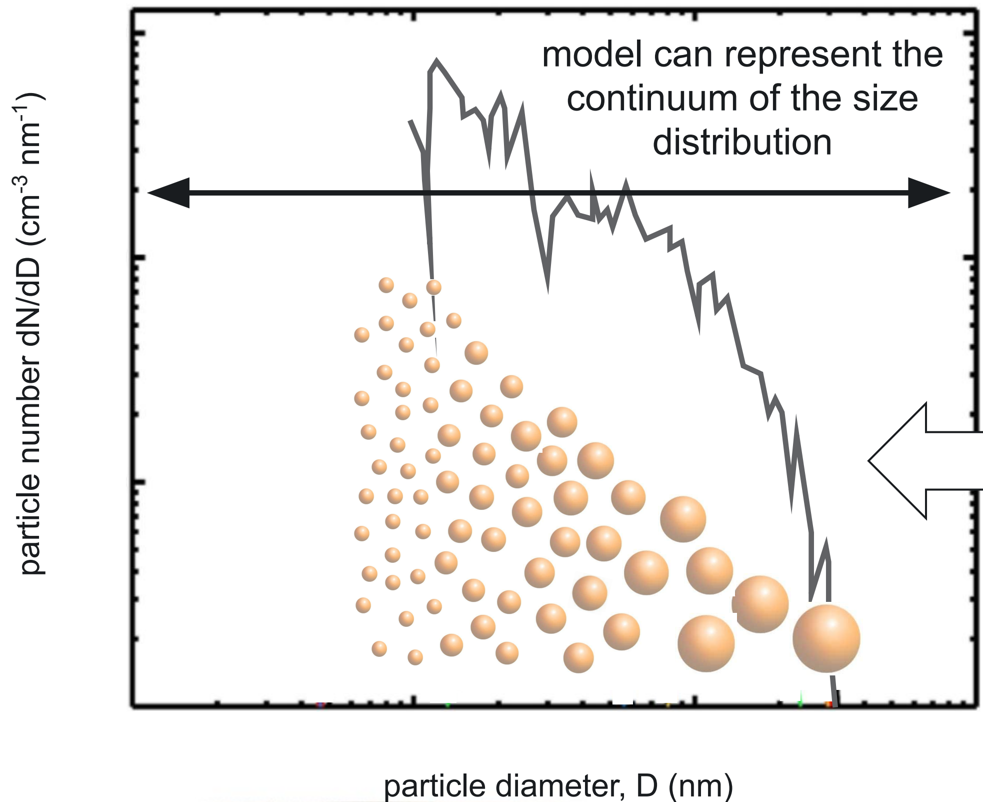
Example: MOSAIC in WRF-Chem

Zaveri et al. JGR, 2008

4 or 8 bins by default but can be configured to any #

Explicit Approach

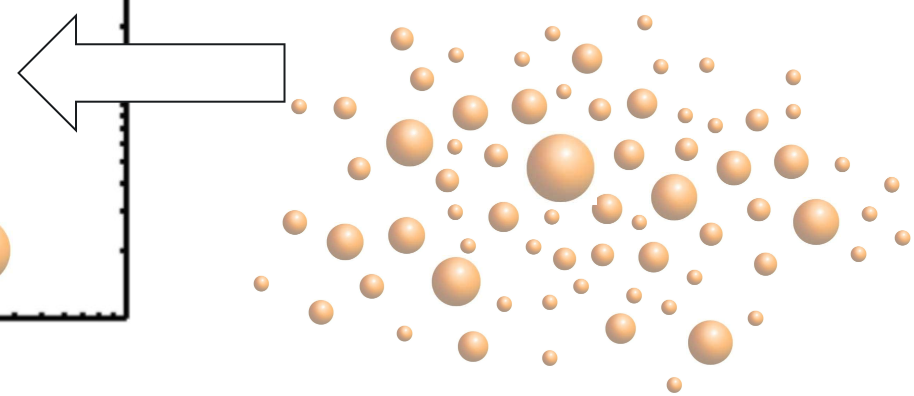
- Represents the size distribution by explicitly simulating each particle in a population of particles. Need to simulate thousands of particles.
- More flexible than both modal and sectional approaches
- Numerically expensive-suitable for research studies (e.g. box modeling)



Example: PartMC-MOSAIC

Riemer et al. JGR, 2010

Zaveri et al. JGR, 2010



Summary

- Microphysics describes what happens to condensed phase in clouds
- Input: state, condensation (macrophysics/turbulence), aerosols
- Output: precipitation, detailed size distributions (for radiation code)
- Morrison Gettelman = bulk 2-moment scheme (mass, number)
- It is coupled to an aerosol activation scheme so aerosols affect cloud drop number concentrations
- Aerosol Scheme is a 4 mode Modal Aerosol Model (MAM)