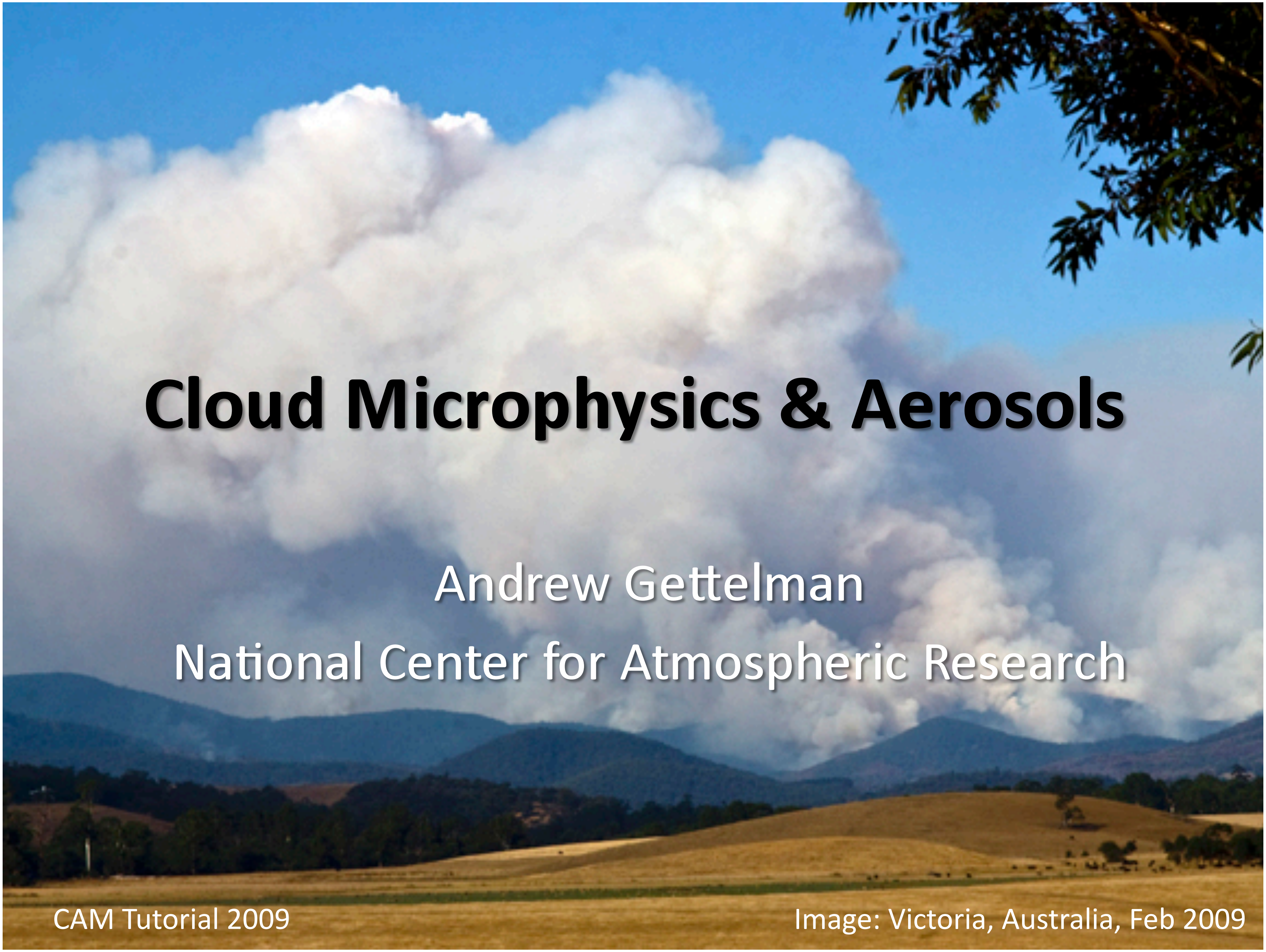

Cloud Microphysics & Aerosols

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CAM Tutorial 2009

Image: Victoria, Australia, Feb 2009

Outline

- What is 'Cloud Microphysics'
- Different Approaches
- CAM implementation of Microphysics
- Aerosol Modeling
- Options in CAM
- Interactions
  - Scavenging / Deposition
  - Aerosol Indirect Effects on Climate

Scope

- "Cloud Microphysics" refers to the condensed phase water processes in the atmosphere
  - Microphysical properties of condensed species
    - size distributions, shapes
  - Distribution of and transformation of condensed species
    - precipitation and phase conversion
- In CAM: this equates to 'stratiform' cloud microphysics
  - Convective clouds have even more heavily parameterized microphysics
- Large Scale Condensation itself is generally handled by "cloud macrophysics" (cloud fraction)

Key operations on Condensed Species

- Condense/Sublimate
- Sediment
- Convert to precipitation
- Determine properties for other processes
  - Chemical species (scavenging)
  - Physical state (size, number) for radiation

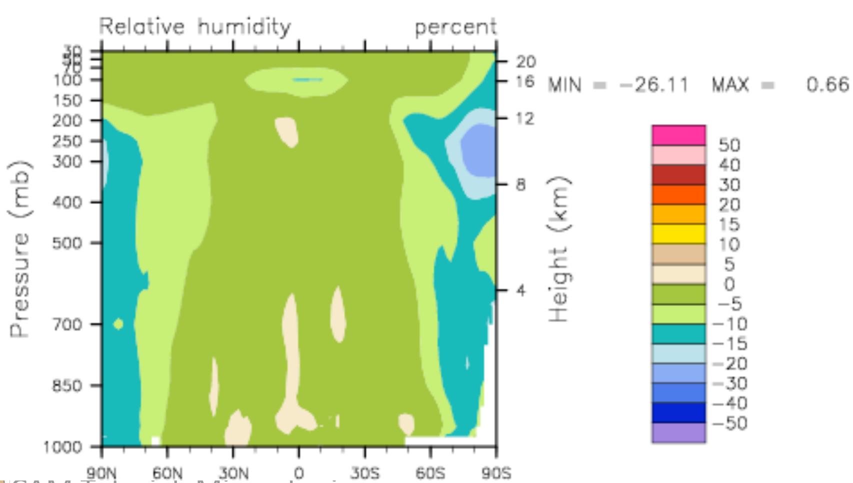
What does this mean for Simulations?

- Microphysics controls details of precipitation
  - Rate, location
  - Overall precipitation limited by energy balance constraints (P-E)
- Coupled with Condensation (macrophysics) it determines cloud properties
  - In CAM: stratiform cloud fraction and properties
  - Also, uses convective detrainment

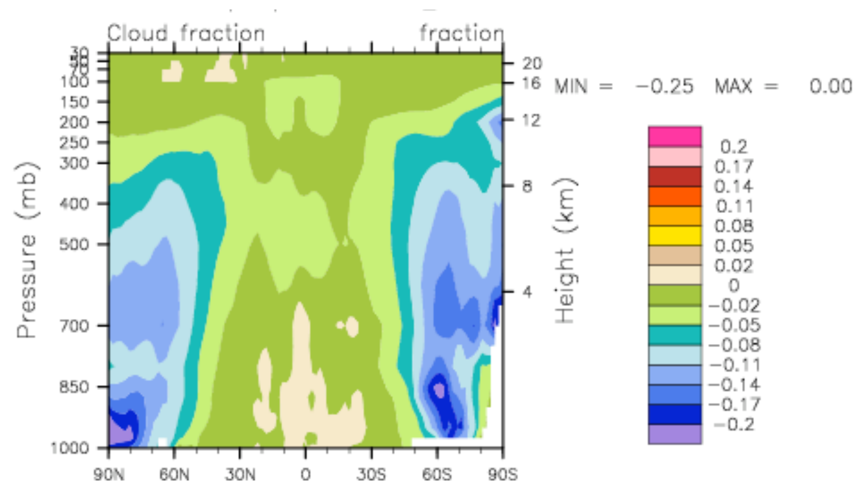
Sample Impact

- Change the vapor deposition process in the microphysics to be more efficient (remove H2O)
  - →Lower RH → Reduced Cloudiness by 20% (51-41%)
  - →Global change of $2Wm^{-2}$ at TOA.

ΔRH



ΔCldFrc



Motivation

- Clouds are a very significant uncertainty in climate models (IPCC, 2007)
- Many ways to define microphysical processes that lead to present state: these methods may respond differently to climate change
- Critical to reduce uncertainties. Goal has been to increase complexity so that process models look more like observations

Different types of Microphysics

- Bulk Microphysics
  - Mass based only (2 species: liquid and ice)
  - Bulk transformations and processes
  - Specified sizes or size distributions
  - Early schemes were diagnostic (e.g.: yesterday)
- Bin Microphysics
  - Multiple size bins (many constituents) with a mass in each. Explicit representation of size distribution
  - Transformations depend on mass and number

Modal Microphysics

- Use an analytic representation of the size distribution and carry around moments of the distribution
  - First moment = mass
  - 2nd moment = number
  - Size distribution reconstructed from an assumed shape.
  - Advantage: represent sizes consistently with computational efficiency

CAM Microphysics

- CAM3.5: Bulk Microphysics with prognostic condensate

  P. J. Rasch and J. E. Kristjansson, 1998

- CAM4.0: Modal Microphysics

  H. Morrison and A. Gettelman, 2008; Gettelman et al 2008

- Start with RK98 scheme, then brief description of MG08

CAM Microphysics

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- CAM4.0: Modal Microphysics

  H. Morrison and A. Gettelman, A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmospheric Model (CAM3), Part I: Description and Numerical Tests *J. Climate*, 21:15, 3642-3659, 2008

CAM 3 Bulk Microphysics

- Coupled to Slingo (1987) RH based cloud fraction
  - Fractional cloudiness: A > 0 when RH > 0.88 or so
- Condensation closure from Zhang et al (2003)
  - Allows partial cloudiness
- Fixed ice & liquid fraction as a function of temperature
  - Not a bad assumption based on observations
- For radiative transfer & sedimentation, assumed Fixed particle sizes for liquid over land/ocean (larger over ocean).
- Ice crystal size is a function of temperature or pressure

CAM3 Bulk Microphysics (2)

- Prognostic variables for Liquid & Ice mass
- Detrained liquid from convection put into stratiform microphysics scheme

Macroscale component

Vapor Tendency
$$\frac{\partial q}{\partial t} = A_q - Q + E_r$$

Temperature Tendency
$$\frac{\partial T}{\partial t} = A_T + \frac{L}{c_p}(Q - E_r)$$

Condensate Tendency
$$\frac{\partial l}{\partial t} = A_l + Q - R_l \ ,$$

A= tendencies due to other processes
Q= net condensation
E_r= net evaporation
R_l= rain/snow formation rate
Macrophysics is concerned with determining “Q”

Subtleties: arise due to (1) in-cloud v. out of cloud regions, (2) newly forming cloud

Microscale Component

- Ice and liquid repartitioned according to T
  - Typically -40 to -10 C (can be changed)
  - Heat is associated with the transformation
- Detrained condensate added
- Precipitation Fluxes determined
- Sedimentation is calculated
  - Ice velocity is a function of size (effective radius, r_{ei})
  - Liquid velocity also, but only 2 values (land, ocean)

Microscale Processes

Conversion Terms:

- Liquid & ice conversion to rain (Auto-conversion)
- Collection of liquid and ice by precipitation
- Collection of Liquid by snow (riming)

Conversion terms are a function of model state, and generally empirical fits to field campaigns (most date from 1980's or so):

Tripoli & Cotton 1980, Kessler 1969, Lin et al 1983, etc

Process Rates

- Complex forms
- Example, autoconversion of liquid water to rain (PWAUT)

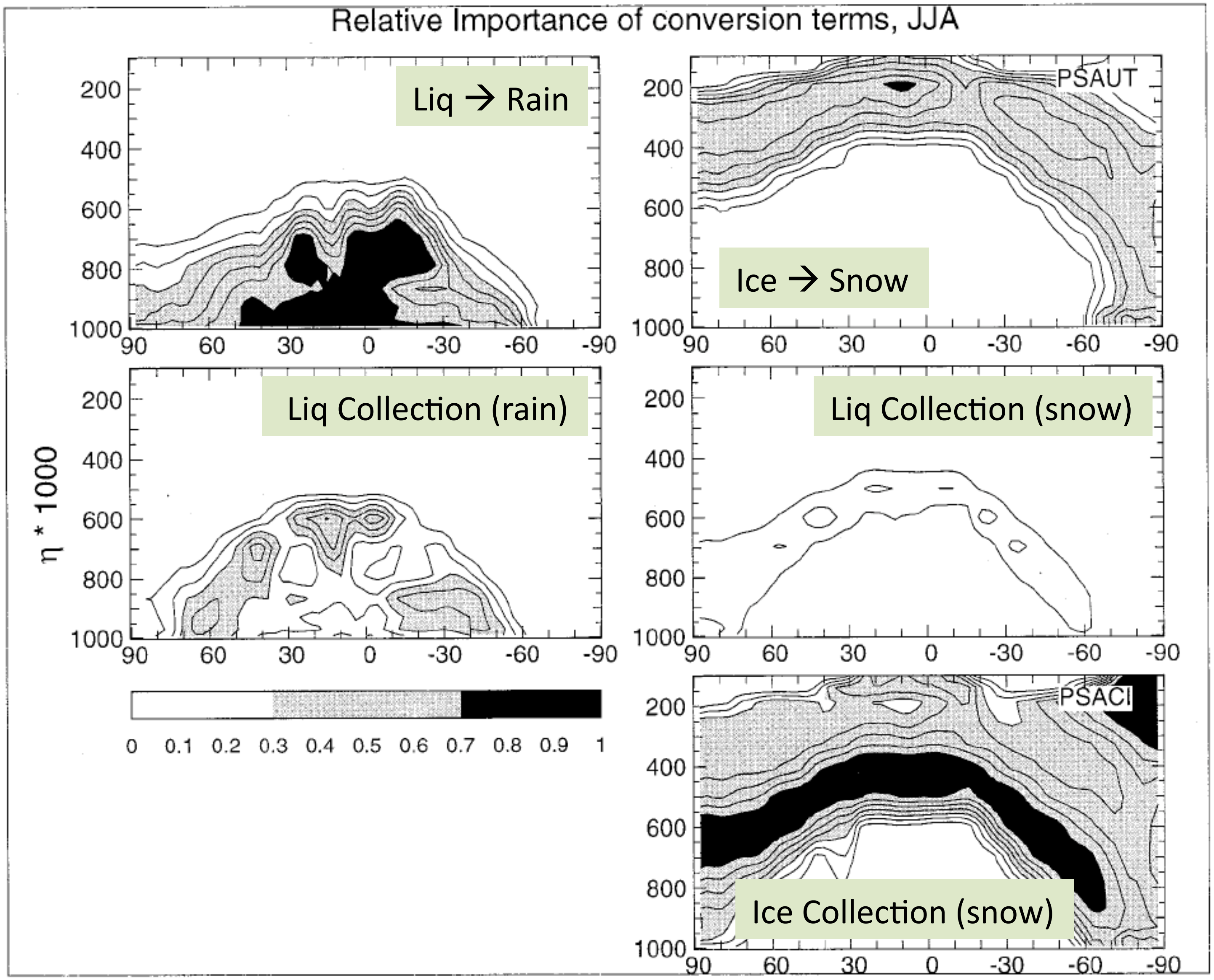
$$PW\,AUT = C_{l,aut}\hat{q}_l^2\rho_a/\rho_w(\hat{q}_l\rho_a/\rho_w N)^{1/3}H(r_{3l} - r_{3lc}).$$

H= heavy-side (binary function 0,1 when expression > or < 0)

N = assumed number density $C_{l,aut}$ is rate based on size

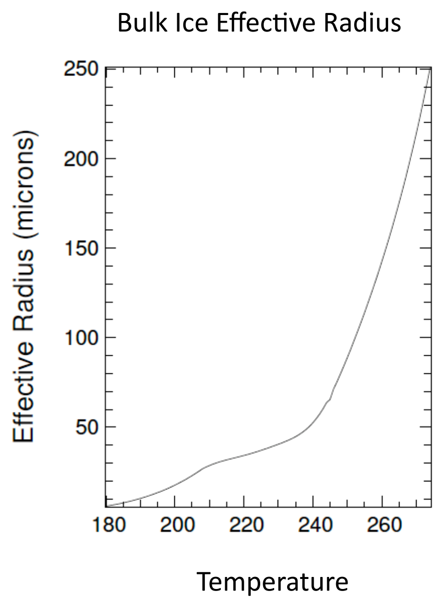
- Form from a 1D model of stratocumulus clouds, modified from earlier cumulus experiments.

Relative Importance of Processes



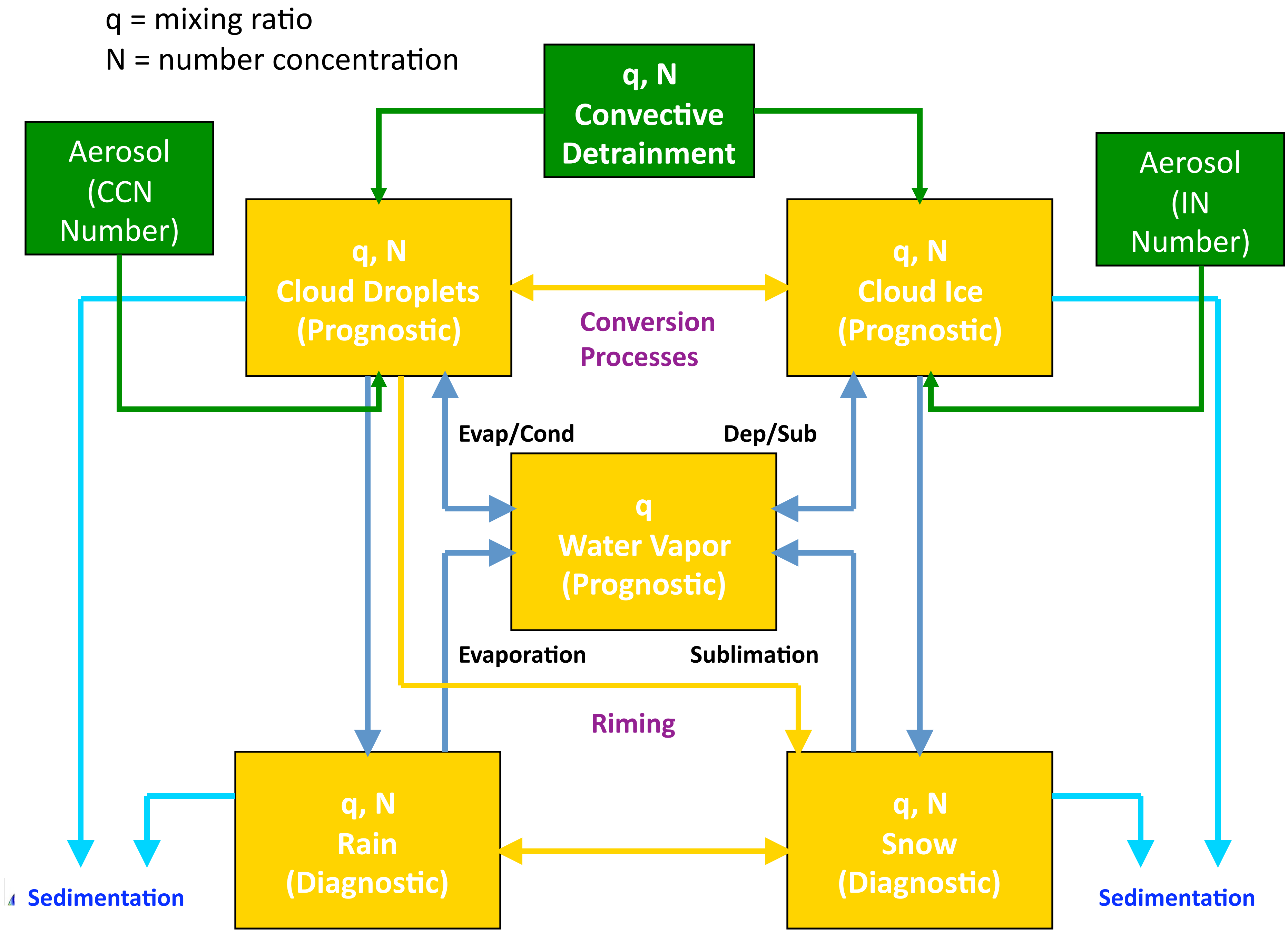
Notes

- For optical calculations, liquid particles assumed to be 8μm over land and 14μm over ocean
- Ice size is a function of temperature (also affects fall speed)

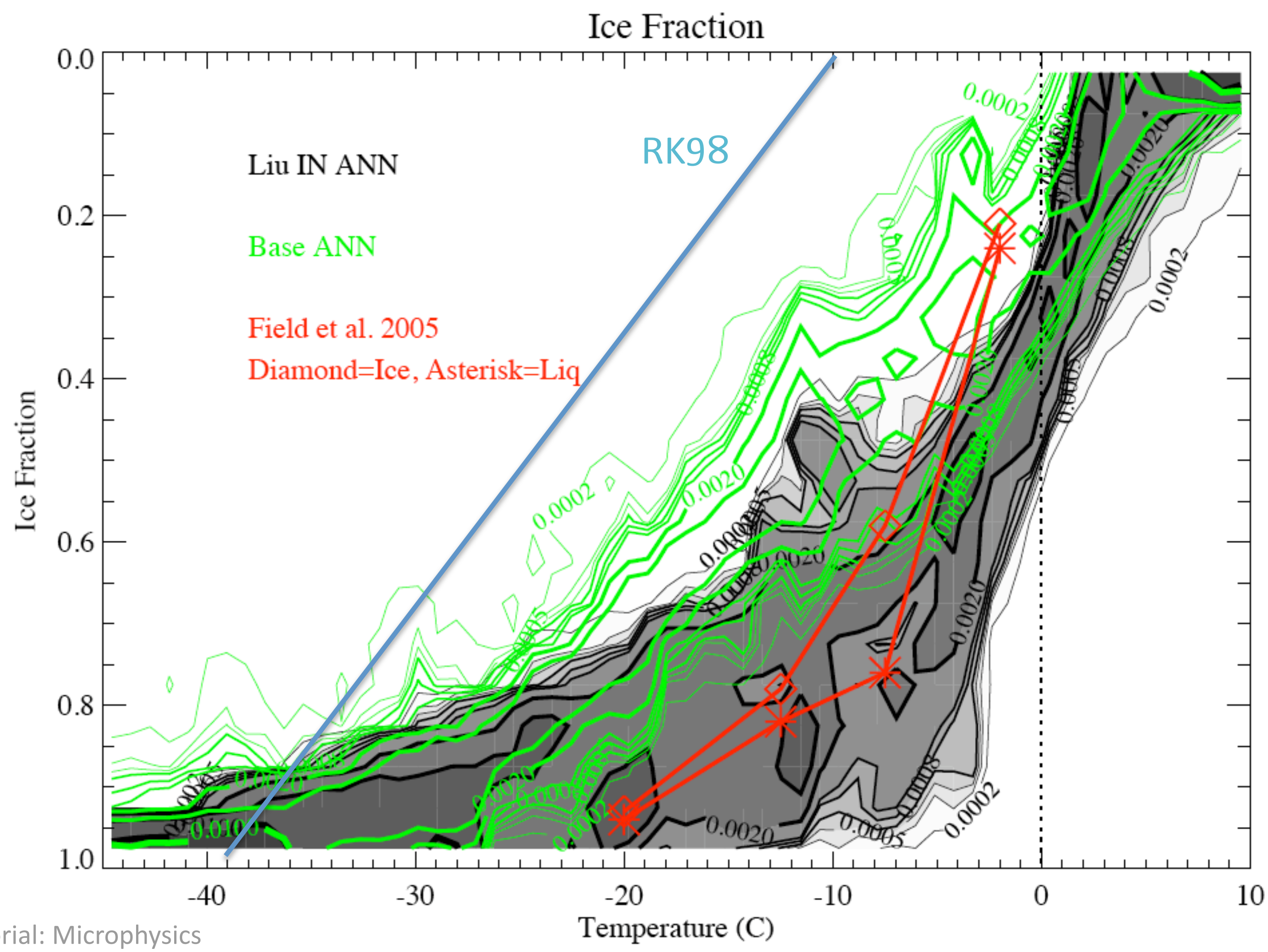


Modal Microphysics Features

- Based on a scheme for meso-scale models
- Addition of liquid & ice prognostic number
- Mixed phase vapor deposition
  - no temperature dependence for liquid v. ice
- Ice super-saturation
- Sub-grid representation of total water
- Activation of cloud liquid and ice by aerosols
- Use sub-grid vertical velocity from TKE
- Diagnostic representation of rain and snow mass & number
- Processes (collection, auto-conversion) similar. Add nucleation processes


q = mixing ratio
N = number concentration
q, N
Convective
Detrainment
Aerosol
(CCN
Number)
Aerosol
(IN
Number)
q, N
Cloud Droplets
(Prognostic)
q, N
Cloud Ice
(Prognostic)
Conversion
Processes
Evap/Cond
Dep/Sub
q
Water Vapor
(Prognostic)
Evaporation
Sublimation
Riming
q, N
Rain
(Diagnostic)
q, N
Snow
(Diagnostic)
Sedimentation
Sedimentation

Ice Fraction (Mixed Phase)



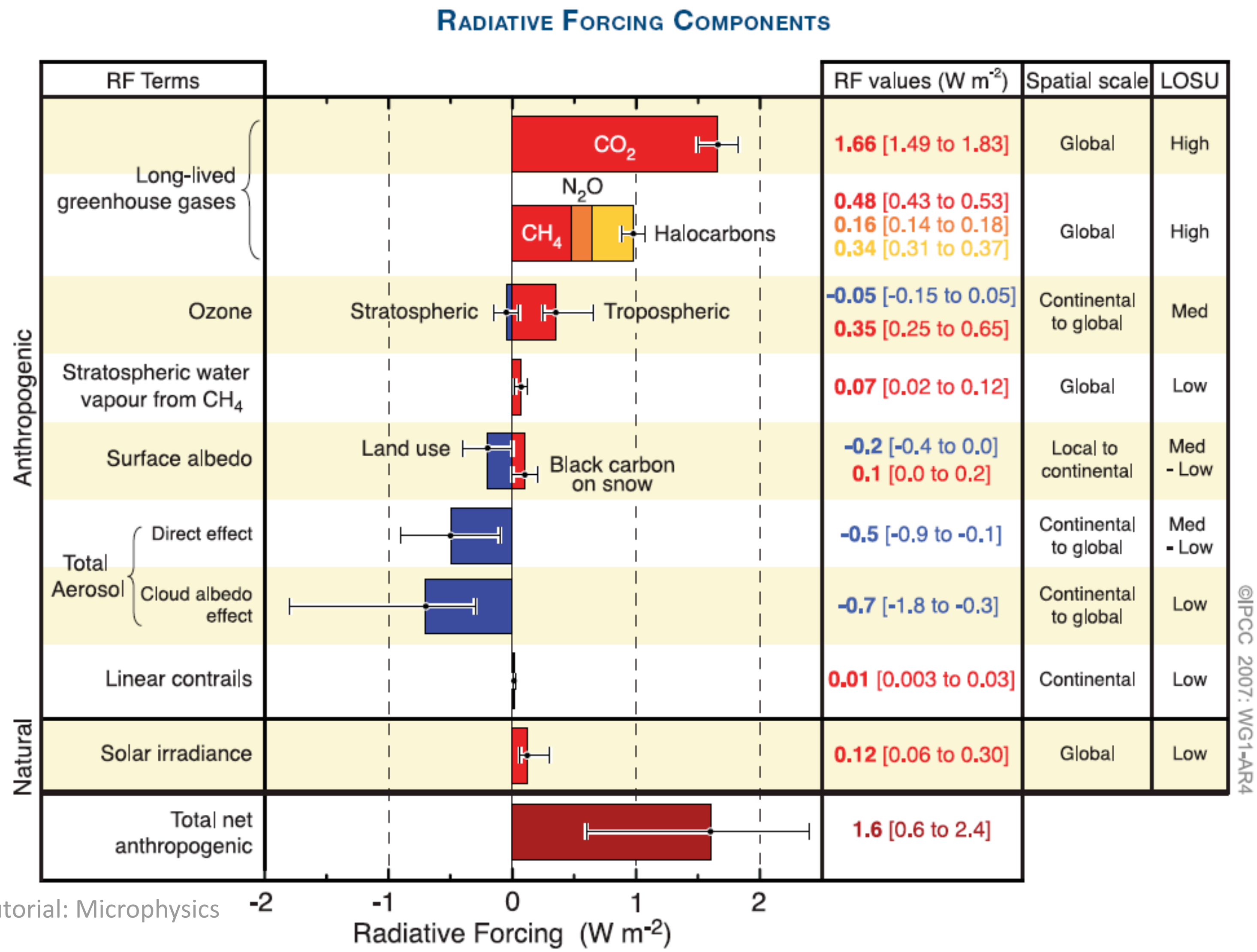
Questions?

Aerosols

Why do we care about aerosols in a climate model?

Aerosols

Aerosols Affect Radiation



Aerosol Modeling

- Physical process model (parameterizations) to simulate a set of aerosol species
- Bulk Model (CAM3)
- Modal Treatment (CAM4)
- Heritage (in order):
  1. Simulate direct effects of aerosols for climate
  2. Chemical transformations of aerosols and interactions of mass with clouds (scavenging & deposition)
  3. Connect aerosols with clouds

Bulk Aerosol Model

- Comes from MOZART chemical transport model (now CAM-CHEM)
- Bulk (mass based) representation of:
  - Sea salt (2 modes/bins)
  - Dust (4 bins)
  - Sulfate: Natural (Volcanic) and Anthropogenic
  - Black and Organic Carbon (Hydrophilic & Hydrophobic): Natural and Anthropogenic
- External mixtures only: masses are independent
- Prescribed sizes: number proportional to mass
- Wet Deposition and Dry Deposition/Scavenging
- CAM 3 includes Aerosol Shortwave effects only!

Dry Deposition

- 'series resistance' method using 'aerodynamic' resistance in lowest model level to determine deposition velocity, V_d

- Then $Flux = V_d n_1$,

  n_1=concentration in lowest level

Wet Deposition/Scavenging

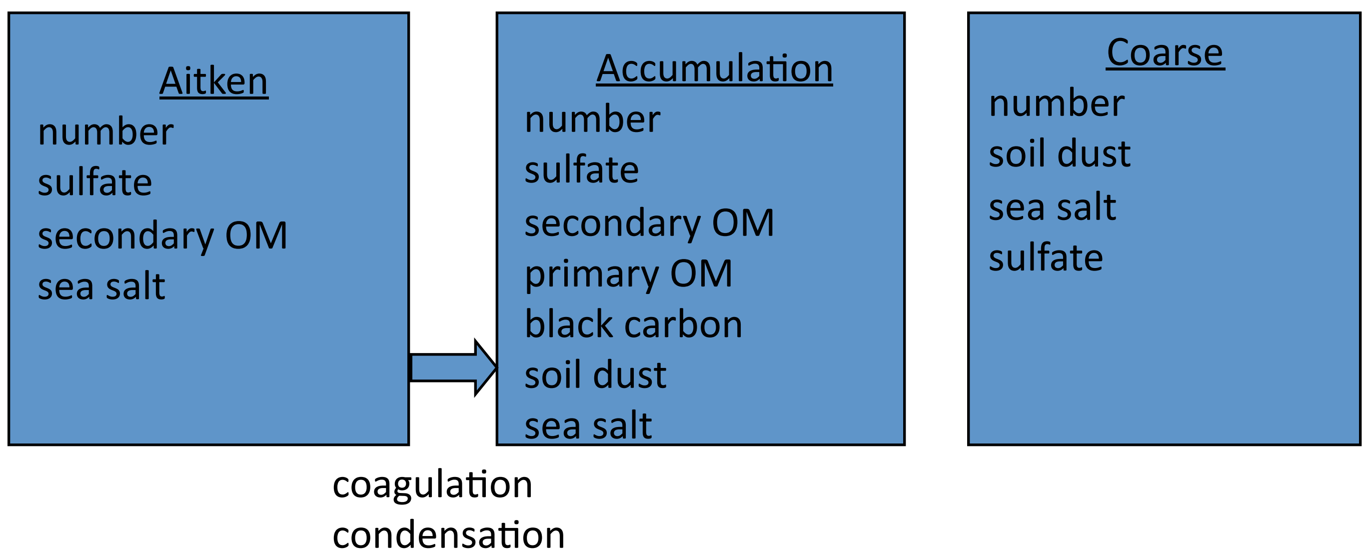
- Gases scavenged only by liquid
  - Based on Henry's law (solubility: $f\ [pH,T]$)
- Aerosols scavenged by liquid and ice
  - In cloud scavenging assumes a fixed fraction remains in cloud water and removed along with fraction of cloud water that precipitates
  - Below cloud scavenging assumed to be a first order loss process $L = C\ P\ q$ where C=collection efficiency, P=precip flux (mm/h) and q = species mixing ratio

Modal Aerosol Model

- Versions: Benchmark 7 mode & Efficient 3 mode
- Internal mixtures (coagulation within & between modes)
- Ultrafine sea-salt
- Condensation of Trace Gases (H_2SO_4) on aerosols
- Aging of carbon to accumulation mode based on sulfate coating
- New Secondary Organic Aerosol Treatment
- New Aerosol Optics: Direct effects in LW and SW
- Emissions available:
  - AEROCOM
  - New IPCC AR5 emissions

3-Mode Aerosol Model

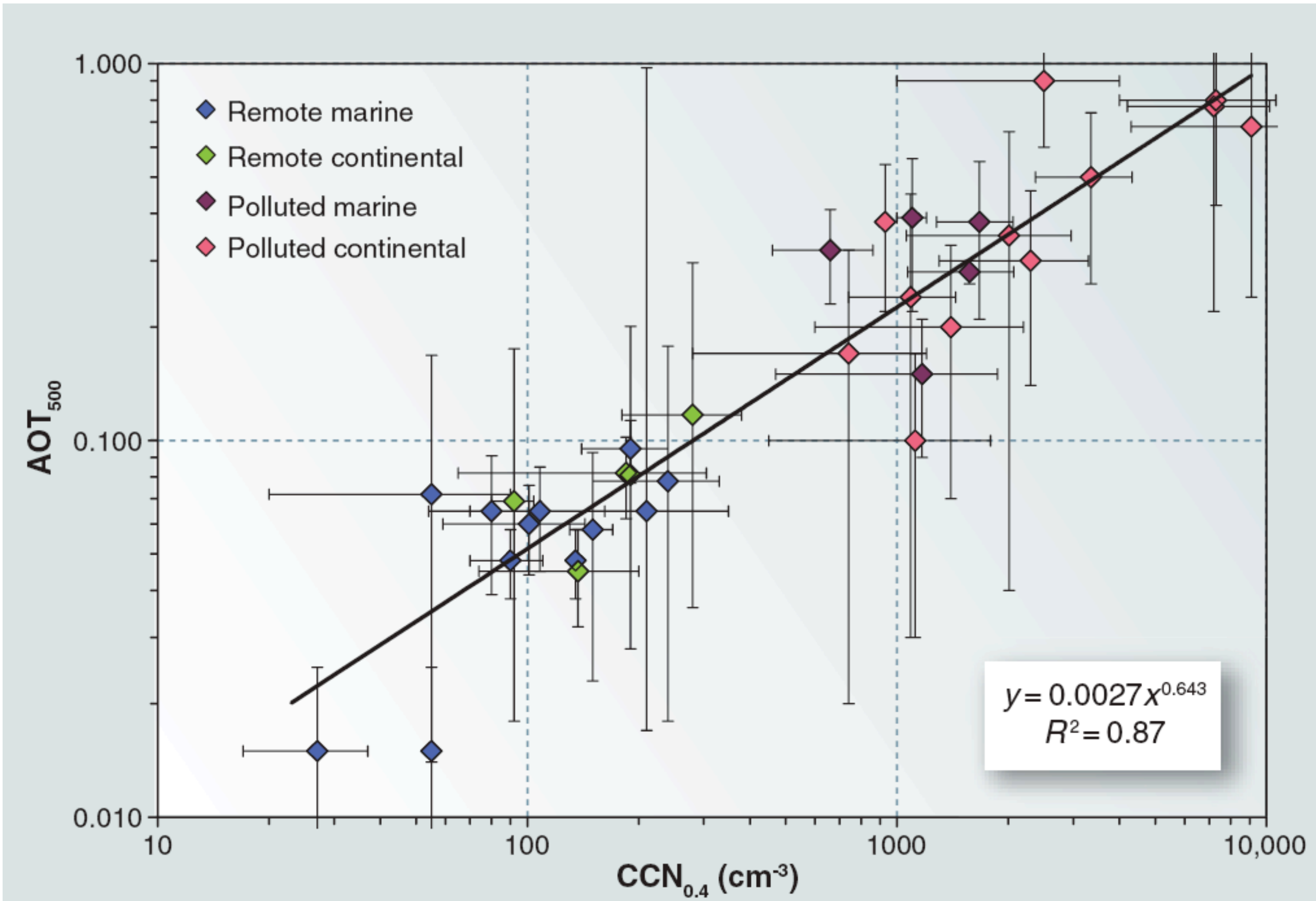
- Assume primary carbon is internally mixed with secondary aerosol
- Sources of dust and seasalt are geographically separate
- Assume ammonium neutralizes sulfate
- 15 total advected species



Key Interactions

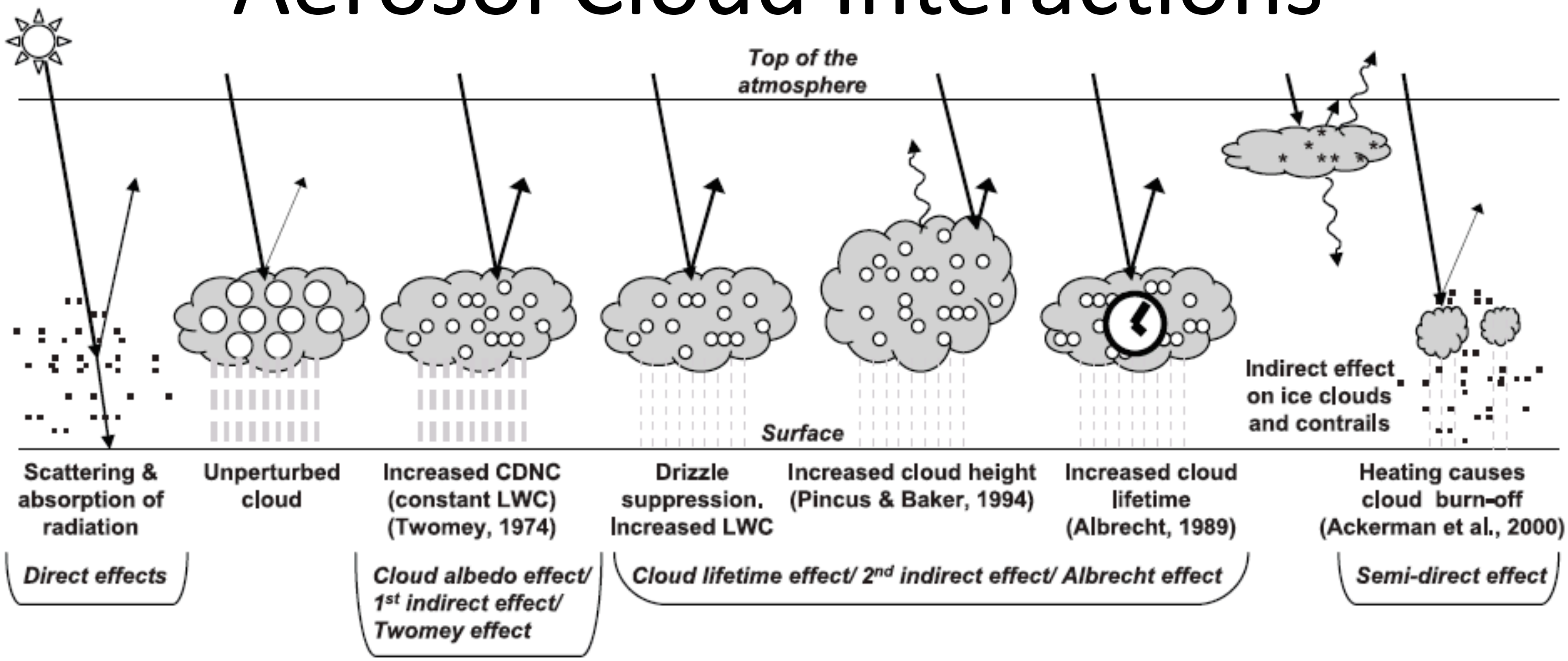
- Aerosols and Cloud Microphysics
  - Aerosol Indirect Effects
- Clouds and Radiation

Aerosol-Cloud Interactions



Rosenfeld et al, Science 2008

Aerosol Cloud Interactions



Aerosols lead to:

- Brighter clouds
- Longer Lasting, less precipitation (supress drizzle)

Aerosols and Mixed/Ice Phase

- Drizzle suppression might increase precipitation intensity in mixed-phase clouds
- Ice indirect effects may be different:
  - Ice nuclei are rare. Some may induce earlier cloud formation (lower super-saturation)
  - This leads to fewer particles (opposite effect)
  - Cirrus clouds also have effects in Longwave

Aerosol-Cloud Interactions in CAM

- CAM3: Direct effects of Aerosols only (SW)
- CAM4/Modal:
  - Direct Effects in LW & SW
  - Indirect effects for Liquid and Ice
- CAM 4: Indirect Effects
  - Aerosol number affects activated number of cloud drops/crystals
  - Ice nucleation: depends on sulfate & dust numbers

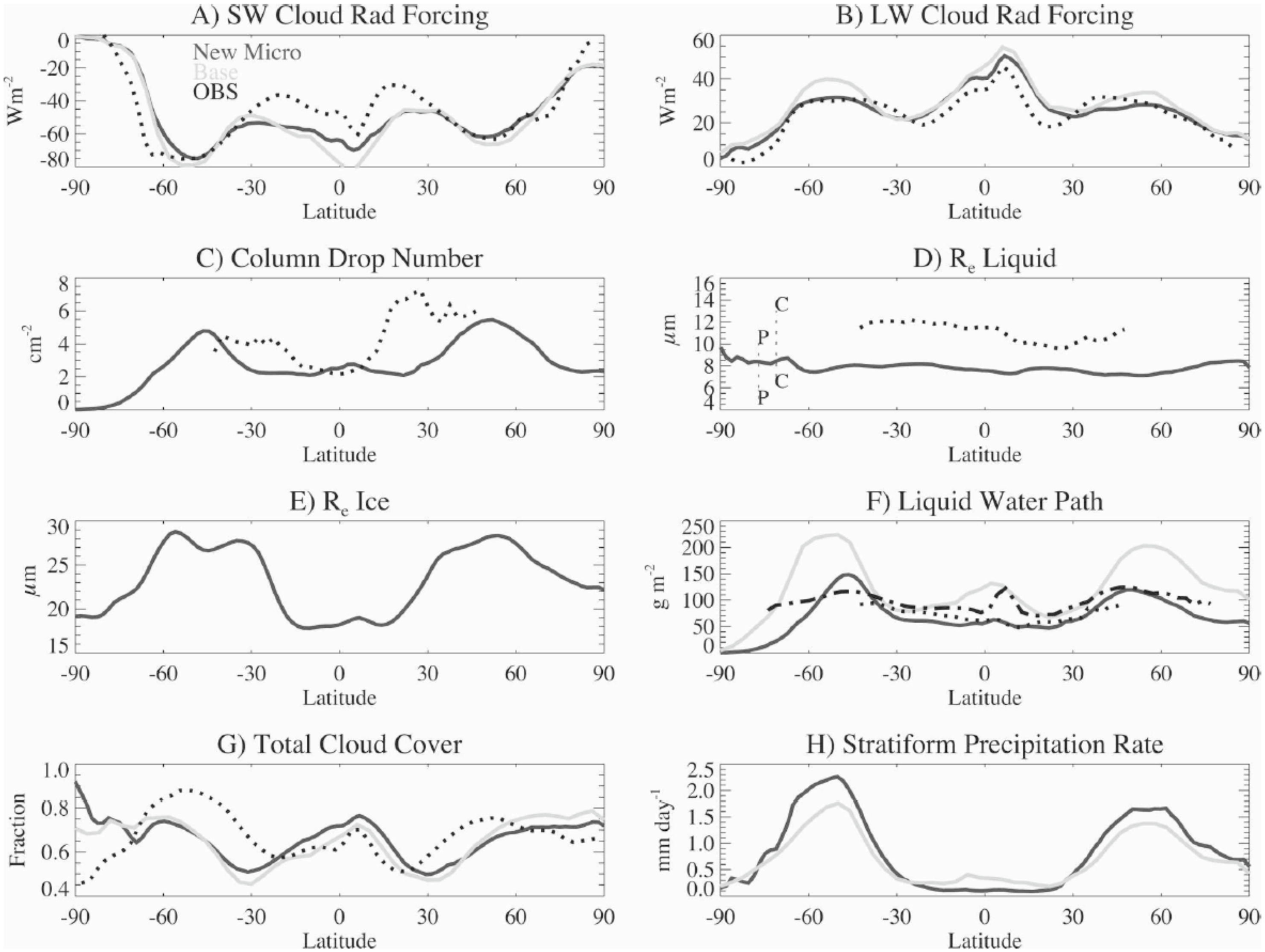
Clouds and Radiation

- Goal has been a consistent treatment of cloud and radiation processes
- Radiation code has detailed representation of cloud vertical structure (overlap)
- Bulk (RK98) scheme has fixed cloud particle size
- Modal Microphysics (MG2008) prognoses number (& particle size): more consistent and flexible treatment.
- Difficulty: we do not know what the particle sizes really are from observations

Liquid Water Path

- Fundamental observational uncertainty:
  - How much condensed water is in the atmosphere?
- We know better the radiative fluxes (RF, LW & SW)
- But then ultimately RF = f(LWP, r_e)
- Multiple Solutions:
  - Different microphysics schemes produce similar cloud radiative forcing with very different sizes and Liquid Water Paths
  - Same radiation code

Old and New Microphysics



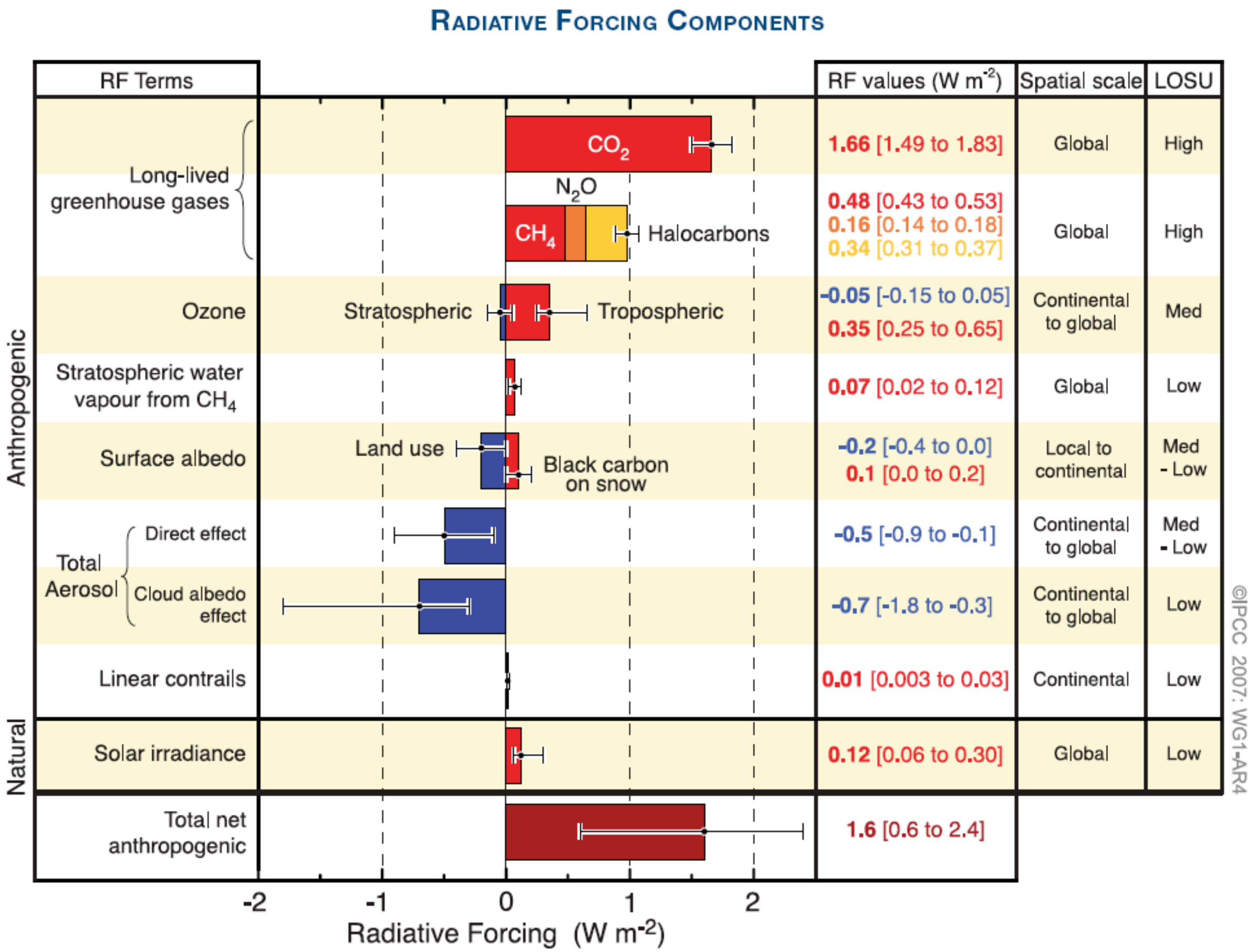
Gettelman et al, 2008

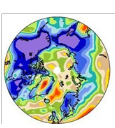
Summary

- Cloud microphysics are a critical part of the climate system
- Basic formulation is a series of process rates
- Bulk scheme has been traditional path
- New 2-mode treatment available
- Observational constraints on clouds are probably not sufficient to constrain important global uncertainties
- Going from small scale → global scale is a challenge
- Aerosols also play an important role in the climate system and interact with clouds
- Aerosol-cloud interactions are very important in understanding climate sensitivity

Aerosols & Climate Change

Radiative Forcing in Climate Models Varies with Aerosols!





CAM

Global Constraints

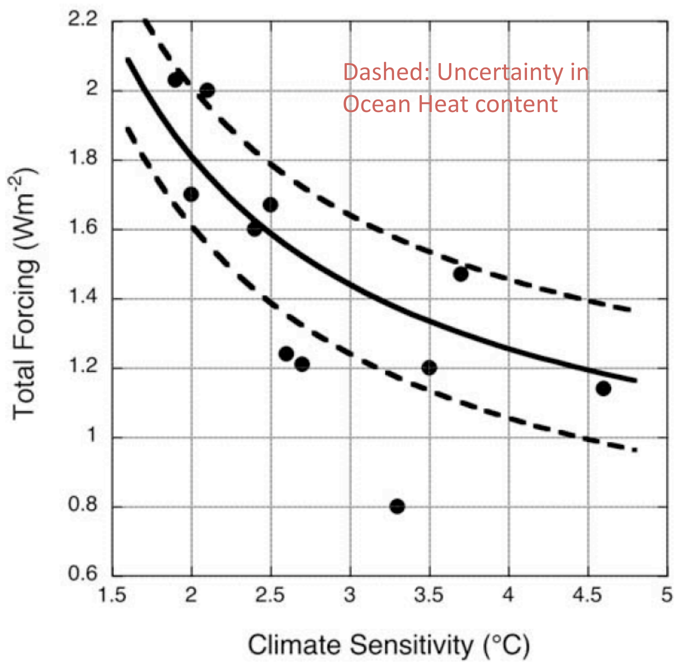
Kiehl 2007, GRL: $\lambda = \Delta Q_{2x} / \Delta T_{2x}$ in equilibrium when H=0

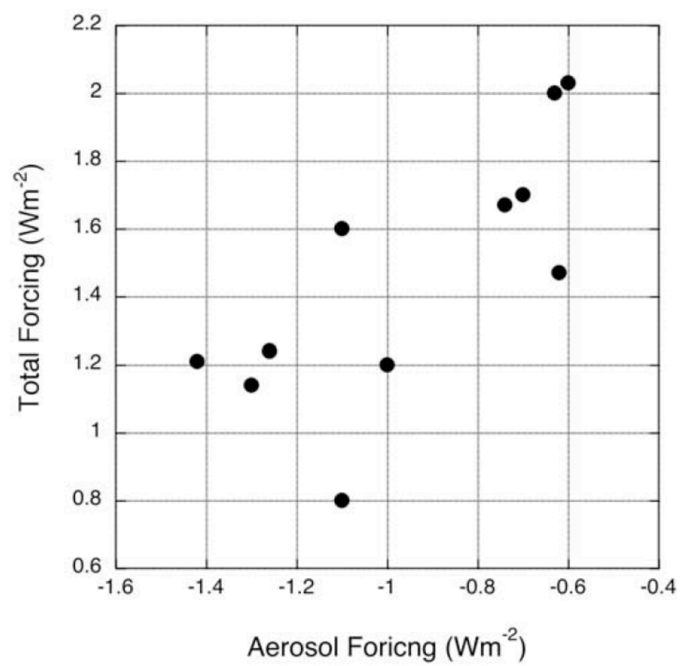
$\Delta Q = \lambda \Delta T + H$

20th Century ΔT, H (Δ ocean heat content) & ΔQ_{2x} known:.

Then, $\Delta Q = F(1/\Delta T_{2x})$

Variations in climate sensitivity (ΔT_{2x}) correspond to differences in total forcing (ΔQ). ΔQ changes due to direct and/or indirect Aerosol forcing





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