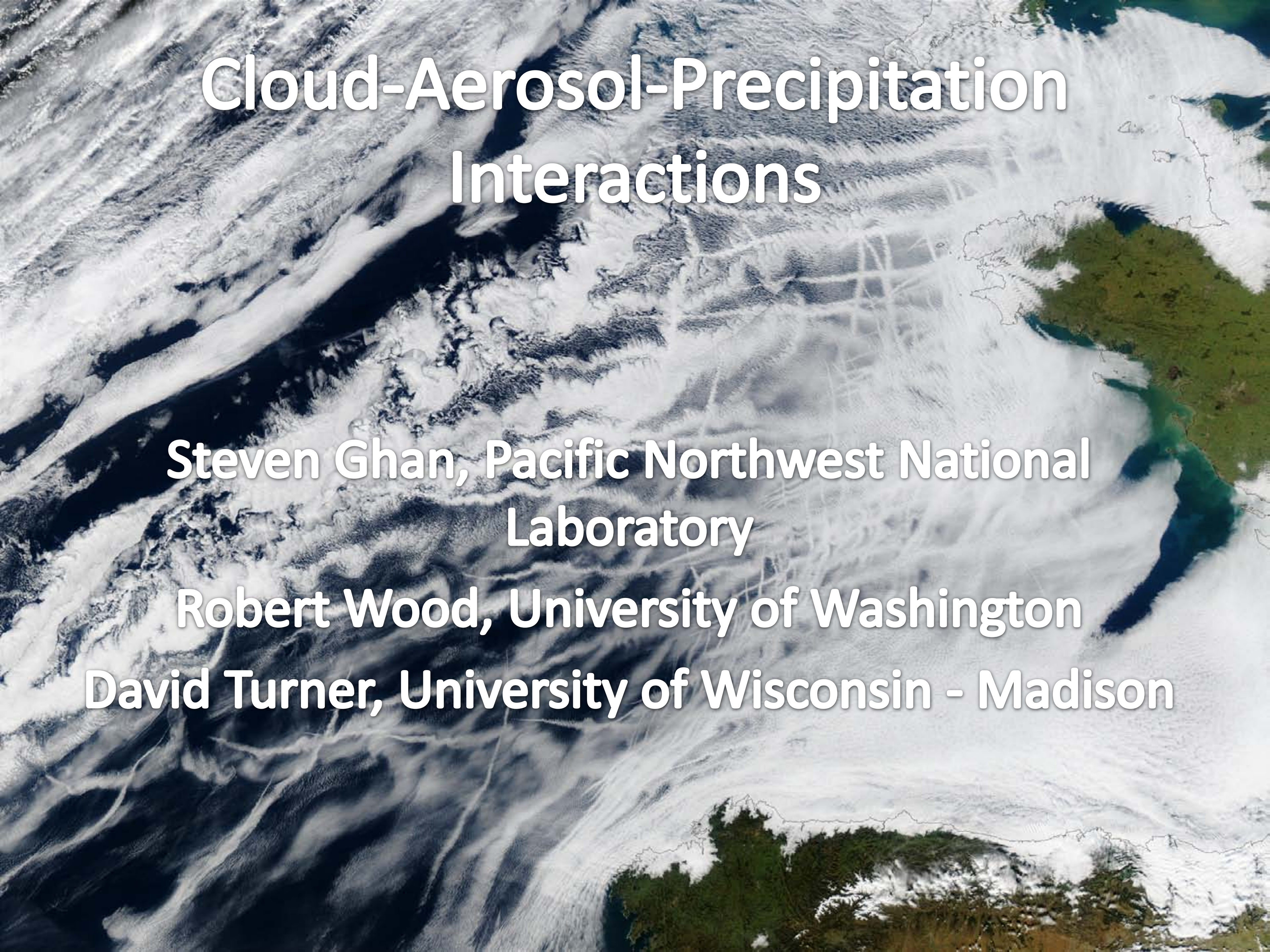


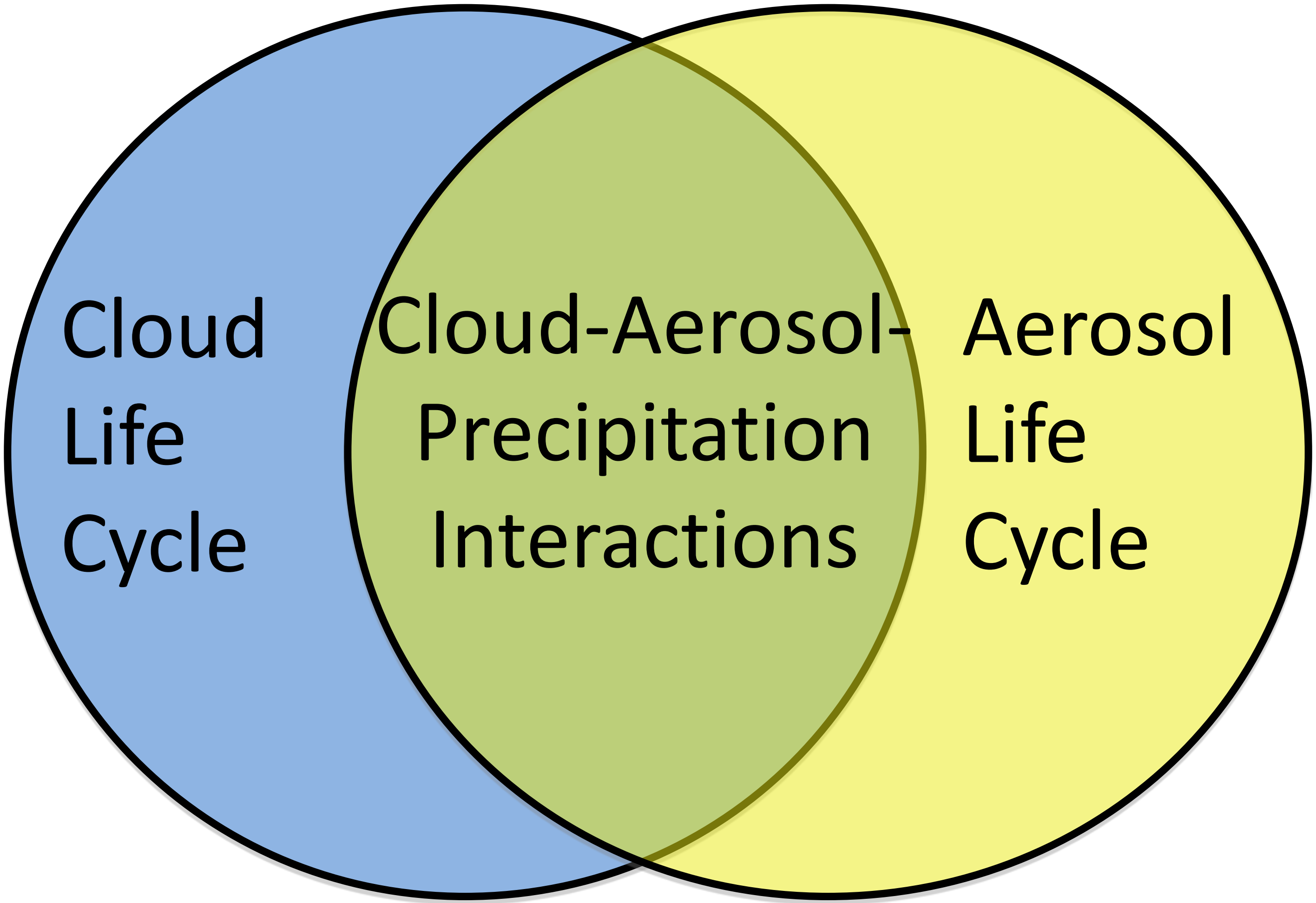
Cloud-Aerosol-Precipitation Interactions

Steven Ghan, Pacific Northwest National Laboratory

Robert Wood, University of Washington

David Turner, University of Wisconsin - Madison

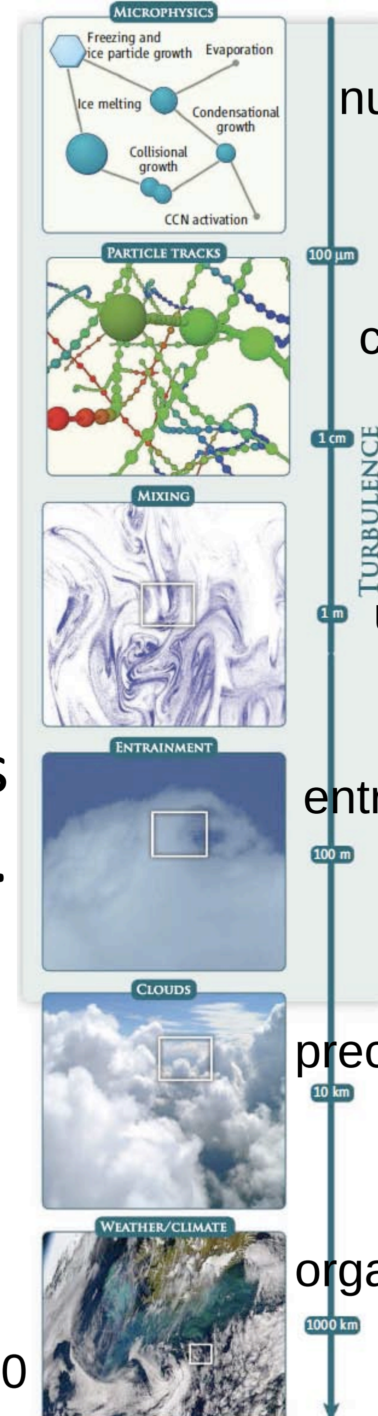
The Intersection of Cloud and Aerosol Life Cycles



- Aerosol effects on clouds
- Cloud effects on aerosol

A Multiscale Challenge

- Cloud-aerosol-precipitation interactions are intimately coupled with important cloud and aerosol processes.
- Improved representation of interactions depends on improved parameterizations of cloud microphysics and macrophysics.
- Creative methods are needed to represent processes across the wide range of spatial scales involved (microns to megameters).



nucleation

collision

updrafts

entrainment

precipitation

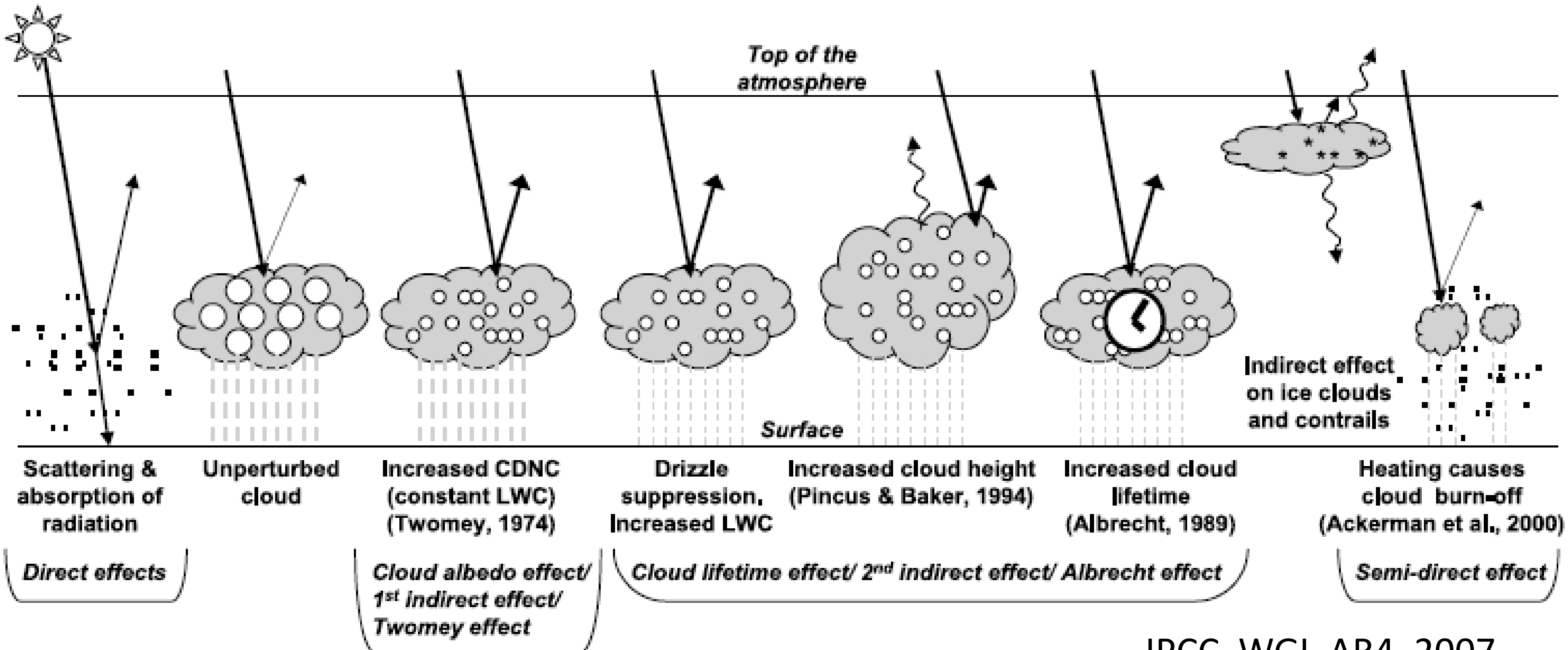
organization

Bodenschatz et al., Science 2010

Outline

- Aerosol effects on clouds and precipitation
- Cloud and precipitation effects on aerosol
- Cloud-aerosol-precipitation interactions

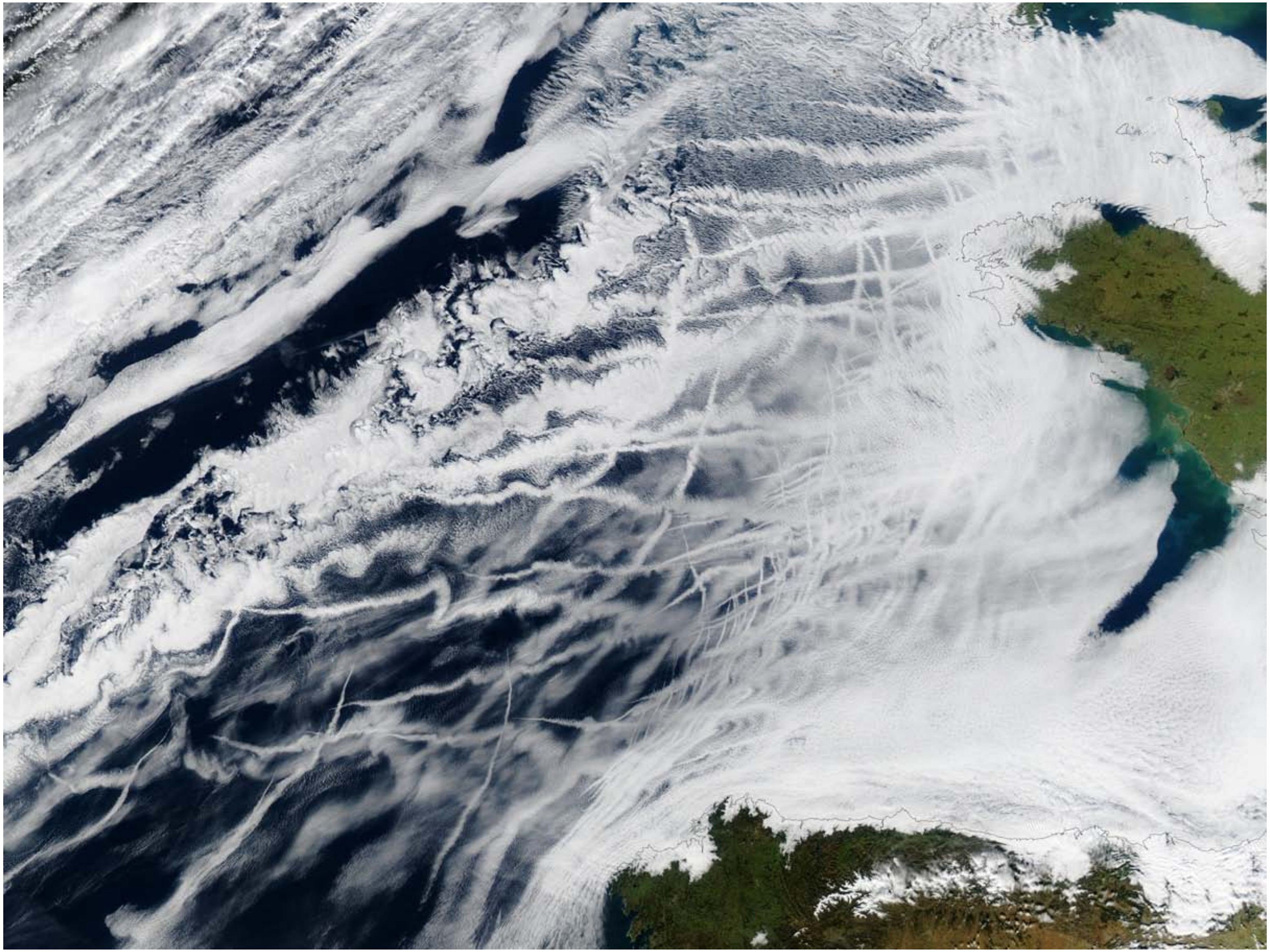
Aerosol Effects on Clouds



IPCC, WGI, AR4, 2007

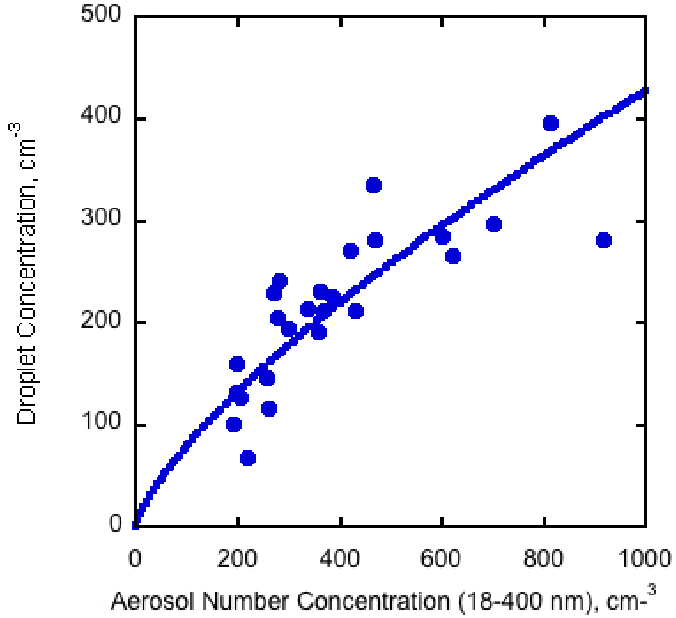
Haywood & Boucher

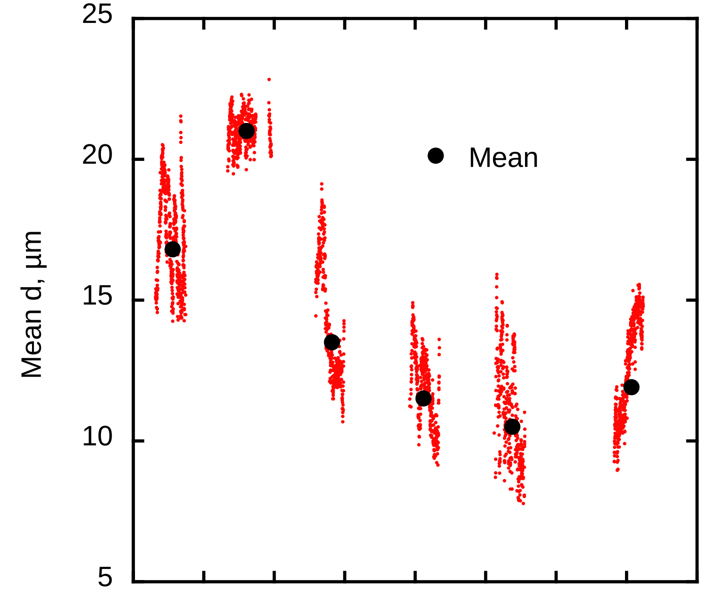
Evidence from Satellite

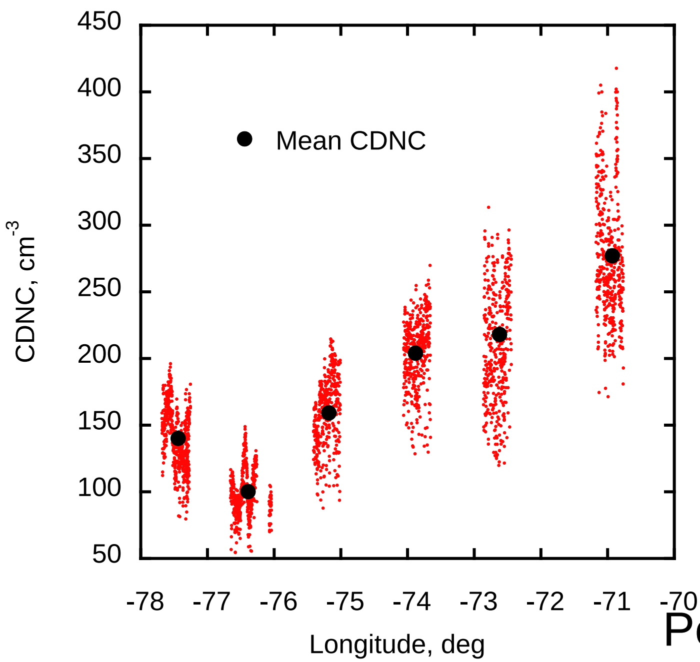


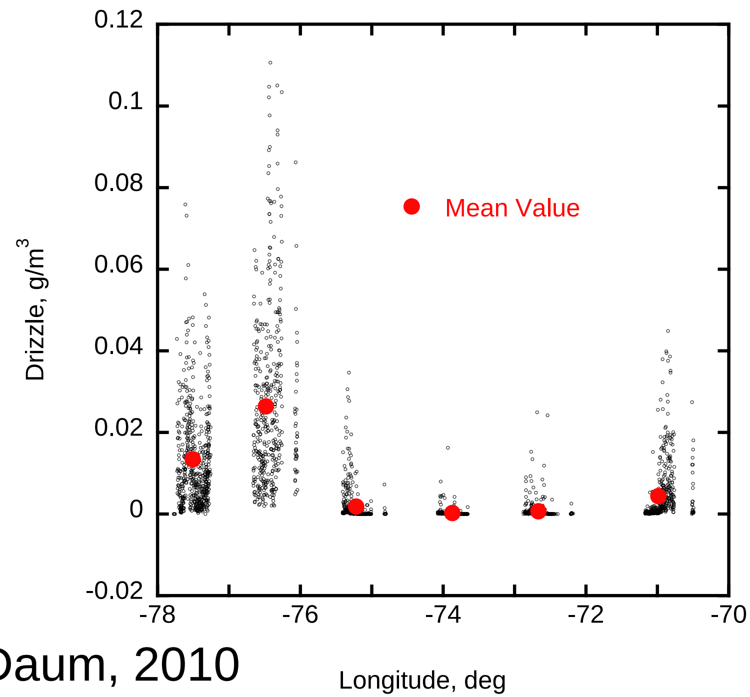
True-color image of northeastern Atlantic from MODIS Aqua on January 27, 2003

Evidence from ARM Observations: VOCALS





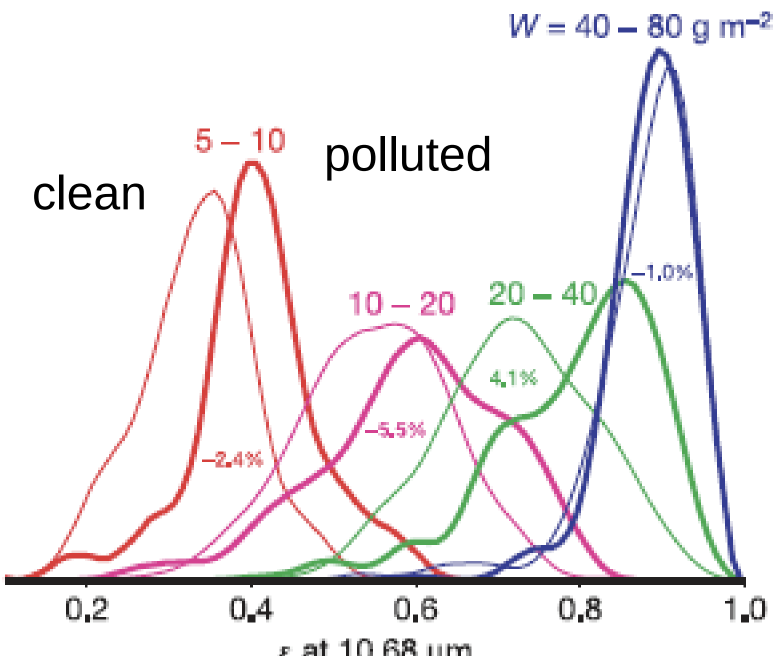




Peter Daum, 2010

Longwave Indirect Effects

- In polar regions anthropogenic aerosol is present during winter, but there is little sunlight for indirect effects on solar energy.
- But polar clouds have low liquid water paths and hence their emissivity is sensitive to aerosol.
- Mean local longwave forcing of 3.3-5.2 W m^{-2}.



a

	σ (Mm^{-1})	$\overline{r_e}$ (µm)	$\overline{N}$ (cm^{-3})	$\overline{W}$ (g m^{-2})
— Polluted	>7.7	9.9	153	33.5
— Clean	<1.6	12.9	53	31.1

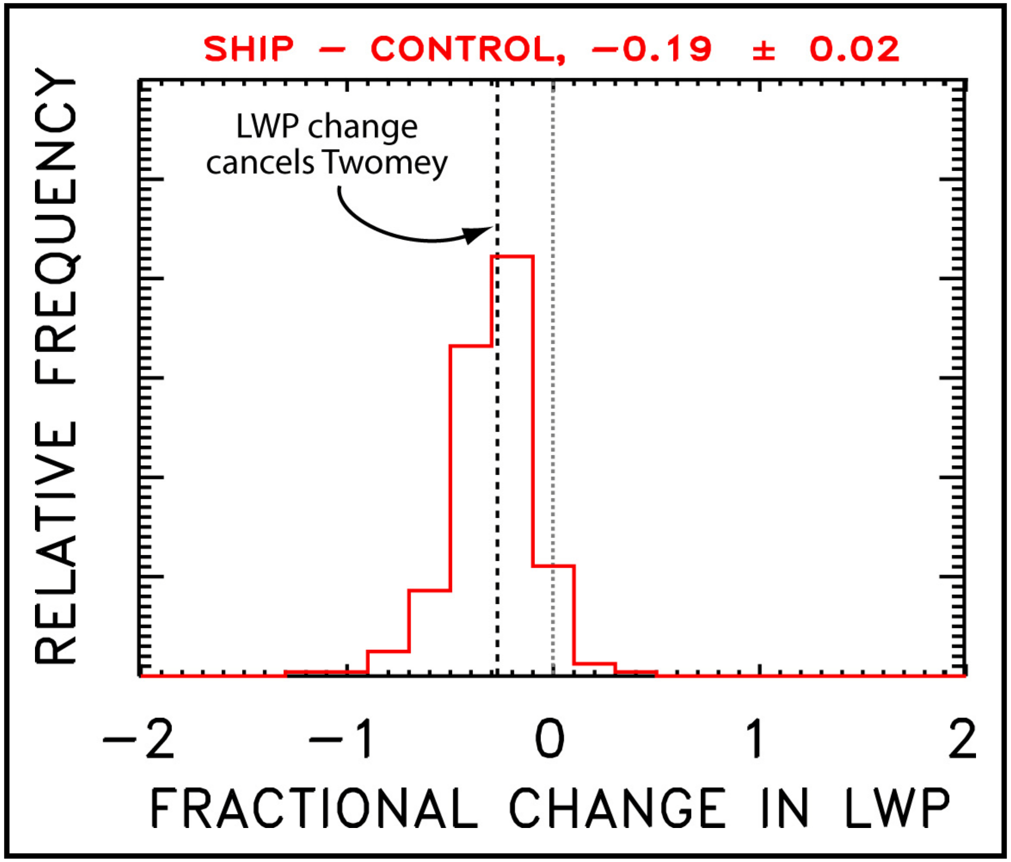
Garrett & Zhao, Nature 2006

Lubin & Vogelmann, 2006

Aerosol Effects on Liquid Water Path

- Ship tracks show evidence of either increase or decrease in LWP with droplet number
- Response seems to depend on a variety of factors.

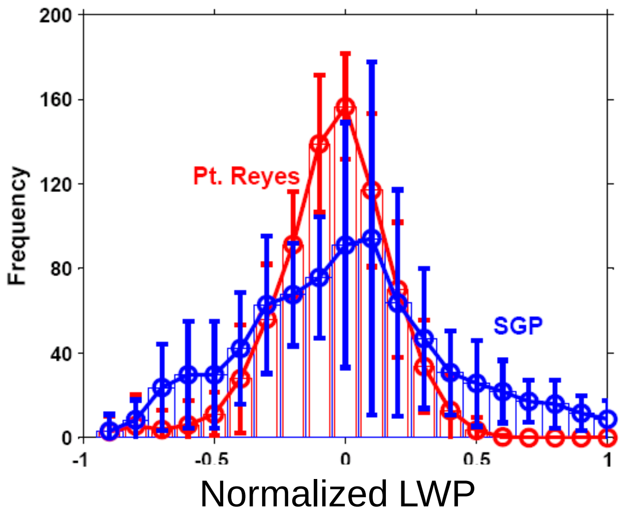
see poster by Petters

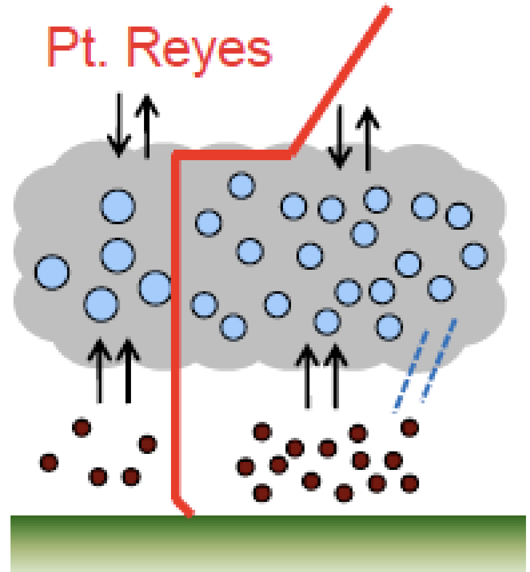


courtesy Jim Coakley, see Coakley & Walsh, JAS 2002

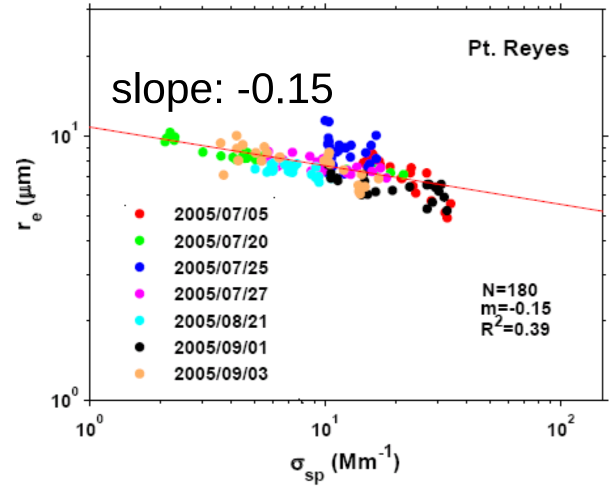
Marine StCu more sensitive to aerosol than continental StCu

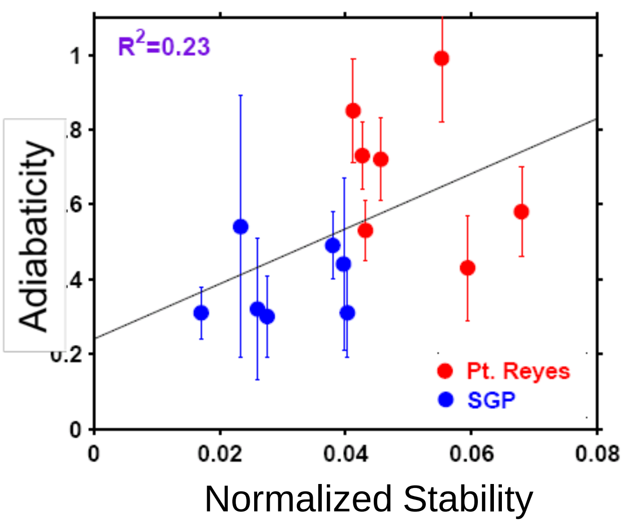
Byung-Gon Kim, 2010

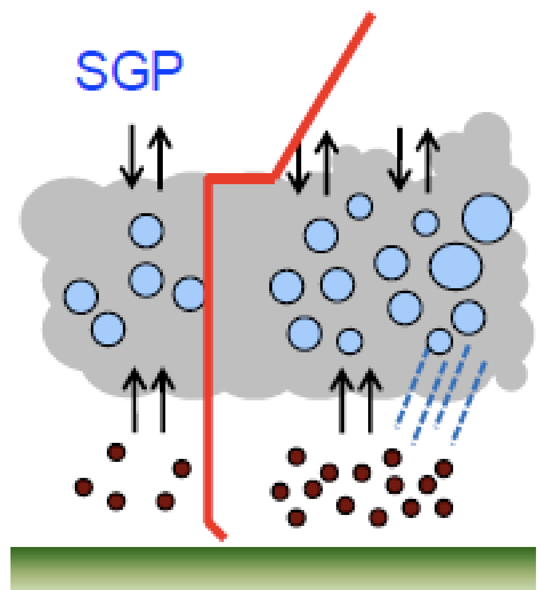




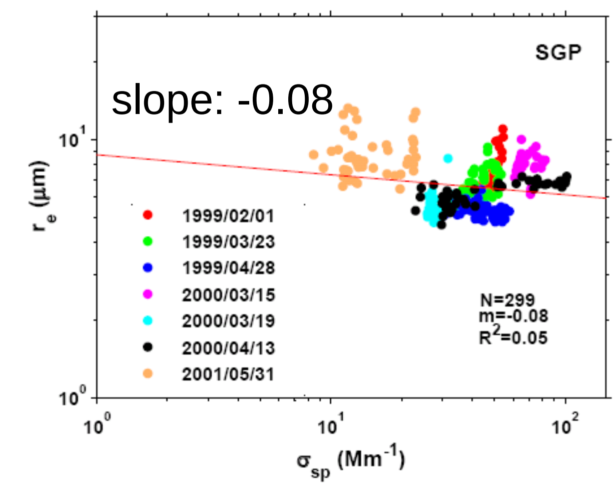
Stronger relationship between aerosol & cloud μphysics in more adiabatic clouds.







Weaker relationship between aerosol & cloud μphysics in subadiabatic clouds.



Impacts of Droplet Nucleation and Autoconversion Schemes on Simulated Global Mean Aerosol Indirect Effects

4 different droplet nucleation parameterizations:

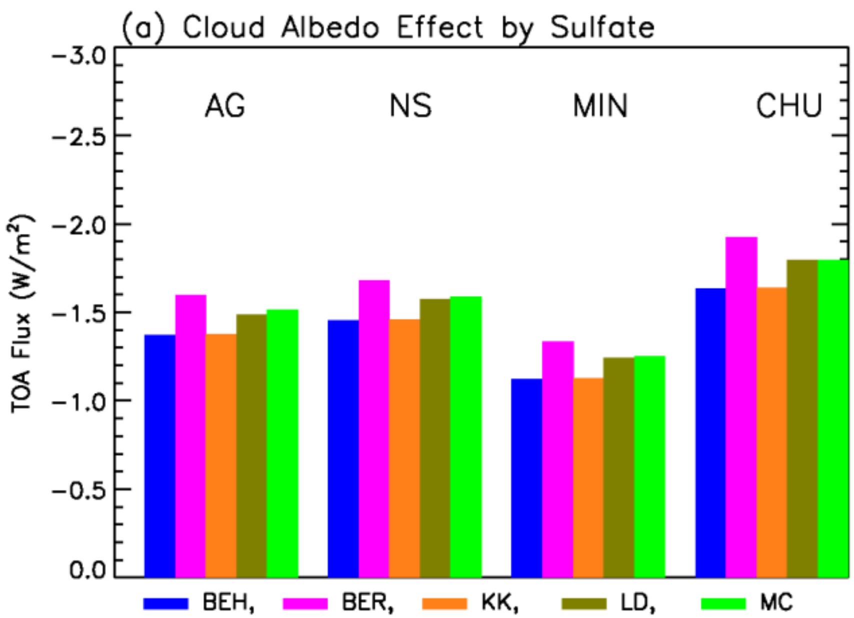
Abdul-Razzak-Ghan (2002), Nenes-Seinfeld (2003), Ming (2006), and Chuang (2002)

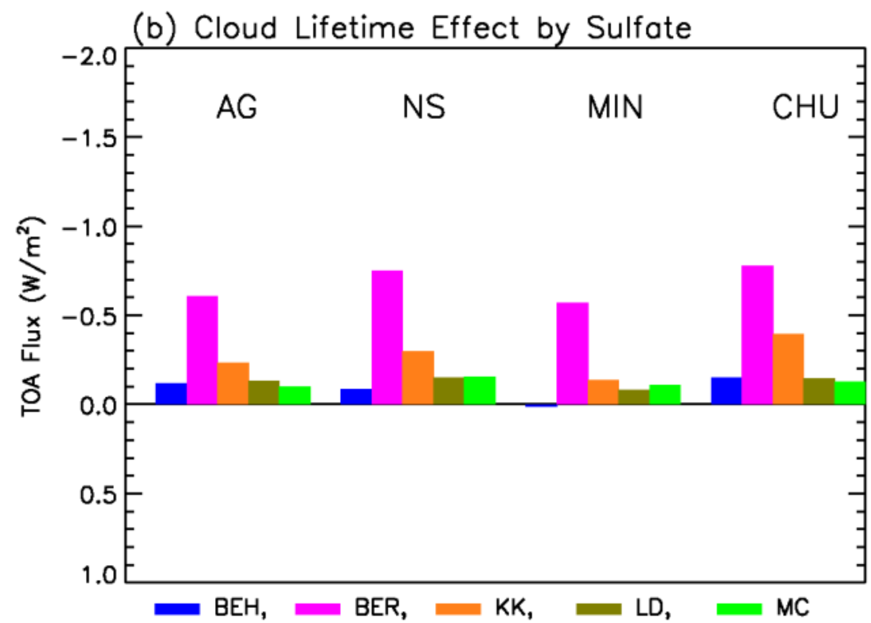
5 different autoconversion schemes:

Beheng (1994), Berry (1968), Khairoutdinov-Kogan (2000), Liu-Daum (2004), Manton-Cotton (1977)

CAM3.5 under CAPT during 2003 May IOP

- Cloud lifetime effect by sulfate is much more sensitive to autoconversion scheme than droplet nucleation parameterization.
- Magnitude of the 2nd aerosol indirect effect is determined by two competing factors that interact nonlinearly: an increase of LWP and a reduction of cloud fraction.

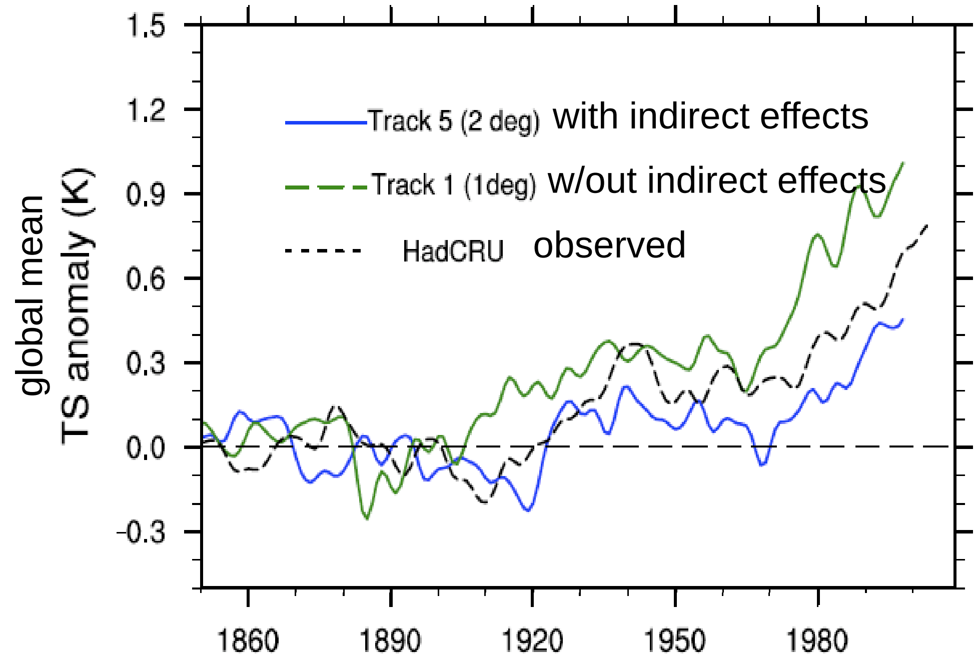




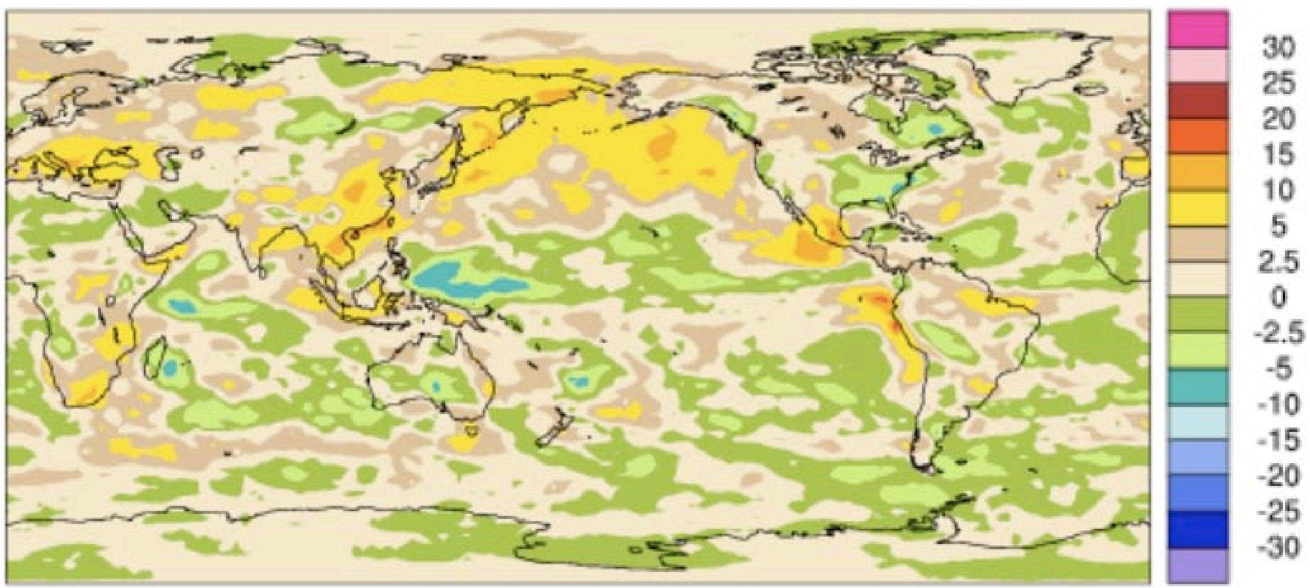
Cathy Chuang, 2010

Contribution to Global Modeling

A treatment of aerosol effects on droplet formation developed with ARM funding is being used in the Community Atmosphere Model (CAM5) to simulate effects of anthropogenic aerosol on clouds and climate for the 20th century.

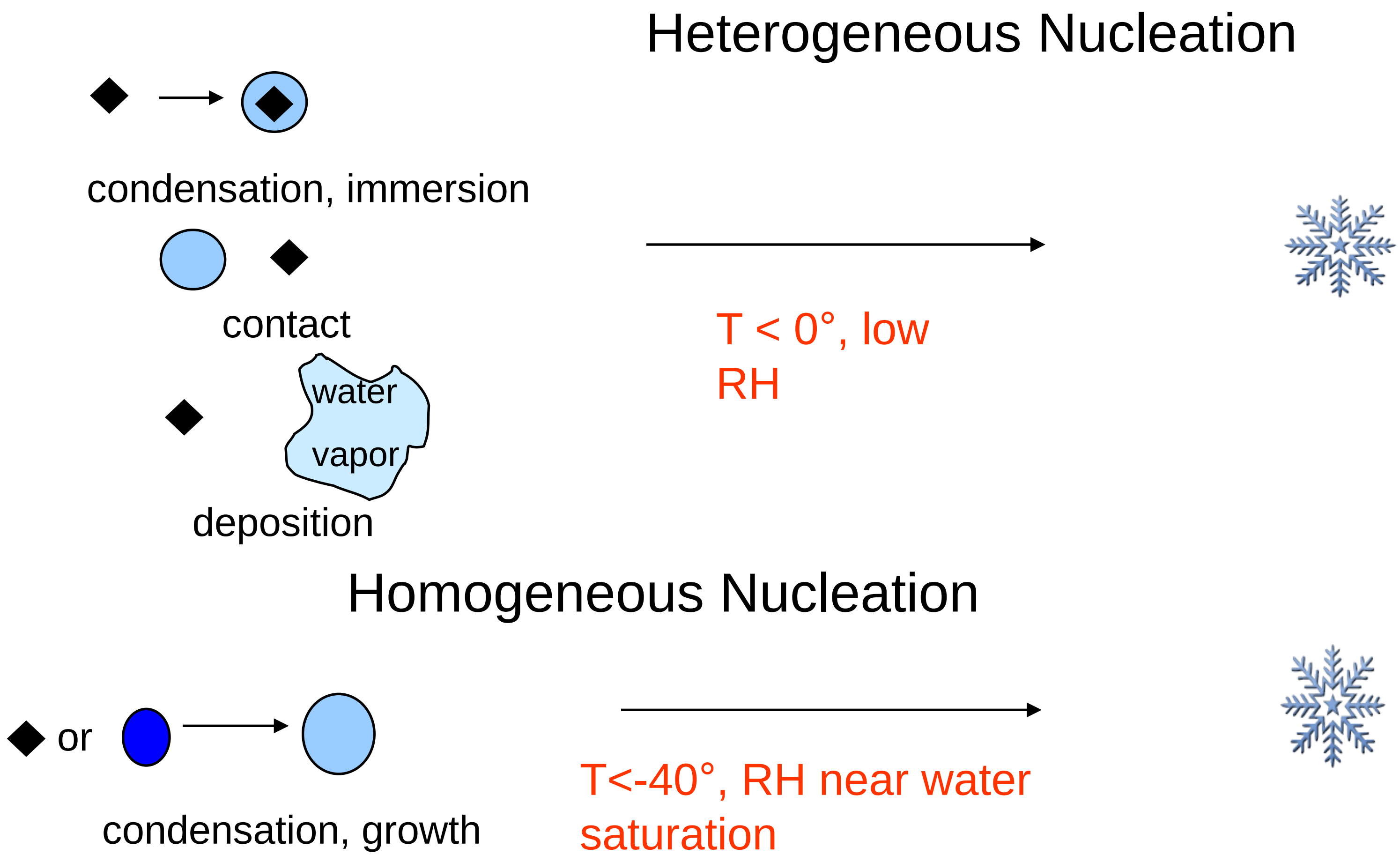


Indirect effect (W m^{-2}) simulated by CAM5



Cecile Hannay, 2010

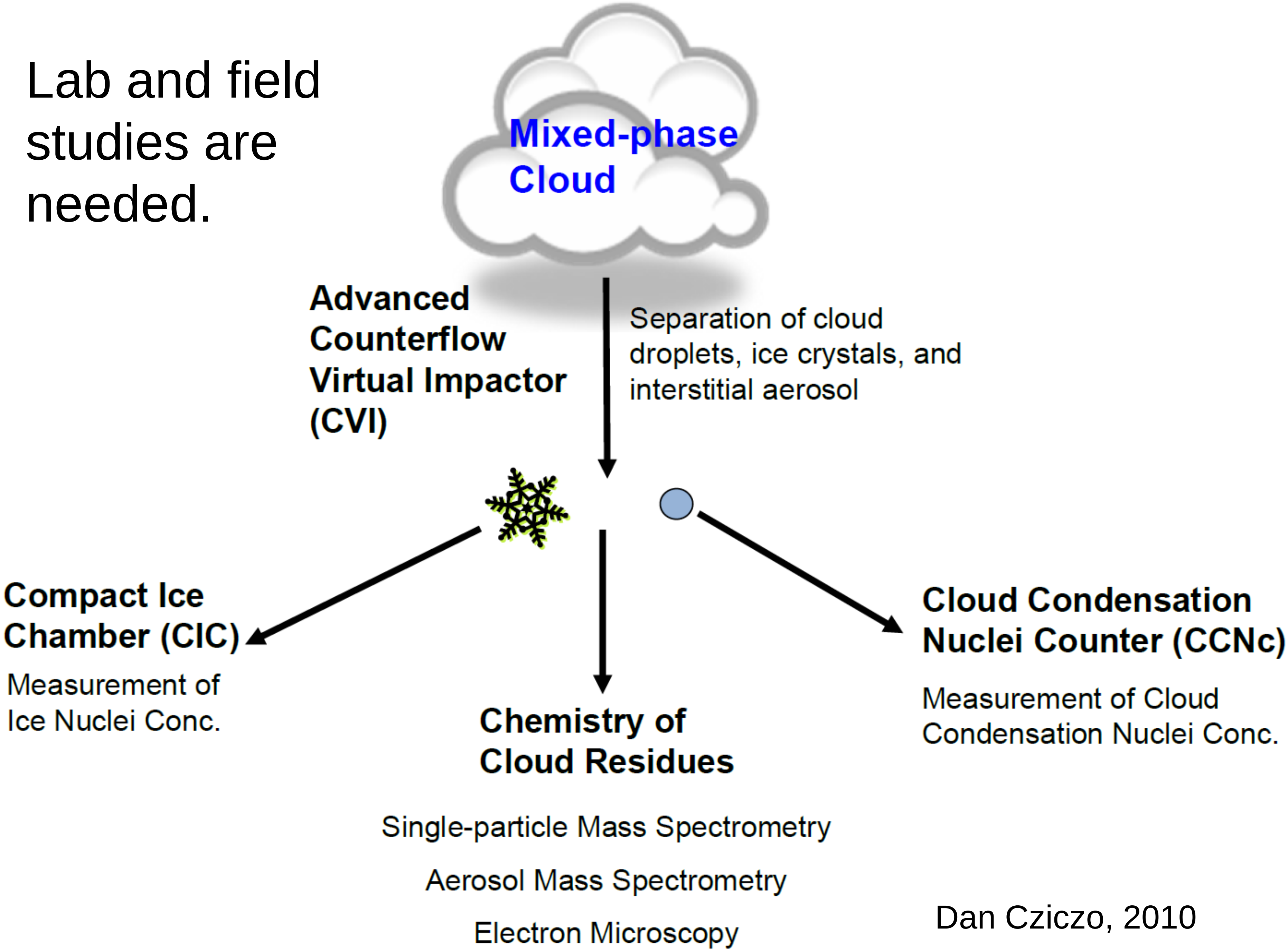
Aerosol Effects on Ice Clouds



Much more complex than effects on warm clouds.

Dan Cziczo, 2009

Lab and field studies are needed.

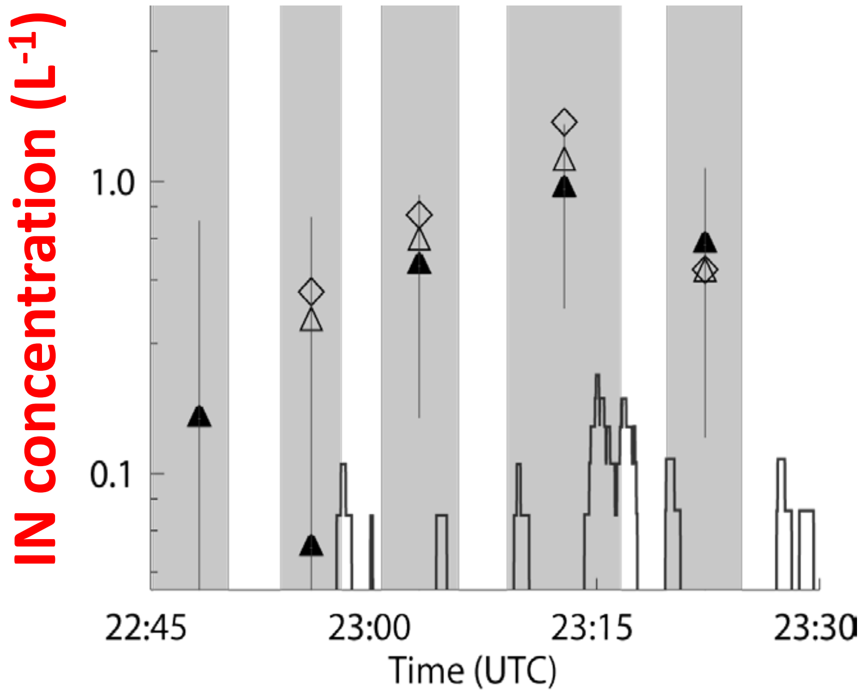


Dan Cziczo, 2010

Validating Heterogeneous Ice Nuclei Models

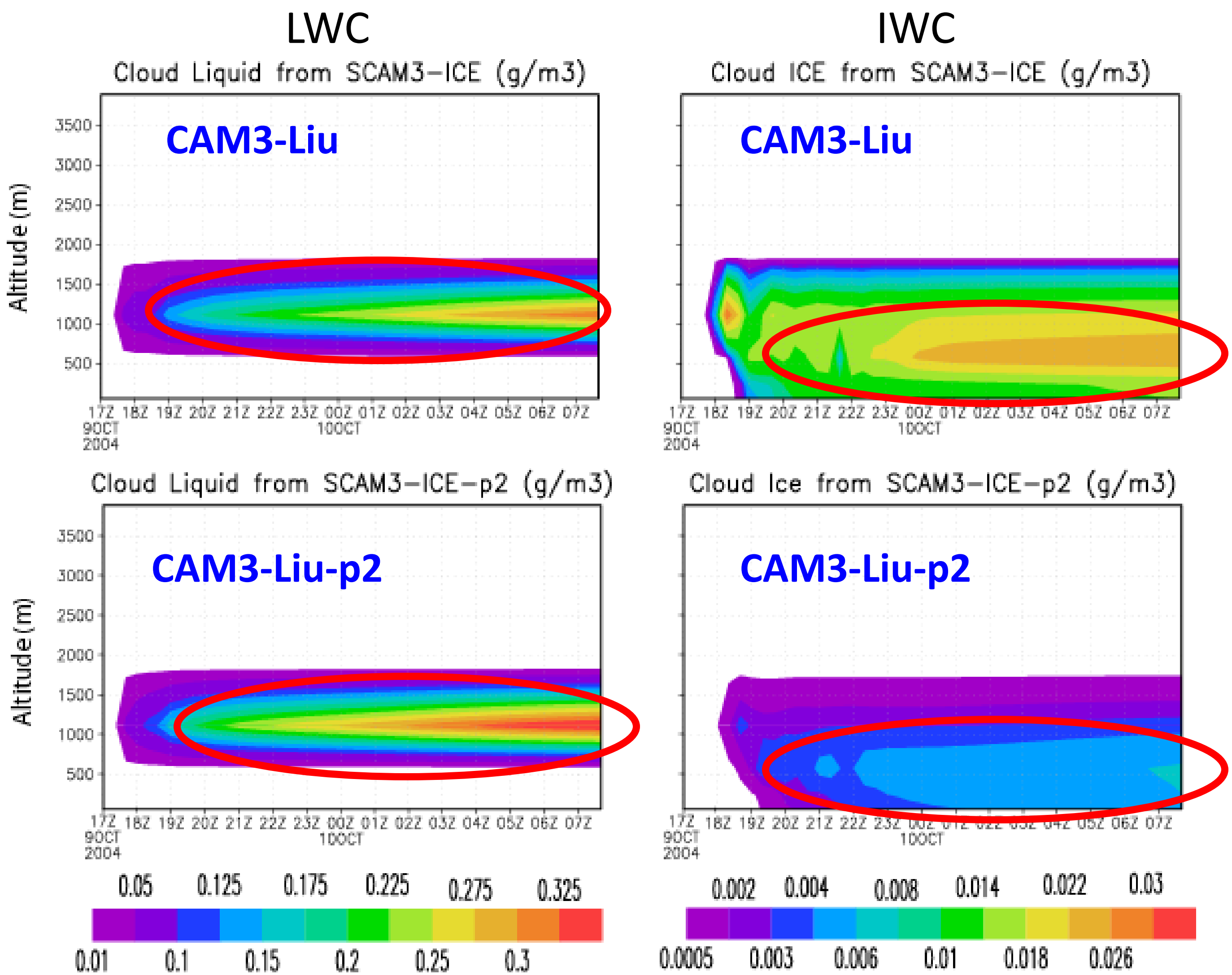
Predicted (Δ), (Phillips *et al*. 2008, *JAS*)
Aircraft CFDC data (▲)

for cases of wave-clouds at -27 °C from ICE-L



Eidhammer *et al.* 2010, *JAS*

Ice Nuclei Concentration Affects Condensed Water Phase

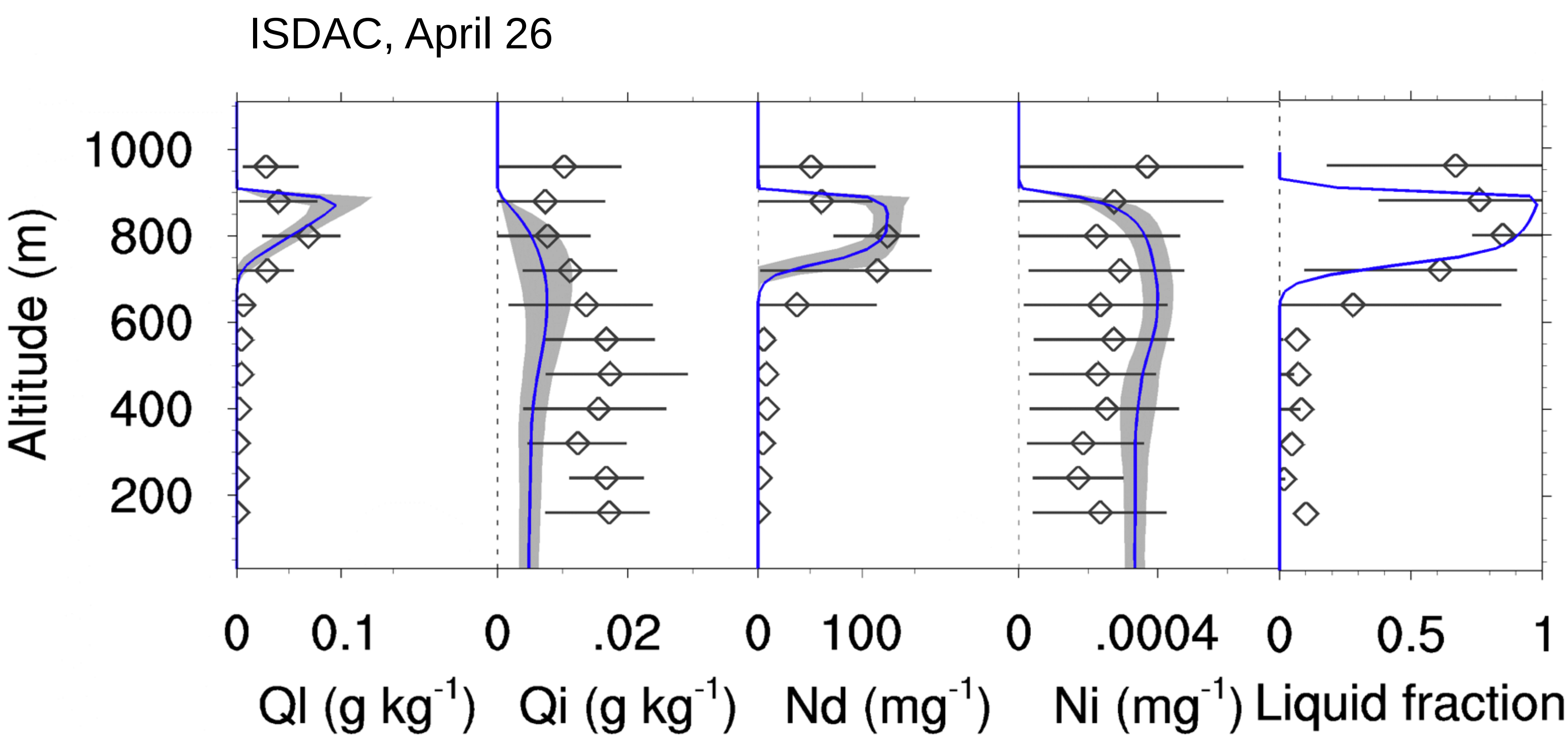


- ***CAM3-Liu (with Meyers et al. ice nuclei number)***
- ***CAM3-Liu-p2 (a sensitivity test with CFDC ice nuclei number ~ 0.2 /L)***
- ***ice nuclei number concentration plays an important role in the simulated mixed-phase clouds***

SCAM Simulations of Mixed-Phase Boundary layer Clouds during M-PACE (Oct. 9-10, 2004)

Liu et al. 2007

Using Field Measurements to Evaluate Simulations by Cloud Models



Mikhail Ovchinnikov, 2010

What needs to be done for aerosol effects on cloud?

- Improve understanding of influence of entrainment on activation and liquid water content.
- Develop and test models of aerosol effects on shallow and deep cumulus clouds.
- Use field and modeling studies to determine conditions when aerosol influence on cloud can be distinguished from other factors.
- Use laboratory and field studies to improve understanding and test physically-based models of anthropogenic aerosol effects on ice nucleation.
- Develop and evaluate models of ice supersaturation.
- Perform closure experiments

Closure experiments: identify key dependencies for a critical process and constrain them with observations

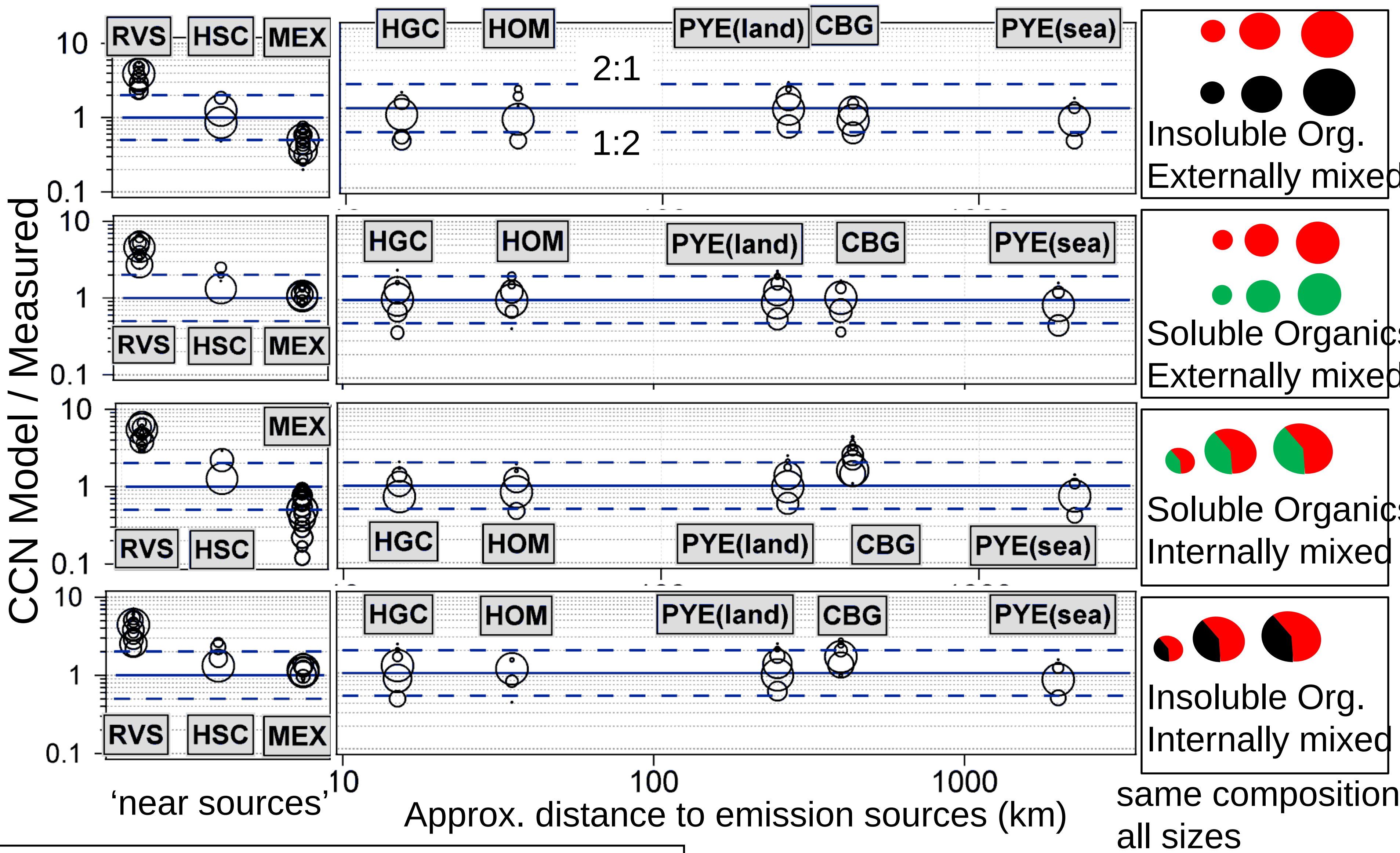
(a) **aerosol activation closure** (two types: aerosol-CCN, aerosol-cloud droplet concentration)

(b) **precipitation closure** (cloud thickness, LWP, microphysics => precipitation)

(c) **column cloud radiative closure** (cloud physical and microphysical properties => radiation, experience of this within ARM)

Closure experiments provide constraints for process and single-column models.

CCN Closure

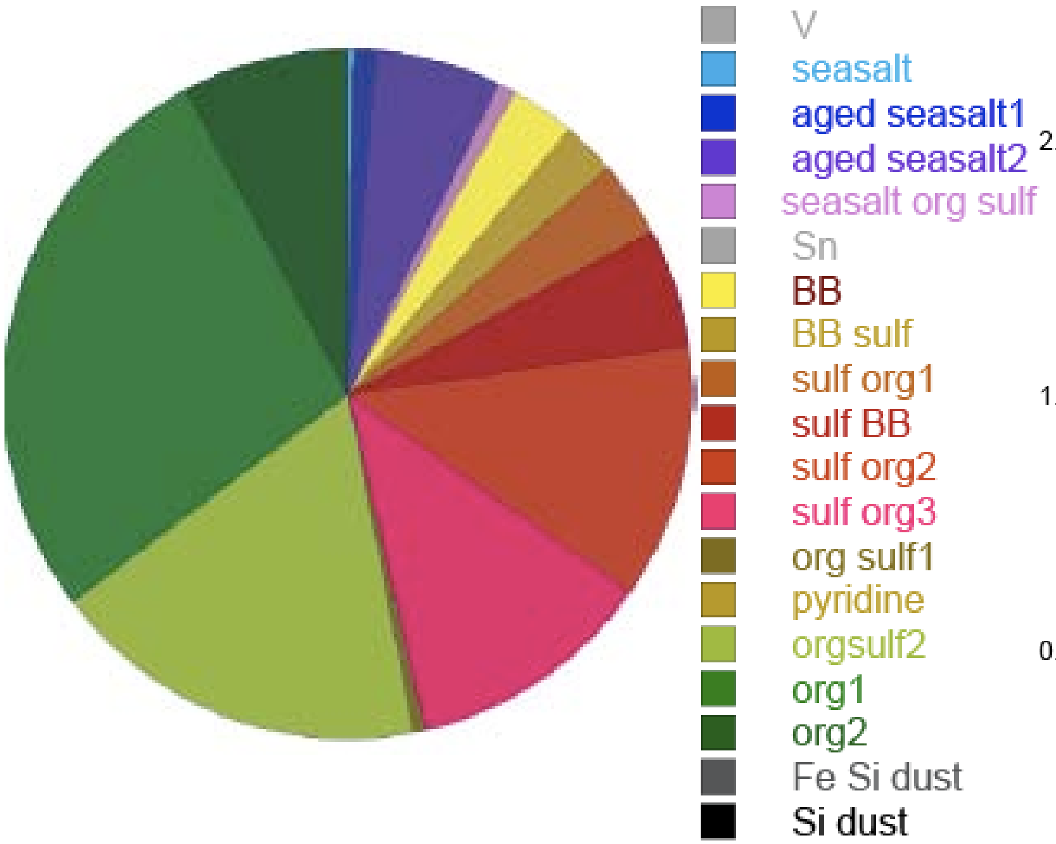


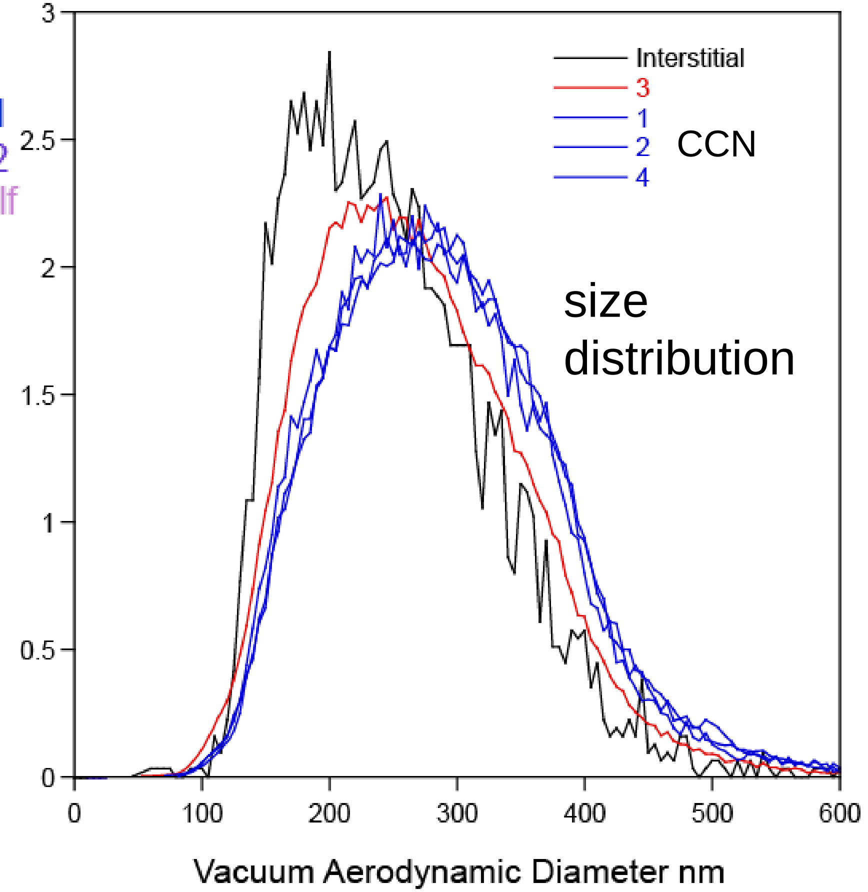
Symbol size ∝ Frequency in CCN closure

Ervens et al., ACPD, 2009

Single particle size and composition measurements can distinguish between internal and external mixtures.

Composition of activated particles, April 26, ISDAC

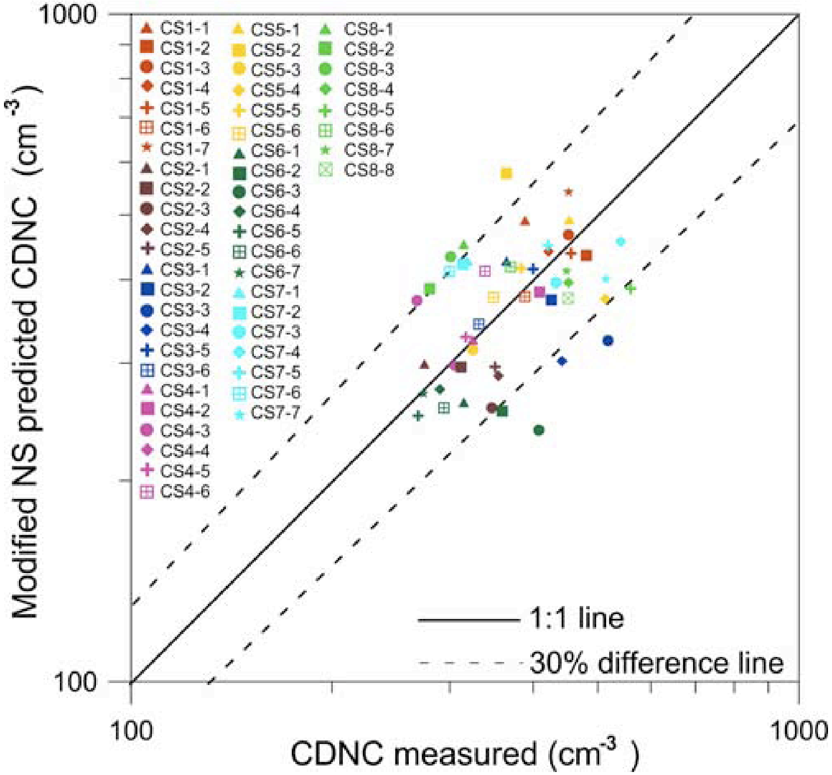




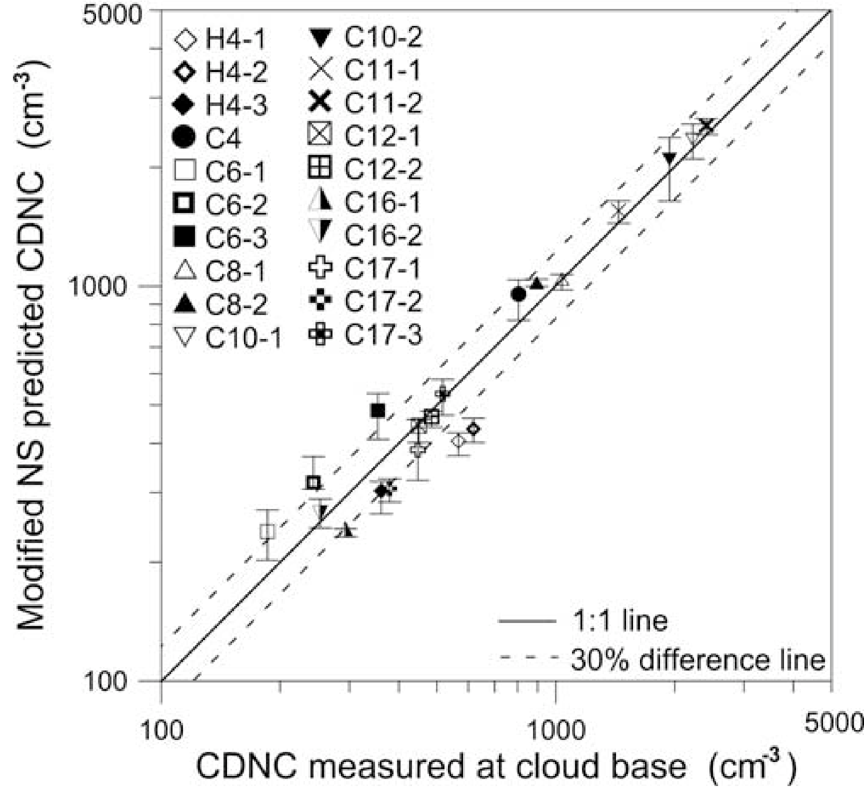
Alla Zelenyuk, 2009

Droplet Number Closure

- In situ measurements of updraft velocity, droplet number, and aerosol composition and size distribution
- Compare parameterized and observed droplet number



stratocumulus clouds



cumulus clouds

Meskhidze et al., JGR 2005

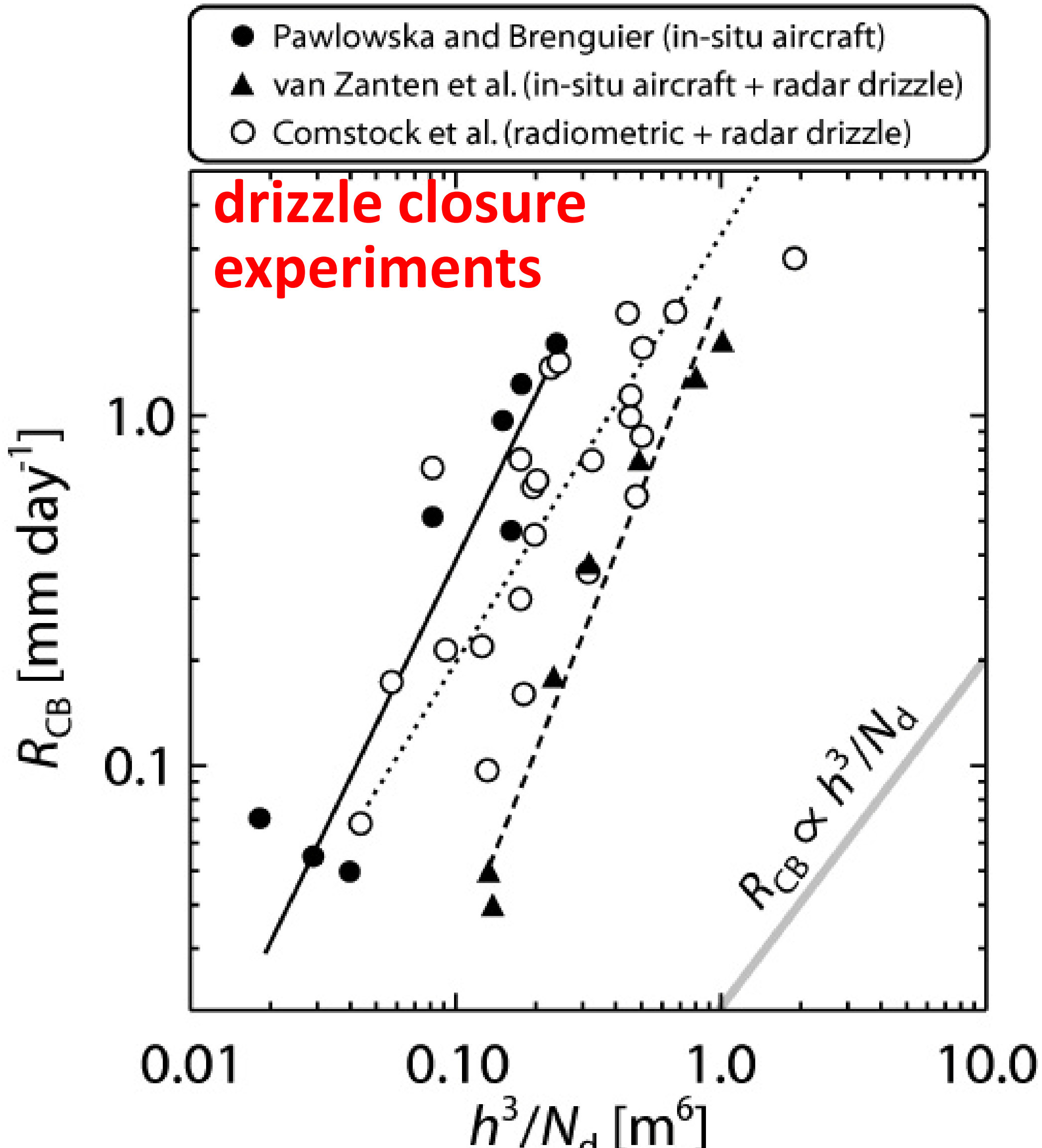
Precipitation closure: Microphysical vs macrophysical control of precipitation

- Major source of discussion and debate

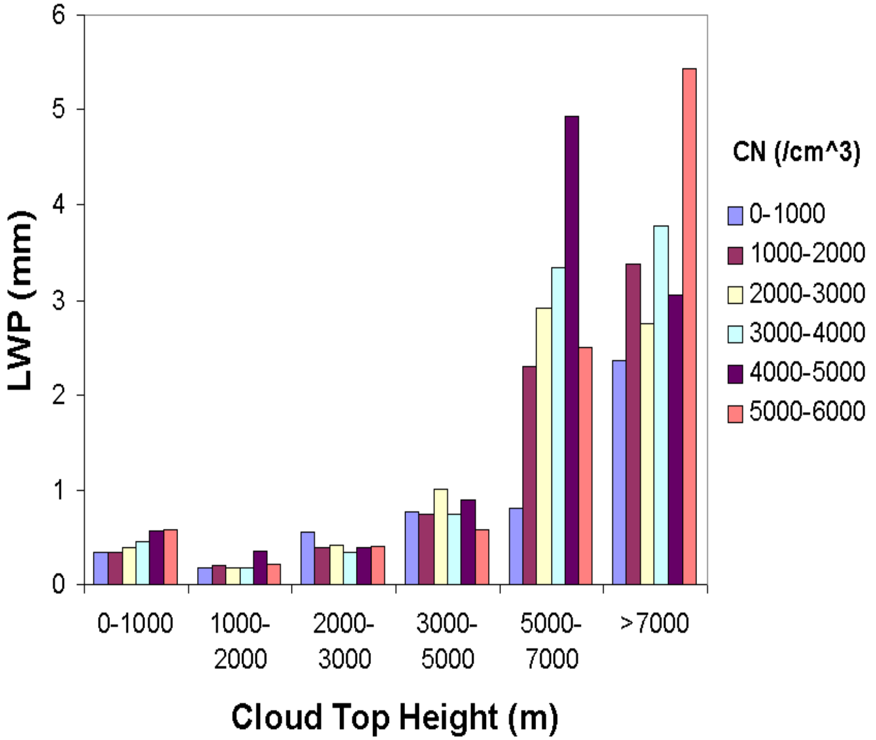
- Strong evidence in stratocumulus (right)

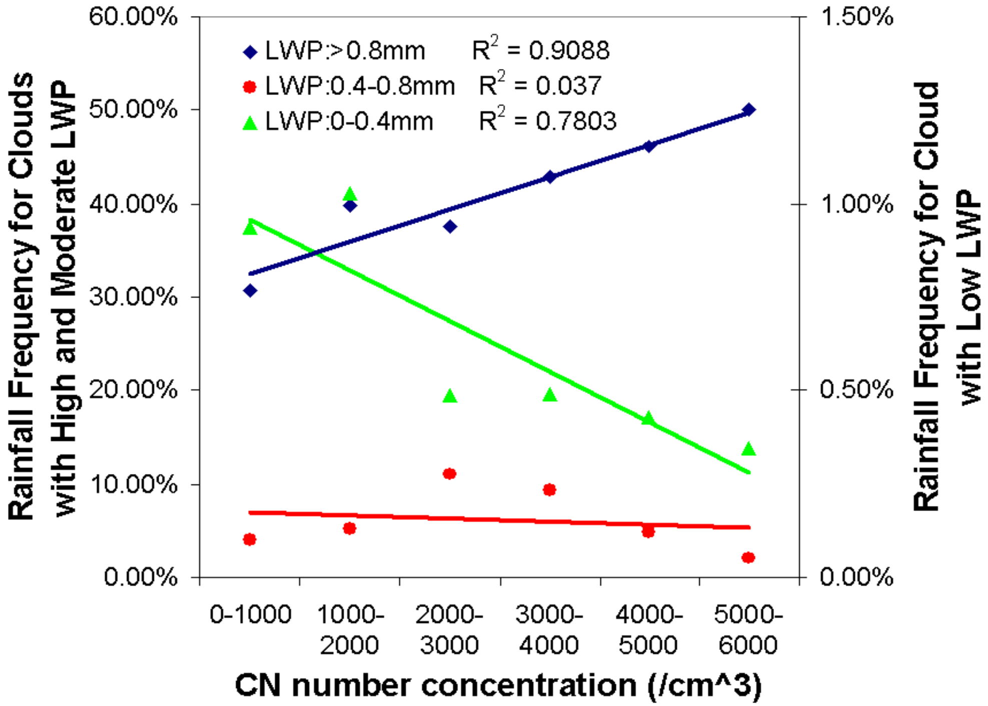
- Weak, if any, evidence in more strongly precipitating clouds

Brenguier and Wood, FIAS, 2009



Aerosol Effects on Precipitation



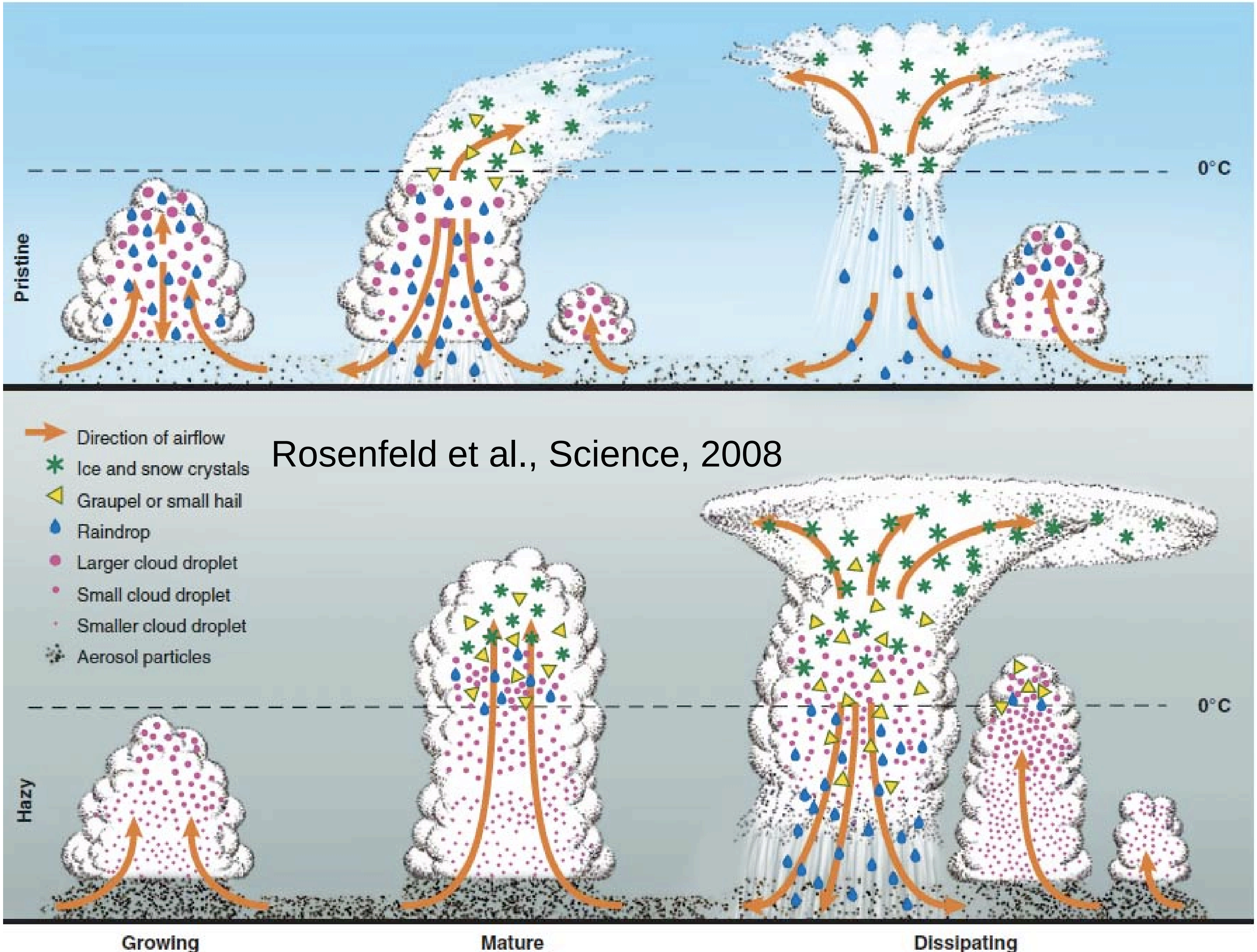


Cloud water content is increased by aerosols much more for high clouds than for low ones.

Rainfall frequency is reduced by aerosols for low liquid water path (LWP), but increased for large LWP.

Zhanqing Li (University of Maryland)

Aerosol Effects on Convective Clouds

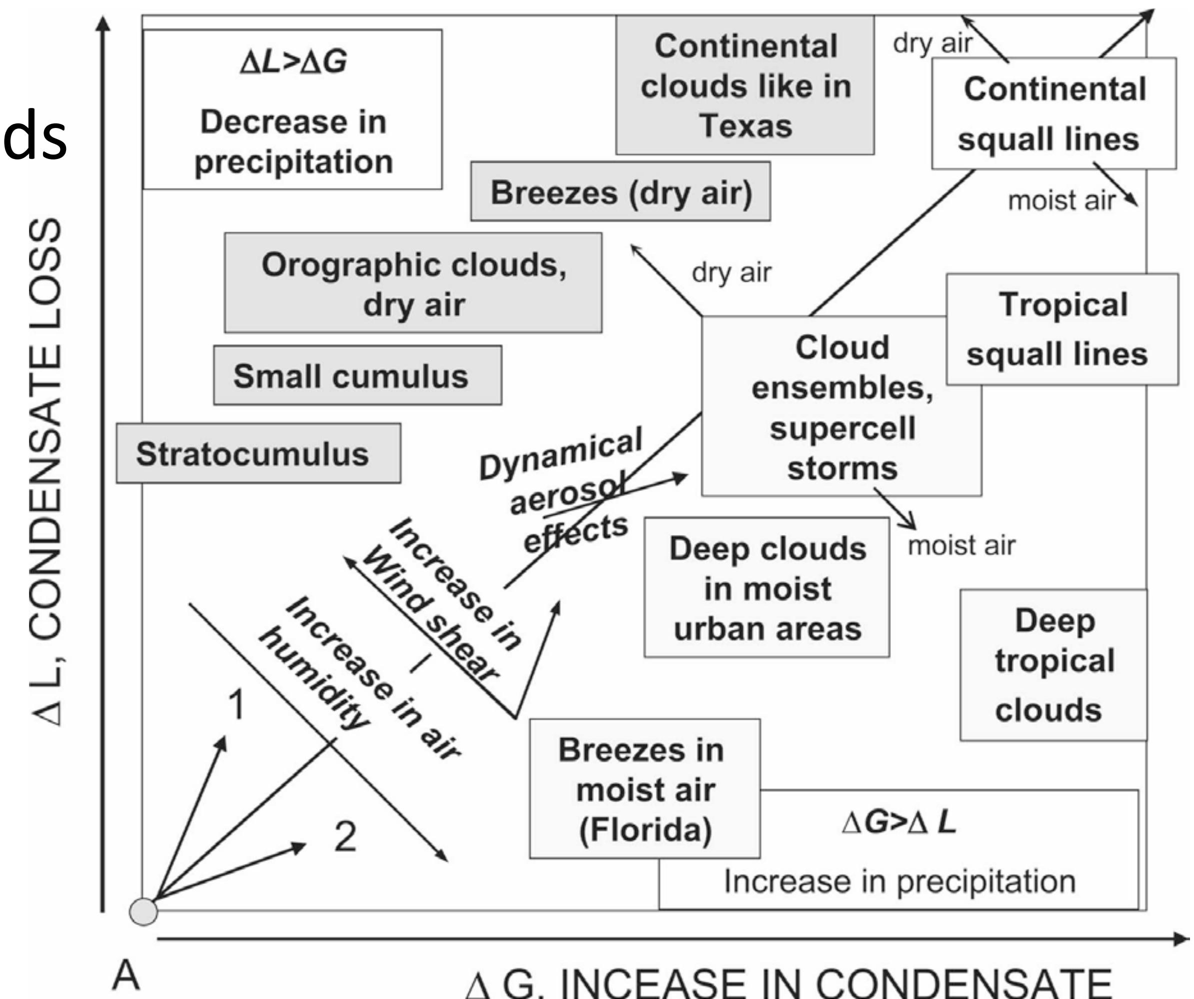


Rosenfeld et al., Science, 2008

Aerosol effects on precipitation depend on cloud type, ambient relative humidity, and wind shear

- Warm clouds
- Cirrus clouds
- Mixed-phase clouds
- Deep convection

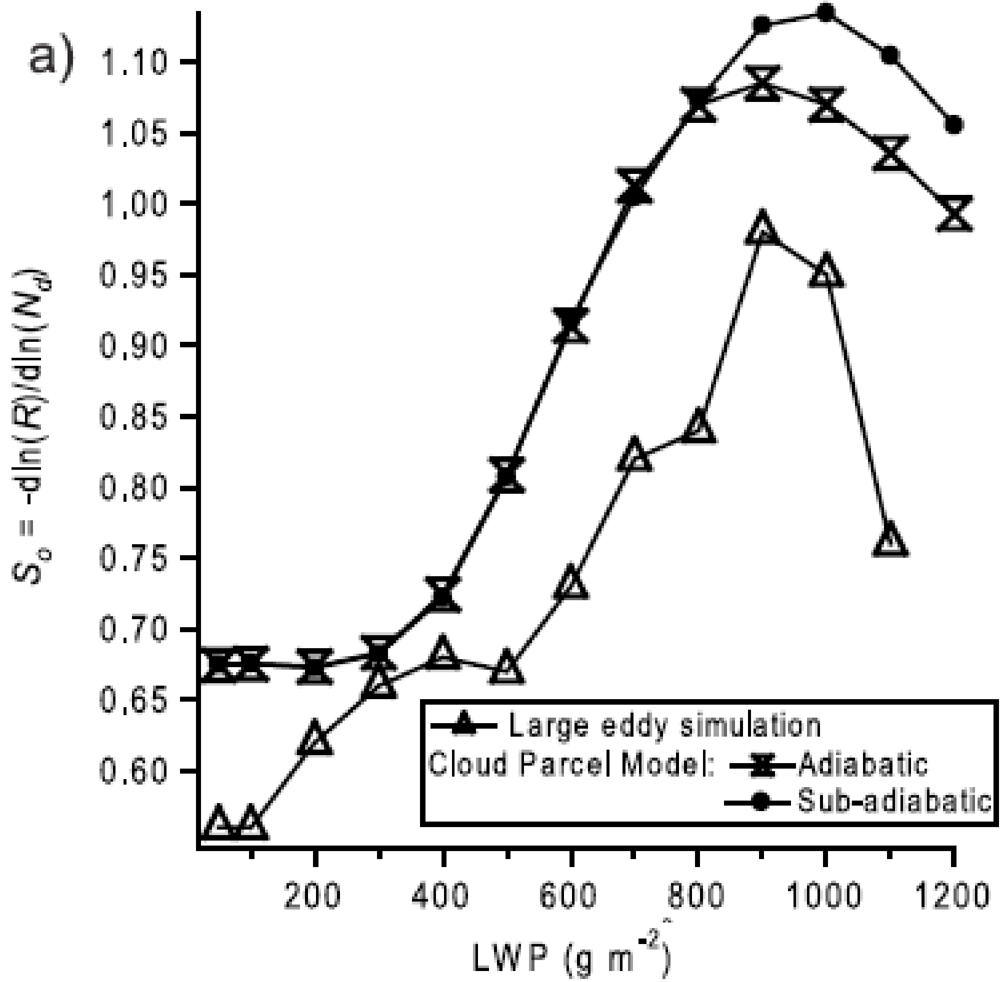
Khain et al., JAS, 2008



Precipitation Susceptibility: $S_p = -\frac{d \ln P}{d \ln N_d}$

Susceptibility is

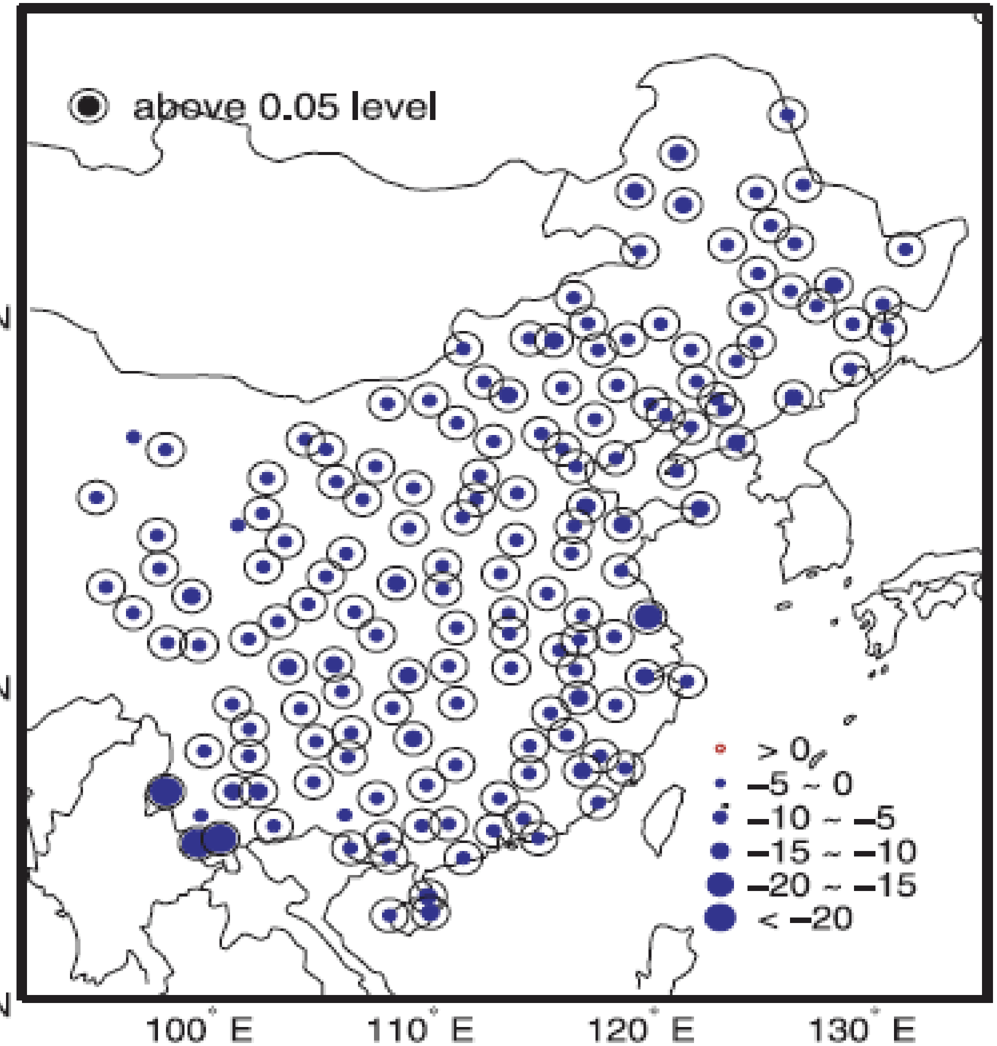
- Low for clouds with little liquid water
- High for clouds with intermediate liquid water
- Low for clouds with plenty of liquid water for precipitation



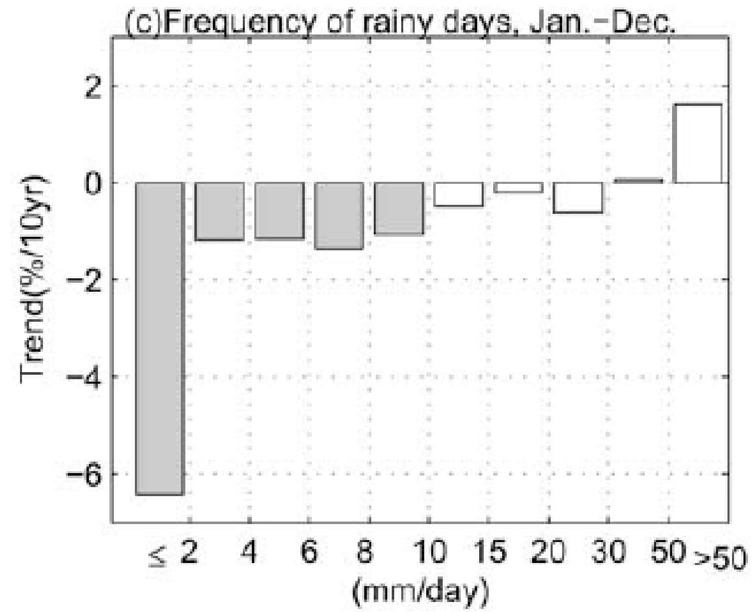
Sorooshian et al., GRL 2009

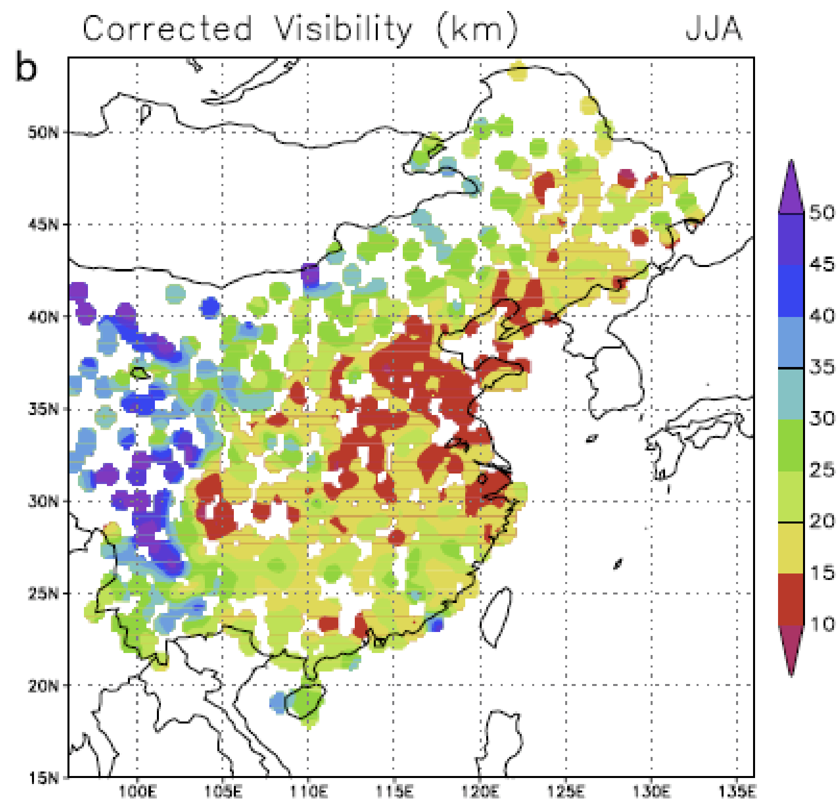
Aerosol Effects on Light Precipitation in China

Trend (days/decade) in light precip (< 5 mm/day)



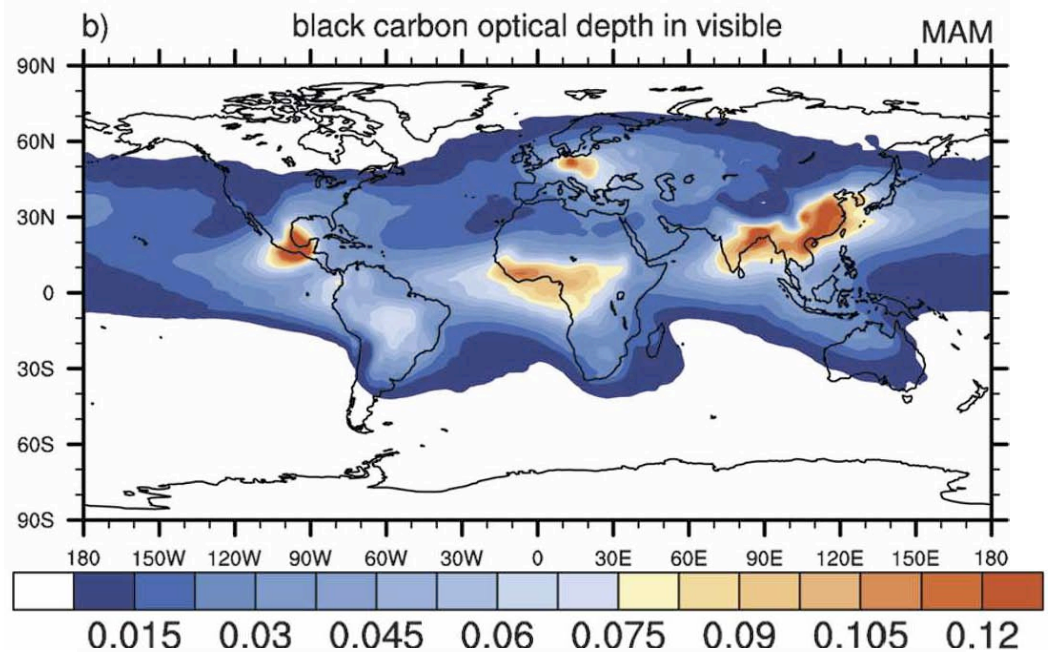
Qian et al., JGR 2009

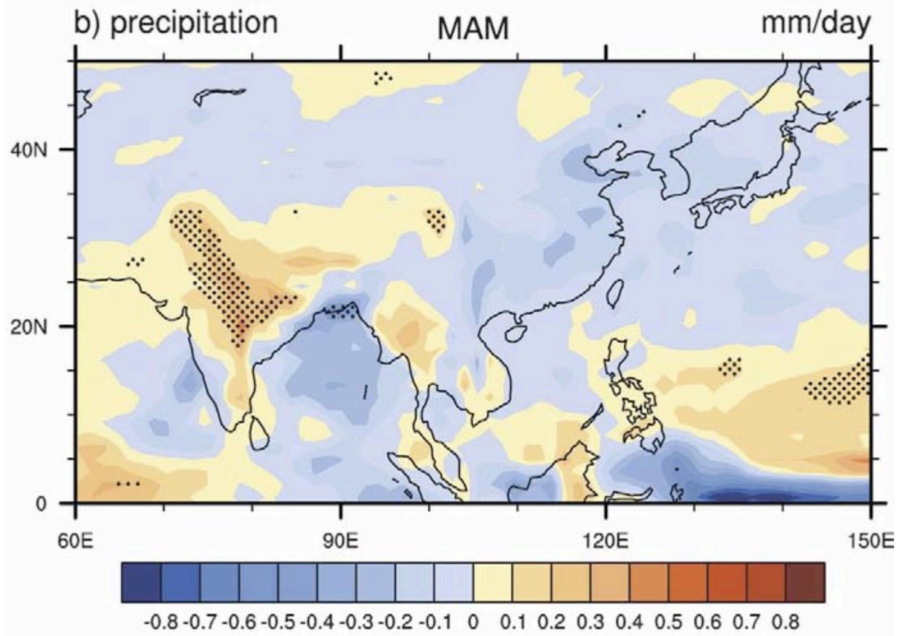




Effects of Radiative Heating on Precipitation

- Heating
  - Inhibits condensation
  - Reduces surface evaporation
  - Suppresses vertical mixing
  - Shifts regional circulation
- Precipitation response
  - Local and regional suppression or enhancement
  - Global suppression





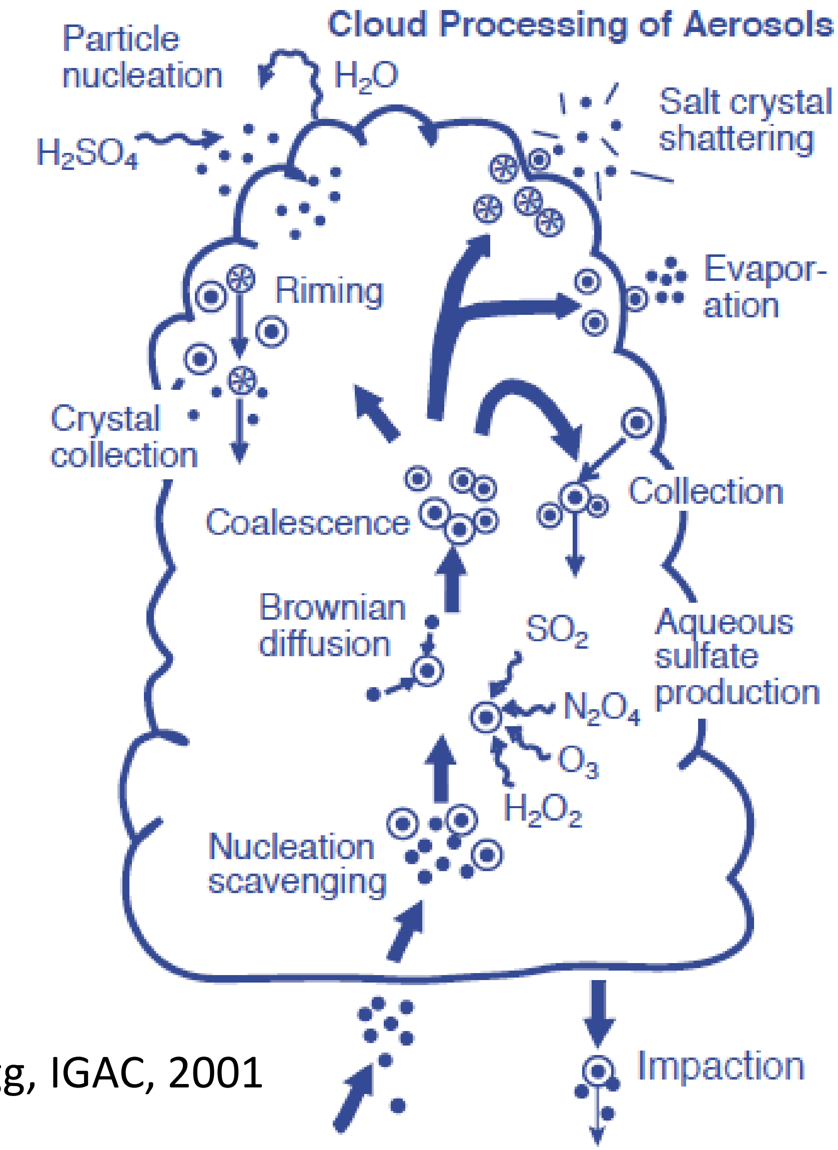
Meehl et al., J. Climate, 2008

What needs to be done for aerosol effects on precipitation?

- Characterize aerosol, including absorption and giant CCN, below a variety of cloud systems in a variety of aerosol regimes.
- Measure spatial distribution of winds and cloud droplet, drizzle and rain size distributions.
- Integrate radar and rain gauge measurements of precipitation.
- Use the velocity and cloud and precipitation measurements to evaluate multiscale simulations given the measured aerosol properties.
- Use sensitivity experiments to separate effects of absorption from effects of activation on precipitation from the clouds.

Cloud and Precipitation Effects on Aerosol

- Vertical transport
- Aqueous chemistry
- Wet removal

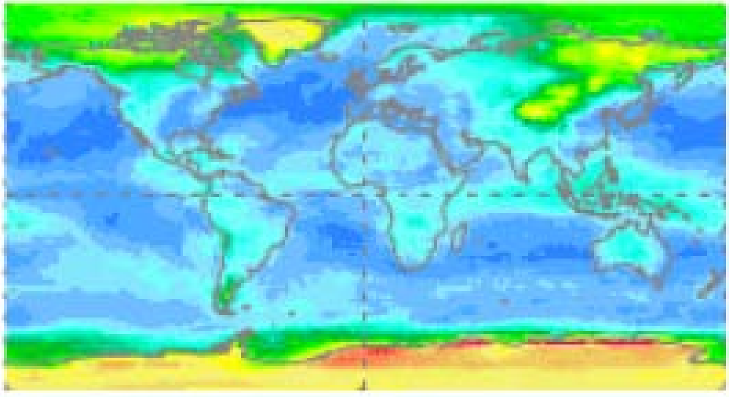


Hegg, IGAC, 2001

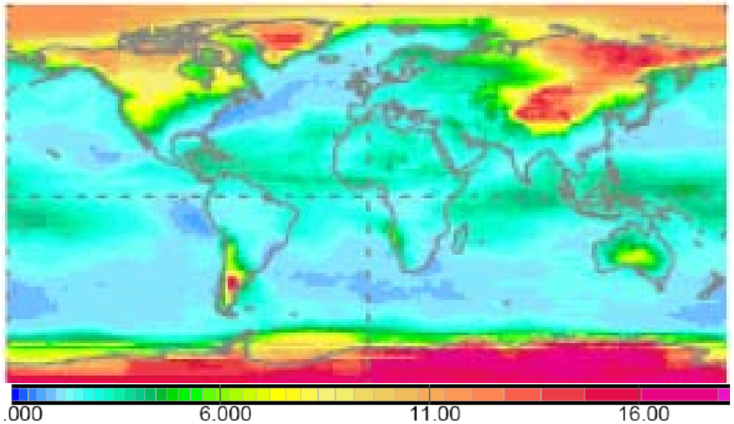
Previous global aerosol modeling studies show diversity in vertical and horizontal distribution due to treatment of cloud effects on aerosol

Max/Min of Central 2/3 of !6 Models

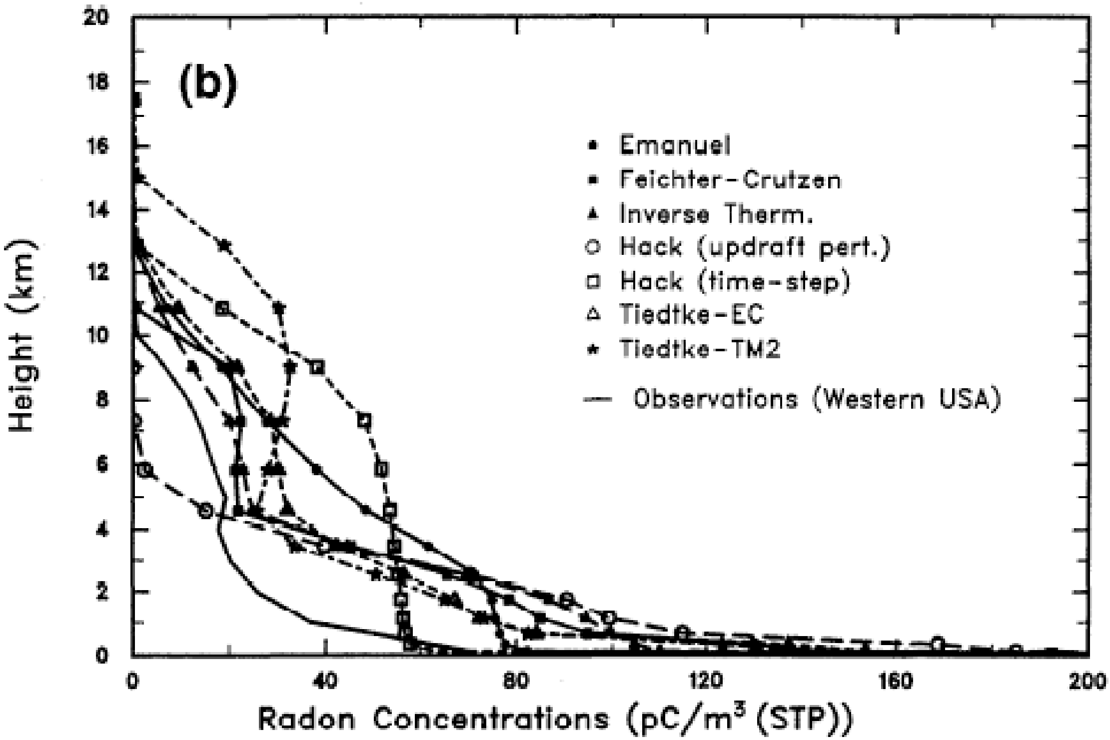
Aerosol Optical Depth



Aerosol Column Mass



Kinne et al., An AeroCom initial assessment. *Atmos. Chem. & Phys.*, 2006.

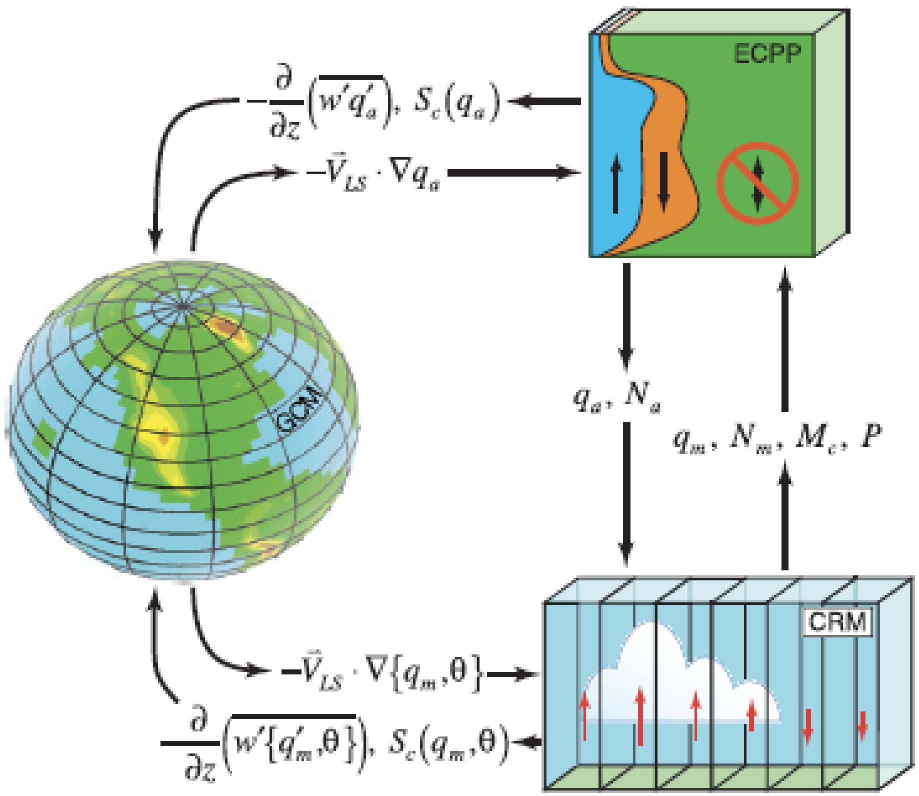


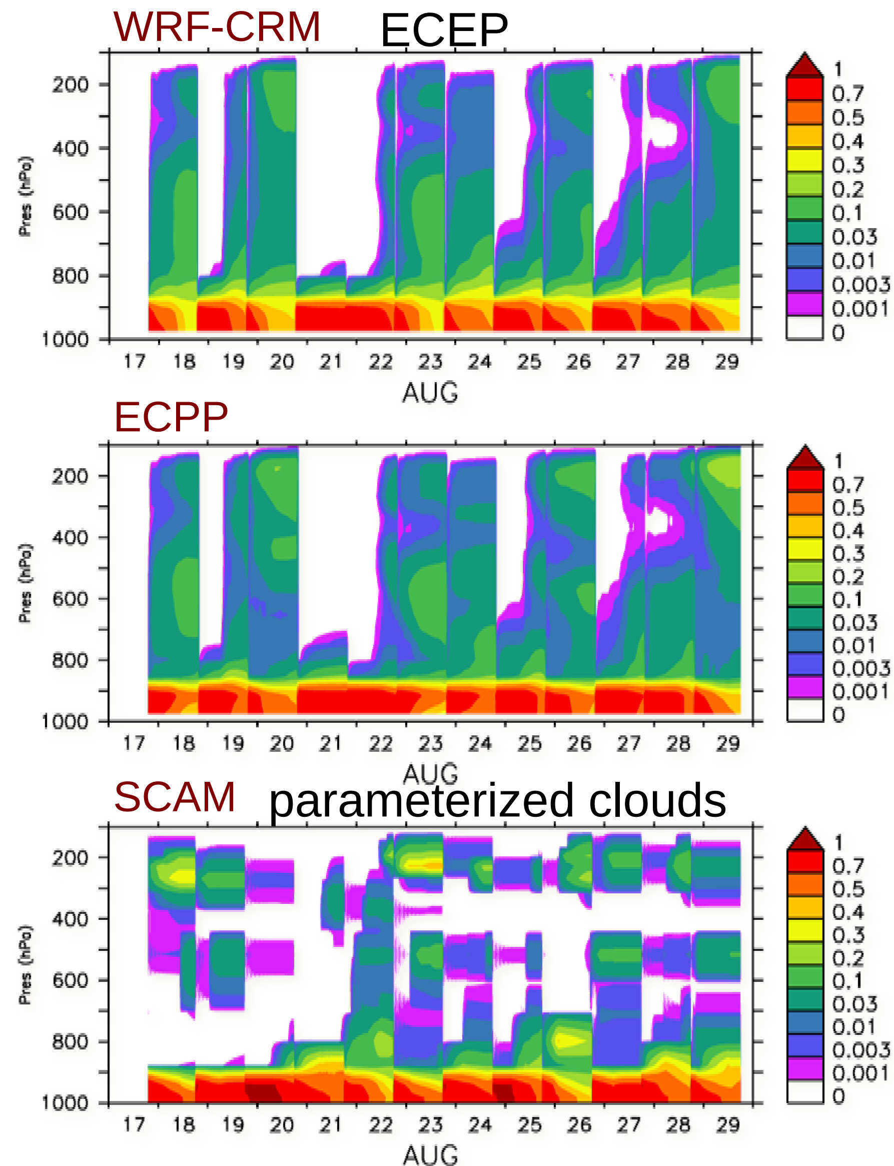
Mahowald et al., JGR, 1995

Using Embedded Cloud-Resolving Models to Treat Cloud Effects on Aerosol

Explicit Clouds Parameterized Pollutants

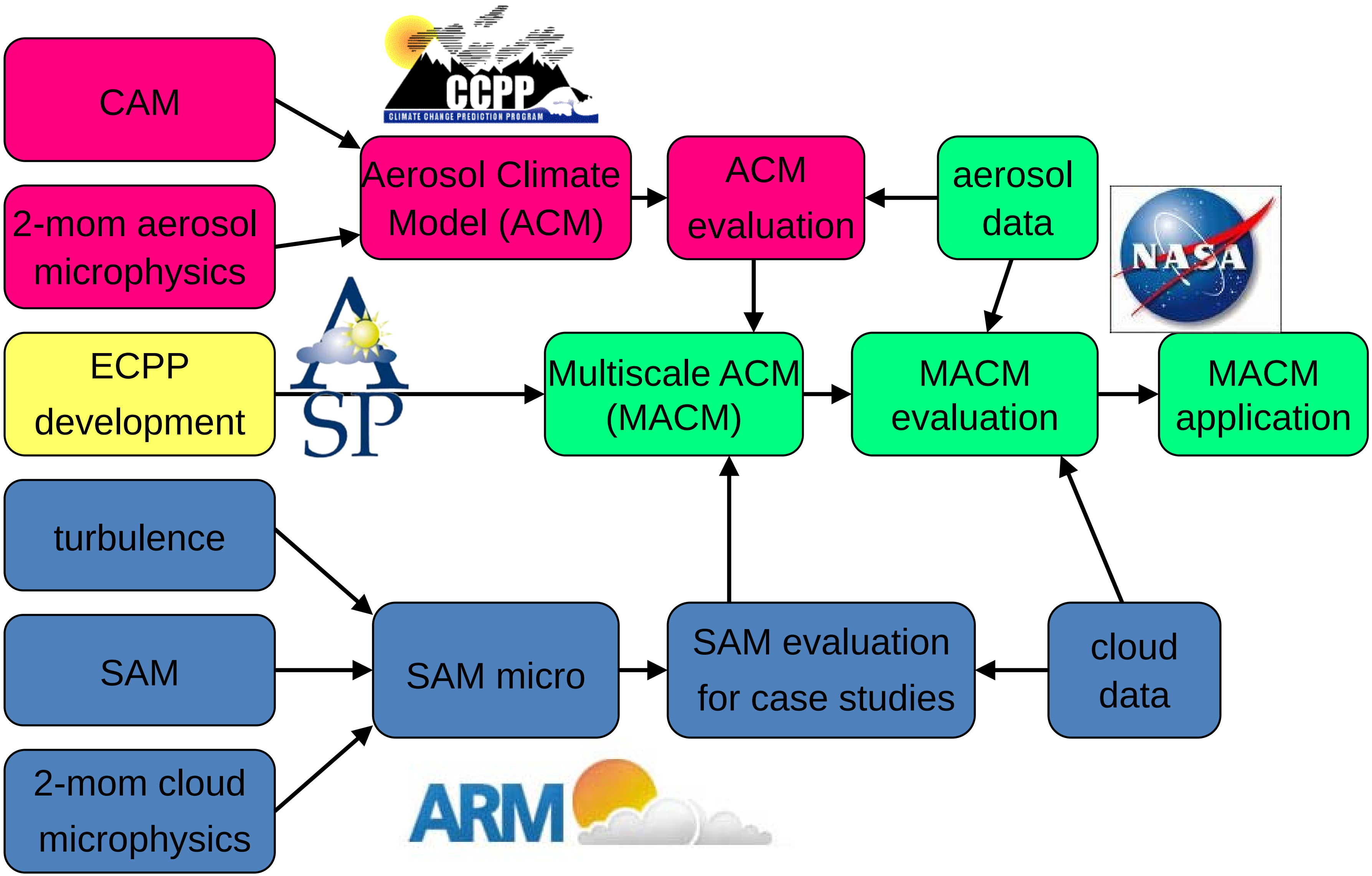
Use WRF as CRM to test concept.



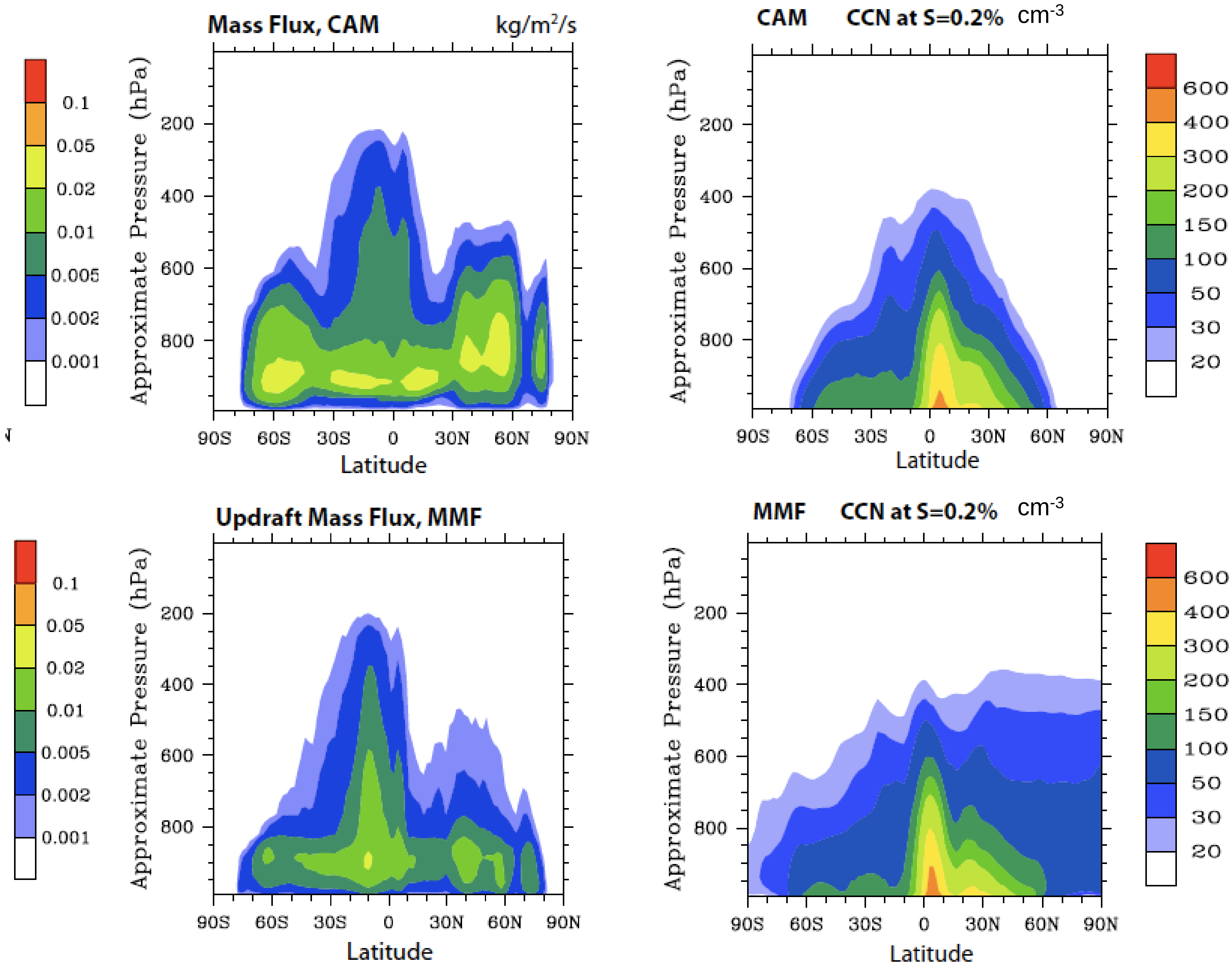


Gustafson et al., Env. Res. Lett, 2008

A Multiscale Aerosol Climate Model



First Look at MACM Results



What needs to be done for cloud effects on aerosol?

- Compare simulations of cloud-aerosol interactions with aerosol column budget measurements for deep convective cases.
- Evaluate global simulations with active remote sensing of aerosol.

Cloud-Aerosol-Precipitation Interactions

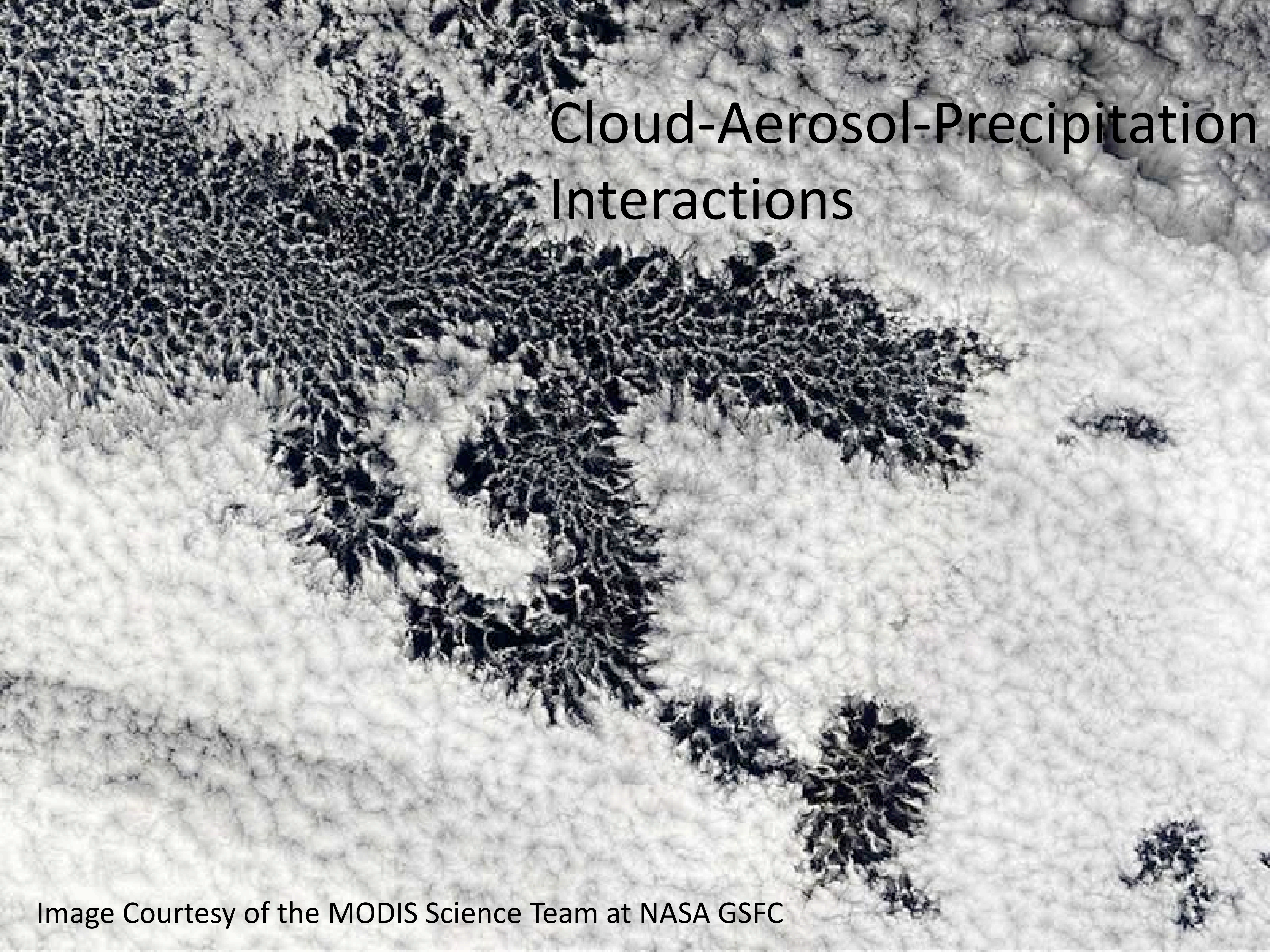
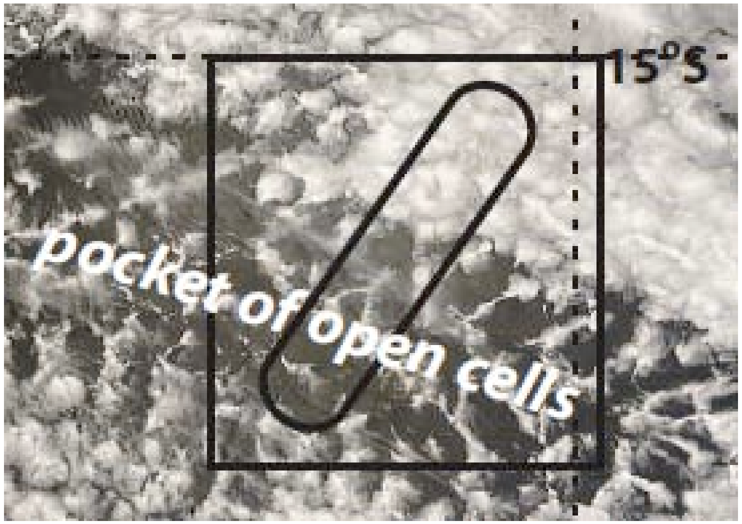
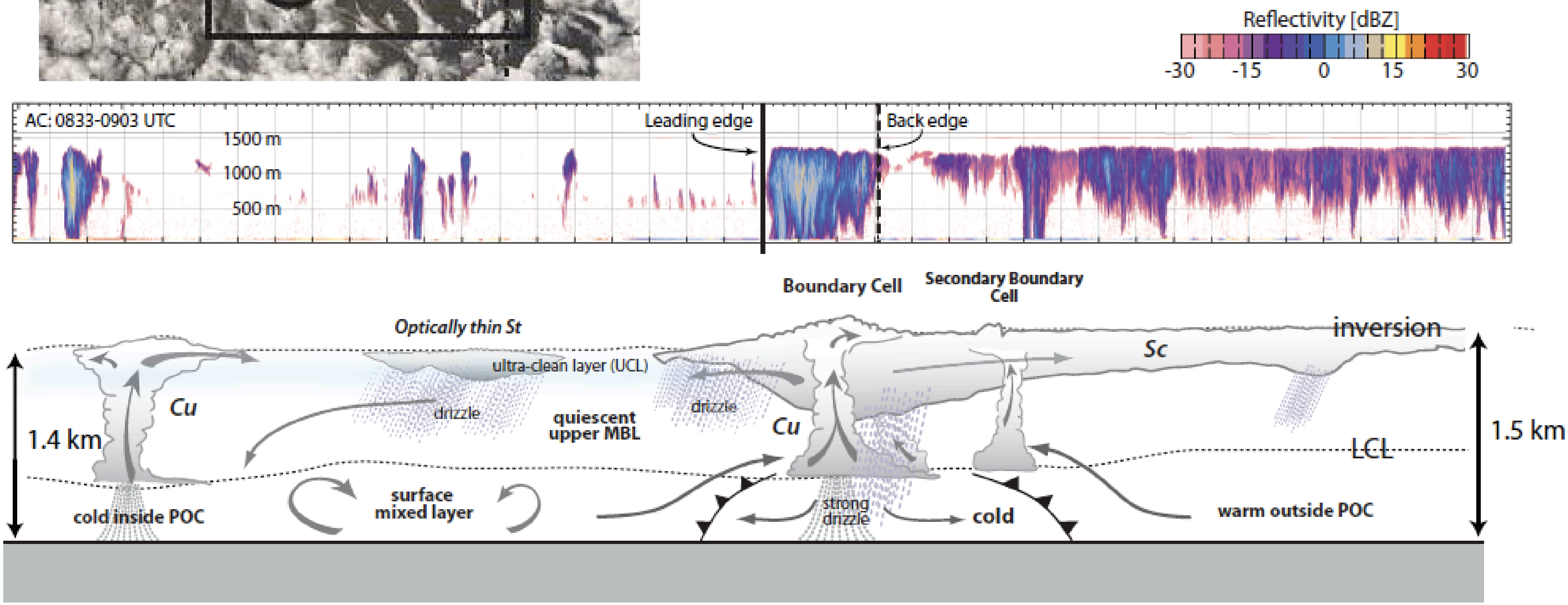


Image Courtesy of the MODIS Science Team at NASA GSFC

Observations During VOCALS



- In situ and remote sensing across transition



Conceptual diagram of the POC-transition-overcast MBL as observed during VOCALS (Wood et al., ACPD, 2010)

What needs to be done for cloud-aerosol-precipitation interactions?

- Analyze VOCALS *in situ* data and Azores AMF data to characterize breakup of stratocumulus.
- Use VOCALS and Azores data to evaluate cloud-resolving simulations with fully interactive clouds and aerosol.
- Perform sensitivity experiments to improve understanding of the breakup mechanism.

The ASR Strategy