A satellite perspective of the influence of aerosol on cloud systems

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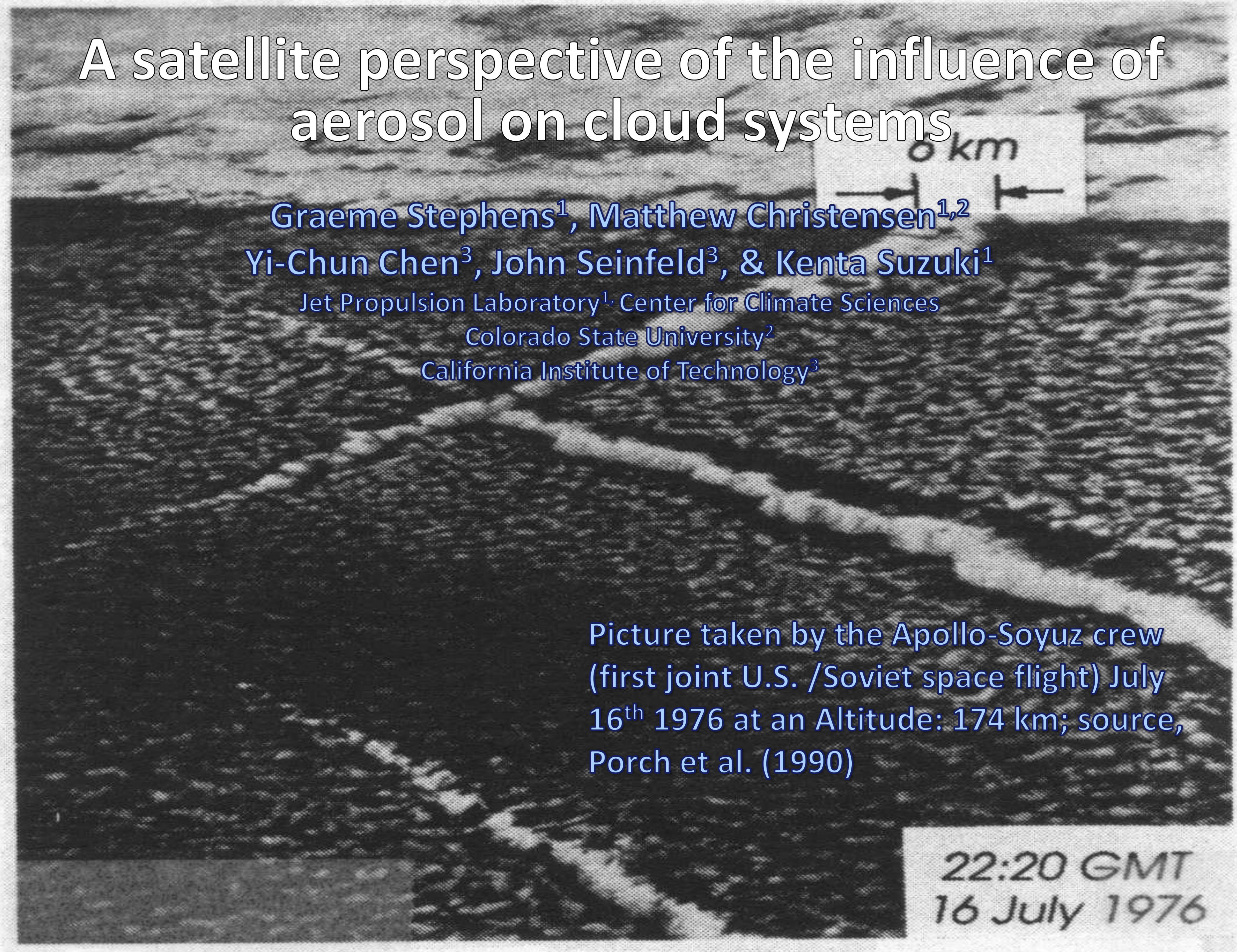
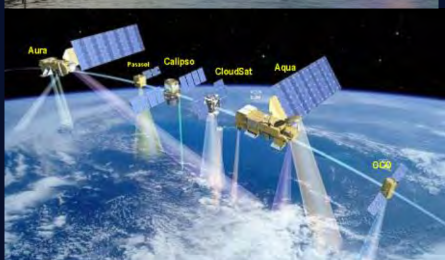


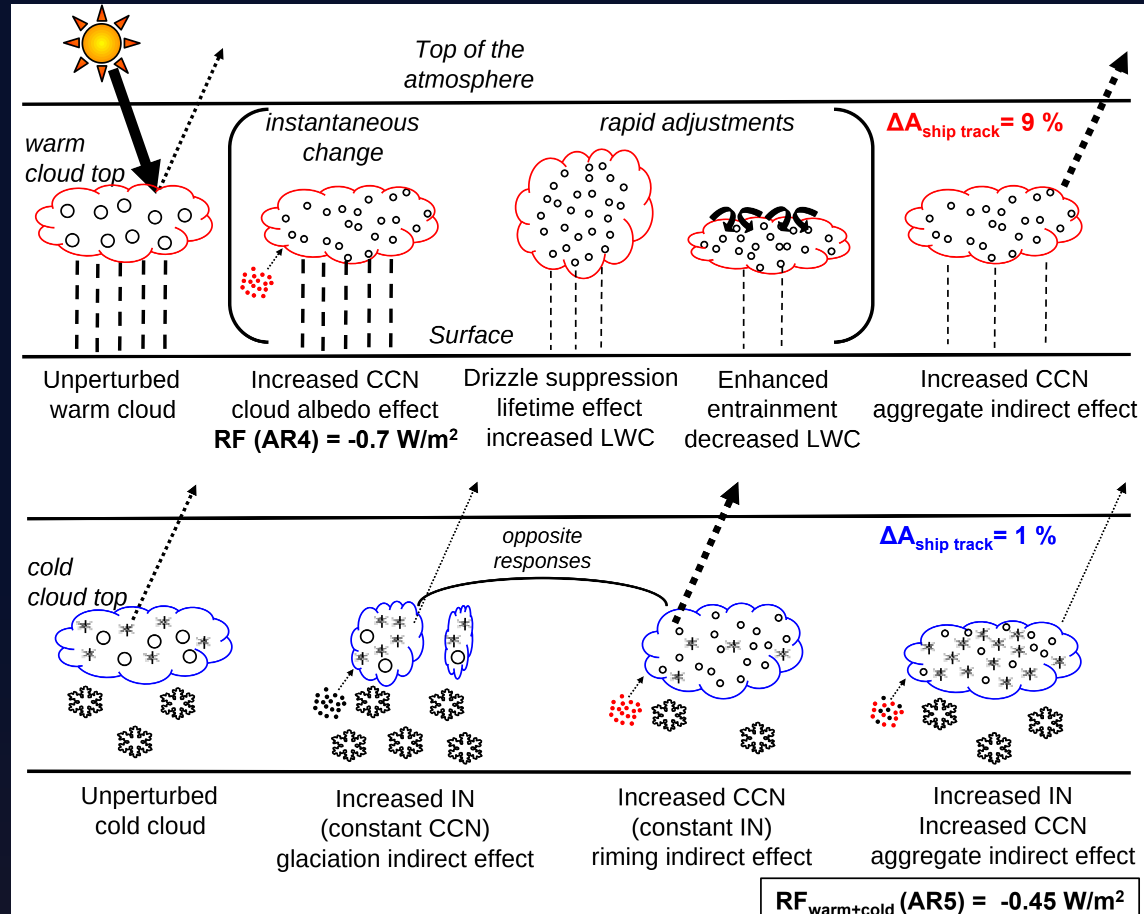
Picture taken by the Apollo-Soyuz crew (first joint U.S. /Soviet space flight) July 16th 1976 at an Altitude: 174 km; source, Porch et al. (1990)



Outline

1) Warm Clouds
- What is observed
- How effects are studied
- A more evolved process view

2) More Speculative
- Cold clouds
- Deep Convection

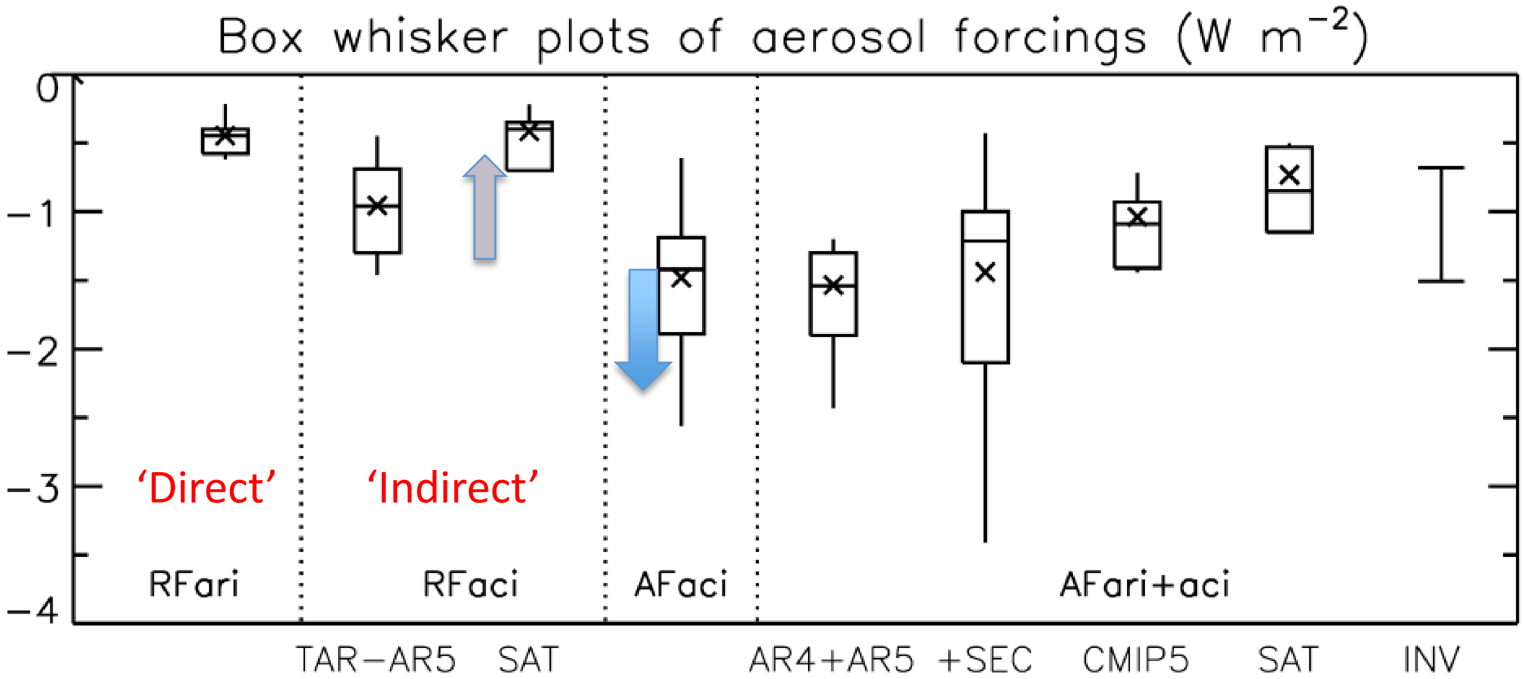


Take home messages:

-The cloud albedo response to aerosol is the result of an aggregation of processes that tend to buffer each other

– the net effect is more directly determined by the response of the water budget of clouds to aerosol.

Albedo and Climate forcings



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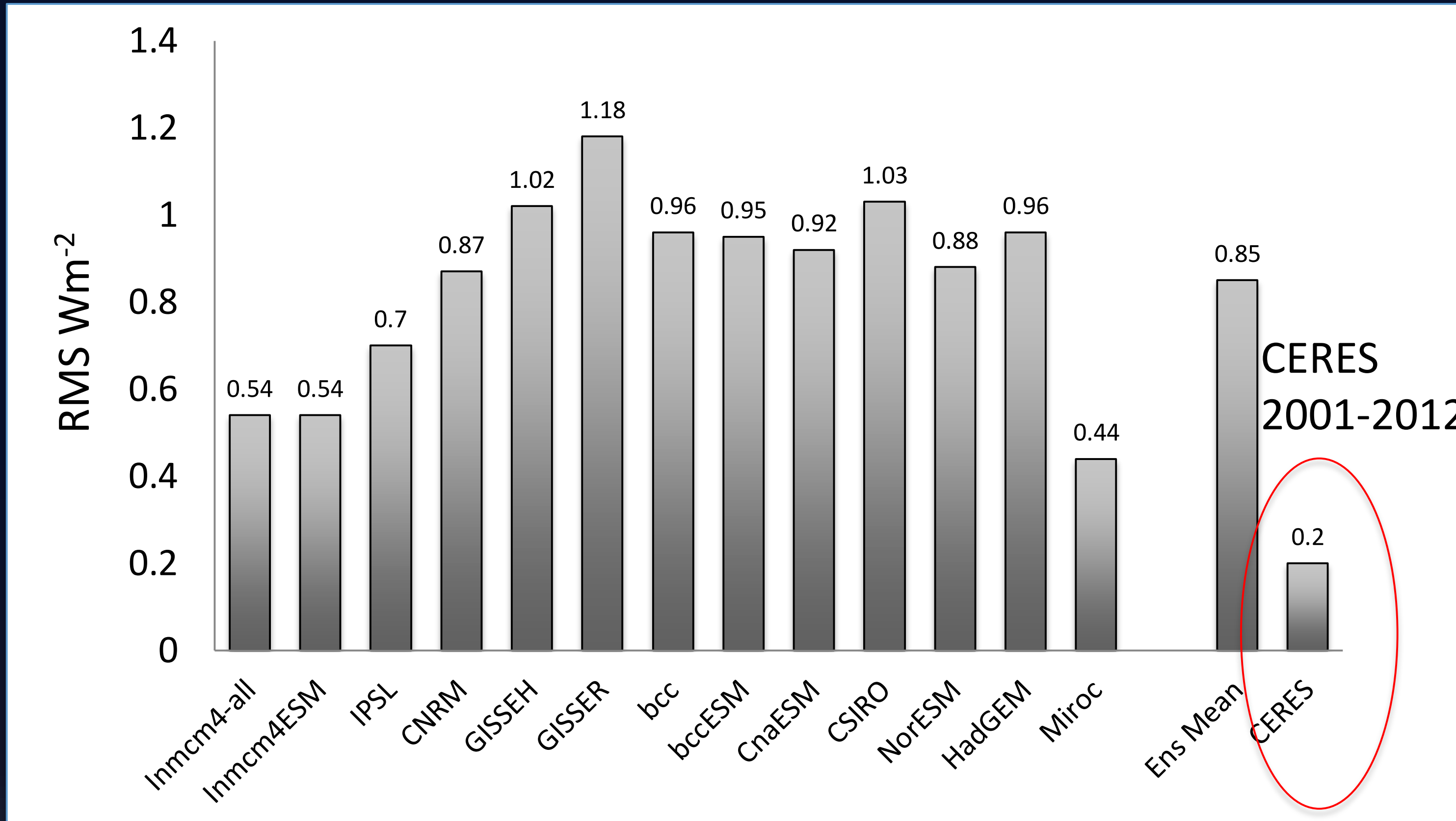
The adjustments of models enhance the initial "Twomey' effect

The adjustments as observed by satellites reduce the effect

Interannual variability of reflected energy

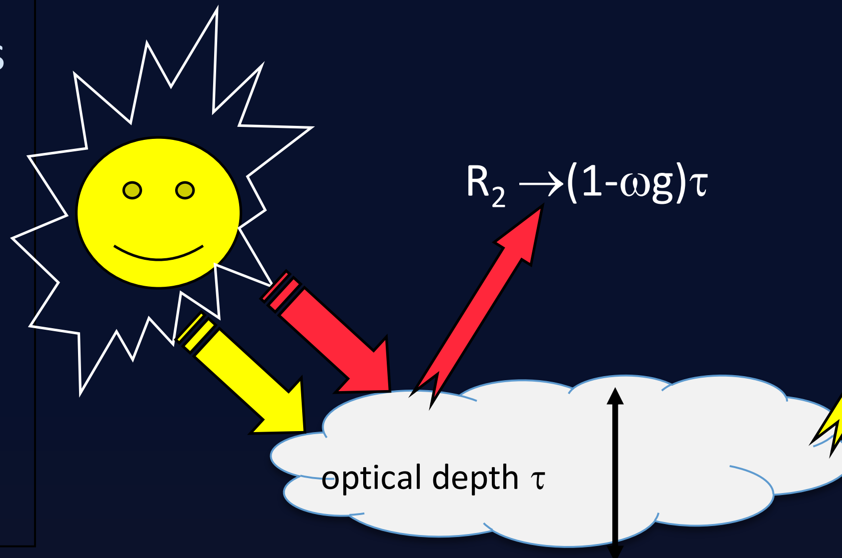


Modeled inter-annual variability of globally averaged fluxes is (on average) 4 times the observed global variability, Source Stephens et al., *'The albedo of Earth', Rev Geophys,2014*

1) Warm cloud microphysics from satellite

Implicit, r>λ

- Twomey, 1969; ‘Theory’
- Twomey & Cocks, 1982’ s first demonstration from aircraft
- Nakajima & King, 1990; streamlined LUT algorithm
- Han et al., 1994; first global maps



$$t \rightarrow \frac{3}{2}\frac{LWP}{r_e}$$

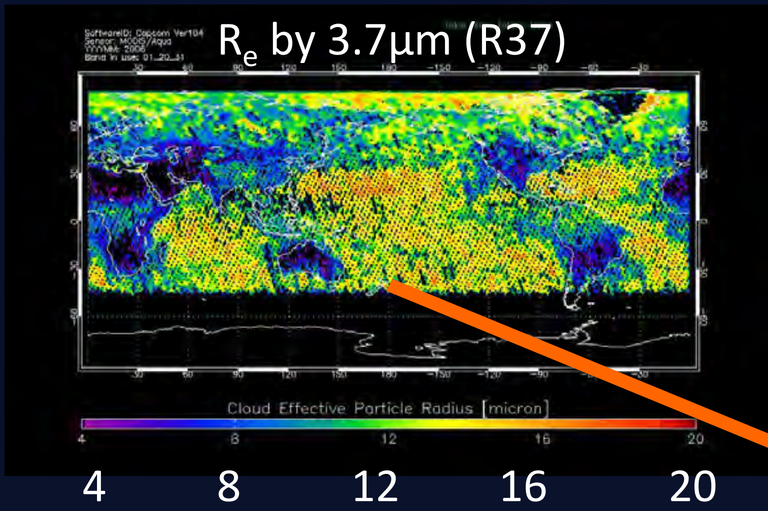
$$LWP \rightarrow \frac{2}{3} t\, r_e$$

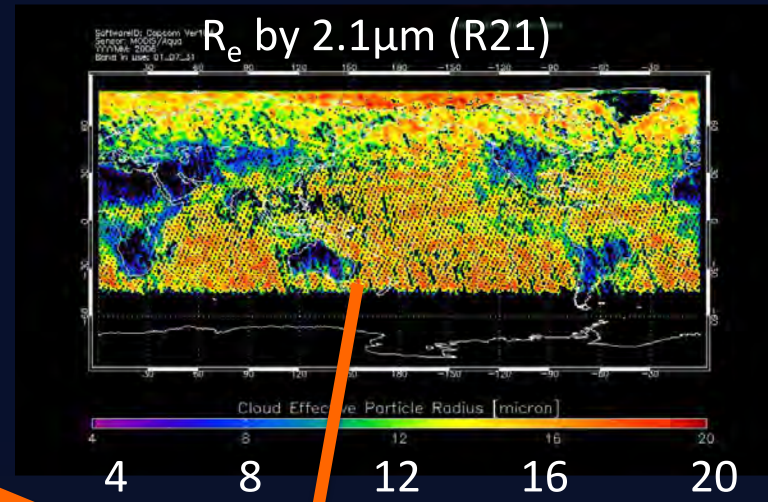
Visible reflectance (R_1) is a function a combination of parameters, i.e. $R \rightarrow (1-g)\tau$

Near-IR reflection (R_2) is a function of optical depth τ and the scattering albedo ω- the latter is a function of particle size r_e.

Measurements of reflection at two wavelengths returns τ and r_e assuming g

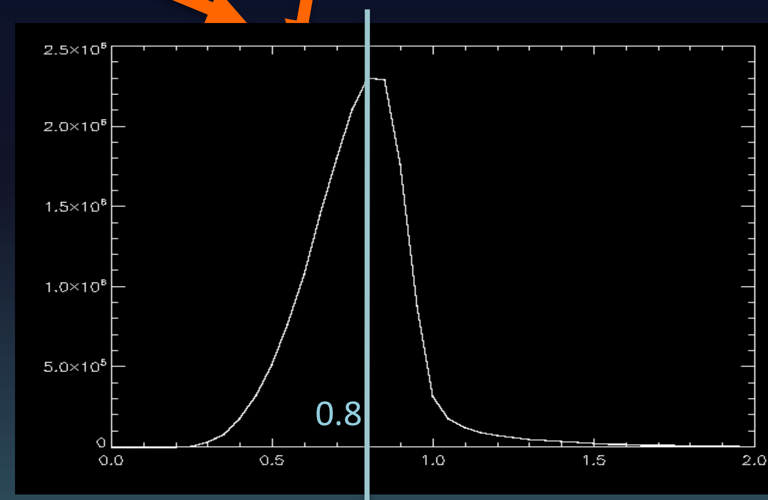
$$\frac{Da}{a}\ \mu\ \frac{Dt}{t} = \frac{DLWP}{LWP} - \frac{Dr_e}{r_e}$$





20+ year conundrum

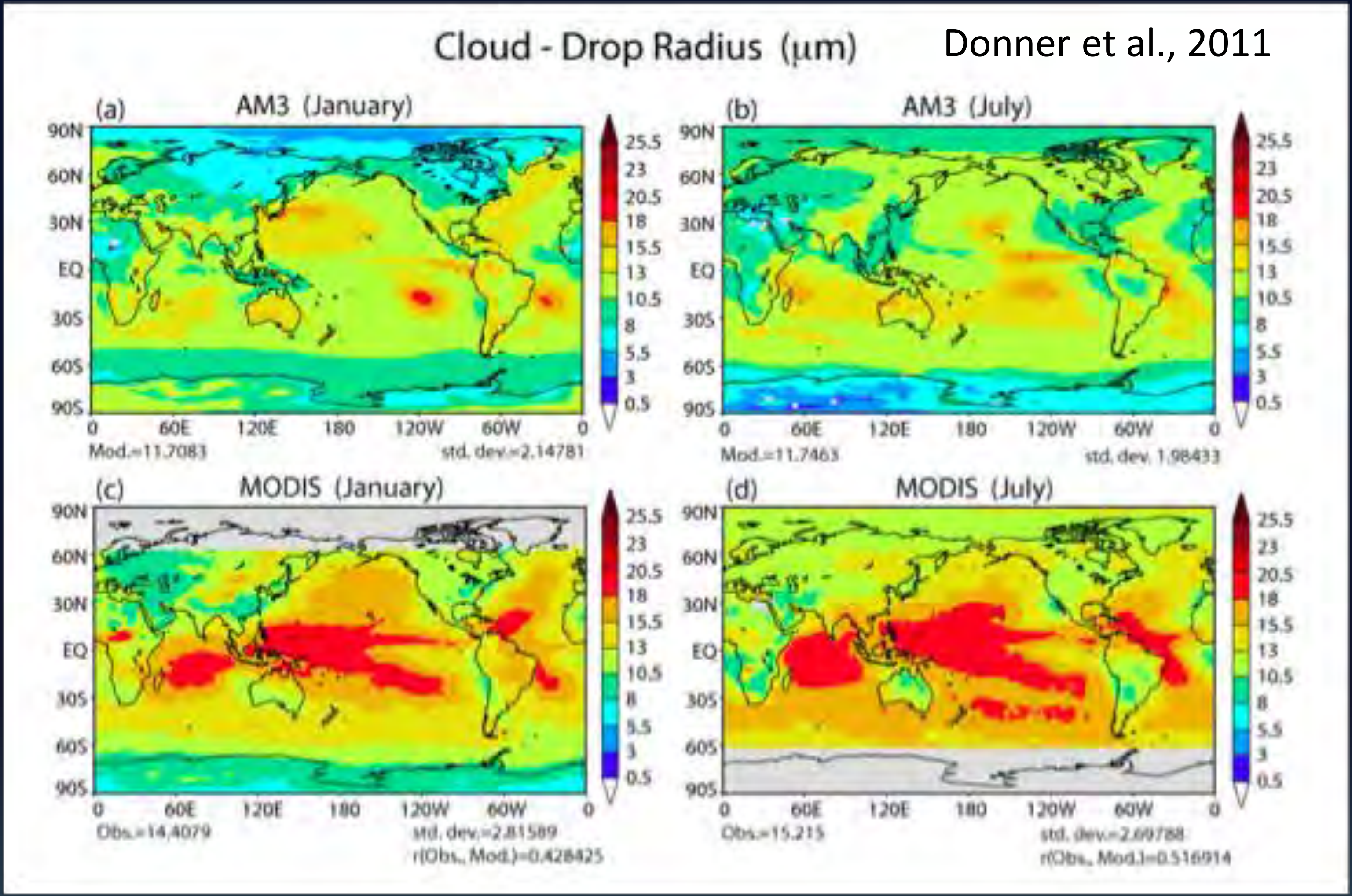
These satellite estimates have variable biases when compared to aircraft measurements



R37/R21 Histogram (Jul. 2006 one month)

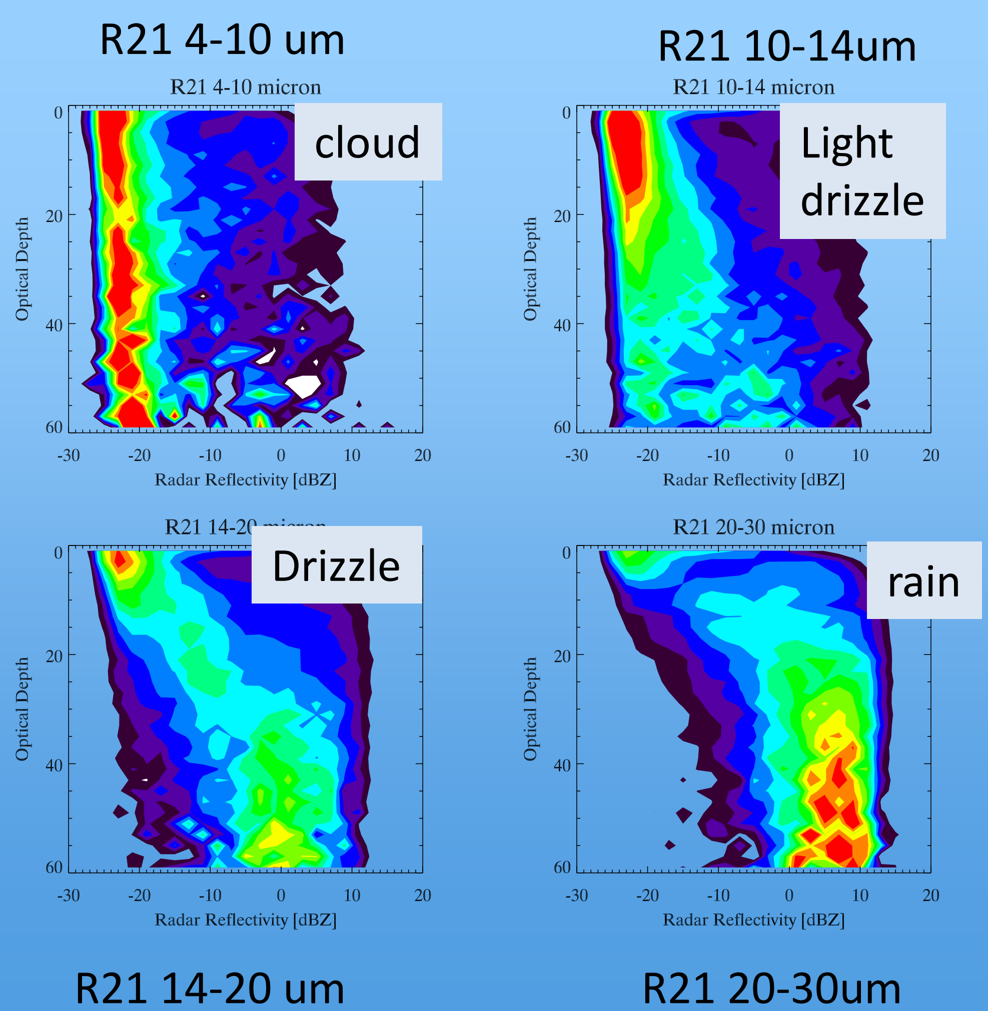
Nakajima, Suzuki, Stephens (2009)

Model and observations



This matters because the strategy for testing aerosol-cloud indirect effects in global models has largely been framed around introducing particle size changes

Conundrum resolved when particle size and radar reflectivity matched

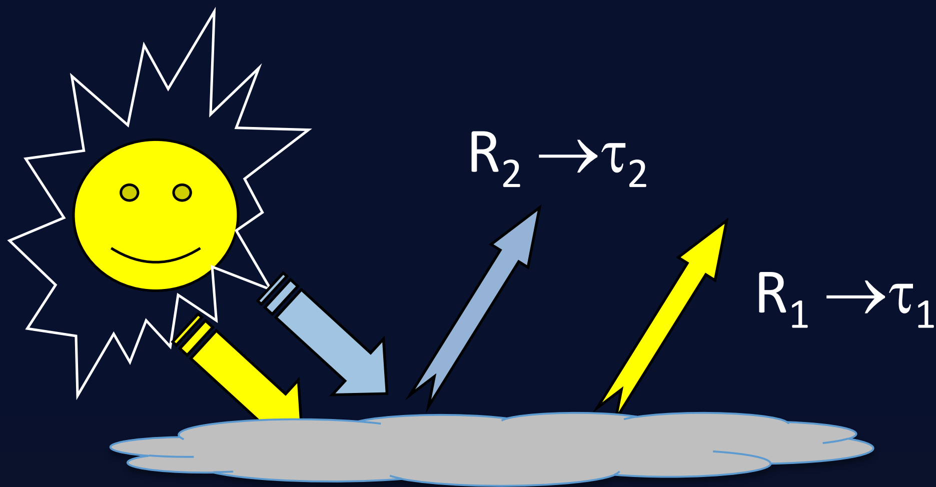


The evolution from cloud water to drizzle to rain evident in the radar profiles also reflected in the MODIS particle sizes @2.1 but not 3.7

The conundrum and its solution is discussed in Nakajima et al., 2010a,b

……or so we claim!!!!!

Aerosol from satellite - Implicit, r~λ

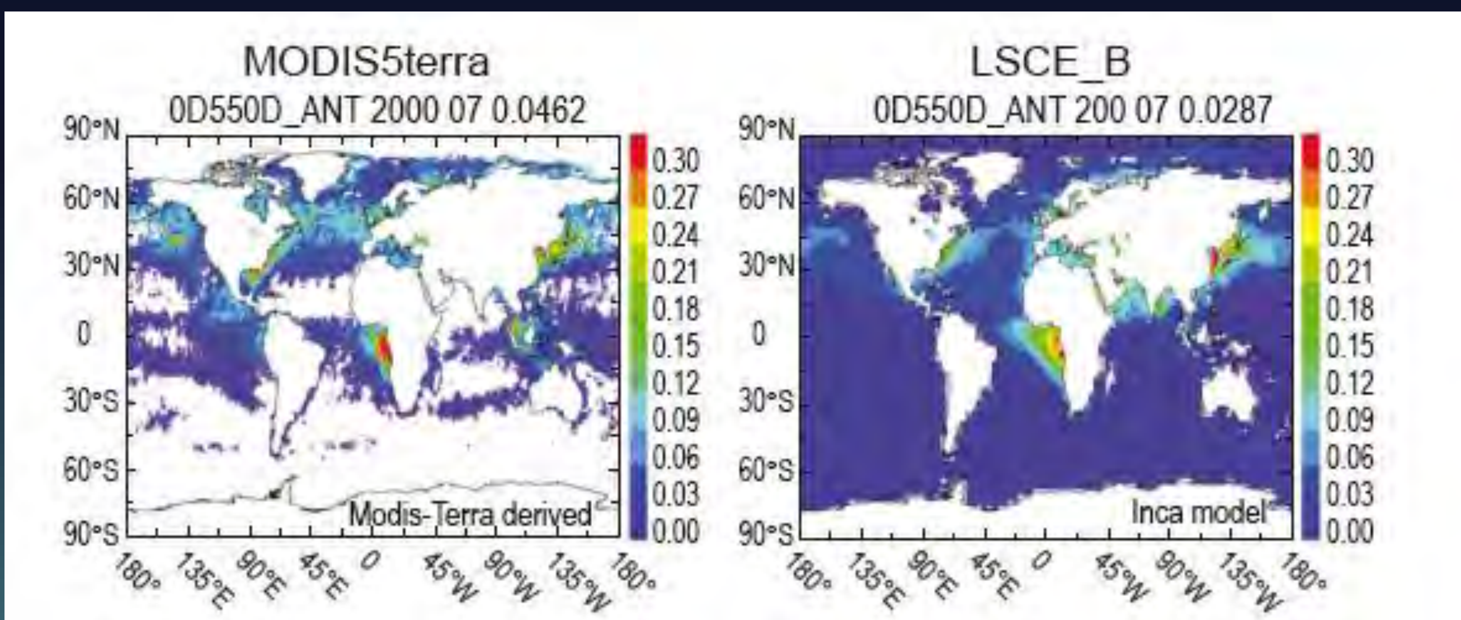


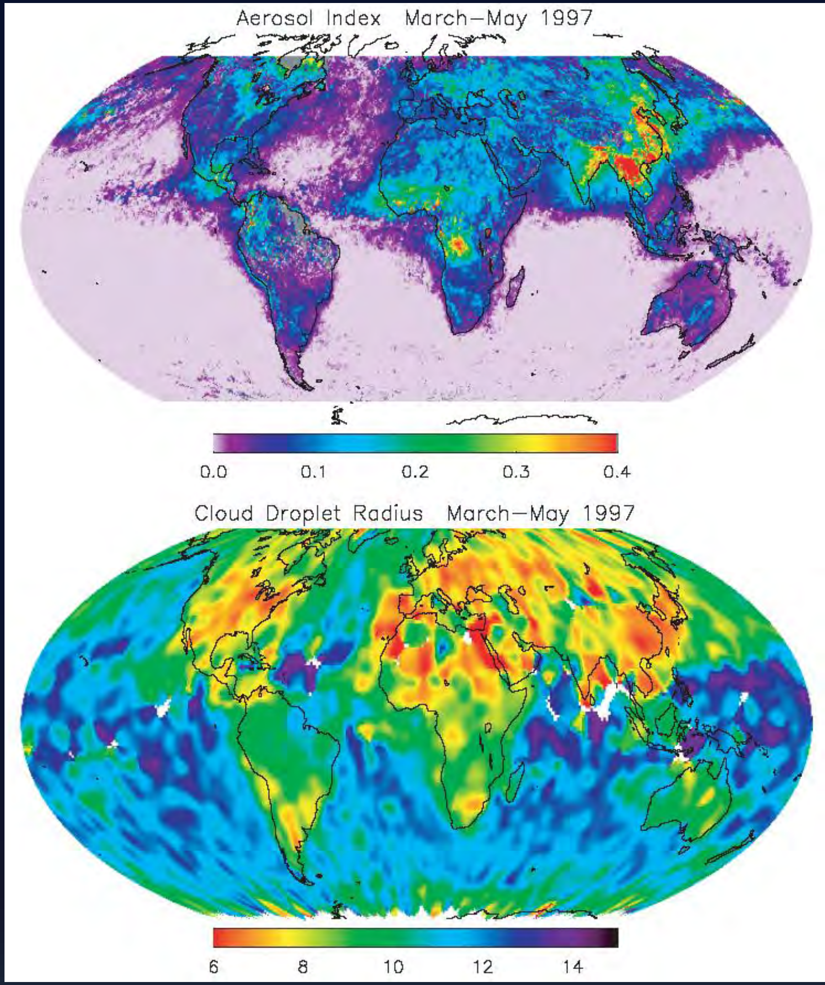
The τ wavelength differential provides bulk information on aerosol size –

- 'Fine mode'- MODIS, Kaufman,2005
- Aerosol exponent (turbidity) α

$AI = \tau \times \alpha$ (Nakajima et al., 2001)

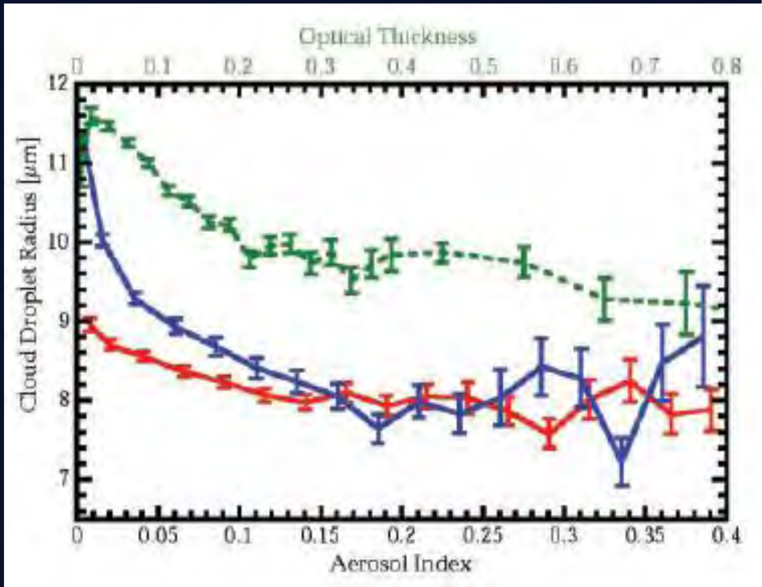
Alternatively - use of assimilated aerosol data in place of satellite data – L'Ecuyer at al., 2010, Chen et al., 2013.





POLDER

Breon et al. (2002), *Science*



r_e reduction with increasing aerosol = 'Twomey' effect

$$\frac{\Delta\tau}{\tau} = \frac{\Delta LWP}{LWP} - \frac{\Delta R_e}{R_e} \propto \frac{\Delta\alpha}{\alpha}$$

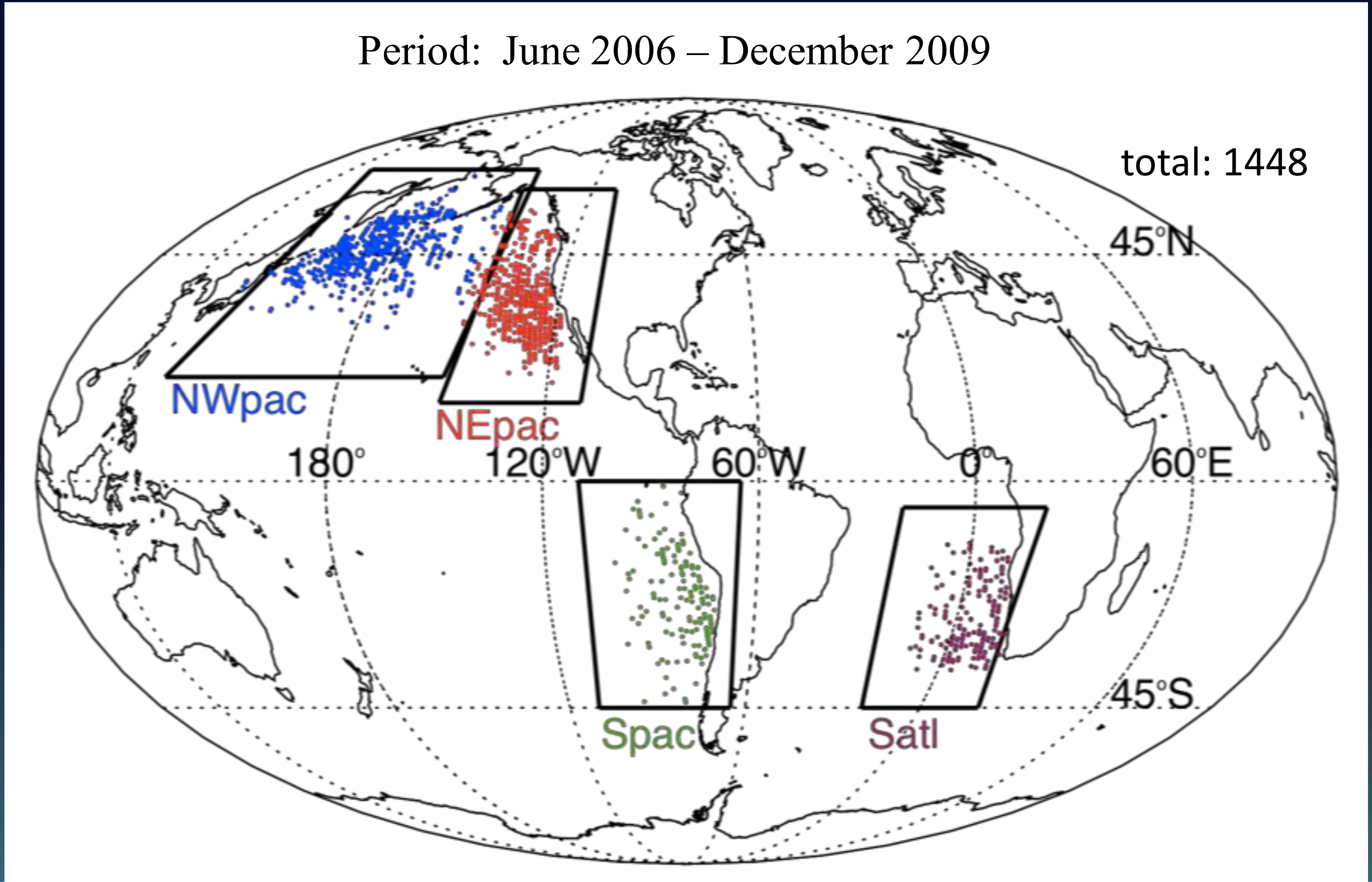
0

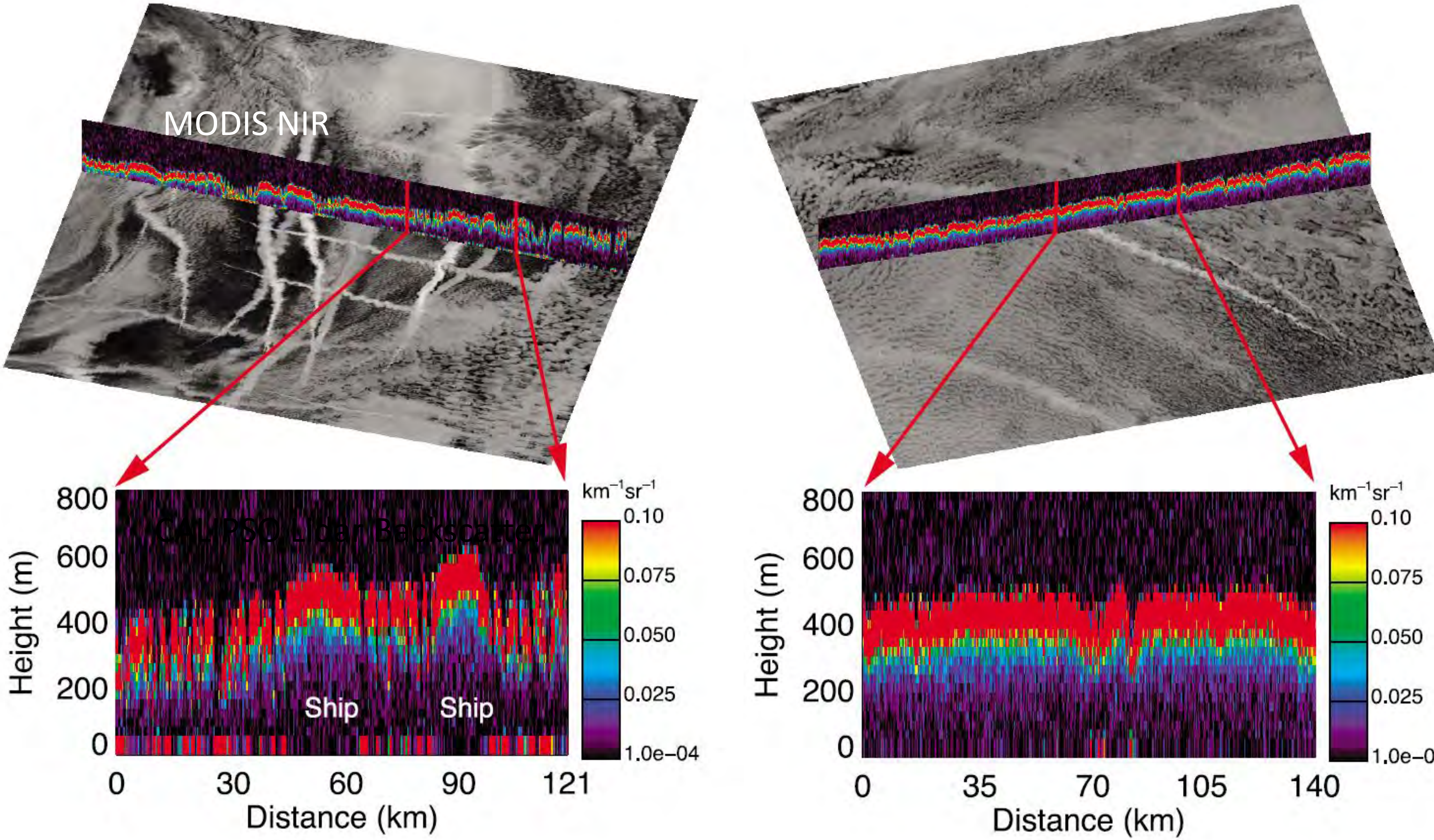
NO

Almost all studies of this type are merely correlations, failing to isolate the Twomey effect (fixed LWP) from other effects. Almost all studies of this type, as well as field experiments supposedly aimed at addressing indirect effects, provide no information about albedo and its change

A-Train Ship Track Database

CALIOP - Lidar cloud top heights
CloudSat Radar- precipitation occurrence, reflectivity
MODIS particle sizes, LWP, AI
AMSRE LWP
CERES albedo



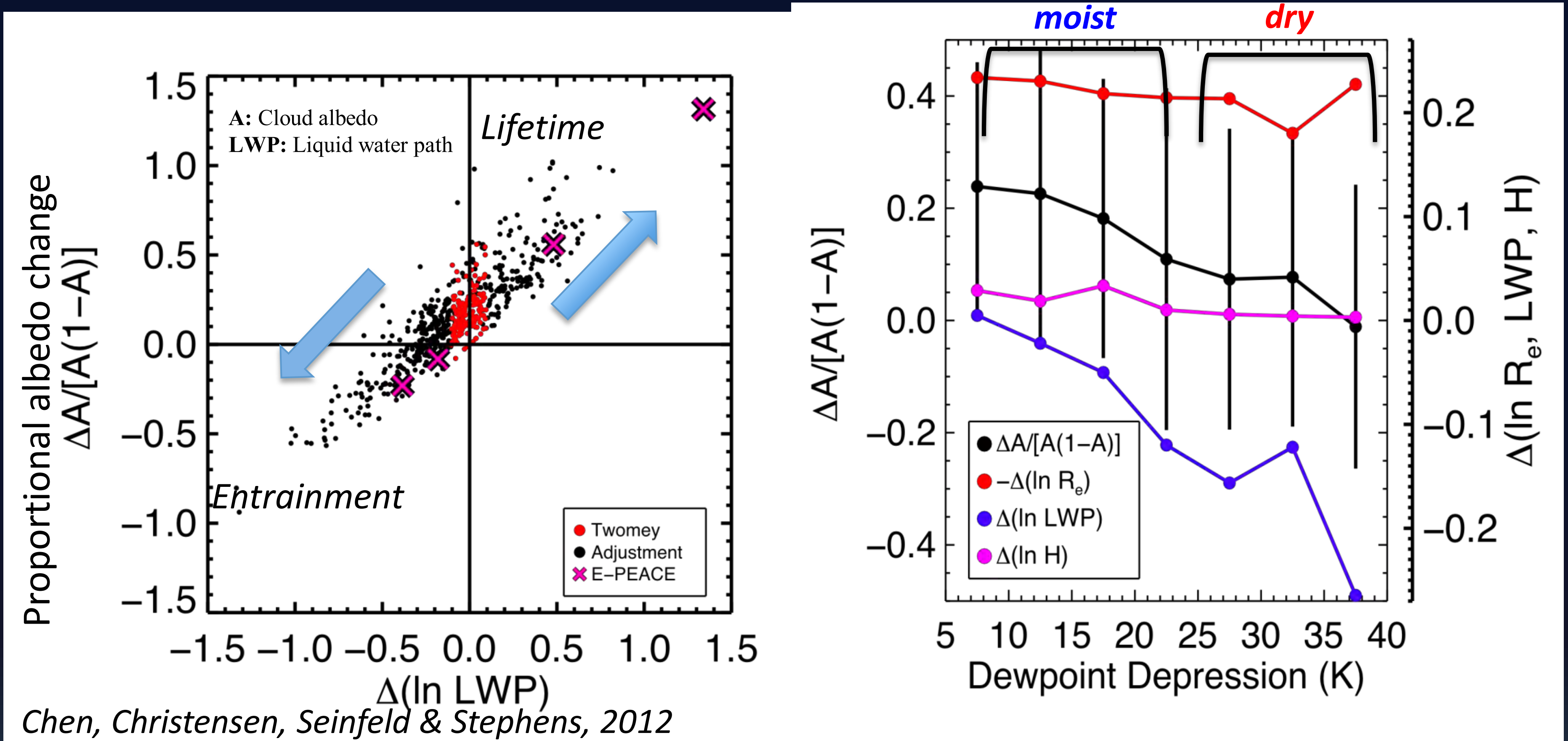


Open cells: 16% increase in cloud top height, large changes in LWP

Closed cells: no change in cloud top height, modest decreases in LWP

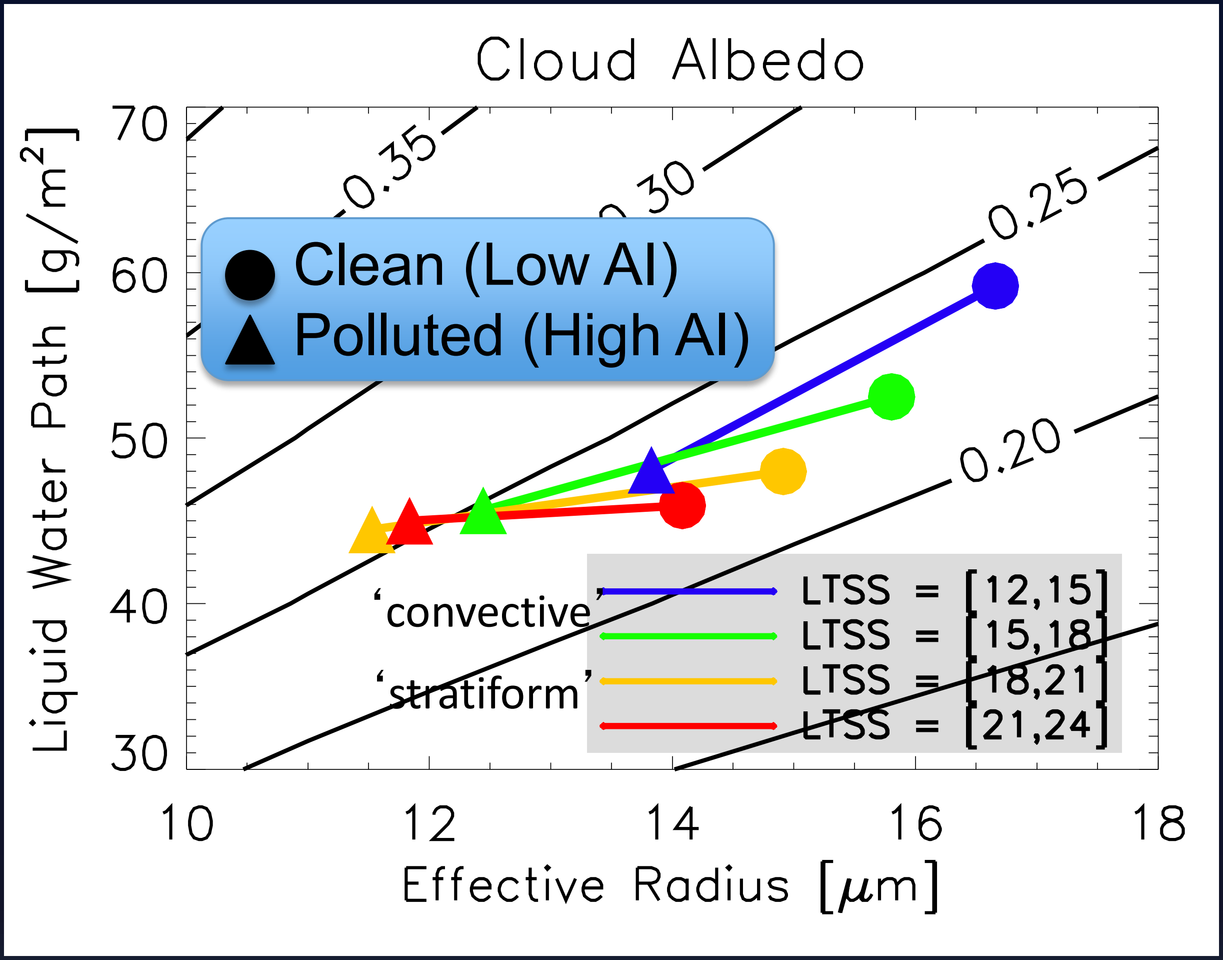
Christensen and Stephens (2011)

The buffering of cloud albedo



Chen, Christensen, Seinfeld & Stephens, 2012

- Differences in liquid water path primarily determine the sign and strength of the cloud albedo response.
- Humidity above cloud tops is responsible for the differences in LWP.
- E-PEACE results are in good agreement with A-train observations.



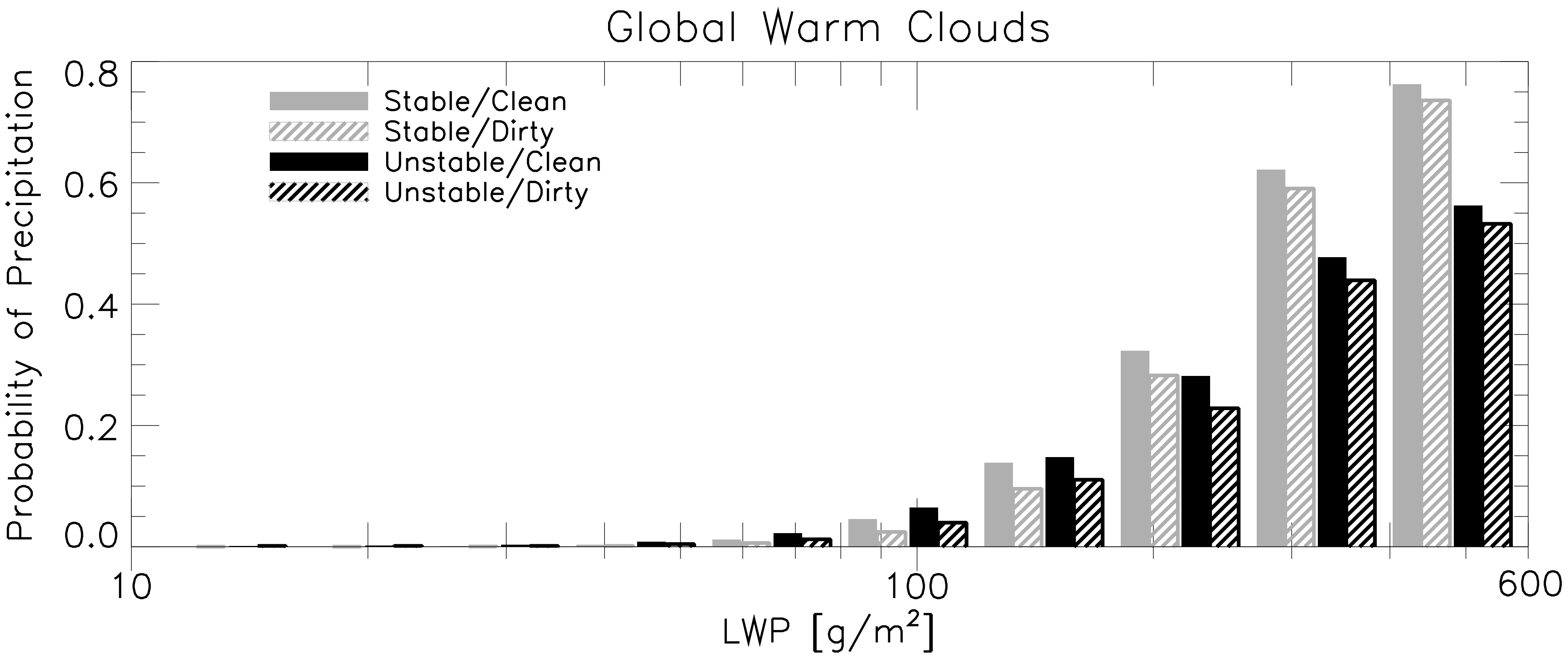
Lebsock et al 2008 find a similar behavior in warm non precipitating clouds globally

Both AMSR-E and MODIS exhibit the same behaviour

The sensitivity of LWP to AI is a function of stability regime

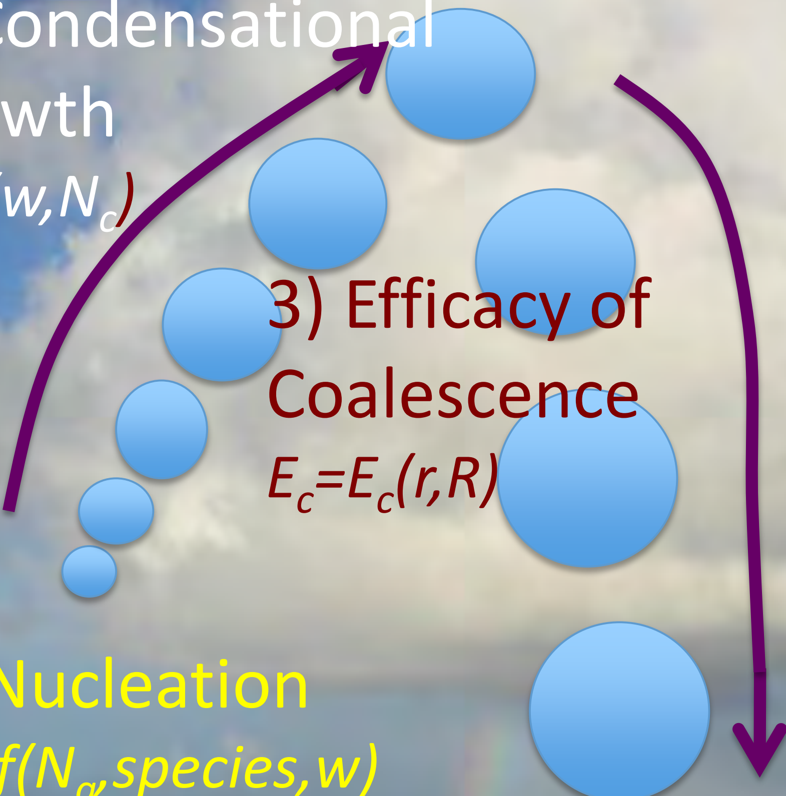
a) Stable regimes -> insensitive (slight decreases in LWP)
b) Unstable regimes -> increasing sensitivity
c) The stability dependent LWP response of clouds should be included in GCM parameterization schemes

Probability of Precipitation and Water Path



1. τ_{cld} and albedo response in precipitating clouds is dominated by the water path effect
2. POP decreased by ~5% in dirty air regardless of LWP

A further look at warm rain



2) Condensational Growth

$S=g(w,N_c)$

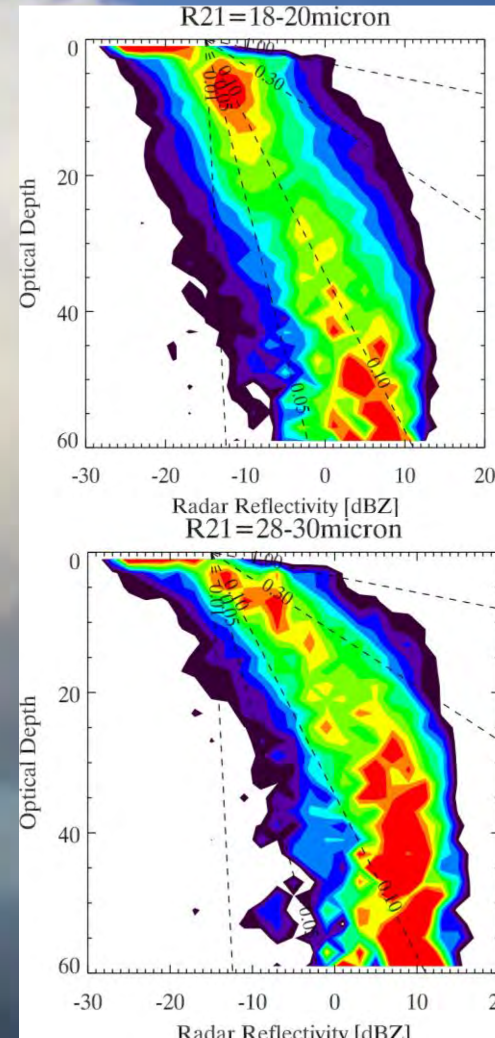
3) Efficacy of Coalescence

$E_c=E_c(r,R)$

1) Nucleation

$N_c=f(N_a,\text{species},w)$

$$\frac{d\ln Z_e}{dt} \approx \frac{\lambda}{6} E_c$$

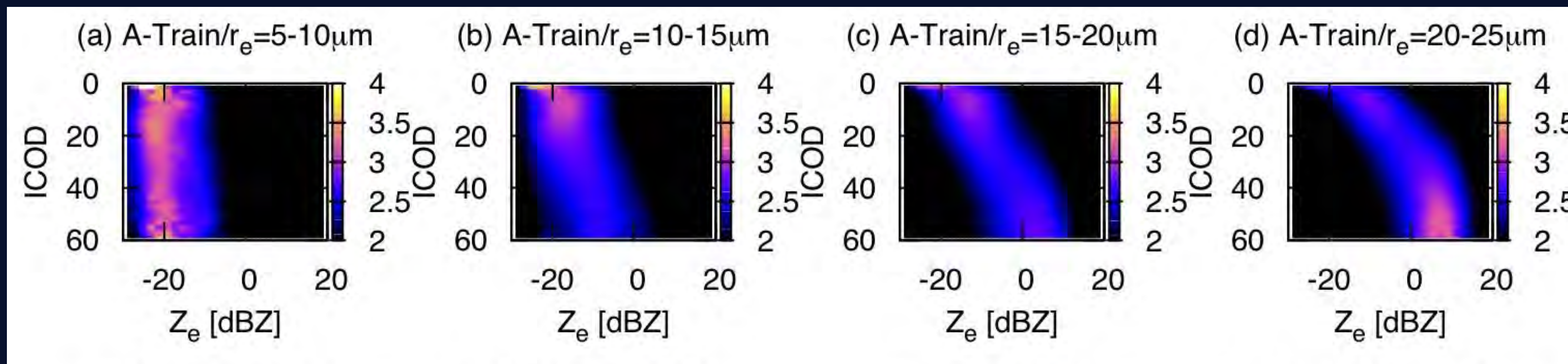


Suzuki *et al.* (JAS 2010)

Photo courtesy Bjorn Stevens

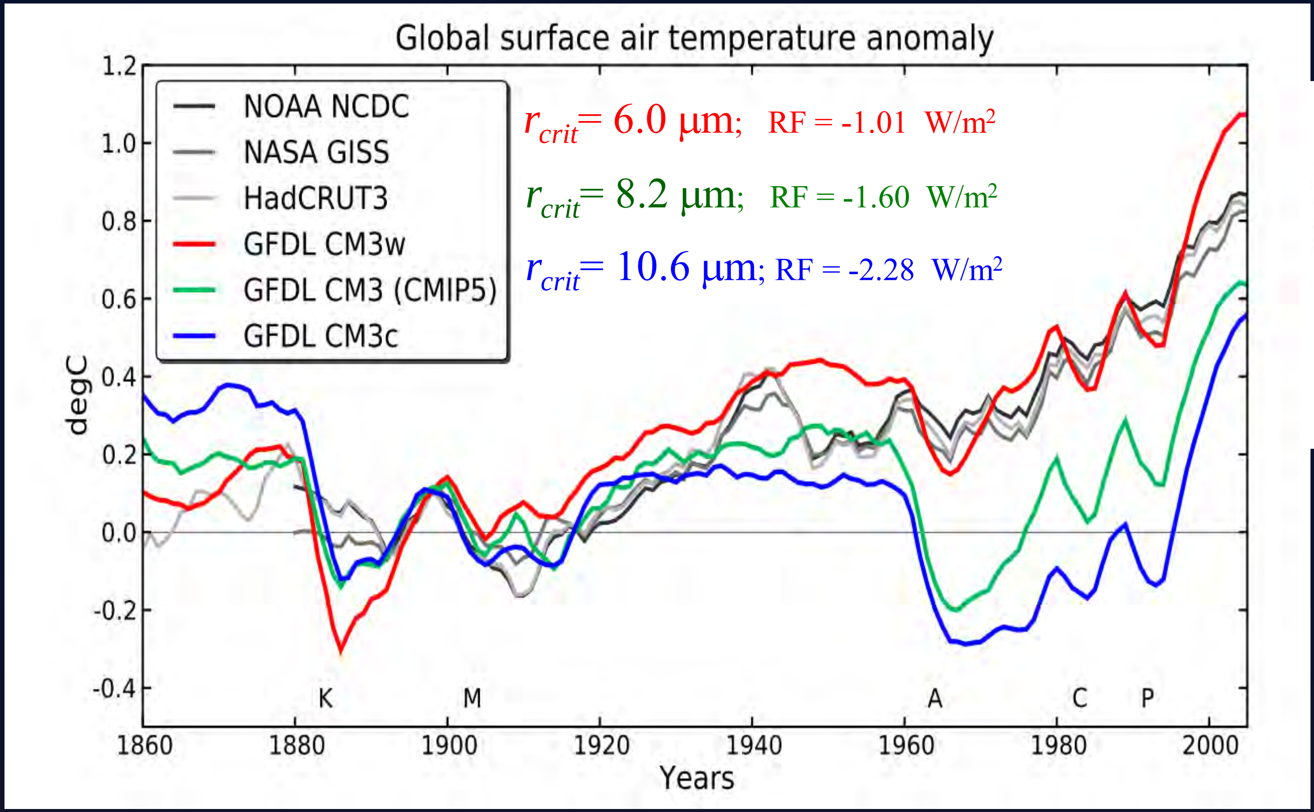
R_e=5-10μm R_e=10-15μm R_e=15-20μm R_e=20-25μm

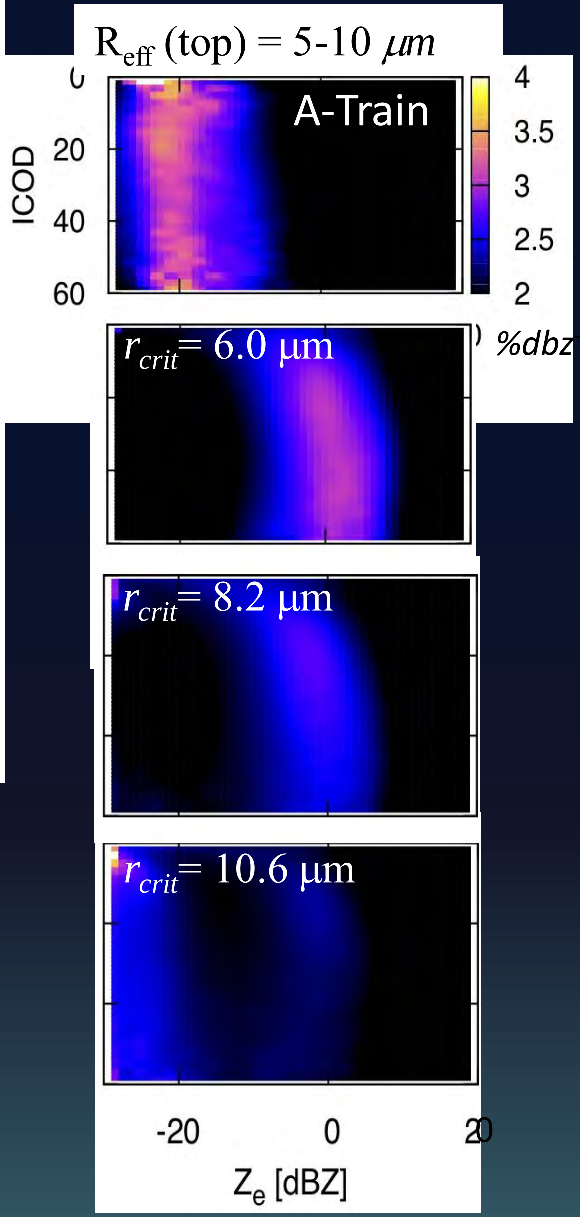
A-Train



Suzuki et al.. 2011

Evaluation of cloud tuning: Implication for climate prediction



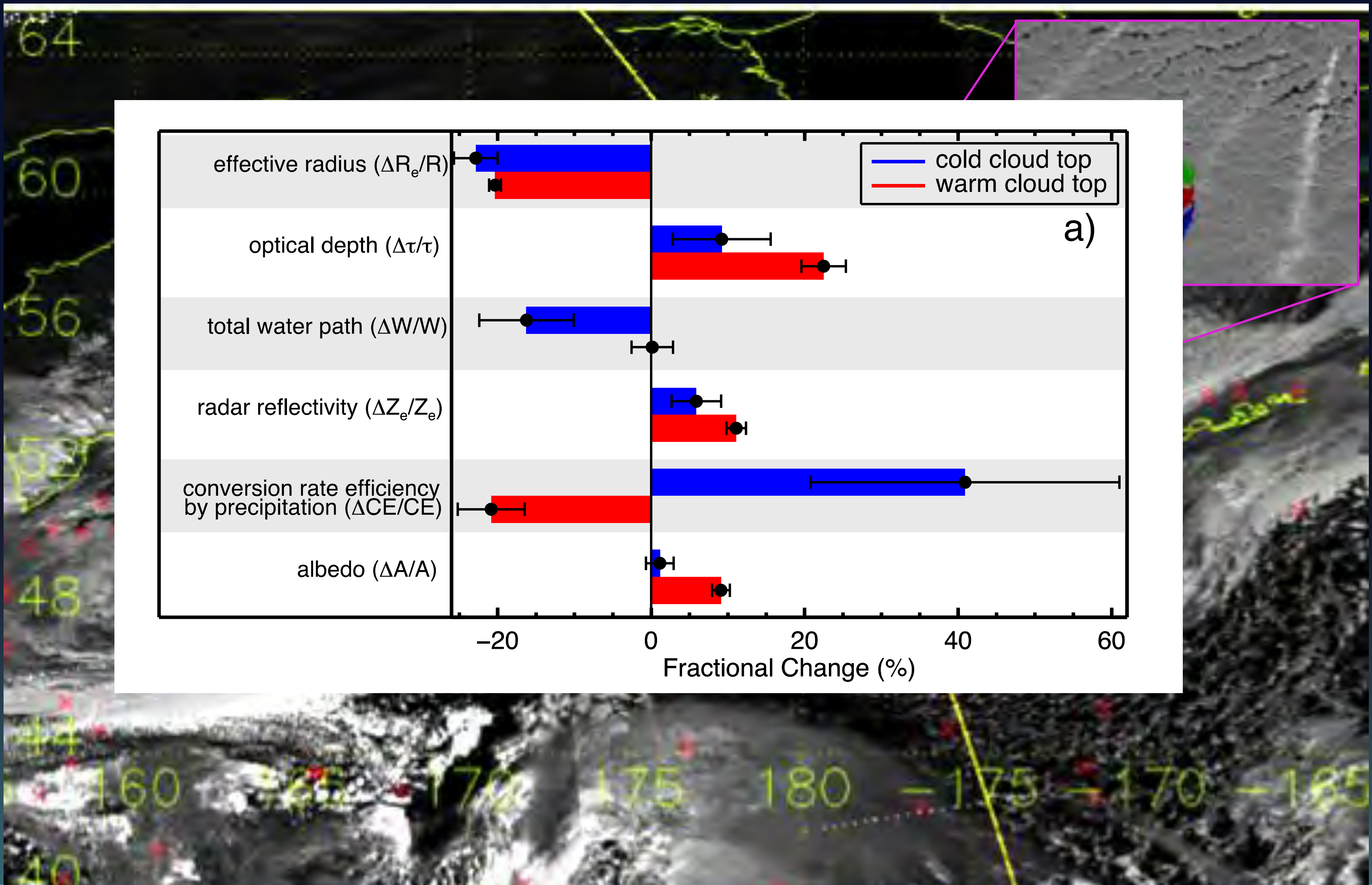


- Autoconversion radius threshold (r_{crit}) strongly modulates the indirect effect.
- Larger r_{crit} produces less drizzle and more cloud water.
- A-Train observations indicate a larger value of r_{crit} than used
  - Causes aerosol indirect effect to be excessively large compared to A-train observations [e.g., Lebsock et al. (2008), Quaas et al. (2008)].

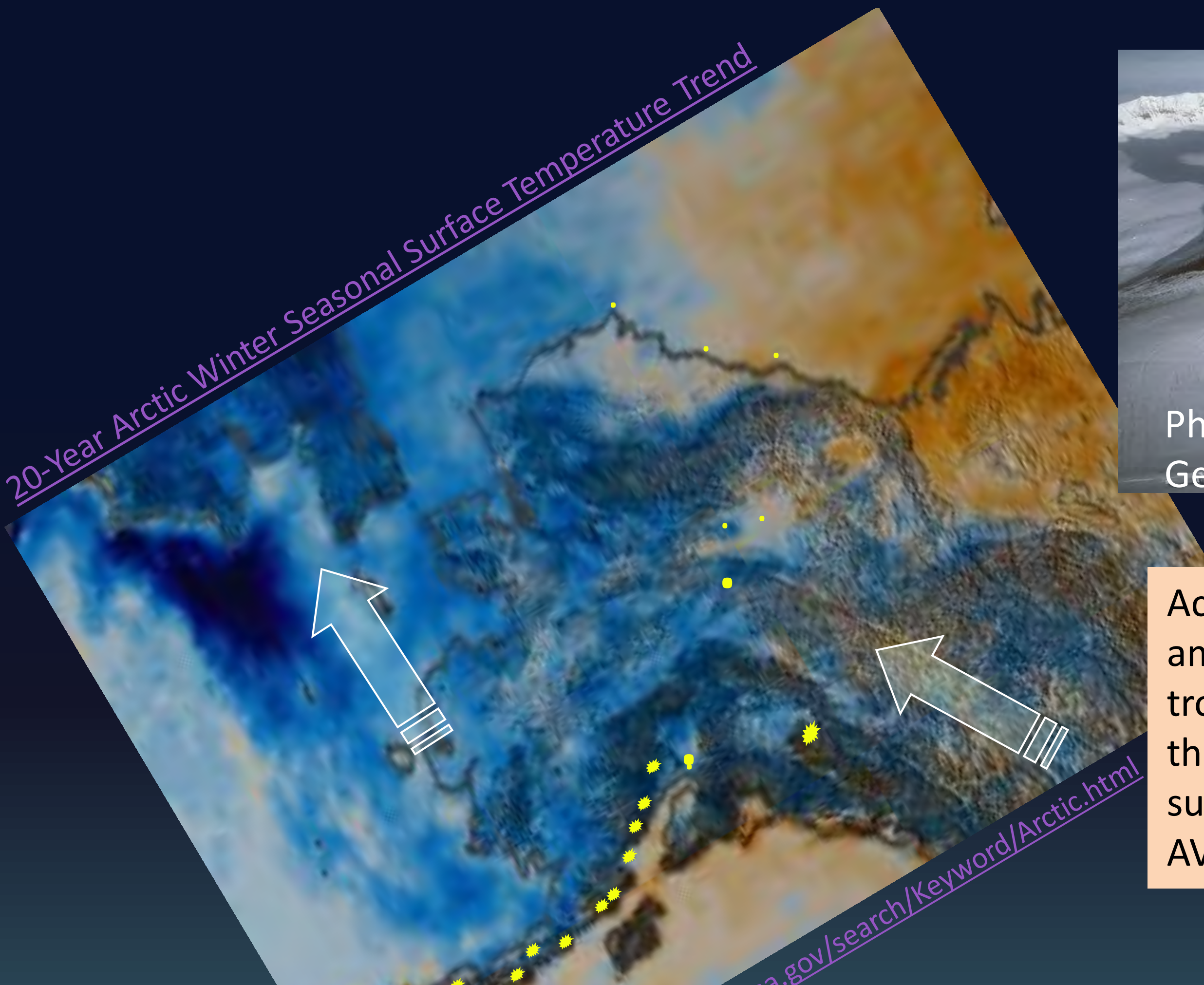
Source: Golaz et al. (2013) & Suzuki et al (2013)

ICOD: in-cloud optical depth

Speculative:1 Mixed phase and Ice clouds



Aerosol-precipitation effects and the wintertime Arctic Temperature
Sulphur Sources and AVHRR Arctic (Wintertime)




Photograph by M.E. Yount, U.S. Geological Survey, January 23, 1984.

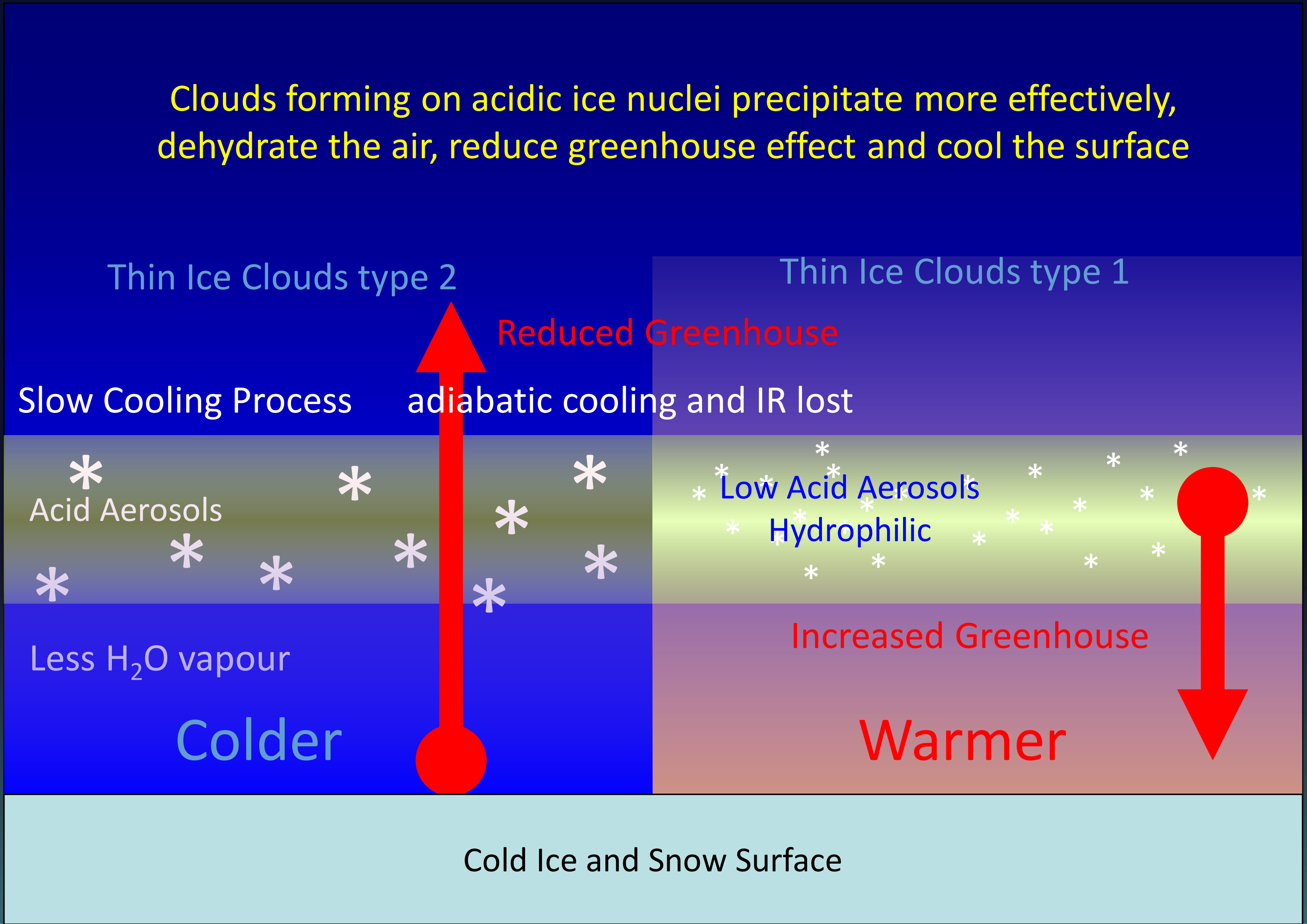
Active Aleutian volcanoes emit large amount of sulphur in the lower troposphere. This is a strong indication that $SO_2 - SO_4$ sources are affecting surface temperatures trends shown in AVHRR.

Blanchet et al., 2010

Mean Annual Trend °C / yr

http://nationalatlas.gov/dynamic/dyn_vol-ak.html

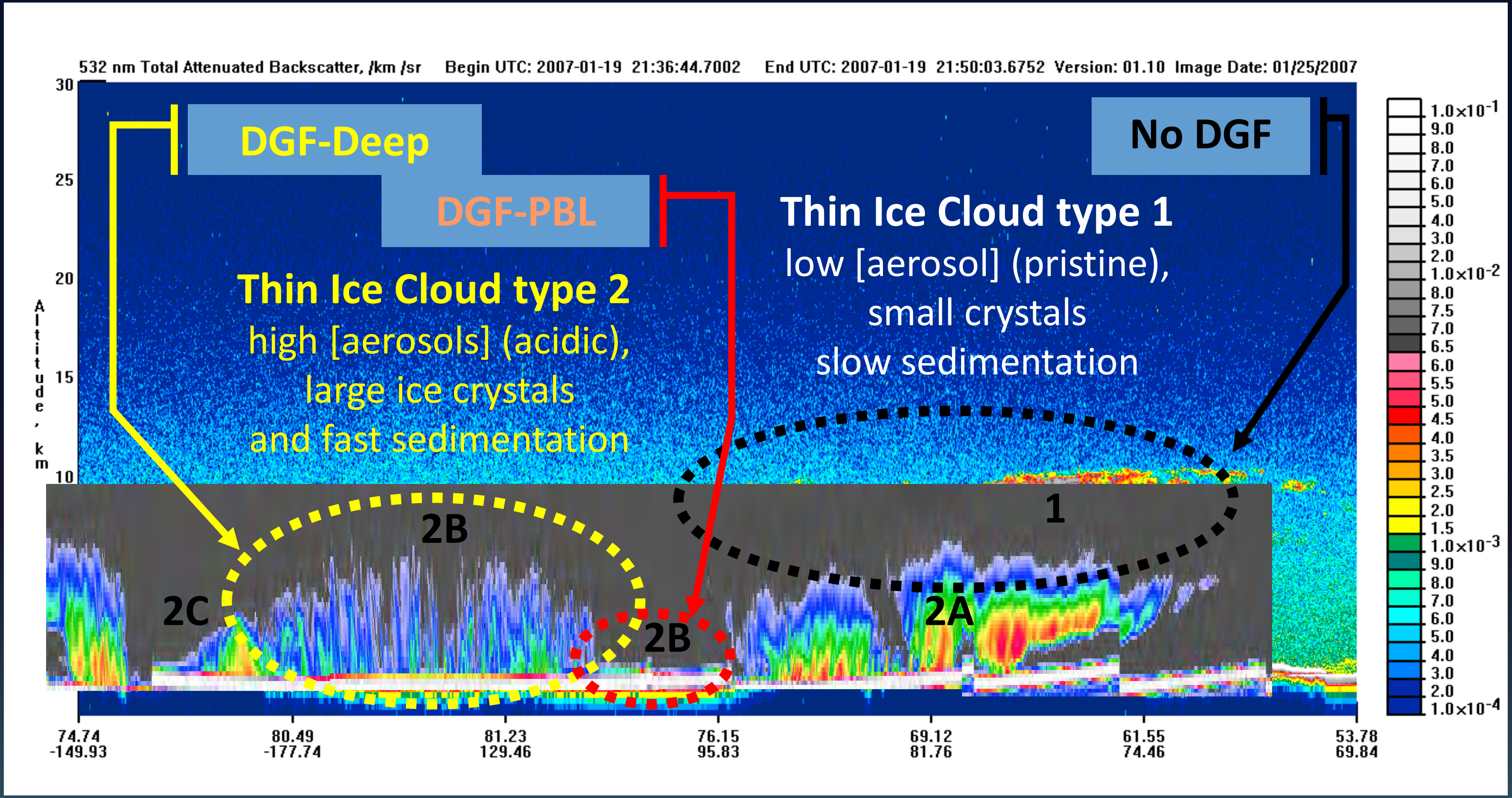
Dehydration-(reverse)Greenhouse Feedback (DGF)



In this environment clouds look different

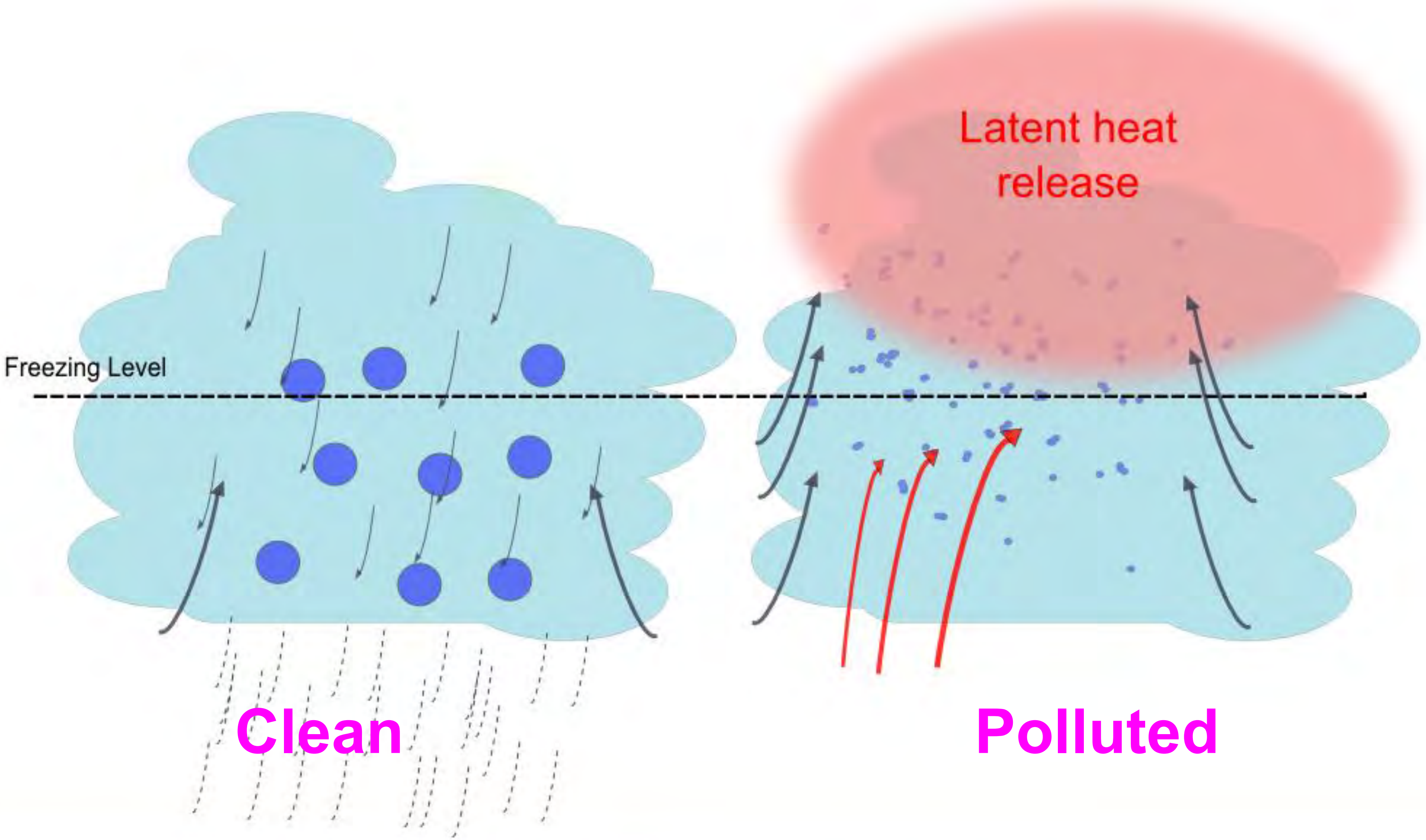
January 19, 2007

Radar – Lidar DGF Signature

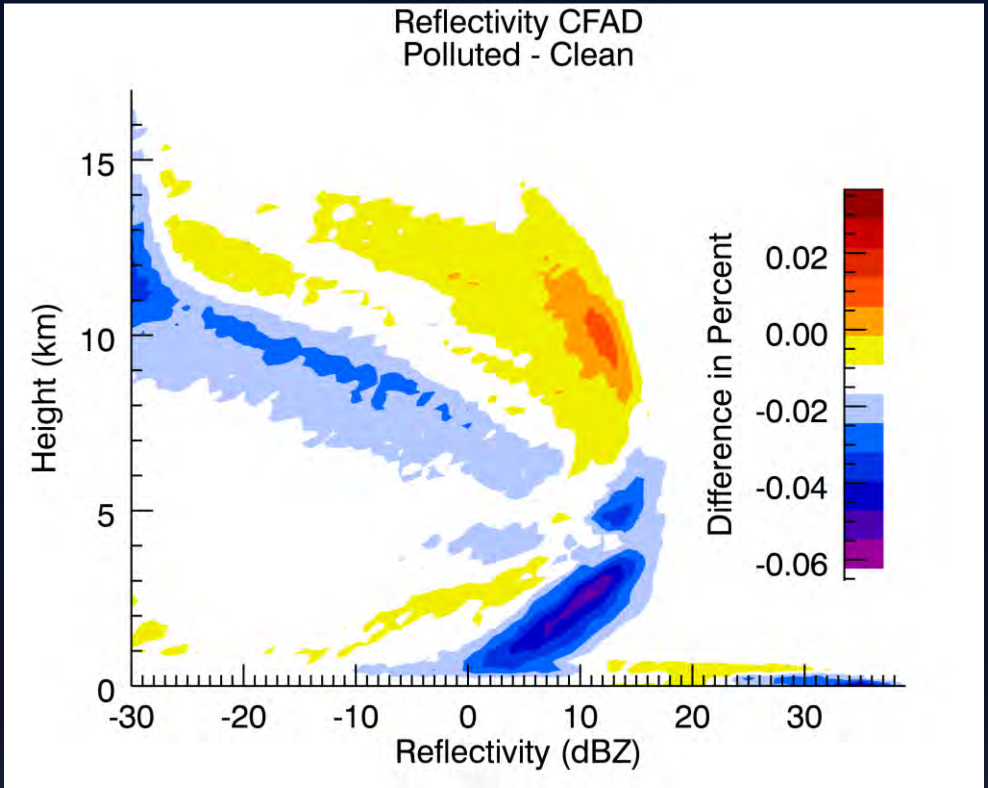


Blanchet, 2010

Speculative 3) Convective storm invigoration by aerosol



More aerosol =>Suppressed drop collection =>more cloud water lofted => more freezing and release of latent heat and eventually more preciptation



Multi-year analysis of Convection over tropical Atlantic , Storer et a., 2013

CloudSat married with assimilated aerosol data from GEMS shows evidence for convective invigoration. The Polluted – clean reflectivity differences indicate storms reach higher, and possess more ice mass (higher reflectivity values) and produce heavier precipitation.

Summary

- Unprecedented satellite capabilities offer glimpses of the complex buffering processes inherent in the aerosol-cloud system.

- Observed indirect radiative effects are typically weaker than modeled effects due to buffering by precipitation and the environment. These effects in the net are determined by net changes to water budgets of clouds systems

- GCM aerosol indirect effects in warm clouds appear to be too sensitive to autoconversion schemes used (at least in one model).

- Higher model resolution will not guarantee improved representation of aerosol effects .

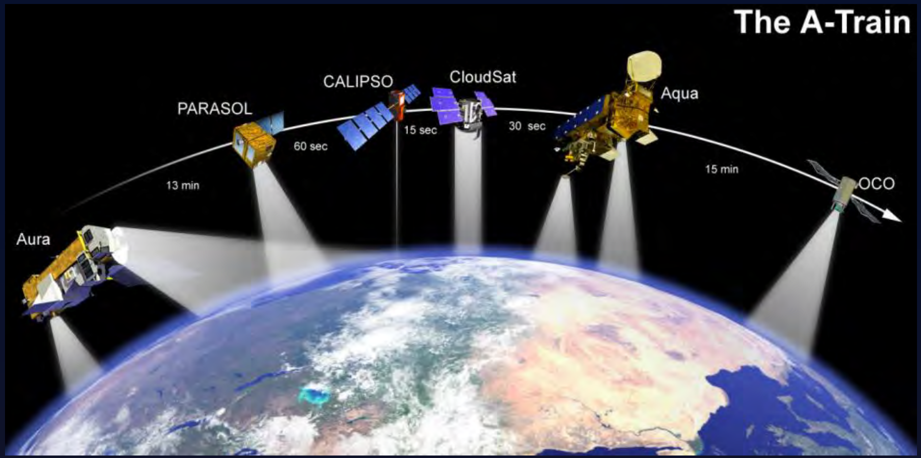
- Aerosol effects in cold clouds is not understood & satellite observations are scant. Aerosol influences on wintertime polar clouds may significantly influence the water budget of the Arctic atmosphere

- Aerosol effects on convection remain speculative.

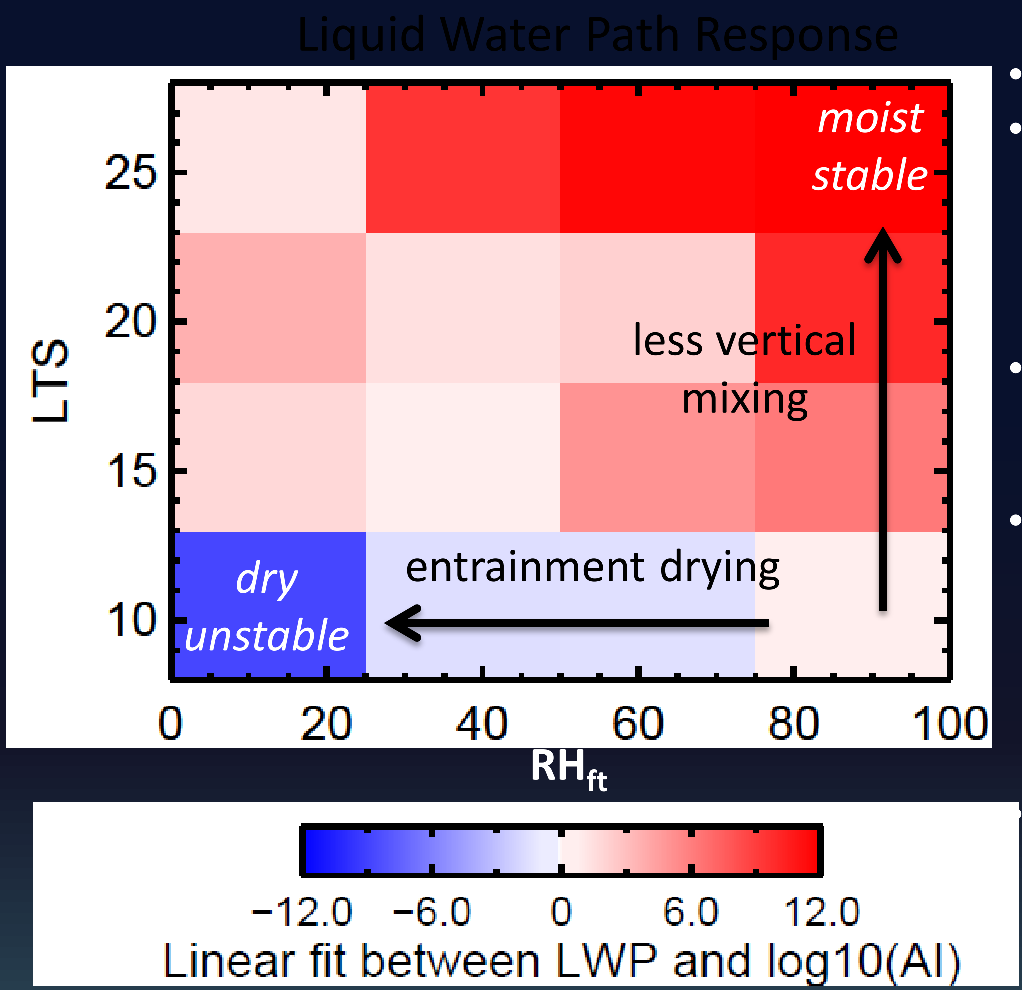
- Perhaps the more important influence of aerosol on clouds is on precipitation rather than cloud albedo

A-Train results

1. CloudSat
   - Precipitation Flag
   - Cloud reflectivity
2. MODIS
   - Cloud effective radius
   - Cloud LWP
   - Aerosol Index
   - Cloud Fraction
3. AMSR-E
   - Cloud LWP
   - Water Vapor
4. CERES
   - Cloud Albedo
5. CALIPSO
   - Cloud top height, CALIOP



Buffering by the Environment

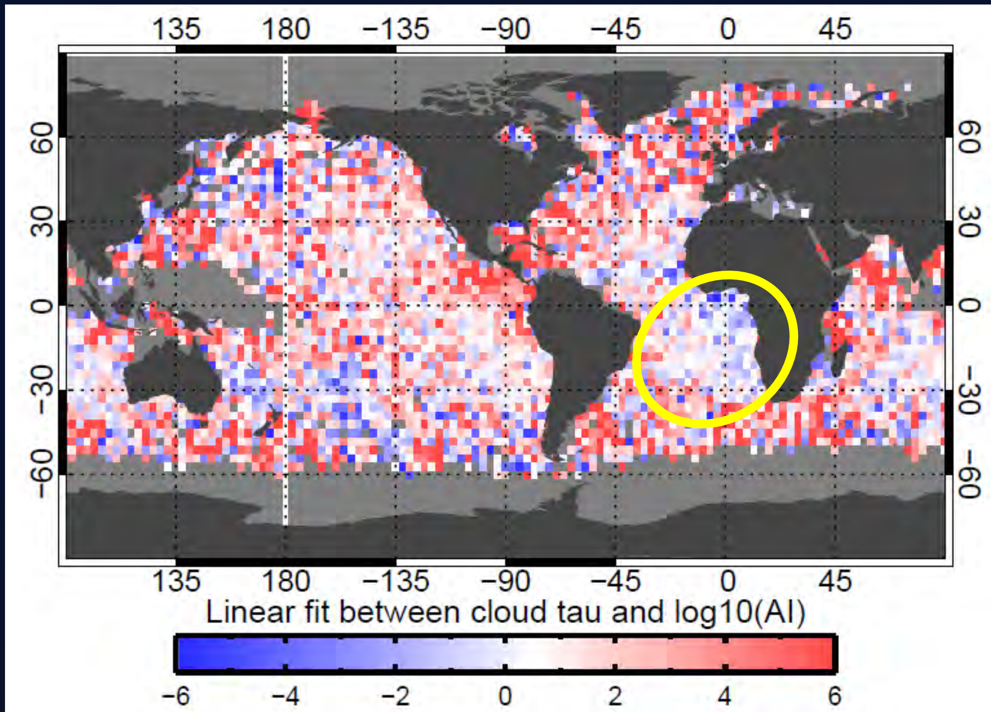


- 4 years of data
- Over 5 million carefully screened retrievals (single layer low-level warm phase cloud detected by CALIPSO, CloudSat, and MODIS).
- Aerosol properties are averaged over 1° regions.
- Entrainment/drying effect is largest in dry and unstable conditions.
  - Consistent with ship track assessment and the LES simulations performed by Ackerman et al. (2004) & Chen et al. (2011).
- Co-variability of LTS and RH_ft *buffer* the liquid water path response to increasing aerosol concentration.

LTS: Lower Troposphere Stability ($LTS = \Theta_{700mb} - \Theta_{surface}$)
RH_{ft}: Free-troposphere Humidity (relative humidity above cloud top)
LWP: Liquid Water Path (MODIS)
AI: Aerosol Index (MODIS)

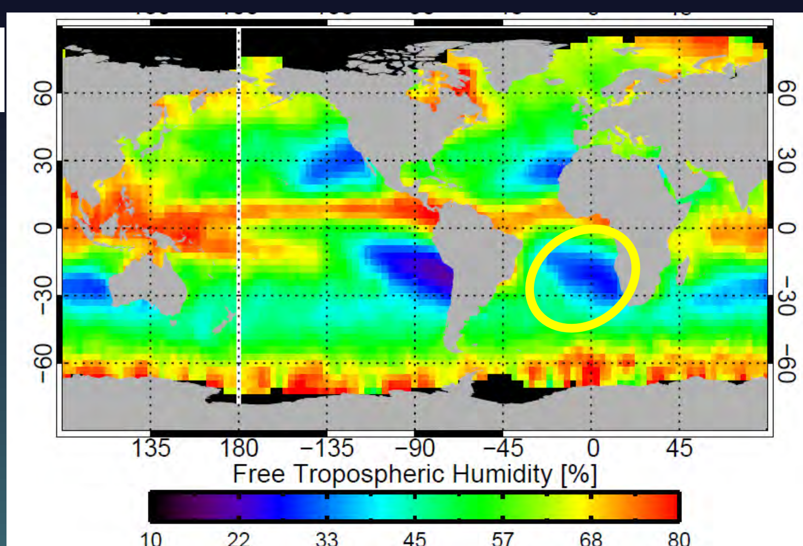
Where on Earth do we see this effect?

Cloud Optical Depth Response

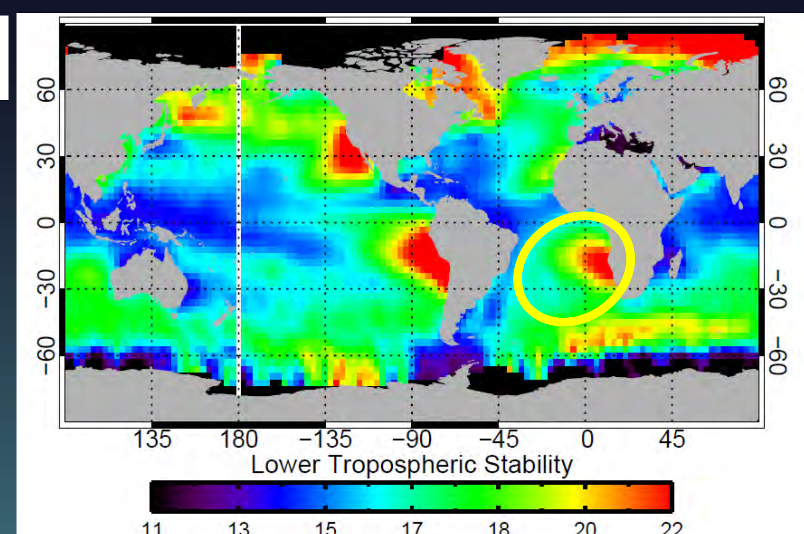


- Predominant regions of Sc exist in dry and stable airmasses.
- Optical depth response in these regions is weakly negative
- Effect of buffering precludes strong indirect effects in these regions.
- Implications for geoengineering
- Chen et al., 2013.

RH_{ft}



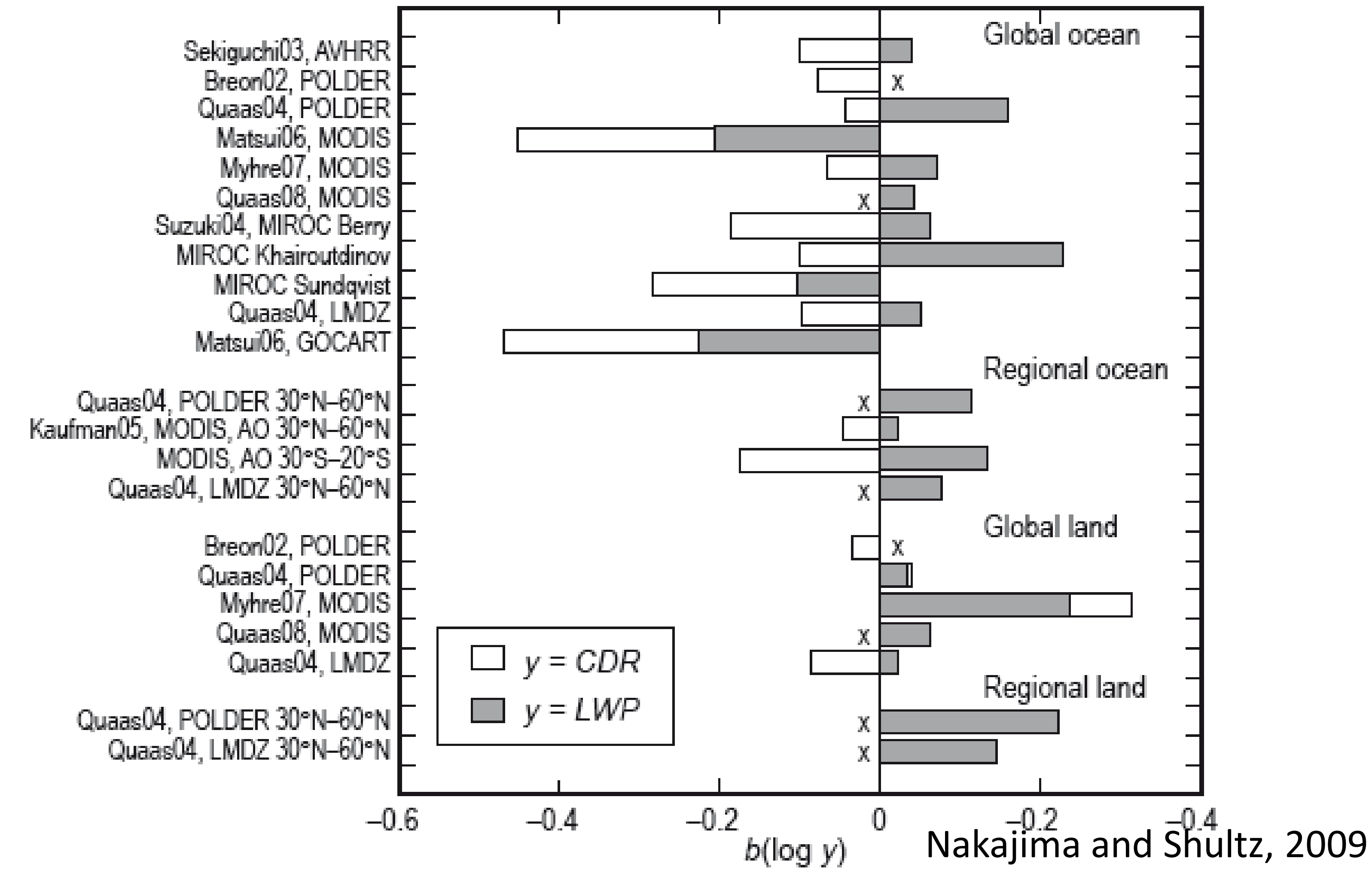
LTS



$$\frac{Dt}{t} = \frac{DLWP}{LWP} - \frac{Dr_e}{r_e} \mu \frac{Da}{a}$$

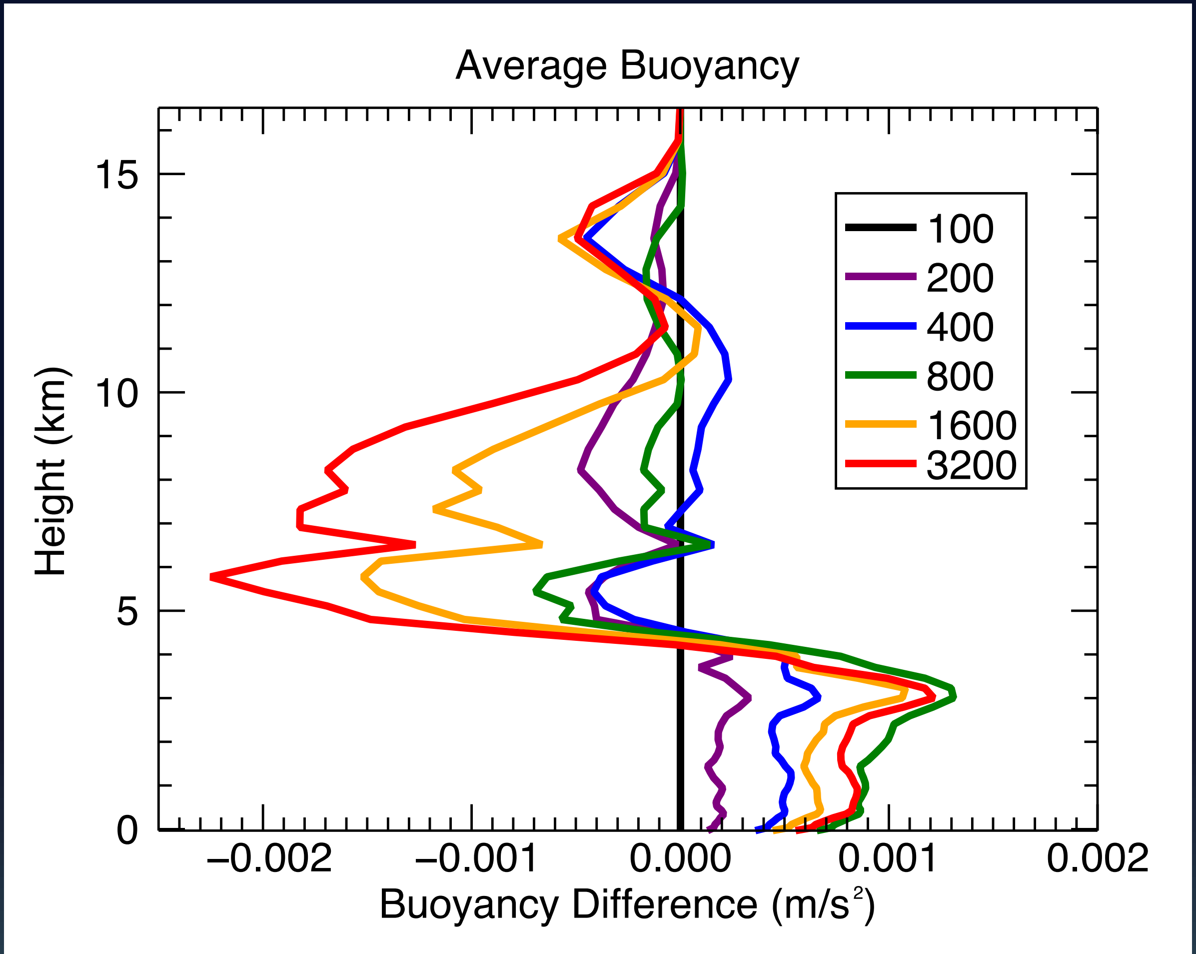
$$CDR = r_e$$

$$b = d\ log\ (y) / \ d\ log(Na)$$



Nakajima and Shultz, 2009

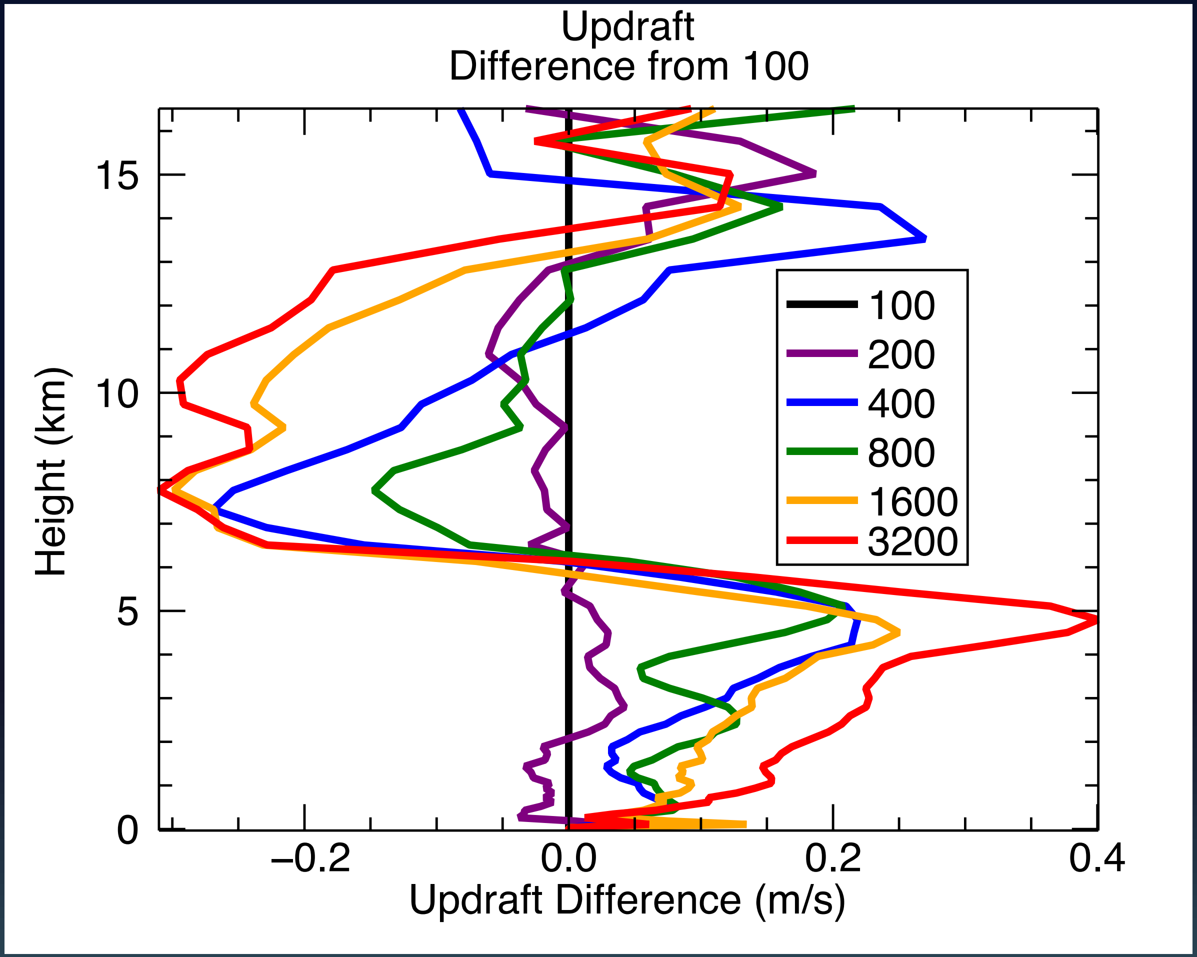
Convective invigoration



$$B = g\left(\frac{\theta'}{\theta_0}\right) - gq_c$$

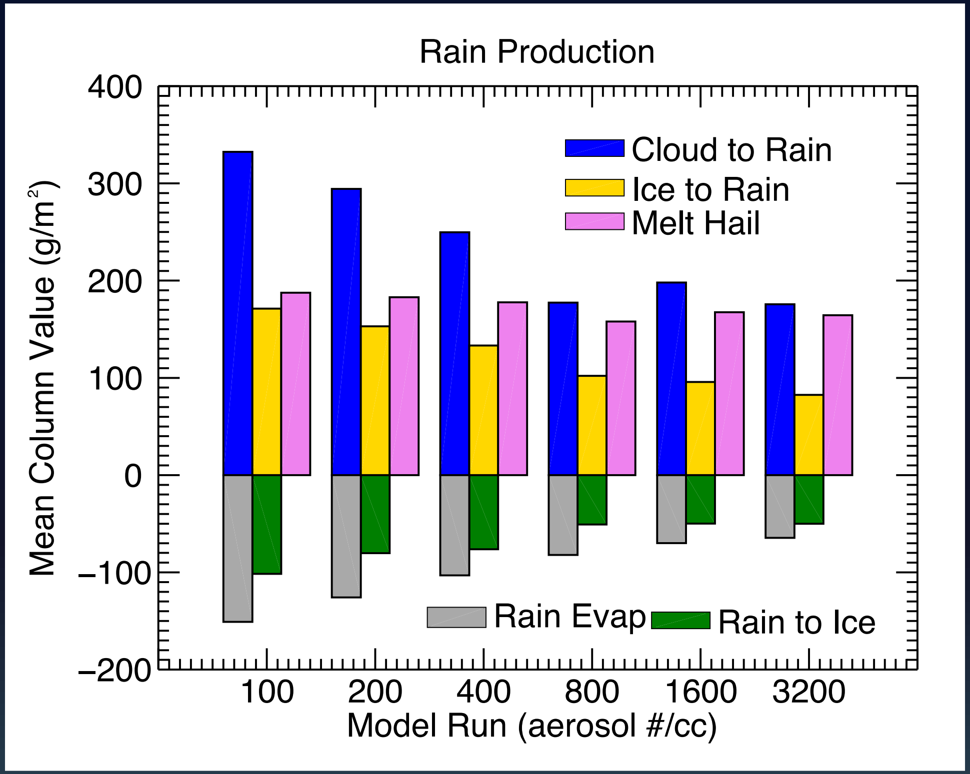
Total buoyancy term, plotted as a difference from the clean run, follows a similar trend as the mean updraft

Convective invigoration



- Average updraft decreases through a large portion of the cloud depth
- Average updraft is determined by a balance between latent heating and condensate loading – both are affected by increased aerosol concentrations
- Average updraft increases in the lower levels due to both decreases in drag from condensate loading and increases in latent heat from changes in condensation and rain evaporation

Production of rain

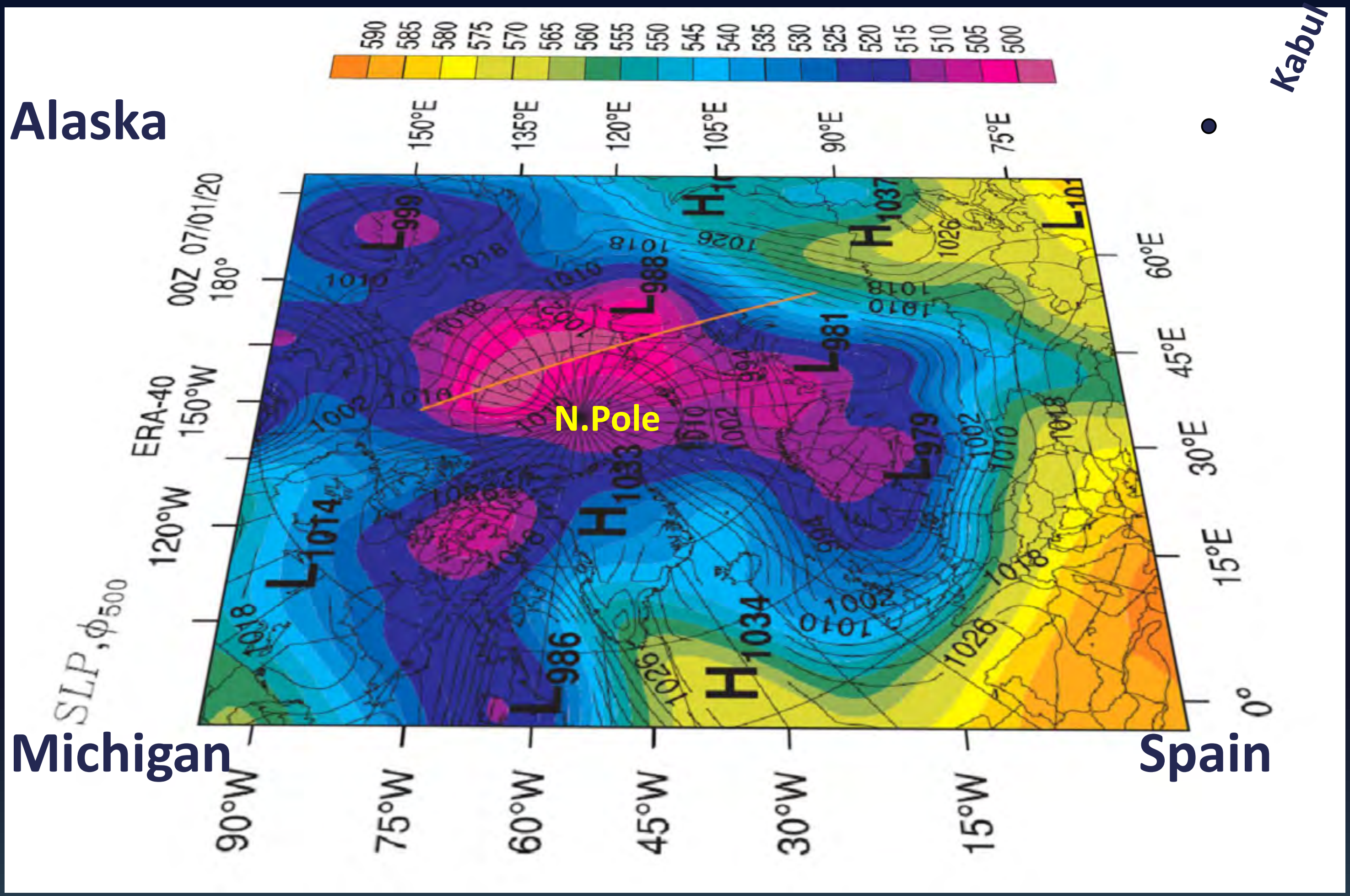


In polluted DCCs:

- Warm rain production decreases dramatically
- Melting of hail doesn't change significantly
- Ice collection by rain decreases
- Total rain production decreases
- Decrease is dominated by change in warm rain production
- Ice phase production of rain becomes more important
- Sinks of rain also decrease because there are fewer and larger rain drops

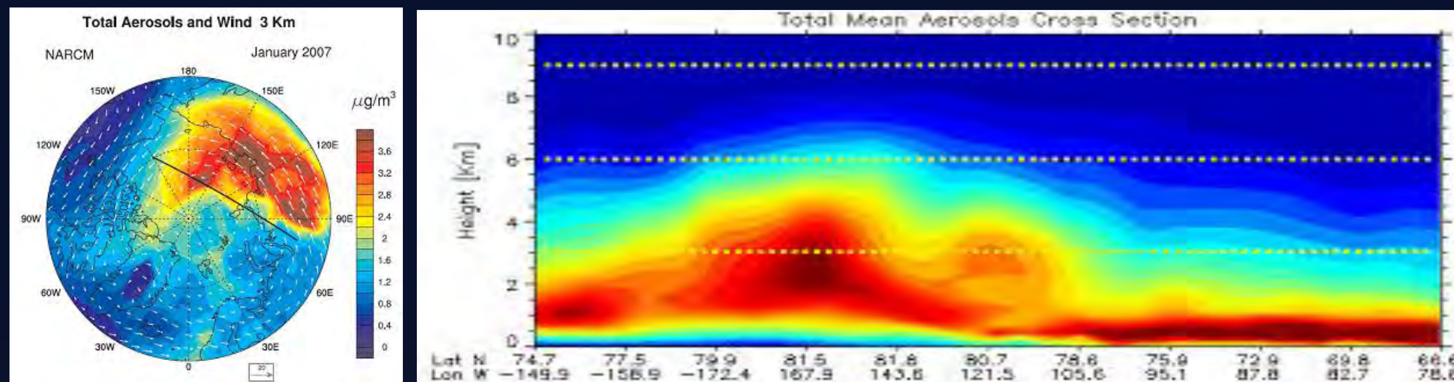
Backup

i) Wintertime storms

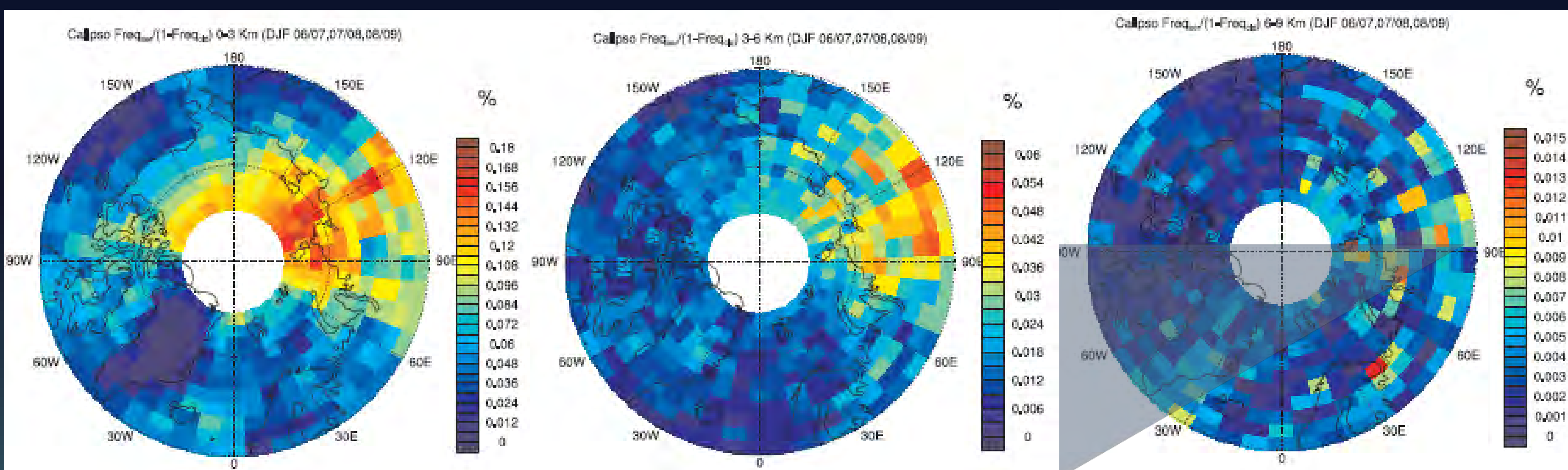


iii) Pollutants Lifted in Cold Regions

Simulated NARCM



Observed CALIPSO

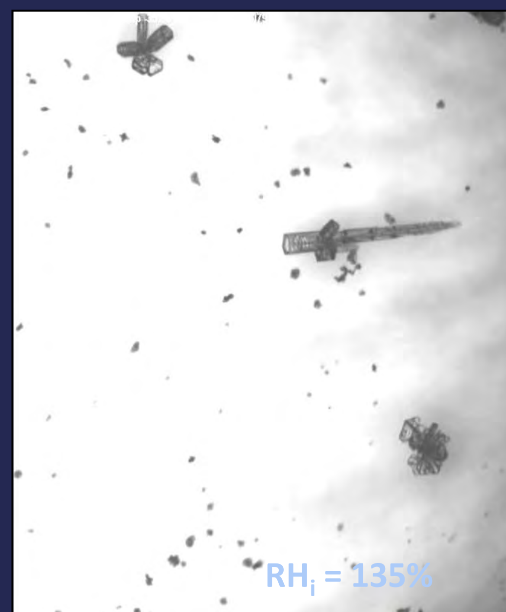


iv) Pollution inhibits nucleation

Manmade acid coating of natural dust

Ref.: Bigg, 1980

Ice crystal nucleation on acid coated aerosols



Ref.: Bertram, 2008

In Laboratory
Allan Bertram at UBC

Flow cell coupled to microscope

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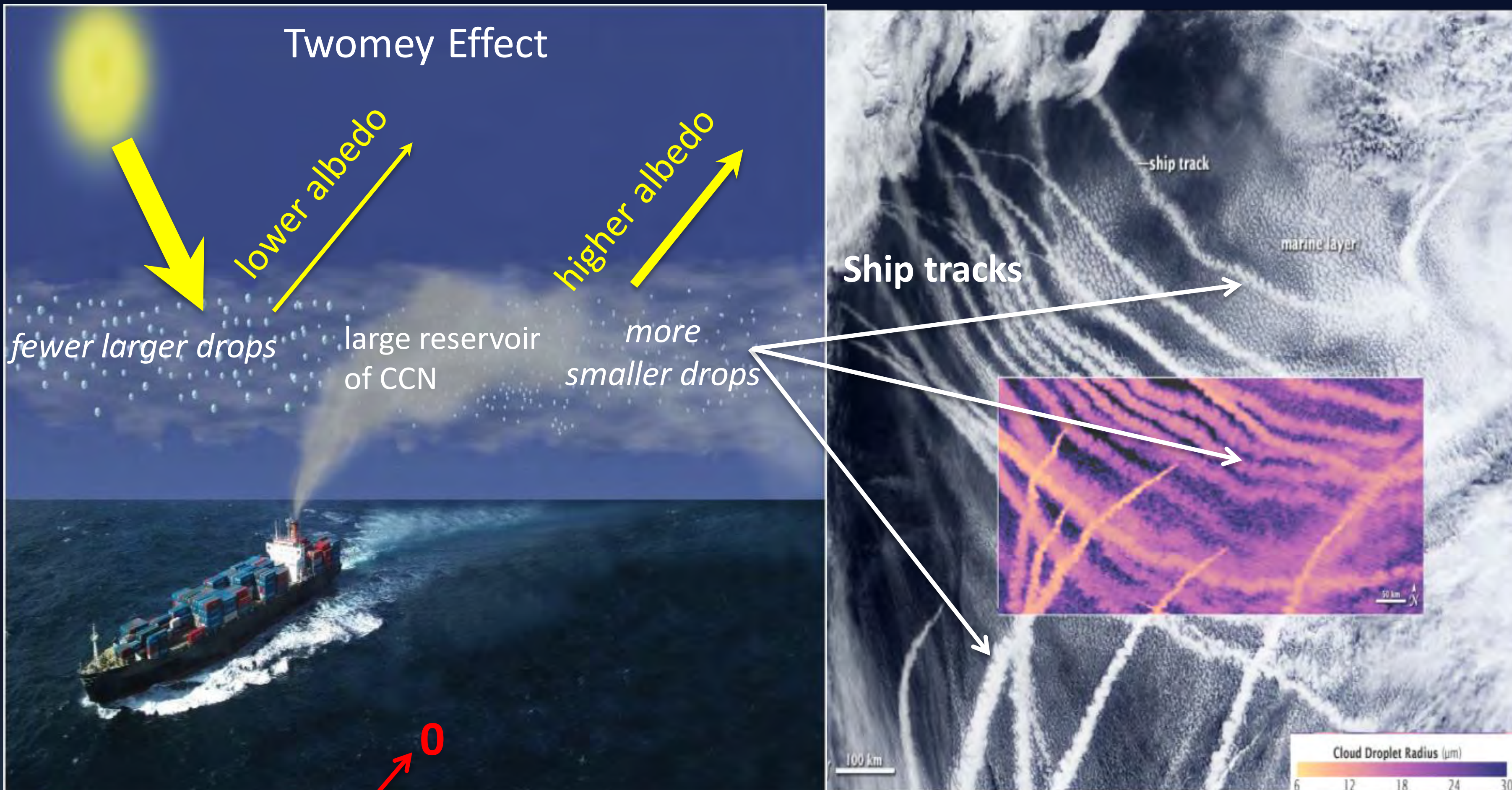
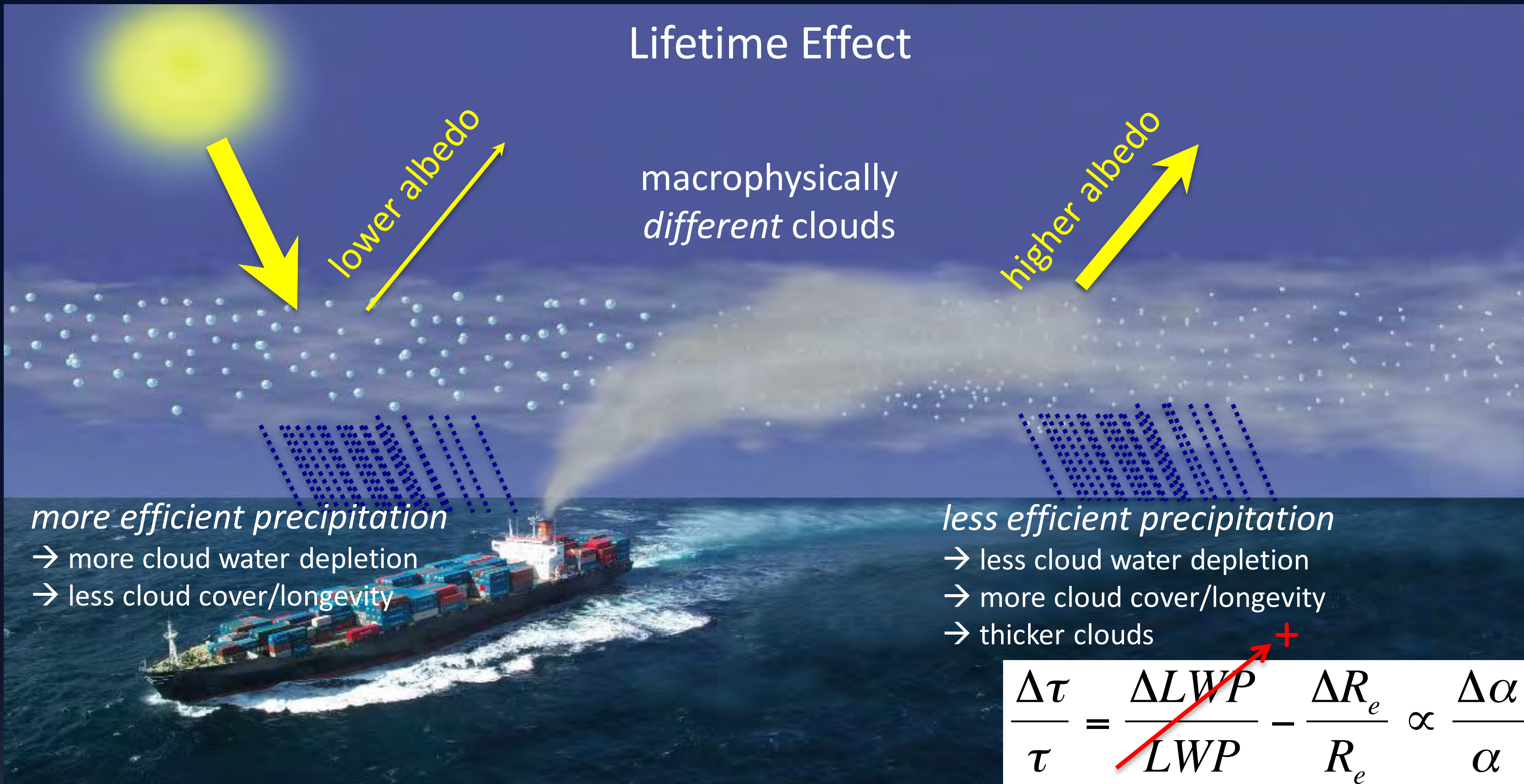
Ship Tracks: a prominent manifestation of the aerosol indirect effect



$$\frac{\Delta\tau}{\tau} = \frac{\Delta LWP}{LWP} - \frac{\Delta R_e}{R_e} \propto \frac{\Delta\alpha}{\alpha}$$

τ: cloud optical thickness
LWP: liquid water path
R_e: effective radius
A: cloud albedo

Buffering Processes



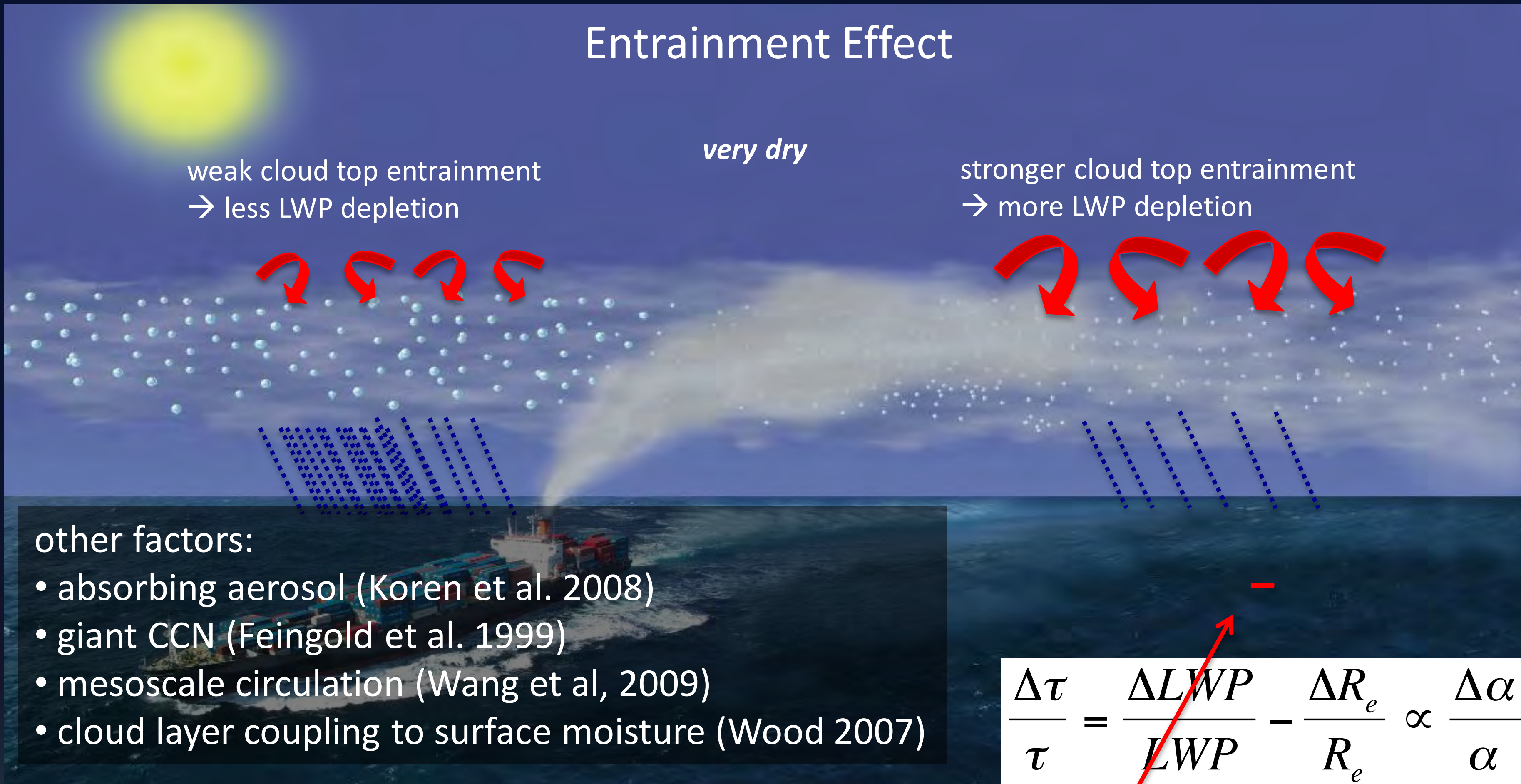
Cloud water path response

ΔLWP = 0 ***Twomey effect:*** **(Twomey, 1974)**

ΔLWP > 0 ***Lifetime effect:*** **(Albrecht, 1989)**

τ: cloud optical thickness
LWP: liquid water path
R_e: effective radius
A: cloud albedo

Buffering Processes



other factors:

- absorbing aerosol (Koren et al. 2008)
- giant CCN (Feingold et al. 1999)
- mesoscale circulation (Wang et al, 2009)
- cloud layer coupling to surface moisture (Wood 2007)

$$\frac{\Delta\tau}{\tau} = \frac{\Delta LWP}{LWP} - \frac{\Delta R_e}{R_e} \propto \frac{\Delta\alpha}{\alpha}$$

τ: cloud optical thickness
LWP: liquid water path
R_e: effective radius
A: cloud albedo

<u>**Cloud water path response**</u>

ΔLWP = 0 ***Twomey effect*** **(Twomey, 1974)**

ΔLWP > 0 ***Lifetime effect*** **(Albrecht, 1989)**

ΔLWP < 0 ***Entrainment effect*** **(Ackerman et al, 2004)**

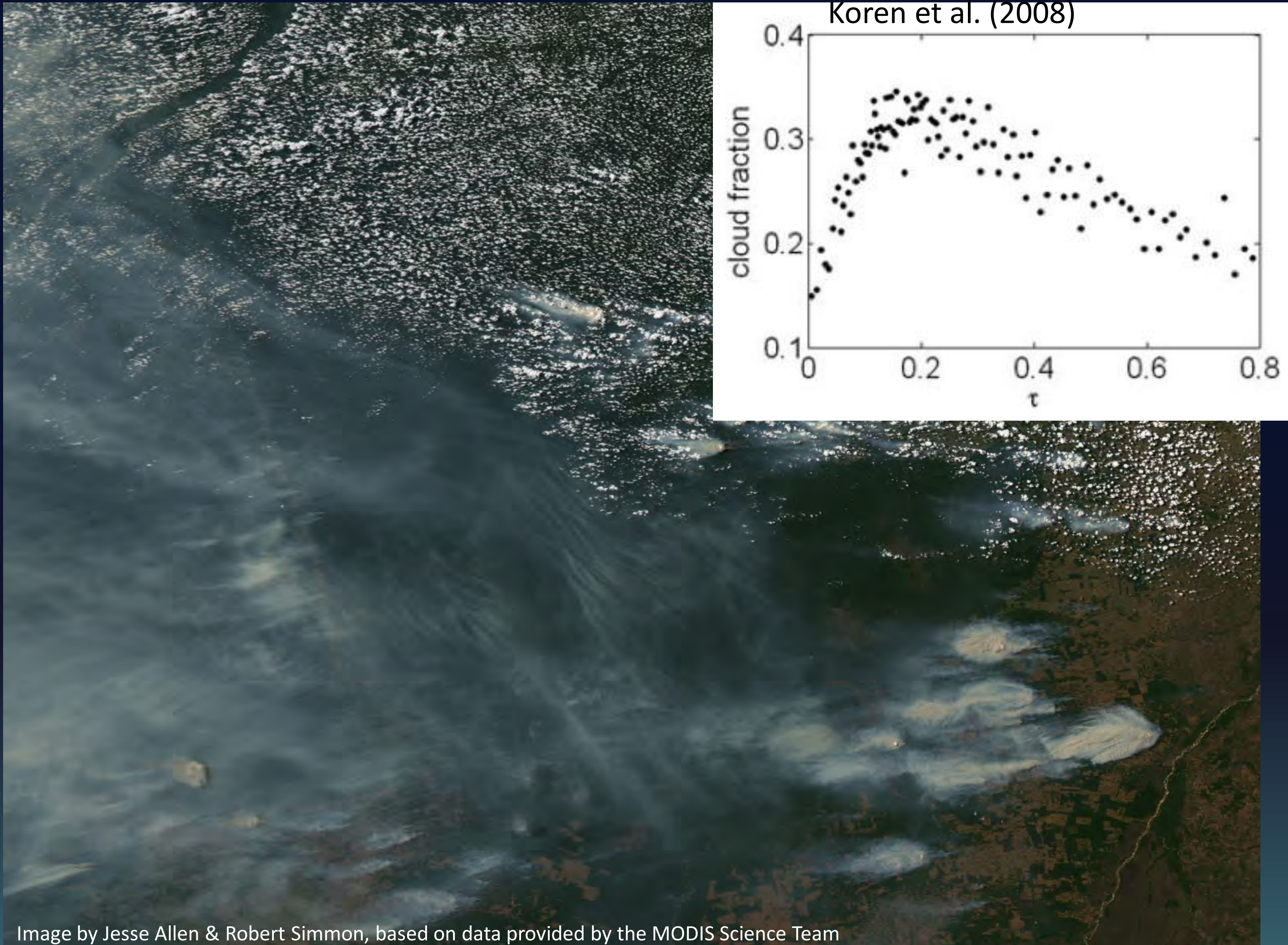
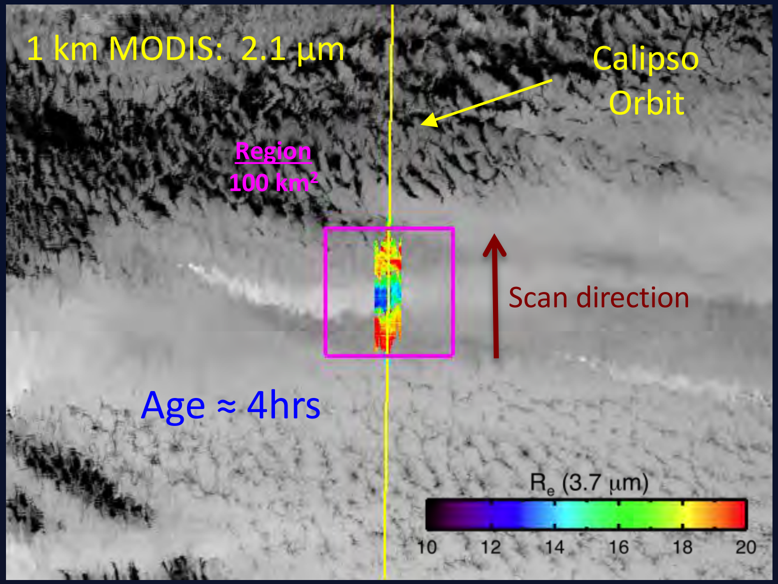
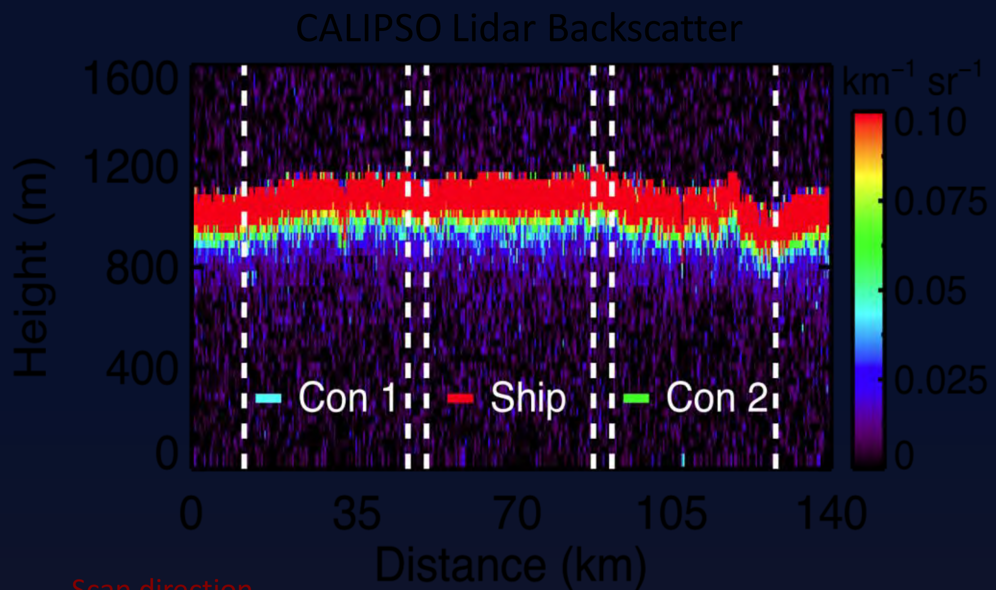


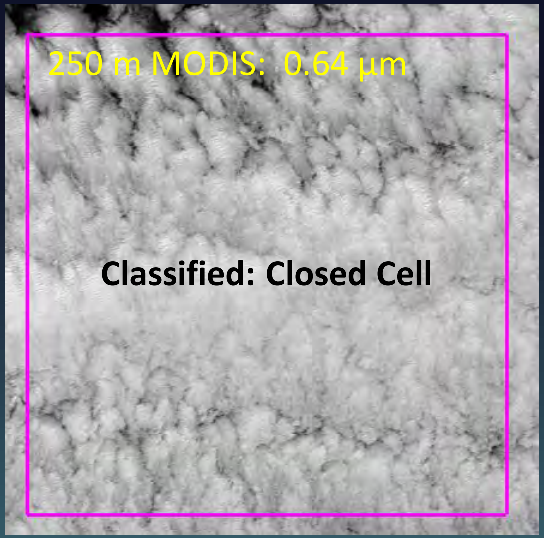
Image by Jesse Allen & Robert Simmon, based on data provided by the MODIS Science Team

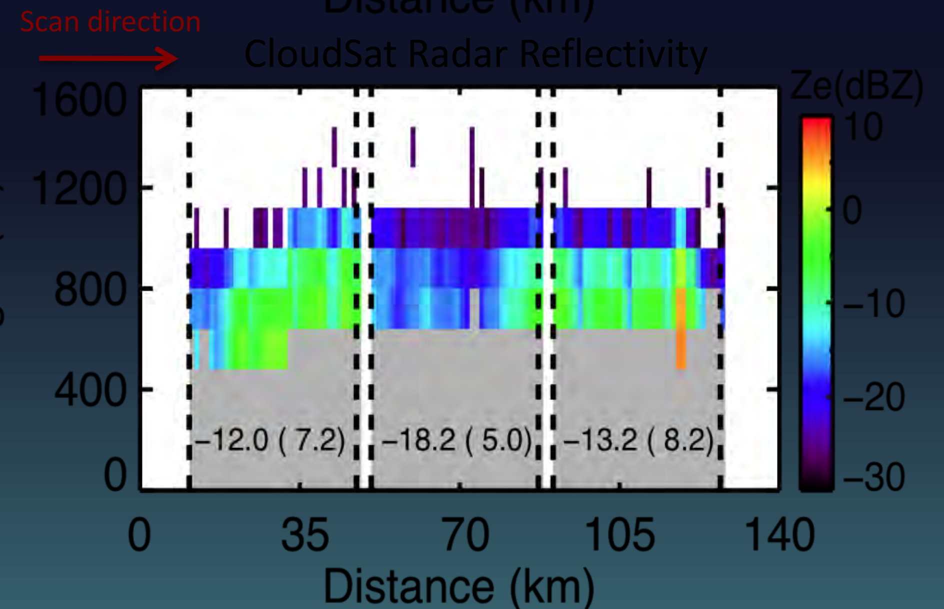
Buffering by Precipitation

aerosol *suppressing* drizzle in ship track





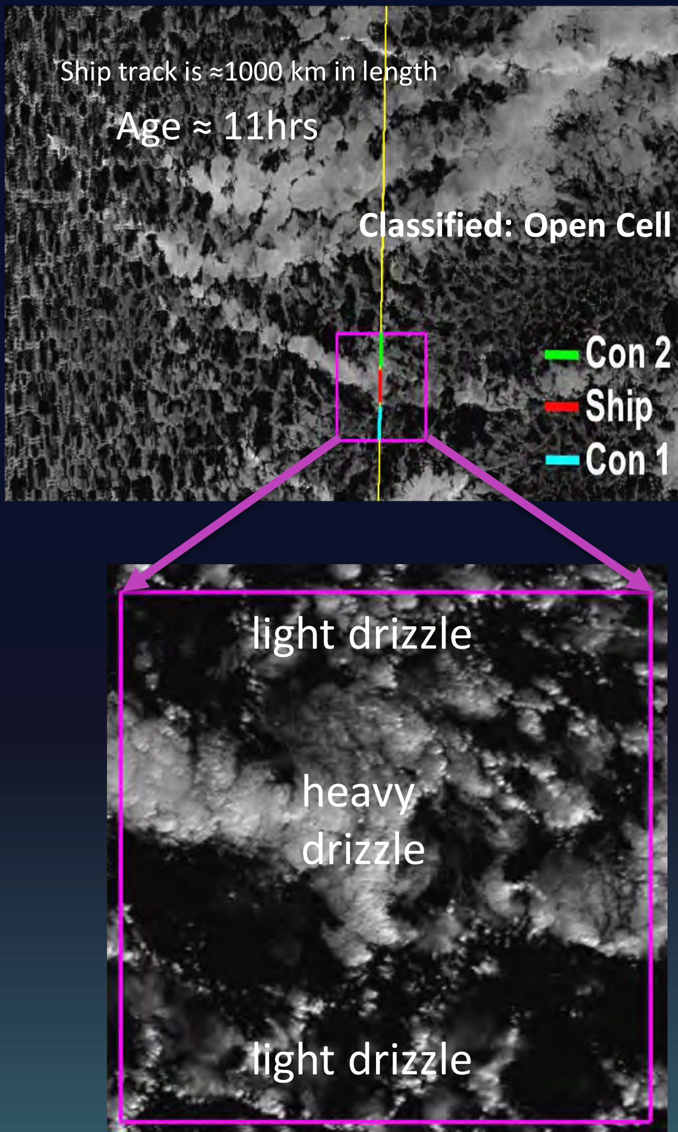




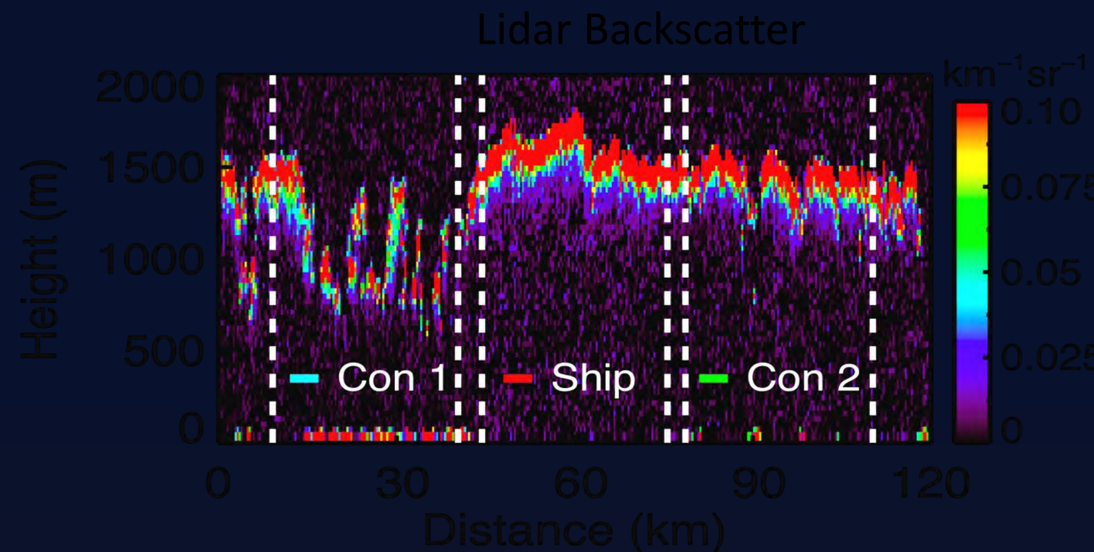
February 3rd, 2008 at 2145 UTC

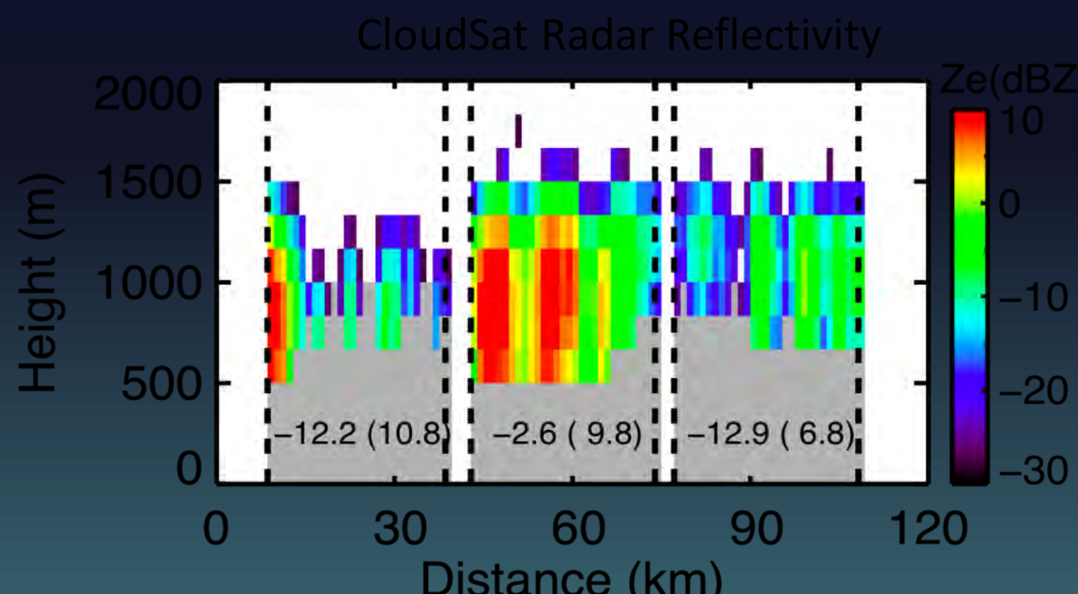
Buffering by Precipitation

aerosol *enhancing* drizzle in ship track



January 11th, 2007 at 2210 UTC





Processes?: Correlation between r_e and τ_c

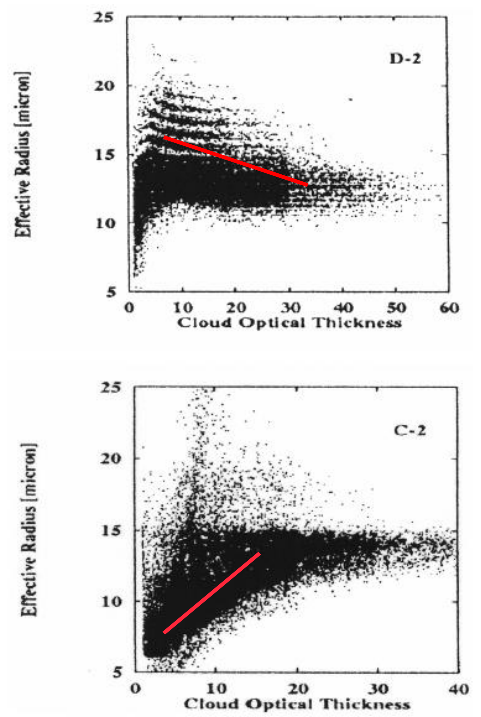
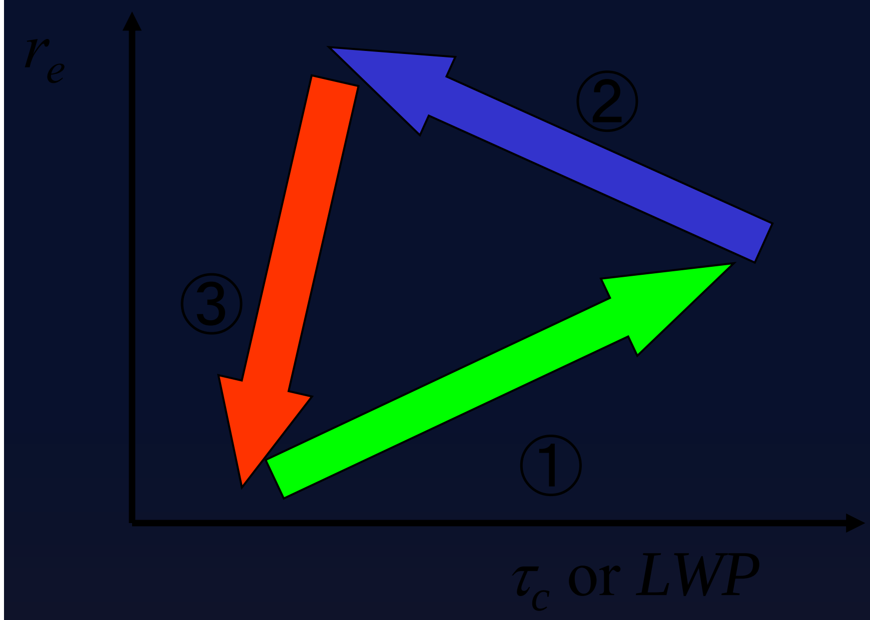


Fig. 1. Scatter plot between effective particle radius and optical thickness obtained from satellite observation over FIRE (upper) and ASTEX (lower) regions (cited from Nakajima and Nakajima 1995)



①non-drizzling stage

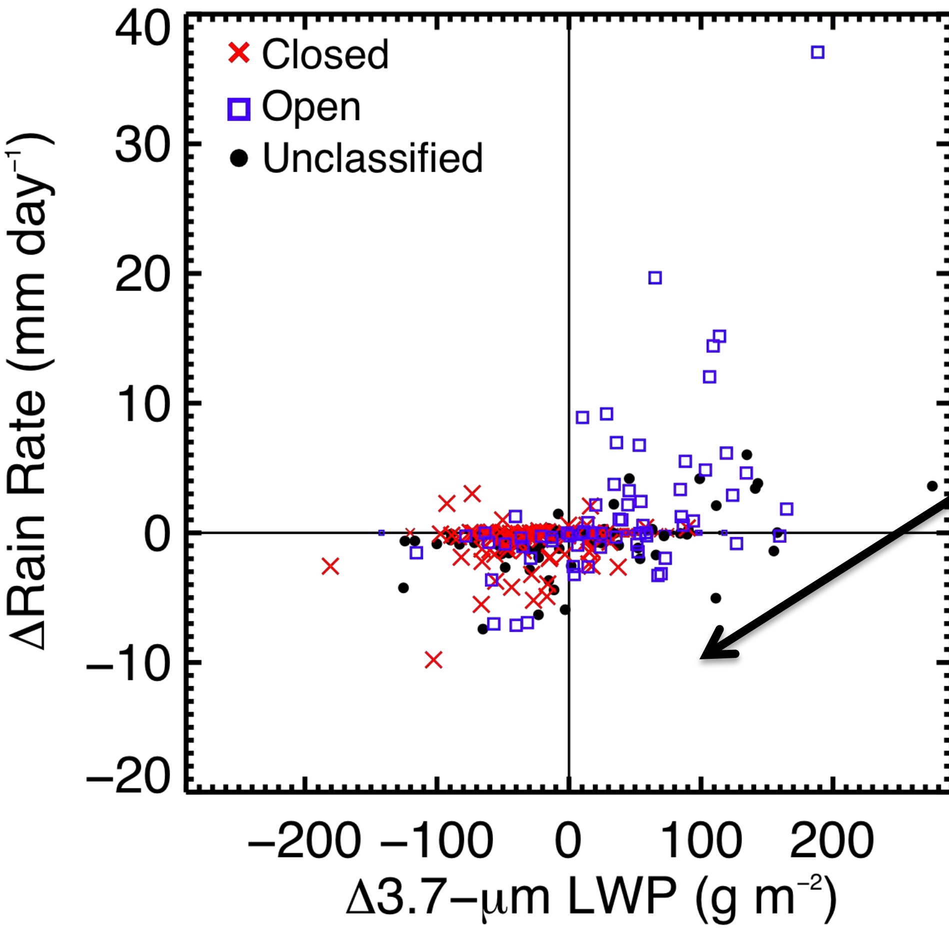
②drizzling stage

③evaporating stage

0 60

Nakajima and Nakajima (JAS 1995)

Buffering by Precipitation



Christensen and Stephens (2012)

- Strong evidence of aerosol affecting drizzle rates.
- Response is **regime dependent**:
  - strong suppression in closed cells
  - enhancement in open cells
- *Increased* liquid water paths are rarely observed when drizzle rates are suppressed by pollution.
  - Contradicts the lifetime effect hypothesis (Albrecht, 1989).
  - Suggests ***buffering*** by precipitation is critical in regulating cloud water path and albedo.

How does precipitation influence climate models response to increasing aerosol?

Understanding the behavior of microphysics scheme

Single-Column Model that mimics NICAM-SPRINTARS cloud microphysics

$$\frac{\partial(\rho q_c(z))}{\partial t} = -\frac{\rho q_c(z) - \rho q_{adb}(z)}{} - \frac{\rho q_c(z)}{}$$

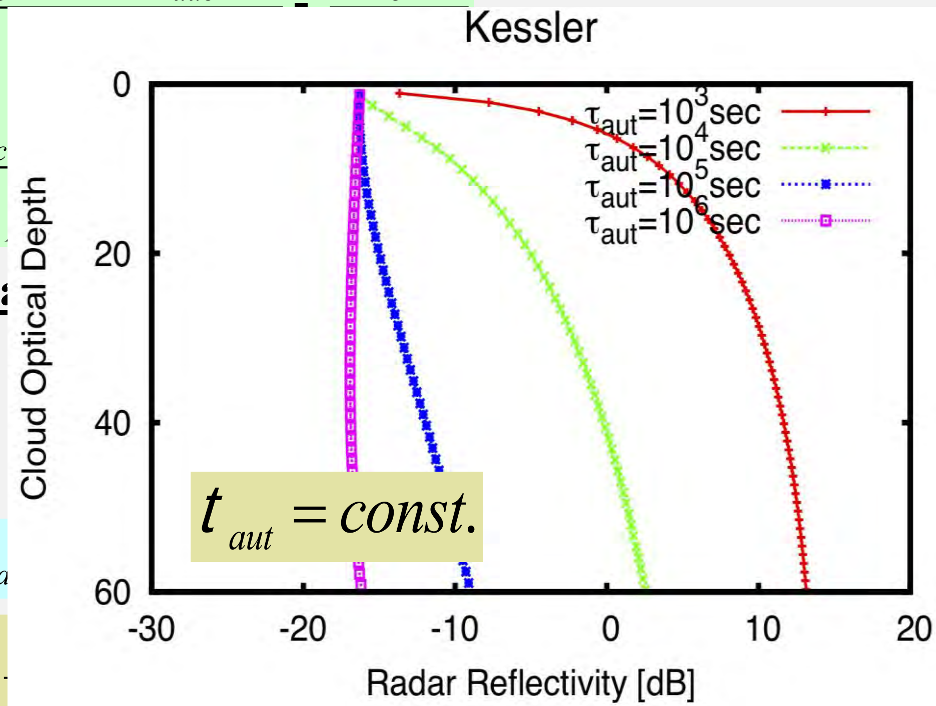
$$\frac{\partial(\rho q_r(z))}{\partial t} = +\frac{\rho q_c}{\tau}$$

ρq_c: cloud water content

content

abatic value

rain water



Rain formation pa

$$\frac{1}{\tau_p} = \frac{1}{\tau_{aut}} + \frac{1}{\tau_{acc}}$$

$$= \frac{N_a N_{c,\max}}{N_a + N_{c,\max}} \sim N_a^{0.7}$$

Auto-conversion: τ_a

cm^{-3})

Berry ('67) $\tau_{aut} = \dots \frac{}{a\rho q_c} \dots (\rho q_c)$

$)^{0.8}$ $\tau_a a$: Aerosol Index

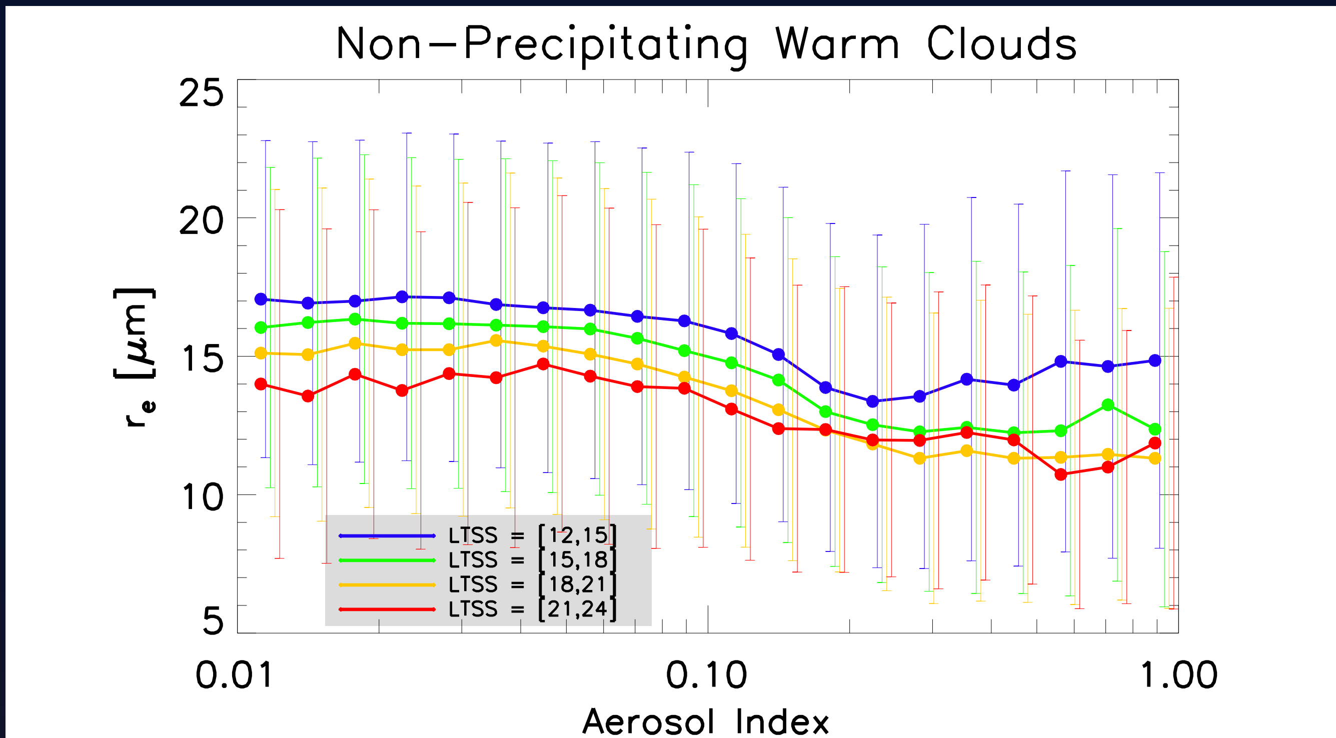
$$\therefore \; N_c \propto (\tau_a a)^{m=0.56}$$

Accretion: $\tau_{acc} = \tau_{acc}(\rho q_r, N_r) = c N_r^{-1/6} (\rho q_r)^{-5/6}$

$$\therefore \; \tau_{aut} \propto N_c \propto (\tau_a a)^{0.56}$$

: representation of the lifetime effect

A-Train results of Lebsock

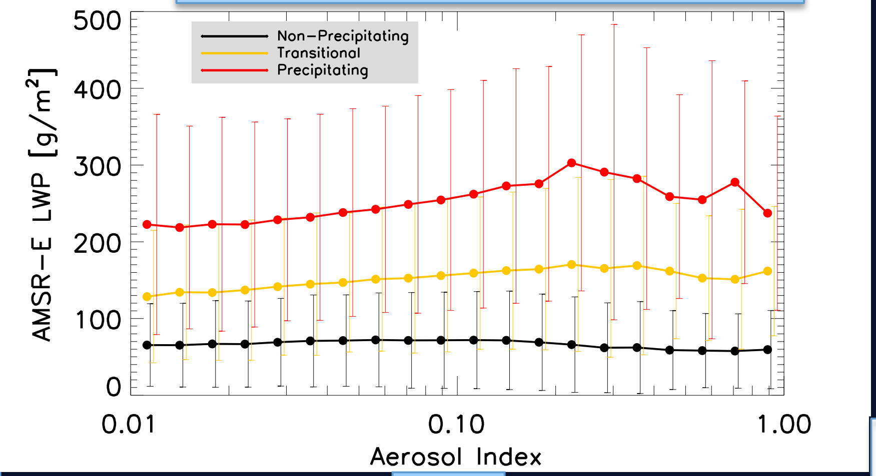


$$Sensitivity = \frac{\partial \log(r_e)}{\partial \log(AI)} = 0.07$$

This parameter forms the basis of GCM parameterizations of the 1st indirect effect

- Sensitivity of effective radius to aerosol is relatively independent of stability
- Value of sensitivity parameter in good agreement with literature (Breon [2002], Matsui [2004])

AMSR-E Water Path

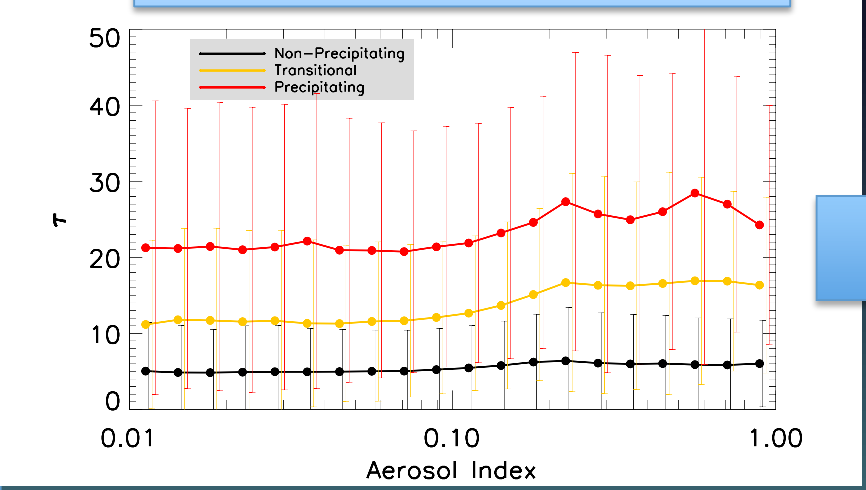


- The water path effect for precipitating clouds dominates the radius effect in the albedo response of these clouds

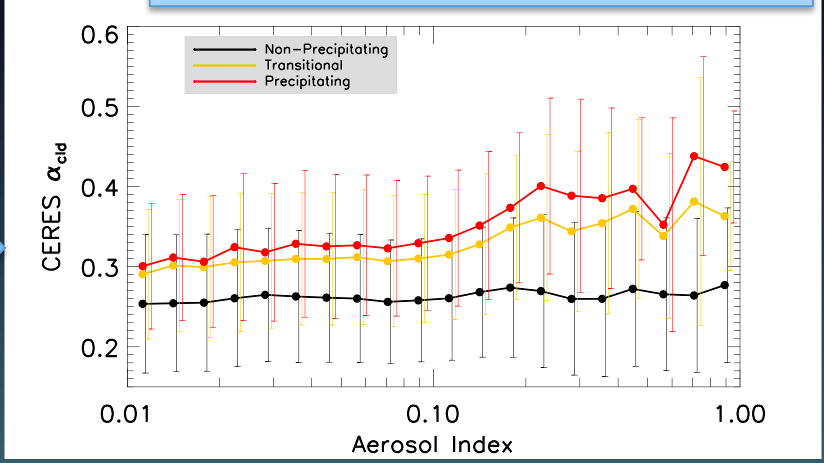
$$\tau = \frac{3\mathrm{LWP}}{2\rho_l r_e}$$

$$\alpha_{cld} \approx F(\tau) = F(r_e, \mathrm{LWP})$$

MODIS Optical Depth

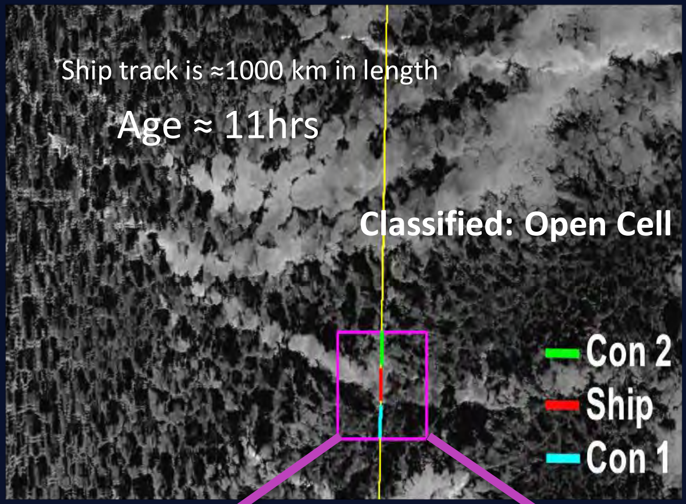


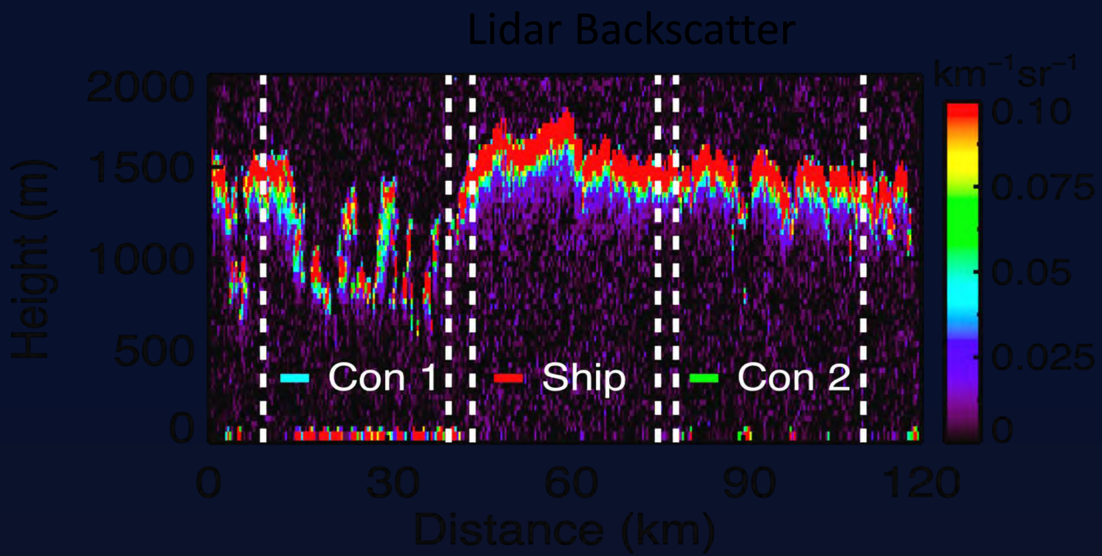
CERES Cloud Albedo

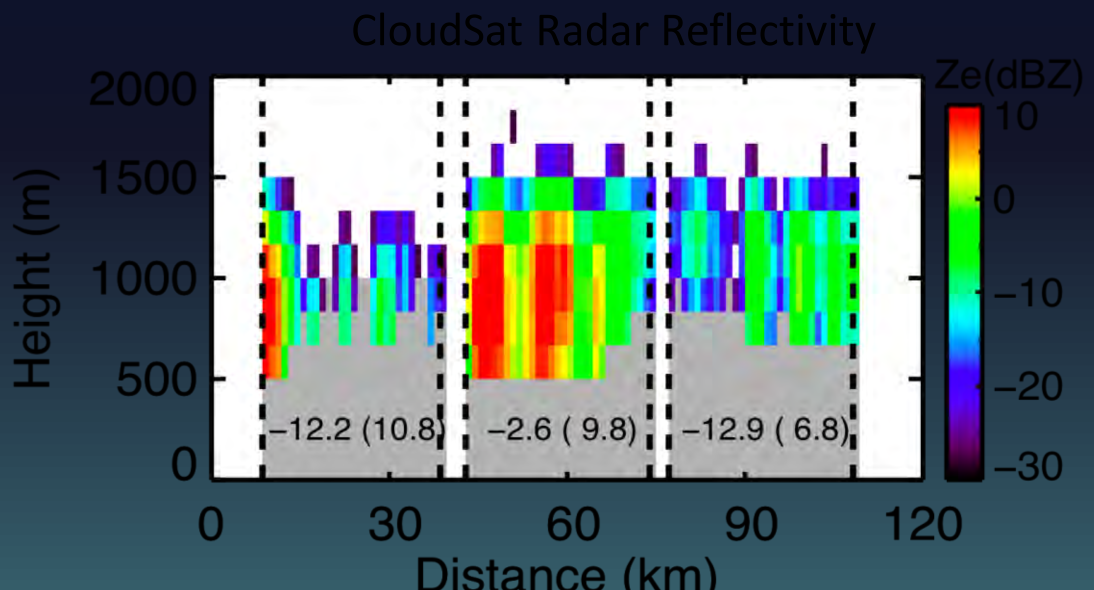


Buffering by Precipitation

aerosol *enhancing* drizzle in ship track



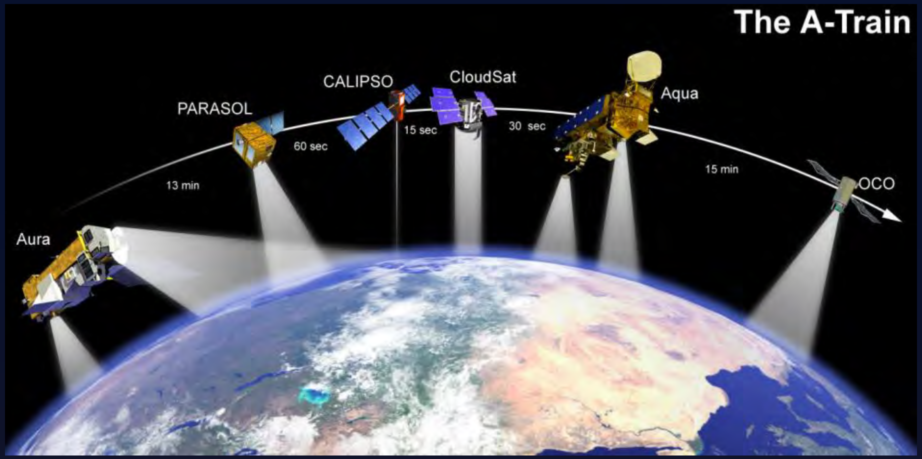




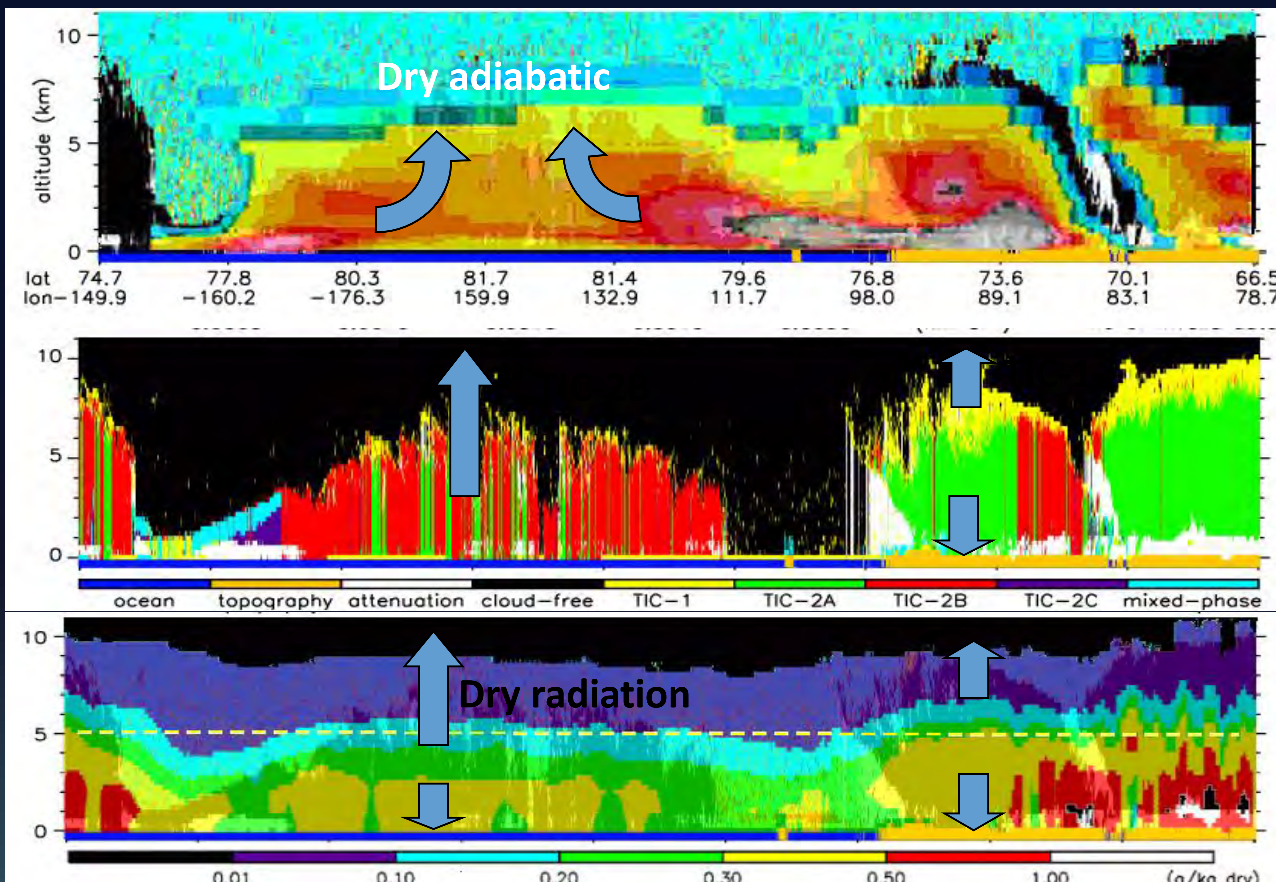
January 11th, 2007 at 2210 UTC

A-Train data.

1. CloudSat
   - Precipitation Flag
   - Cloud reflectivity
2. MODIS
   - Cloud effective radius
   - Cloud LWP
   - Aerosol Index
   - Cloud Fraction
3. AMSR-E
   - Cloud LWP
   - Water Vapor
4. CERES
   - Cloud Albedo
5. CALIPSO
   - Cloud top height, CALIOP



Rapid & sustained cooling of airmass



Process #1: Dynamics

DT ≈ -10 to -20°C

Time scale ~ 1day

Process #2: Direct IR

DT ≈ -16 to +10°C

Time scale: 1 to 5 days

Process #3: Indirect IR

DT ≈ -5 to -10°C

Time scale: 1 to 2 weeks

Total Cooling ≈ -30 to - 50°C