Regimes within the First Aerosol Indirect Effect

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Thanks: Pete Daum, Mike Jensen, Andy Vogelmann, Christine Chiu, Dave Turner

ARM
Atmospheric Radiation Measurement

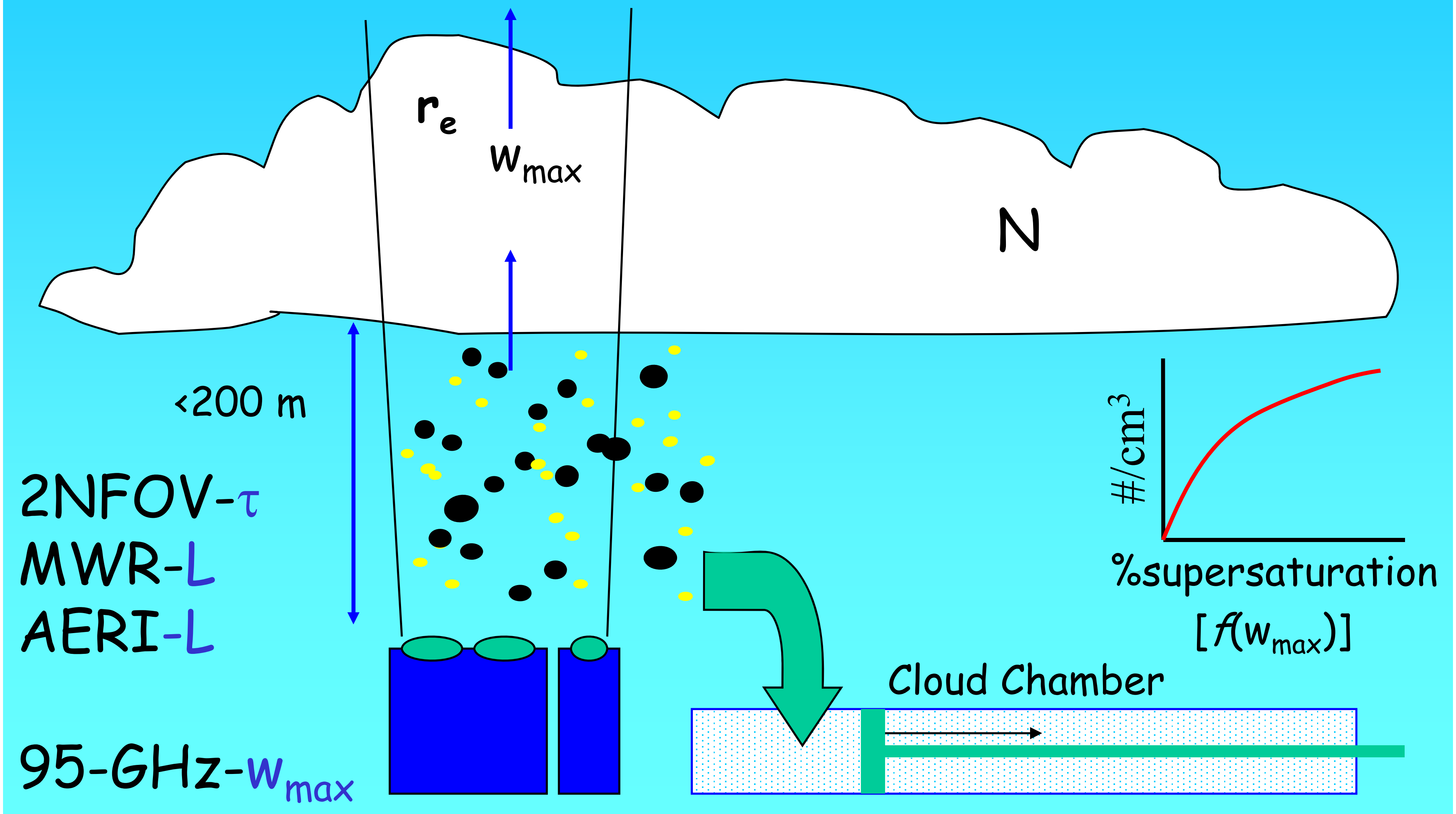
Theory of the First Aerosol Indirect Effect

- In an adiabatic ascent, an increase in the droplet number concentration at constant liquid water mixing ratio results in a decrease in the average droplet radius and an increase in the reflection of incoming sunlight (Twomey, 1974, 1991).
- Key issues for implementation in real atmosphere:
  - **Isolated parcel (no mass or heat exchange)**
  - **Adequate supersaturation (updraft velocity) to activate new Cloud Condensation Nuclei (CCN)**

Key Question!

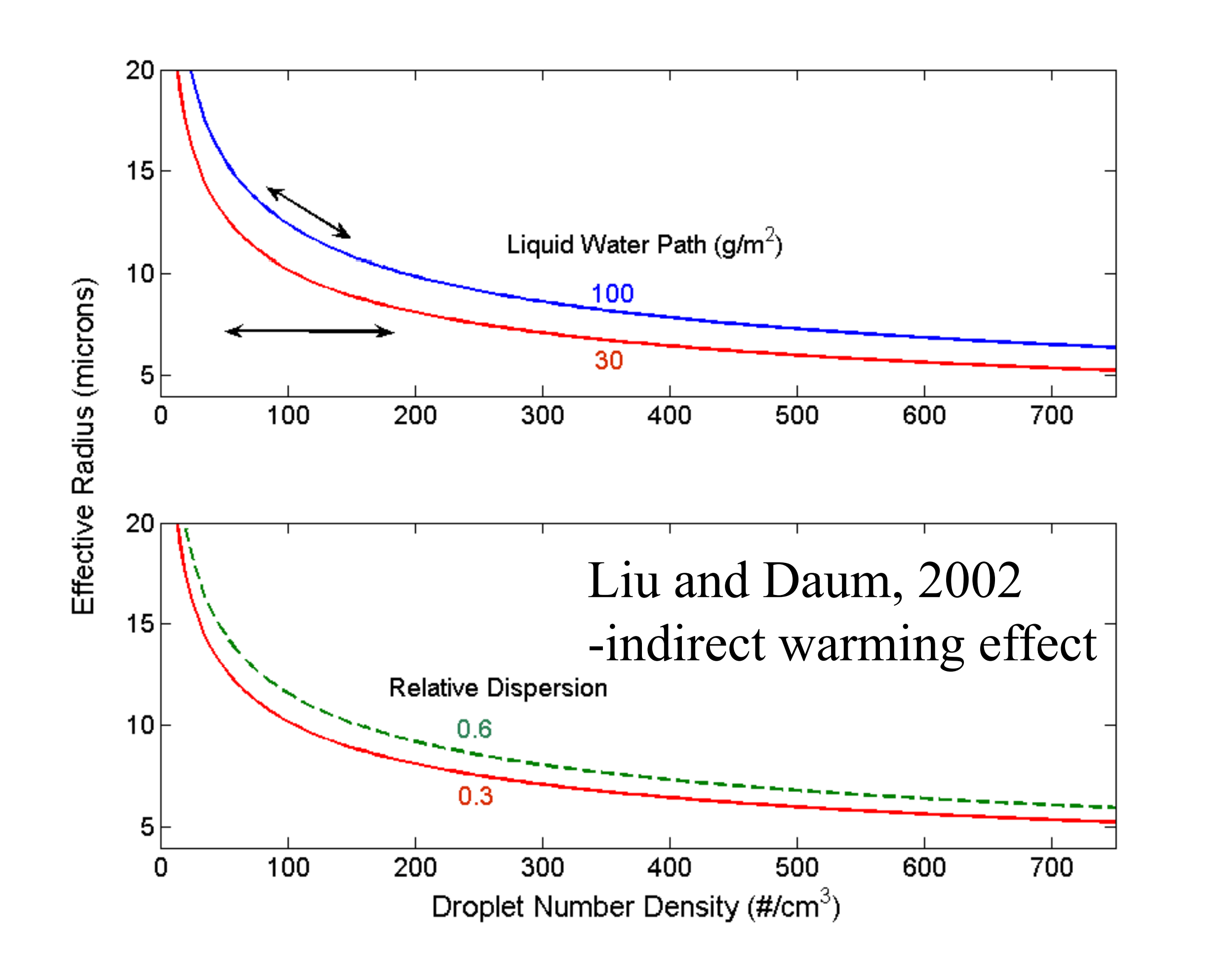
- **Does the adiabatic cloud droplet nucleation process, at constant liquid water path, actually determine the optical properties of the cloud?**

A Basic Experiment

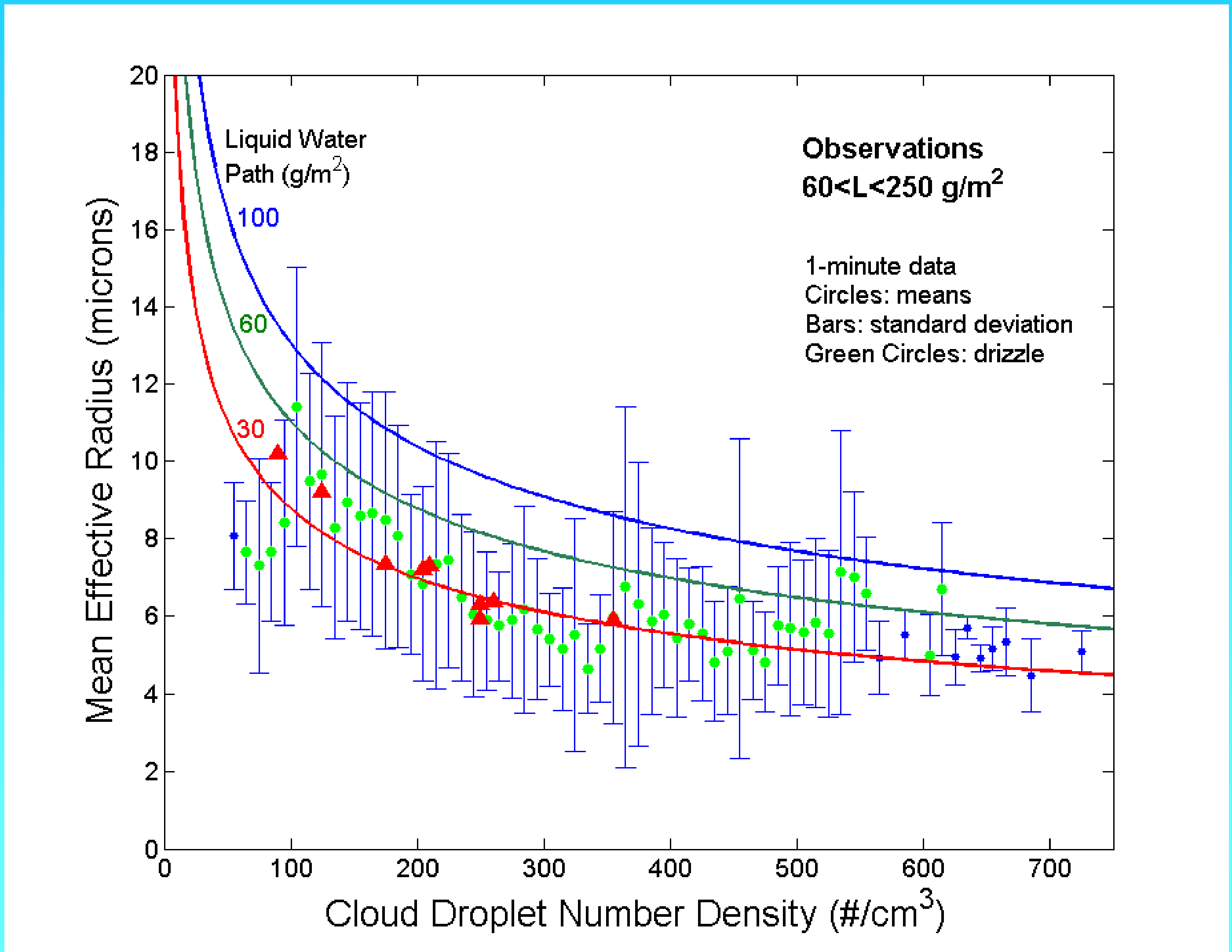


The One-Third Law

- A reduction in the global value of r_e by 2-μm would offset the doubling of CO_2 (Slingo 1990)

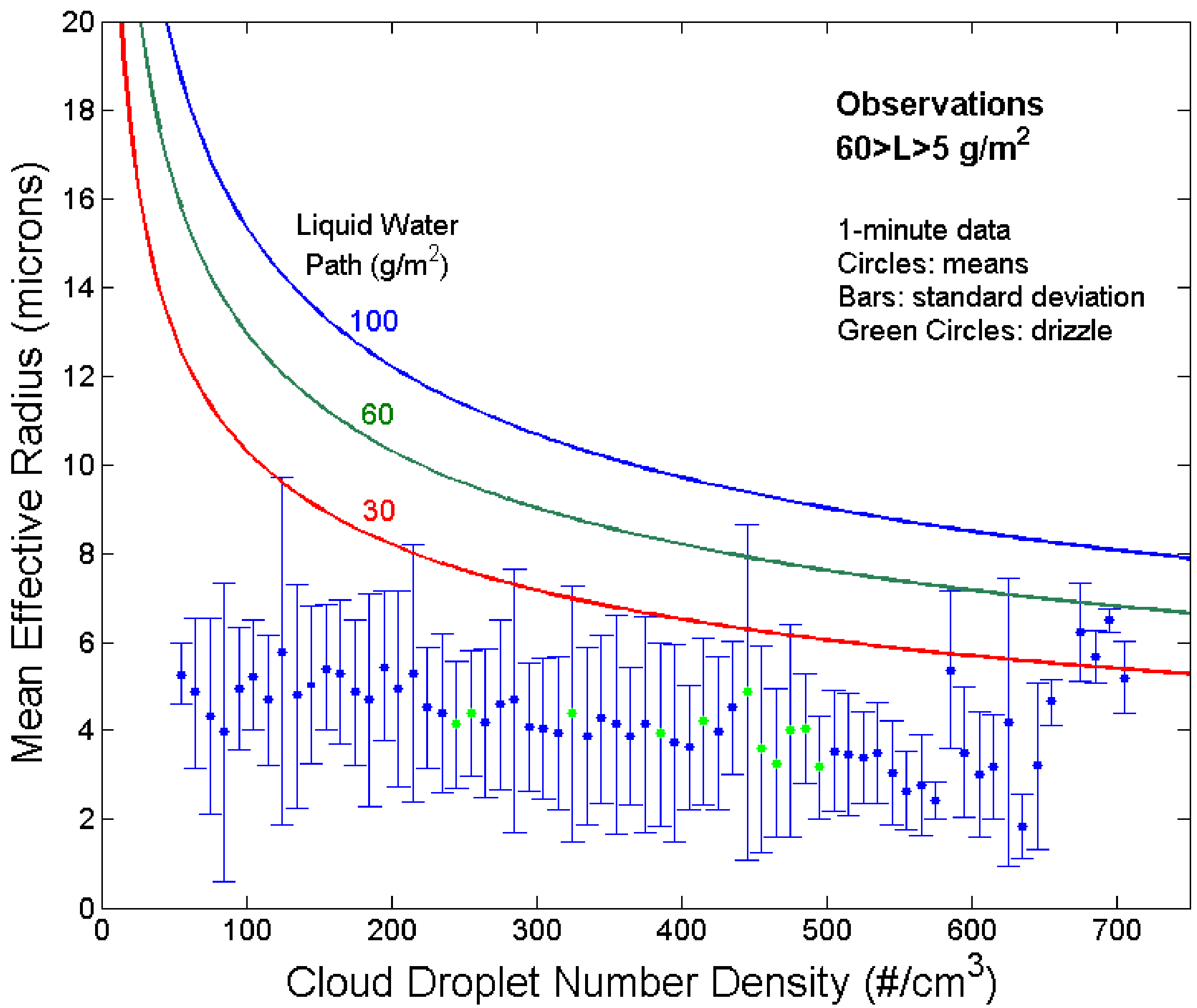


High LWP



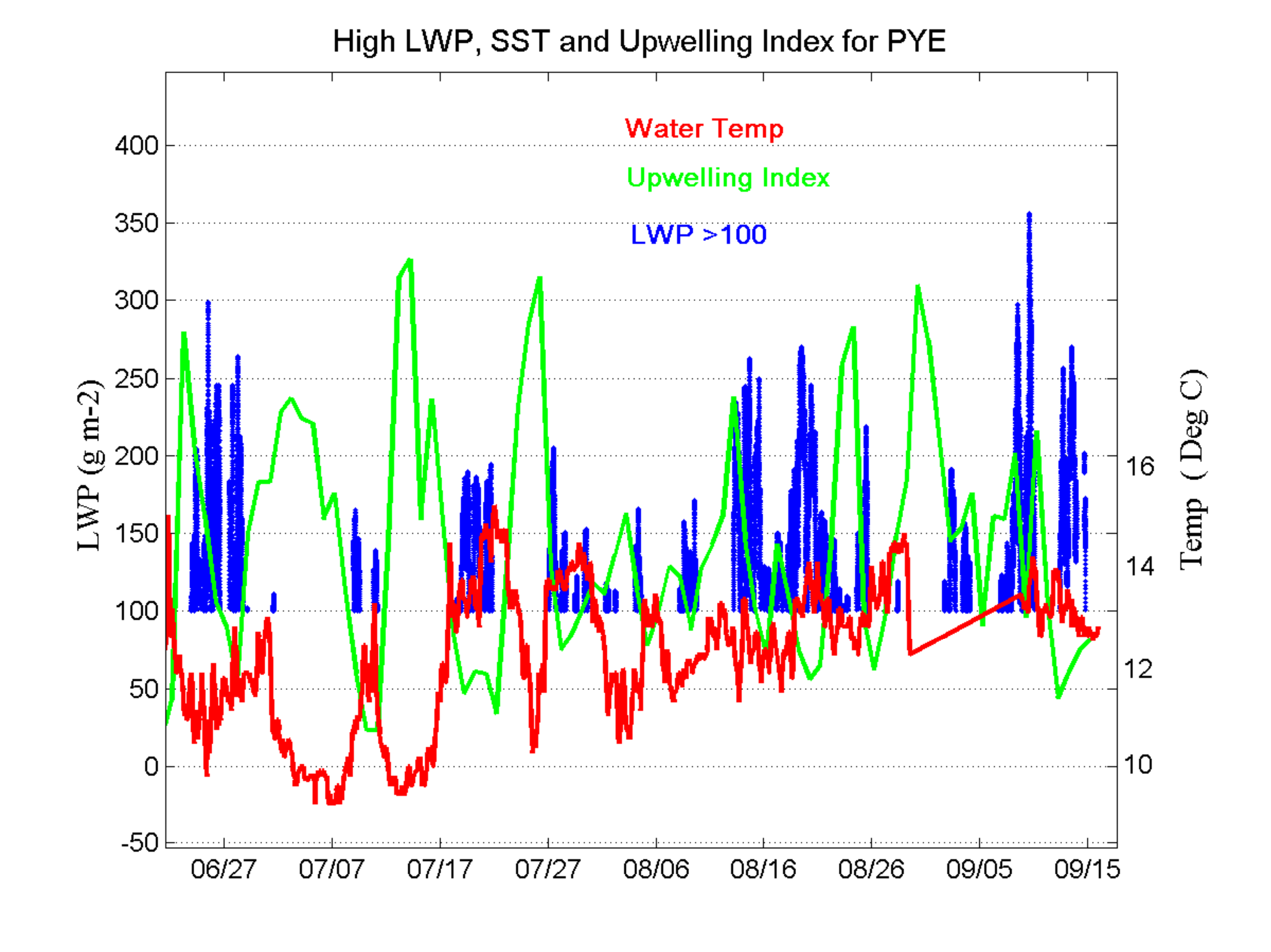
Liquid Water Path (g/m2)
100
60
30
Observations
60<L<250 g/m2
1-minute data
Circles: means
Bars: standard deviation
Green Circles: drizzle
Mean Effective Radius (microns)
Cloud Droplet Number Density (#/cm3)
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
700

Low LWP

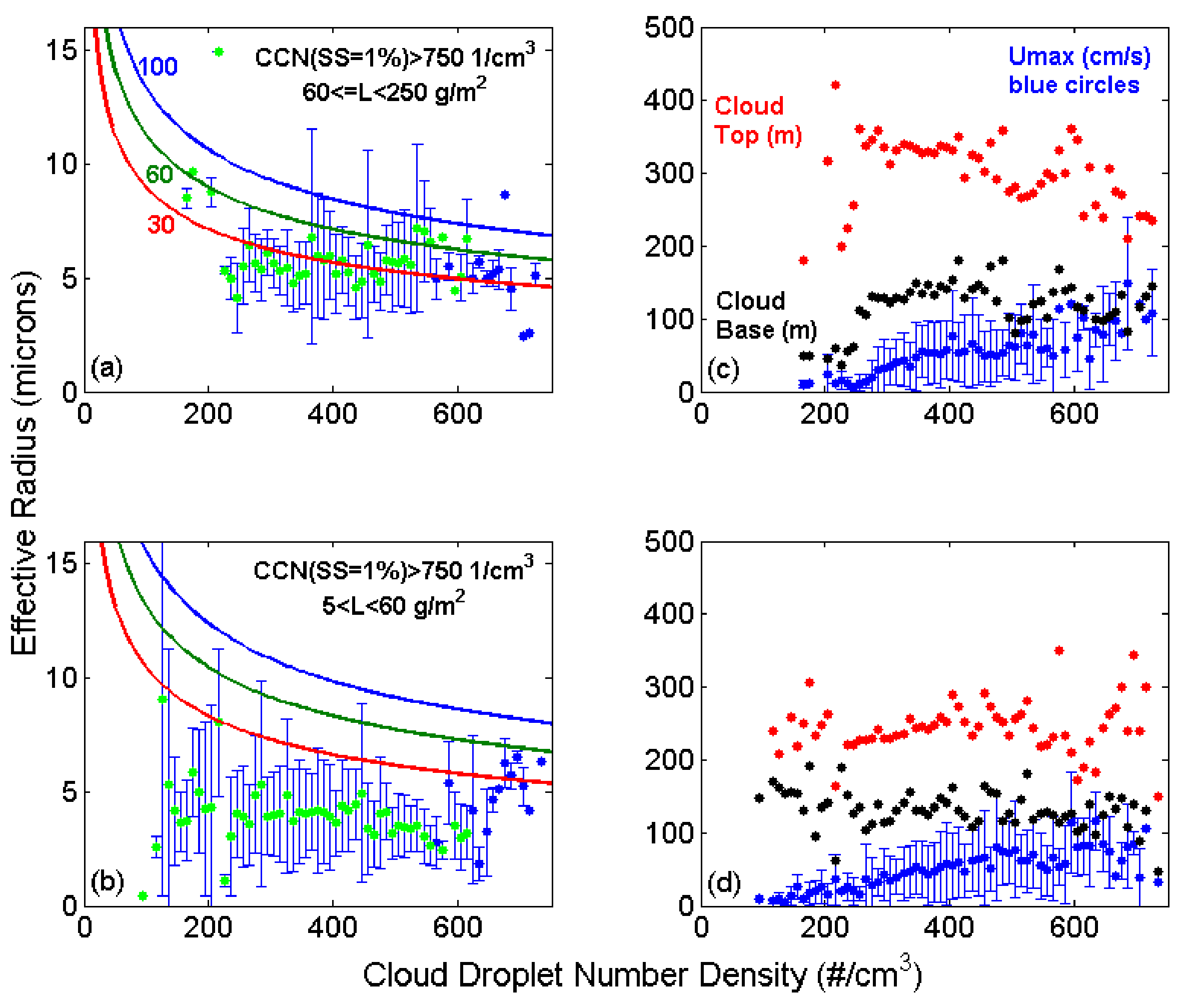


Observations
60>L>5 g/m2
1-minute data
Circles: means
Bars: standard deviation
Green Circles: drizzle
Liquid Water Path (g/m2)
100
60
30
Mean Effective Radius (microns)
Cloud Droplet Number Density (#/cm3)
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
700

LWP and Upwelling



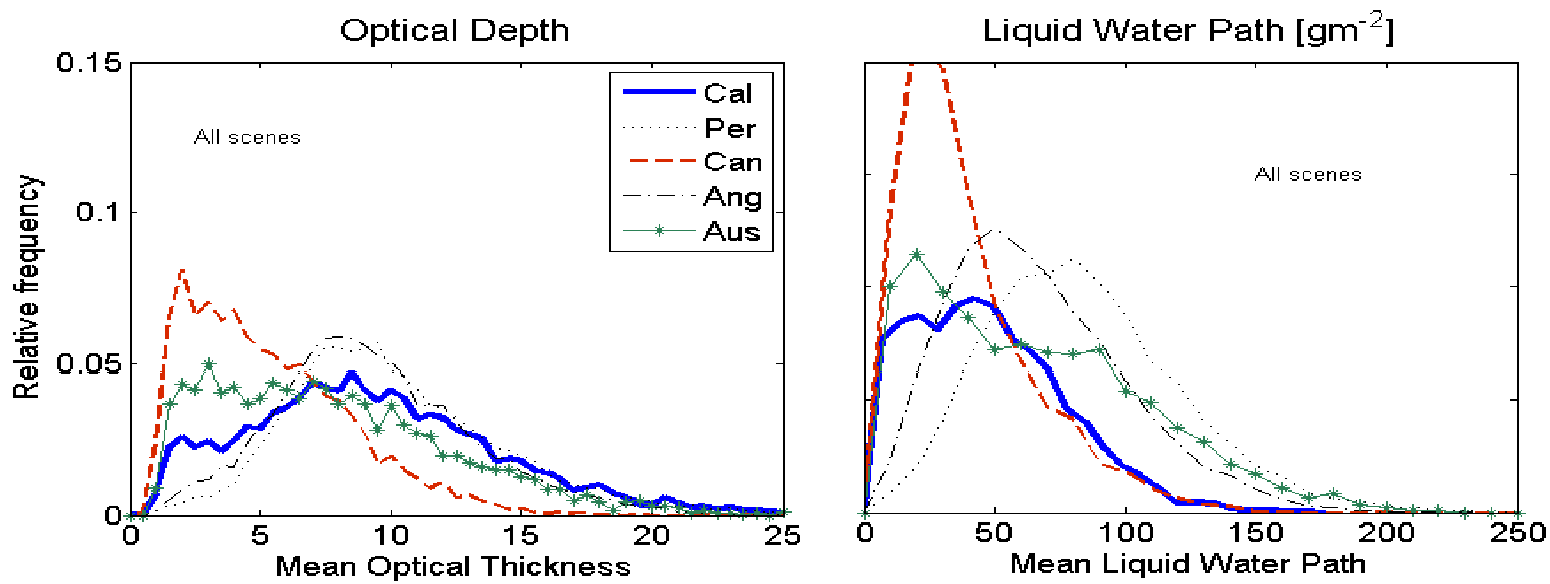
Updraft Limitations?



Summary and Conclusions

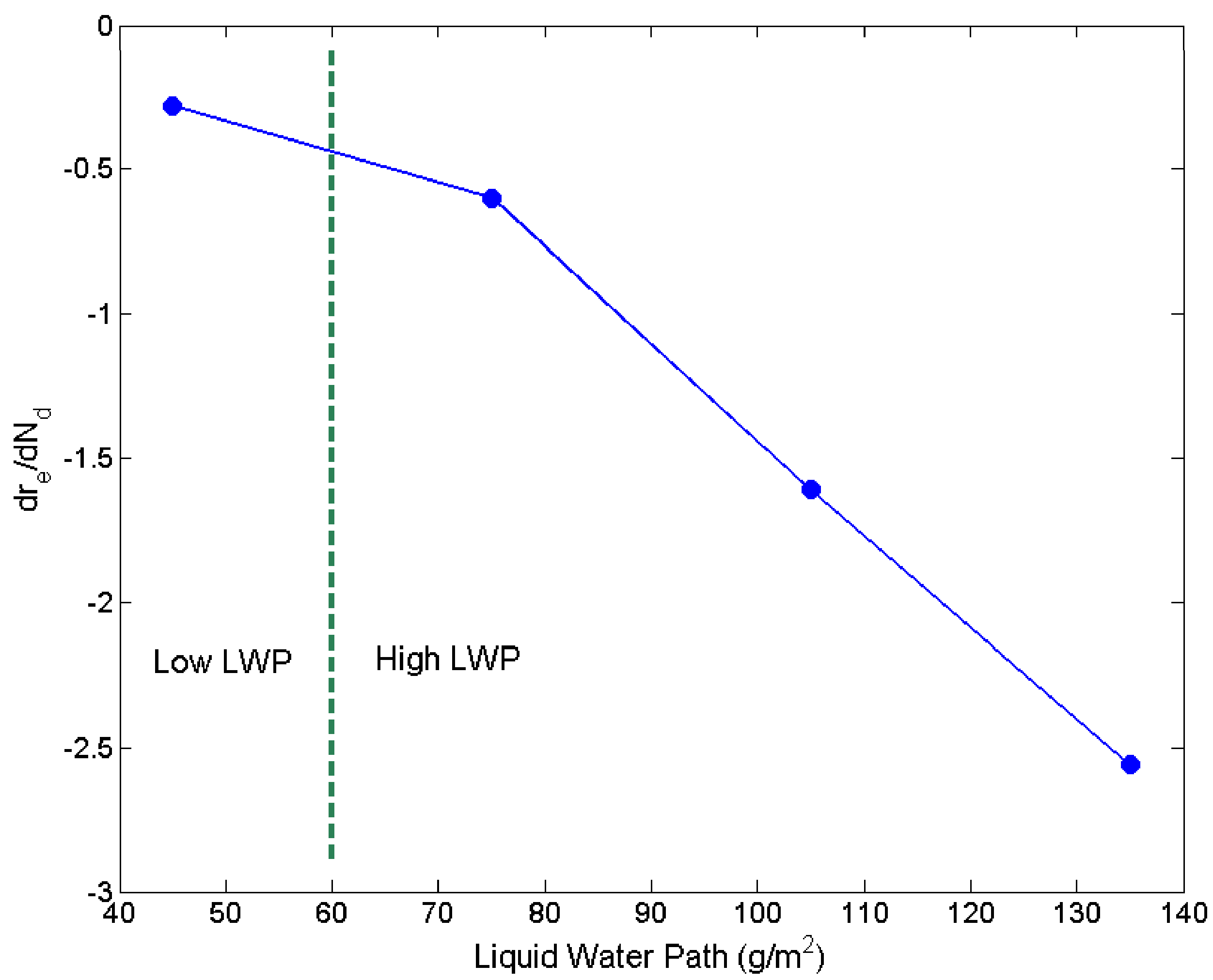
- Observed LWP-dependent regimes within the First Aerosol Indirect Effect
- Recommend that "One-third Law" be applied selectively in coastal stratus
  - may require modification to account for subadiabatic clouds
  - Otherwise, an overestimate of AIE
- Need more extensive data set
- New technique for number density is promising

THE END



Jensen et al. (2007)
5-years MODIS Terra—300x300 km box
Algorithm to remove cloud edge pixels
>30,000 data points

LWP Regimes



0
-0.5
-1
-1.5
-2
-2.5
-3
dr_e/dN_d
40
50
60
70
80
90
100
110
120
130
140
Liquid Water Path (g/m^2)
Low LWP
High LWP

Droplet Microphysics in GCMs

"One-Third Power Law"

Liquid Water Path
[PROGNOSTIC]

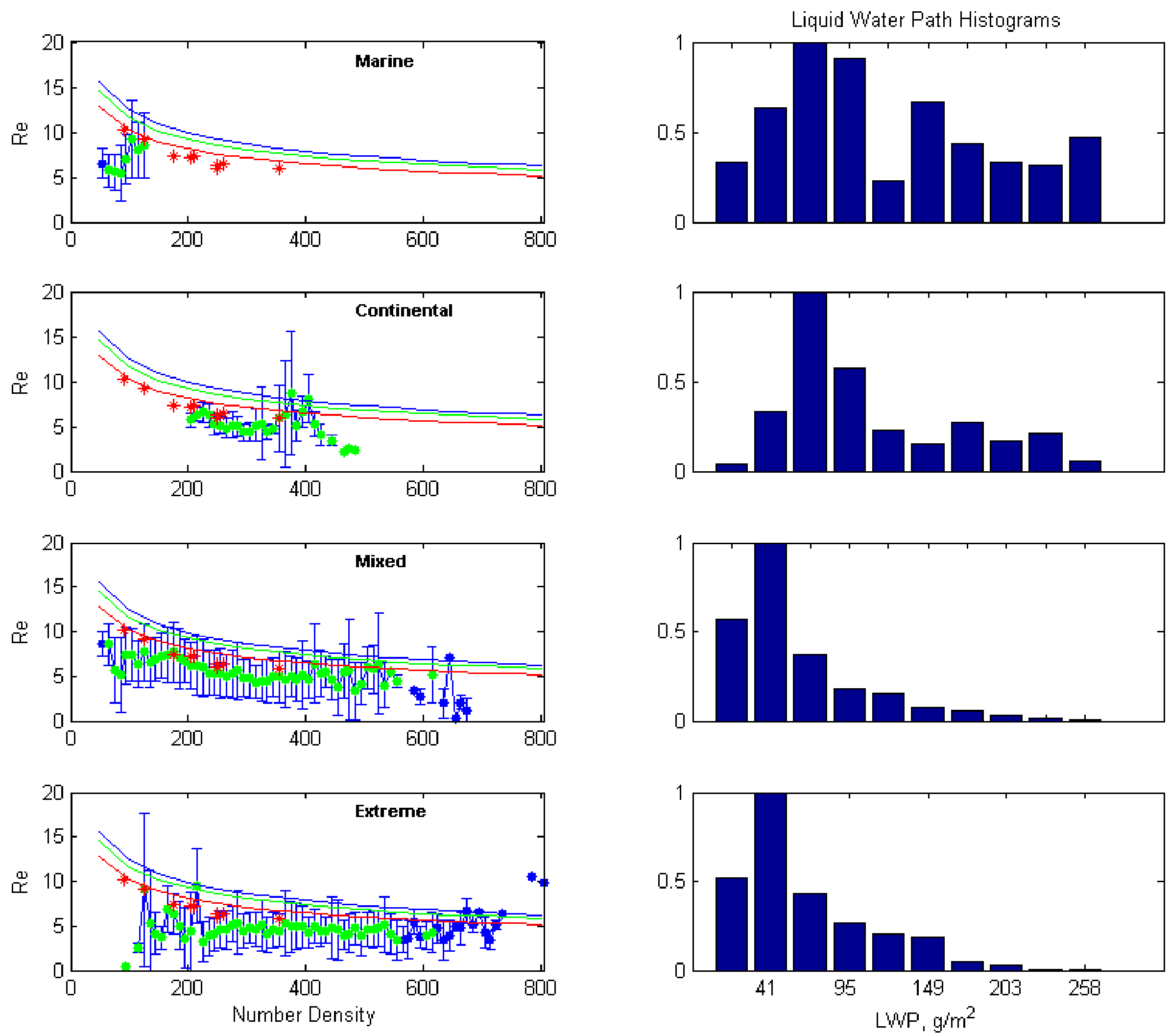
Shortwave Transmission Depends on r_e and L

$$\overline{r}_e = \overline{\beta}\left[C \frac{L}{N \Delta z} \right]^{1/3}$$

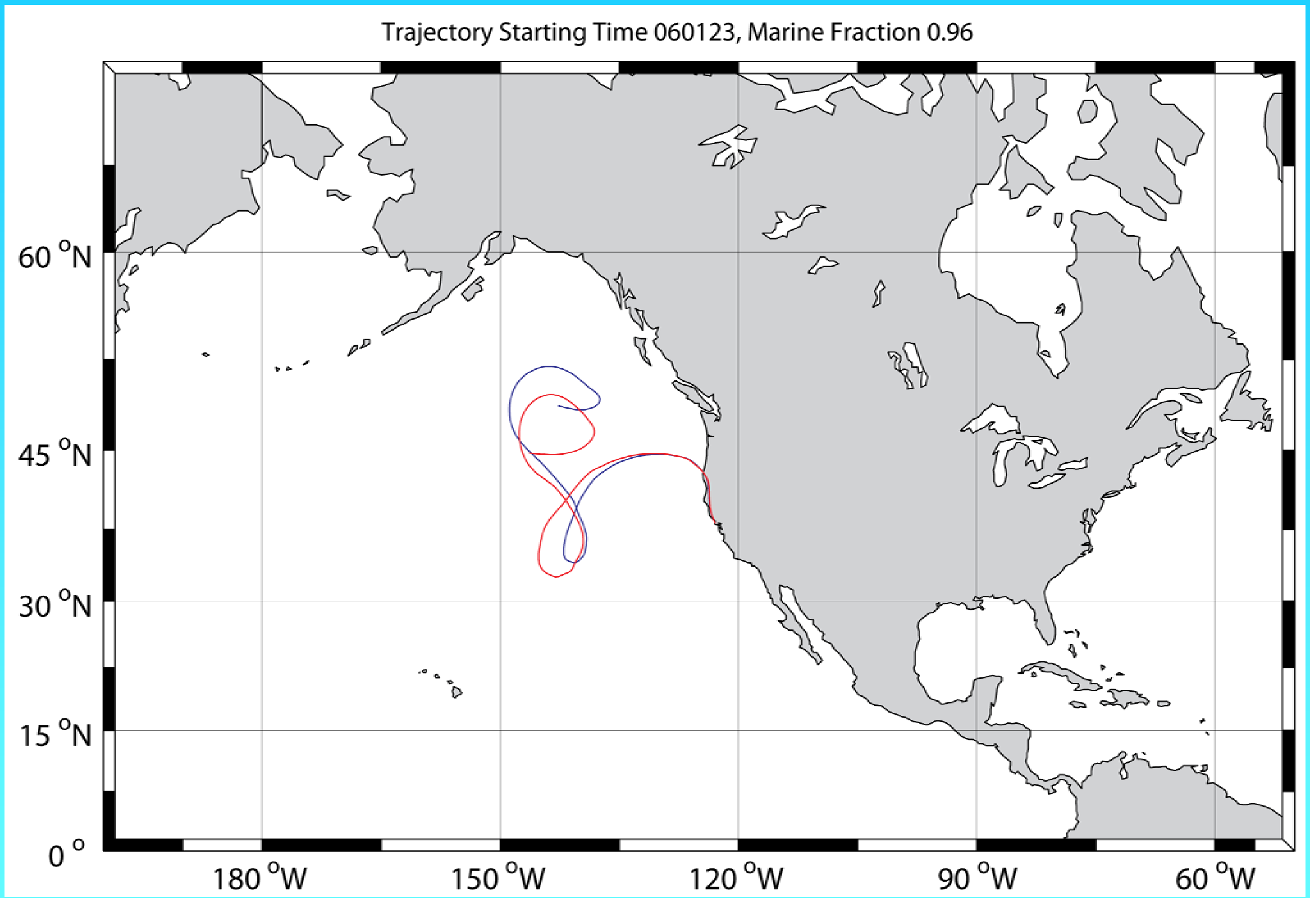
Light Scattering Properties of Cloud Droplets

Relative Dispersion (sigma/mean) [Parameterized]

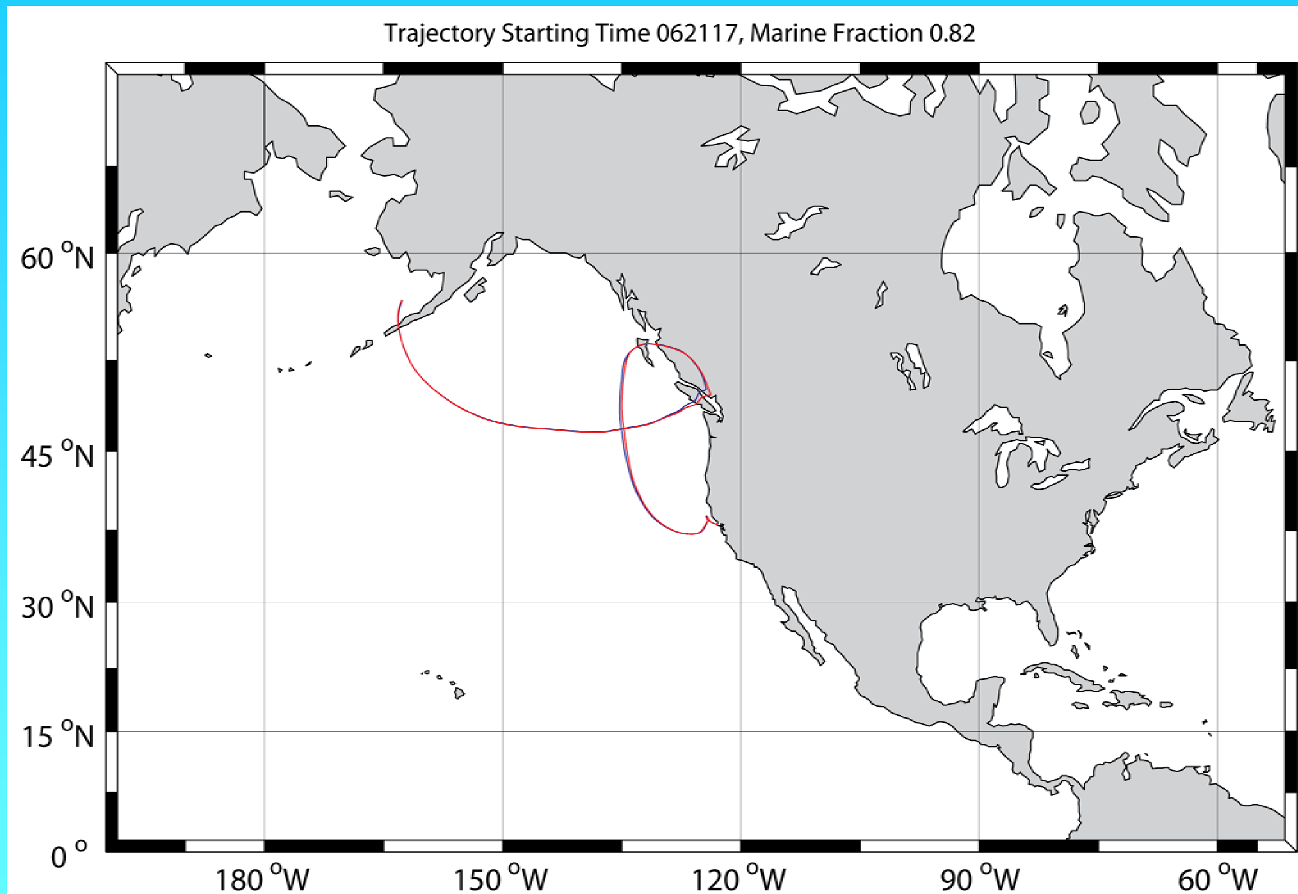
Cloud Droplet Number Density [Sometimes PROGNOSTIC sometimes parameterized]

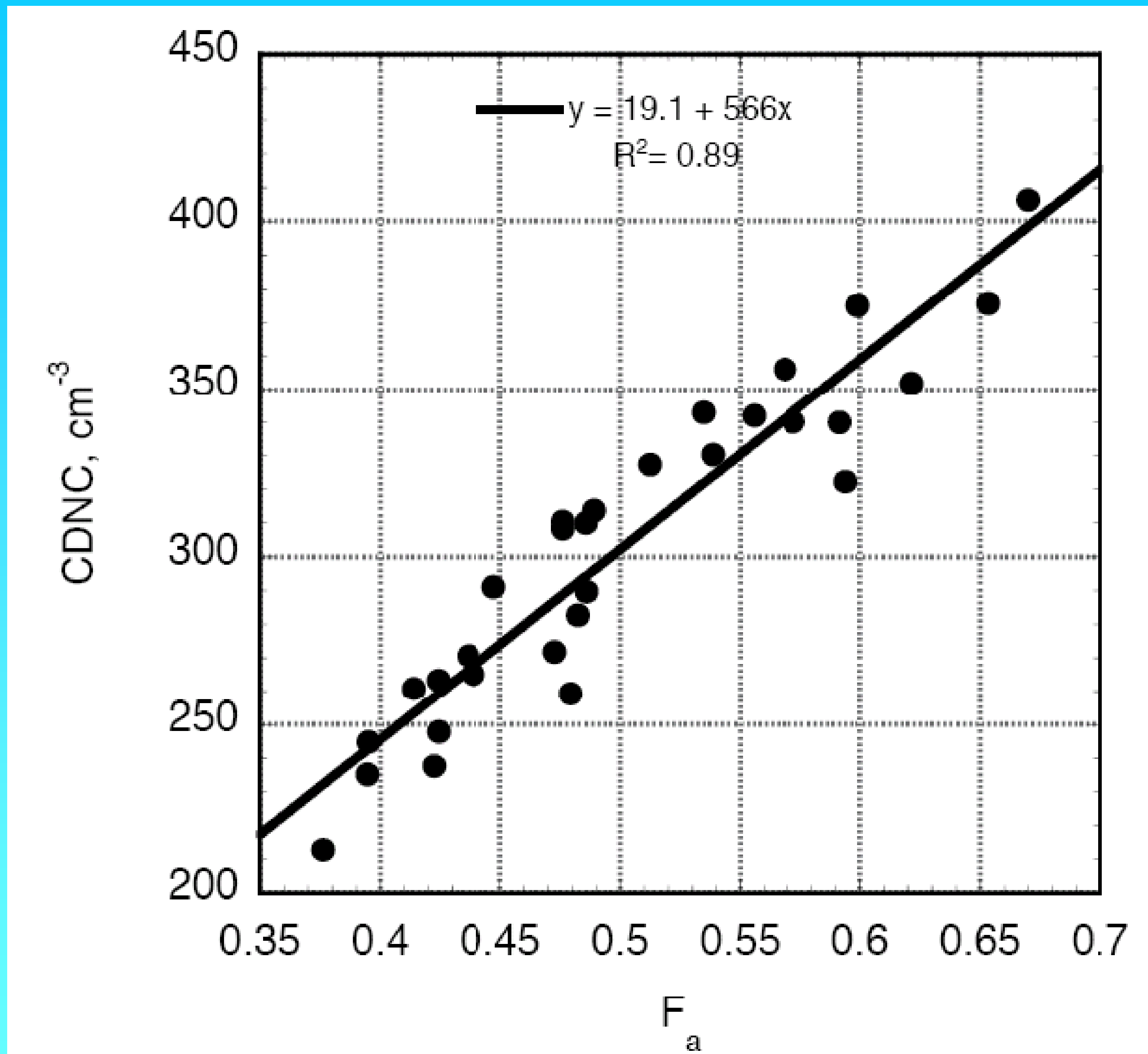


Liquid Water Path Histograms
Marine
Continental
Mixed
Extreme
Re
Number Density
LWP, g/m2
41
95
149
203
258



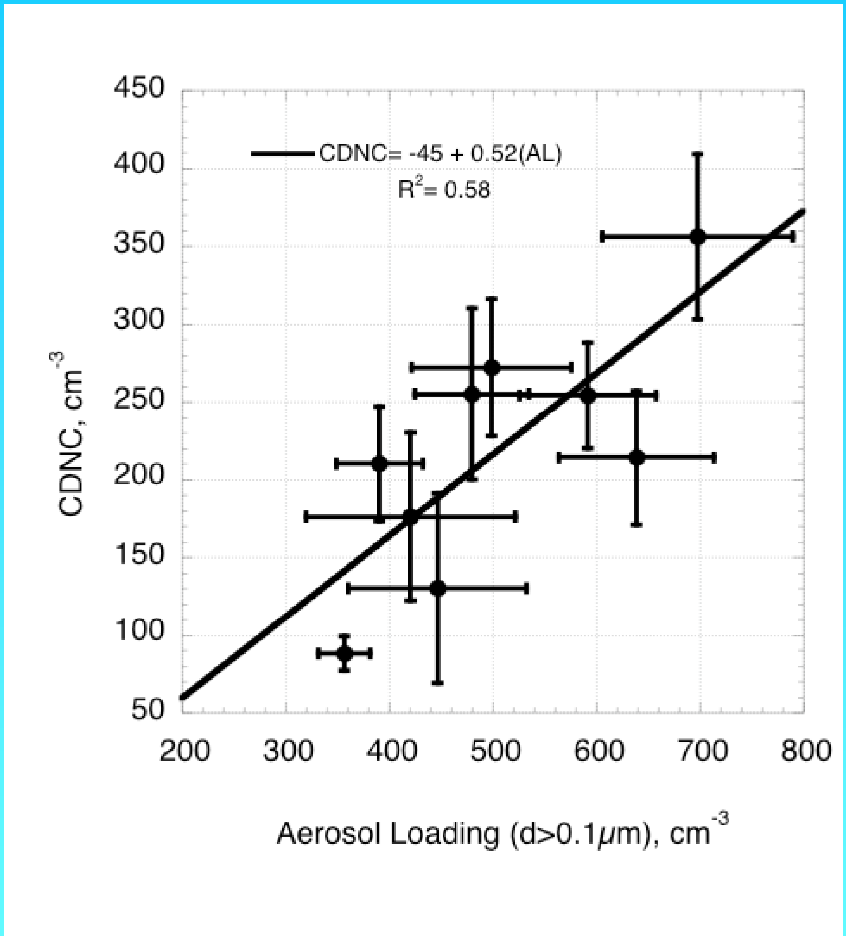
Trajectory Starting Time 060123, Marine Fraction 0.96
60 °N
45 °N
30 °N
15 °N
0 °
180 °W
150 °W
120 °W
90 °W
60 °W

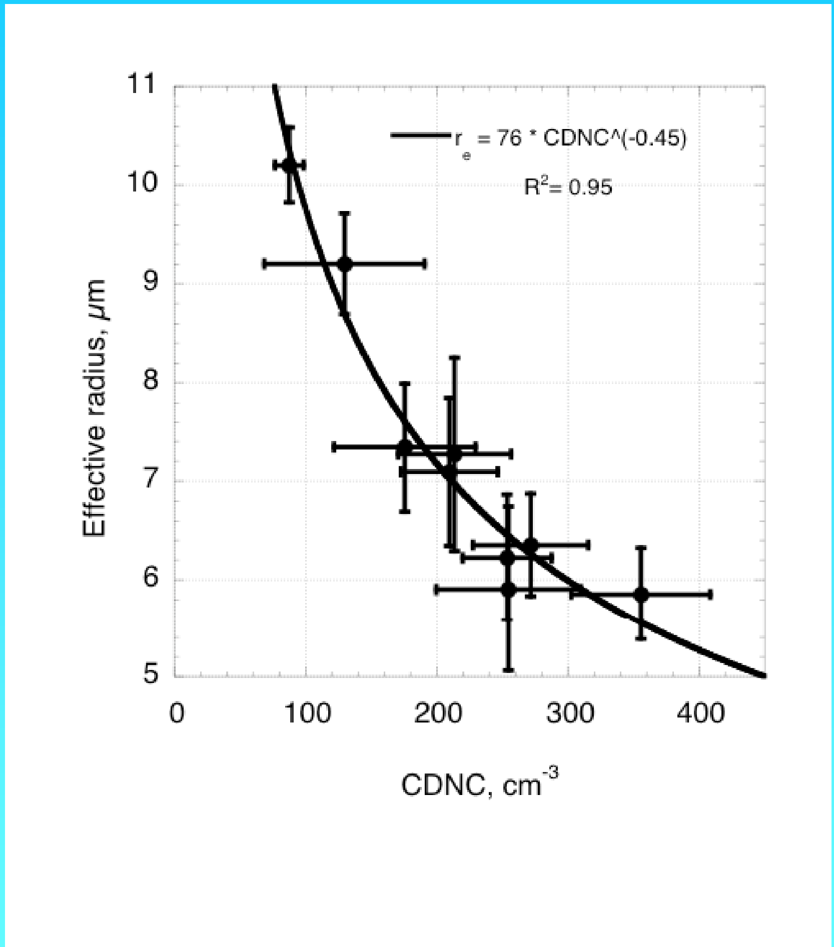

Trajectory Starting Time 062117, Marine Fraction 0.82
60 °N
45 °N
30 °N
15 °N
0 °
180 °W
150 °W
120 °W
90 °W
60 °W



y = 19.1 + 566x
R2= 0.89
CDNC, cm-3
Fa
450
400
350
300
250
200
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7

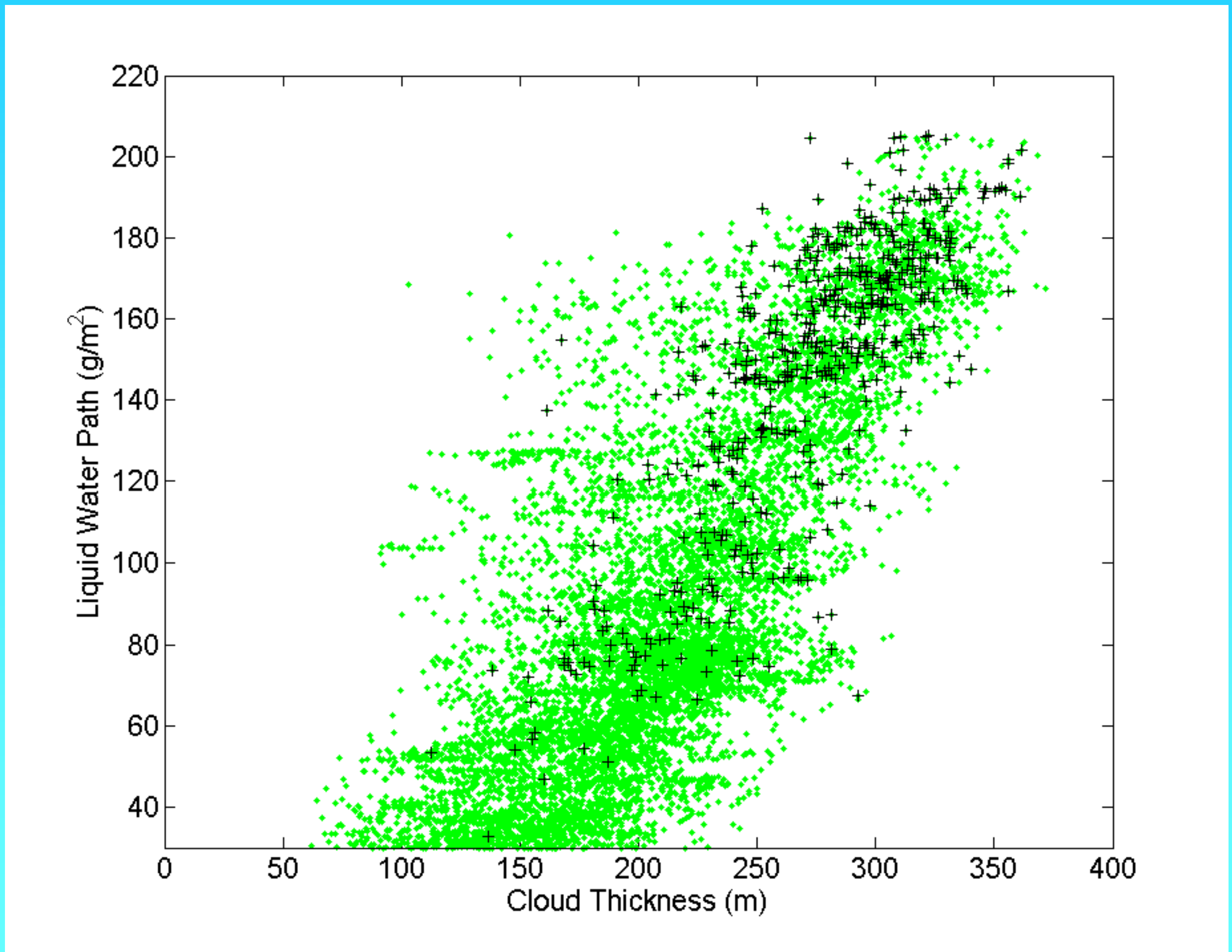
Results from G-1 Flights During MASE

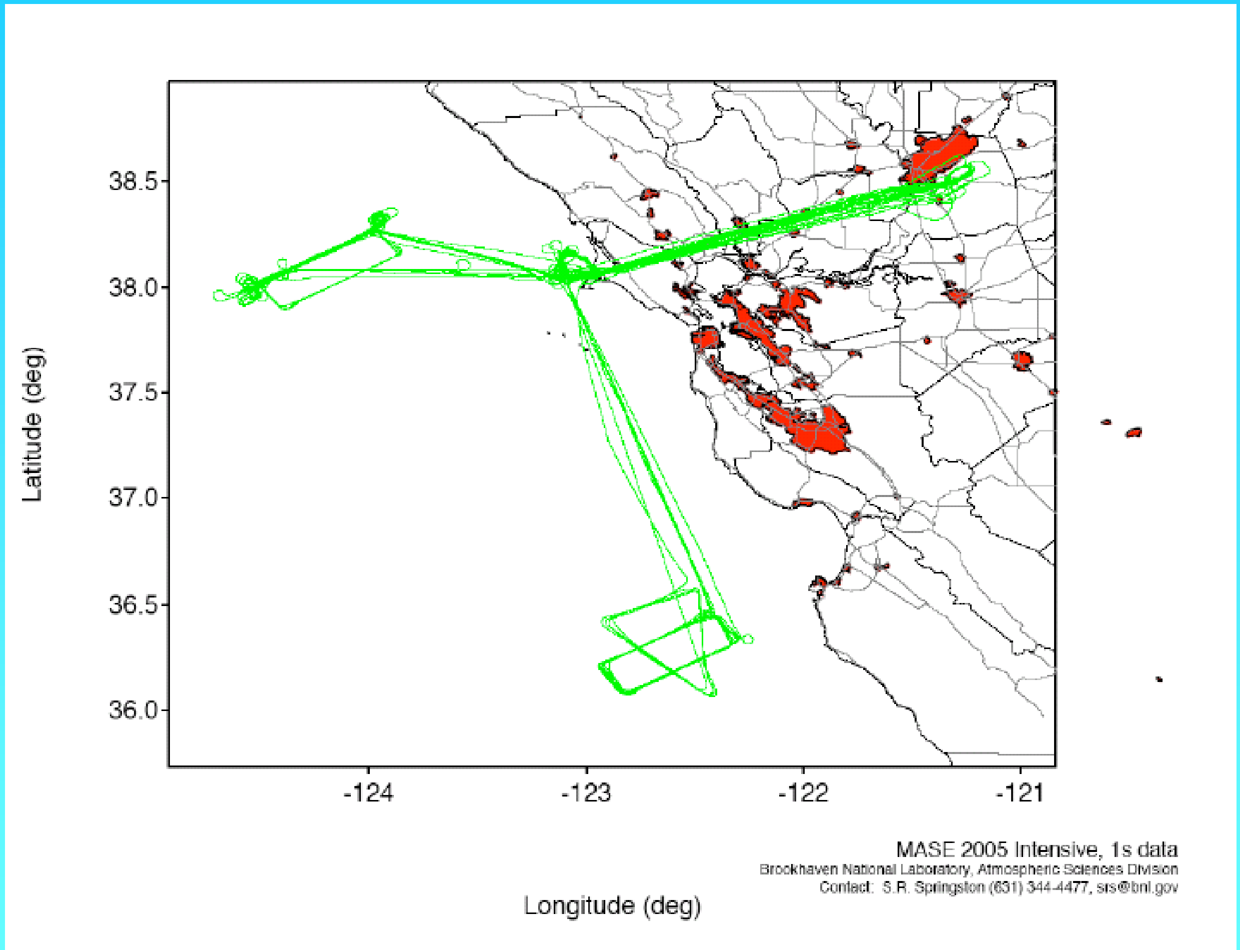




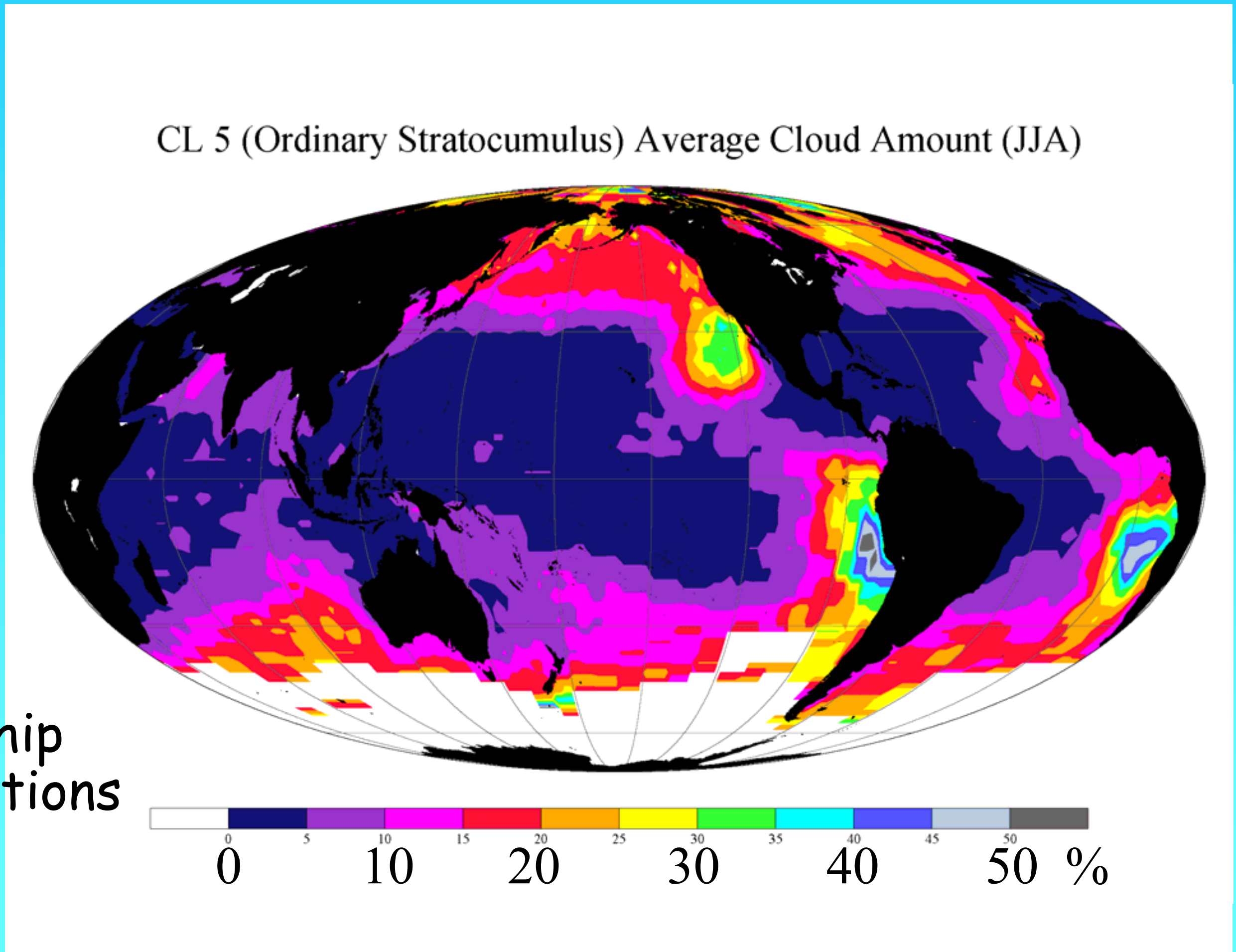
Increasing aerosol concentrations observed with increasing droplet concentrations and a decrease in the effective radius.

LWP and Drizzle




38.5
38.0
37.5
37.0
36.5
36.0
Latitude (deg)
-124
-123
-122
-121
Longitude (deg)
MASE 2005 Intensive, 1s data
Brookhaven National Laboratory, Atmospheric Sciences Division
Contact: S.R. Springston (631) 344-4477, srs@bnl.gov

Marine Stratocumulus



J. Norris
1954-1992
Synoptic Ship
Observations

Aerosol Shortwave Indirect Effects

- First (or Twomey Effect): "We can with some confidence predict that clouds in the future will contain more droplets per unit volume and, other things being equal, these droplets must become smaller" Twomey, S., 1991 Aerosols, clouds, and radiation. *Atmos. Env.*, 25A, 2435-2442. (originally proposed in 1974)

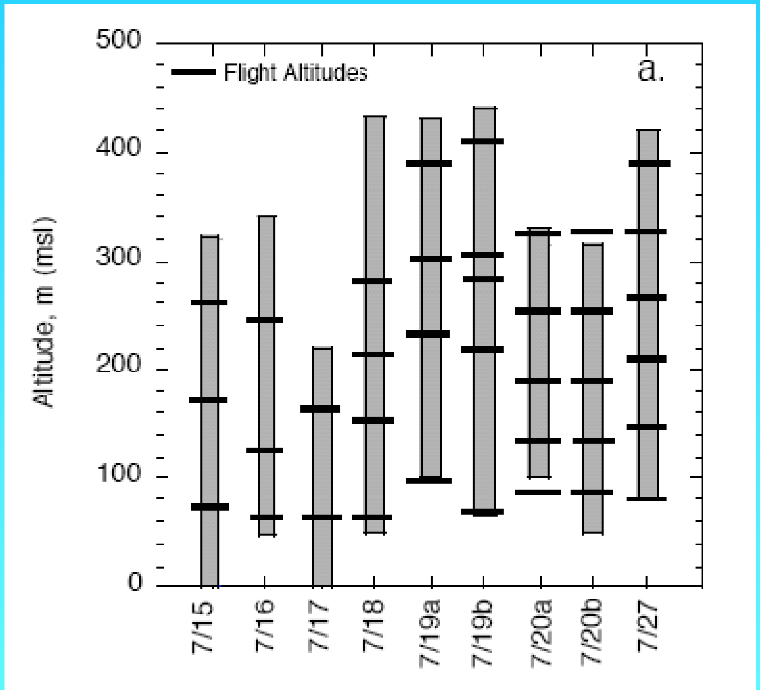
- Second (or Albrecht Effect): "Increases in aerosol concentrations over the oceans may increase the amount of low level cloudiness through a reduction in drizzle—a process that regulates the liquid water content and energetics of shallow marine clouds" Albrecht, B.A., 1989: Aerosols, cloud microphysics, and fractional cloudiness. Science, 245, 1227-1230.

The Adiabatic Cloud Model

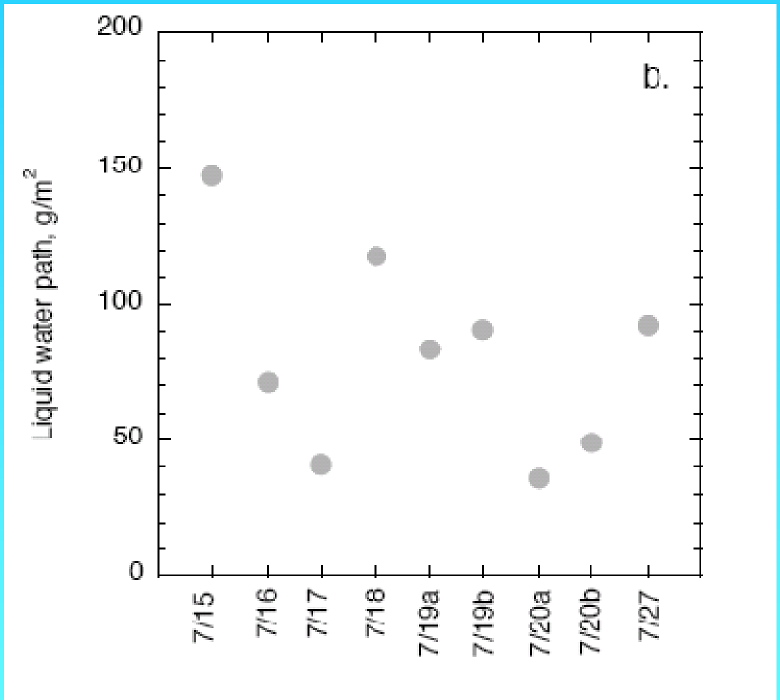
- Many past studies use an adiabatic cloud model to compute the adiabatic cloud droplet number density, which is subsequently linked to effective radius to examine the Aerosol First Indirect Effect
  - Penner et al., 2005; Feingold et al., 200X; Brengiuer et al., 2005; ect.
  - Assume the nucleation properties of the aerosol particles

Effects of Mixing

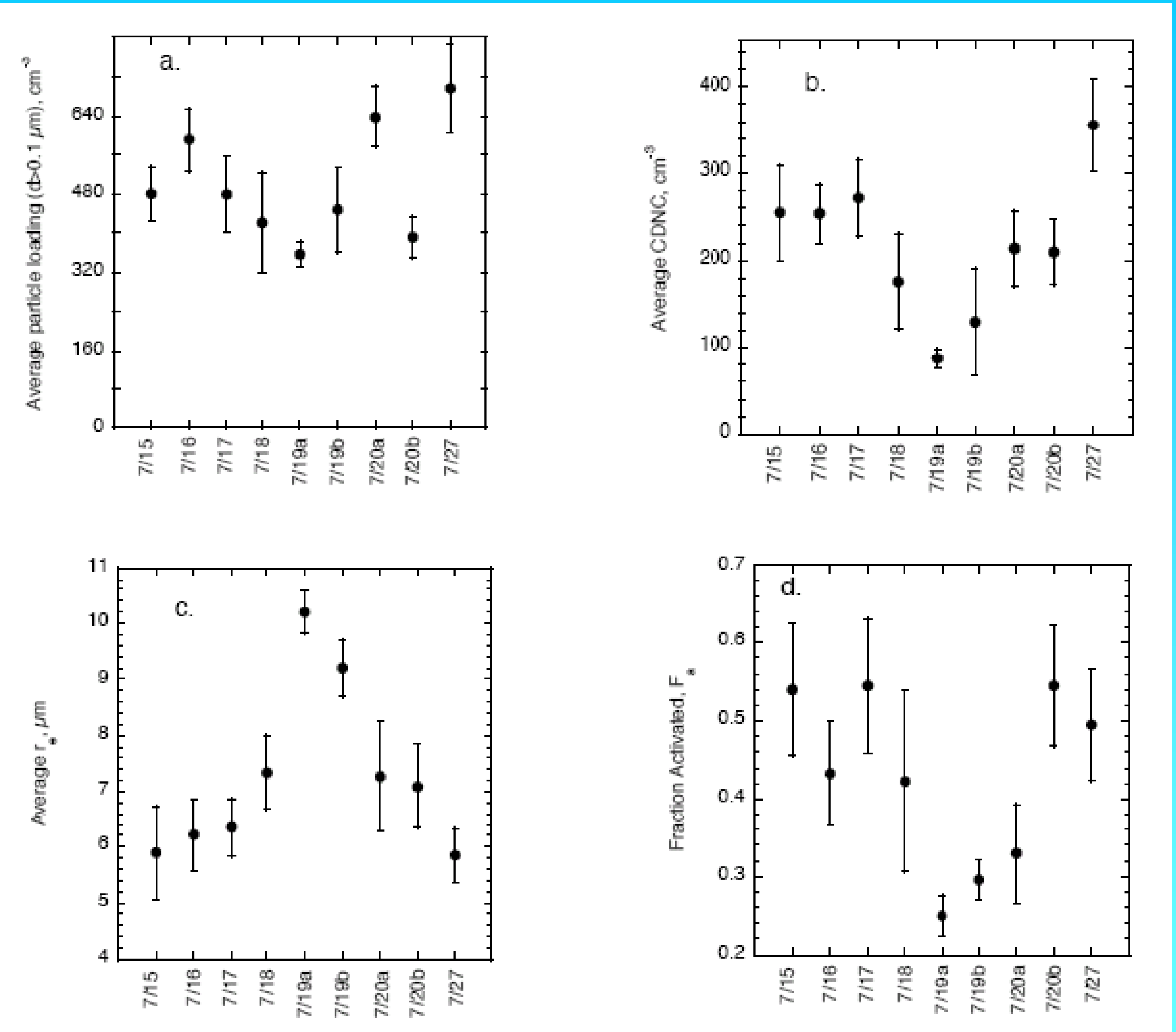
- Homogeneous versus heterogeneous mixing
  - AIE impacts apparently different
  - Thin clouds—heterogeneous?
- Wood: Cancellation of aerosol indirect effects through cloud thinning
  - Cloud base height is critical factor
  - Zcb<400 m feedbacks cancel Twomey
  - Consistent with low LWP results
- SGP: New results that support homogeneous mixing in clouds with higher LWP

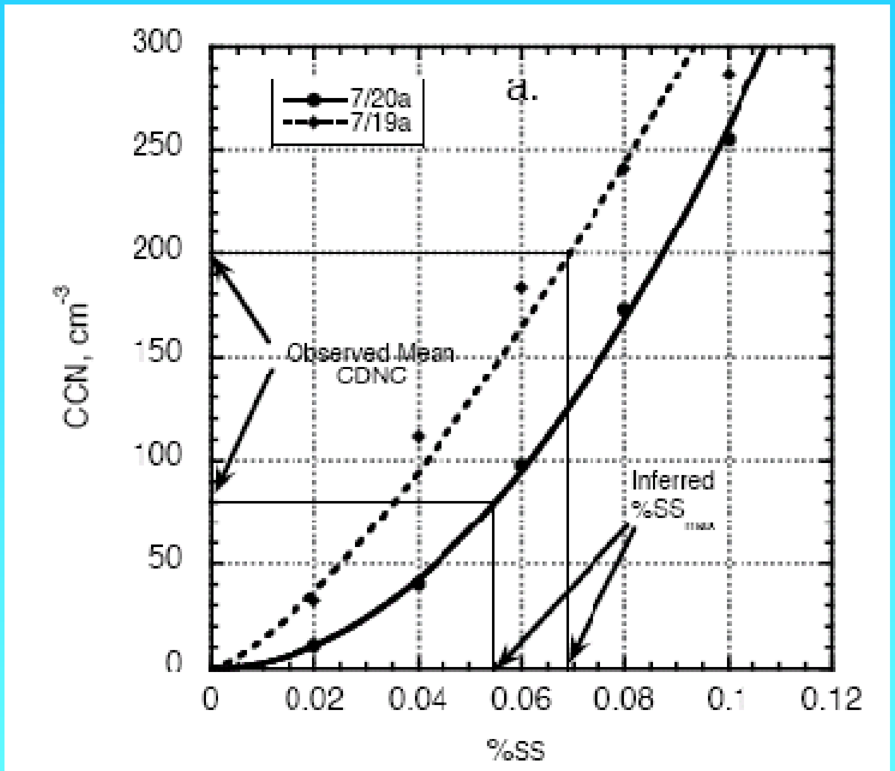


Altitude, m (msl)
Flight Altitudes
a.
0
100
200
300
400
500
7/15
7/16
7/17
7/18
7/19a
7/19b
7/20a
7/20b
7/27



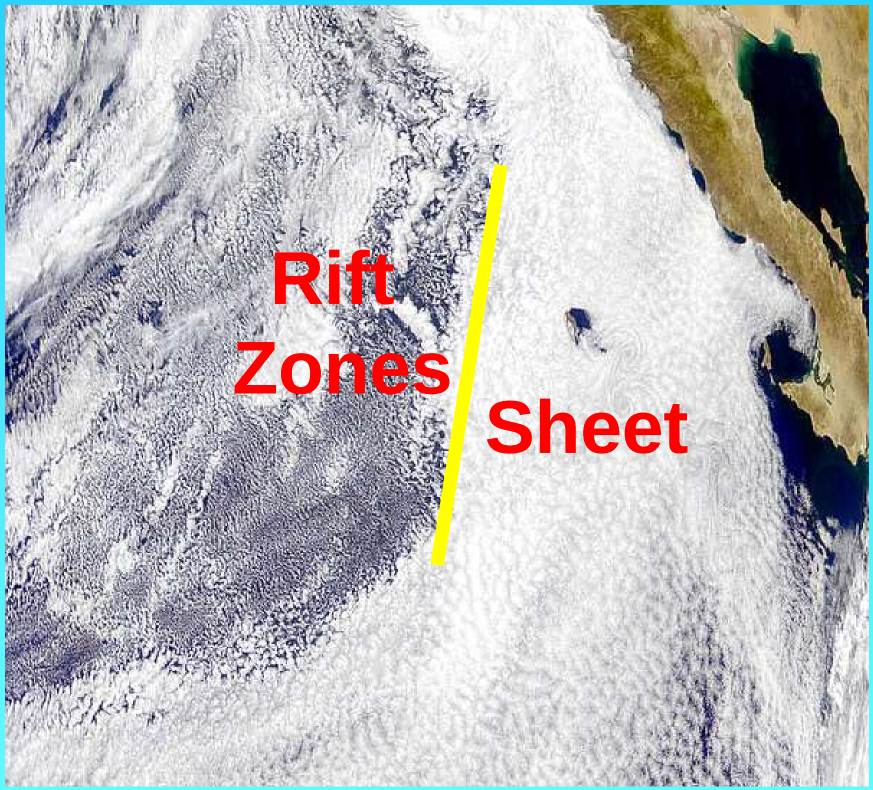
Liquid water path, g/m²
b.
0
50
100
150
200
7/15
7/16
7/17
7/18
7/19a
7/19b
7/20a
7/20b
7/27

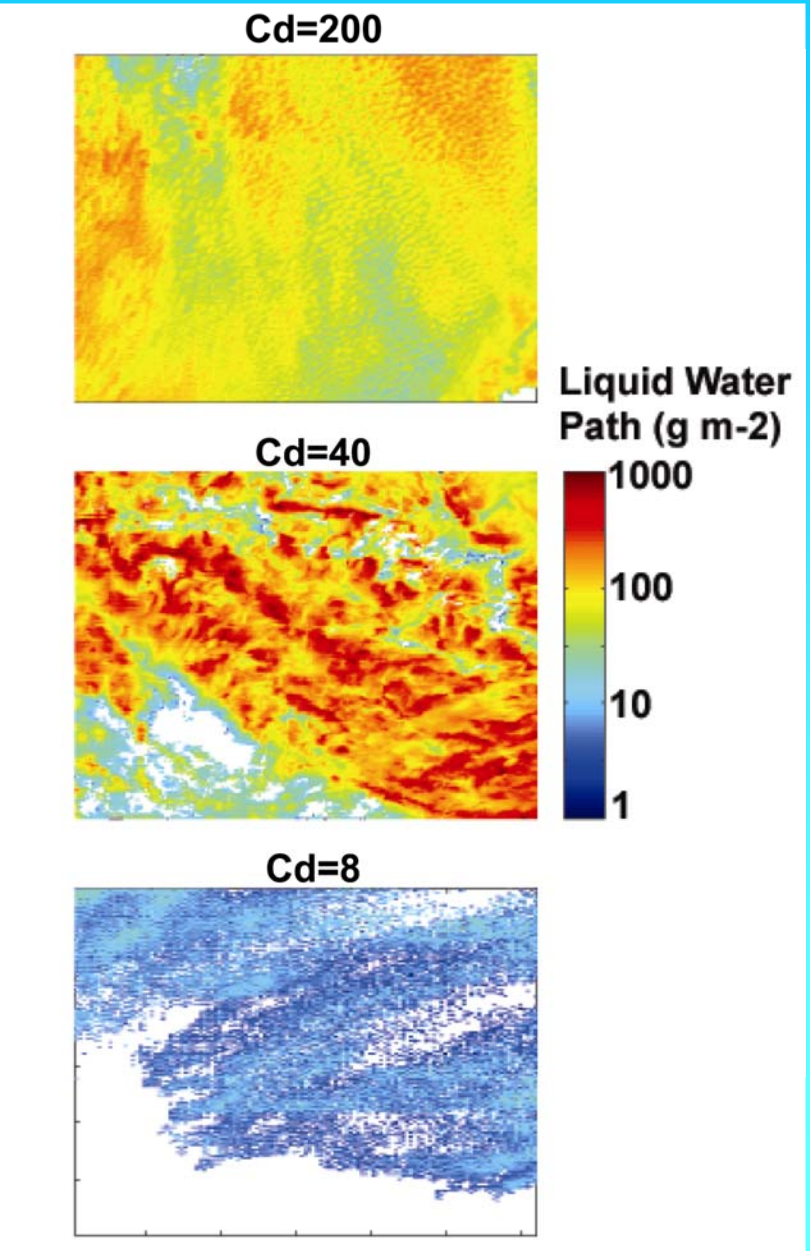

a.
Average particle loading (d>0.1 μm), cm-3
0
160
320
480
640
7/15
7/16
7/17
7/18
7/19a
7/19b
7/20a
7/20b
7/27
b.
Average CDNC, cm-3
0
100
200
300
400
c.
Average re, μm
4
5
6
7
8
9
10
11
d.
Fraction Activated, Fa
0.2
0.3
0.4
0.5
0.6
0.7



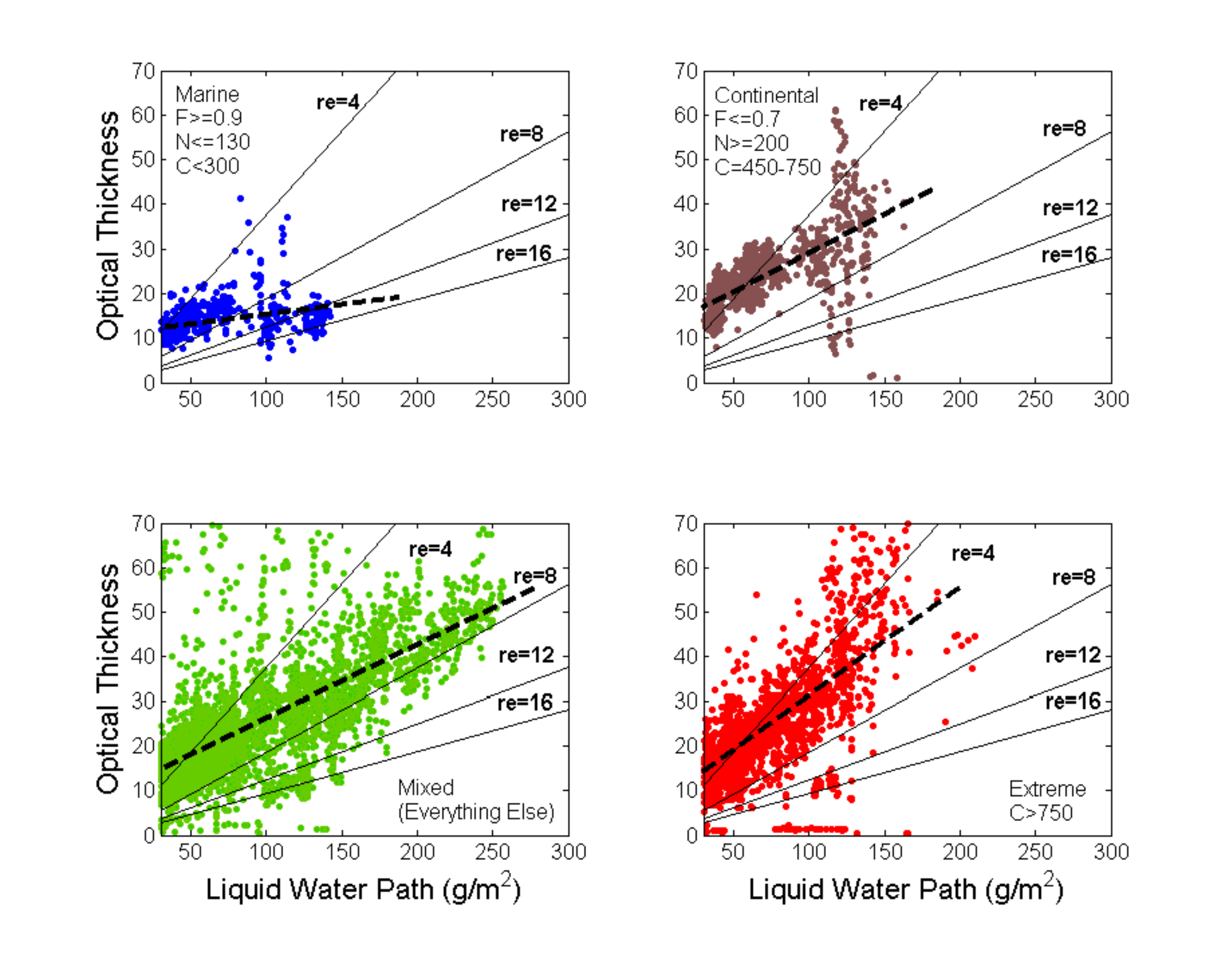
CCN, cm^{-3}
%SS
7/20a
7/19a
a.
Observed Mean CDNC
Inferred %SS$_{max}$
0
50
100
150
200
250
300
0
0.02
0.04
0.06
0.08
0.1
0.12

MODIS Analyses: Effective cloud diameter





r_e vs LWP response varies with air mass



Telford, J.W.(1996)

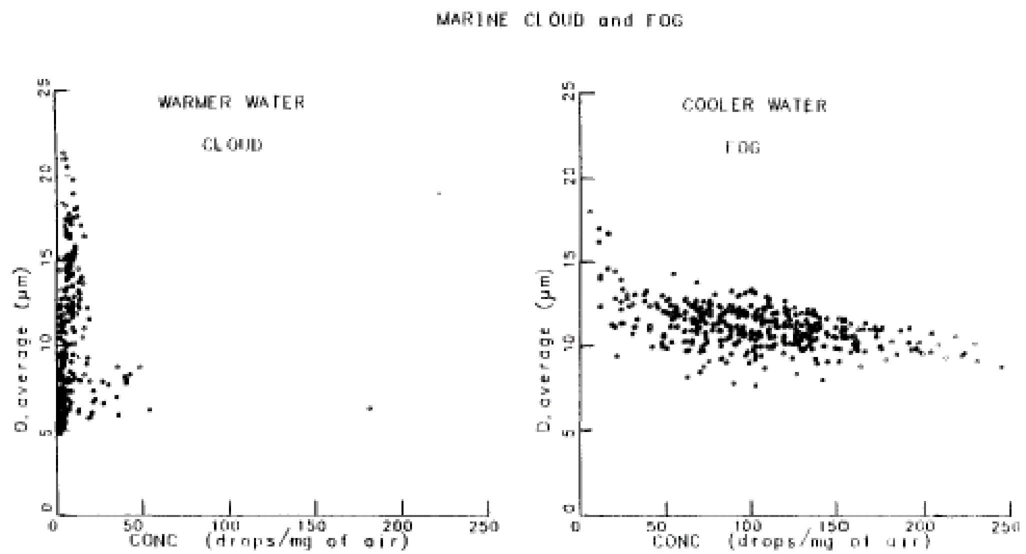
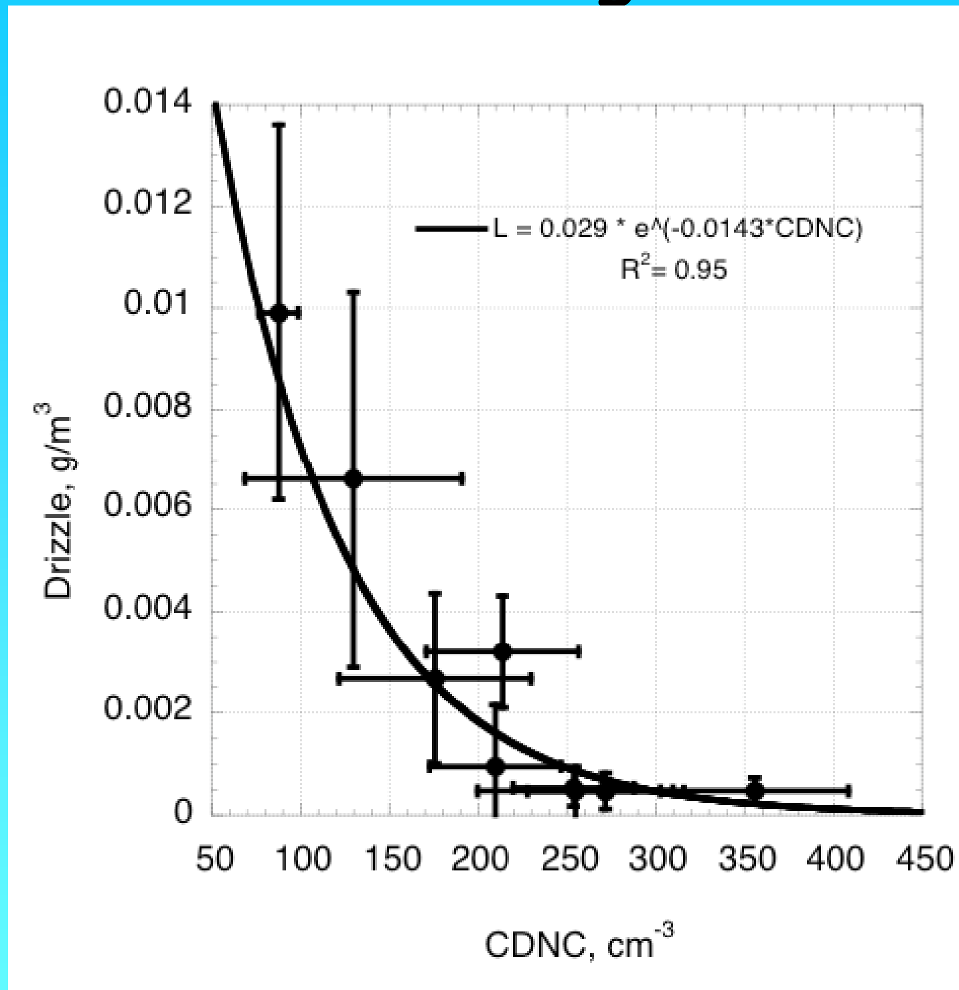
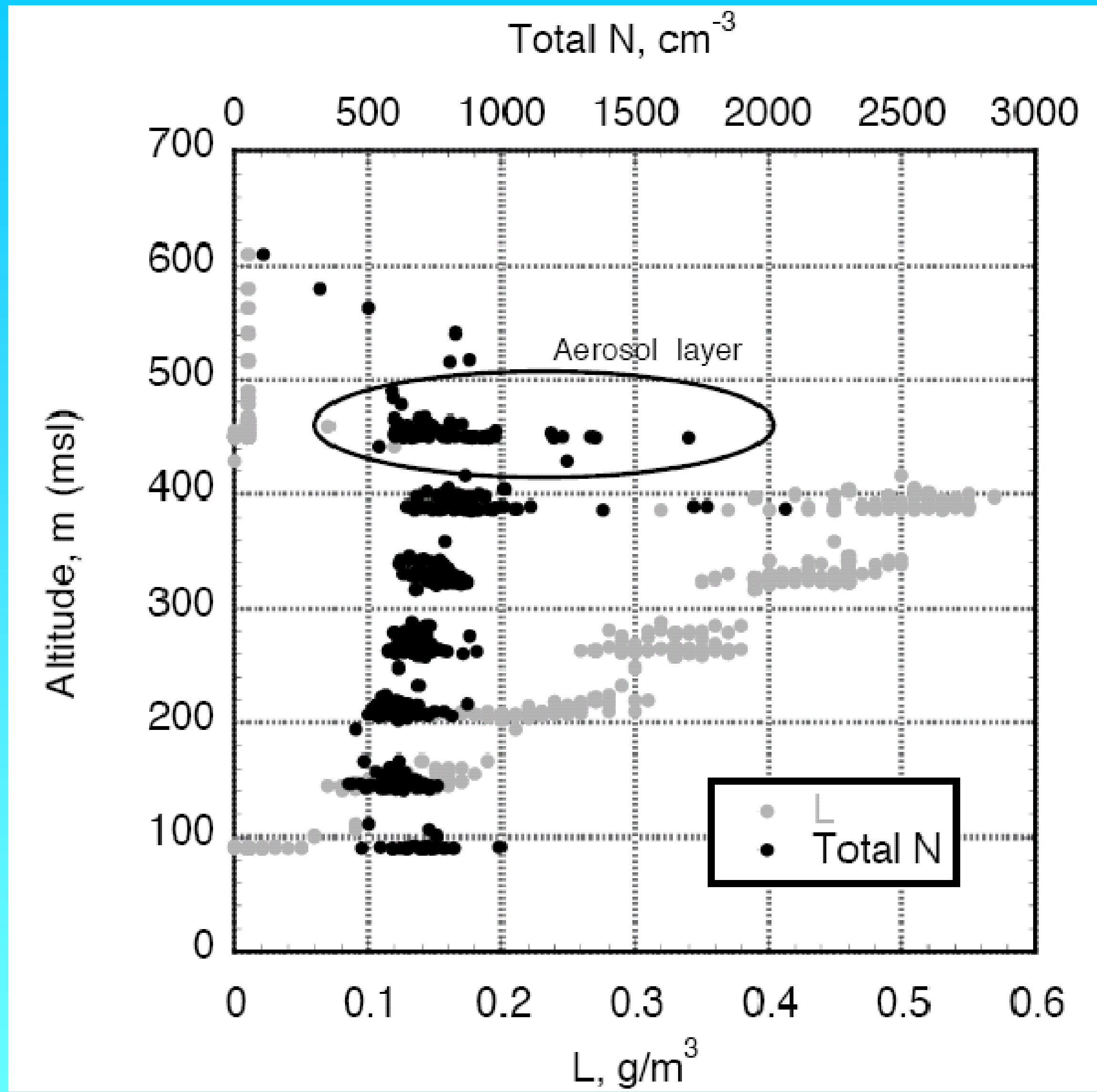


Fig. 2. The droplet spectra are compared over warm and cool water. The fog began convecting after reaching the warmer water beyond the coastal upwelling, and became diluted. The drop concentration over the warm water decreased to about 10% of the maximum in fog, and some parcels had average drop size diameters above 20 μm. The fog converted to small cumulus clouds, and the base rose as the dilution proceeded, and the tops penetrated through the inversion and soon the cloud totally evaporated. In the equilibrium fog over the cooler water the entrainment of dry air stopped after the fog formed near the coast. There was no turbulence in the fog and the average drop size was almost constant. The initial stage in ETEM (entity type entrainment mixing) leads us to expect equal sized drops with varying concentrations. This is fig. 6 from Telford and Chai (1993a).

Results from G-1 Flights During MASE

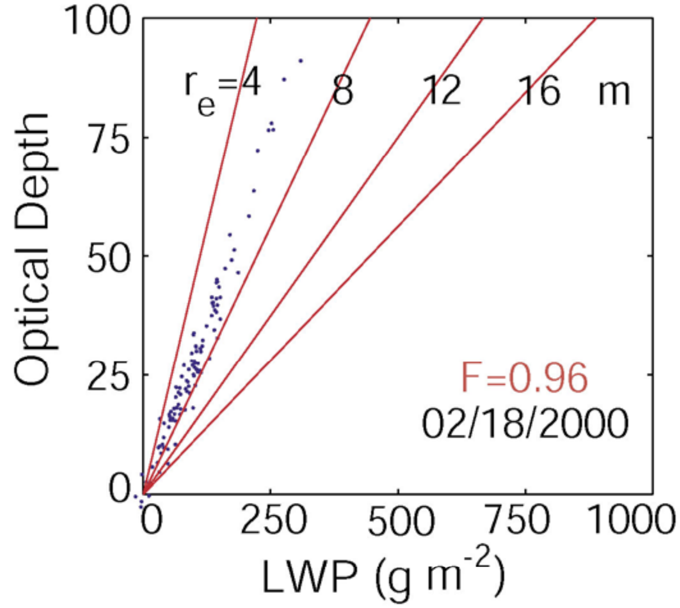


Increasing cloud droplet concentrations observed coincidently with a decrease in the drizzle concentration.


Total N, cm^{-3}
0
500
1000
1500
2000
2500
3000
700
600
500
400
300
200
100
0
Aerosol layer
Altitude, m (msl)
L
Total N
0
0.1
0.2
0.3
0.4
0.5
0.6
L, g/m^3

CLOUD OPTICAL DEPTH VS. LIQUID WATER PATH

North Central Oklahoma, 2000



Kim, Schwartz, Miller, and Min, JGR, 2003

Optical depth is highly correlated with and strongly dependent on liquid water path.

Tight cluster of points about a diagonal line through the origin is indicative of constant effective radius over the day.

Slope is inversely proportional to effective radius.

F, fraction of variance accounted for by regression = 96%.

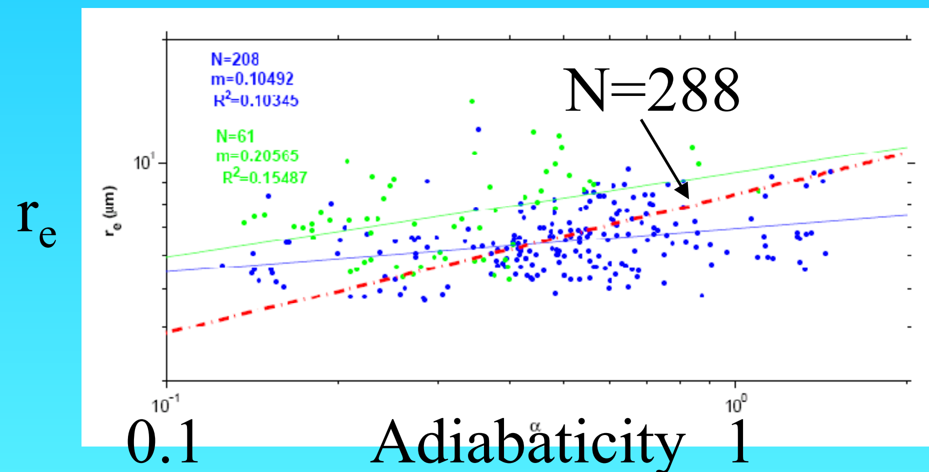
r_e r_e	Homogeneous Mixing	Heterogeneous mixing		
		Extreme case	Secondary activation	Enhanced growth
Underlying mechanism	Faster Mixing	Uniform evaporation	Nucleation	Coalescence
a_N and a_L	$a_N=1$	$a_N = a_L$	$a_N > a_L$	$a_N < a_L$
Mixing function	Mixing does not change N but reduce the sizes		Stronger mixing results in more droplets,	Stronger mixing results in less but bigger droplets
Response of r_e	Depending on a_b and a_L	r_e independent of a_L	decreases with decreasing a_L	increases with decreasing a_L
Formula	$r_e = \alpha_\beta r_{ea} \left(\alpha_L\right)^{1/3}$	$r_e = \alpha_\beta r_{ea}$	$r_e = \alpha_\beta \left(\frac{\alpha_L}{\alpha_N}\right)^{1/3} r_{ea}$	$r_e = \alpha_\beta \left(\frac{\alpha_L}{\alpha_N}\right)^{1/3} r_{ea}$
AIE Effect	?	No change	More AIE effect	Less AIE effect

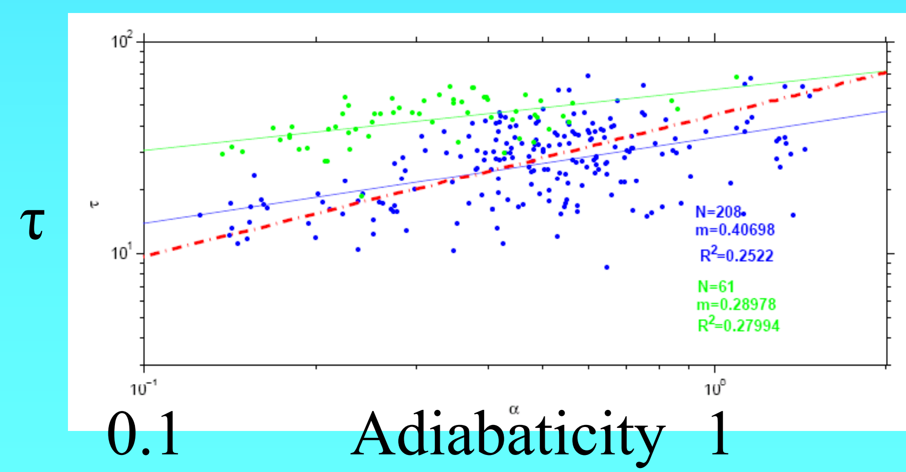
Impacts of Cloud Dynamics on Cloud Microphysics

Adiabaticity, α
α = 1: adiabatic
α < 1: sub-adiabatic

Bins of Cloud Thickness

Blue: 50-600m
Green: 600-1000m





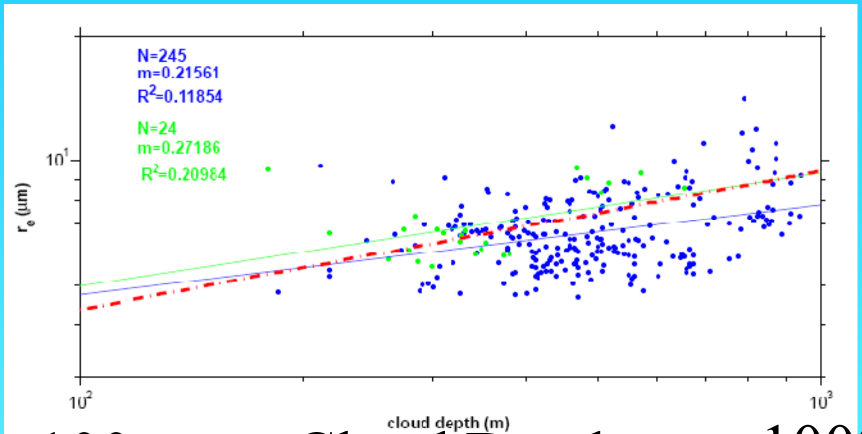
Collaborators: B.G. Kim, Steve Schwartz

Impacts of Cloud Dynamics on Cloud Microphysics

Bins of Adiabaticity

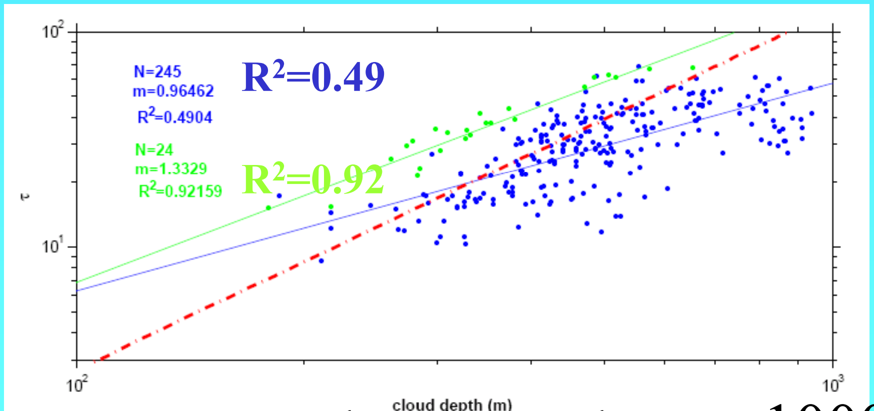
Blue: 0.1-0.9
Green: 0.9-1.5

r_e



100 Cloud Depth 1000

τ



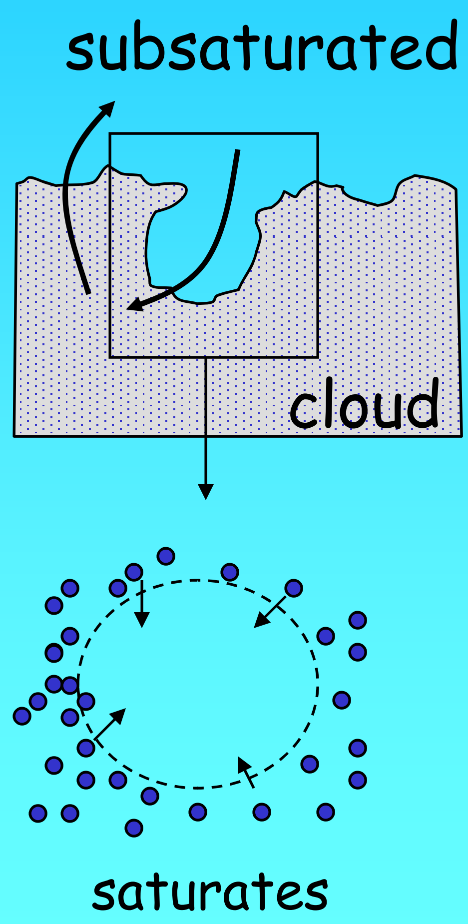
100 Cloud Depth 1000

Collaborators: B.G. Kim, Steve Schwartz

The Entity-Type Entrainment Mixing Process

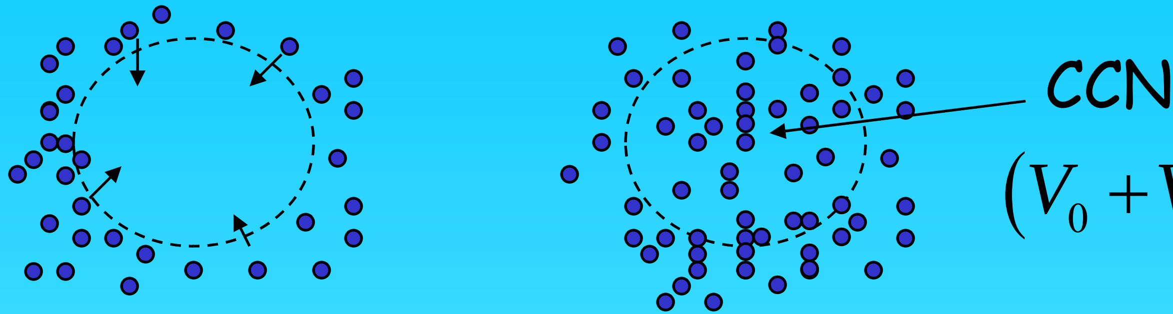
J.W. Telford

Stage 1



1. Droplets evaporate into subsaturated air
2. Cooling
3. Descending vortex
4. Saturation

Stage 1 Stage 2

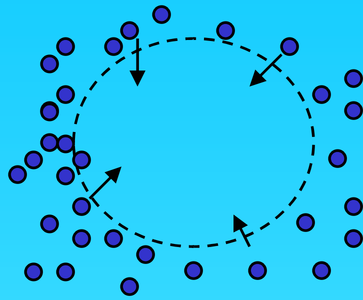


saturates well-mixed

$$\left(V_0 + V_c\right)\left(C_0 + C_{ic} + n_{ed}\right)$$

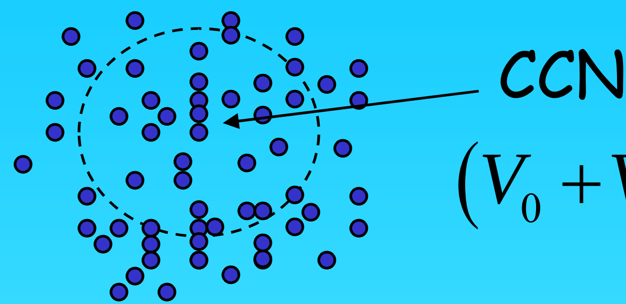
1. Reduction in size and number of entrained droplets prior to saturation
2. Droplets enter turbule after saturation with no change in size
3. Drastic changes in number concentration from parcel to parcel

Stage 1



saturates

Stage 2

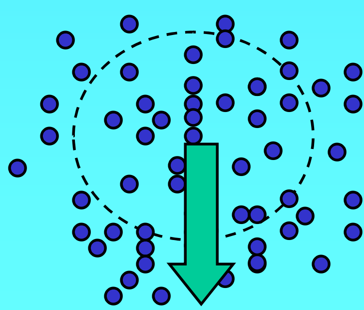


$$\left(V_0 + V_c\right)\left(C_0 + C_{ic} + n_{ed}\right)$$

well-mixed

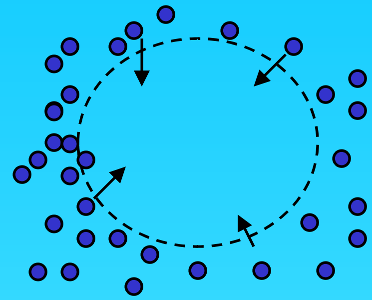
1. Evaporation to smaller sizes than at same pressure during undiluted ascent
2. Same amount of water has to evaporate from less droplets
3. Continued entrainment of larger undiluted drops adds a supply of larger drops
4. Parcel contains a wide range of diameters

Stage 3



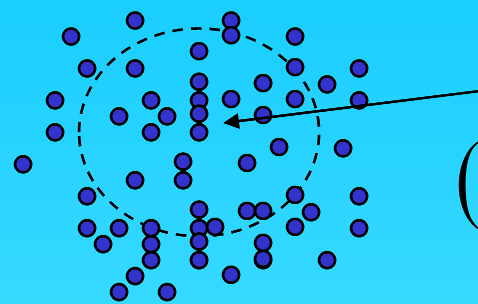
descent

Stage 1



saturates

Stage 2



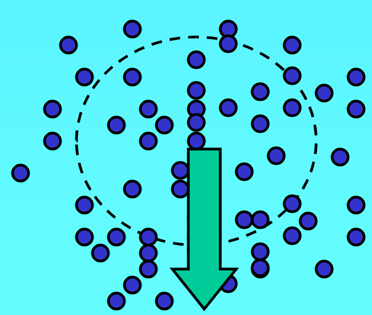
well-mixed

CCN

$$\left(V_0 + V_c\right)\left(C_0 + C_{ic} + n_{ed}\right)$$

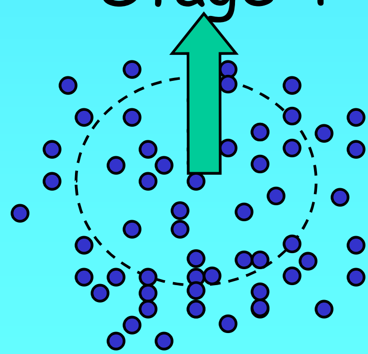
1. Rise to accommodate newly descending parcels
2. Few biggest droplets acquire a disproportionate fraction of new water
3. Large droplets formed
4. Mocks giant nuclei

Stage 3



descent

Stage 4



re-ascent

Observables Checklist

- Stage 1
  - Reduced reflectivity in pockets near cloud top
  - Considerable variability in reflectivity near cloud top
- Stage 2 and 3
  - Large variations in number density from parcel to parcel
  - Descent
  - Lower reflectivity and wider spectral width in the downdrafts relative to the updrafts
- Stage 4
  - Possible enhanced reflectivity in some updrafts due to the presence of exceptionally large droplets.

Cloud Droplet Size Distributions in Low-Level Stratiform Clouds

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(Manuscript received 29 May 1998, in final form 10 February 1999)

TABLE 3. Summary of results in Tables 1 and 2, listing mean values and standard deviations of various microphysical quantities for marine and continental clouds.

	Marine	Continental
$N_{t,obs}$ (cm^{-3})		
mean	74	288
std dev	45	159
$D_{m,obs}$ (μm)		
mean	14.2	8.2
std dev	3.4	3.9
$\sigma_{x,obs}$ (μm)		
mean	5.8	3.1
std dev	2.0	1.2
LWC_{obs} ($g\ m^{-3}$)		
mean	0.18	0.19
std dev	0.14	0.21

Number Density

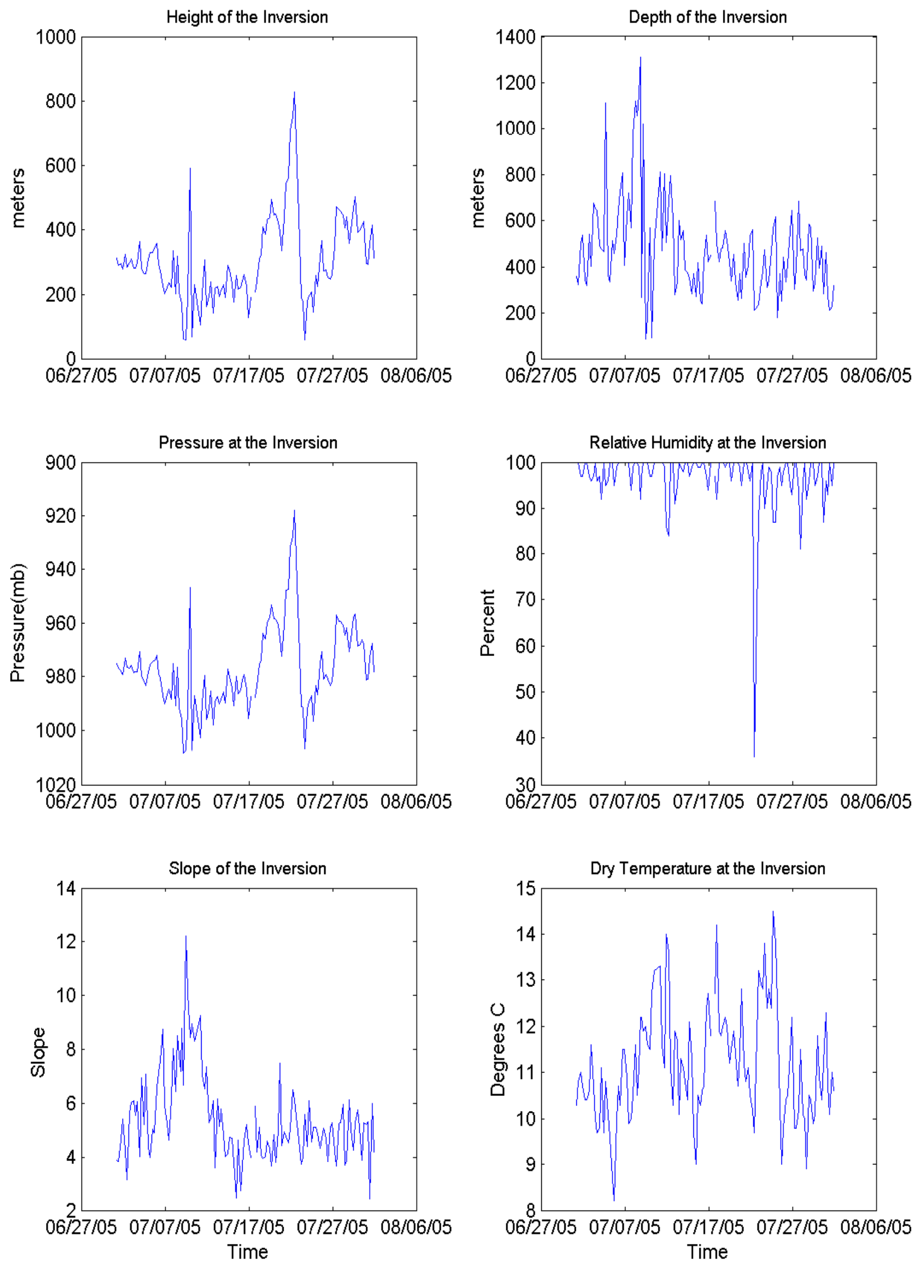
Mean and Standard Deviation

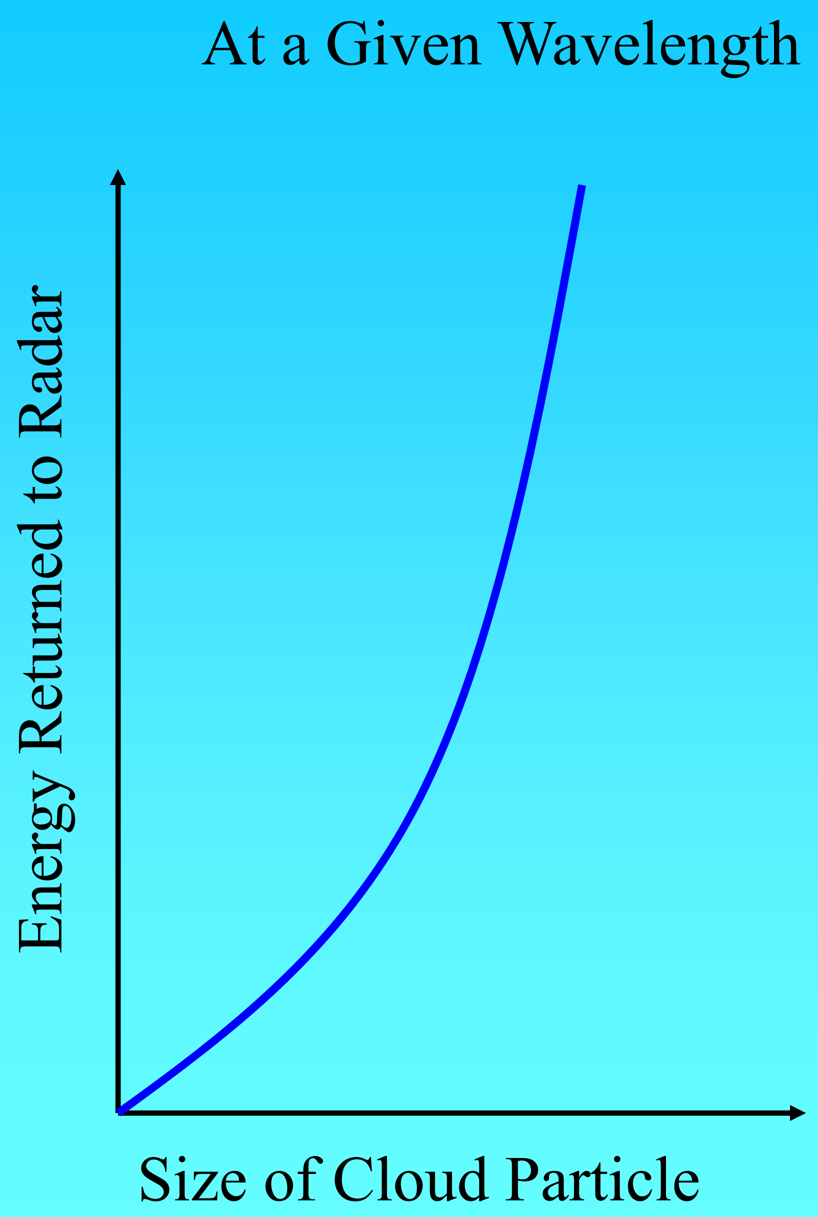
Continental

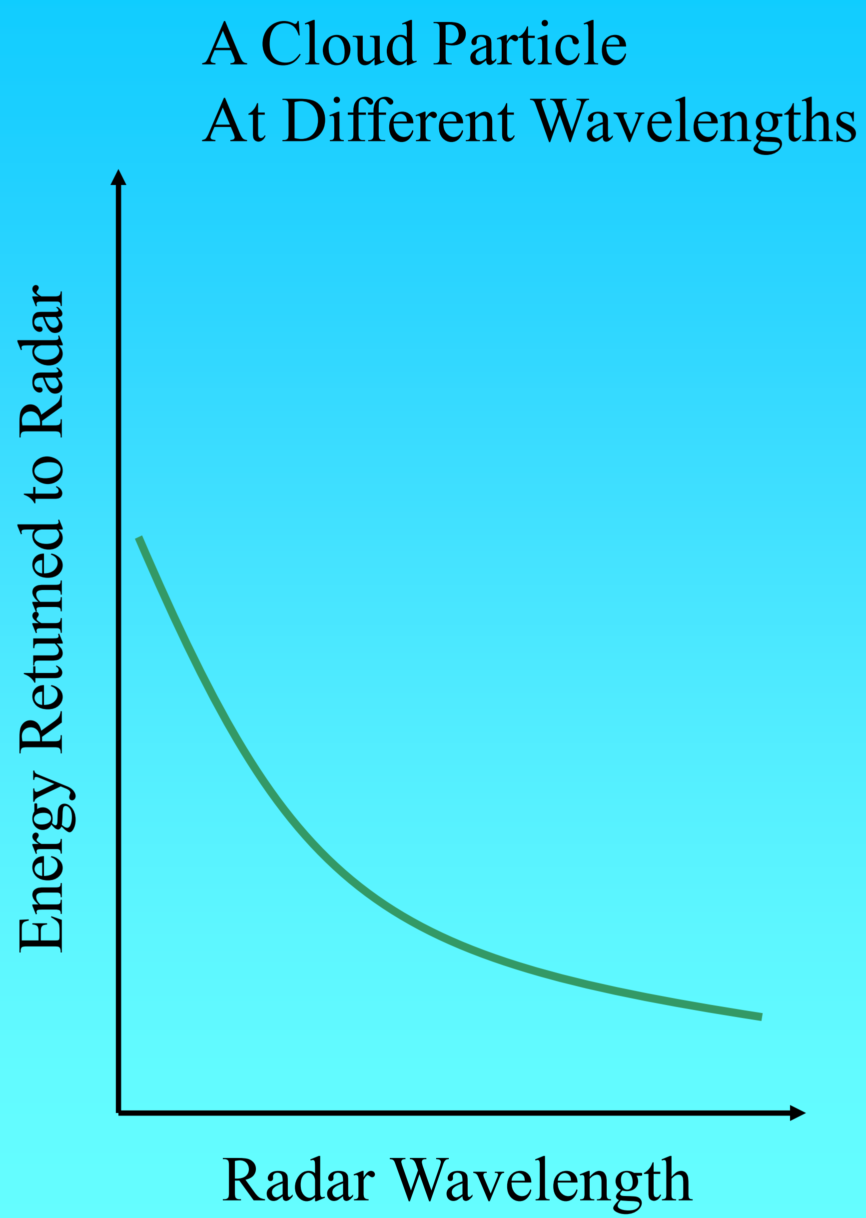
288 cm^{-3}

159 cm^{-3}

July 2005 Marine Inversion Data




At a Given Wavelength
Energy Returned to Radar
Size of Cloud Particle


A Cloud Particle
At Different Wavelengths
Energy Returned to Radar
Radar Wavelength

Fundamental Relationships

$$D_{\uparrow} / I_0 = \frac{(1-g)\tau}{2+(1-g)\tau}$$

Shortwave Albedo

Assume $Q_e \approx 2$

$$\tau = \frac{3}{2}\frac{L}{\rho_w r_e}$$

Liquid Water Path (LWP)

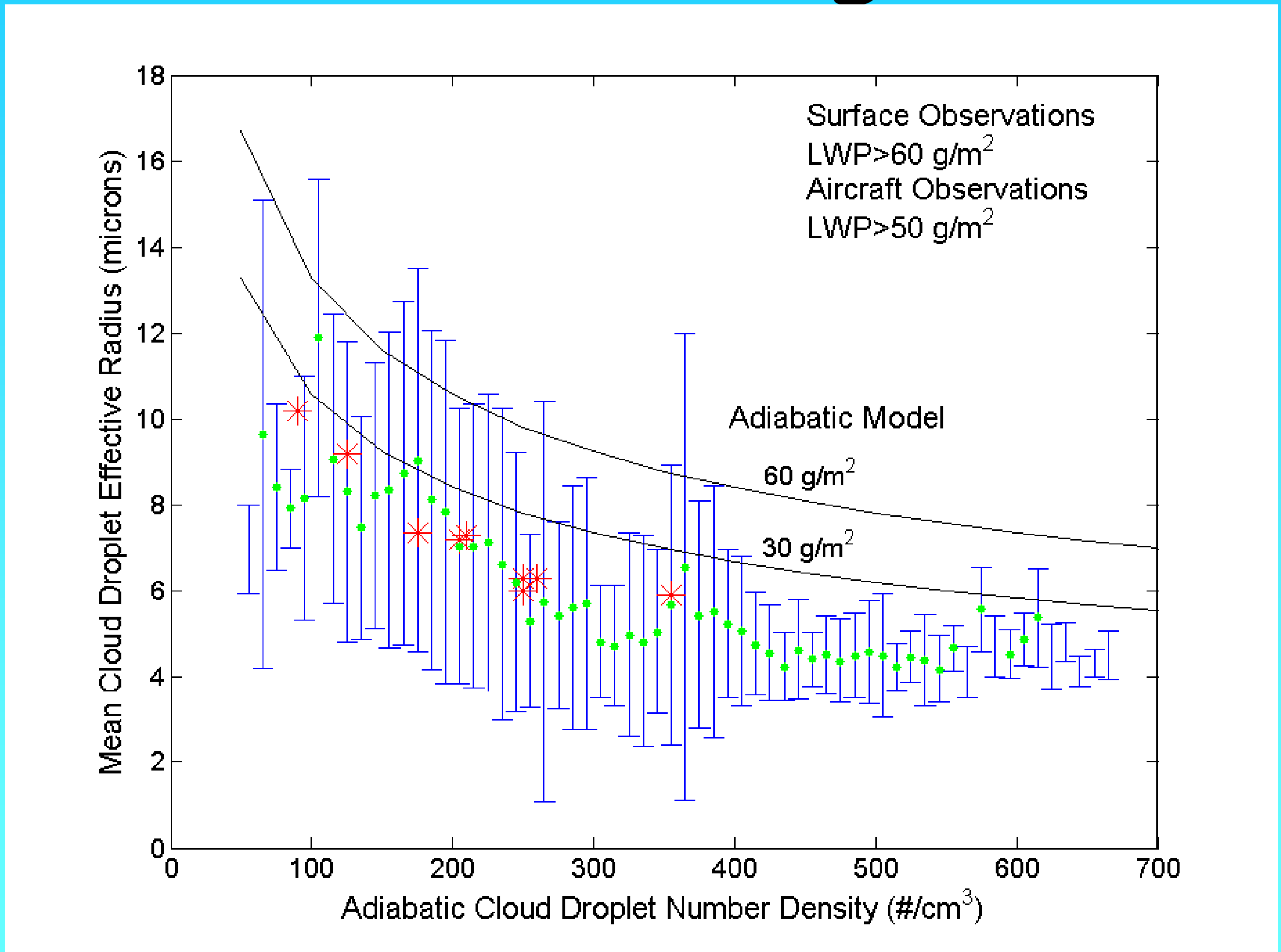
How much total liquid in the cloud?

How much surface area does the liquid have?

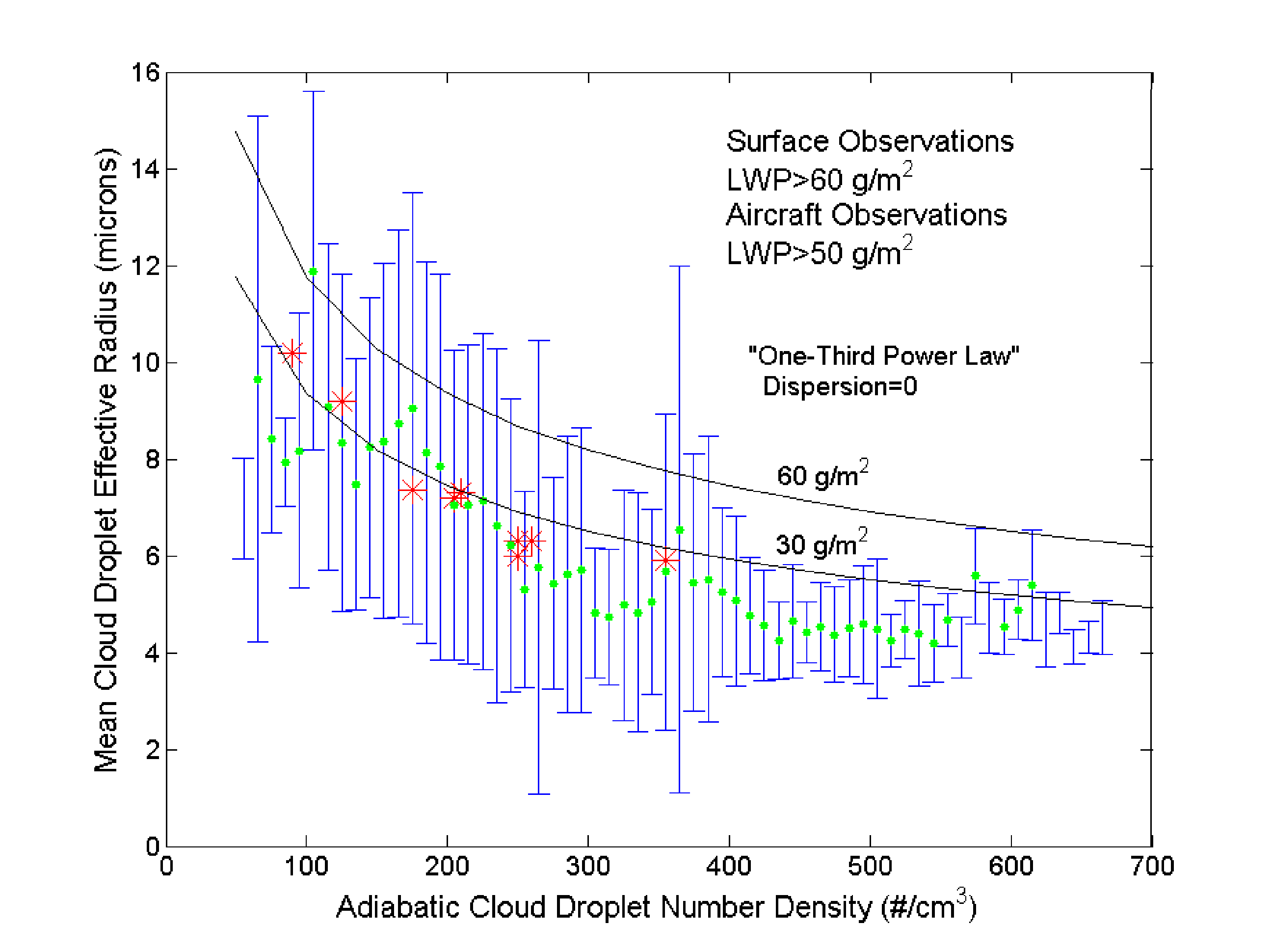
Effective Radius

--Mean radius for scattering

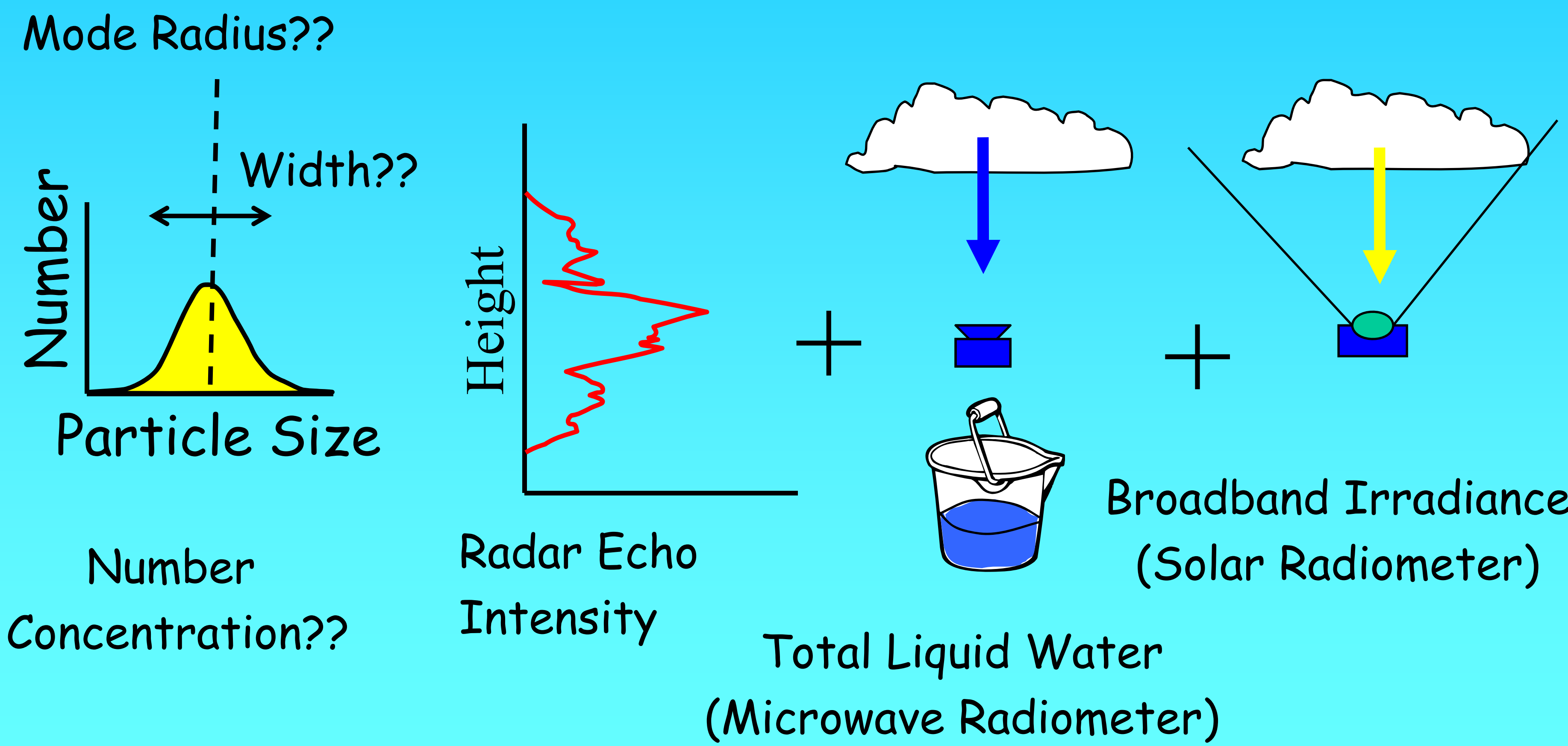
Results for High LWP



Results for High LWP



Remotely Sensing the Cloud Droplet Distribution



Effective Radius