Diagnosing Cloud Microphysical Process Information from Remote Sensing Measurements—A Feasibility Study Using Aircraft Data. Part I: Tropical Anvils Measured during TC4

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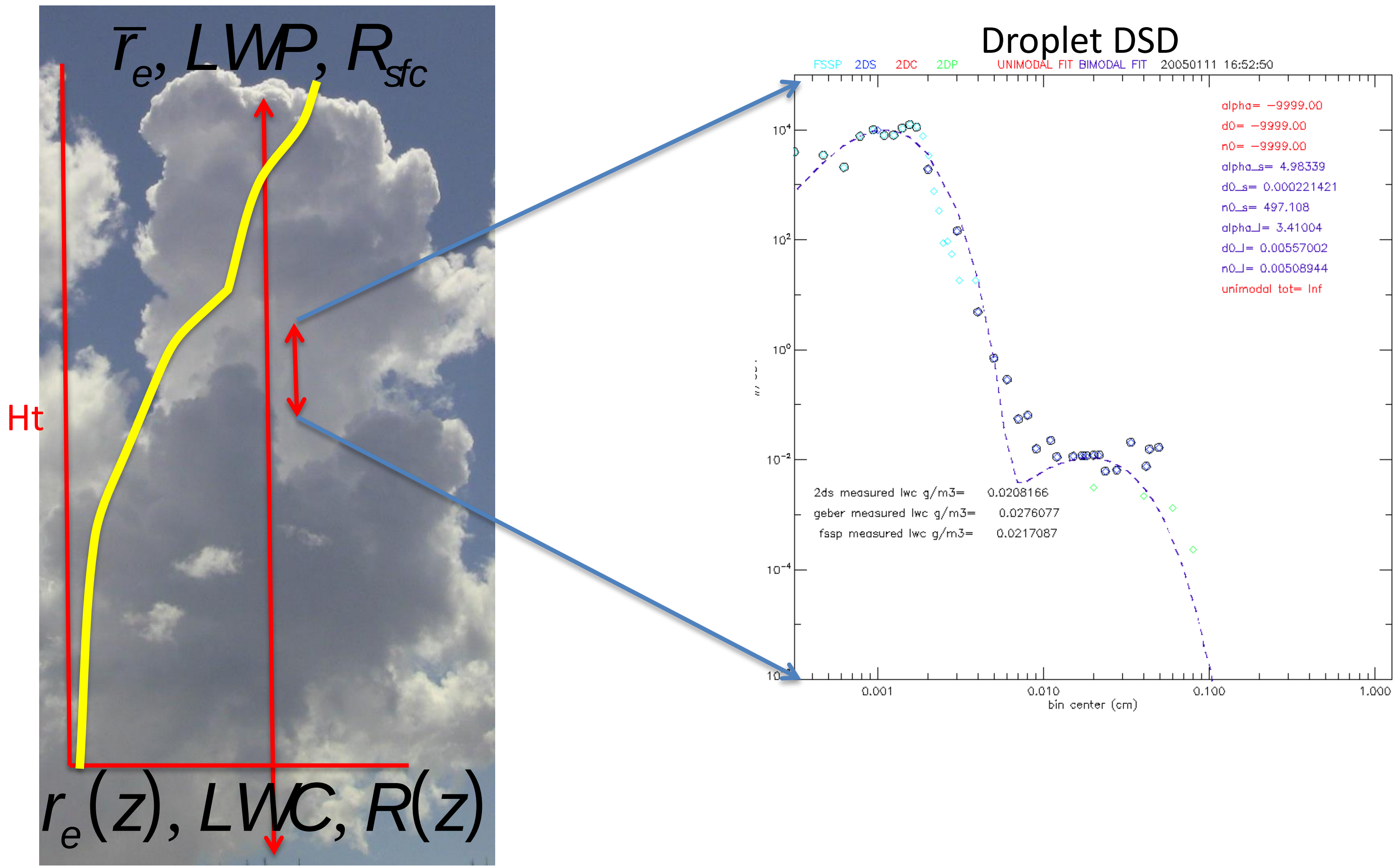
Evolution of Satellite Measurement Strategy

Past (passive): Characterize the bulk properties of profiles (Column mean properties)

Present (A-Train, GPM): Characterize the basic profile of microphysics (LWC(z), re(z))

Future? (ACE): Characterize the processes that drive changes to particles in the column



By Processes we mean the conversion of one hydrometeor species to another. Here we are interested in collection (specifically self collection)…

$$\frac{\partial r_p}{\partial t} = \frac{Ep}{4 r_0} \int N(D_p) \left[\int N(D_c) m_c (D_c + D_p)^2 dV \, dD_c \right] dD_p$$

The terms in the collection equation are either measured directly N(D), can be inferred (V) or approximated (M-D, A-D) or assumed E. So processes *can* be estimated from the in situ measurements using numerical solutions of the double integral (Field et al., and others).

Consider a parameterization of processes by Khairoutdinov and Kogan (2000)

Rico Clouds (Rauber et al, 2008)

Autoconversion – growth of cloud mode droplets to precipitation size

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

Accretion – collection of cloud drops by falling precipitation

$$\left(\frac{\partial q_r}{\partial t}\right)_{accre} = 57 (q_c q_r)^{1.15}$$

Note: No time derivative on RHS.

We can conceive of two approaches whereby remote sensing could perhaps “observe” microphysical process…

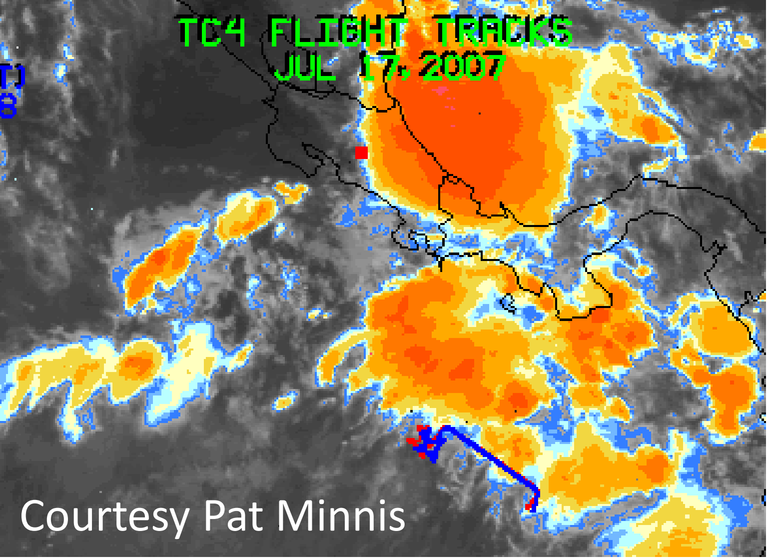
1. Take two measurements of the same volume separated in time and observe changes to the measureables from which process can be inferred (i.e. a train of small satellites)

2. Use the collection kernel and a broad suite of measurements to diagnose (retrieve) the dominant process instantaneously.

$$\left(\frac{\partial q_r}{\partial t}\right)_{accre} = 57\left(q_c q_r\right)^{1.15}$$

Fundamentally, we need to know something quantitative about the particles being collected and the particles doing the collecting- simultaneously.

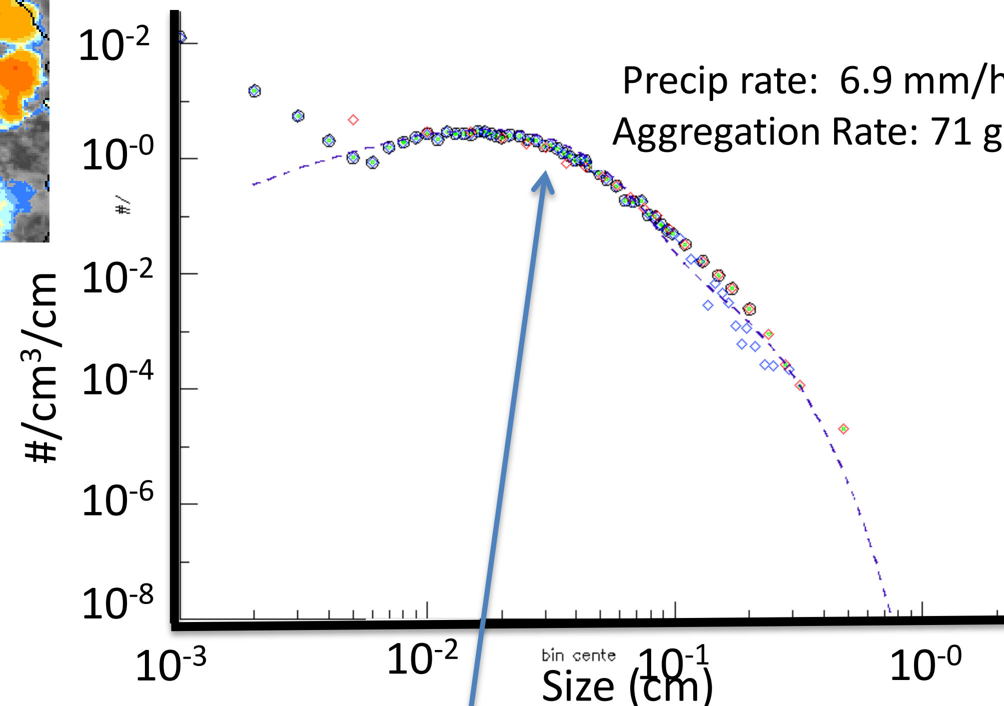
An Example



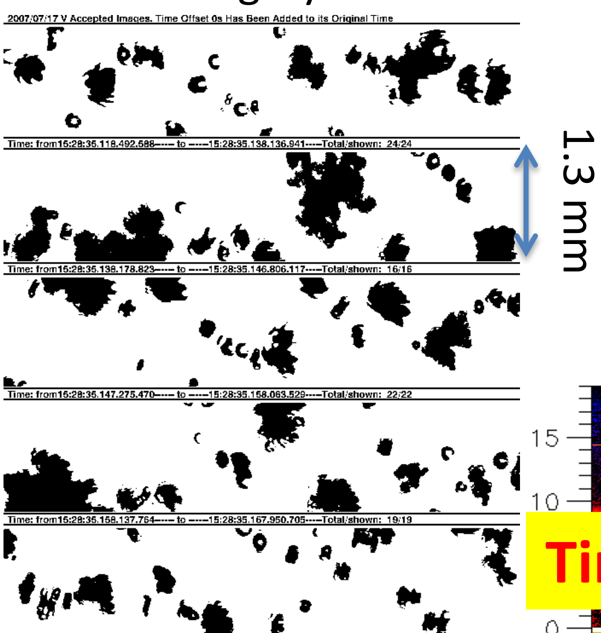
dBZ Ku: +15.3 dBZ w: +13.3
Vd Ku: 159.8 Vd w: 149.9

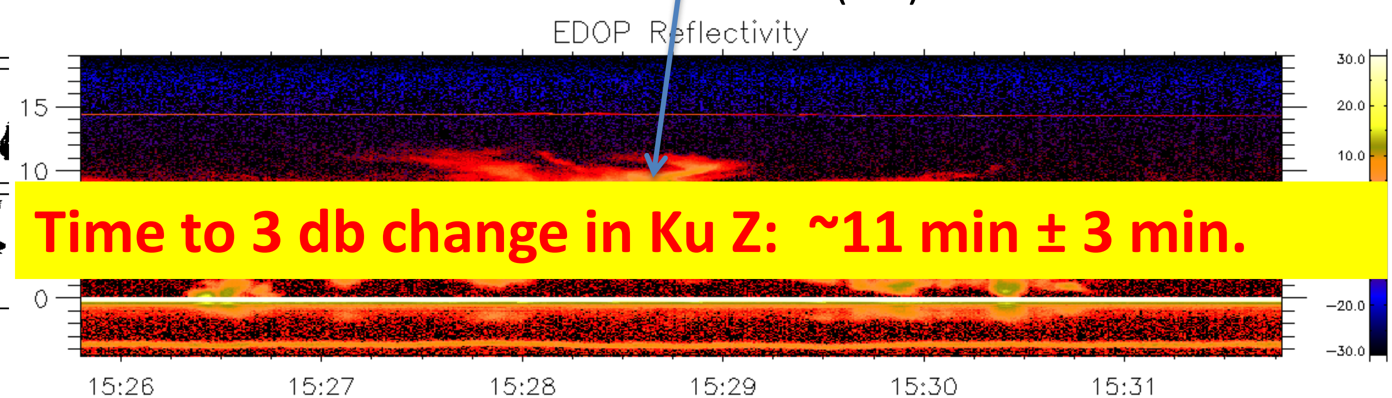
r_e: 404 microns
Nt: 121 per liter
IWC=0.44 g/m^3

Precip rate: 6.9 mm/hr
Aggregation Rate: 71 g/m^2/km/hr



2DS Imagery at 15:38:35



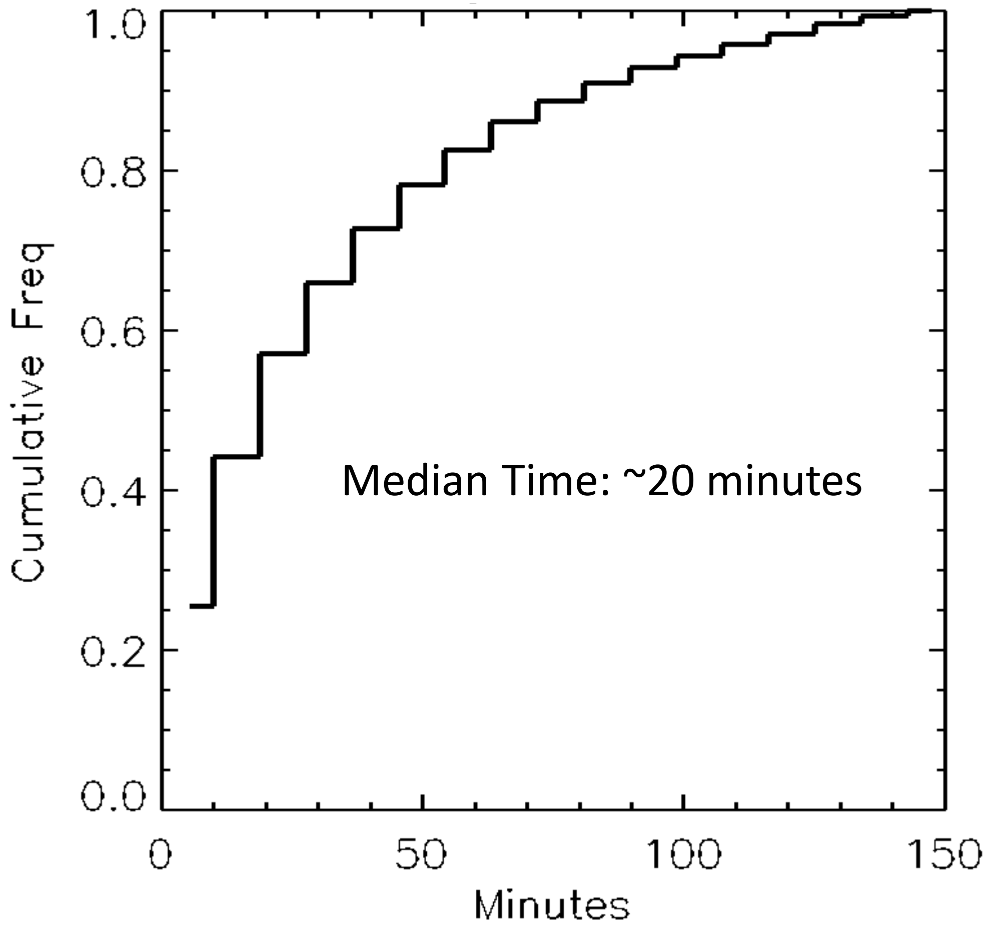


Time to 3 db change in Ku Z: ~11 min ± 3 min.

Can Process Rates be inferred by watching radar measureables change?

Cumulative Distribution Function derived from all ice clouds sampled during TC4

Time to 3db change in Z due to Aggregation



Can Process be inferred from some combination of radar measureables? Or Can Process information be retrieved?

We examine *Information Content* as a function of Measurement Error and assumed parameters (Forward Model Error), and the sensitivity (d(Z, Vd)/d(parameter)) using PSD's directly measured during TC4.

Consider a Retrieval problem posed as follows:

$$y = \begin{bmatrix} Z_{HiFreq} \\ dZ \\ Vd_{HiFreq} \\ dVd \end{bmatrix} \qquad x = \begin{bmatrix} Aggregation\ Rate \\ precipitation\ Rate \end{bmatrix} \qquad K_x = \frac{\partial y}{\partial x}$$

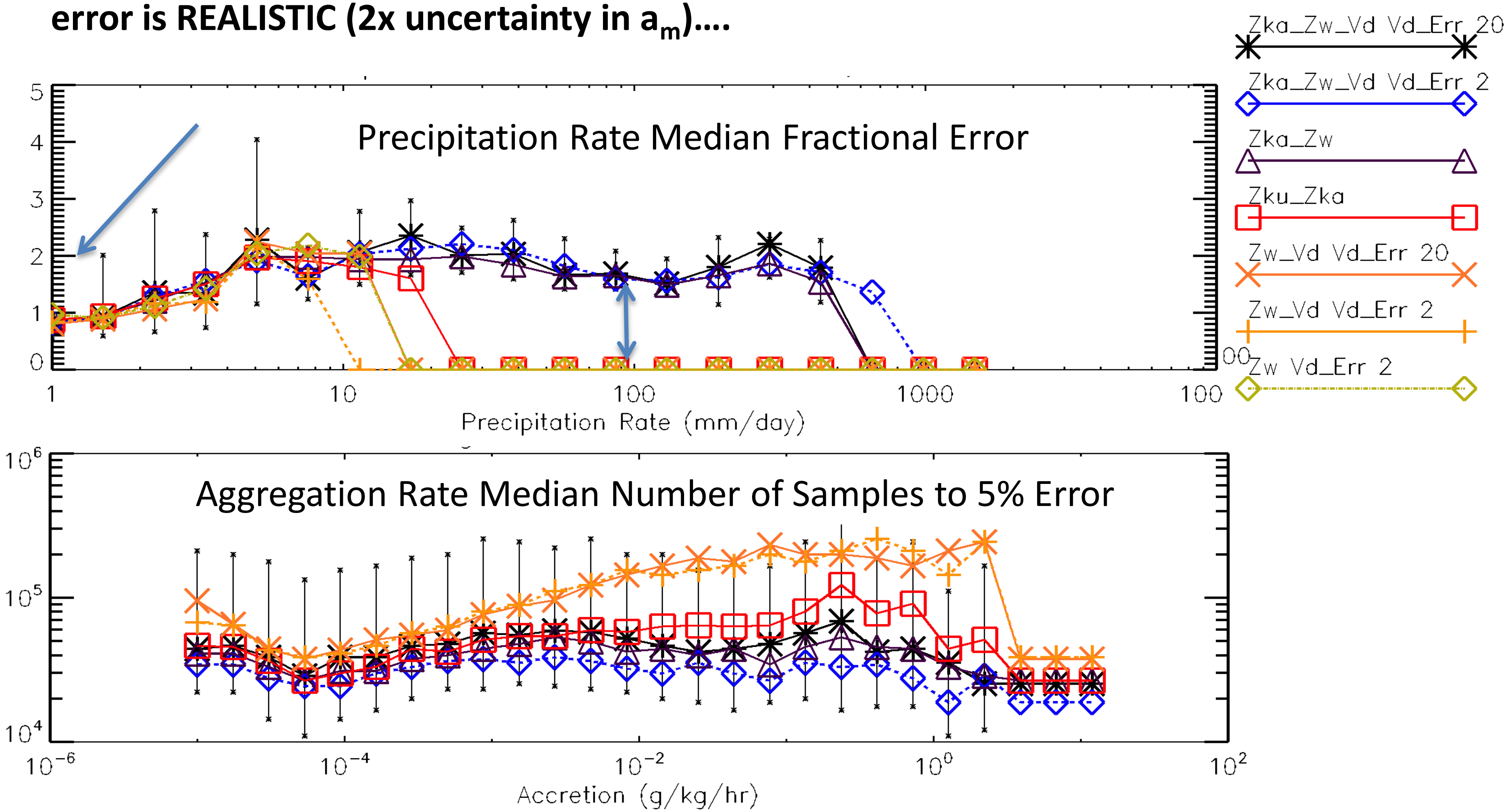
$N_y x N_x$ Matrix of Sensitivities

Prior and S_a derived from in situ statistics

- Using optimal estimation methodology, derive uncertainty in *x* as a function of various combinations of frequencies, with and without Doppler of varying precision
- Allow for **forward model error** determined by uncertainty in $M=a_m D^{b_m}$ that drives uncertainty in radar backscatter cross section and Doppler velocity.

Can Process be inferred from some combination of radar measureables?

Examine Skill of Various Algorithms at Retrieving **Precip Rate** when the **forward model error is REALISTIC (2x uncertainty in a_m)….**



- Single Frequency with Doppler (and Ku/Ka) lose all information at higher precip rates
- Errors in Precip retrieval Rise to 200% for all algorithms.
- Doppler provides no advantage

Can Process be inferred from some combination of radar measureables?
Can Process information be retrieved?

Sensitivity of Measureables to Assumptions (factor of 2 uncertainty in a_m)

$$\frac{\partial Z_w}{\partial a_m} \approx 6.5\,dB \qquad \frac{\partial V_d}{\partial a_m} \approx 175\,{}^{cm}\!/\!_{s}$$

Sensitivity of Measureables to Desired Geophysical Parameters

$$\frac{\partial Z_w}{\partial P} \approx 9\,dB \qquad \frac{\partial Z_w}{\partial Agg} \approx -2\,dB \qquad \frac{\partial V_d}{\partial P} \approx 10\,{}^{cm}\!/\!_{s}$$

Sensitivity of observations to assumptions is at least as large and in some cases MUCH larger than the sensitivity of the observations to desired geophysical parameters.

Perhaps we should be retrieving the assumptions and assuming the geophysical parameters? - Rhetorical question for now…

Anvil Productivities of Tropical Deep Convective Clusters and Their Regional Differences

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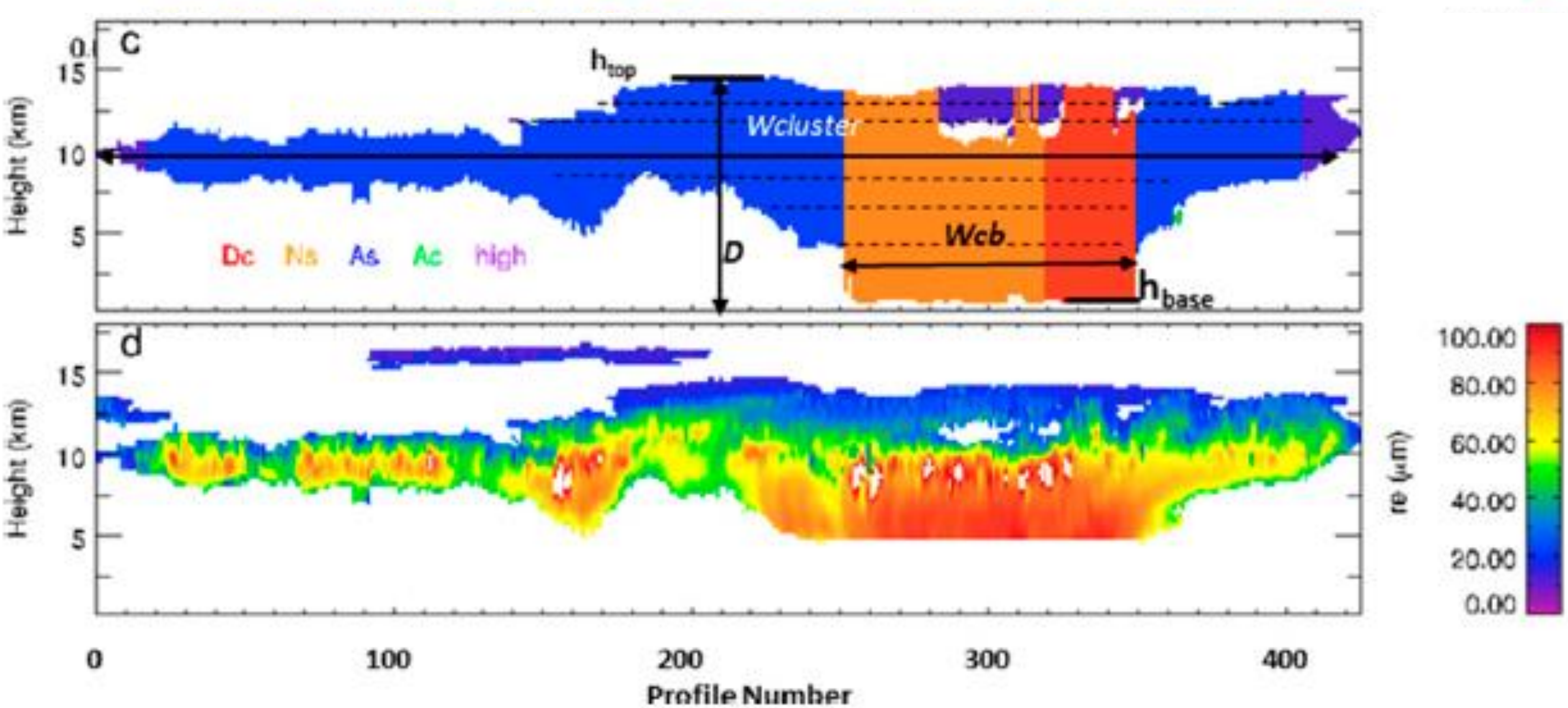

$$r_w = \frac{W_{\text{anvil}}}{W_{\text{cluster}}},$$ Anvil Scale Ratio

$$r_v = \frac{V_{\text{anvil}}}{V_{\text{cluster}}},$$ Anvil Volume Ratio

$$r_m = \frac{\text{IM}_{\text{anvil}}}{\text{IM}_{\text{cluster}}}.$$ Anvil Mass Ratio

Appears to be a common scaling behavior in anvil productivity when cast in terms of these ratios.

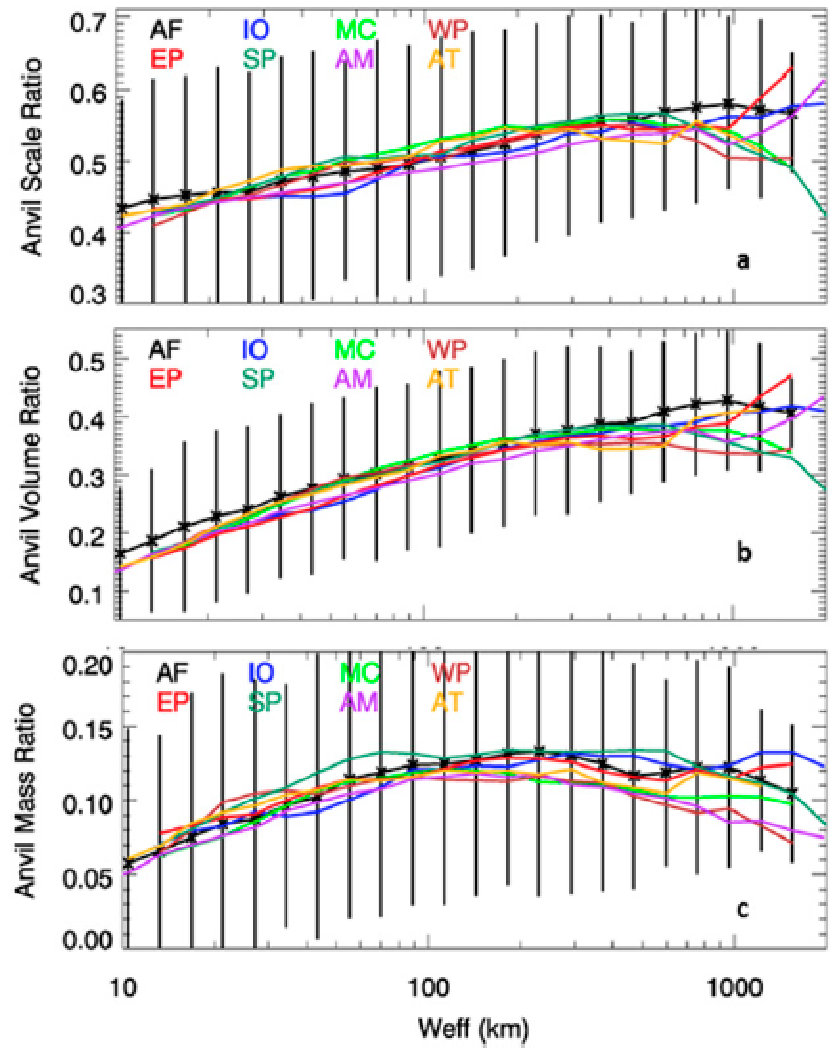

FIG. 9. Composite mean of (a) anvil scale ratio (r_w), (b) cross section volume ratio (r_v), and (c) ice mass ratio (r_m) of total anvil to the whole convective cluster for the eight regions. Vertical black bar lines are the standard deviations of clusters at AF.

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Key Points:
- Mean value of ice water path is a poor diagnostic of cirrus radiative impact
- Both radar and lidar are needed

Cloud properties and radiative effects of the Asian summer monsoon derived from A-Train data

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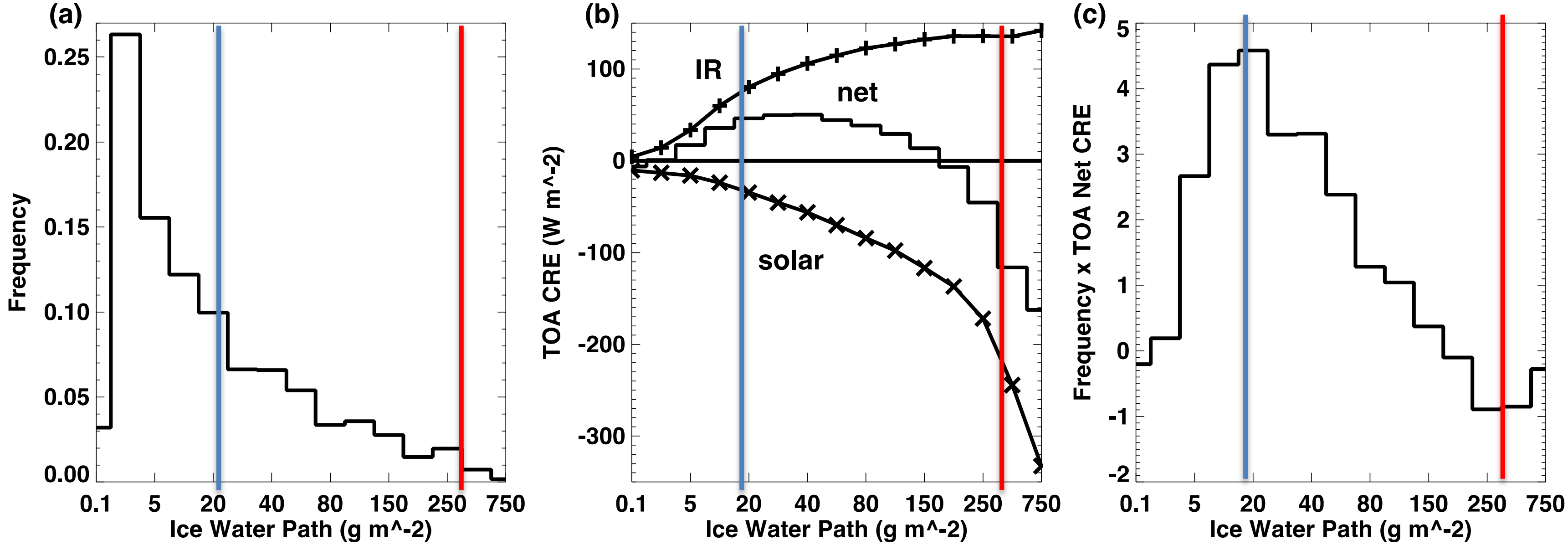
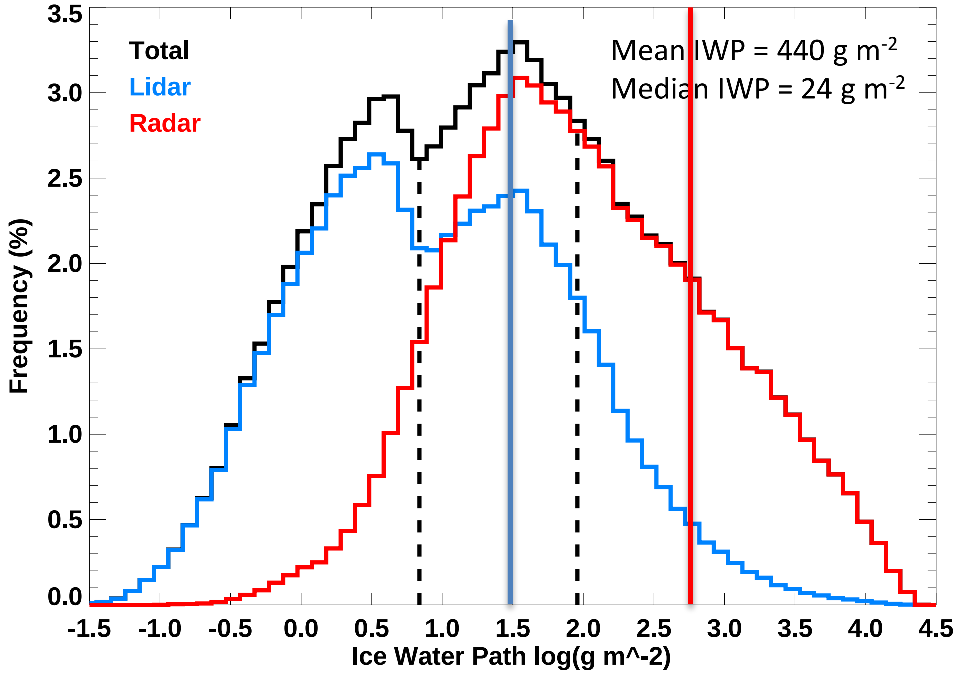
What Cirrus Are Most Important to the Radiation Budget of the Tropical Atmosphere?

Relationships between ice water path (IWP) and radiative effects for cirrus clouds (tops > 10 Km, thickness < 6 Km)



- Given their frequency of occurrence (a) and mean net cloud radiative effect at the top of the atmosphere (b), cirrus with IWP ~ 10-30 g m^{-2} contribute most to heating at TOA (c).
- Cirrus that are most important radiatively (IWP ~ 20 g m^{-2}) at TOA are more representative of the median value of the IWP distribution than the mean value.
- The radiatively important cirrus (IWP range 5-60 g m^{-2}) at TOA correspond to the portion of the IWP distribution that requires both radar and lidar to fully observe. (Berry and Mace, 2014)

PDF of log(Ice Water Path) from 2C-ICE dataset



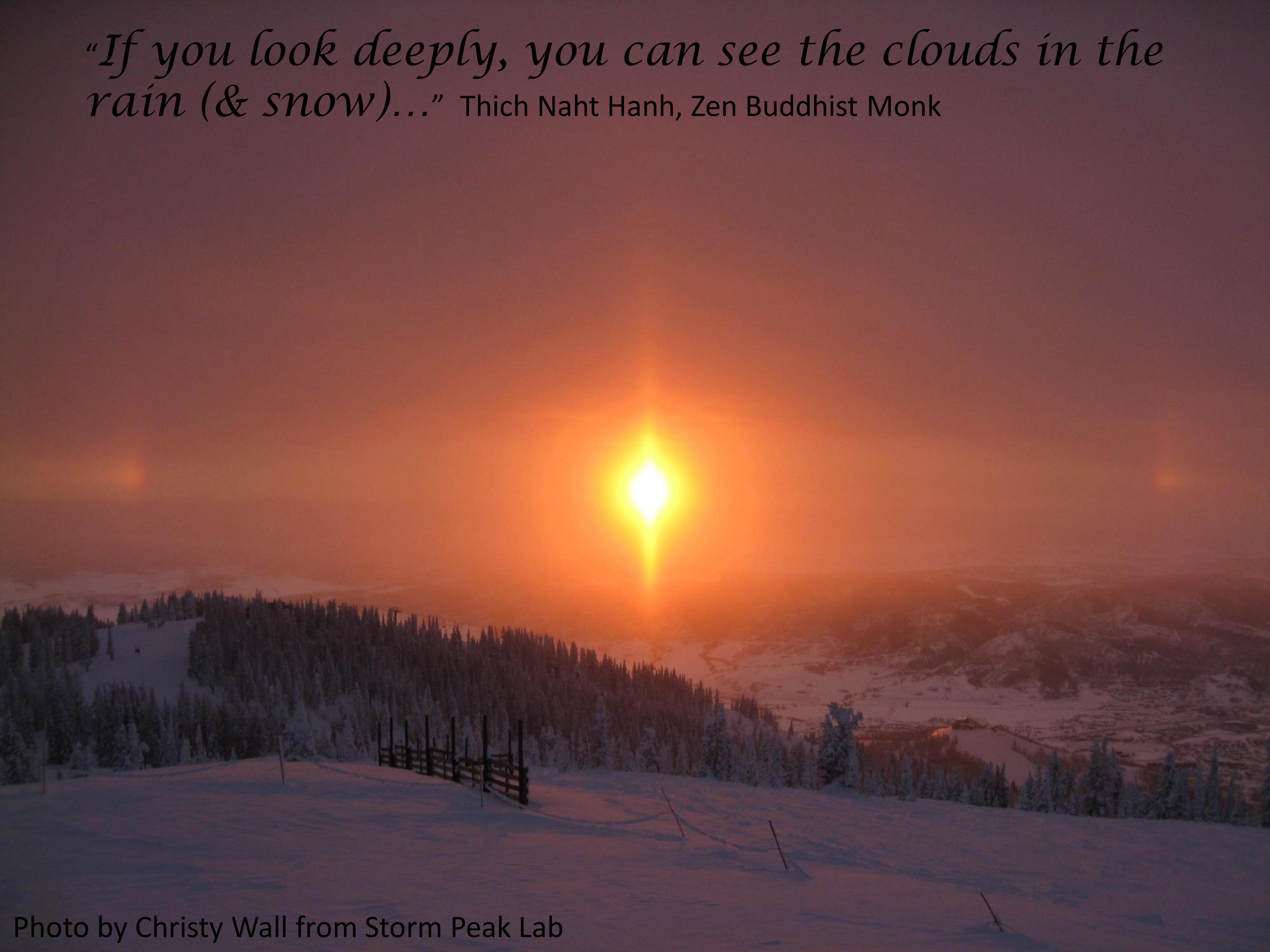
- Both CloudSat radar and CALIPSO lidar are needed to describe the full ice water path (IWP) distribution
- Greatest synergy between radar and lidar occurs at IWP = 5-13 g m^{-2}
- Cirrus cloud radiative effect vs. IWP shows cirrus with IWP < 200 g m^{-2} produce net warming at TOA

- **Peak in top of atmosphere Cloud Radiative Effect Concentrated in Middle Tercile (~20 g m^{-2}) where lidar-radar synergy is maximized and necessary (Berry and Mace, 2014)**

Summary and Conclusions:

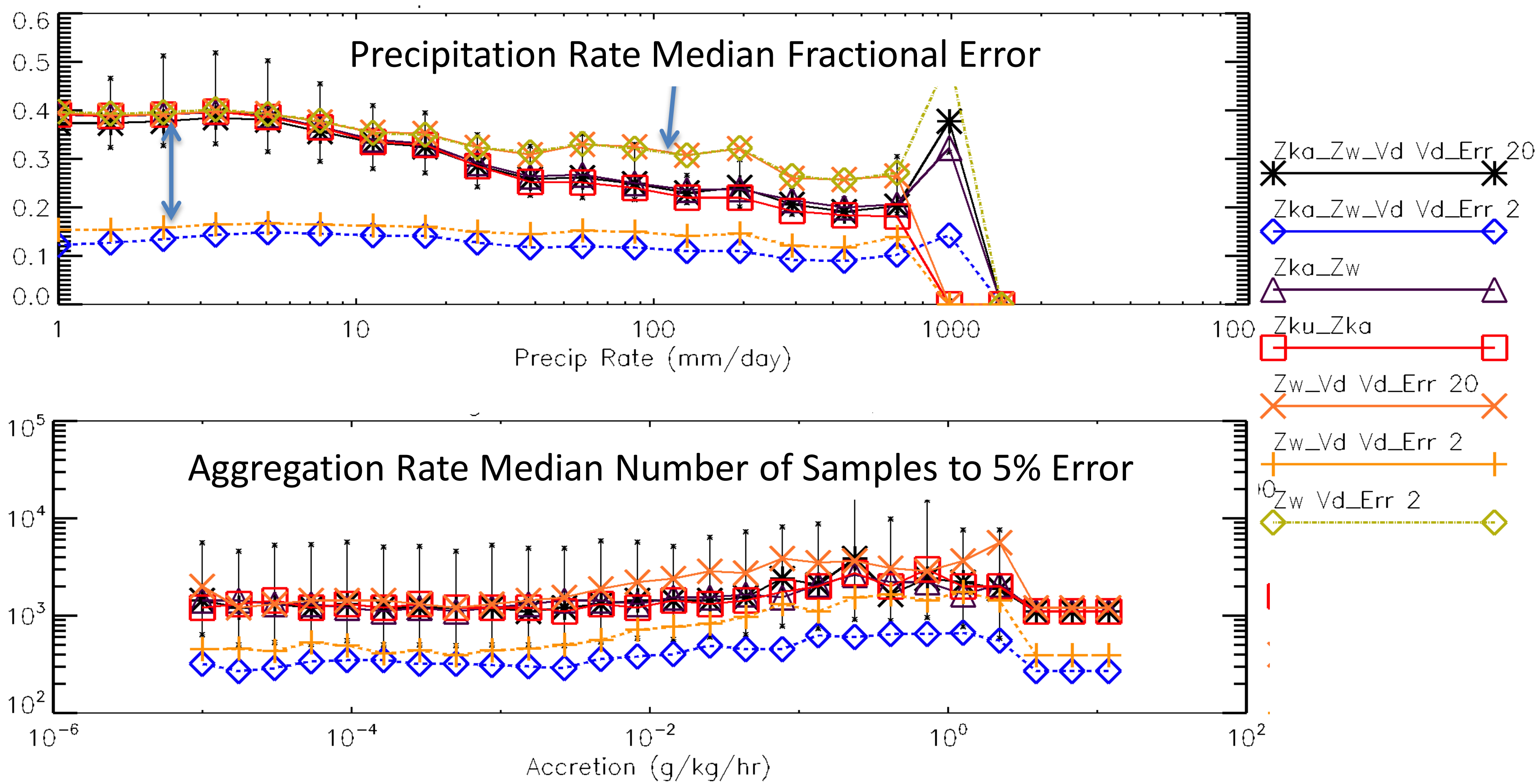
- We considered two issues.
  - Is it reasonable to consider diagnosing process rates from remote sensing data using 1) multi frequency retrievals and 2) temporally resolved measurements from trains of small satellites (or ground-based radar)?
  - What is the effect of assuming realistic uncertainties in ice crystal physical properties?

- We find that
  - Process rates (self collection) can be retrieved with significant averaging but…
  - Changes in Z due to aggregation would be observable from trains of satellites but...
  - Realistic uncertainties in ice-crystal properties drive uncertainties and MUST be considered if meaningful error bars are to be derived.


"If you look deeply, you can see the clouds in the rain (& snow)…" Thich Naht Hanh, Zen Buddhist Monk
Photo by Christy Wall from Storm Peak Lab

Can Process be inferred from some combination of radar measureables?

First, Examine Skill of Various Algorithms when the **forward model error is ZERO….**



- Doppler Velocity provides a major advantage – but only when it has very small measurement error.
- There is an advantage to Dual Frequency over Single frequency with realistic Doppler at the higher Precip and Aggregation Rates.

- The Representation of microphysical processes in models is proving to be THE limiting factor in high resolution simulations.
- Will become a critical issue as models move to global cloud resolving resolution in the next decade.

Sensitivity to Graupel/Hail Parameterization:

- The peak stratiform and convective areas differed by 105% and 150% respectively
- Accumulated precipitation varied by a 558%
- (Adams et al., 2013)

Sensitivity to Riming of ice in Mixed Phase:

- Surface snowfall rates and totals vary by 200 – 300% due to differences between bin and bulk microphysical riming schemes
- (Saleeby and Cotton, 2008)

Sensitivity to Droplet Breakup in Rain:

- Small changes to droplet breakup parameters => 500-600% differences in precipitation rates
- (Morrison et al., 2012)

Sensitivity to Microphysical Scheme Complexity (# of moments):

- 300-400% differences in surface precipitation due to the number of moments predicted => feedbacks to storm dynamics

Theory

The collection Eqn:

$$\frac{\partial r_p}{\partial t} = \frac{p}{4 r_0} \int N(D_p) \left[\int E(D) N(D_c) m_c (D_c + D_p)^2 \, dV \, dD_c \right] dD_p$$

Represents the time change of precipitation mass per unit mass of air due to collection of cloud-mode (liquid or ice)

We want to know the time *change in radar measureable* due to collection of cloud-mode hydrometeors.

If we multiply the outer integral by $\frac{r_0 s_B(D_p)}{m_P(D_p)}$, then…

$$\frac{\partial Z_{l_{radar}}}{\partial t} = \frac{C_{l_{radar}} p}{4} \int \frac{s_b(D_p)}{m(D_p)} N(D_p) \left[\int E(D) N(D_c) m_c (D_c + D_p)^2 \, dV \, dD_c \right] dD_p$$

We can quantify a time rate of change of radar reflectivity due to collection of cloud mode.

Similarly, for Doppler Velocity.

Solve Numerically for each measured PSD fitted by gamma functions.

Using T-Matrix and Mie theory, we can explore sensitivity to multiple frequencies, sensitivity to differential Doppler, etc

Can Process be inferred from some combination of radar measureables?

OE

$$\Phi(x,y,a) = \left(y - F(x)\right)^T S_y^{-1}\left(y - F(x)\right) + (x-a)^T S_a^{-1}(x-a)$$

Basic Assumption: Everything is uncertain. PSD's are bimodal – cloud and precip coexist

Measurements: Two Frequency Doppler Radar (Ka-W)

$$S_x = \left(K_x^T S_y^{-1} K_x + S_a^{-1}\right)^{-1}$$

$$S_y = S_e + K_b S_b K_b^T$$

$$H \propto \frac{S_a}{S_x} = S_a\left(K_x^T S_y^{-1} K_x + S_a^{-1}\right)$$

We will examine Information Content (H) as a function of Instrument Noise and Forward Model Error (Sy), the terms of the Jacobian (dZ/d(parameter)) using PSD'd directly measured during TC4 and SEAC4RS

Consider a Retrieval problem posed as follows:

$$y = \begin{bmatrix} Z_{HiFreq} \\ dZ \\ Vd_{HiFreq} \\ dVd \end{bmatrix} \quad x = \begin{bmatrix} \text{Precip Rate} \\ \text{Accretion} \\ a_m \\ b_m \end{bmatrix}$$

$$K_x = \frac{\partial y}{\partial x}$$ 4x4 Matrix of Sensitivities

Prior and S_a derived from in situ statistics – TC4 and SEAC4RS

Method

- We manipulate the collection kernel to provide the time rate of change of Z due to the collection process.

    - Then we estimate how far apart in time two radar measurements would need to be to capture some measureable change.

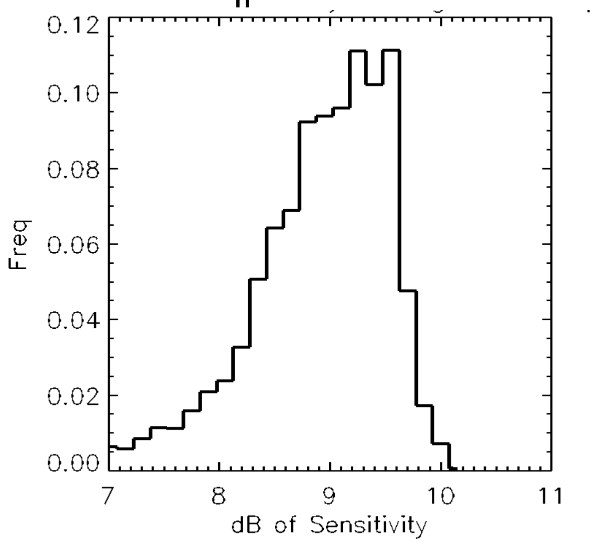
- We simulate dual frequency Doppler radars like those that may fly in space to determine the degree to which the simulated measurements *are sensitive to the inferred collection process*. Here we specifically target self-collection of single-mode ice distributions.

    - Is there *information* in the measurements about processes of interest?

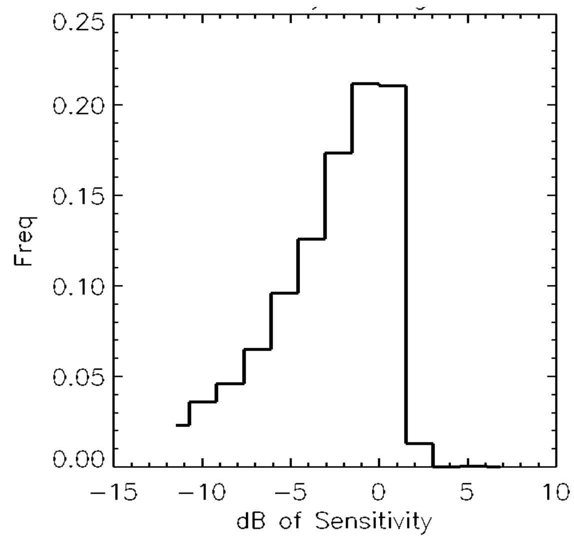
Can Process be inferred from some combination of radar measureables?
Can Process information be retrieved?

What is the sensitivity of Z to Precipitation Rate and Aggregation Rate?

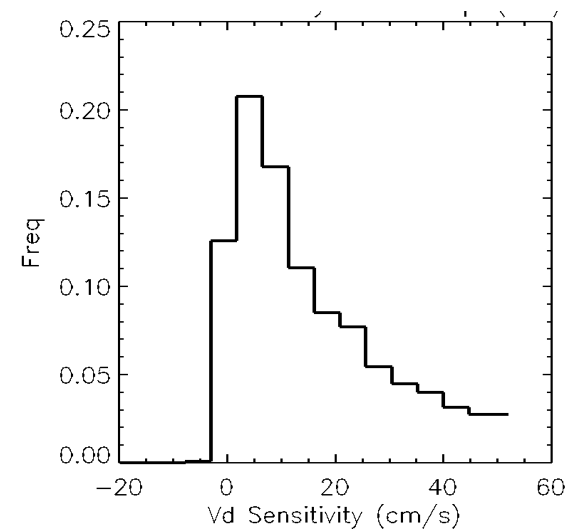
$$\frac{\partial Z_w}{\partial P} \approx 9dB$$



$$\frac{\partial Z_w}{\partial Agg} \approx -2dB$$



$$\frac{\partial V_d}{\partial P} \approx 10 \, {}^{cm}\!/_{s}$$



Can Process be inferred from some combination of radar measureables?
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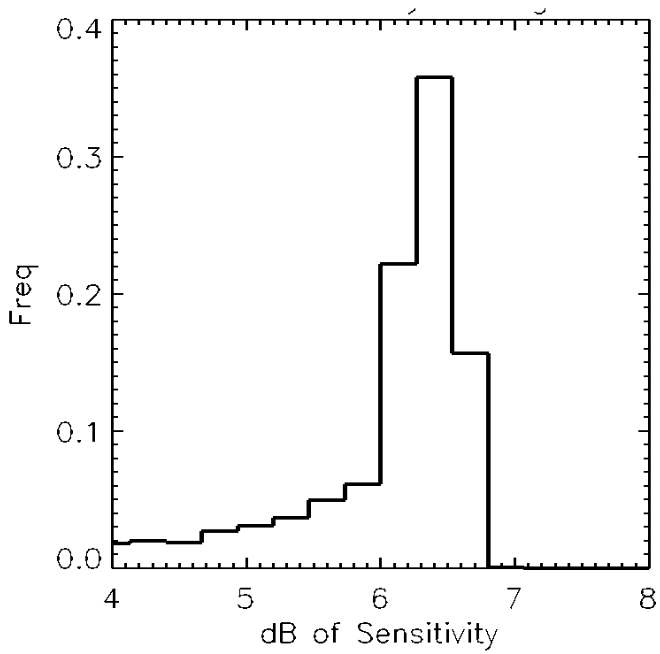
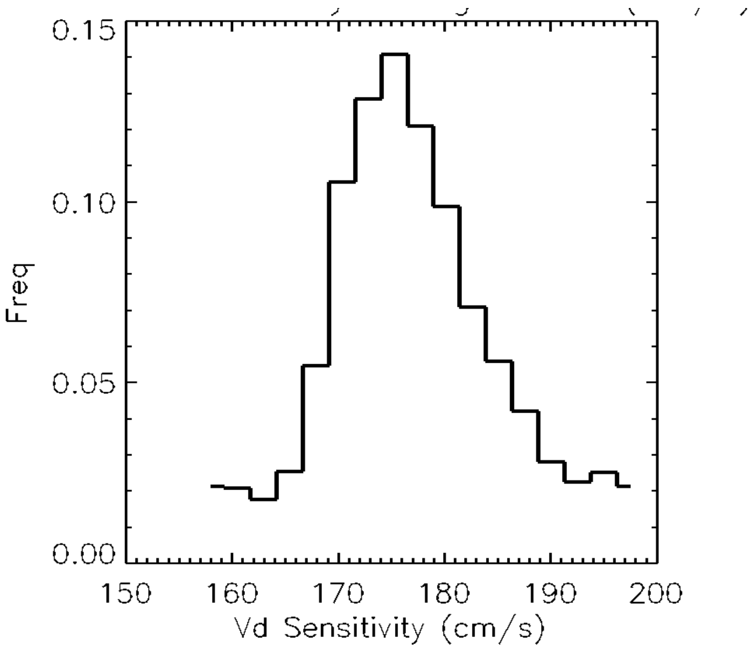
What is the sensitivity of Z and Vd to Ice Crystal Assumptions that control Forward Model Error ?

$$\frac{\partial Z_w}{\partial a_m} \approx 6.5dB$$

$$\frac{\partial V_d}{\partial a_m} \approx 175\, {}^{cm}\!/_{s}$$





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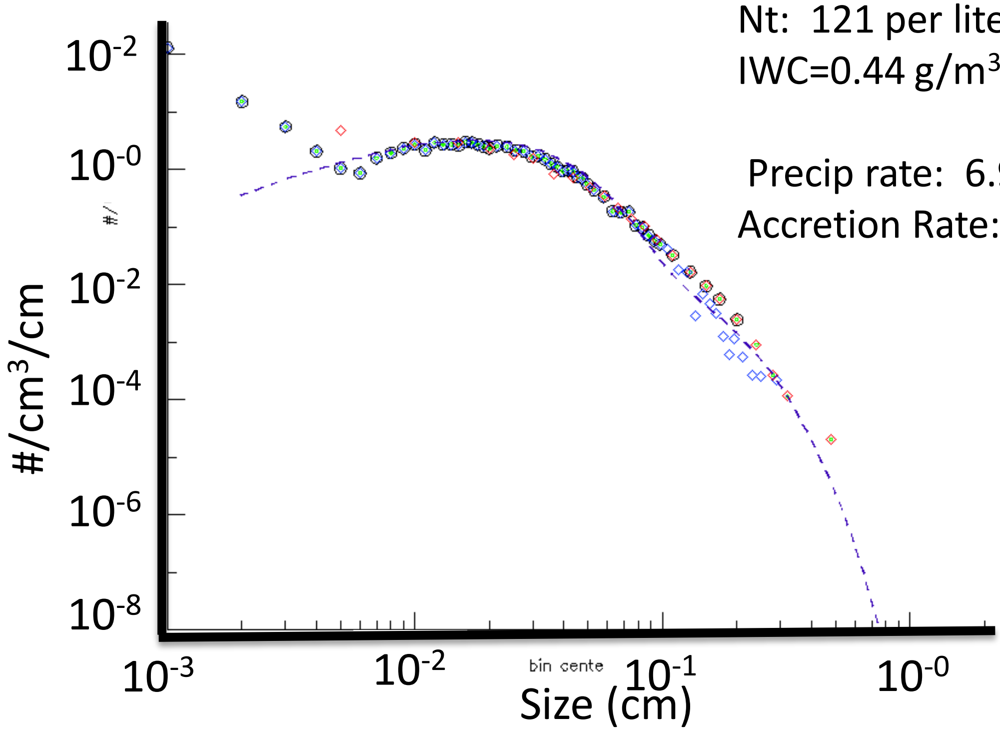

Time to 3 db change in Ku Z: ~11 min ± 3 min.

Radar Remote Sensing Microphysical Processes? Feasibility using In Situ Data from TC4

Jay Mace

Measurements Provided by: Paul Lawson and Gerry Heymsfield