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

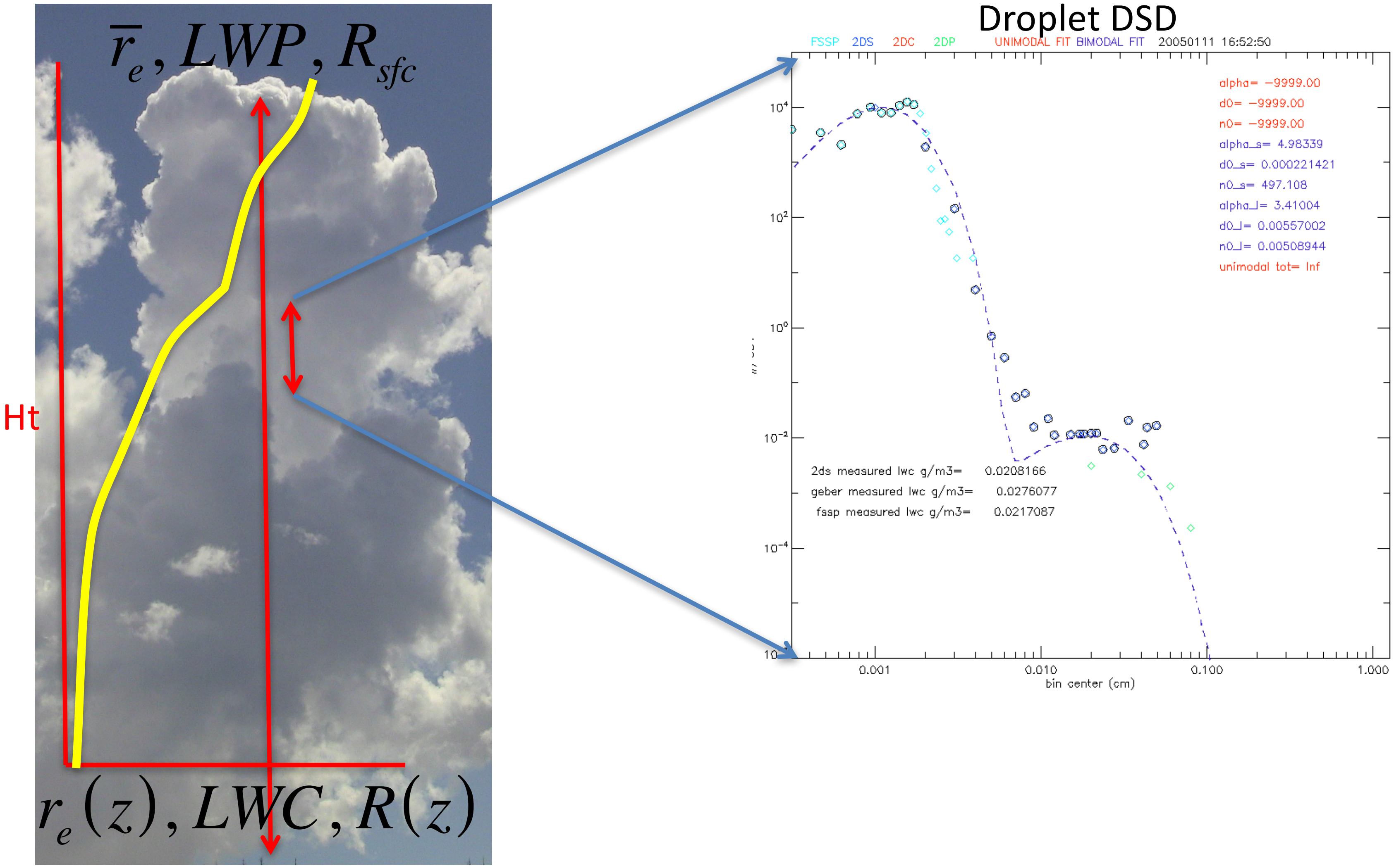
Jay Mace
Zhuocan Xu, and Jeana Mascio
Measurements Provided by: Paul Lawson and Gerry Heymsfield

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/CAPPM): 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)…

$$\frac{\partial r_p}{\partial t} = \frac{E\pi}{4\rho_0} \int N(D_p) \left[\int N(D_c) m_c (D_c + D_p)^2 \delta V \, dD_c \right] dD_p$$

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)

Autoconversion – growth of cloud mode droplets to precipitation size

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

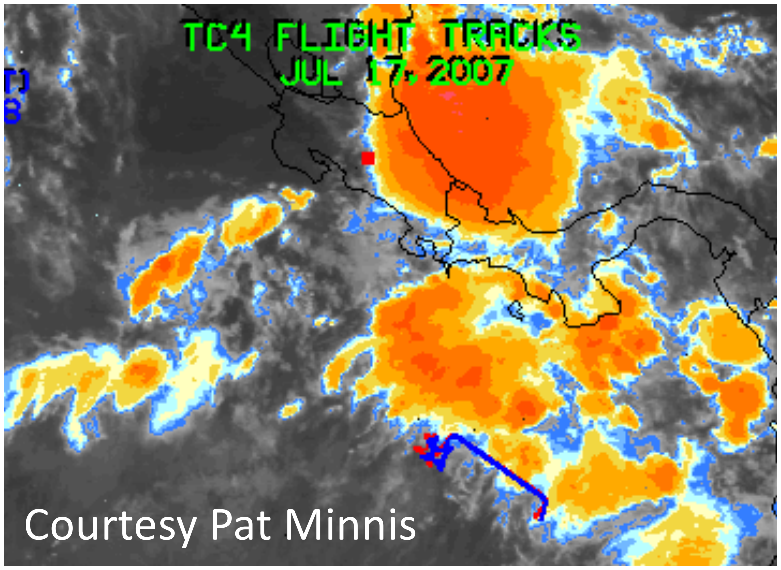
Accretion – collection of cloud drops by falling precipitation

Note: No time derivative on RHS.

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

Reference: Mace and Benson, 2016, Submitted to JAMC

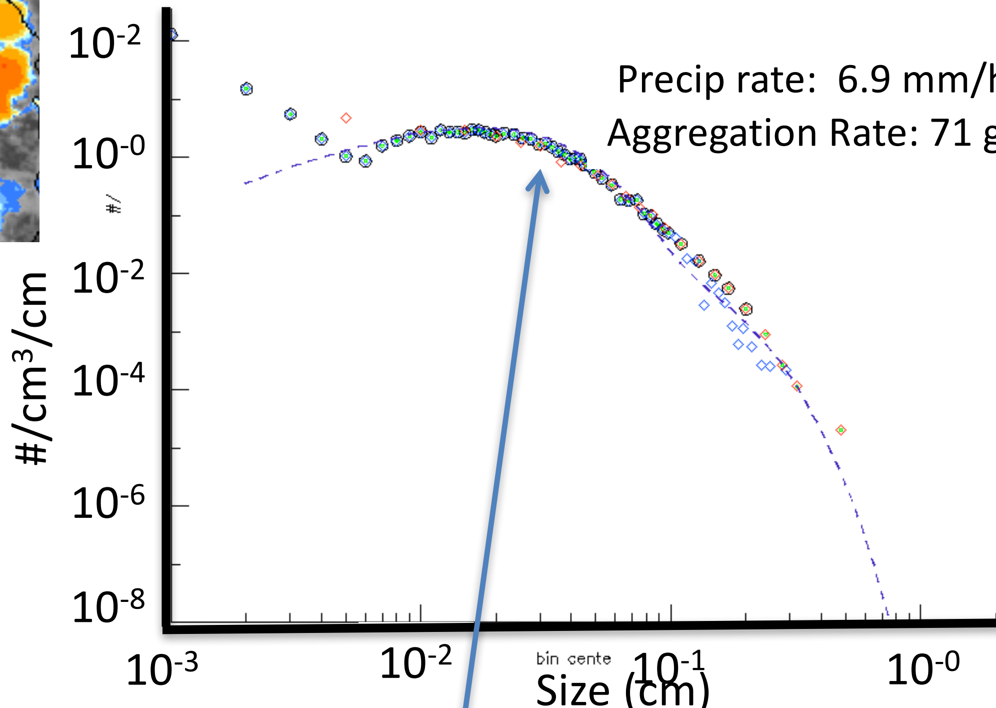
An Example



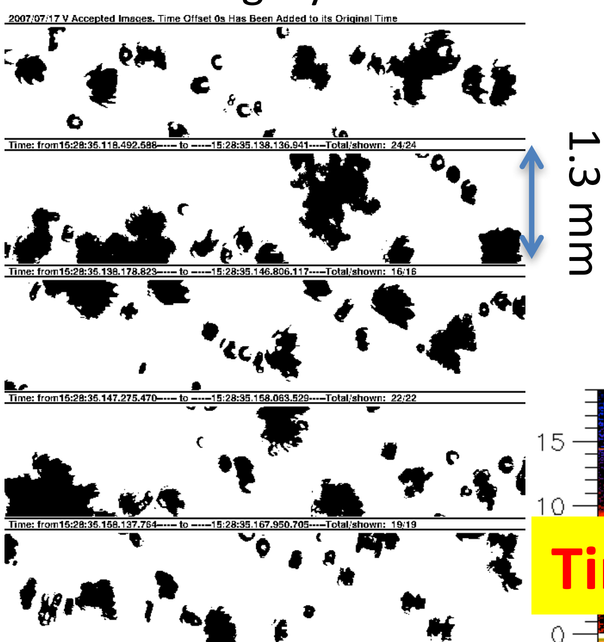
dBZ X: +15.3 dBZ w: +13.3
Vd X: 159.8 Vd w: 149.9

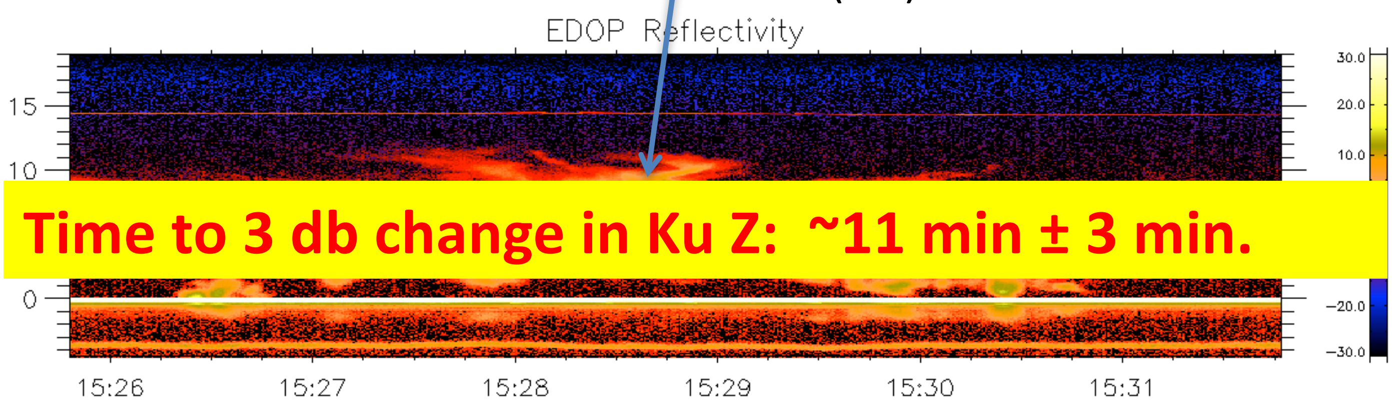
r_e: 404 microns
Nt: 121 per liter
IWC=0.44 g/m^3

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 be inferred from some combination of radar measureables?

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:

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

N_y by N_x Matrix of Sensitivities

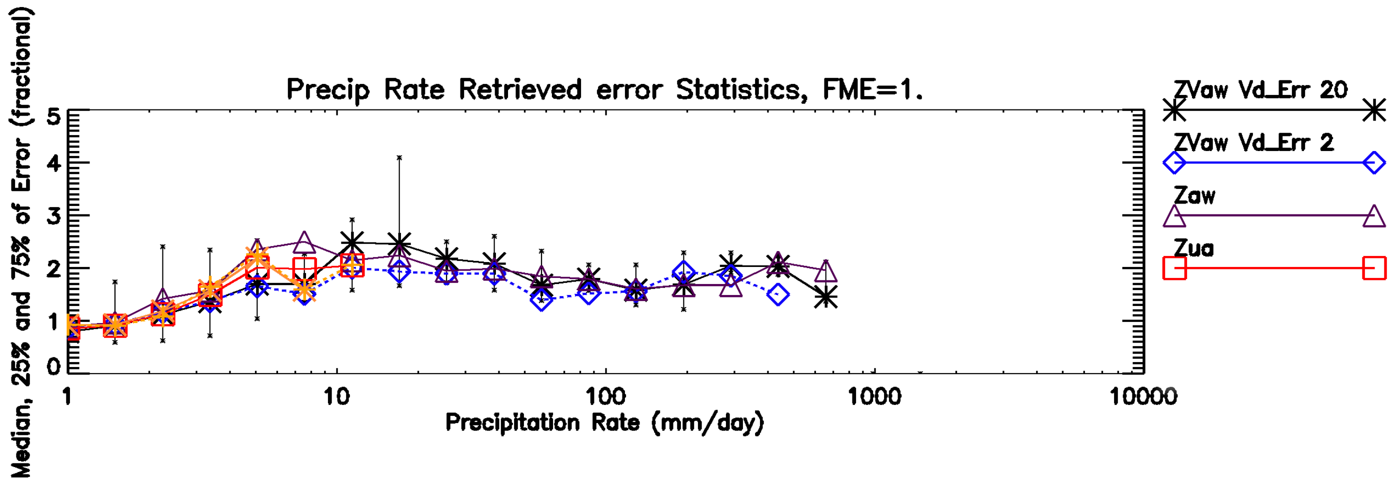
Prior and S_a derived from in TC4 situ statistics

- 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 $M=a_mD^{bm}$ that drives uncertainty in radar backscatter cross section (T-Matrix) and Doppler velocity.

What is the error characteristics of retrieved Precipitation Rates in Tropical Anvils?

Low Density Ice



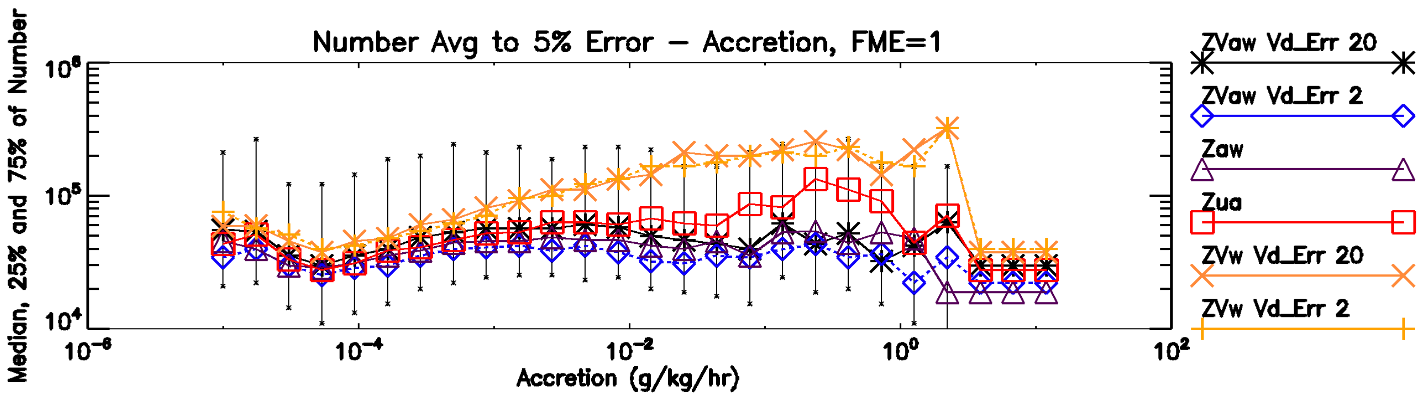
High Density Ice

This image cannot currently be displayed.

What is the error characteristics of retrieved Aggregation Rates in Tropical Anvils?

The number of independent samples required to reduce uncertainty to 5%

Low Density Ice



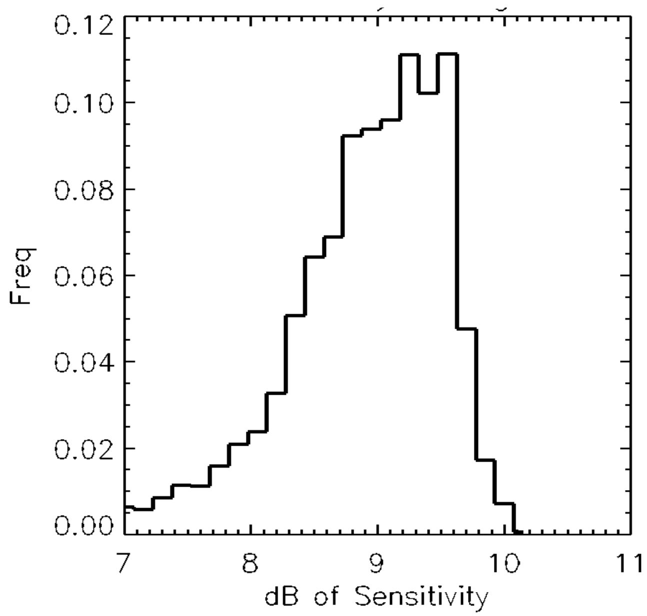
High Density Ice

This image cannot currently be displayed.

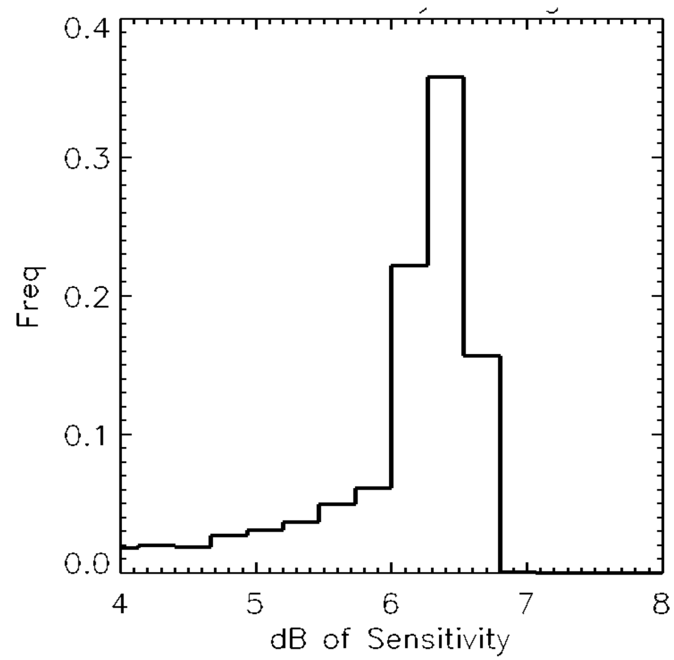
Findings:

- Ice crystal bulk density uncertainty dominates error in P and A
- Significant averaging is generally required to retrieve aggregation rate
- Ka and W bands provide superior results in tropical anvils.

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

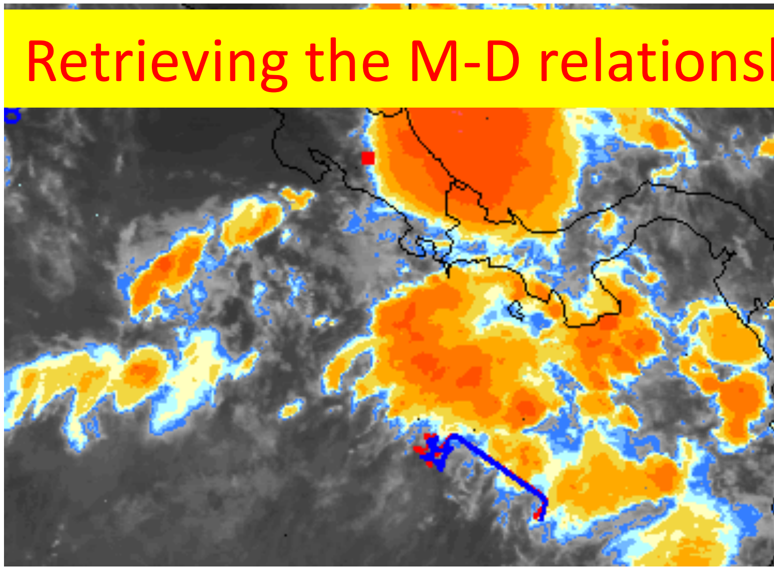


$$\frac{\partial Z_w}{\partial a_m} \simeq 6.5dB$$

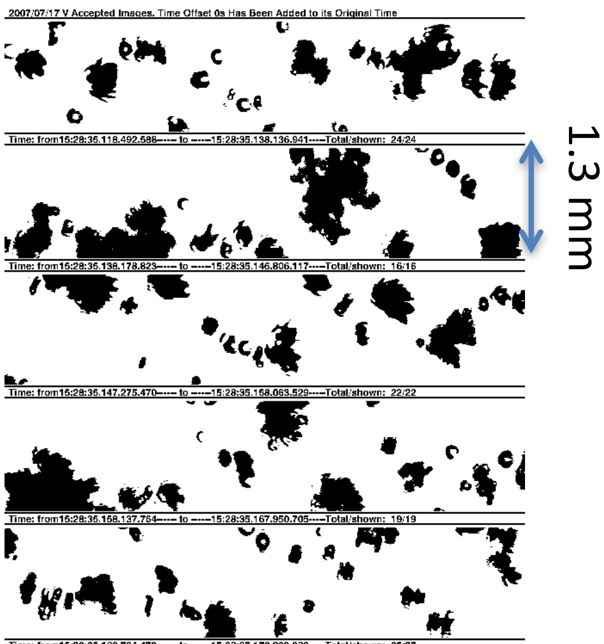


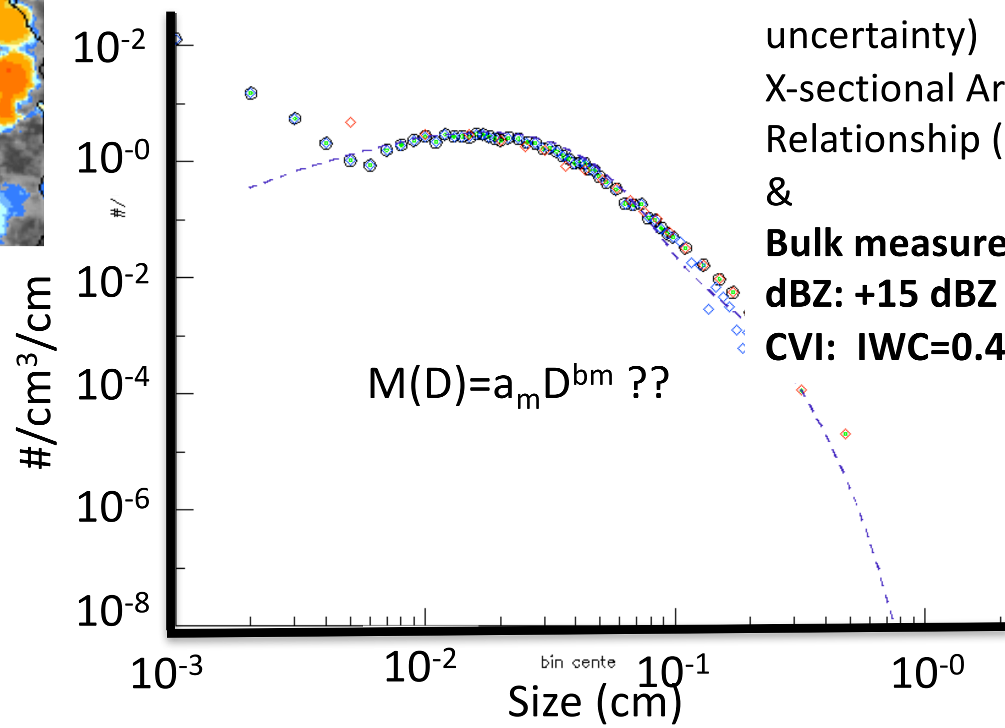
Next: Examine whether we can say something about the ice crystal Mass- and Area-Dimensional power laws from in situ data?

Retrieving the M-D relationship using in situ and remote sensing…..



2DS Imagery at 15:38:35





We know:

PSD is known (with uncertainty)

X-sectional Area - D Relationship (Easy)

&

Bulk measurements:

dBZ: +15 dBZ

CVI: IWC=0.44 g/m^3

Develop 2 OE retrievals of a_m and b_m.

- **Common elements: PSD (10 sec w/ variability), A-D**
- **Different elements: use dBZ in one and CVI IWC in another**

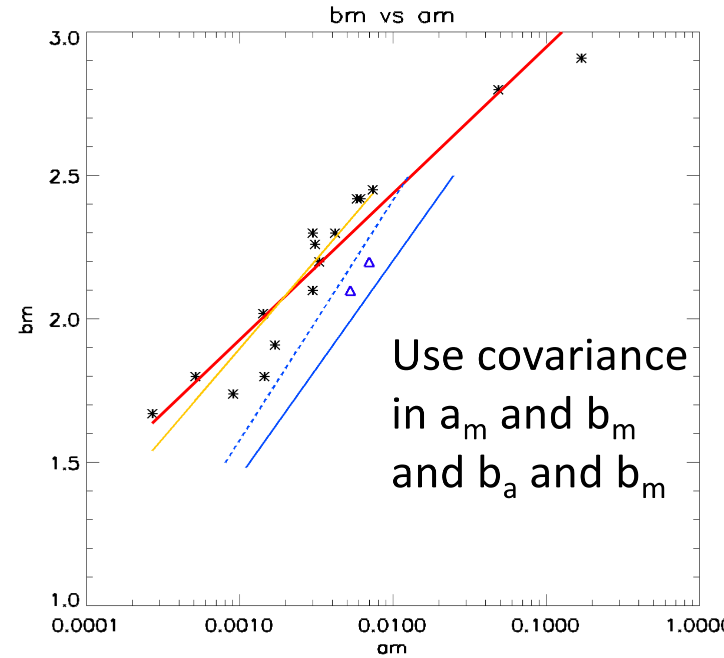
References: Mascio and Mace, 2016, JGR Submitted; Xu and Mace, 2016, JAMC, Submitted

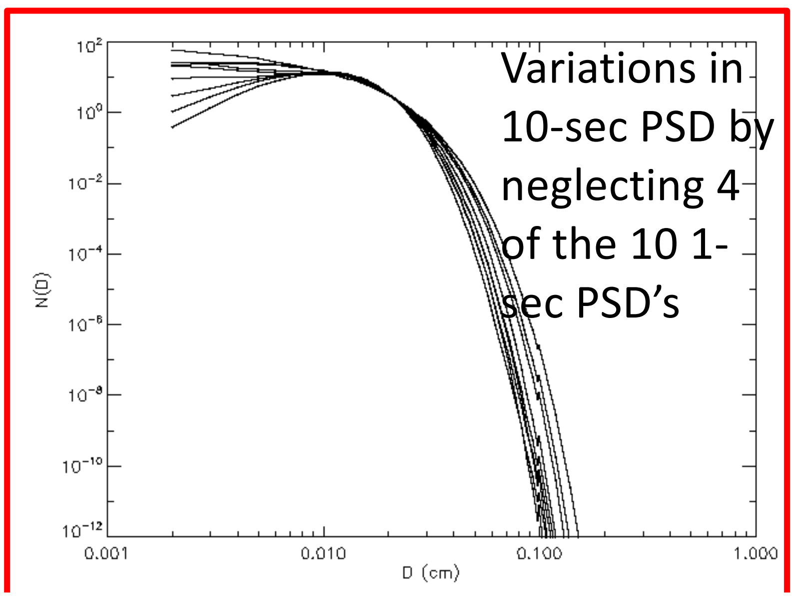
Uncertainties calculated from.

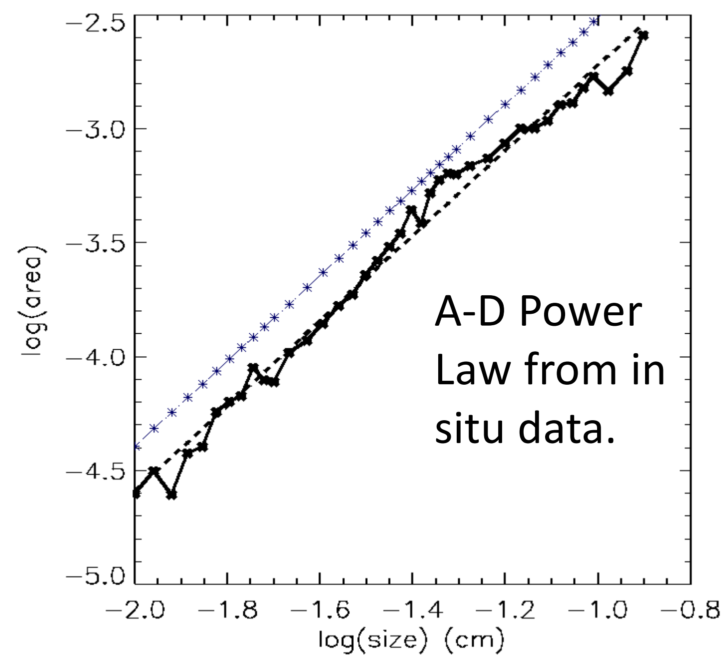
$$S_x = \left(S_a^{-1} + K_x^T S_y^{-1} K_x\right)^{-1}$$

S_y = instrumental noise and uncertainties of forward model assumptions and empirical parameters (*FME: Forward model Error*)

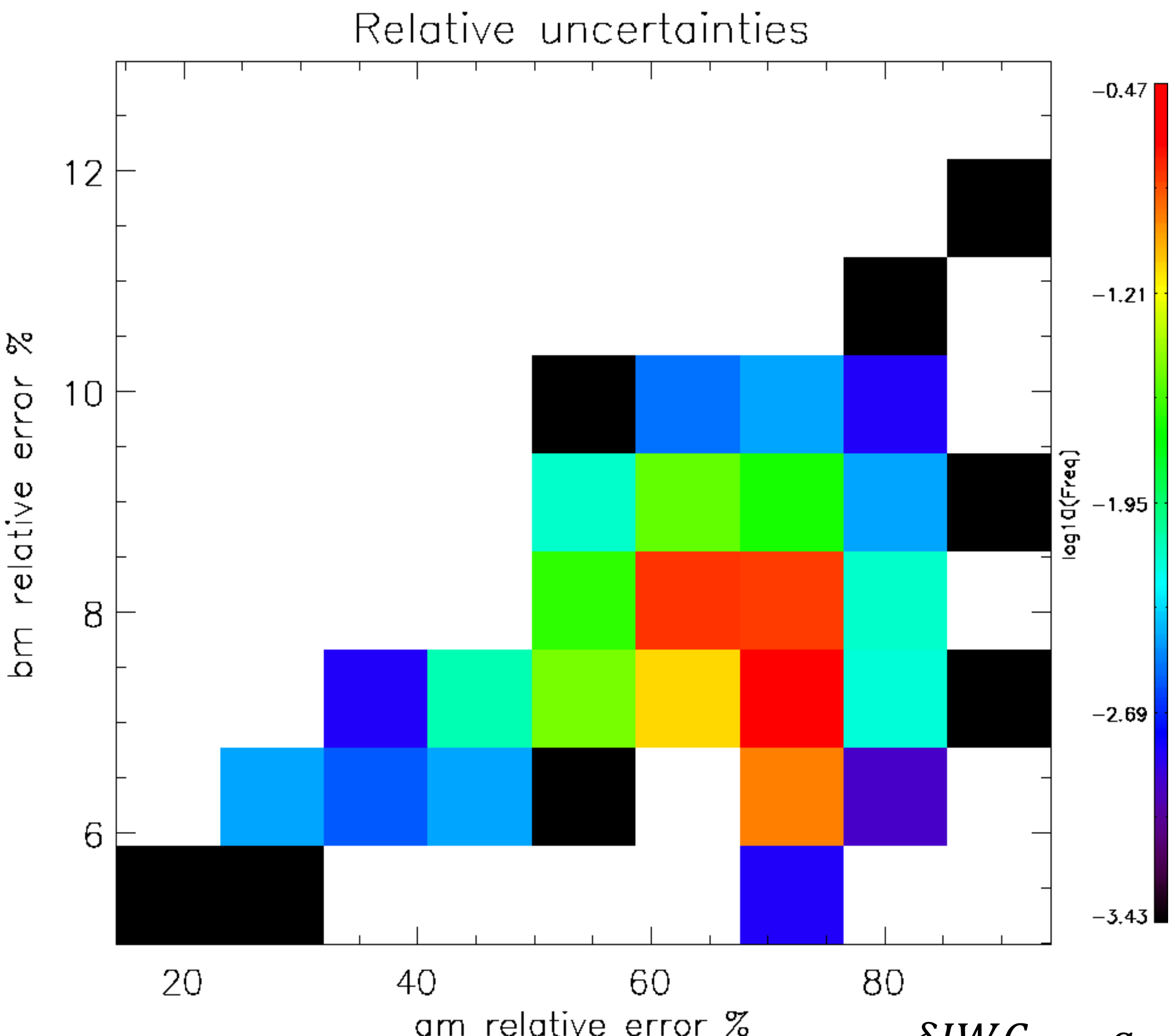
$$S_y = S_\varepsilon + FME$$







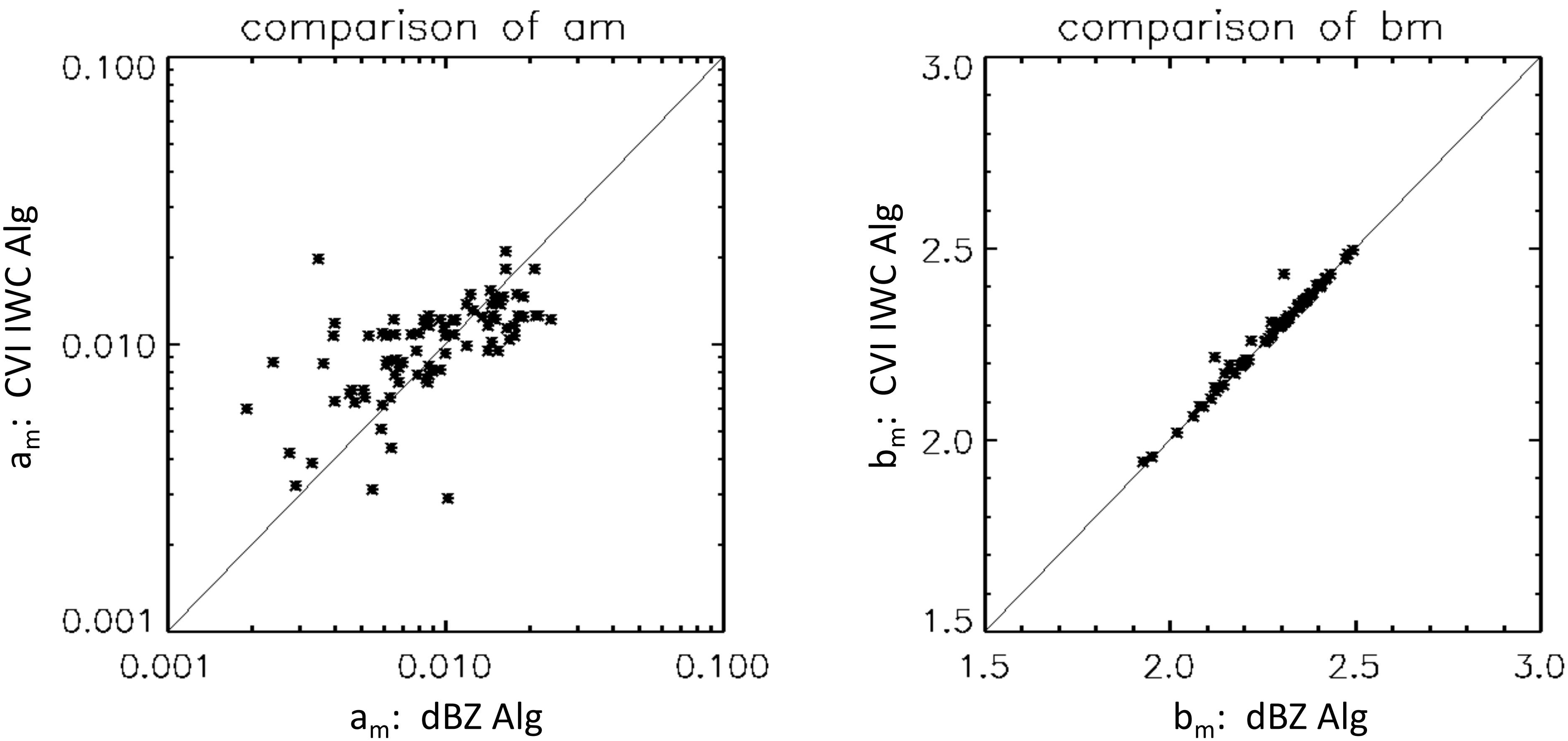
Retrieved Relative Uncertainties



$$\frac{\delta IWC}{IWC} = \frac{a_m}{IWC}\frac{\partial IWC}{\partial a_m}\frac{\sigma_{a_m}}{a_m} = \frac{\partial lnIWC}{\partial lna_m}\frac{\sigma_{a_m}}{a_m}$$

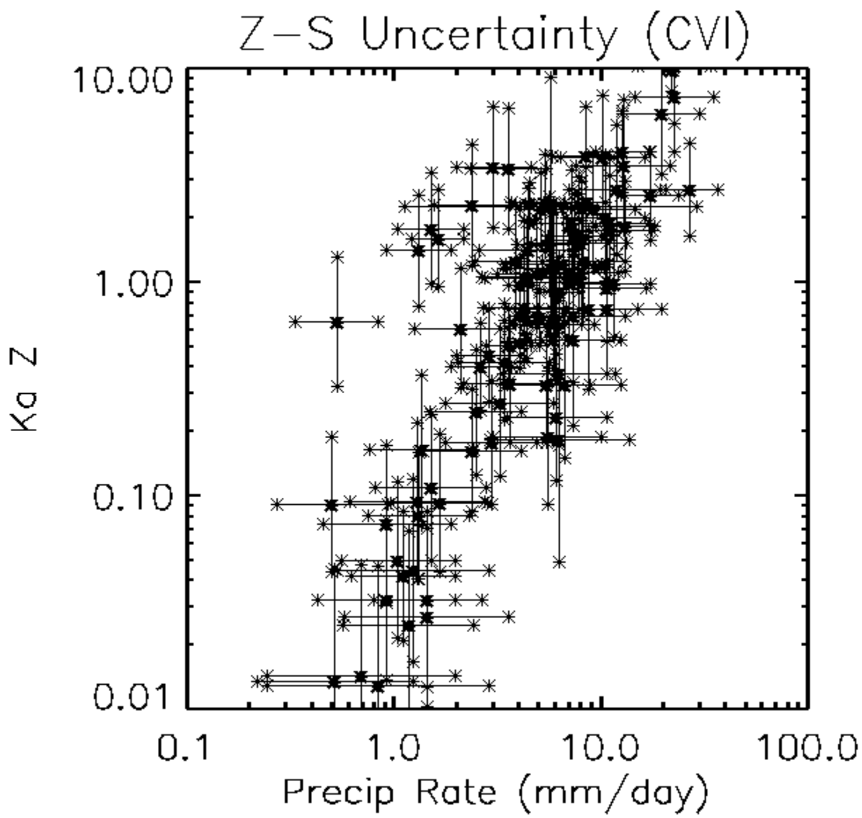
From Xu and Mace, 2016

Comparison of M-D Power Law Params for TC4 Ice Clouds

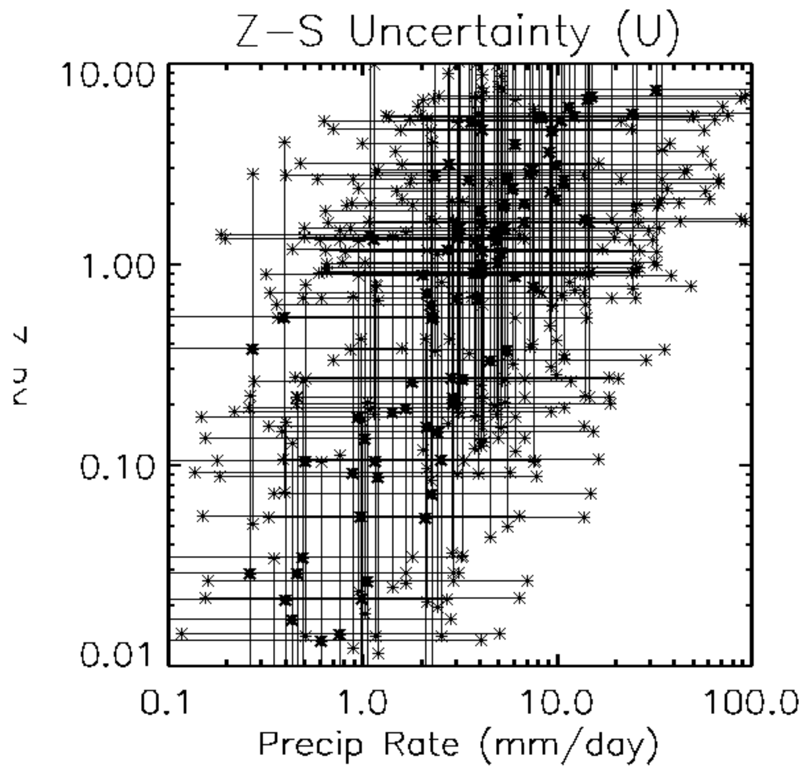


Implications of NOT knowing M-D to Snow Retrievals

Take uncertainty in Z and uncertainty in Snowfall Rate (S) due to M-D uncertainty and illustrate Z-S relationship uncertainty:



Use the case by case retrieved M-D with uncertainty



Use the mean and Standard Deviation of the TC4 M-D

Implications: Z-S is essentially unconstrained with assumed M-D

Summary and Conclusions

- Process information (aggregation) is within reach for dual frequency radar
  - At least for TC4 anvils, Ka/W bands provide the most information.
  - Uncertainty is very much dependent on the ice crystal properties and our knowledge of them

- In general error in dual frequency snowfall is driven by uncertainty in M-D

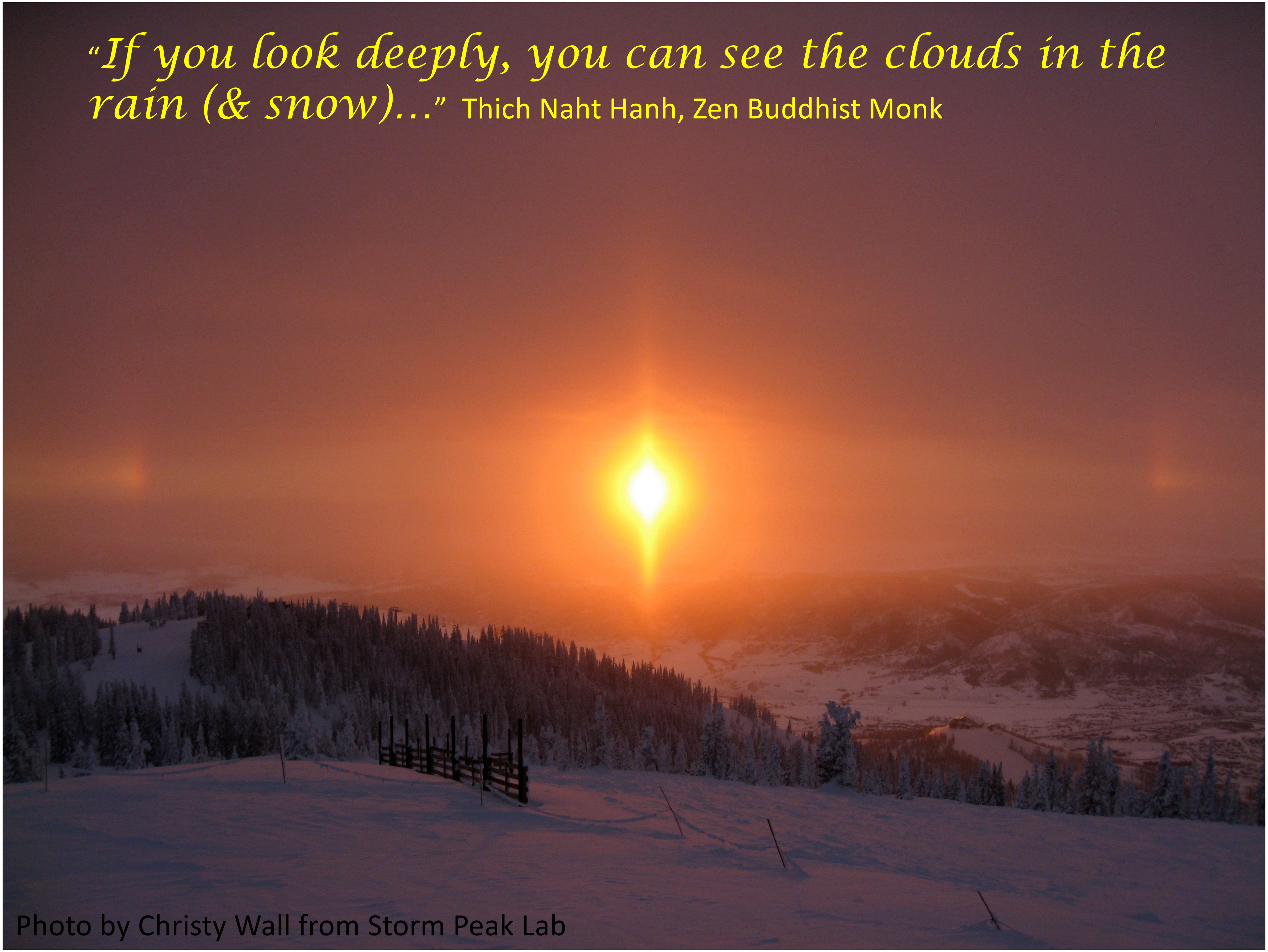
- Developed pair of algorithms to retrieve M-D using in situ PSD with bulk measurement (IWC or dBZ)

- Uncertainty in retrieved a_m and b_m is ~80% and 10% respectively.

- Demonstrated the influence of M-D uncertainty on Z-S
  - When specific M-D is unknown, Z-S is essentially unconstrained

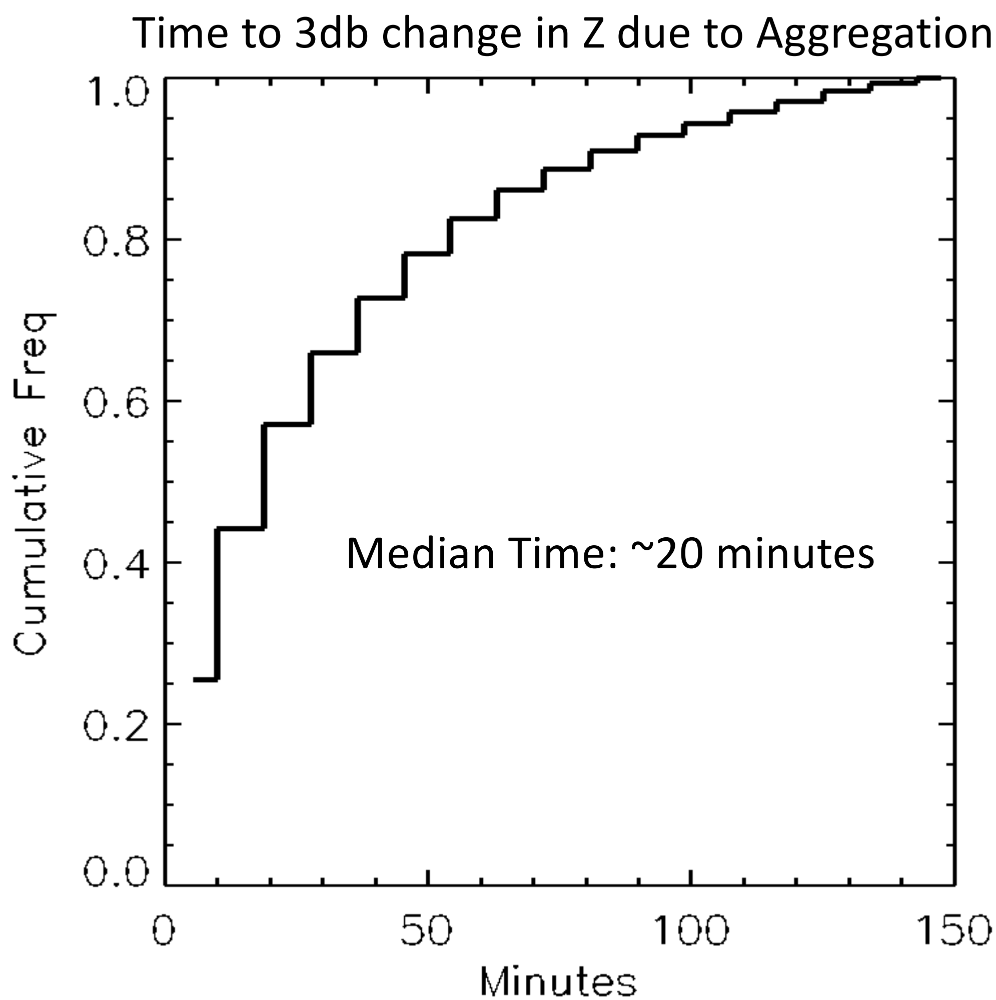
- Next: Apply analysis to IPHEX and Olympex in situ data

Recommendation: Must systematically characterize the statistics (variance and covariance) of ice crystal bulk density in the atmosphere.


"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 Rates be inferred by watching radar measureables change?

Cumulative Distribution Function derived from all ice clouds sampled during TC4



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)

$$\frac{\partial Z_w}{\partial a_m} \simeq 6.5dB \qquad \frac{\partial V_d}{\partial a_m} \simeq 175\, {cm}/{s}$$

Sensitivity of Measureables to Desired Geophysical Parameters

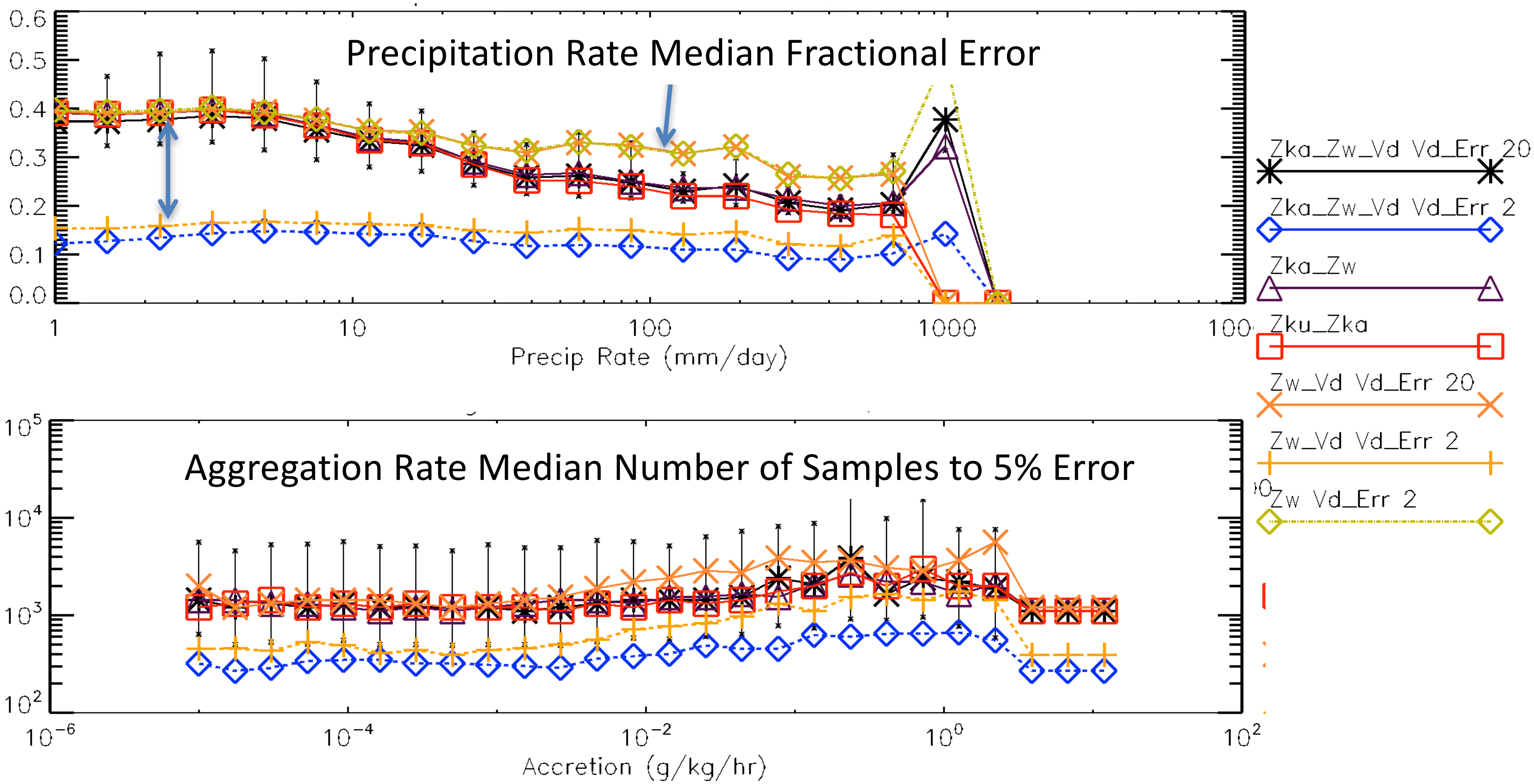
$$\frac{\partial Z_w}{\partial P} \simeq 9dB \qquad \frac{\partial Z_w}{\partial Agg} \simeq -2dB \qquad \frac{\partial V_d}{\partial P} \simeq 10\, {cm}/{s}$$

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…

Can Process be inferred from some combination of radar measureables?

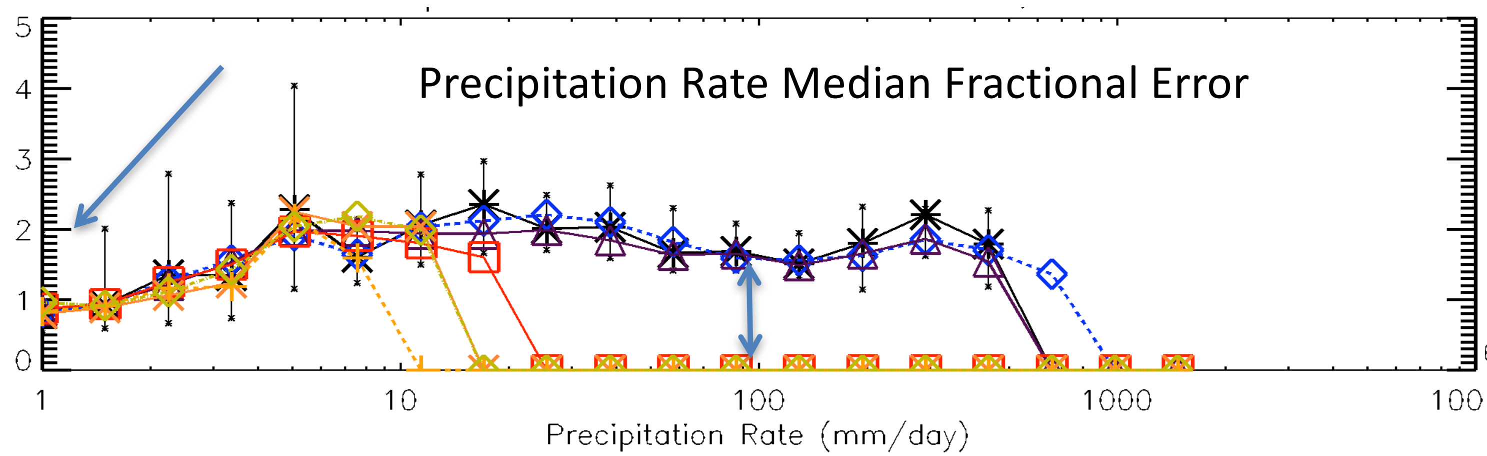
First, Examine Skill of Various Algorithms when the **forward model error is ZERO….**

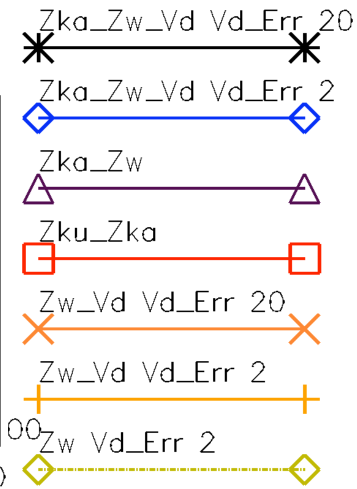


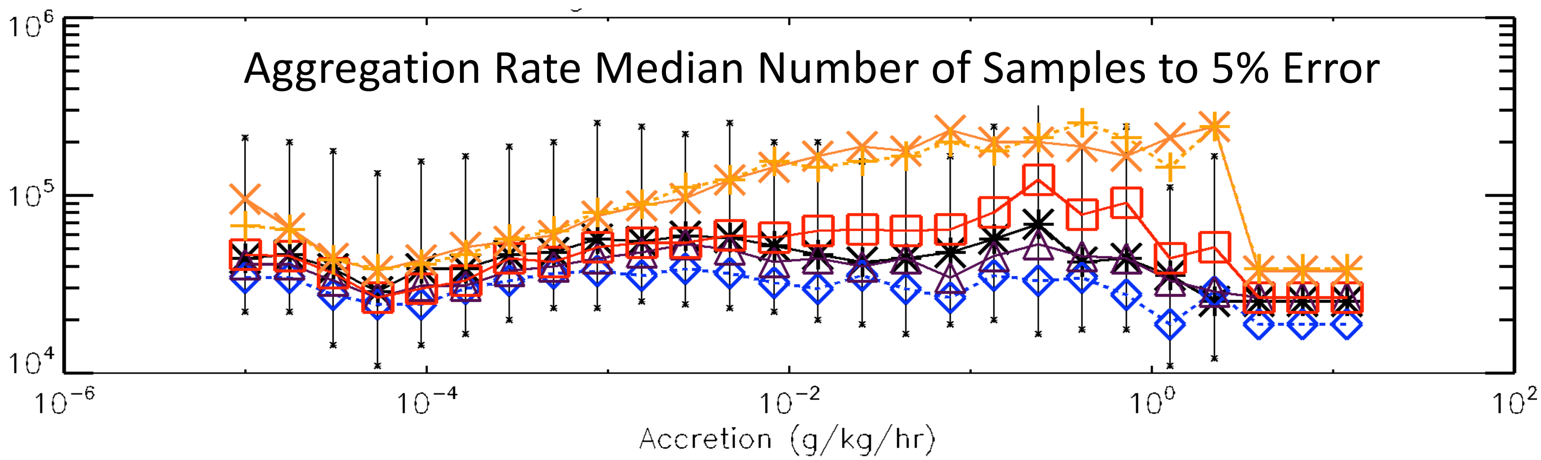
- Doppler Velocity provides a major advantage – but only when it has *very* small measurement error.
- There is an advantage to Dual Frequency over Single frequency with realistic Doppler at the higher Precip and Aggregation Rates.

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

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.

- 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: $$\frac{\partial r_p}{\partial t} = \frac{\pi}{4\rho_0}\int N(D_p)\left[\int E(D)N(D_c)m_c(D_c+D_p)^2\,\delta V\,dD_c\right]dD_p$$

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 $\frac{\rho_0\sigma_B(D_p)}{m_P(D_p)}$, then…

$$\frac{\partial Z_{\lambda_{radar}}}{\partial t} = \frac{C_{\lambda_{radar}}\pi}{4}\int \frac{\sigma_b(D_p)}{m(D_p)}N(D_p)\left[\int E(D)N(D_c)m_c(D_c+D_p)^2\,\delta V\,dD_c\right]dD_p$$

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

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

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

Measurements: Two Frequency Doppler Radar (Ka-W)

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

$$S_y = S_\varepsilon + K_b S_b K_b^T$$

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

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:

$$y = \begin{bmatrix} Z_{HiFreq} \\ \delta Z \\ Vd_{HiFreq} \\ \delta Vd \end{bmatrix} \quad x = \begin{bmatrix} Precip\ Rate \\ Accretion \\ a_m \\ b_m \end{bmatrix}$$

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

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

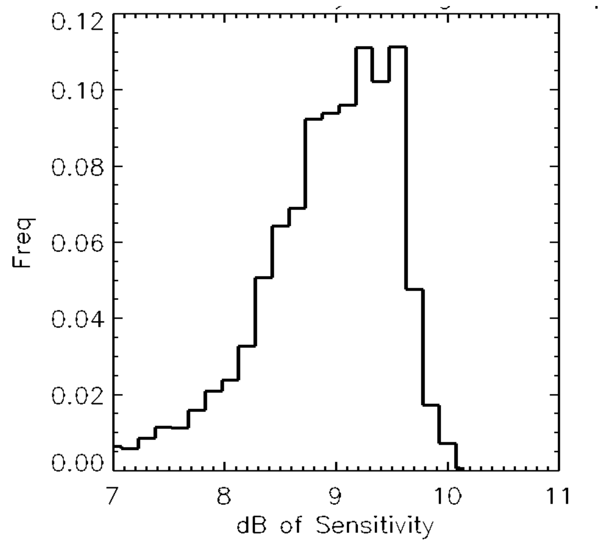
Method

- 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?

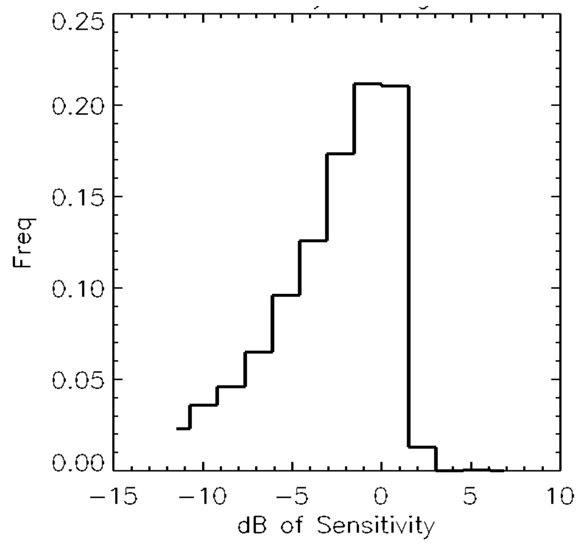
Can Process be inferred from some combination of radar measureables? Can Process information be retrieved?

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

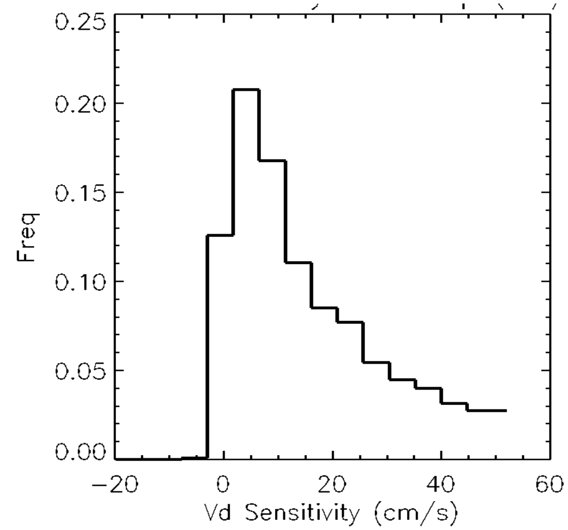
$$\frac{\partial Z_w}{\partial P} \simeq 9dB$$



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



$$\frac{\partial V_d}{\partial P} \simeq 10 \, {cm}/{s}$$

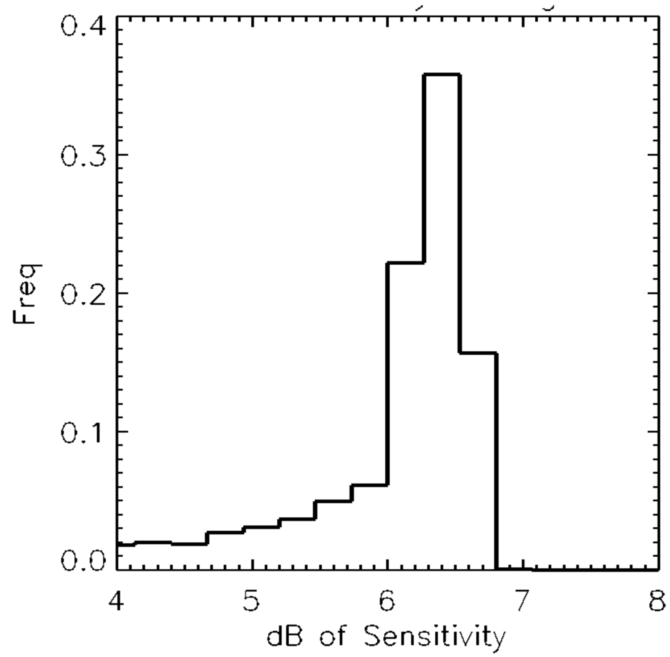


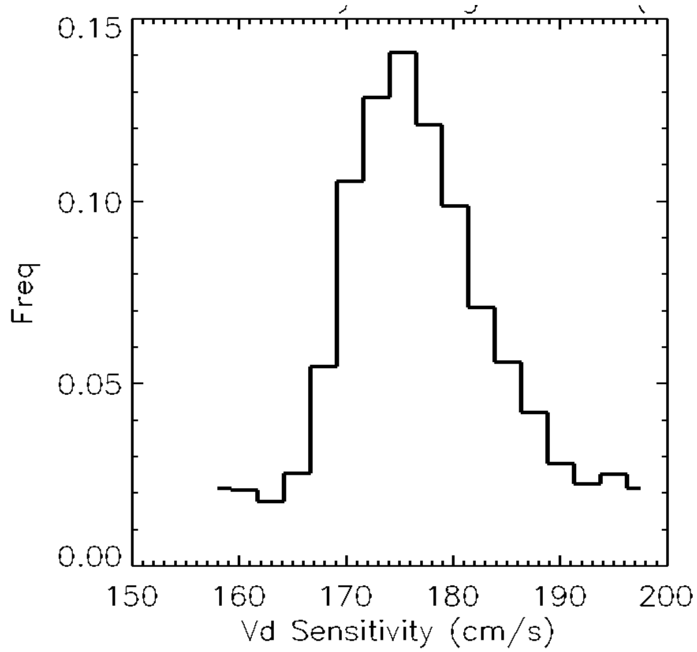
Can Process be inferred from some combination of radar measureables?
Can Process information be retrieved?

What is the sensitivity of Z and Vd to Ice Crystal Assumptions that control Forward Model Error ?

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

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





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

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

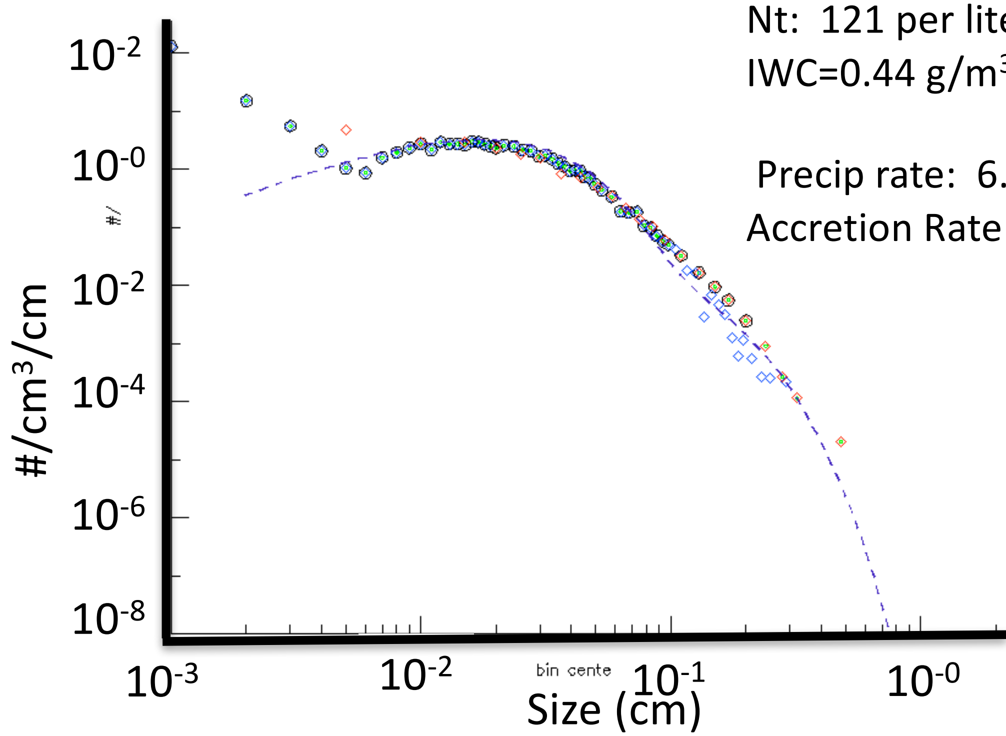
$$\frac{\partial V_d}{\partial P} \simeq 10\, {}^{cm}\!/_{s}$$

Can Process be inferred by watching radar measureables change?

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
Accretion Rate: 71 g/m^2/km/hr



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