Ice/Snow Radar-based Retrievals

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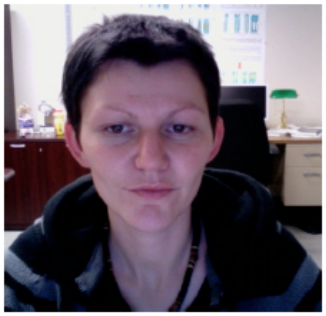

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Outline

1. Uncertainties in the relationships linking ice/snow microphysics to radar observables

2. Normalization of the mass/density-size relationship

3. Ensemble-based approach to quantify the uncertainty in the microphysics - radar observables relationships

4. Consideration of riming process

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1. Uncertainties in the relations linking ice/snow μ-physics to radar observables

Effect of nonsphericity, mainly in the presence of the non-Rayleigh effects:

Particle backscattering computation

Mass/density and aspect ratio dimensional relationships

Orientation behavior

Structure details required in more accurate computation methods
determination of bulk effective dielectric constant

Fall speed (area ratio+orientation) for Doppler

Particle Size Distribution (PSD) shape representation

Uncertainty due to the PSD shape related to the choice/ variability of the generic PSD, *h(x) is expressed by* C_p

$$\mathrm{M}_p = \boxed{C_p}\left[\mathrm{M}_i\right]^{\frac{j-p}{j-i}}\left[\mathrm{M}_j\right]^{\frac{p-i}{j-i}}$$

Math Box: Let GG (generalized gamma function) with two shape parameters (μ and c) chosen to represent a generic PSD form

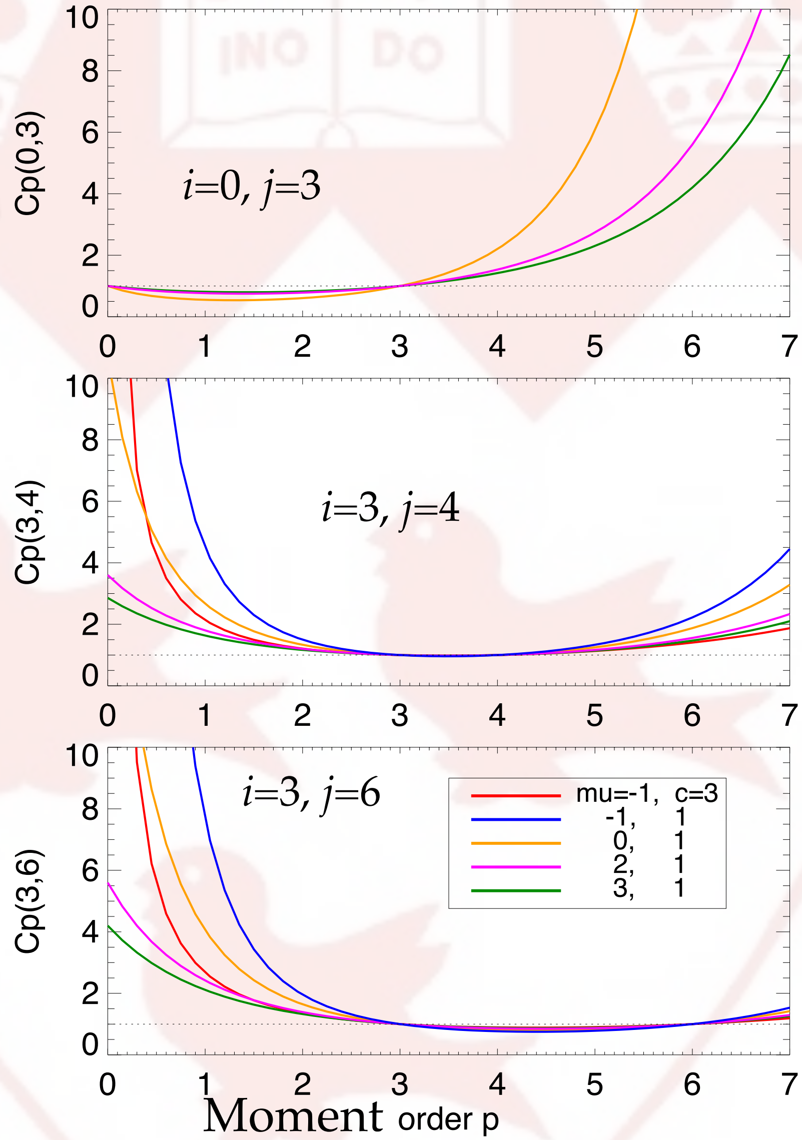
$$h(x) = A \cdot x^{\mu} \exp\left[-\lambda x^{c}\right]$$

with

$$x \equiv D/\left(\mathrm{M}_j/\mathrm{M}_i\right)^{1/(j-i)} \qquad A, \lambda = f(i, j, \mu, c)$$

gives

$$\Gamma_q \equiv \Gamma\left[(\mu+1+q)/c\right] \qquad \boxed{C_p = \frac{\Gamma_p}{\Gamma_i}\left[\frac{\Gamma_j}{\Gamma_i}\right]^{\frac{i-p}{j-i}}}$$

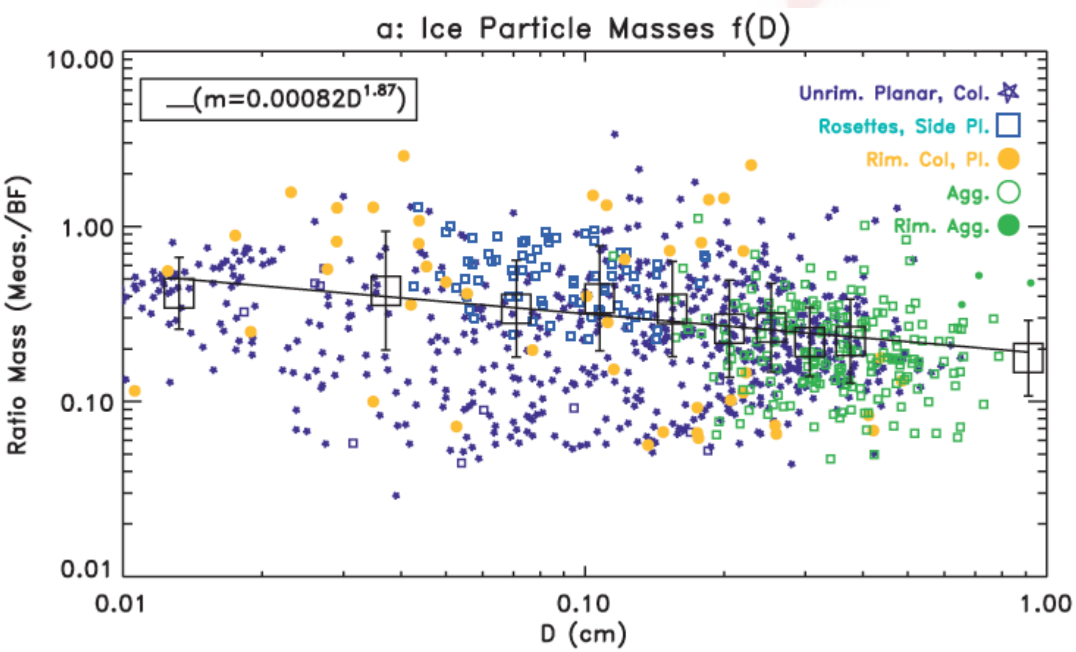


2. Normalization of the mass/density-size relationship

a. Conventional two-parameter power law

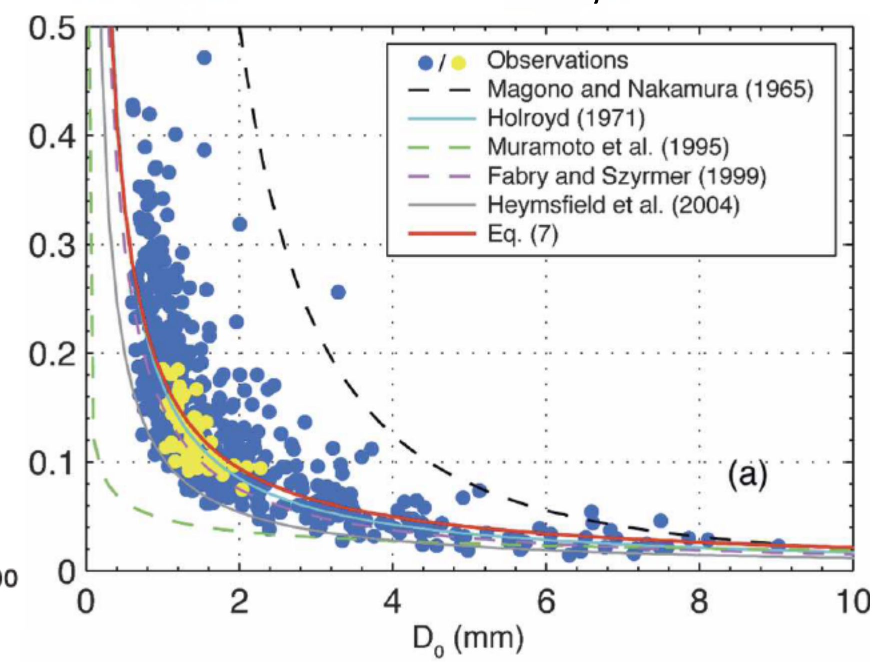
$$m = a_m D^{b_m} \xrightarrow[\text{spher.}]{} \rho_{eff} = (6/\pi) a_m D^{b_m - 3}$$

1. For most particle habits, two or even three sets of parameters a_m and b_m required to cover the entire range of observed PSDs.
2. Impossibility to accurately predict mass relation on the basis of the actual knowledge.
3. Very large dynamic range (almost two orders of variability).



Particle mass as derived from BF95 (Brown and Francis 1995) divided by the mass as measured (Heymsfield et al. 2010)

Snowflake density



Relationships between bulk density and particle Median volume diameter (Brandes et al. 2007)

2. Normalization of the mass/density-size relationship

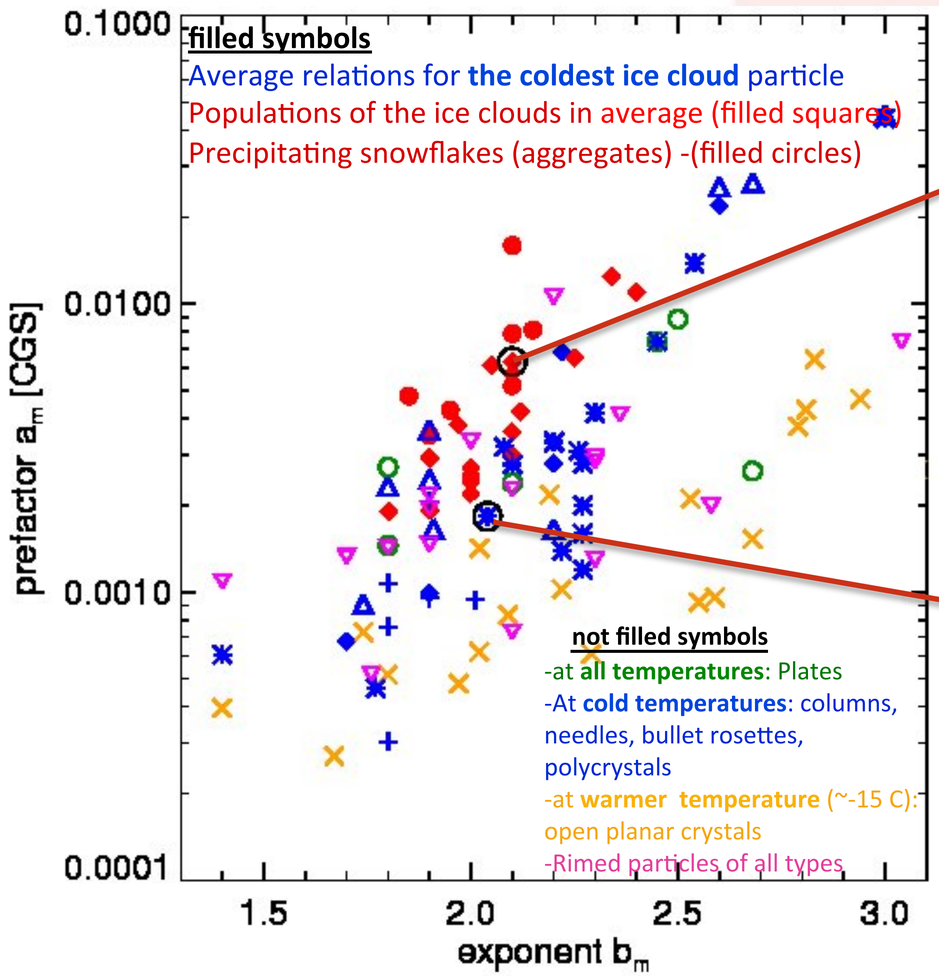
a. Conventional two-parameter power law

$$\rho_{eff} = (6/\pi) a_m D^{b_m - 3}$$

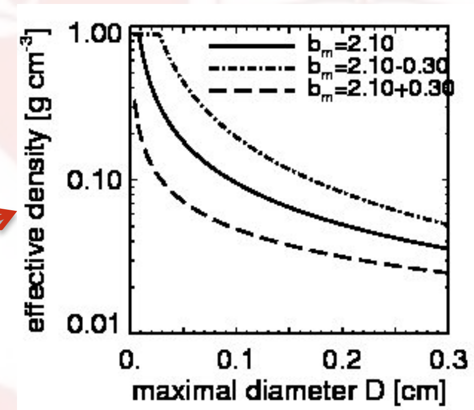
Empirically-derived mass-size power law

$m = a_m D^{bm}$

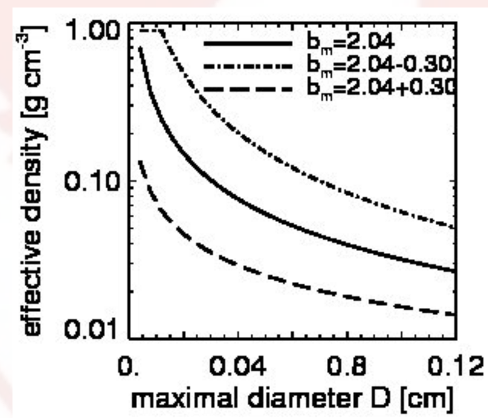
Relationship between the prefactor a_m and the exponent b_m



Examples of ρ_{eff}-sensitivity to b_m



A.
a_m=0.0063 g cm$^{-2.1}$
for convect. generated
D>0.0151 cm
Heymsfield et al. 2010

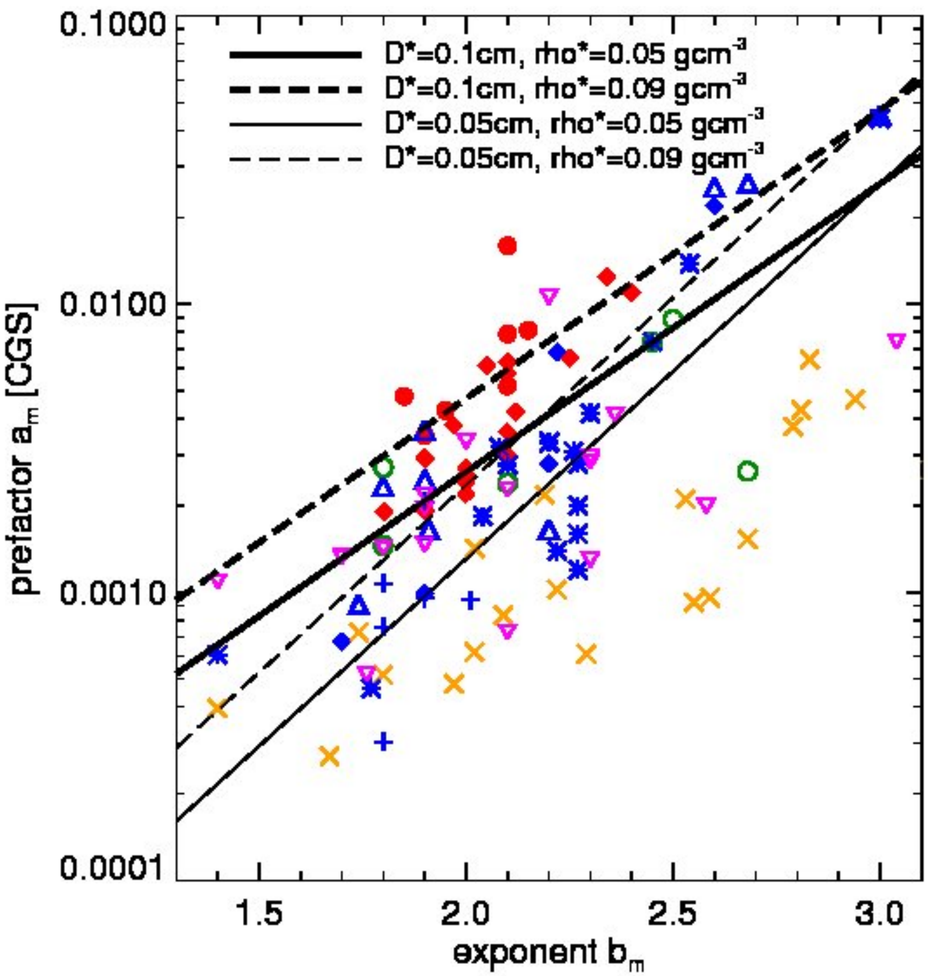


B.
a_m=0.00183 g cm$^{-2.04}$
CPI rosettes
Heymsfield et al. 2002

2. Normalization of the mass/density-size relationship

b. One-parameter normalized mass expression

Mass controlling parameter*: m** or *ρ**, respectively mass or density of the reference diameter *D** representing the PSD size interval dominating the bulk quantities of interest.



$$m(D) = m^*(D/D^*)^{b_m}$$

$$\rho_{eff}(D) = \rho^*(D/D^*)^{b_m-3}$$

$$\rho^* = m^*/\left(\pi/6\,(D^*)^3\right)$$

For a given *D**:

*m**(*ρ**) groups together the sets [a_m, b_m] that define exactly the same mass/density for particles with *D=D**

Value of *D**:

adapted to the size controlling the bulk quantities, closely related to the PSD characteristic size (from observation: estimation mainly based on measured U, and/or Z and T)

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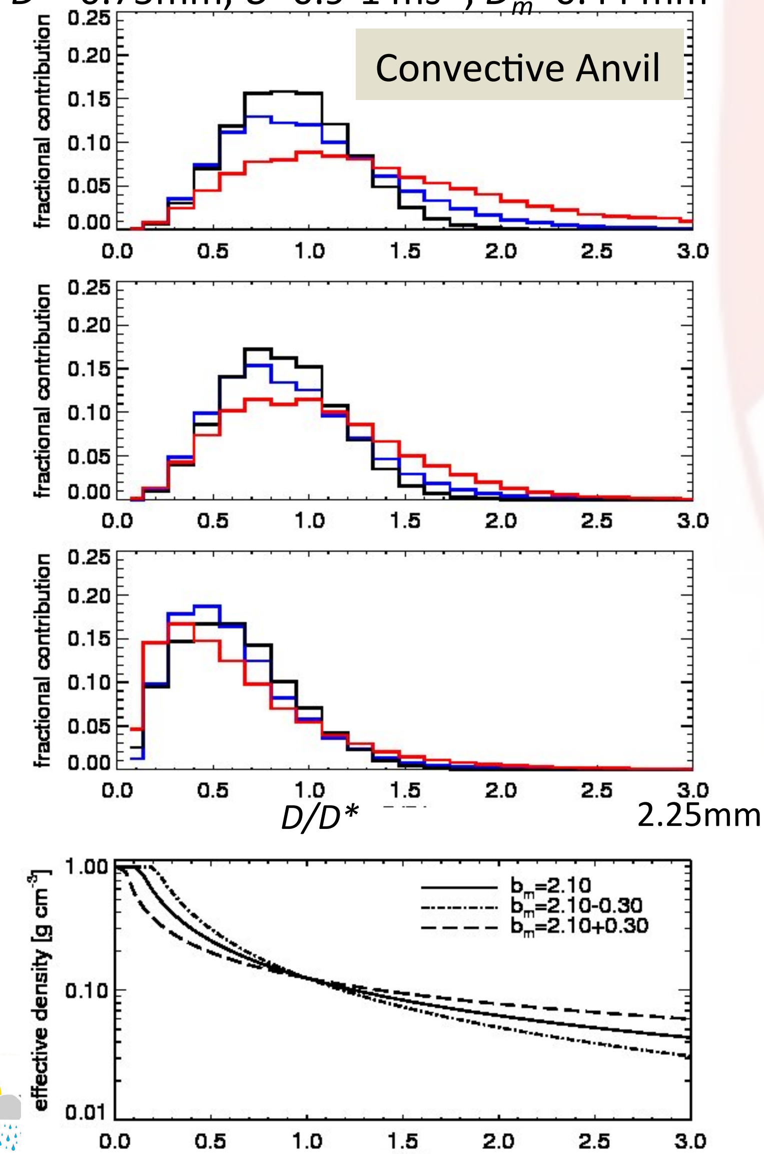
2. Normalization of the mass/density-size relationship

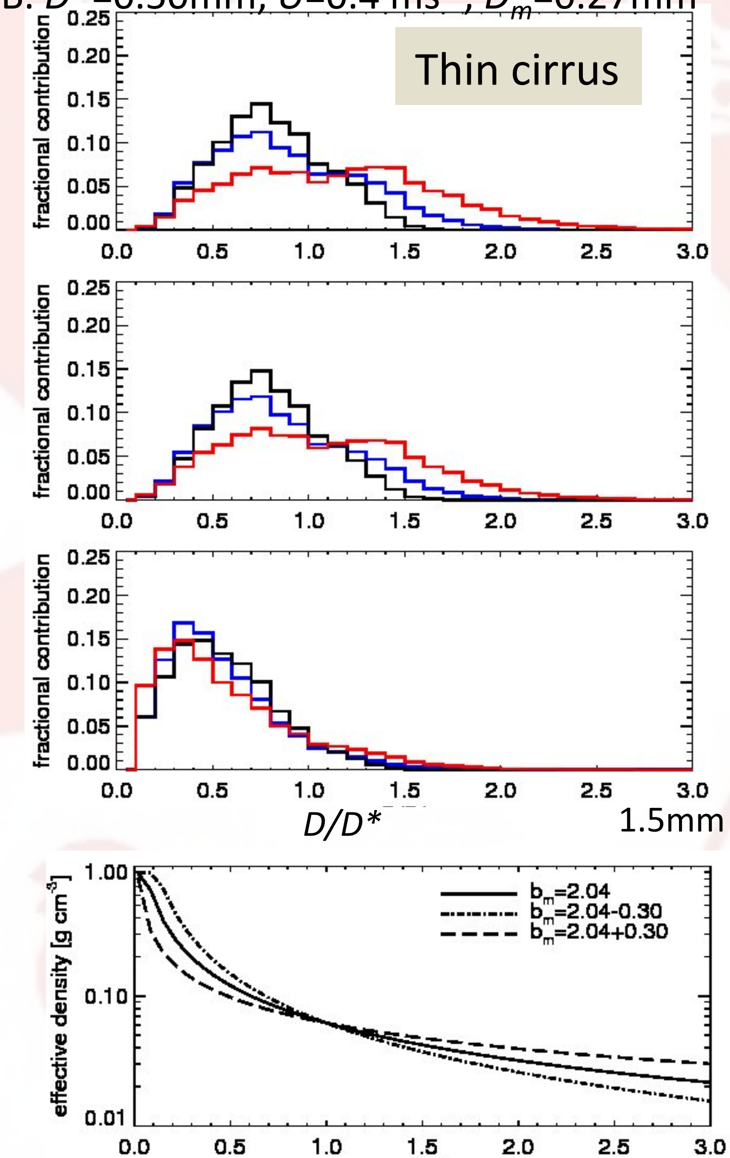
c. Fractional contribution in size categories of *D/D** calculated for three different PSD shapes normalized by mass-weighted diameter

Fractional contribution to:

A. D^*=0.75mm, U=0.9-1 ms^{-1}, D_m=0.44 mm



B. D^*=0.50mm, U=0.4 ms^{-1}, D_m=0.27mm



Reflectivity $Z^{(X)}$

Reflectivity $Z^{(W)}$

Mass content IWC

Effective density ρ_{eff}

3. Ensemble-based method to derive the relations microphysics-radar observables

WHY?

- Requirement of limited number of parameters used to describe microphysics.
- As shown in the published studies: no one microphysical model could account for all
  variability that is observed in natural conditions.

ADVANTAGE?

i) to take into account the large variety of the relations found in natural ice/snow, and

ii) to quantify uncertainty in the derived average relations caused by this variety.

HOW?

Model descriptors given by different combinations of microphysical assumptions considered as chief contributors to uncertainty in the relations linking ice/snow microphysics to radar observables, could be mainly:

i) mass/density of individual particle

ii) velocity-mass relationship

iii) PSD functional form

$\boxed{Z = MC \cdot f(D_m, \rho^*)}$

$\boxed{U_z = f(D_m, \rho^*)}$

The ensemble mean is assumed to be **<u>the best estimate</u>**.

The ensemble spread is a measure of associated **uncertainty**.

Calculations of the two forward model equations using the ensemble approach

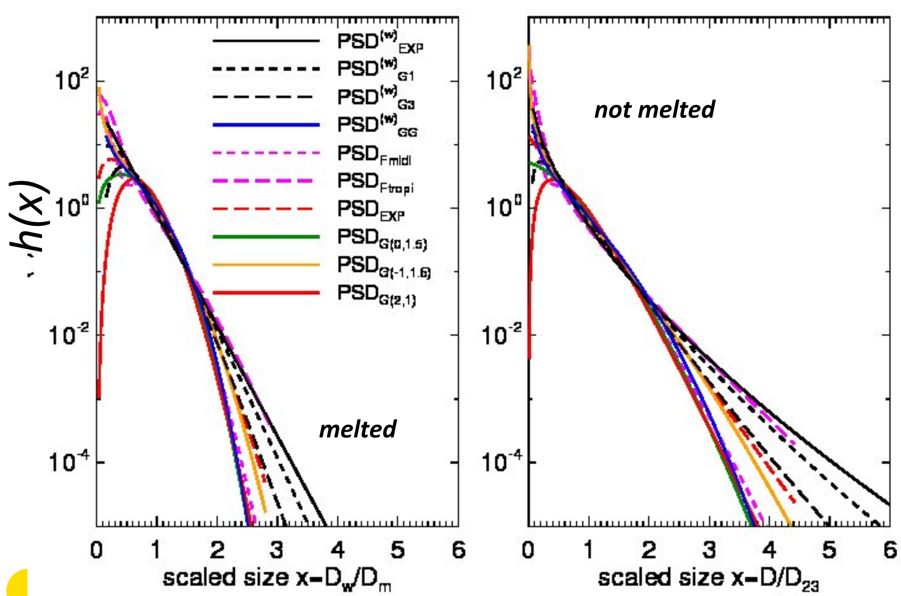
Ensemble generation and regression-based fit for ensemble average and standard deviation

-Particle Size Distribution (PSD)
within two-moment normalization approach

-10 general forms taken from observational studies

with melted diameter D_w as size descriptor and 3rd and 4th normalizing moments (Sekhon & Srivastava 1970; Delanoë et al. 2005)

with actual size D as size descriptor and 2rd and 3th normalizing moments (Field et al. 2007; Heymsfield et al. 2008; Szyrmer et al. 2009)



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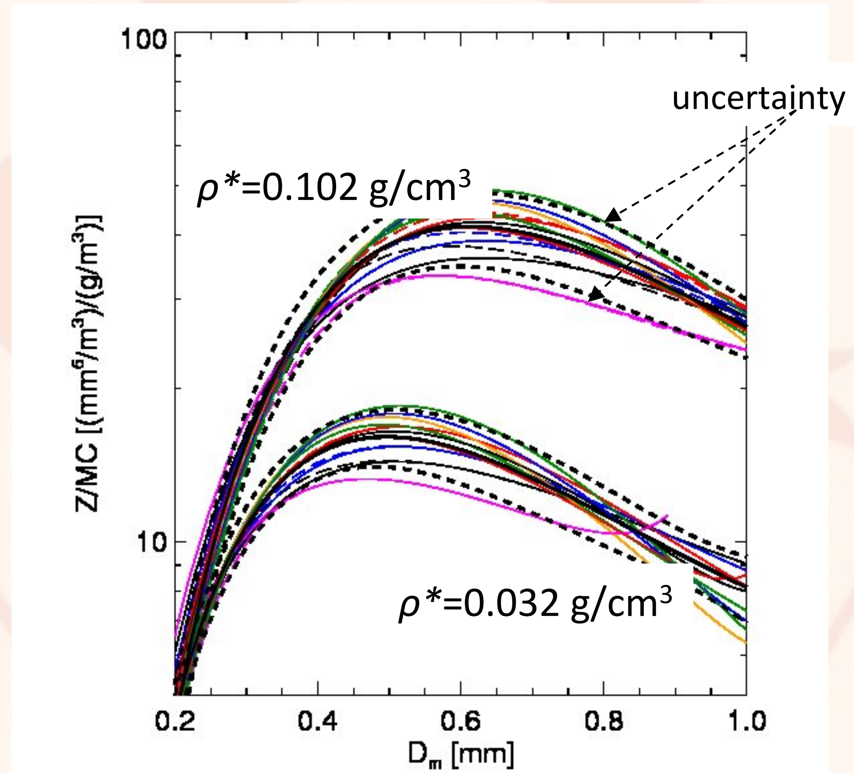
- different PSD analytical functions with assumed complete and truncated forms
- different values of density parameter ρ*

$Z=MC \cdot f(D_m, \rho^*)$

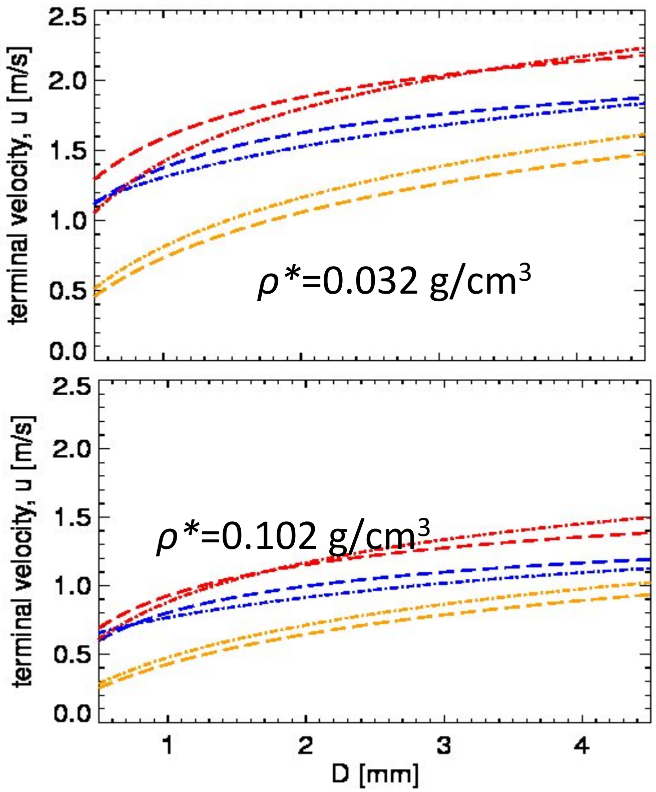


Calculations of the two forward model equations using the ensemble approach

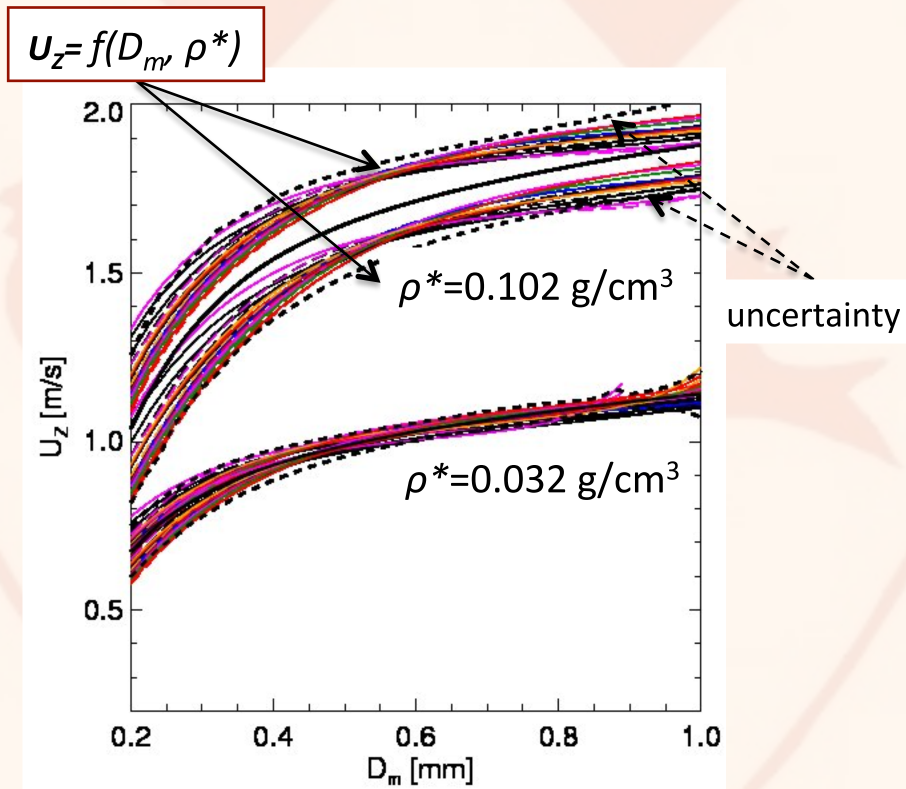
Ensemble generation and regression-based fit for ensemble average and standard deviation

-Terminal velocity computation consistent with particle density **from Heymsfield and Westbrook (2010) method using different mass-area ratio relationships:**

Heymsfield (2003), Baker and Lawson (2006)
Heymsfield et al. (2002), Szyrmer and Zawadzki (2010)
Heymsfield et al. (2002) Magono and Nakamura (1965) and Kajikawa (1982)



-different PSD analytical functions with assumed complete and truncated forms
- **different values of density parameter ρ***
- **few assumptions of mass-terminal velocity calculation with various mass-area ratio relationships**



Calculations of density increase from gradient of reflectivity-weighted velocity U_Z during the riming process (RIM)

Main assumptions:
- in the riming conditions, the contribution to the vertical gradient of U_z due to other processes is negligible
- the physical size of particle does not increase *via* the riming process

The increase of an individual snowflake mass due to the collection of supercooled cloud droplets is given by:

$$\left.\frac{dm(D)}{dt}\right|_{RIM} = \int K(D, D_{lc}) m_{lc}(D_{lc}) n_{lc} dD_{lc}$$

$$\left.\frac{d\rho^*}{dz}\right|_{RIM} = \frac{dU_Z}{dz} f(U_Z, \rho^*)$$

Estimated increase of density from the U_Z gradient and the values of U_Z and density.

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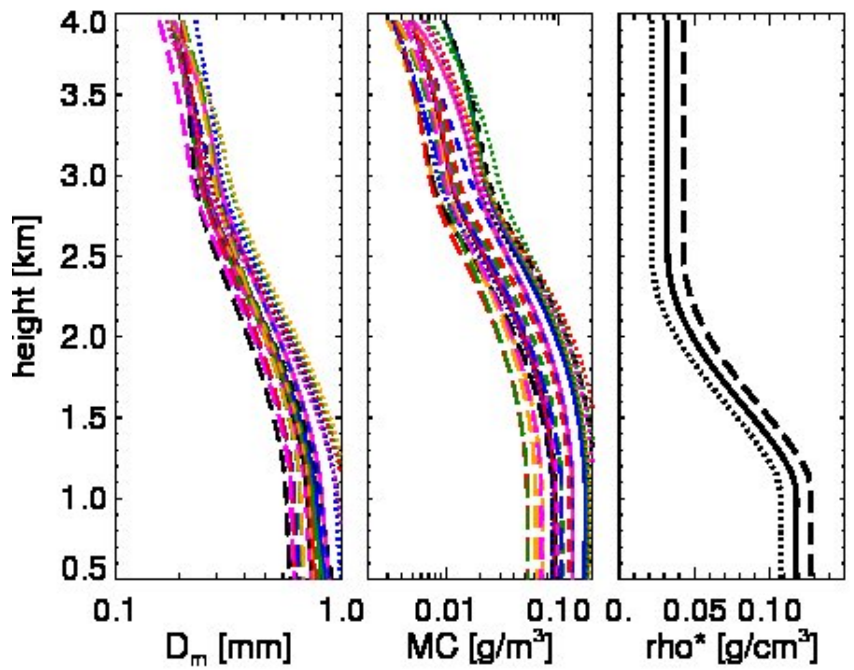
F. Application of the cold microphysics 1-D steady-state bin model

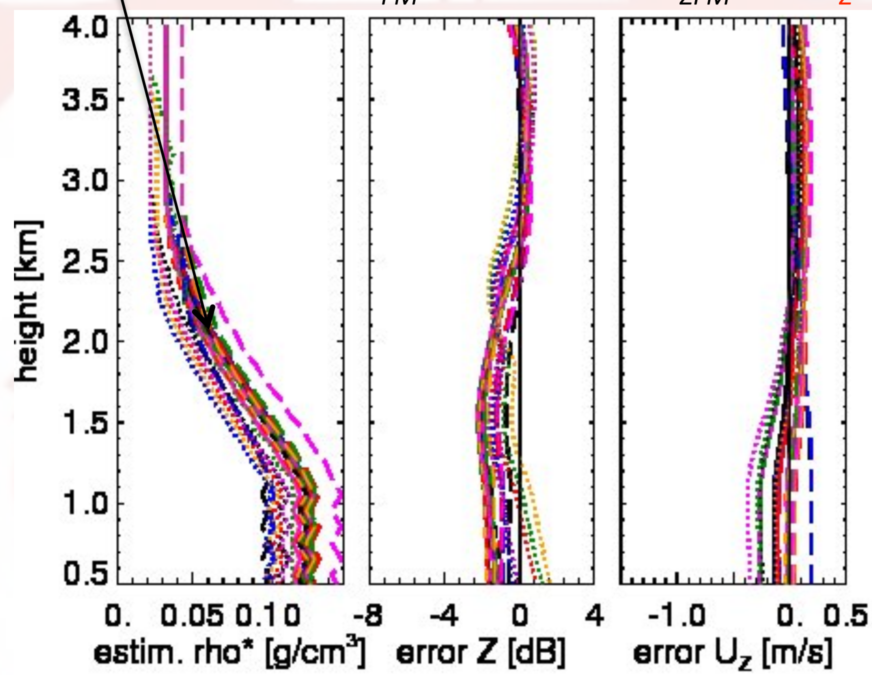
Calculation of the Z_{FM} and U_{ZFM} profiles using the two forward model (FM) relations and the developed relation for estimate of density increase

$$\left.\frac{d\rho^*}{dz}\right|_{RIM} = f\left(\frac{dU_Z}{dz}, U_Z, \rho^*\right)$$

State vector profiles



Calculated differences between Z_{FM} and Z and U_{ZFM} and U_Z



From D_m and MC (and parameter ρ^*) calculated profiles of :

$$\boxed{Z_{FM} = MC \cdot f(D_m, \rho^*)}$$

$$\boxed{\mathbf{U_Z} = f(D_m, \rho^*)}$$

error Z $= 10\log Z_{FM} - Z$

error U_Z $= U_{ZFM} - U_Z$

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Z and U_z: spectral calculations from model outputs shown at previous slide

The uncertainty introduced by the **backscattering computations** is large due to the dependence of the radar return on the details of the ice/snow particle microstructure

The proposed concept of **normalized mass/density vs size relationship** can reduce the uncertainty introduced by the selection of the conventional mass-diameter power-law relationship and by the selection of the PSD shape (Szyrmer et al., 2012; 2013)

The effect of **riming** on particle density needs to be considered. The degree of riming can be inferred by the gradient of the Doppler velocity, the Doppler velocity magnitude and the reference density above the liquid layer (Tatarevic et al., 2013).

An **ensemble**-based method to derive the relations microphysics-radar observables is proposed to address the stochastic nature of snow (Szyrmer and Zawadzki, 2013)

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