Radar Microphysical Retrievals and Climatology of the Vertical Profiles of Microphysical Variables in Different Weather Systems

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PROM meeting, Kiel, Germany, 17 July 2023

Relations for polarimetric microphysical retrievals in ice

Rayleigh approximation, valid at centimeter wavelengths

(1) Ice water content (IWC)

$$IWC(K_{DP}, Z) = 3.3\times 10^{-3}(K_{DP}\lambda)^{0.67} Z^{0.33}$$

(2) Mean volume diameter ($D_m = M_4/M_3$)

$$D_m(K_{DP}, Z) = 0.67\left(\frac{Z}{K_{DP}\lambda}\right)^{1/3}$$

(3) Total number concentration (N_t)

$$\log(N_t) = 3.39 + 2\log(IWC) - 0.1Z(dBZ)$$

$$\rho_s(D) = \alpha_0 f_{rim} D^{-1}$$

$$f_{rim} = 1/(1 - FR)$$

f_{rim} is the degree of riming
FR is the rime mass fraction

λ is the radar wavelength in mm
Z is in mm^6m^{-3}
K_{DP} is in deg/km
IWC is in $g\ m^{-3}$
D_m is in mm
N_t is in L^{-1}

Initial assumptions

- Existing polarimetric radar retrieval relations in ice are based on several assumptions regarding the degree of riming f_{rim} , shape parameter μ of gamma PSD, average shape or aspect ratio a/b of particles, and their orientations commonly characterized by the width of the mean canting angle distribution σ.

- Original retrieval relations were derived assuming Rayleigh scattering approximation for the exponential PSD ($\mu = 0$), unrimed snow ($f_{rim} = 1$) or snow with a certain f_{rim} factor, average aspect ratio $a/b = 0.6$, and the typical value of $\sigma = 20°$.

- These initial assumptions seem to be generally good, but they definitely need some additional tune up based on the matching of the results of polarimetric retrievals with the results of in situ microphysical measurements either at the surface or onboard research aircrafts or by comparing polarimetric retrievals with the multi-frequency ones.

Dunnavan et al. , 2022: Radar Retrieval Evaluation and Investigation of Dendritic Growth Layer Polarimetric Signatures in a Winter Storm. *Journal of Applied Meteorology and Climatology*, **61**, 11, 1679–1705,

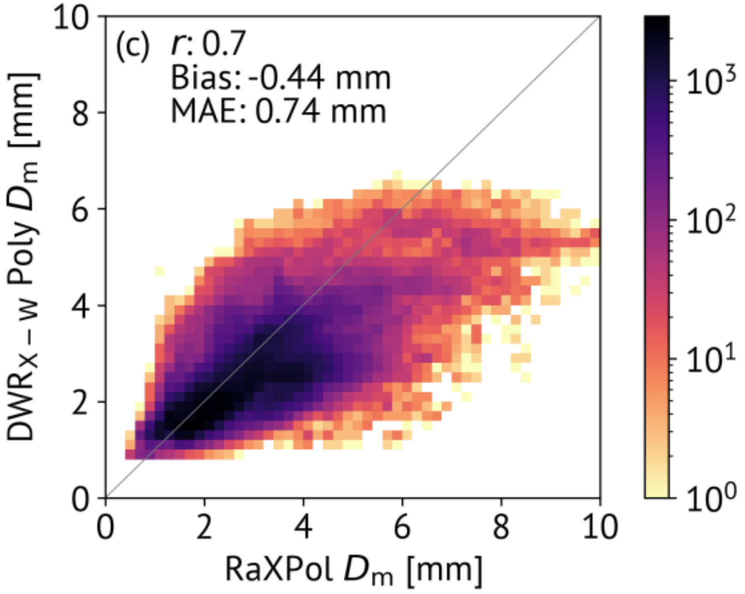
Comparison of multifrequency and polarimetric microphysical retrievals during IMPACTS

Dunnavan et al. 2023: High-resolution snowstorm measurements and retrievals using cross-platform multi-frequency and polarimetric radars. GRL, 50, 11 ,1 - 11

NASA ER-2 aircraft multifrequency radar measurements (X, Ku, Ka, W bands)

OU RaXPol X-band ground-based polarimetric radar

25 Feb 2022



$$D_m = 1.31 + 0.146\,DWR + 0.0209\,DWR^2 - 4.27\times10^{-4}\,DWR^3$$

$$DWR = DWR_{X-W}$$

$$D_m = 0.336\left(\frac{Z}{K_{DP}}\right)^{1/3}$$

The agreement between two estimates of the mean volume diameter D_m is good for $D_m < 6$ mm

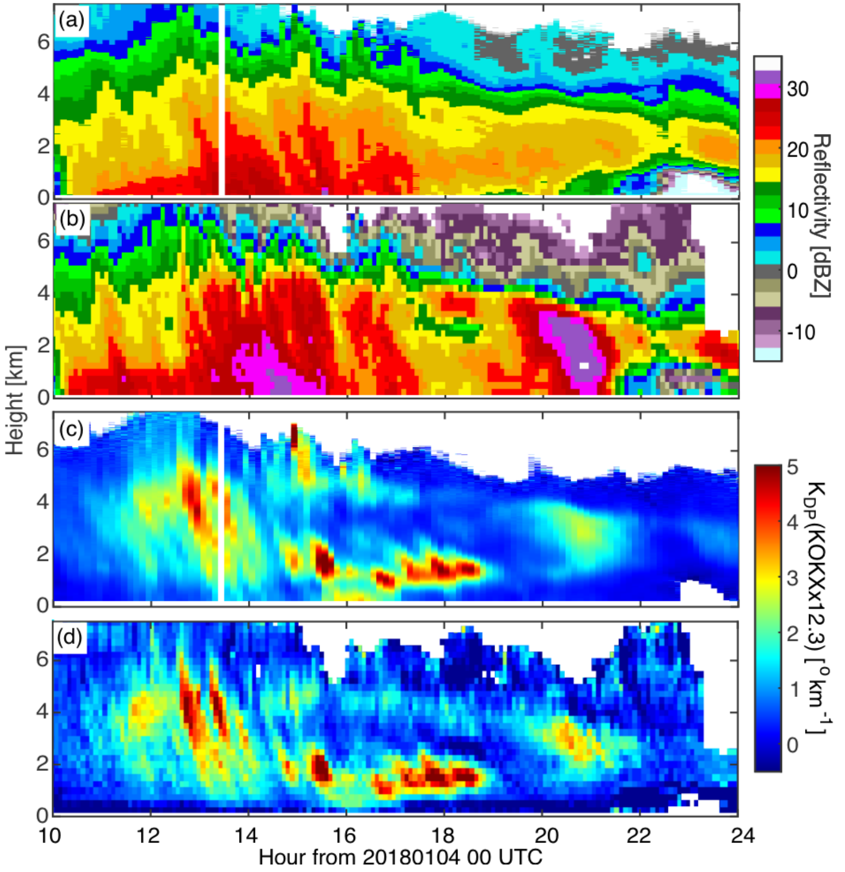
A synthesis of polarimetric and dual-frequency radar observations of winter storms for estimating ice water content

Joint project of the University of Oklahoma and Stony Brook University

IWC(N_t,Z)

IWC(K_{DP},Z,f_{rim})

- Using QVP and CVP techniques, it is possible to match the measurements of non-collocated radars and estimate the dual-wavelength ratios
- The product $K_{DP}\lambda$ is invariant from S- to Ka-band frequencies
- Polarimetric microphysical retrieval algorithms originally developed for S band can be applied to millimeter wavelengths after some modification



Z(Ka) QVP

Z(S) CVP

K_{DP}(Ka) QVP

K_{DP}(S) CVP

How to modify existing polarimetric retrieval relations for millimeter wavelengths?

$$D_m = 0.67\left(\frac{Z}{K_{DP}\lambda}\right)^{1/3} = 0.67\left(\frac{10^{0.1dBZ}}{K_{DP}\lambda}\right)^{1/3} \rightarrow \quad D_m = 0.67\left(\frac{10^{0.1(dBZ+DWR)}}{K_{DP}\lambda}\right)^{1/3}$$

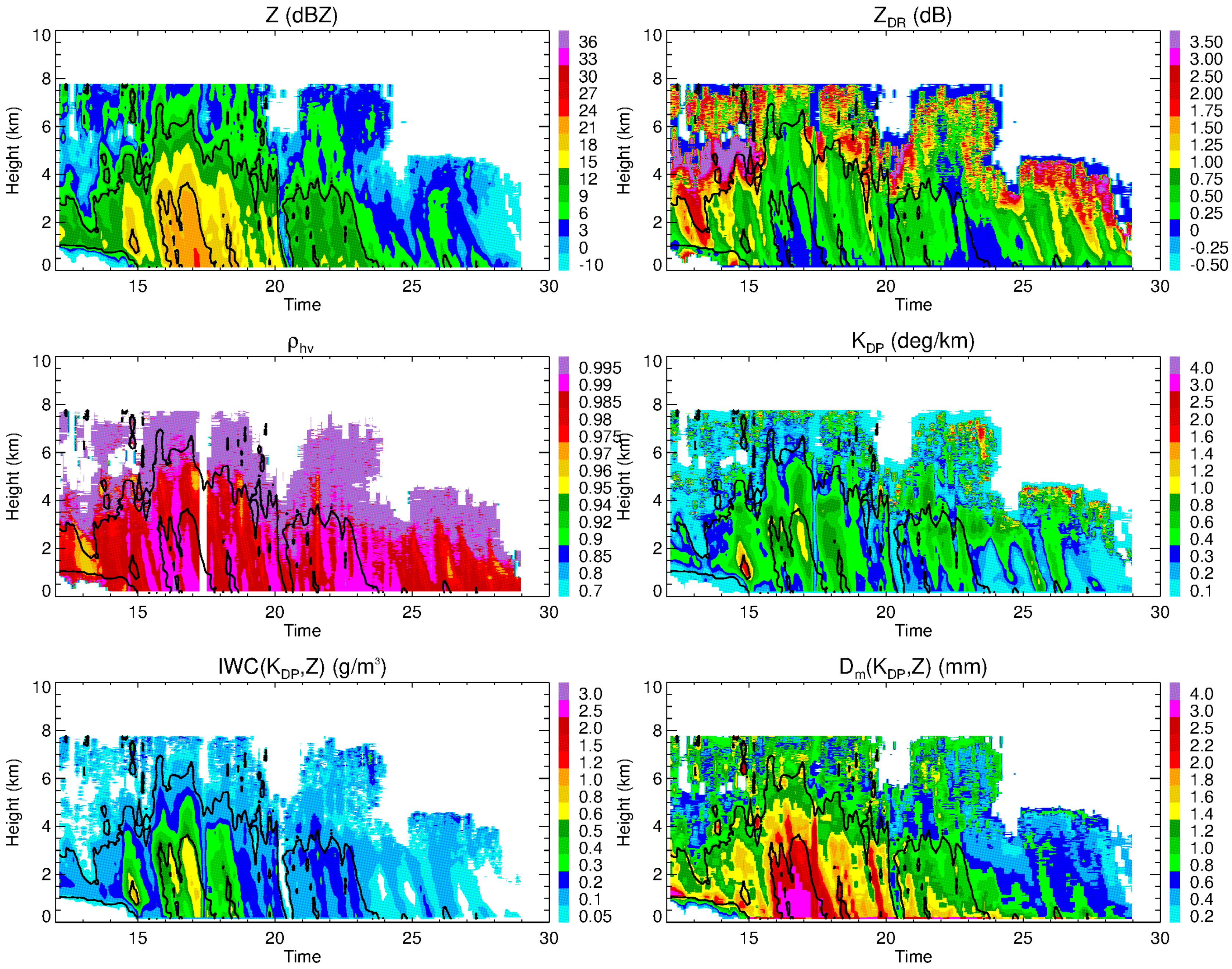
$$DWR_{S/Ka} \approx D_m^{1.73}$$

$$D_m = 0.67\left(\frac{10^{0.1(dBZ+D_m^{1.73})}}{K_{DP}\lambda}\right)^{1/3}$$

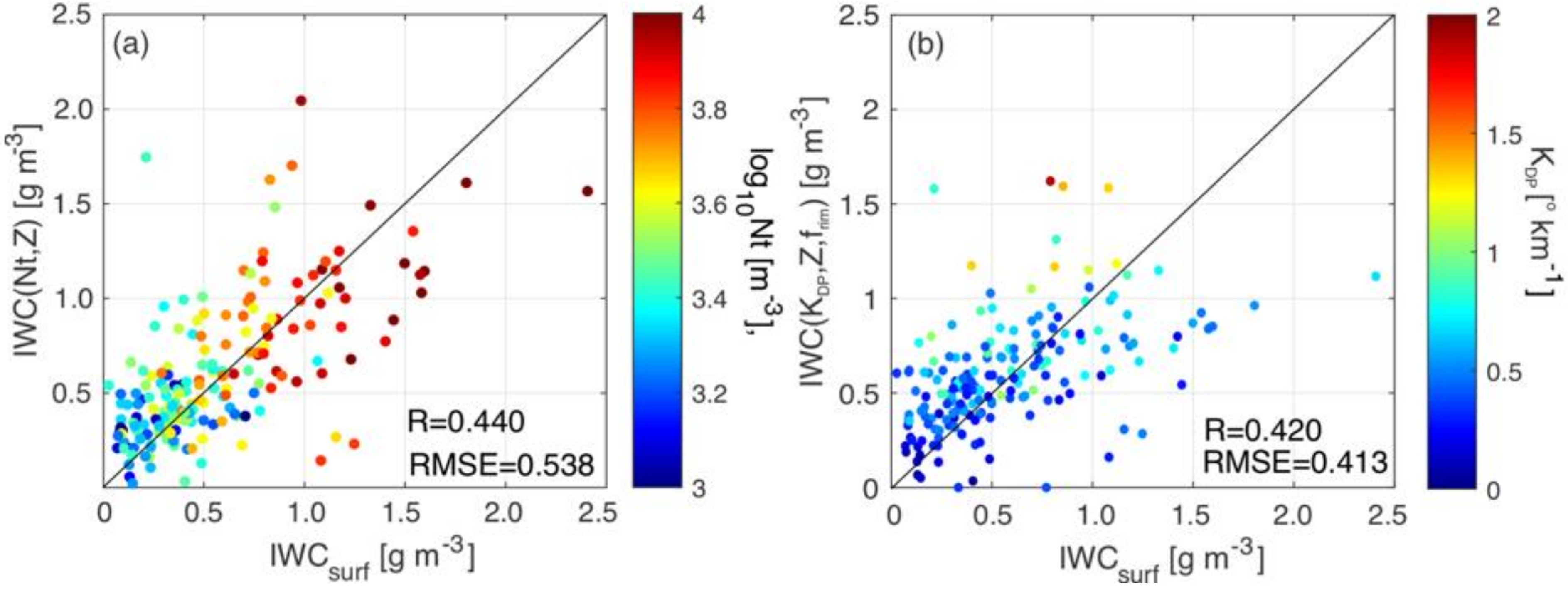
$$IWC = 7.09\times10^{-2}\, f_{rim}^{-0.94}(K_{DP}\lambda)^{0.66}10^{0.028(dBZ+D_m^{1.73})}$$

$$\log(N_t) = 3.39 + 2\log(IWC) - 0.1(dBZ + D_m^{1.73})$$

Ka-band polarimetric retrievals, 2017/12/09



Scatterplots of IWC measured by pluvio / disdrometer versus their estimates from IWC(K_{DP},Z,f_{rim}) and IWC(N_t,Z) relations for 7 KASPR winter cases



Nonpolarimetric retrieval relations

Using N_t instead of K_{DP} in combination with Z

$$IWC(N_t, Z) = f(\mu) N_t^{1/2} Z^{1/2}$$

μ = 0

$$IWC = 0.0143 N_t^{1/2} Z^{1/2}$$

μ = -0.5

$$IWC = 0.0102 N_t^{1/2} Z^{1/2}$$

- **The advantage of the IWC(N_t,Z) estimate is that it is insensitive to the variability of particles' shapes, orientations, and degree of riming**

- **The idea is to polarimetrically estimate N_t in the dendritic growth layer (DGL) where polarimetric signatures are most pronounced and project N_t(DGL) down to the surface using some physical considerations**

Conservation of precipitation flux (collision – coalescence only)

Simple Rayleigh relations for exponential PSD

$$IWC \propto f_{rim} N_t D_m^2 \qquad S \propto f_{rim}^{1/4} N_t D_m^{2.2} \qquad Z \propto f_{rim}^2 N_t D_m^4 \qquad K_{DP} \propto F_s F_o f_{rim}^2 N_t D_m$$

Assuming conservation of S and constant f_{rim}, the product $C = N_t D_m{}^{2.2}$ is constant. Therefore

$$IWC \propto C \; f_{rim} D_m^{-0.2} \qquad Z \propto C \; f_{rim}^2 D_m^{1.8} \qquad K_{DP} \propto C \; F_s F_o f_{rim}^2 D_m^{-1.2}$$

$$N_t \propto S^{2.22} Z^{-1.22}$$

$$N_t = N_{t,top} \exp[-0.28(Z - Z_{top})]$$

Z is in dB

$$D_m = D_{m,top} \exp[0.13(Z - Z_{top})]$$

Simple analytical expressions for steady-state vapor growth and collision-coalescence particle size distribution parameter profiles

Dunnavan, E. and A. Ryzhkov, 2023: Simple analytical expressions for steady-state vapor growth and collision – coalescence particle size distribution parameter profiles. JAS, conditionally accepted.

Vertical advection *Vapor deposition* *Collision-coalescence gain and loss*

$$\frac{\partial[v_t \cdot n(x,z)]}{\partial z} = -\frac{\partial}{\partial x}\left[\frac{dx}{dt}\cdot n(x,z)\right] + \frac{1}{2}\int_{y=0}^{x} n(x-y,z)n(y,z)K(x-y,y)dy - n(x,z)\int_{0}^{\infty} n(y,z)K(x,y)dy$$

$$\frac{dD_m}{dh} = C_{D_m}\overline{E}N_t D_m^3$$

$$D_m(h) = D_{m,top}e^{C_{D_m}\overline{E}N_{t,top}D_{m,top}^2(h_{top}-h)}$$

$$\frac{dN_t}{dh} = -C_{N_t}\overline{E}N_t^2 D_m^2$$

$$N_t(h) = N_{t,top}e^{-C_{N_t}\overline{E}N_{t,top}D_{m,top}^2(h_{top}-h)}$$

Pure collision-coalescence

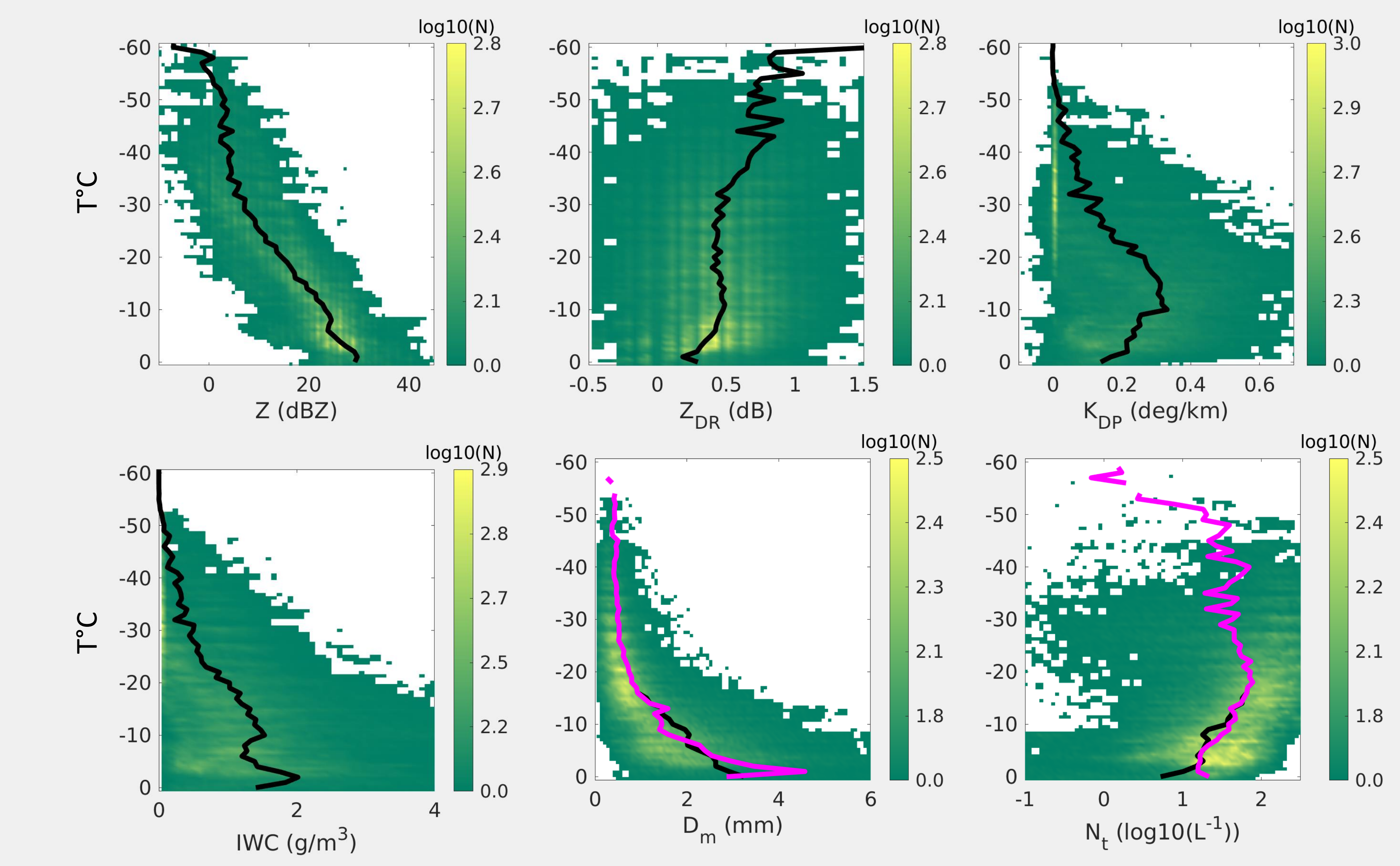
$$N_t \approx N_{t,top}e^{-0.23(Z-Z_{top})} \qquad D_m \approx D_{m,top}e^{0.11(Z-Z_{top})}$$

Radar reflectivity Z is in dB

$\overline{E}$ *is the collision-coalescence efficiency*

C_{Dm} and C_{Nt} depend on the exponents of the m(D) and v_t(D) relations

Summary of CVPs for 25 synoptic snowstorms



Optimal relations for synoptic heavy snow

$$D_m(Z) = D_{m,top}\exp[0.12(Z - Z_{top})]$$

$$D_m(h) = D_{m,top}\exp[0.0054 N_{t,top} D_{m,top}^2 (h_{top} - h)]$$

$$N_t(h) = N_{t,top}\exp[-0.0026 N_{t,top} D_{m,top}^2 (h_{top} - h)]$$

N_t is in 1/L, D_m is in mm, h is in km, Z is in dBZ

h_{top} means the DGL height

Conclusions

- The original methodology for polarimetric radar microphysical retrievals in ice valid at centimeter wavelengths was modified for utilization at millimeter radar wavelengths (Ka band)

- A new nonpolarimetric retrieval technique utilizing combination of Z and N_t has been suggested

- This technique assumes that N_t has to be polarimetrically estimated at a single altitude with pronounced polarimetric signatures (e.g., DGL) and its full vertical profile can be restored using simple analytical formulas derived from physical considerations

- The new technique quantifies the collision – coalescence process in snow and rain particularly well and shows the best promise for heavy synoptic snowfall

- The steady-state model equations can be used to estimate PSD parameters and precipitation rates in regions where radar retrievals are either difficult to perform due to instrumental uncertainties or in areas where radar variables are unavailable