Polarimetric microphysical retrievals. Challenges and promises

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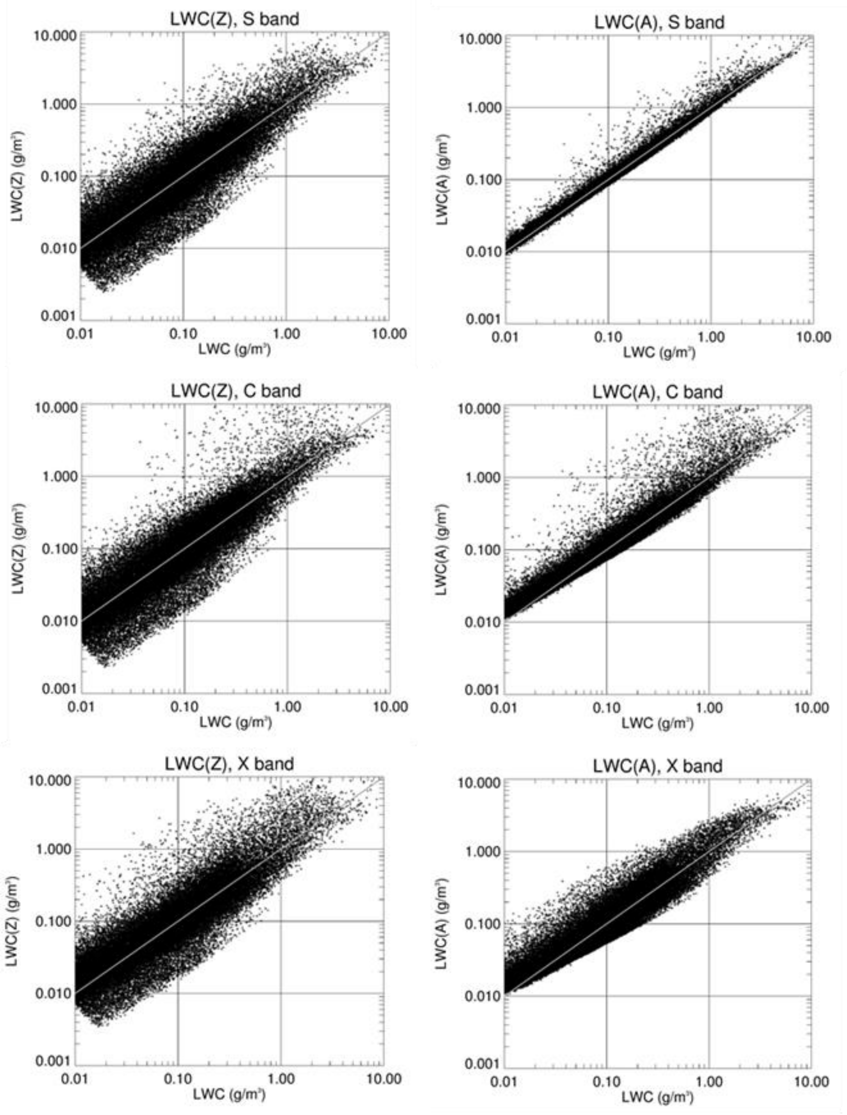
Estimation of liquid water content (LWC) from specific attenuation A



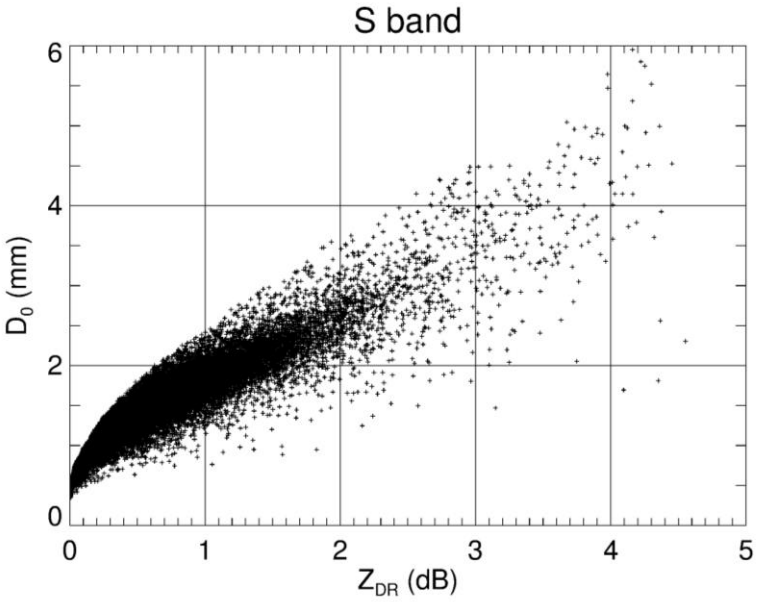
Temperature, °C	S band (λ = 11.0 cm)	C band (λ = 5.3 cm)	X band (λ = 3.2 cm)
0	$LWC = 70.3\ A^{0.921}$	$LWC = 8.57\ A^{0.814}$	$LWC = 2.25\ A^{0.767}$
10	$LWC = 92.4\ A^{0.922}$	$LWC = 9.79\ A^{0.800}$	$LWC = 2.14\ A^{0.731}$
20	$LWC = 119\ A^{0.924}$	$LWC = 11.6\ A^{0.794}$	$LWC = 2.10\ A^{0.698}$
30	$LWC = 150\ A^{0.926}$	$LWC = 14.1\ A^{0.794}$	$LWC = 2.10\ A^{0.669}$

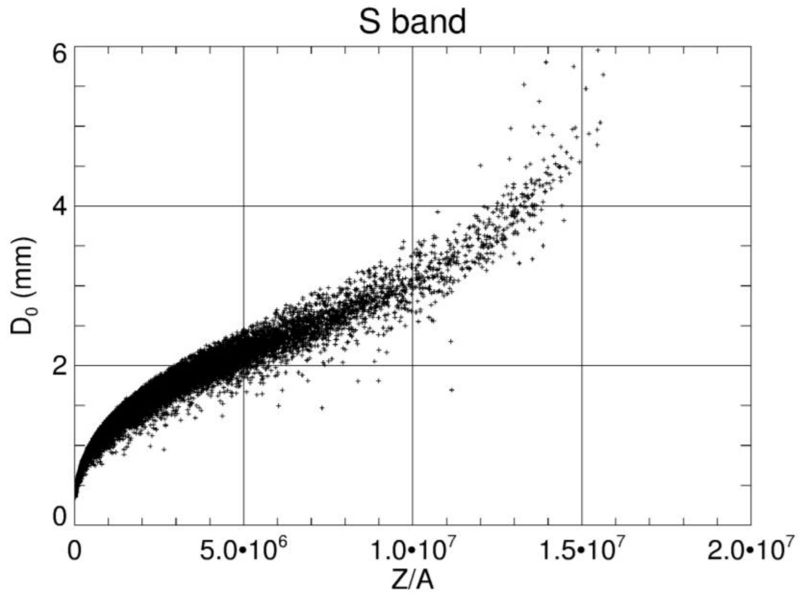
At S band

$$LWC = (70.3 + 1.99T + 0.023T^2)A^{0.924}$$

- A-based estimates of LWC are more accurate than its conventional estimates from Z
- A more sophisticated technique for computing specific attenuation has been suggested recently

Estimation of the mean volume diameter of raindrops D_m





Bringi and Chandrasekar (2001)

$$D_m = 1.62\ Z_{DR}^{0.49}$$

Bringi et al. (2002)

$$D_m = 1.97\ Z_{DR}^{0.49}$$

Brandes et al. (2002)

$$D_0 = 0.171 Z_{DR}^3 - 0.725 Z_{DR}^2 + 1.48 Z_{DR} + 0.717$$

S band

T = 20°

$$D_m = 0.630 + 0.675x - 0.124x^2 + 0.0115x^3 - 0.00034x^4$$

$$x = \frac{Z}{A} 10^{-6}$$

$$[Z] = mm^6 m^{-3}, \quad [Z_{DR}] = dB, \quad [A] = dB/km, \quad [D_m] = mm$$

Caveats: Z_{DR} should be well calibrated, A is a function of radar wavelength and temperature

Relations for polarimetric microphysical retrievals in ice

(1) $$IWC(K_{DP}, Z_{DR}) = 4.0 \times 10^{-3} \frac{K_{DP}\lambda}{1 - Z_{dr}^{-1}}$$

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

(3) $$D_m(K_{DP}, Z_{DP}) = -0.1 + 2.0 \left(\frac{Z_{DP}}{K_{DP}\lambda} \right)^{1/2}$$

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

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

$$\rho_s = \alpha D^{-1}$$

$$Z_{dr} = 10^{0.1 Z_{DR}(dB)}$$

$$Z_{DP} = Z_H - Z_V$$

λ is the radar wavelength in mm

Z is in $mm^6 m^{-3}$

Z_{DP} is in $mm^6 m^{-3}$

K_{DP} is in deg/km

IWC is in g m^{-3}

D_m is in mm

N_t is in L^{-1}

Eqs. (1) and (3) are utilized if $Z_{DR} > Z_{DR}^{(t)}$ and Eqs (2) and (4) are used otherwise ($Z_{DR}^{(t)}$ = 0.4 dB)

Estimates (1) and (3) are immune to the variability of the particles' shapes and orientations

Basic assumptions

(1) Density is inversely proportional to the particle size

$$\rho_s(D) = \alpha_0 f_{rim} D^{-1} \qquad f_{rim} = \frac{1}{1-FR} \qquad FR = \frac{m}{M}$$

- rime mass fraction

(2) Unrimed ice (f_{rim} = 1)

(3) Size distribution is exponential (μ = 0)

(4) Oblate spheroids with aspect ratio equal to 0.6

(5) The width of the canting angle distribution σ = 20°

Overall performance of the existing microphysical retrievals

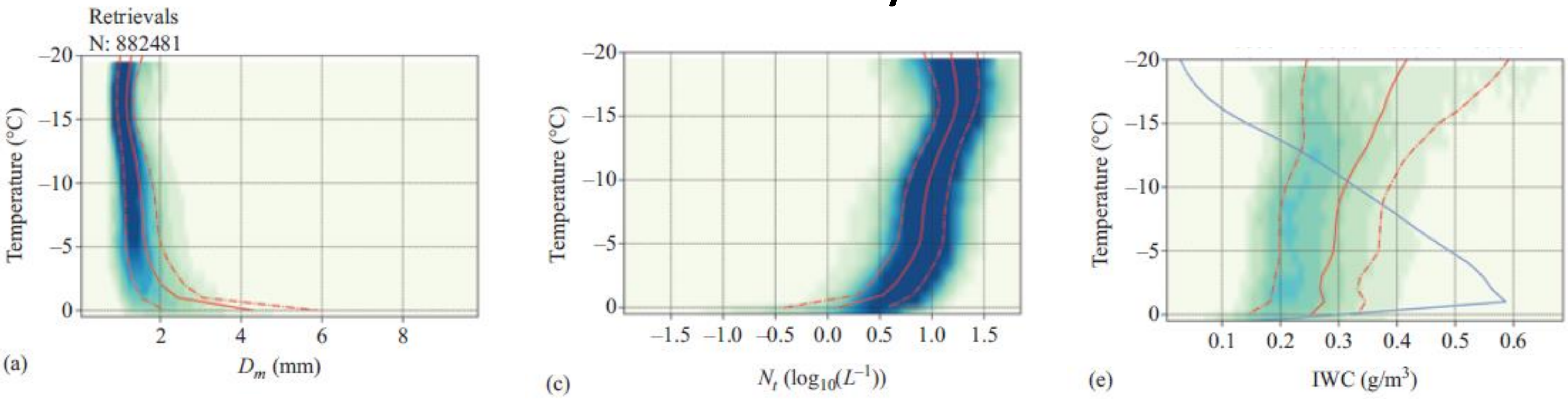
- Basic retrieval equations yield quite reasonable results as occasional comparisons with in situ aircraft measurements show

- Preliminary climatologies of the vertical profiles of microphysical parameters have been created for different types of weather systems in various geographical areas

- It was found that tropical cyclones are characterized by higher concentrations of smaller size ice particles compared to the continental MCSs

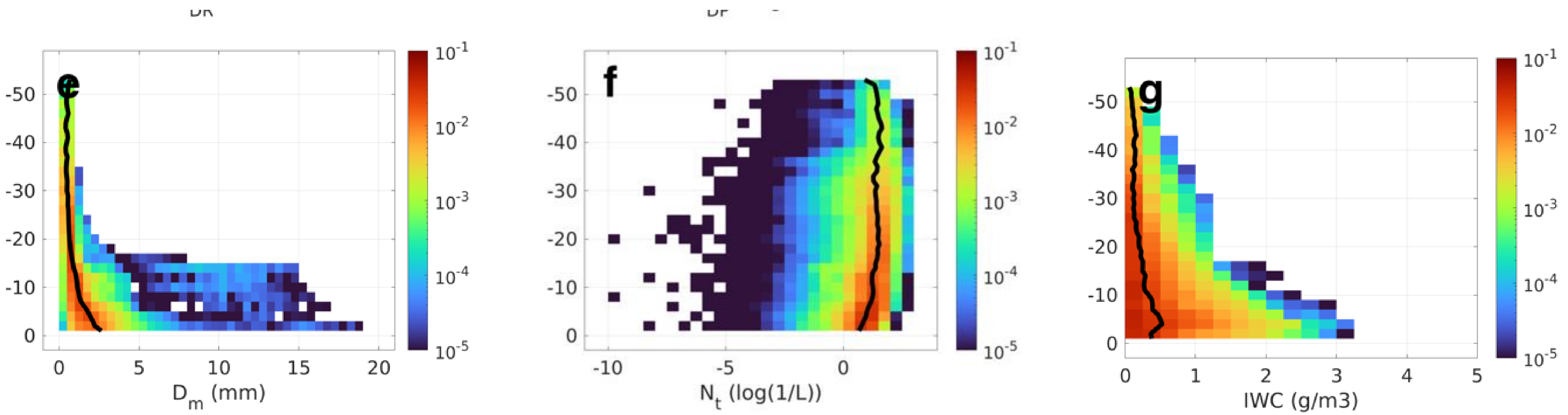
- It was found that most of the NWP models overestimate the size of ice and underestimate their concentration (likely due to inadequate treatment of secondary ice production)

Germany



Retrievals
N: 882481
Temperature (°C)
(a)
D_m (mm)
(c)
N_t (log10(L^-1))
(e)
IWC (g/m^3)

USA



e
D_m (mm)
f
N_t (log(1/L))
g
IWC (g/m3)
10^-1
10^-2
10^-3
10^-4
10^-5

Parameterization of the vertical profiles of N_t and D_m

Dunnavan, E. and A. Ryzhkov, 2023: Simple analytical expressions for steady-state vapor growth and collision – coalescence particle size distribution parameter profiles. J. Atmos. Sci, 80, 2531 - 2544

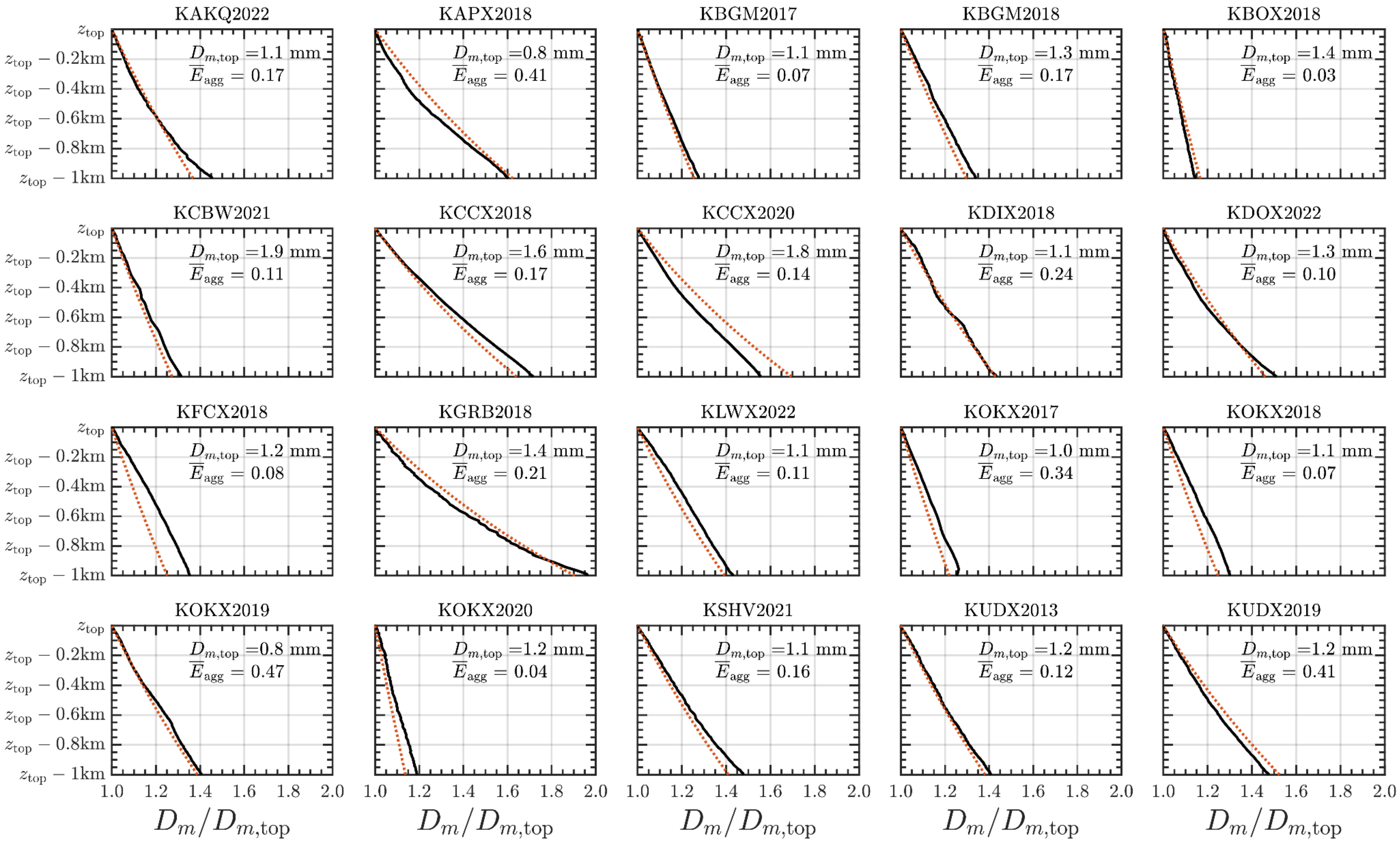
$$N_t(h) = N_{t,top}[1 + C_{tot} E_{agg} A_{top}(h_{top} - h)]^{-C_{N_t}/C_{tot}}$$

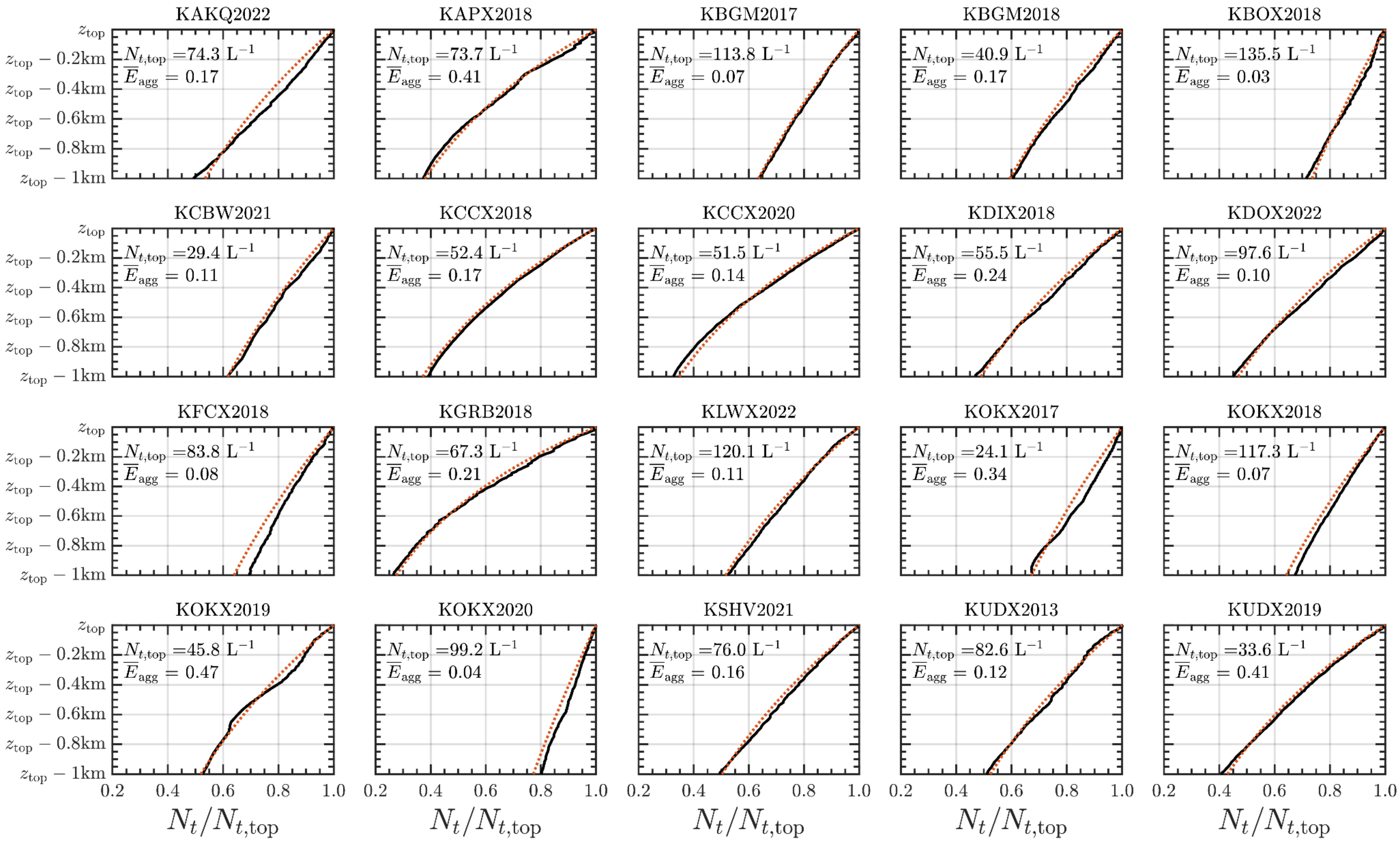
$$D_m(h) = D_{m,top}[1 + C_{tot} E_{agg} A_{top}(h_{top} - h)]^{C_{D_m}/C_{tot}}$$

$$A_{top} = N_{t,top} D_{m,top}^2 \qquad C_{tot} = C_{N_t} - 2C_{D_m}$$

E_{agg} is the collision- coalescence efficiency

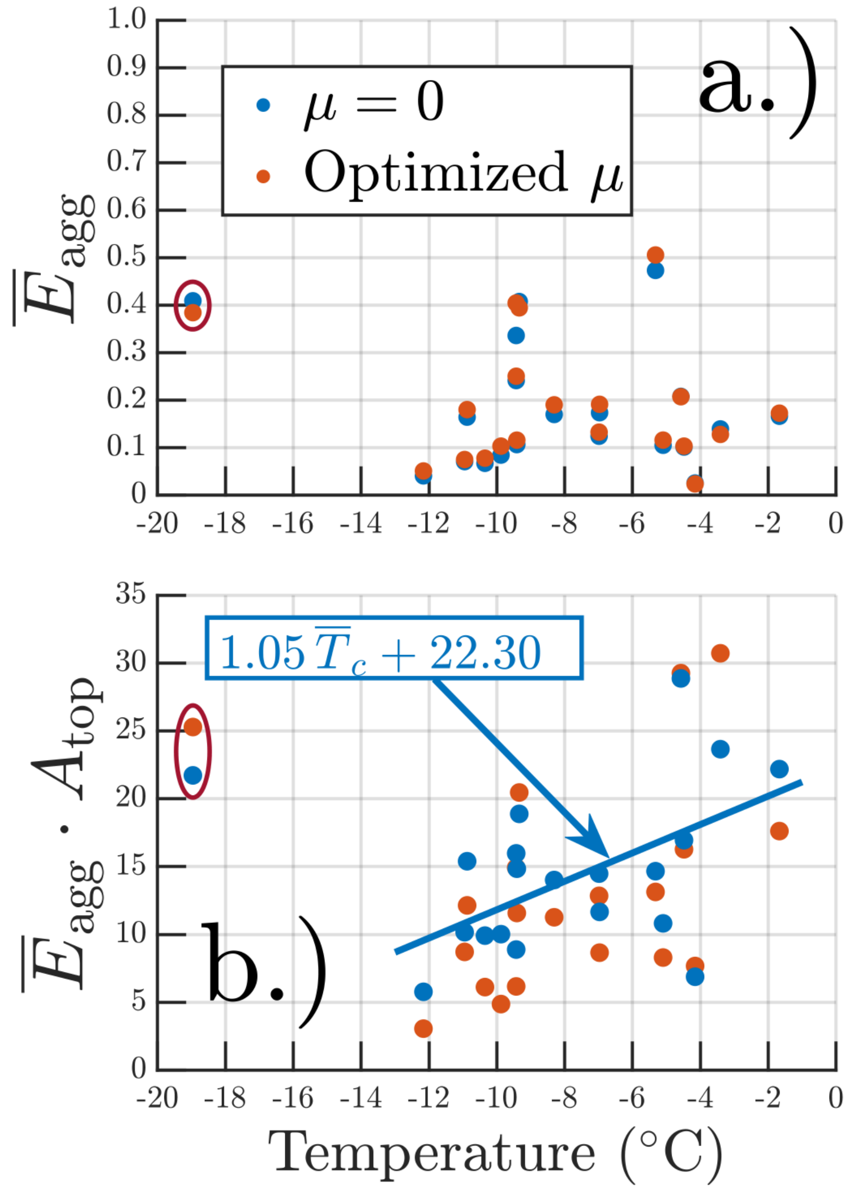
C_{Nt} and C_{Dm} are analytic functions of μ and the exponents of the ρ(D) and V(D) power-law relations


KAKQ2022
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.17
KAPX2018
$D_{m,\mathrm{top}}$ =0.8 mm
$\overline{E}_{\mathrm{agg}}$ = 0.41
KBGM2017
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.07
KBGM2018
$D_{m,\mathrm{top}}$ =1.3 mm
$\overline{E}_{\mathrm{agg}}$ = 0.17
KBOX2018
$D_{m,\mathrm{top}}$ =1.4 mm
$\overline{E}_{\mathrm{agg}}$ = 0.03
KCBW2021
$D_{m,\mathrm{top}}$ =1.9 mm
$\overline{E}_{\mathrm{agg}}$ = 0.11
KCCX2018
$D_{m,\mathrm{top}}$ =1.6 mm
$\overline{E}_{\mathrm{agg}}$ = 0.17
KCCX2020
$D_{m,\mathrm{top}}$ =1.8 mm
$\overline{E}_{\mathrm{agg}}$ = 0.14
KDIX2018
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.24
KDOX2022
$D_{m,\mathrm{top}}$ =1.3 mm
$\overline{E}_{\mathrm{agg}}$ = 0.10
KFCX2018
$D_{m,\mathrm{top}}$ =1.2 mm
$\overline{E}_{\mathrm{agg}}$ = 0.08
KGRB2018
$D_{m,\mathrm{top}}$ =1.4 mm
$\overline{E}_{\mathrm{agg}}$ = 0.21
KLWX2022
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.11
KOKX2017
$D_{m,\mathrm{top}}$ =1.0 mm
$\overline{E}_{\mathrm{agg}}$ = 0.34
KOKX2018
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.07
KOKX2019
$D_{m,\mathrm{top}}$ =0.8 mm
$\overline{E}_{\mathrm{agg}}$ = 0.47
KOKX2020
$D_{m,\mathrm{top}}$ =1.2 mm
$\overline{E}_{\mathrm{agg}}$ = 0.04
KSHV2021
$D_{m,\mathrm{top}}$ =1.1 mm
$\overline{E}_{\mathrm{agg}}$ = 0.16
KUDX2013
$D_{m,\mathrm{top}}$ =1.2 mm
$\overline{E}_{\mathrm{agg}}$ = 0.12
KUDX2019
$D_{m,\mathrm{top}}$ =1.2 mm
$\overline{E}_{\mathrm{agg}}$ = 0.41
z_{top}
$z_{\mathrm{top}} - 0.2$km
$z_{\mathrm{top}} - 0.4$km
$z_{\mathrm{top}} - 0.6$km
$z_{\mathrm{top}} - 0.8$km
$z_{\mathrm{top}} - 1$km
1.0 1.2 1.4 1.6 1.8 2.0
$D_m/D_{m,\mathrm{top}}$


KAKQ2022
$N_{t,\mathrm{top}}$ =74.3 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.17
KAPX2018
$N_{t,\mathrm{top}}$ =73.7 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.41
KBGM2017
$N_{t,\mathrm{top}}$ =113.8 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.07
KBGM2018
$N_{t,\mathrm{top}}$ =40.9 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.17
KBOX2018
$N_{t,\mathrm{top}}$ =135.5 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.03
KCBW2021
$N_{t,\mathrm{top}}$ =29.4 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.11
KCCX2018
$N_{t,\mathrm{top}}$ =52.4 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.17
KCCX2020
$N_{t,\mathrm{top}}$ =51.5 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.14
KDIX2018
$N_{t,\mathrm{top}}$ =55.5 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.24
KDOX2022
$N_{t,\mathrm{top}}$ =97.6 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.10
KFCX2018
$N_{t,\mathrm{top}}$ =83.8 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.08
KGRB2018
$N_{t,\mathrm{top}}$ =67.3 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.21
KLWX2022
$N_{t,\mathrm{top}}$ =120.1 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.11
KOKX2017
$N_{t,\mathrm{top}}$ =24.1 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.34
KOKX2018
$N_{t,\mathrm{top}}$ =117.3 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.07
KOKX2019
$N_{t,\mathrm{top}}$ =45.8 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.47
KOKX2020
$N_{t,\mathrm{top}}$ =99.2 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.04
KSHV2021
$N_{t,\mathrm{top}}$ =76.0 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.16
KUDX2013
$N_{t,\mathrm{top}}$ =82.6 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.12
KUDX2019
$N_{t,\mathrm{top}}$ =33.6 L^{-1}
$\overline{E}_{\mathrm{agg}}$ = 0.41
z_{top}
z_{top} − 0.2km
z_{top} − 0.4km
z_{top} − 0.6km
z_{top} − 0.8km
z_{top} − 1km
0.2 0.4 0.6 0.8 1.0
$N_t/N_{t,\mathrm{top}}$

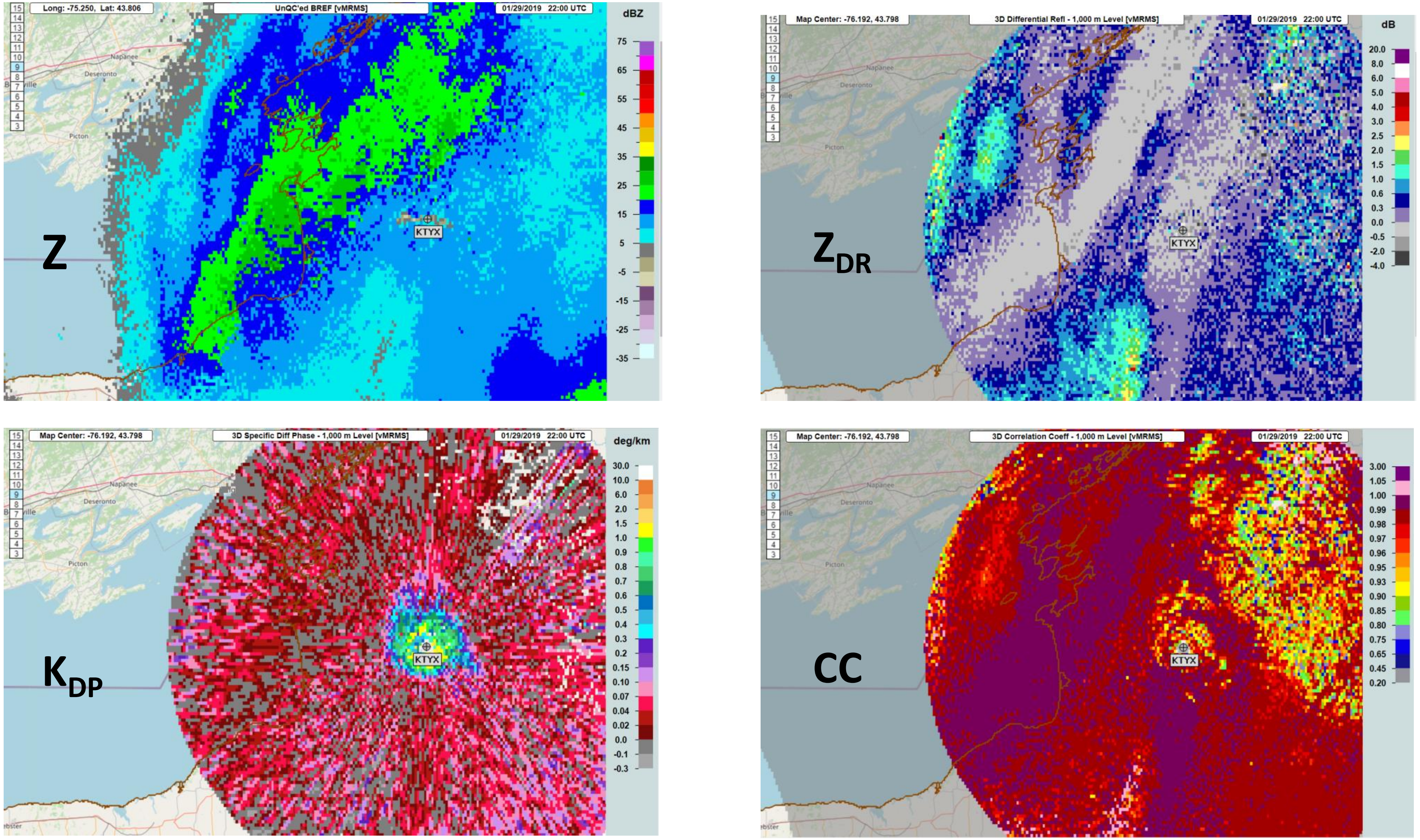
Estimation of the collision-coalescence efficiency E_{agg}

Optimized E_{agg} and $E_{agg}A_{top}$ as functions of the 1- km layer temperature obtained via matching of theoretical and polarimetrically retrieved vertical profiles of N_t and D_m



Classical example of lake-effect snow. Eastern Lake Ontario. KTYX WSR-88D radar

2018/01/28, 22:00 UTC

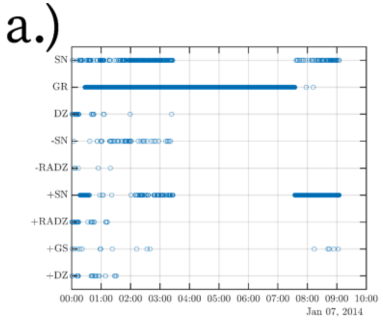


Lake-effect snow (LES)

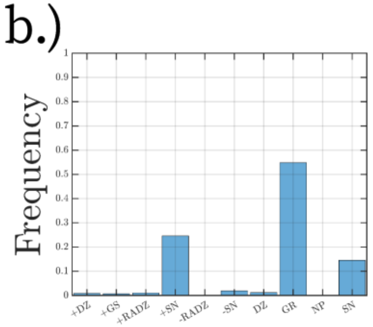
J. Hu, A. Ryzhkov, and E. Dunnavan, 2024: Vertical profile climatology of polarimetric radar variables and retrieved microphysical parameters in synoptic and lake effect snowstorms. JGR, conditionally accepted.

Ontario Winter Lake-effect Systems (OWLeS) field campaign

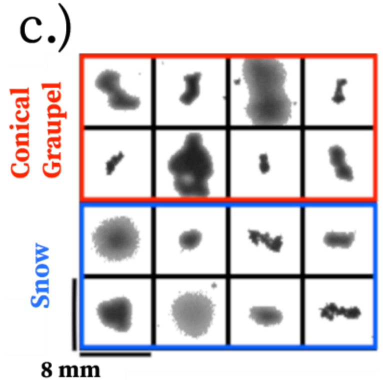
2017/01/07



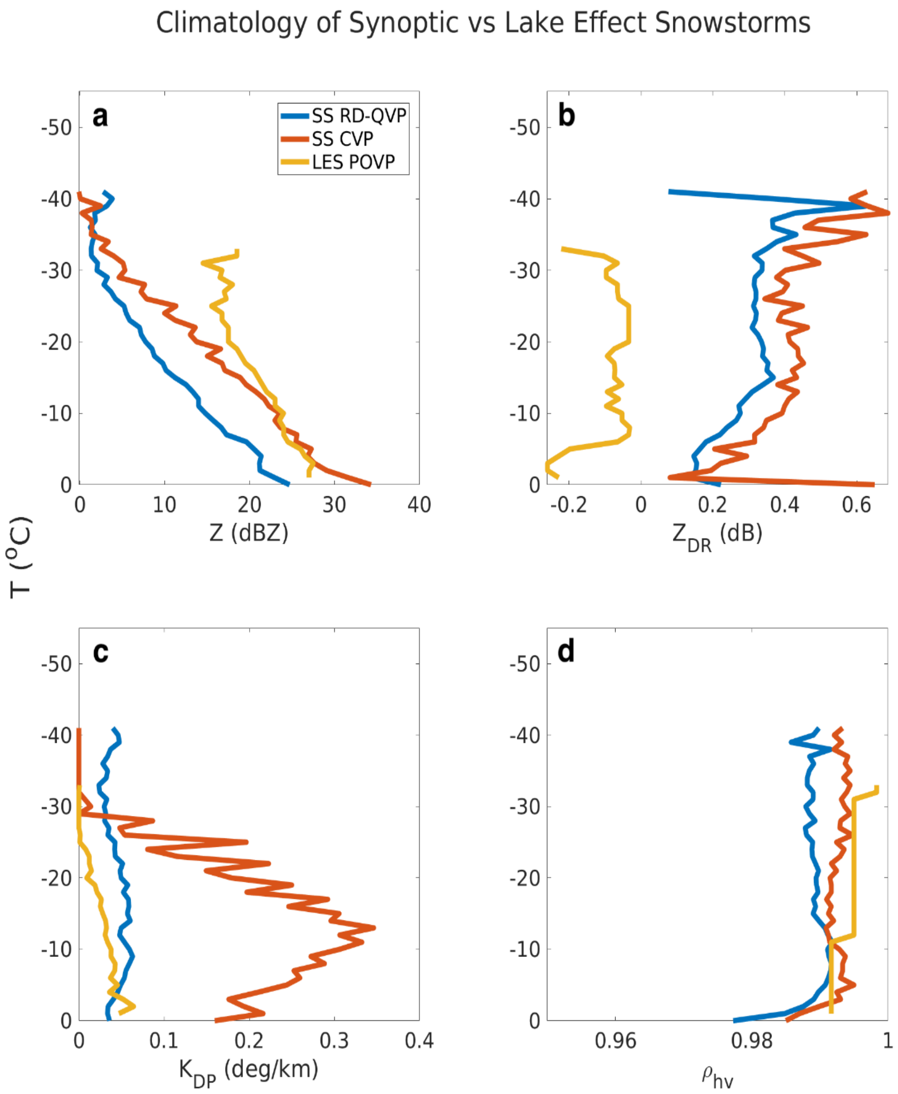
METAR codes



Frequency distribution of METAR codes



PIP images of graupel and regular snow aggregates



SS RD-QVP – background profiles for synoptic snowstorms

SS CVP – high ice water content (HIWC) profiles for synoptic storms

LES POVP – lake-effect snow POVP profiles

Modified retrieval formulas

$$IWC(N_t, Z, \mu) = 0.0147\ f_0(\mu) N_t^{0.5} Z^{0.5}$$

Oue et al. 2024

$$f_0(\mu) = 1 + 0.33\mu - 0.043\mu^2$$

$$IWC(K_{DP}, Z, f_{rim}) = 6.13\times10^{-2}\ f_{rim}^{-0.94} (K_{DP}\lambda)^{0.66} Z^{0.28}$$

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

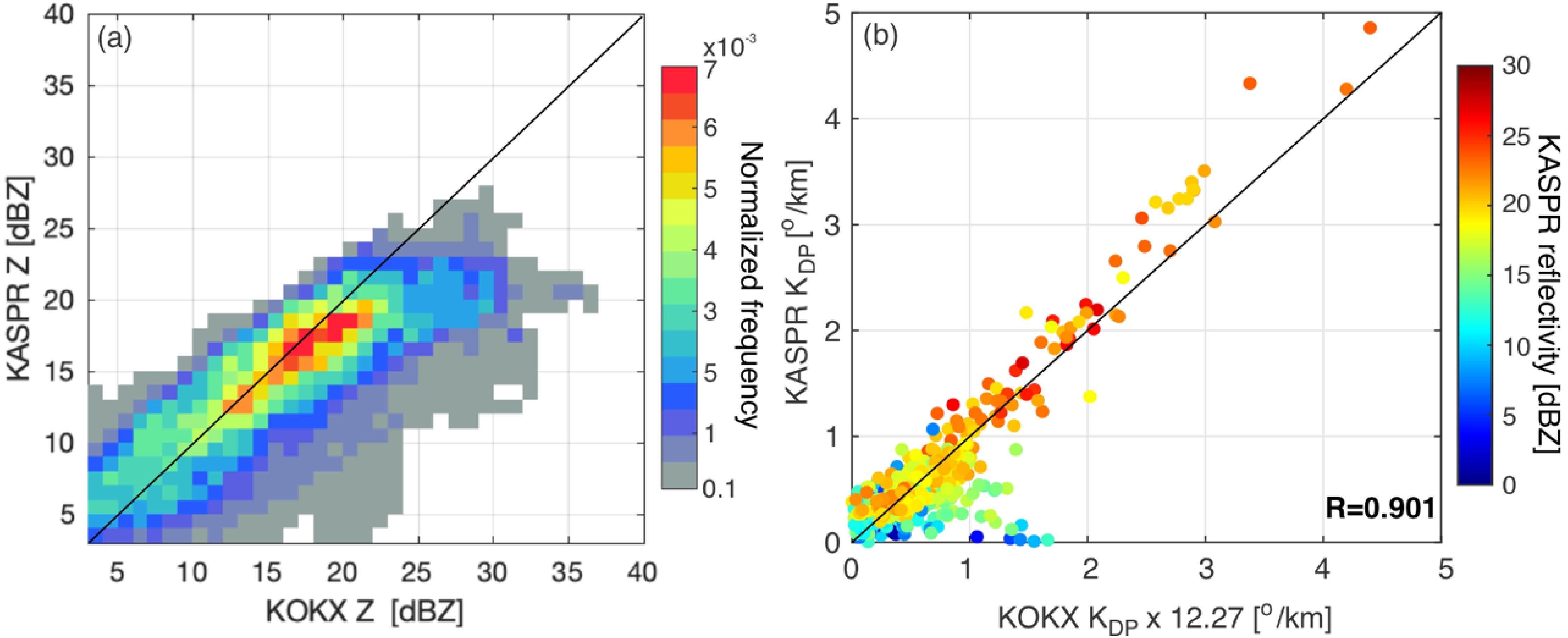
$$DWR = \alpha D_m^{\beta}$$

$$N_t = 0.13\, f_{rim}^{-2} \frac{10^{0.1(dBZ+\alpha D_m^{\beta})}}{D_m^4}$$

These relations explicitly include dependencies on μ and f_{rim} and can be applied at millimeter radar wavelengths

Comparison of Z and K_{DP} at S and Ka bands

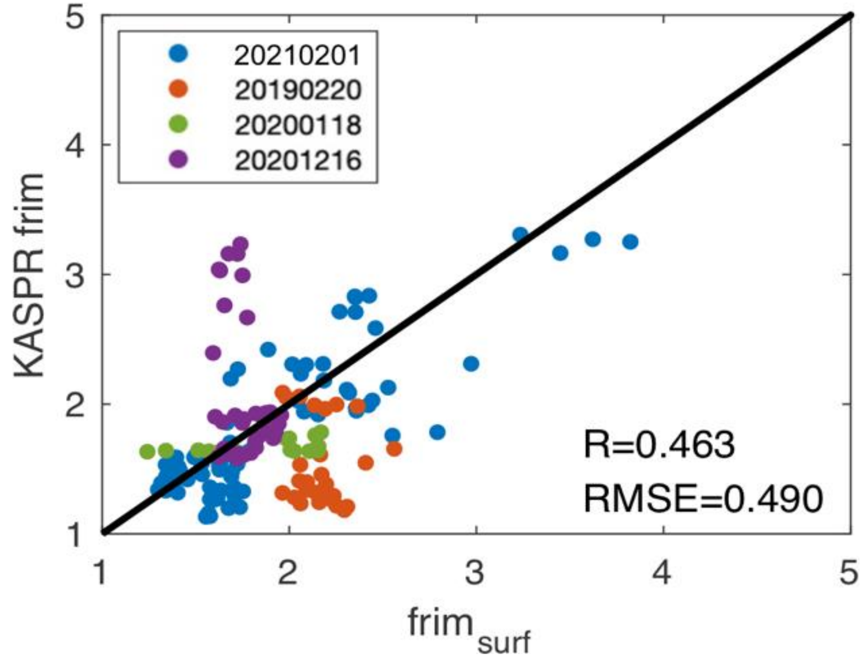
KASPR – Ka band, KOKX WSR-88D – S band



K_{DP} is almost perfectly frequency-scaled

Typical values of μ and f_{rim} from the KASPR measurements

Case	μ
2017/12/09	-1.3
2017/12/14	0.4
2018/01/04	-0.1
2019/02/20	-0.7
2020/01/18	-1.0
2020/12/16 - 17	-0.7
2021/02/01	0.6

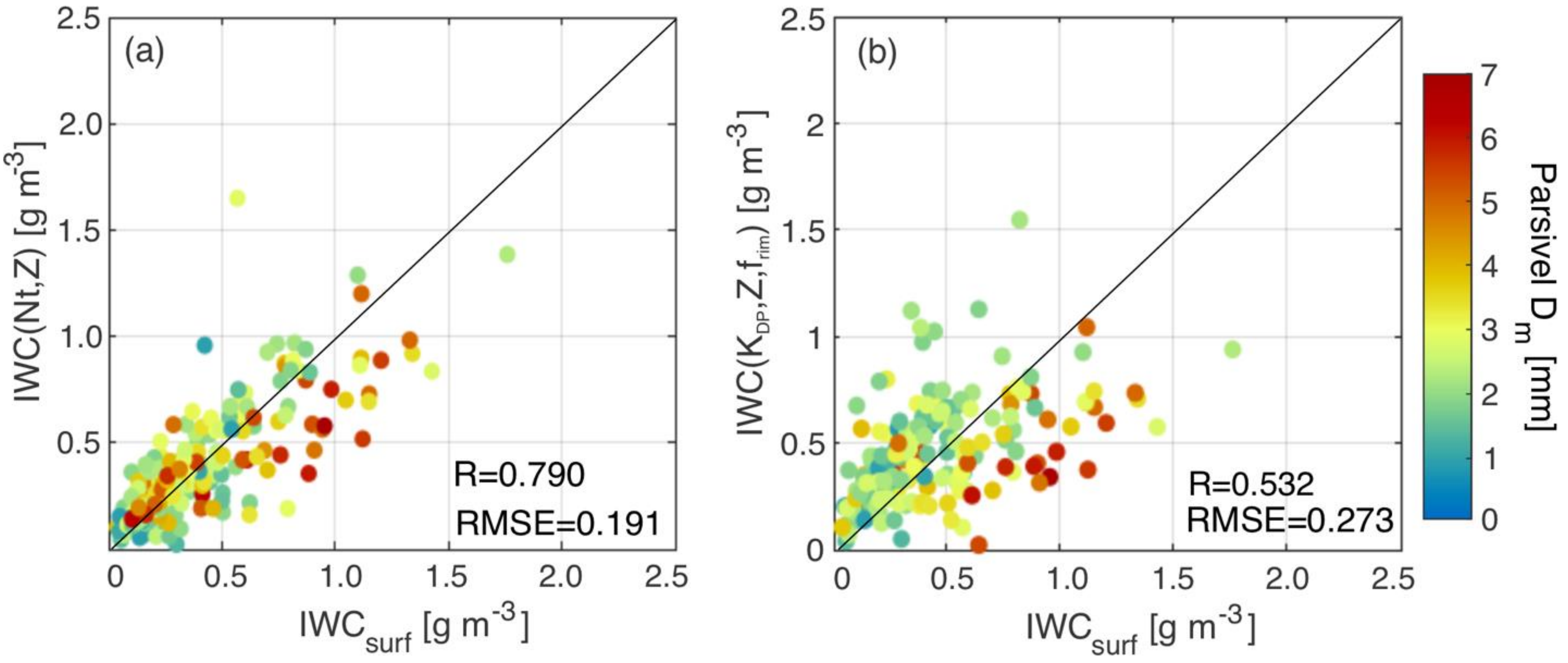


<μ> = -0.4

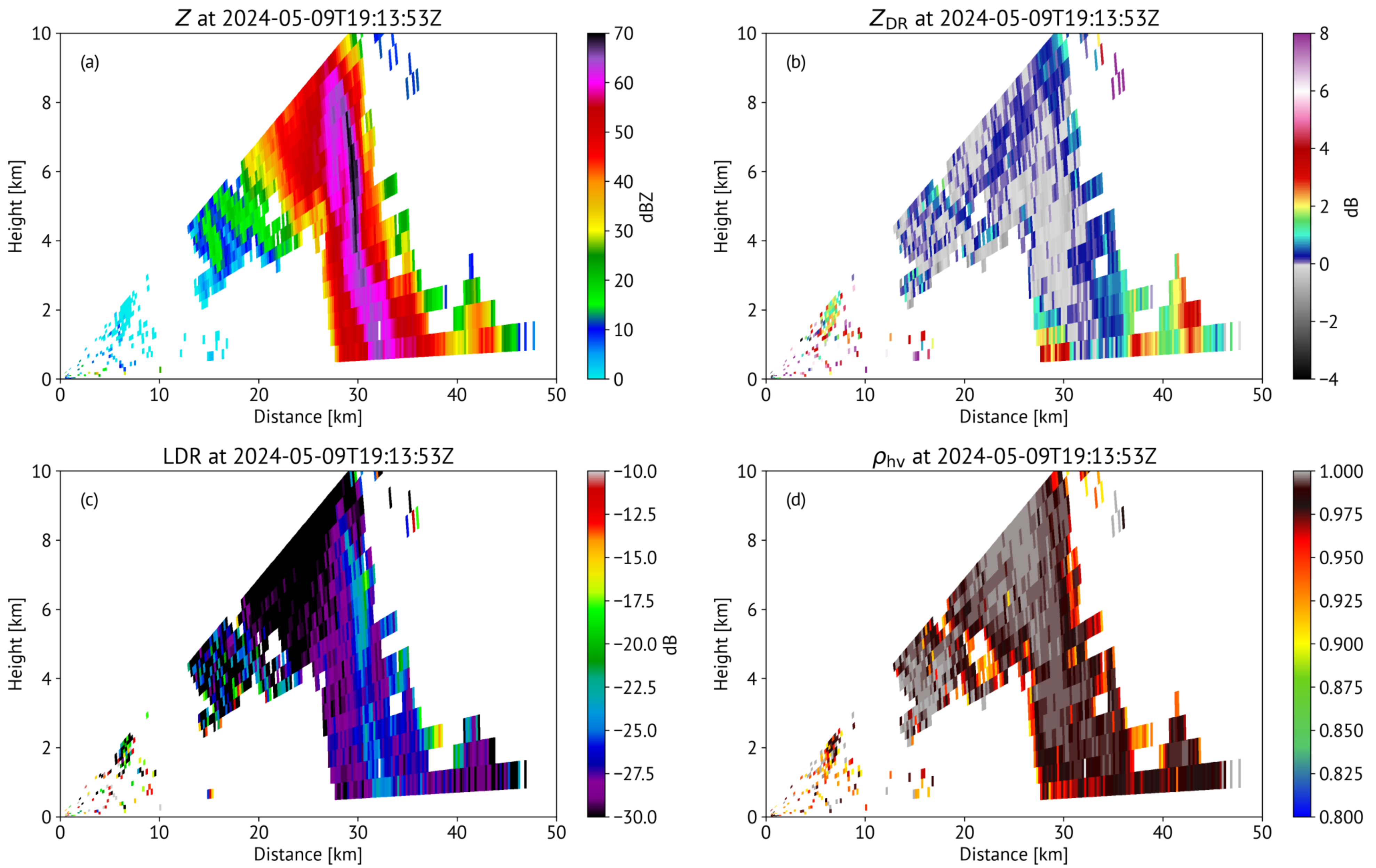
<f_{rim}> = 1.8

Summary of the KASPR estimates of IWC using two methods

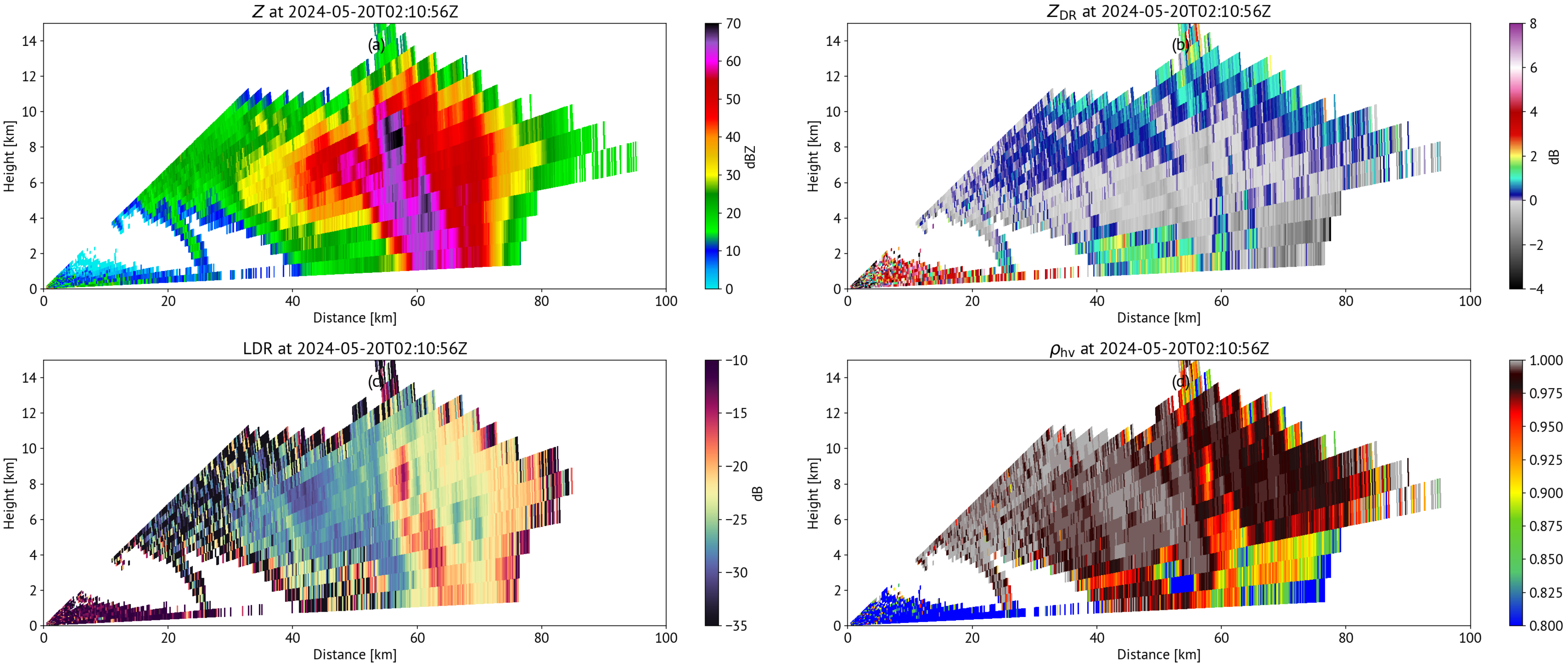
Oue et al. 2024



Simultaneous measurements of Z_{DR} and LDR (linear depolarization ratio) with PAR



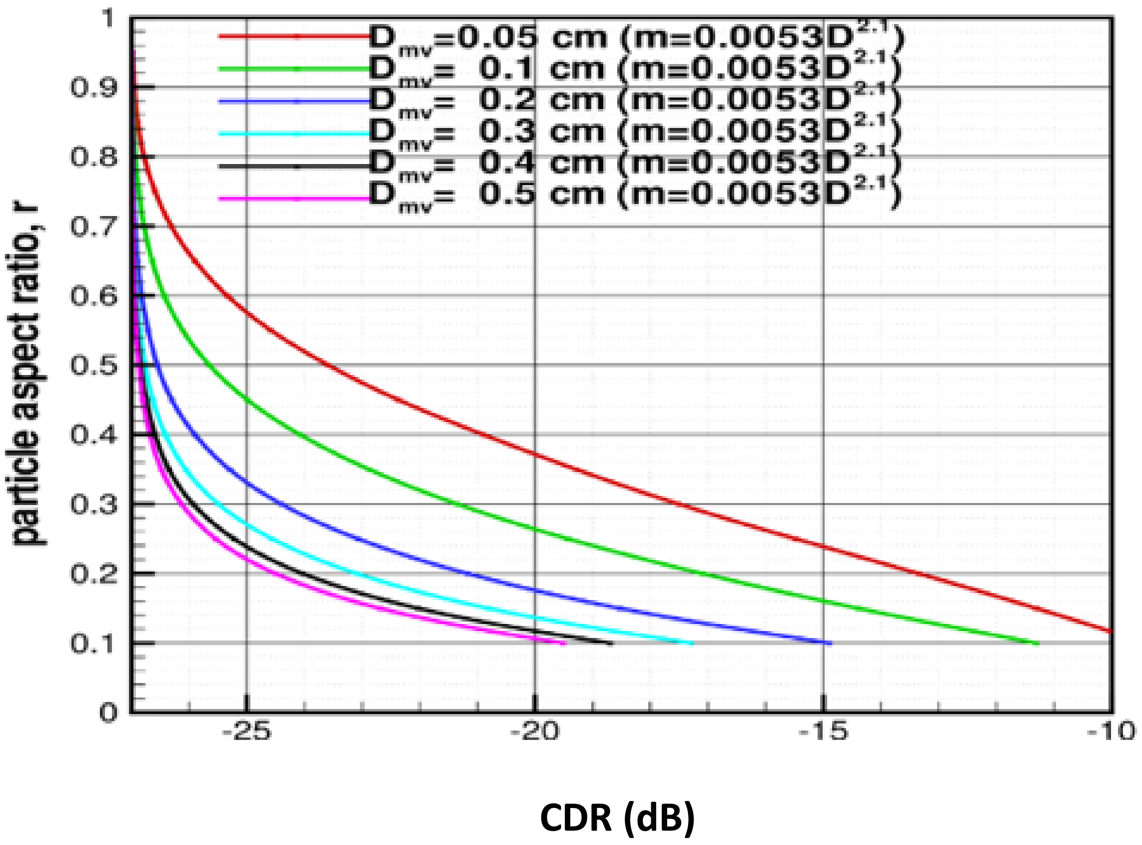
Simultaneous measurements of Z_{DR} and LDR with PAR



Using circular depolarization ratio (CDR) to estimate particle aspect ratio

$$Cdr \approx \rho_s(D)(L_a - L_b)$$

$L_a - L_b$ is the shape factor



Matrosov, S., 2020: Ice hydrometeor shape estimations using polarimetric operational and research radar measurements. Atmosphere

Particle orientations from the LDR – CDR pair

$$\frac{L_{dr}}{C_{dr}} \approx (1 + Z_{dr}^{-1/2})^2 (\sigma^2 + <\alpha>^2)$$

For $Z_{DR} \approx 0$ dB

$$\sigma(\deg) \approx \frac{90}{\pi} 10^{0.05(LDR - CDR)}$$

LDR and CDR are in dB

Conclusions

- Microphysical retrievals in liquid phase will benefit from the use of specific attenuation A

- Variability of the shape factor of size distributions μ, riming factor f_{rim}, shapes and orientations of ice particles are the main causes of uncertainties in ice microphysical retrievals

- Such uncertainties can be reduced using independent measurements of size distributions and degree of riming and utilization of polarimetric relations immune to the variability of shapes and orientations (whenever is possible) as well as results of in situ verification using microphysical probes

- Polarimetric microphysical retrievals at millimeter radar wavelengths might be beneficial because of high K_{DP} and its relative insensitivity to the effects of resonance scattering on larger size hydrometeors

- Phased array radars (PAR) provide unique opportunity to simultaneously estimate conventional polarimetric radar variables (Z, Z_{DR},K_{DP}) and depolarization ratios (LDR, CDR) which will allow retrievals of particle shapes and orientations