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Maximilian Maahn, Nina Maherndl, Nils Pfeifer, Sabine Hörnig

Quantifying Riming by Combining the Video In Situ Snowfall Sensor with Cloud Radar Observations

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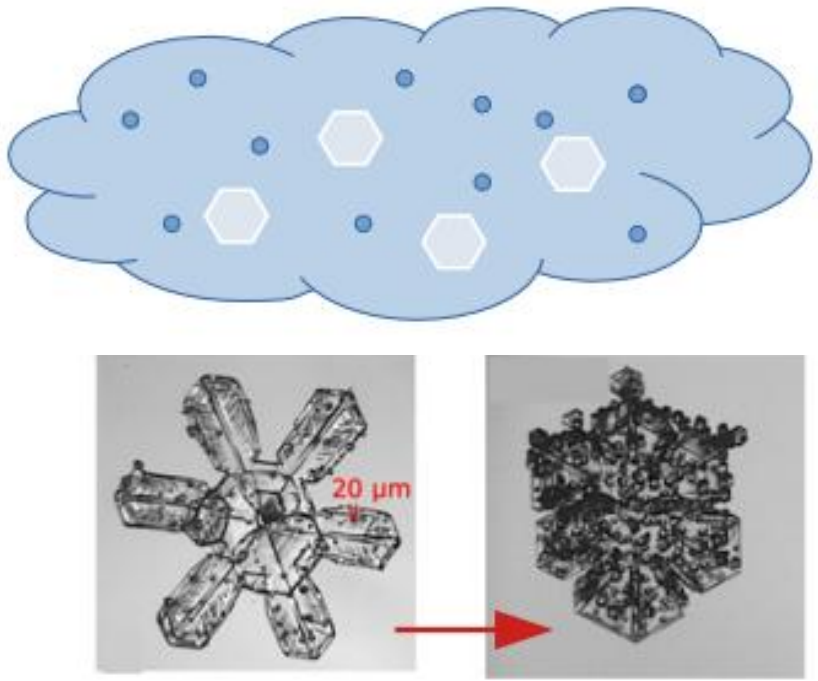
WHY ARE WE INTERESTED IN RIMING?



Adapted from Waitz et al. (2022)

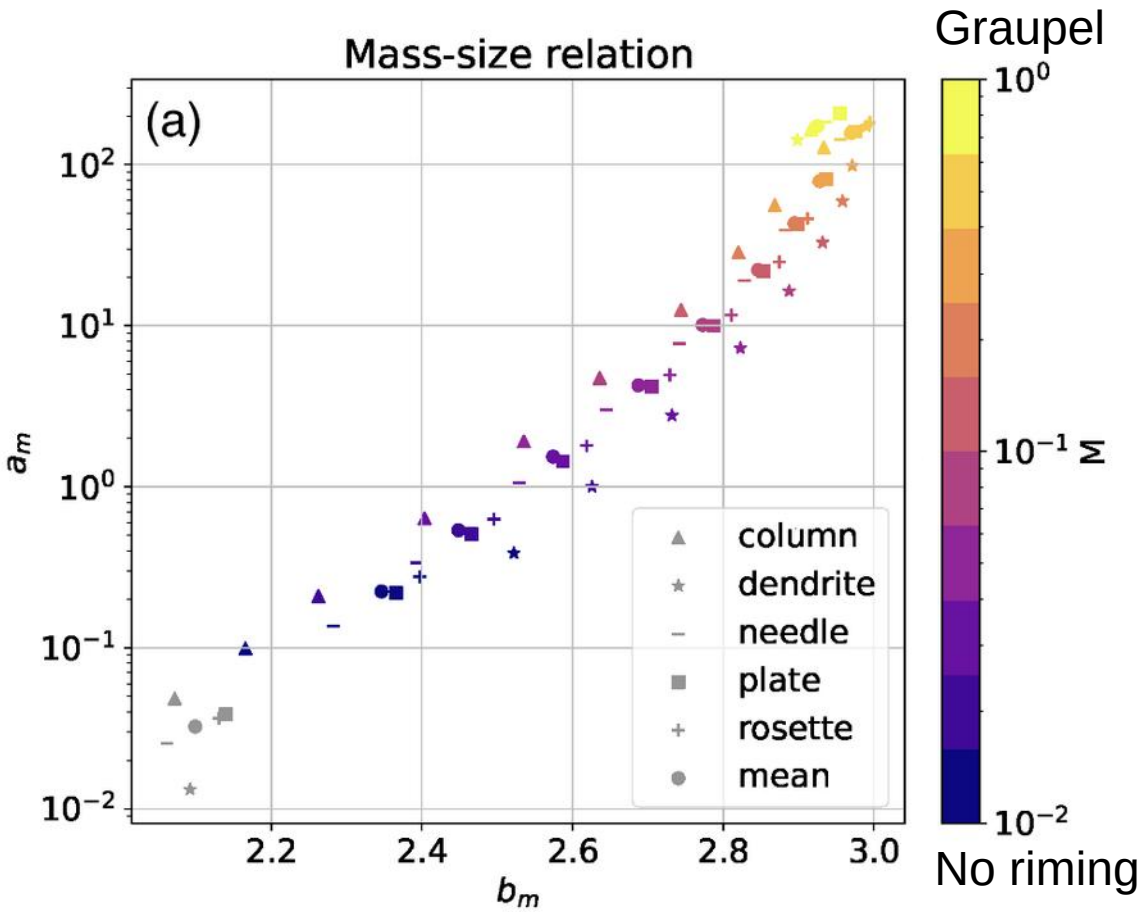
- In mixed-phase clouds, cloud ice and water droplets coexist
- Riming describes how droplets freeze onto ice crystals
- Riming one of most efficient precipitation formation processes
- Difficult to quantify from observations
- Process not sufficiently understood for weather & climate models

Research question:
How can we quantify riming from observations?

COMBINED RIMING RETRIEVAL

1. Use aggregation and riming model to estimate scattering properties and mass-size relations of rimed aggregates

$$M = \frac{m_{rime}}{m_g} \qquad m_g = \frac{\pi}{6} \rho_{rime} D_{max}^3$$



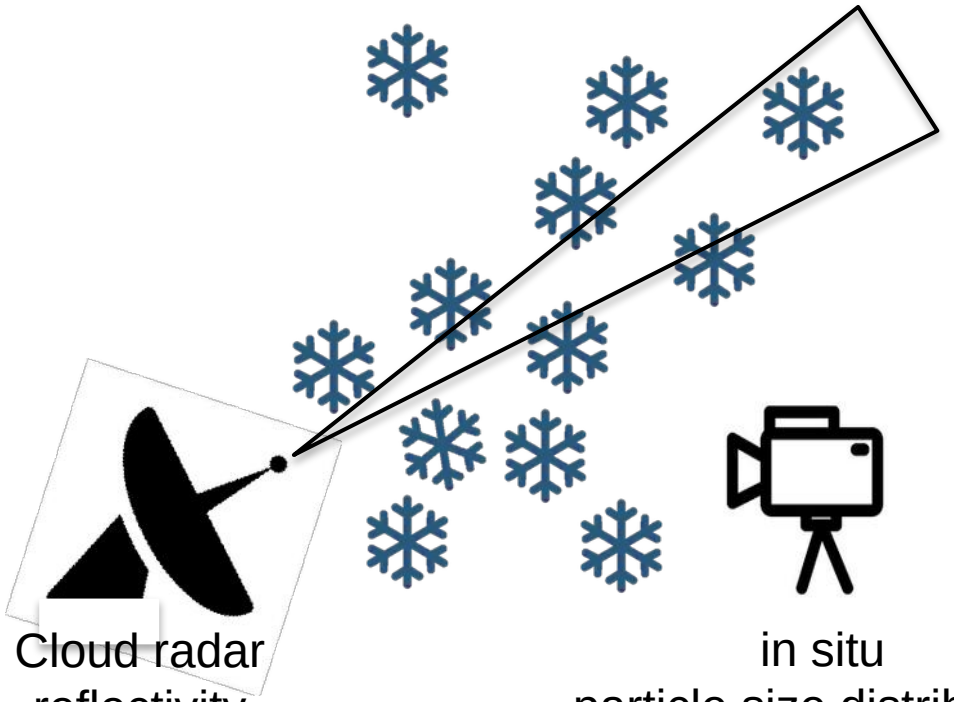
$$m(D) = a_m D_{max}^{b_m}$$

COMBINED RIMING RETRIEVAL

1. Use aggregation and riming model to estimate scattering properties and mass-size relations of rimed aggregates

$$M = \frac{m_{rime}}{m_g} \qquad m_g = \frac{\pi}{6} \rho_{rime} D_{max}^3$$

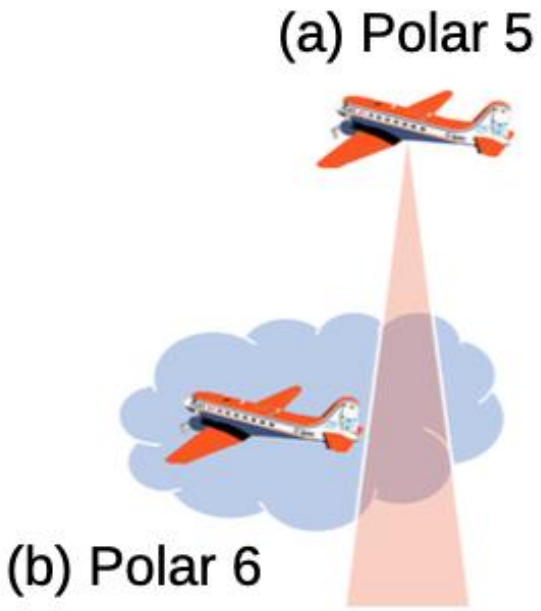
2. Retrieve normalized rime mass M by combining collocated radar and in situ observations

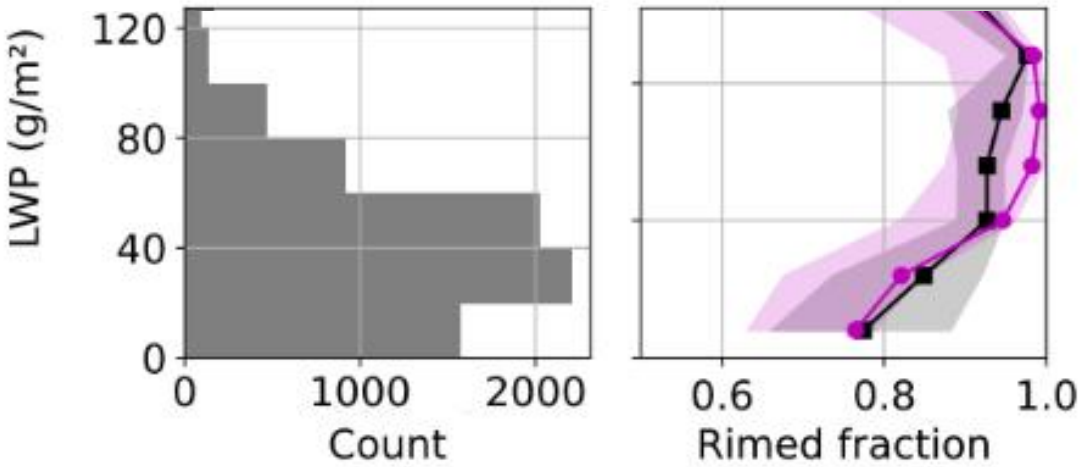


RIMING IN CLOUDS WITH LOW LIQUID WATER PATHS

Apply retrieval to airborne data from HALO-(AC)³

Collocated radar and
in situ observations

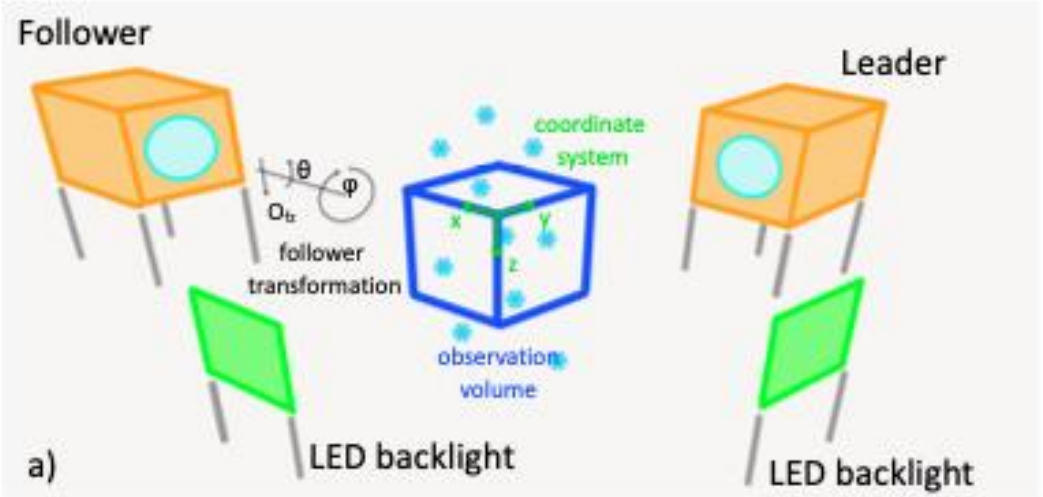




- ~80% of clouds LWP < 40 g/m² are rimed
- Does turbulence extent the contact time between ice and liquid?

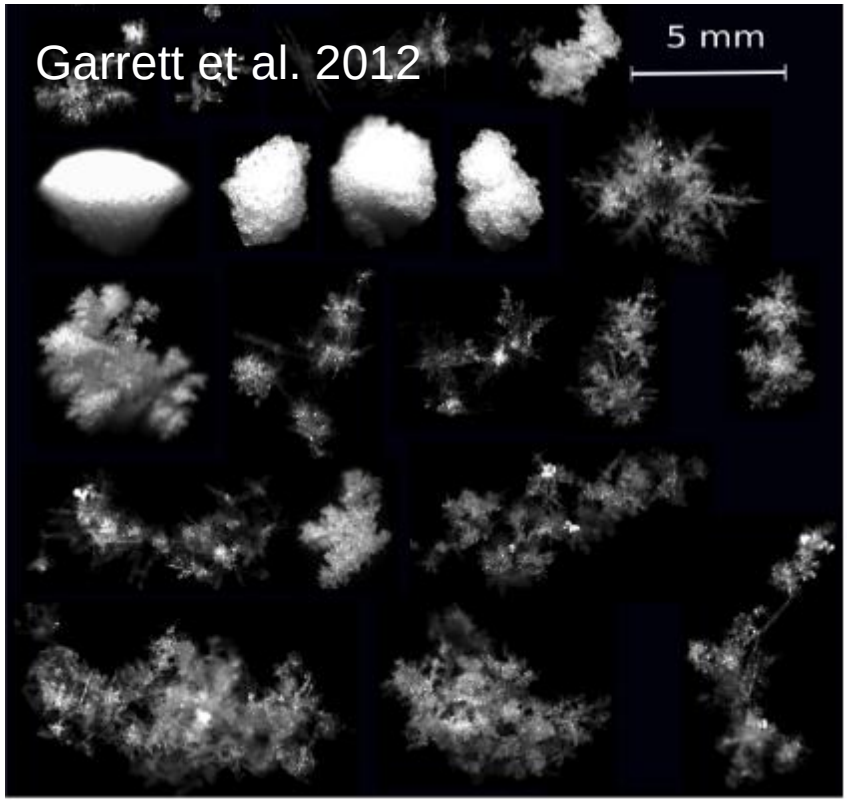
VIDEO IN SITU SNOWFALL SENSOR (VISSS)

- use two cameras to observe from two angles and constrain observation volume
- combine high resolution images (42 to 59 µm) and large sampling volume (up to 75 x 75 x 61 mm)
- high framerate (150 - 270 Hz) allows for tracking of particles
- minimize wind disturbance
- open source hardware & software



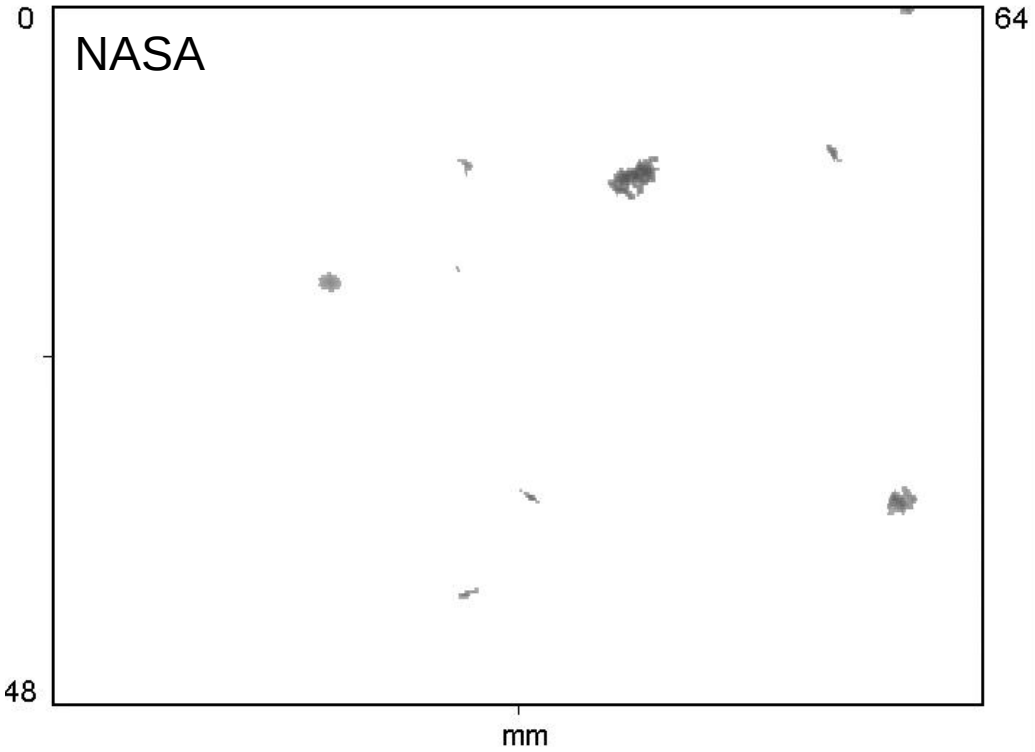
Why develop your own instrument?

ESTABLISHED IN SITU SENSORS



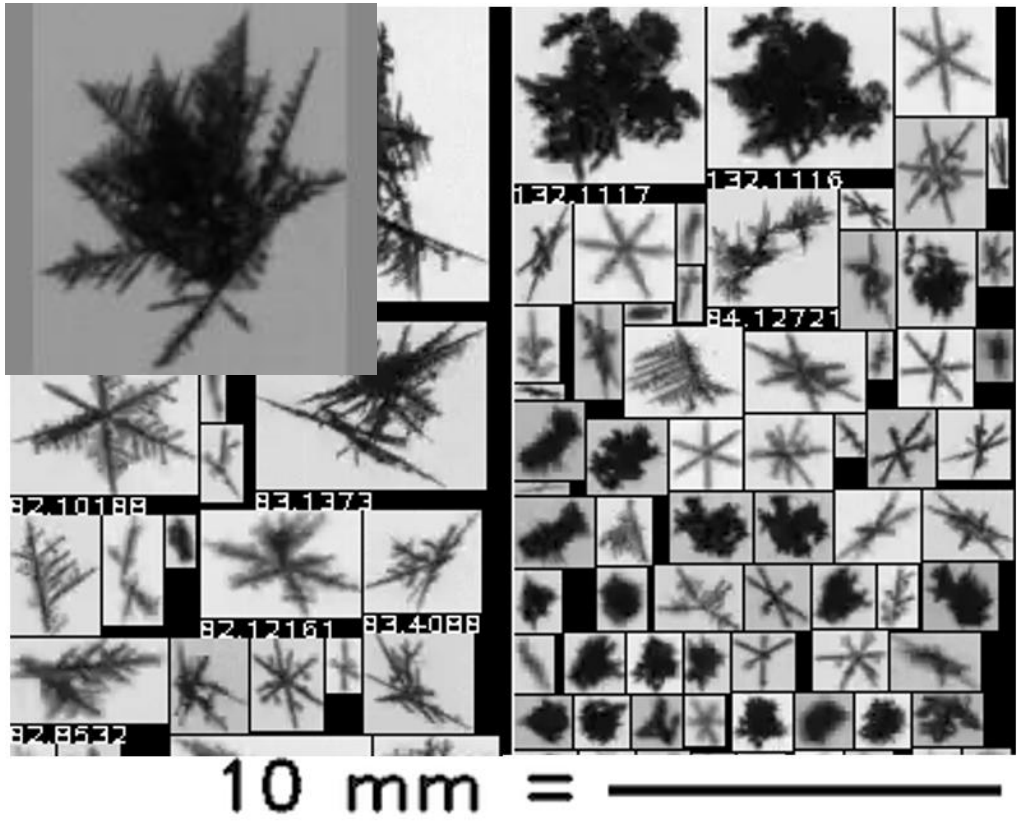
Few high-quality particle observations

OR



Many low-quality particle observations

VIDEO IN SITU SNOWFALL SENSOR (VISSS)



Many high-quality observations for

- Identifying dominant growth process
  - Aggregation
  - Riming
- Quantifying precipitation properties
  - Particle shape
  - Particle type
  - Particle number concentration
  - Particle fall velocity
- Constraining remote sensing observations

APPLY COMBINED RETRIEVAL TO VISSS DATA

- ARM SAIL campaign in 2022/23 in Colorado
- Almost 10 m snowfall
- Use collocated RPG 94 GHz radar measuring at 40° elevation
- Use 1st generation VISSS

What is the sensitivity of the Z-IWC relation to riming?

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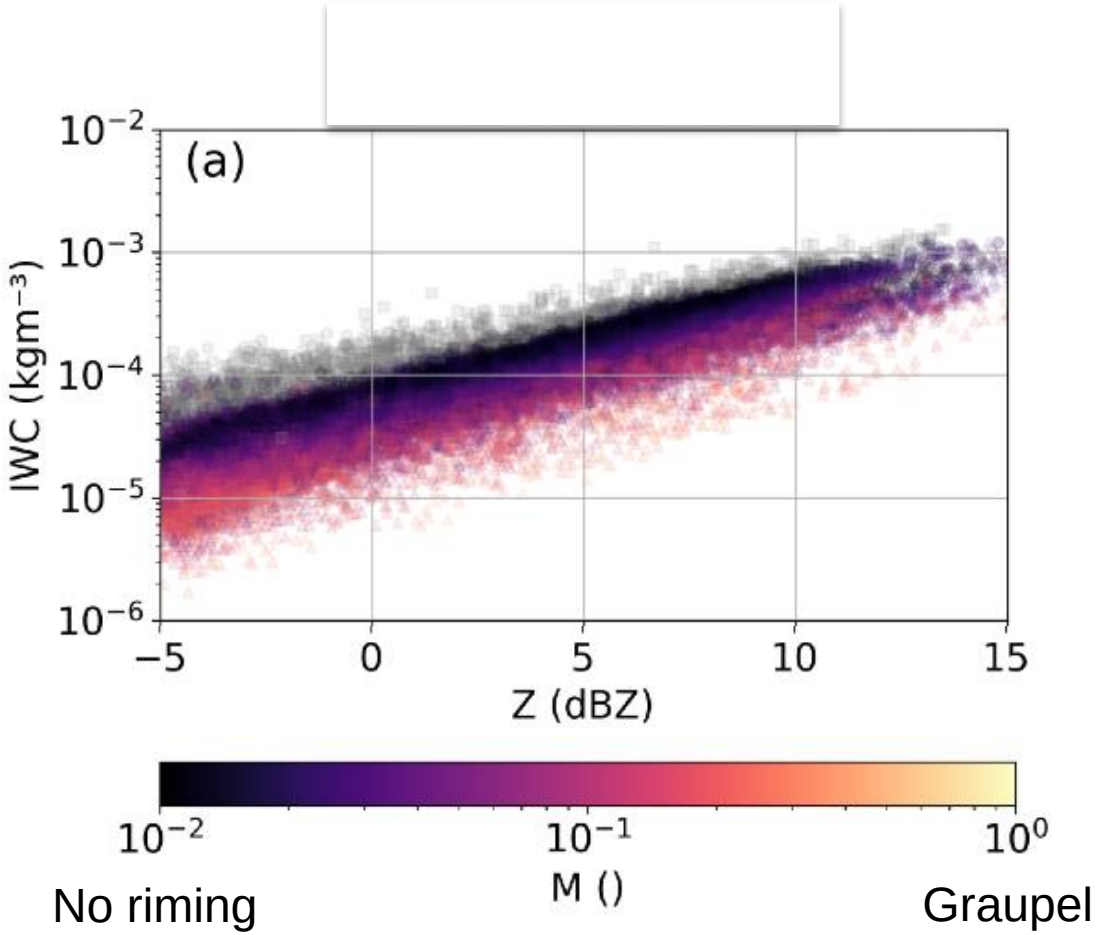
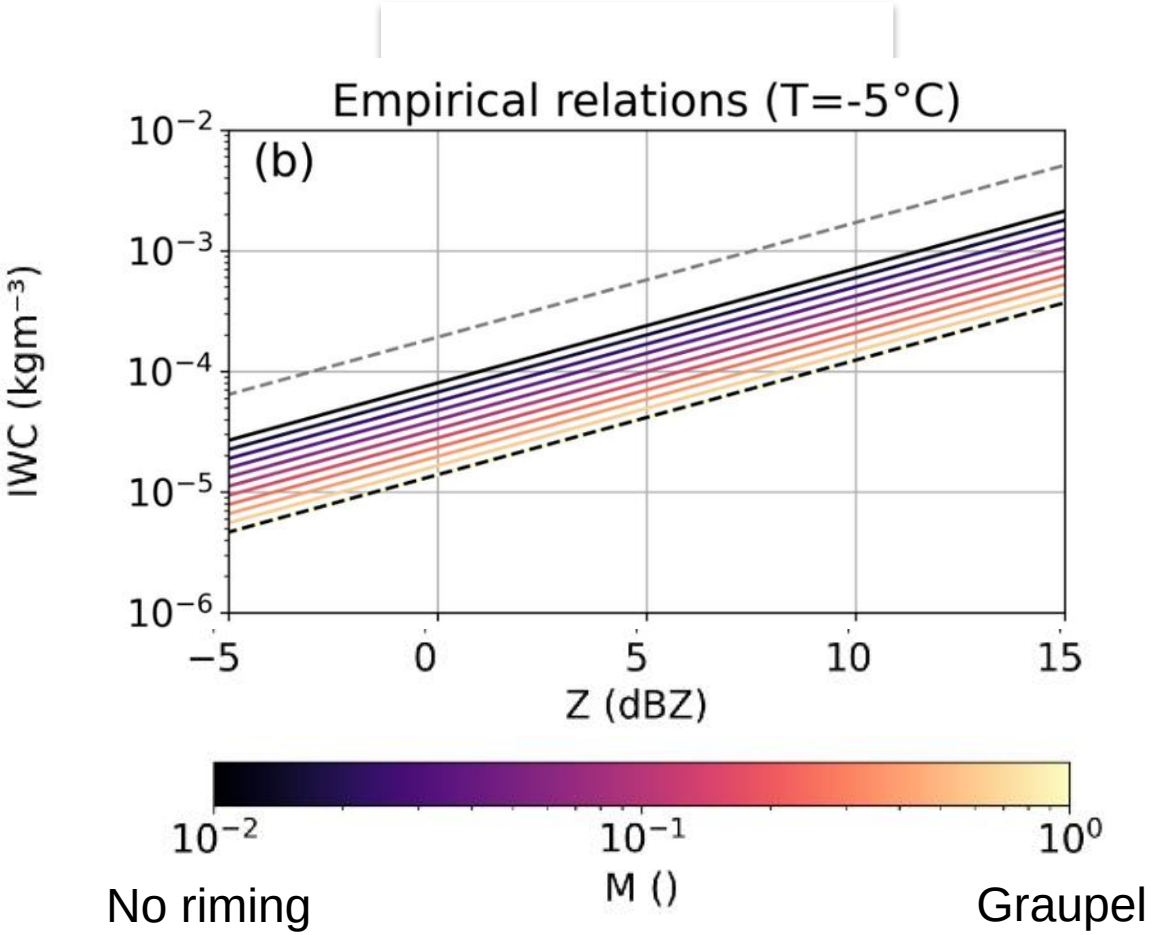
Maherndl et al (2025)

SENSITIVITY OF THE REFLECTIVITY (Z) – ICE WATER CONTENT (IWC) RELATION TO RIMING



- IWC from the VISSS & radar
- Z from the radar
- Retrievals of ice water content based on radar reflectivity are inaccurate
- Riming explains large part of Z-IWC (and Z-S) relation variability!

SENSITIVITY OF THE REFLECTIVITY (Z) – ICE WATER CONTENT (IWC) RELATION TO RIMING



How can we measure riming *without* in situ information?

- IWC from the VISSS & radar
- Z from the radar
- Retrievals of ice water content based on radar reflectivity are inaccurate
- Riming explains large part of Z-IWC (and Z-S) relation variability!
- We can derive Z-IWC (and Z-S) relations as a function of riming

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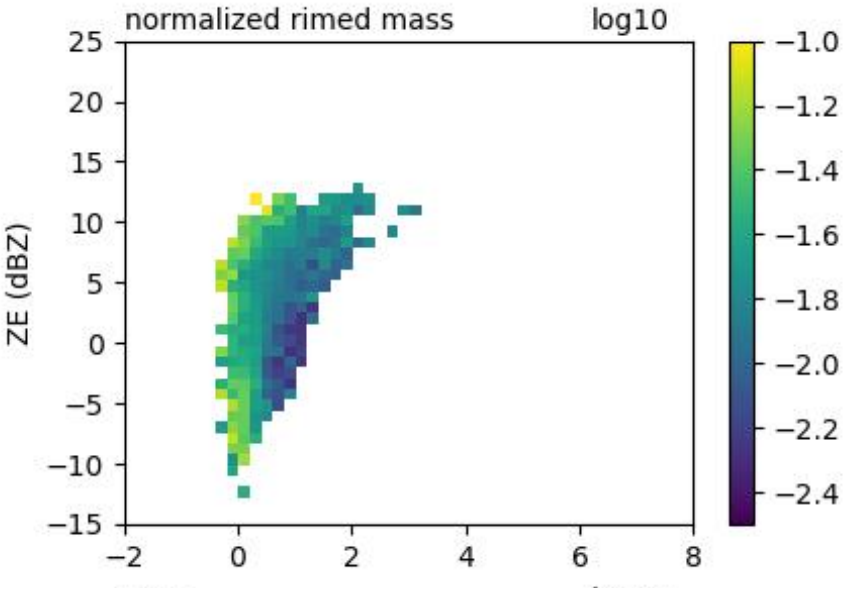
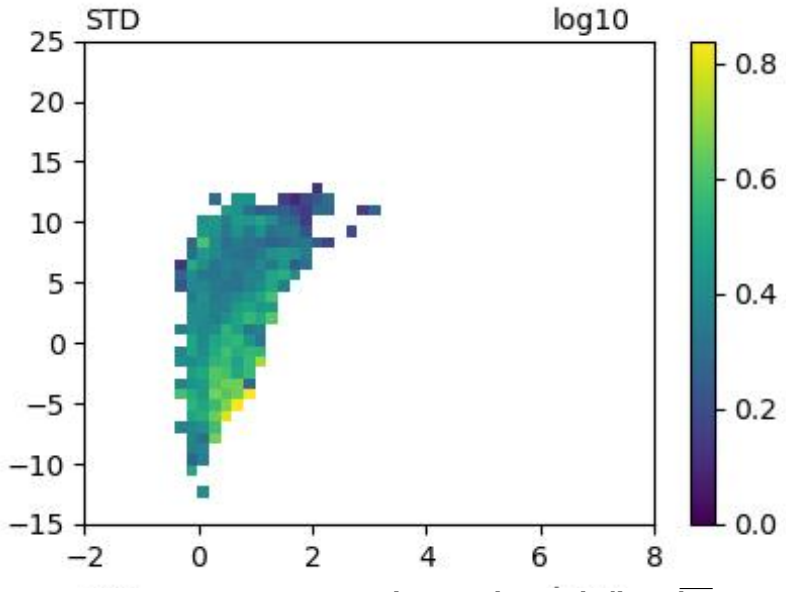
Maherndl et al (2025)

QUANTIFY RIMING WITH POLARIMETRIC RADAR

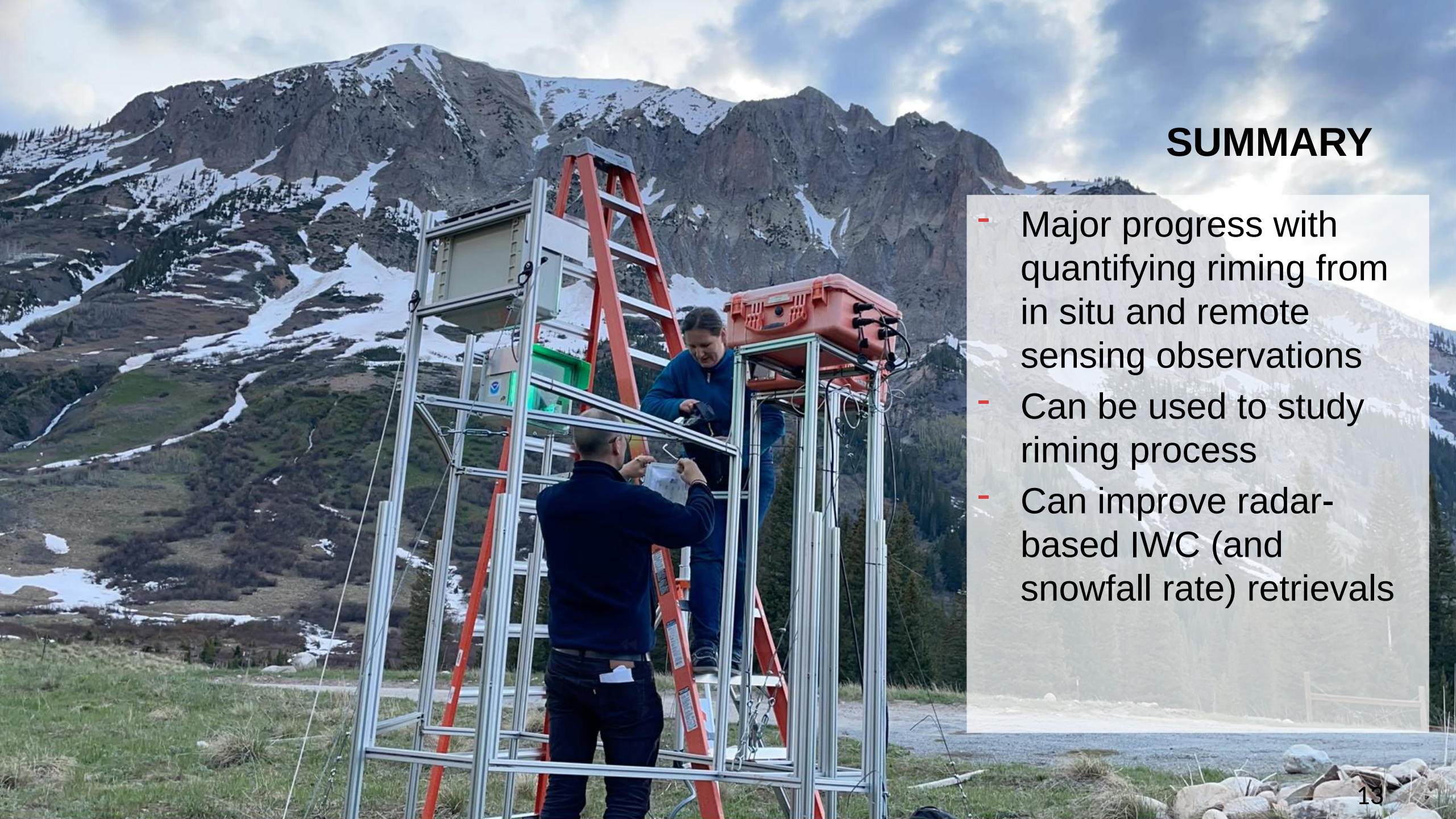
Mean normalized rime mass



Standard deviation norm. rime mass



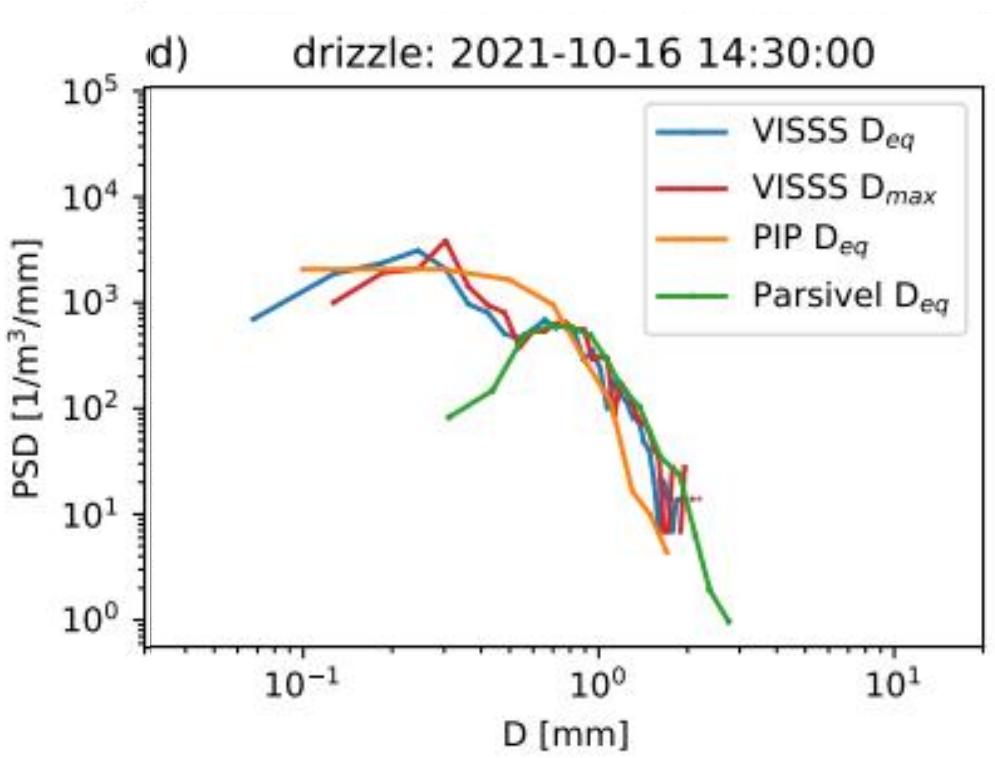
- Understand impact of riming on polarimetric variable based on *observations*
- Potential for riming retrieval based on polarimetric cloud radar observations?



SUMMARY

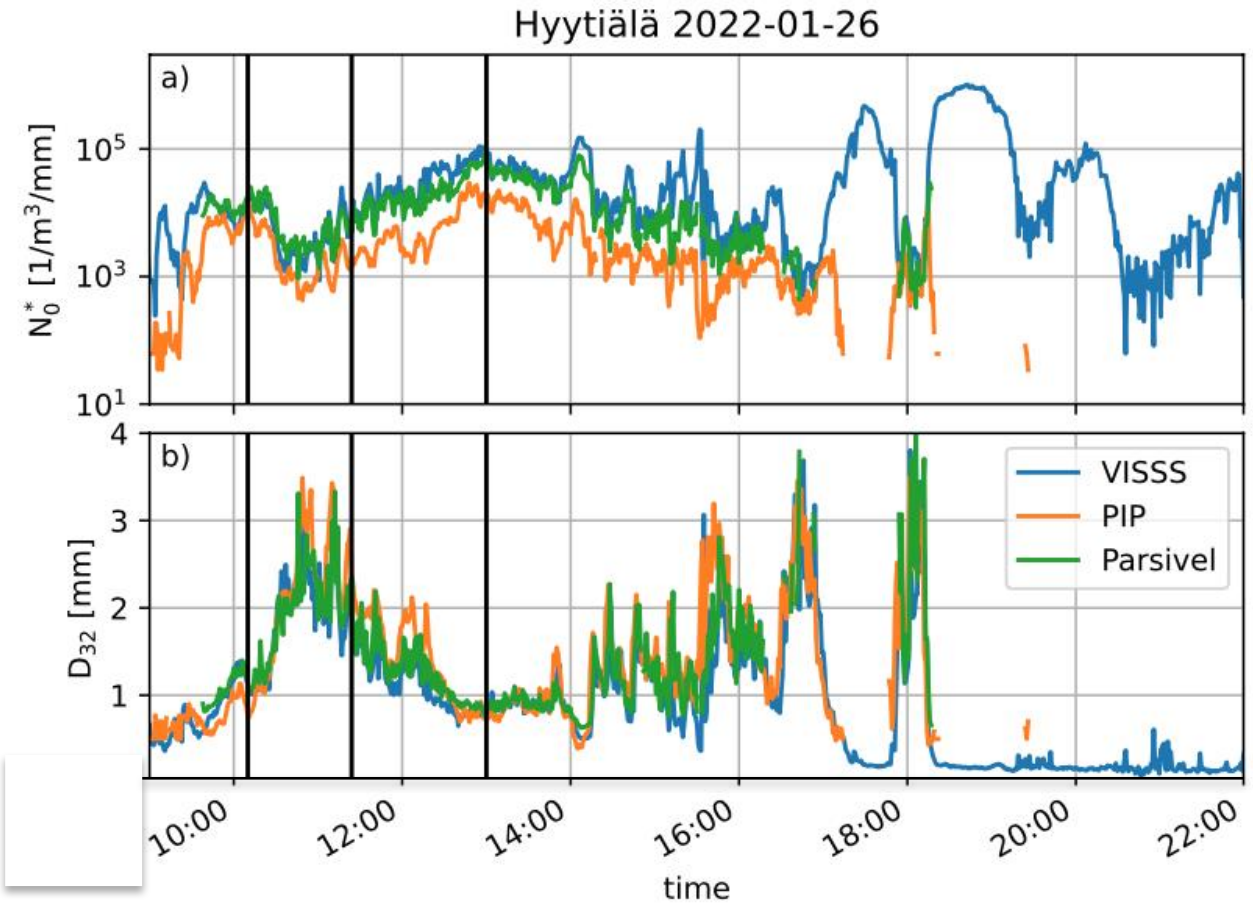
- Major progress with quantifying riming from in situ and remote sensing observations
- Can be used to study riming process
- Can improve radar-based IWC (and snowfall rate) retrievals

COMPARISON WITH PIP AND PARSIVEL AT HYYTIÄLÄ



- Good agreement of mass weighted mean diameter
- VISSS (and Parsivel) N_0 larger than PIP N_0, likely due to better sensitivity to small particles (D< 1mm)
- VISSS observes up to 100.000 particles per minute
- For drizzle spectra, excellent agreement with Parsivel for D>0.5 mm

COMPARISON WITH PIP AND PARSIVEL AT HYYTIÄLÄ



- Good agreement of mass weighted mean diameter
- VISSS (and Parsivel) N_0 larger than PIP N_0, likely due to better sensitivity to small particles (D< 1mm)
- VISSS observes easily 10.000 particles per minute

DEPLOYMENTS

MOSAiC, 2019/20

Hyytiälä, Finland
2021/22 & since 2023

Ny-Ålesund,
Svalbard since 2021

SAIL, Colorado
2022/23

Eriswil,
Switzerland
2023/24

> 2600 days observations, 1.000.000.000.000 snow particles

Research Example II

STUDYING THE RIMING PROCESS

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SPP PROM

TR 172 $(AC)^3$

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