EarthCARE 2026 Science and Validation workshop

8–12 June 2026 | Rhodes House | Oxford, UK

Constraining ice-cloud radiative properties through collocated measurements: a radiative-closure perspective from PERCUSION

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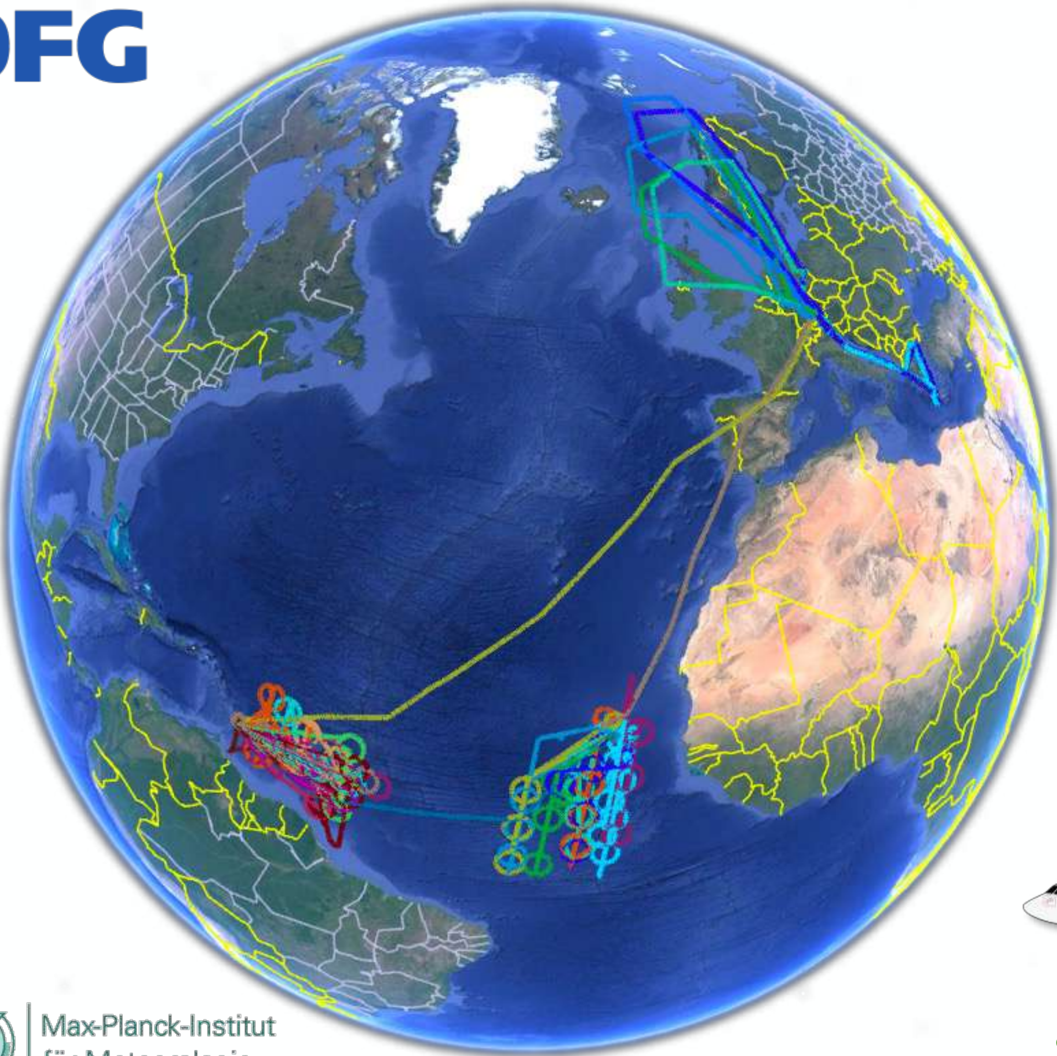
3) Meteorological Institut Munich, Ludwig Maximilians University, Germany

Data and Methods

Our validation approach

PERCUSION – A campaign with a focus on validation

Persistent EarthCARE underflight studies of the ITCZ and organized convection



Campaign period

09 Aug – 19 Nov 2024

Campaign locations

- Cape Verde / Sal: ITCZ, Aerosol
- Barbados: ITCZ, Convective organization
- Germany: Dedicated validation flights

Campaign duration – 9 weeks

- 296 flight hours (incl. transfer and certification)
- 28 Scientific flights: 11 (Sal), 10 (Barbados), 7 (Germany)
- 33 EarthCARE / 4 PACE underpasses
- Embedded within the *ORCESTRA* campaign:

MAESTRO
SAFIRE ATR-42

CELLO
INCAS King Air

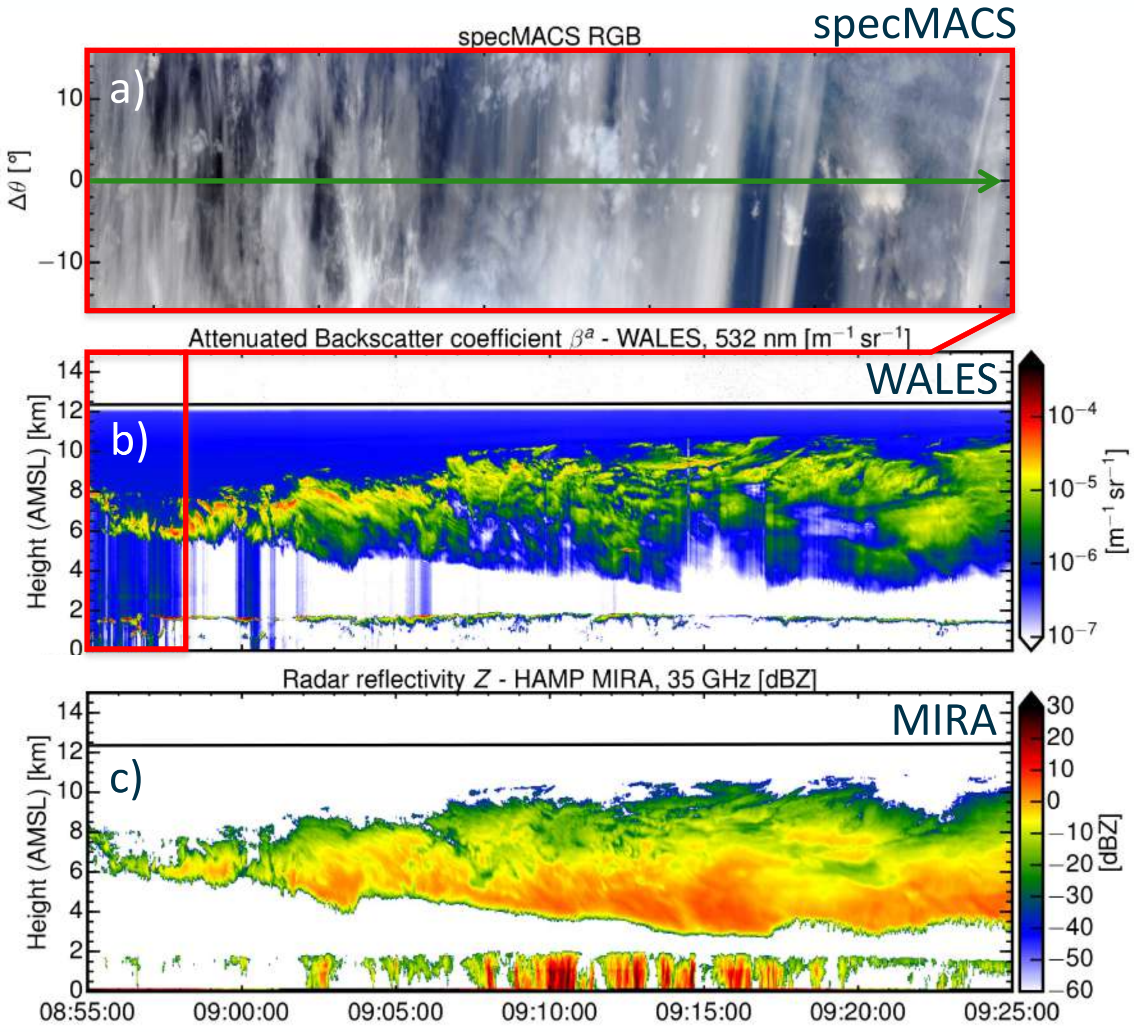
BOW-TIE / PICCOLO
RV METEOR / SEA-Pol

Max-Planck-Institut für Meteorologie

The platform – the High Altitude and long Range Aircraft

The HALO remote sensing payload – a unique validation asset

- G550, max. alt 15 km / max. range: 8000 km
- In operation since 2012
- operated by DLR



Scientific Instruments

HSRL-Lidar (WALES, 532 nm – Wirth et al. 2009)
Cloud Radar (HAMP MIRA, 35 GHz – Ewald et al. 2019)
Hyper-Spectral Imager (specMACS – Ewald et al. 2016)
Hyper-Spectral Radiometer (SMART – Wendisch et al. 2016)

The retrieval – the VarCloud framework

The precursor ice cloud retrieval for ACM-CAP on A-Train

Basis of VarCloud (HALO/ATR-42) and DARDAR (A-Train)

Optimal estimate approach (Delanoë 2008, Cazenave, 2019)

State vector x
A priori profile of α, S, N

Forward modeling of measurements

Lidar signal
incl. multiple scattering

Radar signal
LUT based reflectivities

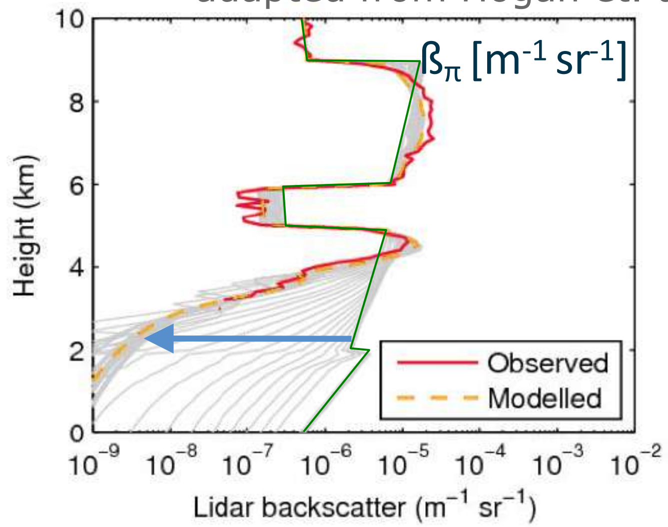
Comparison with measurements
WALES $ß_\pi$ and MIRA Z

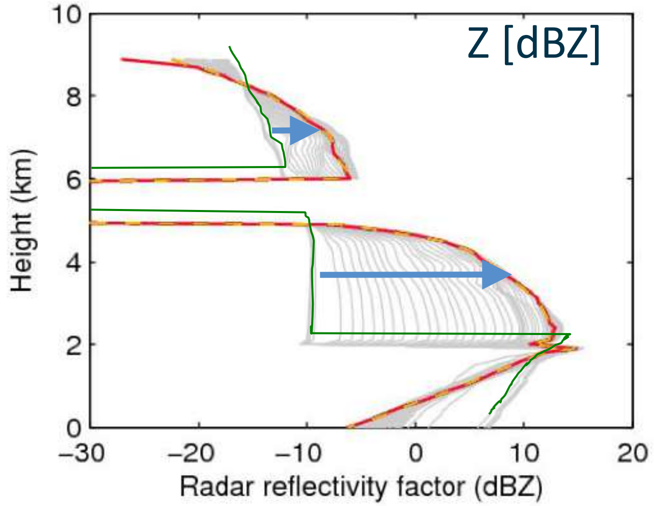
yes / converged? / no

Microphysical properties
Calculate IWC and reff

Gauss-Newton iteration
Derive new state vector x

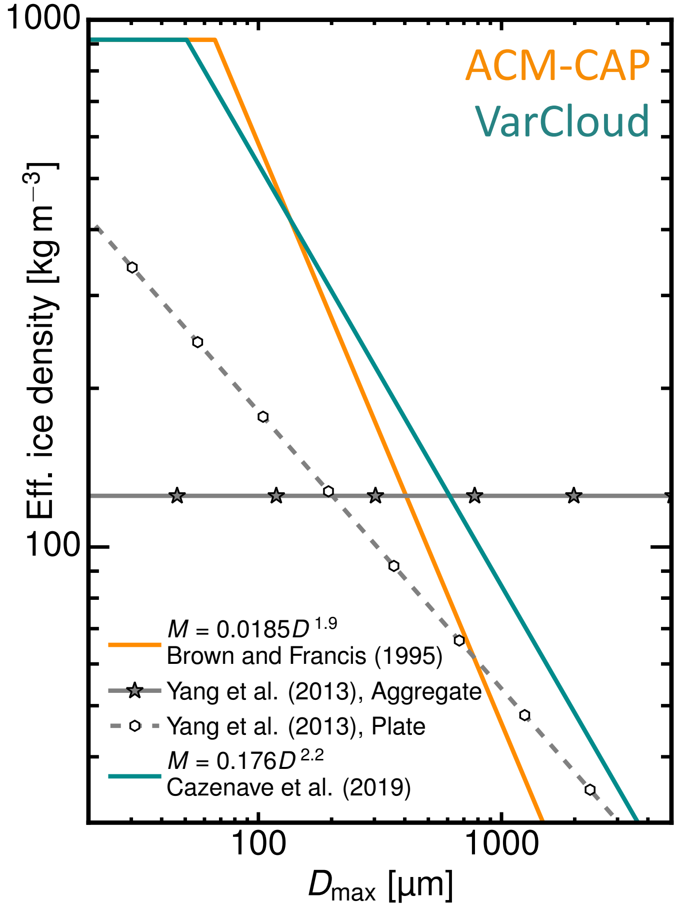
adapted from Hogan et. al.





The model – the ice crystal model of VarCloud

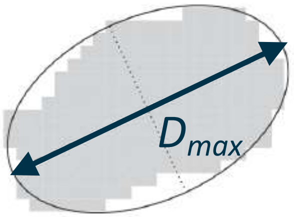
The mass-size relationship of soft spheroids and explicit ice crystal shapes



following Delanoe et. al. 2014

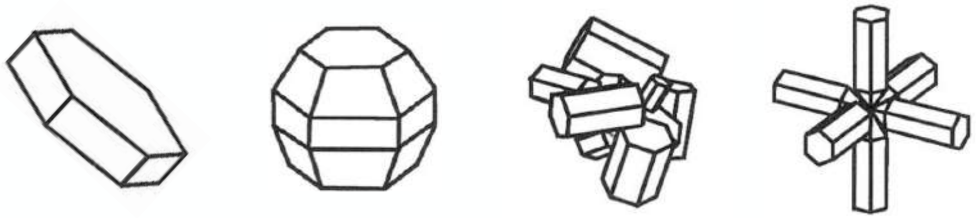
1) Soft spheroid approach, e.g. Hogan et. al. 2011

- ***ACM-CAP***: *Shannon et al (2023)*
  Brown and Francis (1995)
  $M(D) = 0.0185\ D^{1.9}$



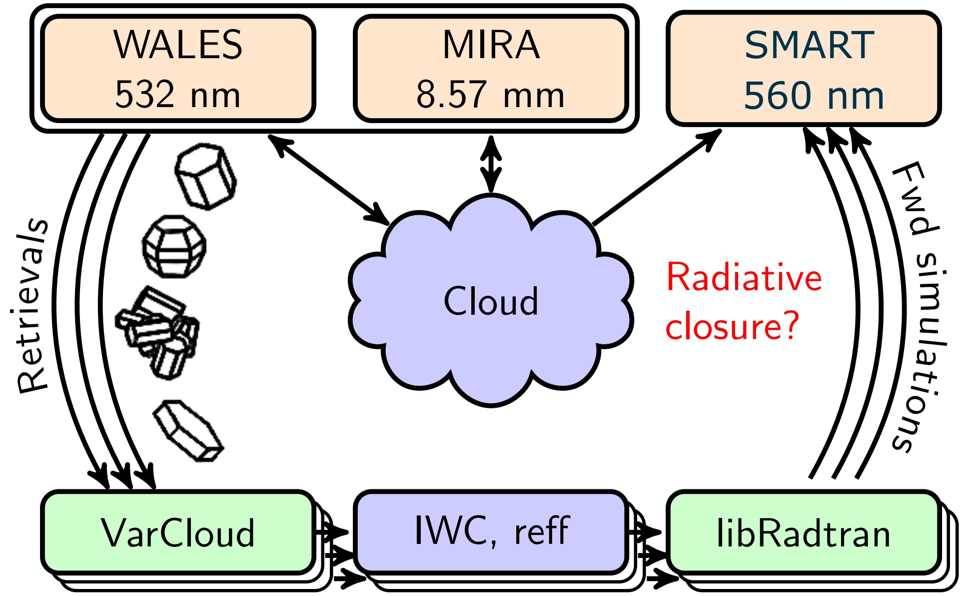
- ***VarCloud Varpy-mix***: *Aubry et al. (2019)*
  Heymsfield et al (2010) "composite mixture"
  $M(D) = 0.176\ D^{2.2}$

2) Explicit habit approach, e.g. Yang et. al. 2013



The closure – a check for plausibility

Does the retrieved ice cloud produce the correct solar reflectance?



https://doi.org/10.5194/amt-2020-448

Atmospheric Measurement Techniques
Discussions
Open Access

Why we need radar, lidar, and solar radiance observations to constrain ice cloud microphysics

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[2]LATMOS/UVSQ/IPSL/CNRS, Guyancourt, France
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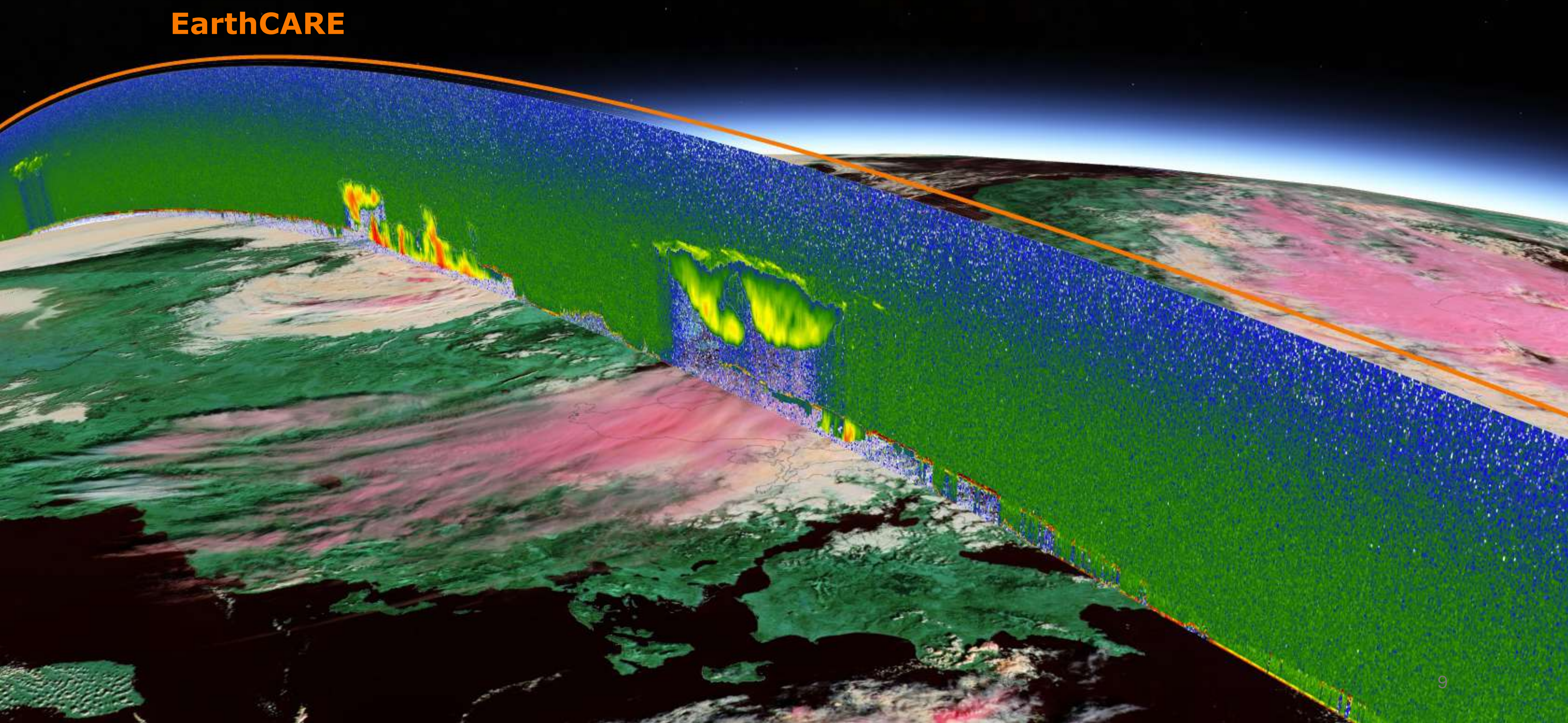
Retrieval Comparison

VarCloud vs ACM-CAP

HALO-20241110a

Cirrus embedded within occluded front over Greece

NOAA-21 / VIIRS
(Bands M3-I3-M11)
12:01 UTC



HALO-20241110a

Cirrus embedded within occluded front over Greece

NOAA-21 / VIIRS
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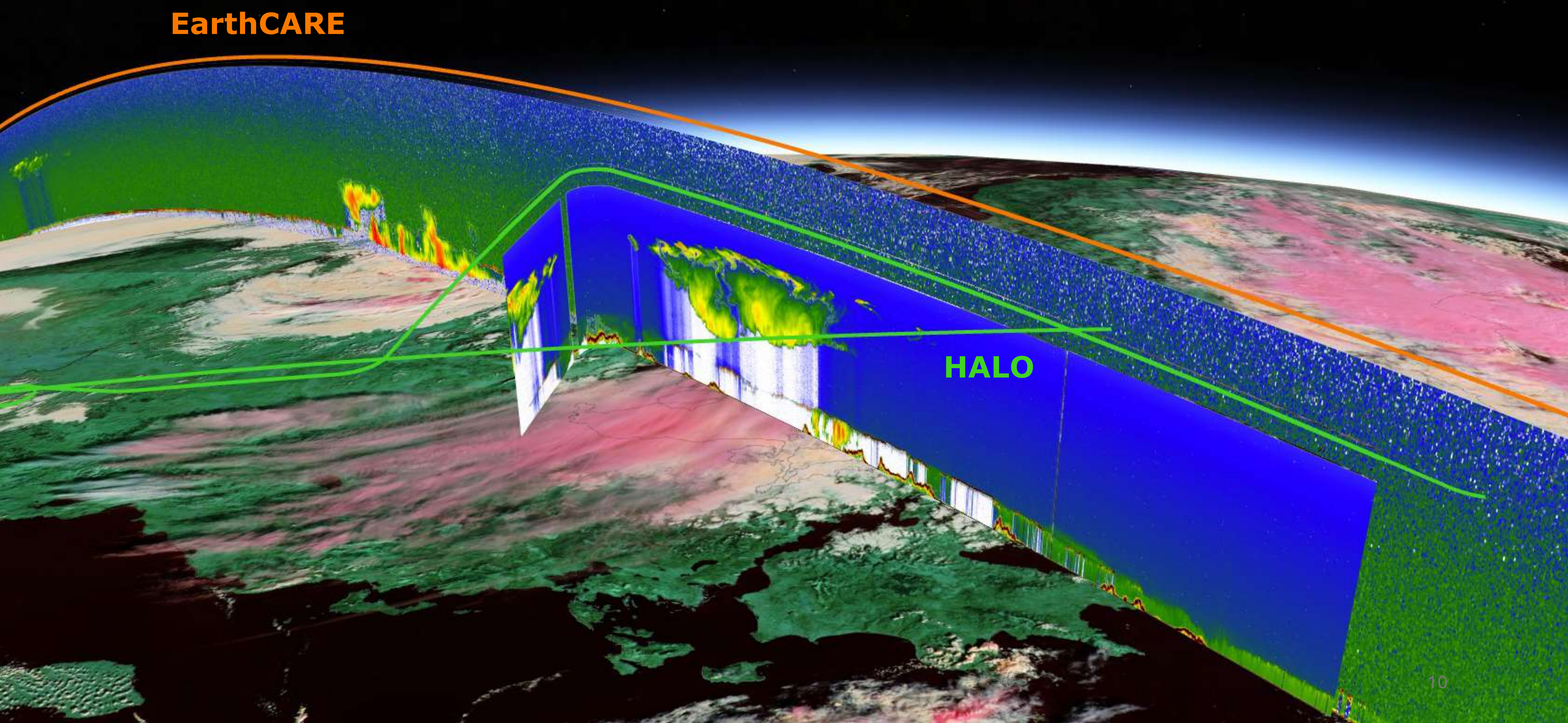
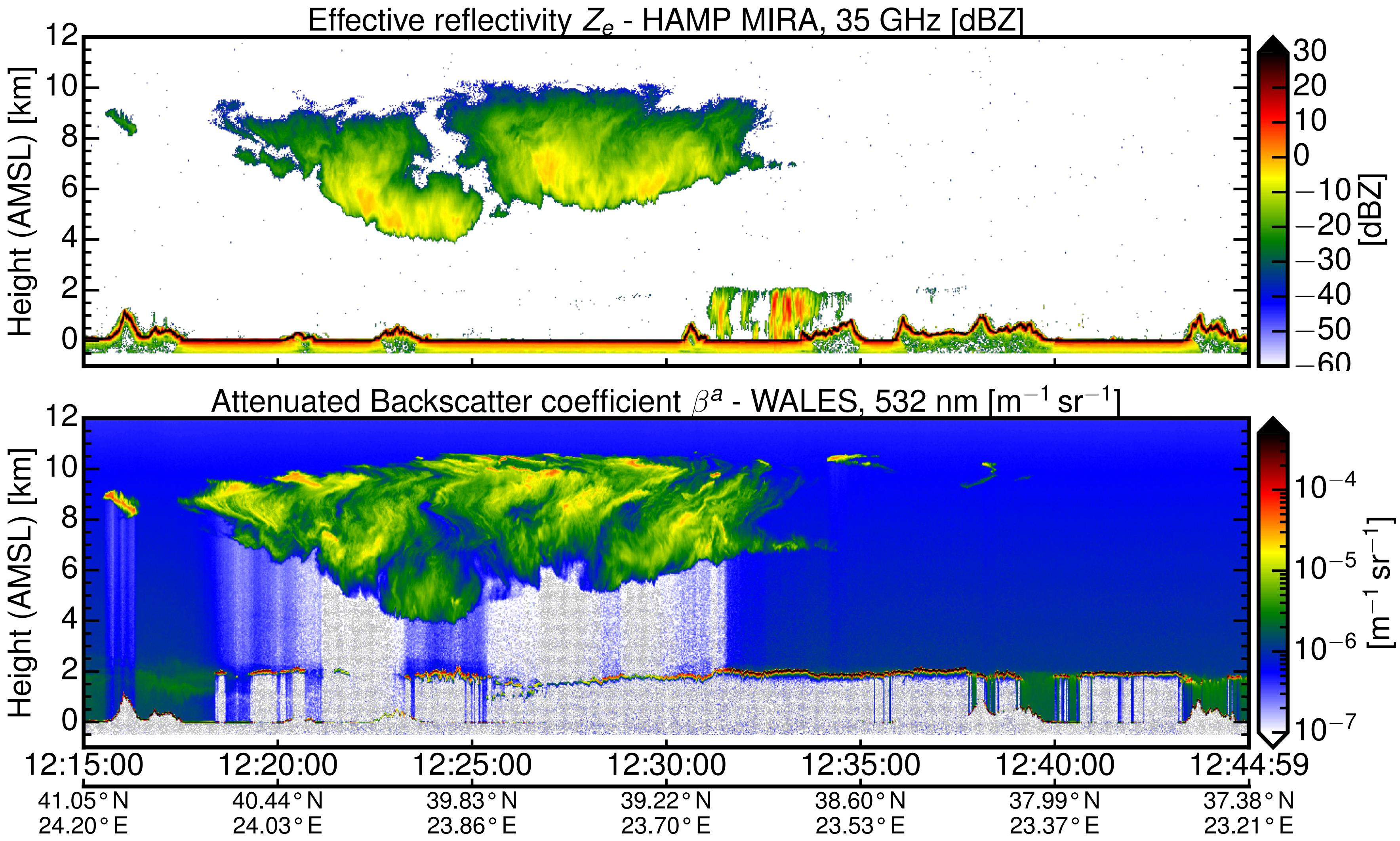
12:01 UTC



HALO-20241110a – HALO measurement

Observed radar reflectivity (MIRA) and attenuated parallel backscatter (WALES)

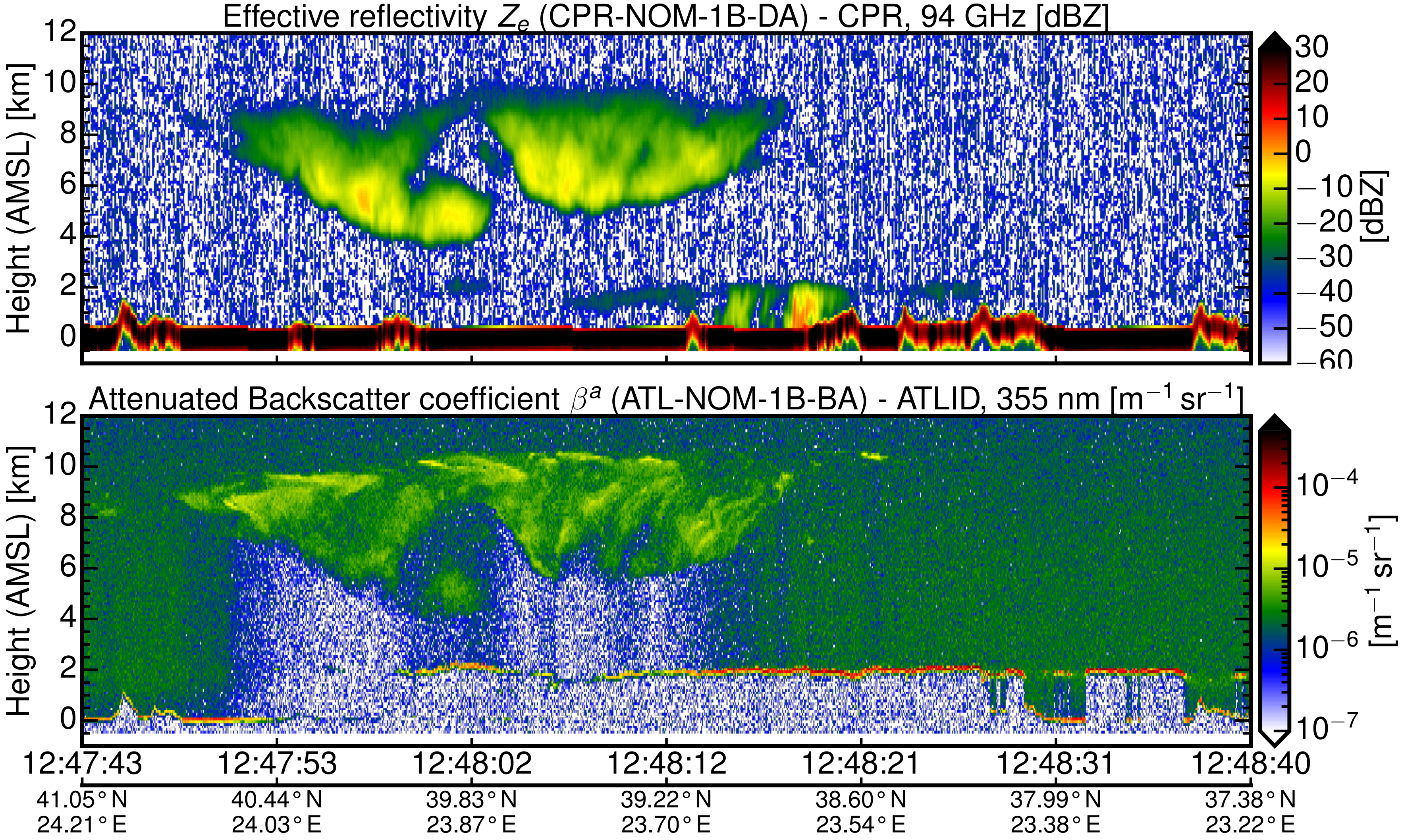


MIRA
Radar reflectivity

WALES
Attenuated parallel backscatter

HALO-20241110a – EarthCARE measurement

Observed radar reflectivity (CPR) and attenuated parallel backscatter (ATLID)

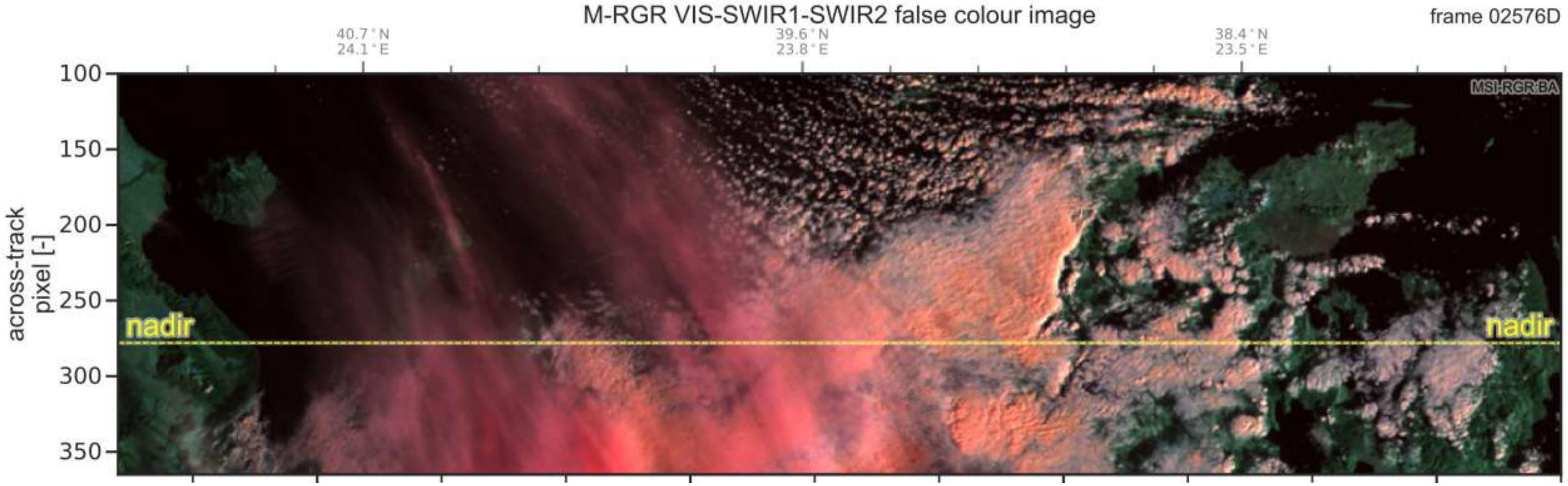


CPR-NOM-1B
Radar reflectivity

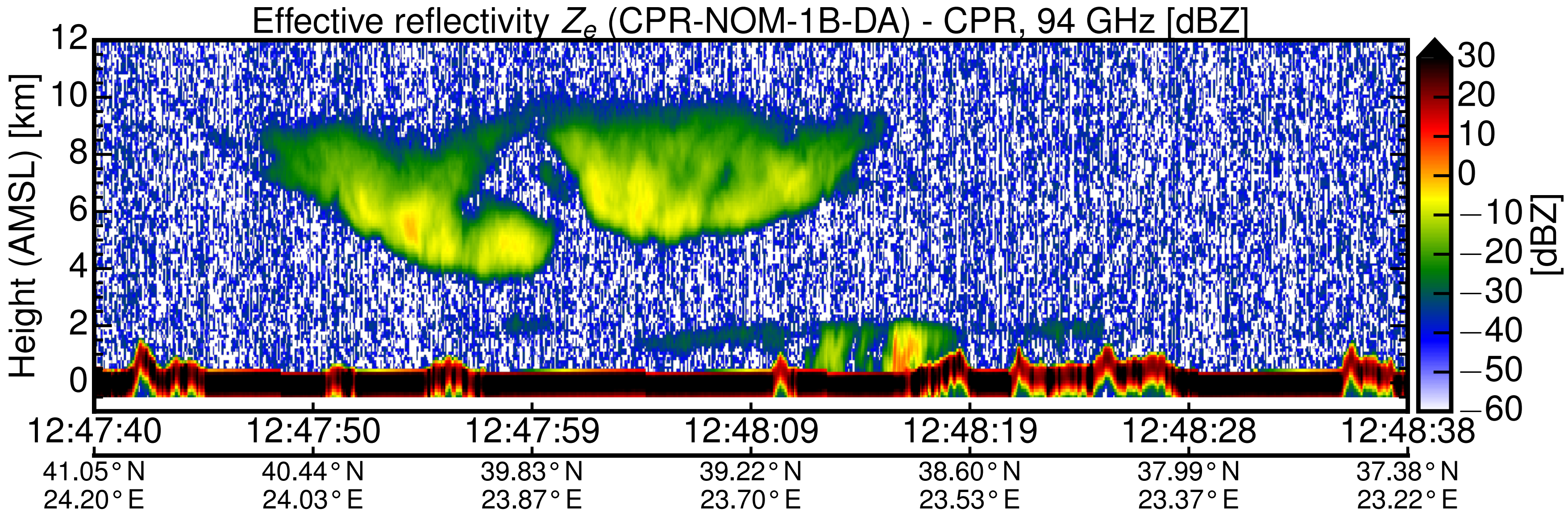
ATL-NOM-1B
Attenuated parallel backscatter

HALO-20241110a – EarthCARE measurement

Observed false color composite (MSI) and radar reflectivity (MIRA)



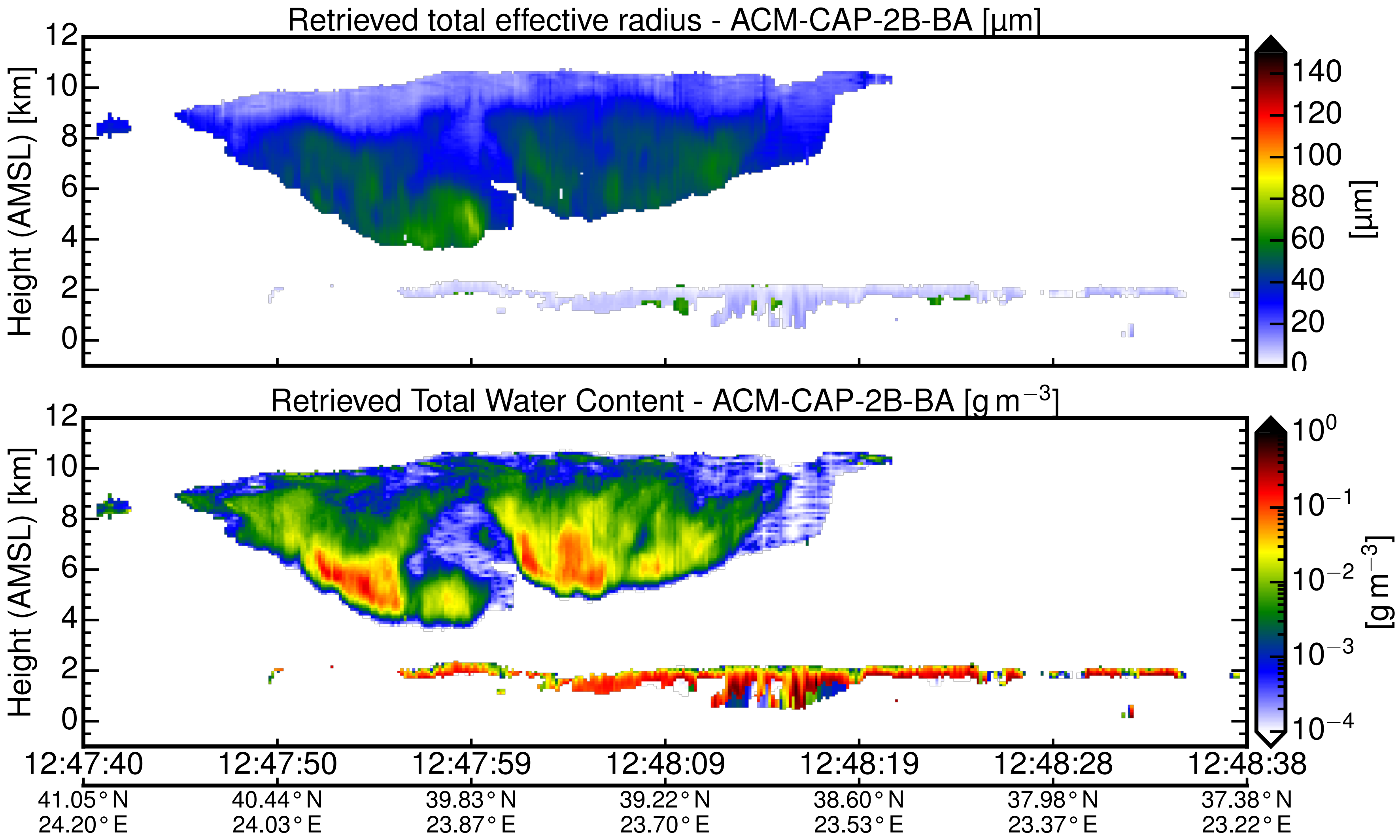
MSI-RGR
False colour
VIS-SWIR1-SWIR2



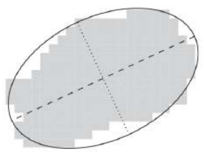
CPR-NOM-1B
Radar
reflectivity

Retrieval comparison – Captivate retrieval (ACM-CAP-2B-BA)

Using ice model from Shannon et al (2023), Brown and Francis m(D)



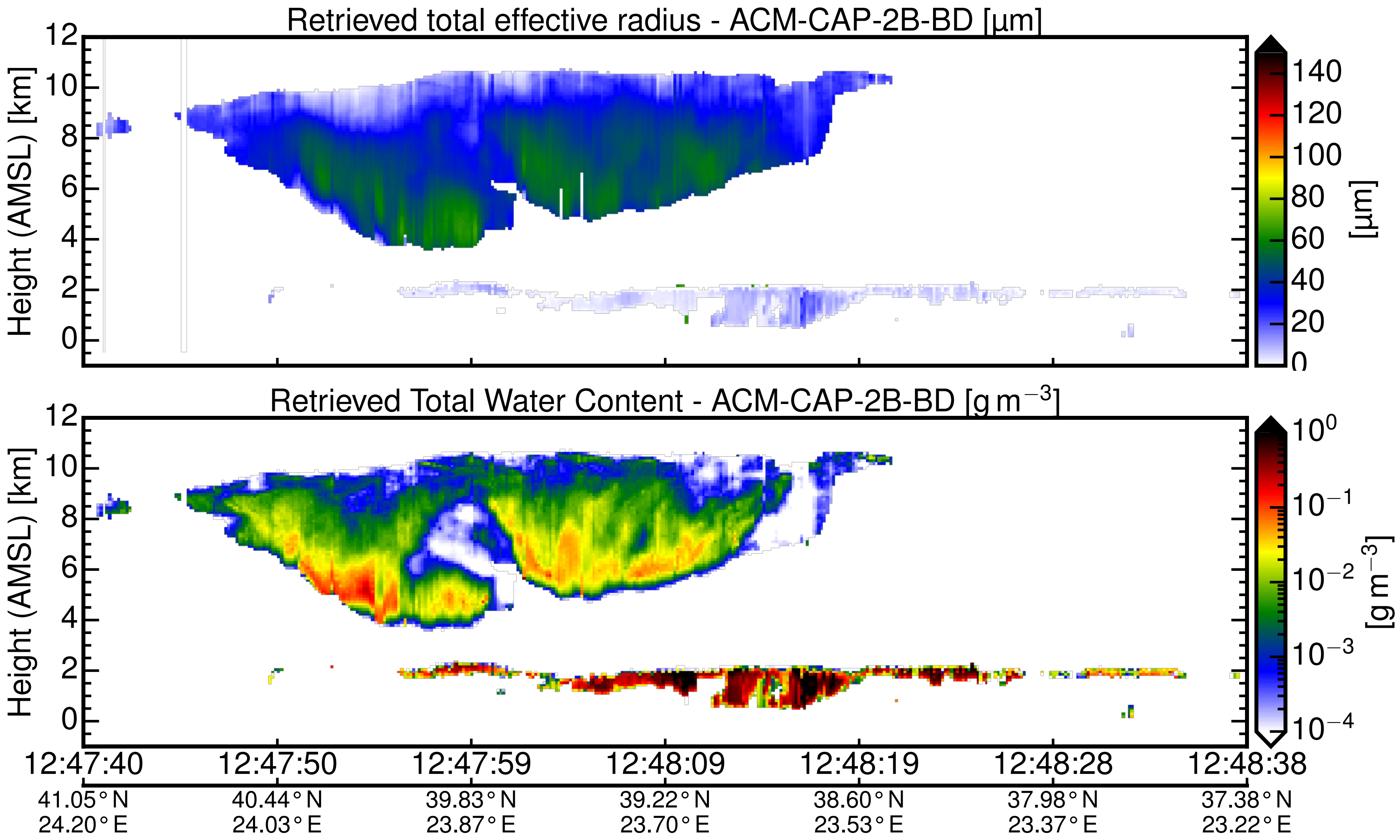
REFF
Ice effective radius



IWC
Ice water content

Retrieval comparison – Captivate retrieval (ACM-CAP-2B-BD)

Using ice model from Shannon et al (2023), Brown and Francis m(D)

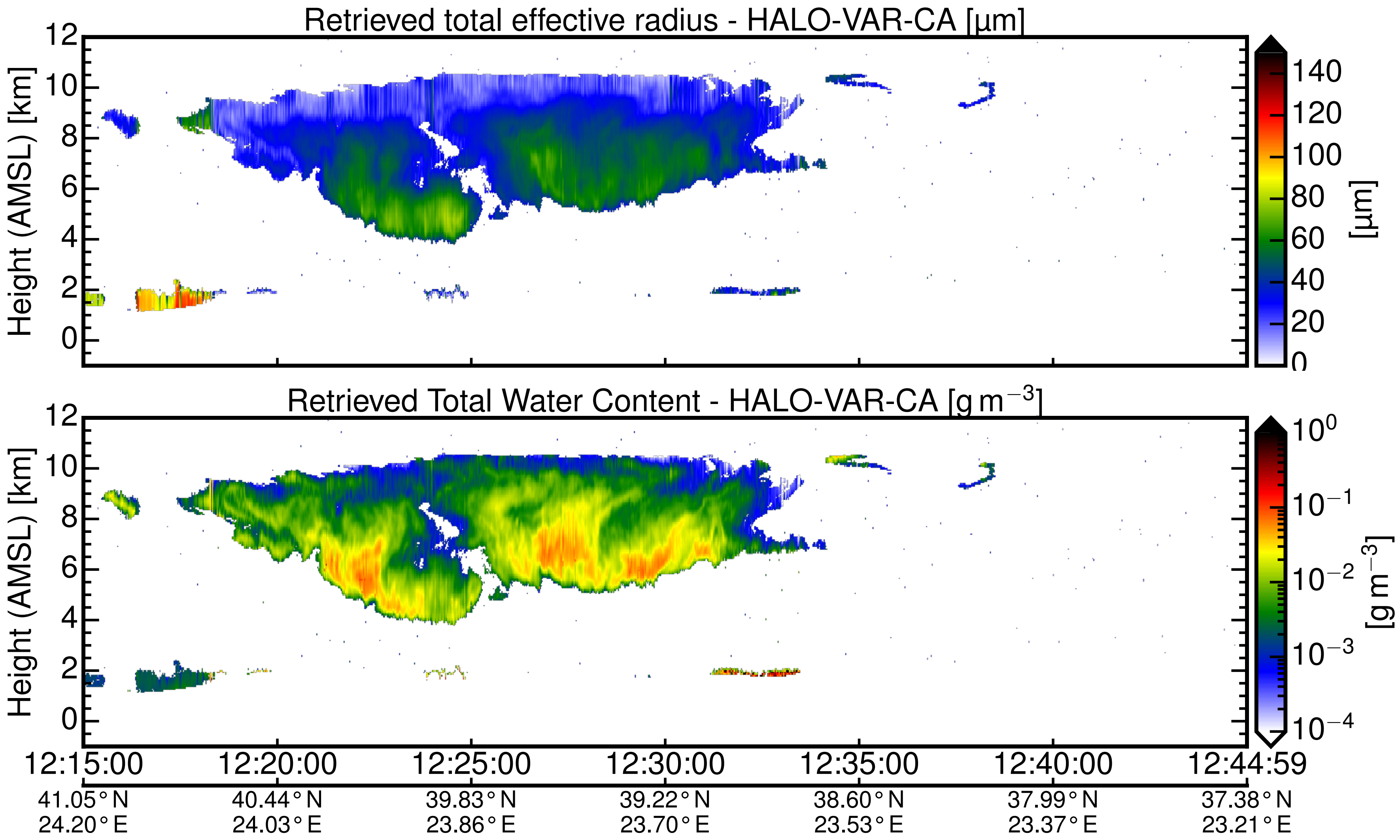


BA → BD

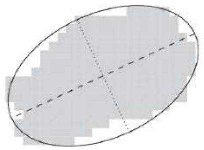
- \+ NIR/SWIR included
- \+ Improved rain microphysics
- \+ ATLID now with linear representation

Retrieval comparison – VarCloud retrieval (HALO)

Using ice model from Aubry et al (2024), Heymsfield Composite (varpy-mix-ca)



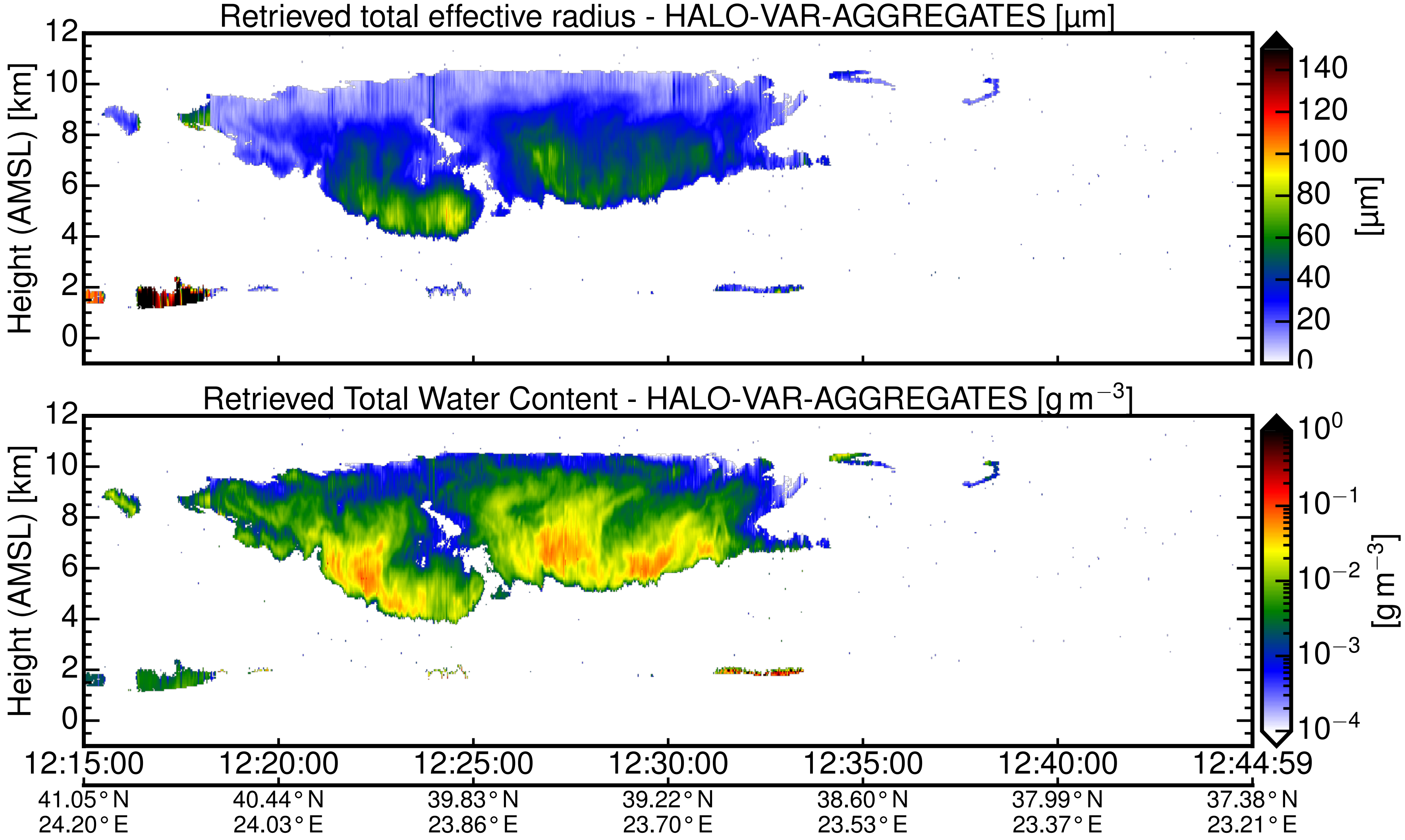
REFF
Ice effective radius



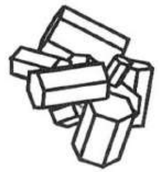
IWC
Ice water content

Retrieval comparison – VarCloud retrieval (HALO)

Using ice model from Yang et al (2013), Aggregates (varpy-mix-aggregates)



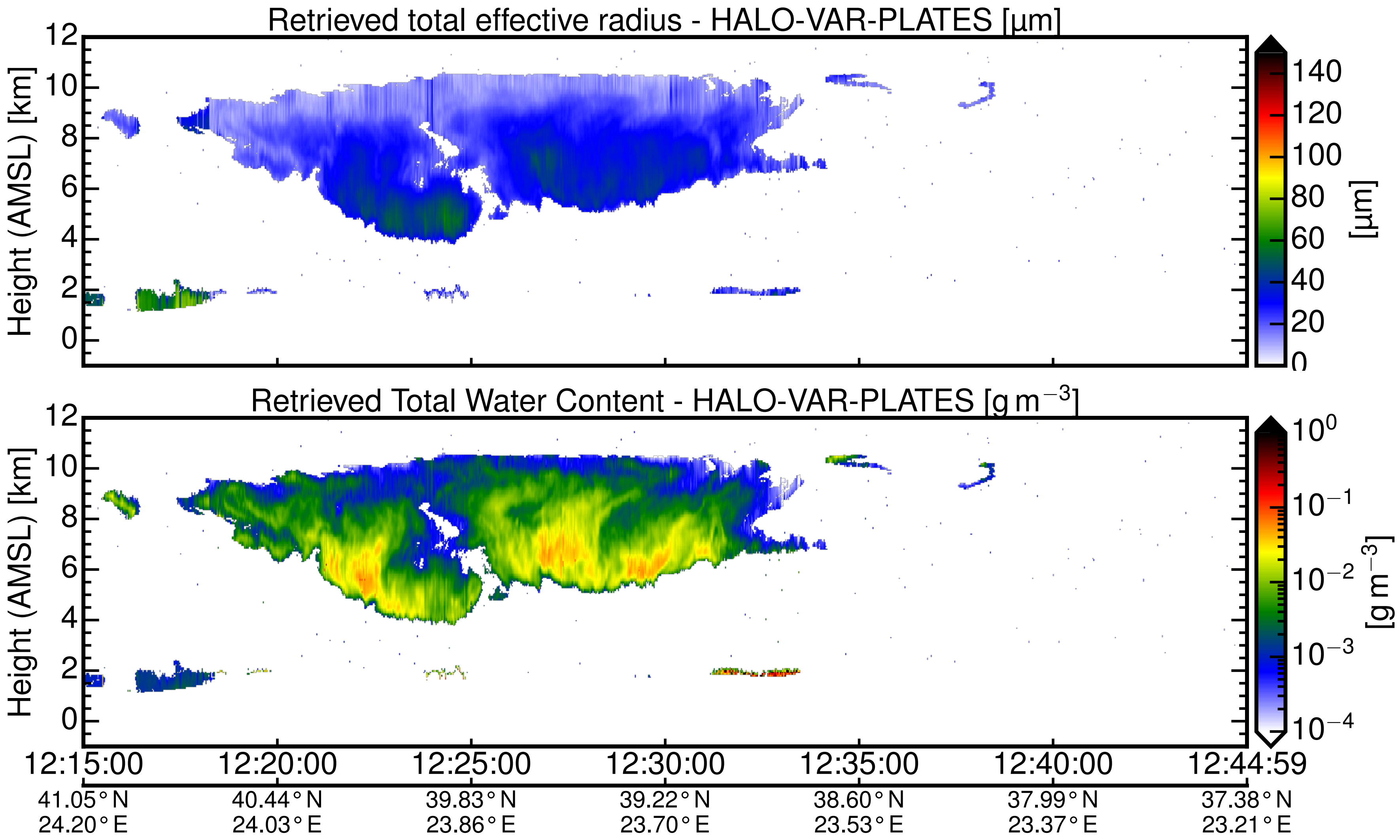
REFF
Ice effective radius



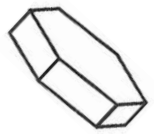
IWC
Ice water content

Retrieval comparison – VarCloud retrieval (HALO)

Using ice model from Yang et al (2013), Plates (varpy-mix-plates)



REFF
Ice effective radius

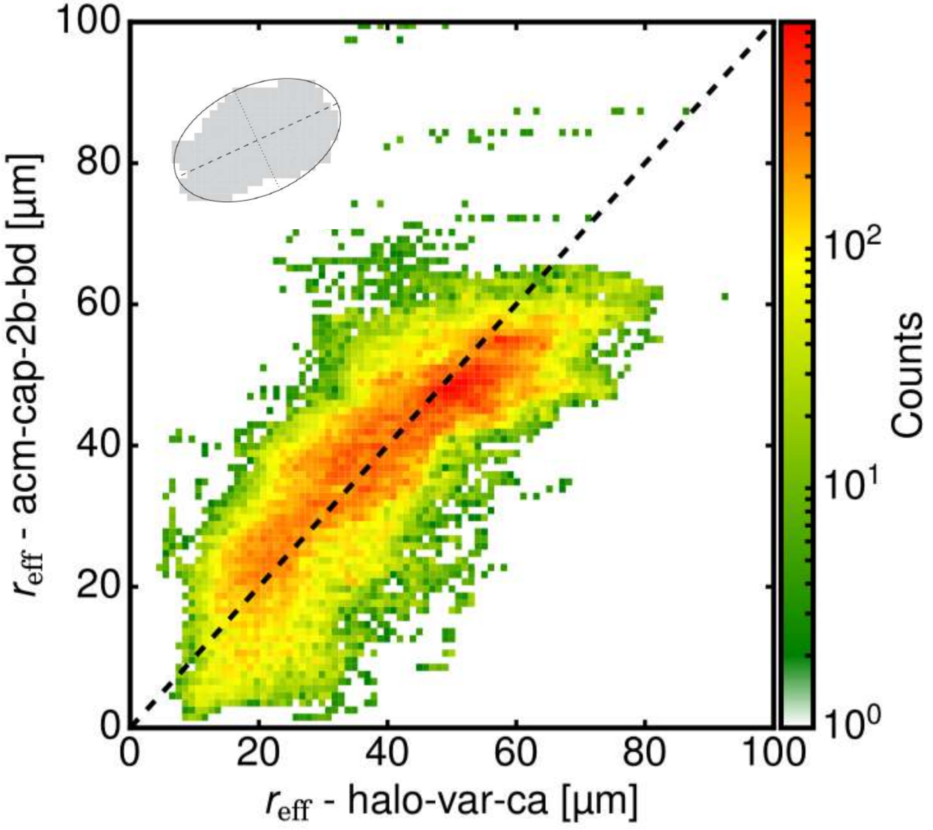


IWC
Ice water content

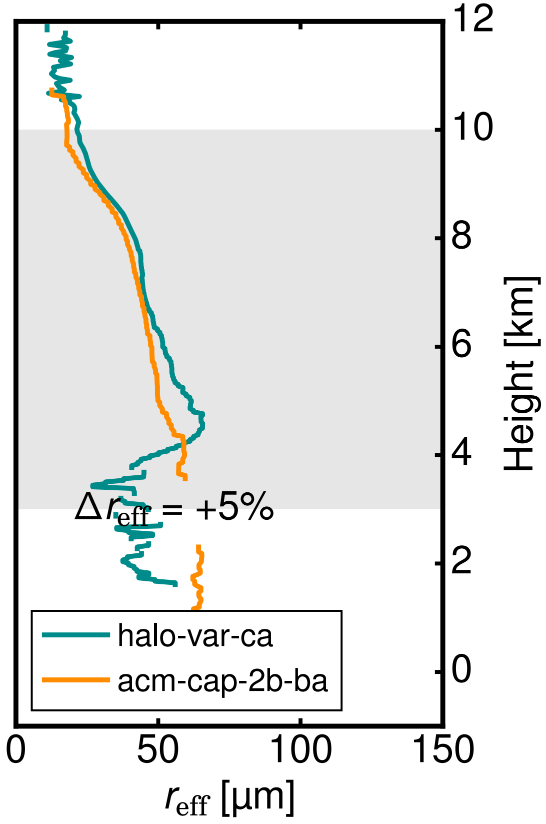
Retrieval comparison – VarCloud (HALO) and ACM-CAP-2B-BA

Using ice model from Aubry et al (2024), Heymsfield Composite (varpy-mix-ca)

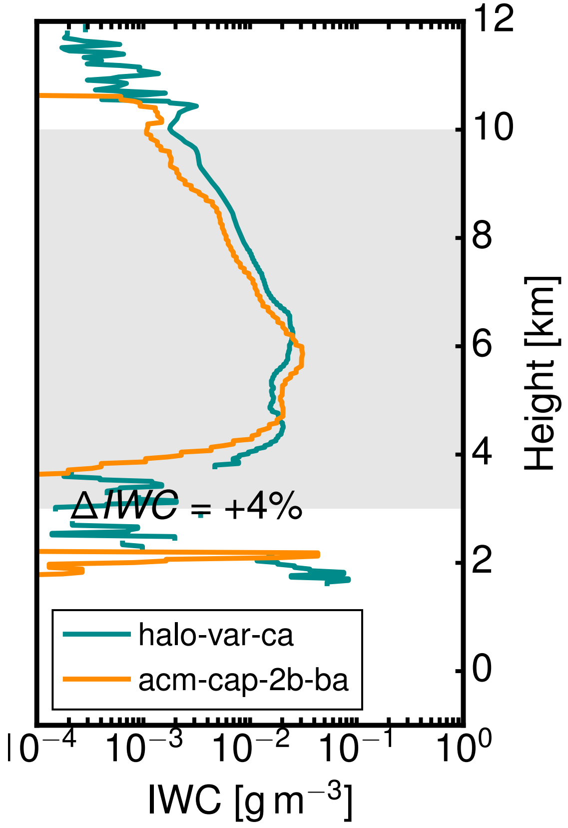
Effective radius



Avg. Effective radius



Avg. Ice water content



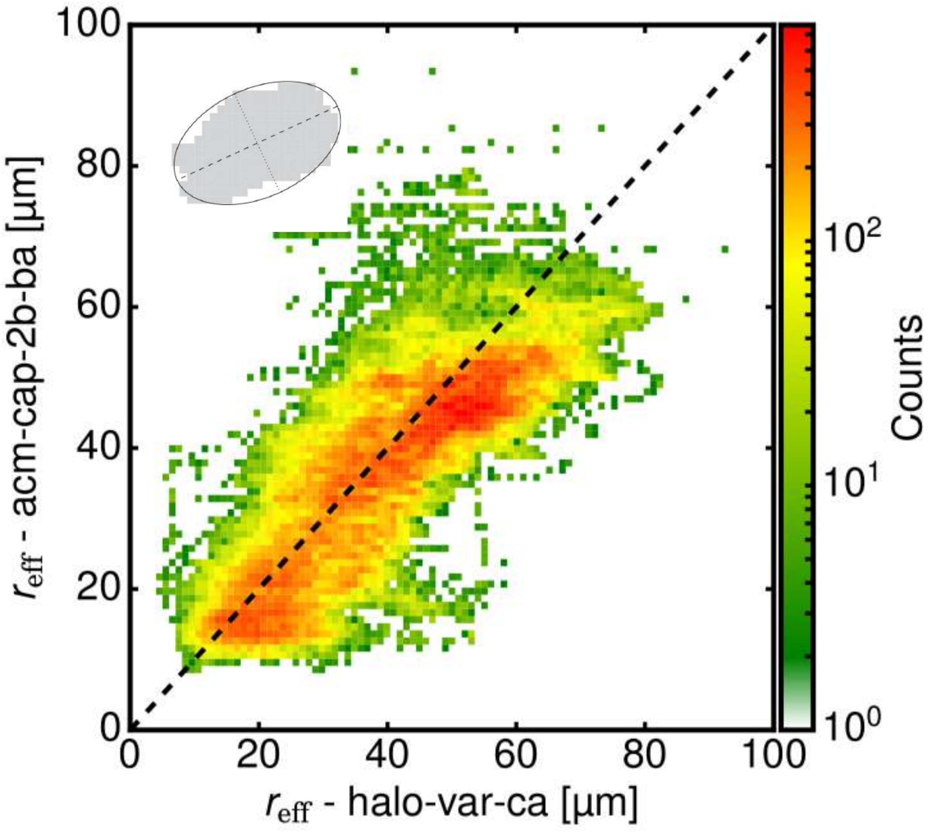
→ *VarCloud with **slighly larger r_{eff}***
→ *VarCloud **slighty larger IWC***

→ *+5% difference in r_{eff} to ACM-CAP-2B-BA*
→ *+4% difference in IWC to ACM-CAP-2B-BA*

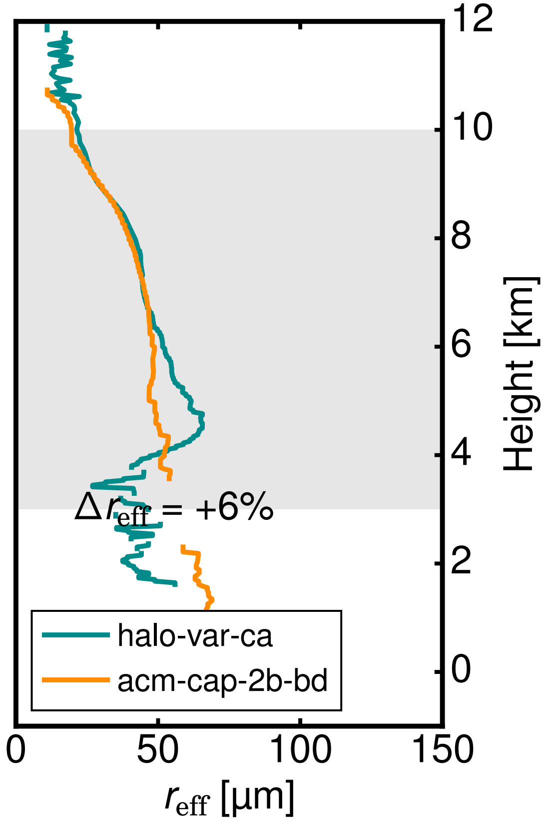
Retrieval comparison – VarCloud (HALO) and ACM-CAP-2B-BD

Using ice model from Aubry et al (2024), Heymsfield Composite (varpy-mix-ca)

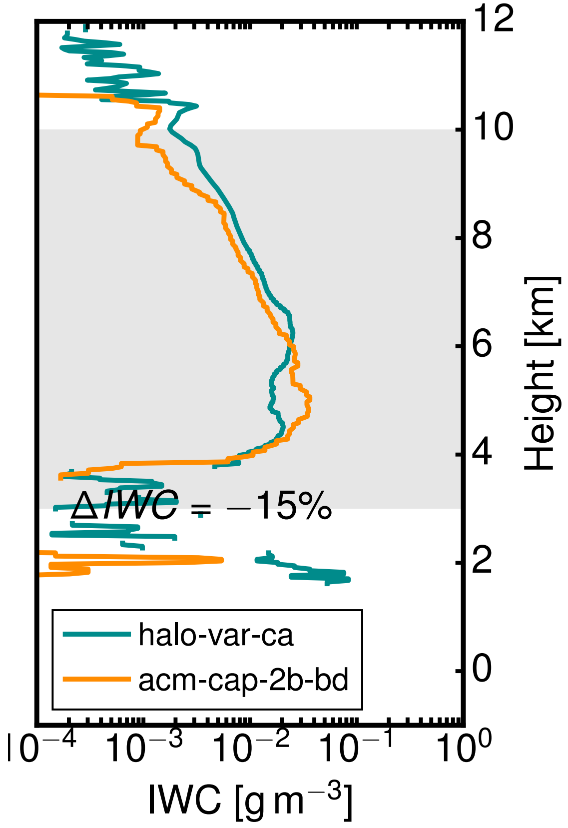
Effective radius



Avg. Effective radius



Avg. Ice water content



→ *VarCloud with **slighly larger r_{eff}***

→ *VarCloud **slighty lower IWC***

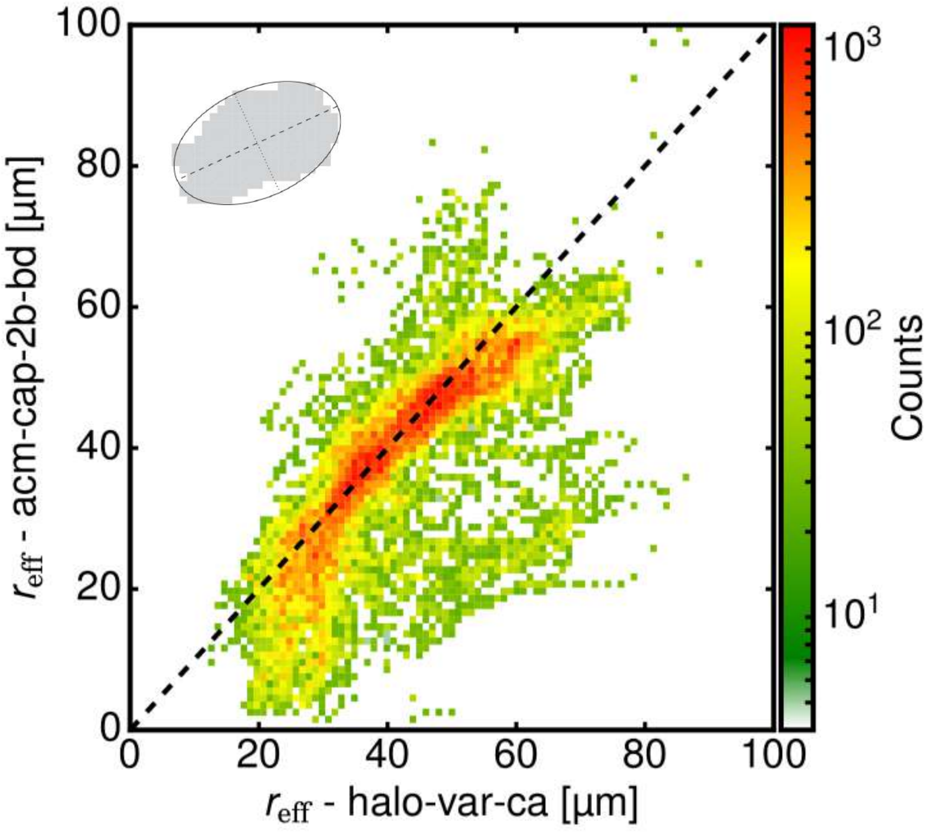
→ *+6% difference in r_{eff} to ACM-CAP-2B-BD*

→ *-15% difference in IWC to ACM-CAP-2B-BD*

Retrieval comparison – VarCloud (EarthCARE) and ACM-CAP-2B-BD

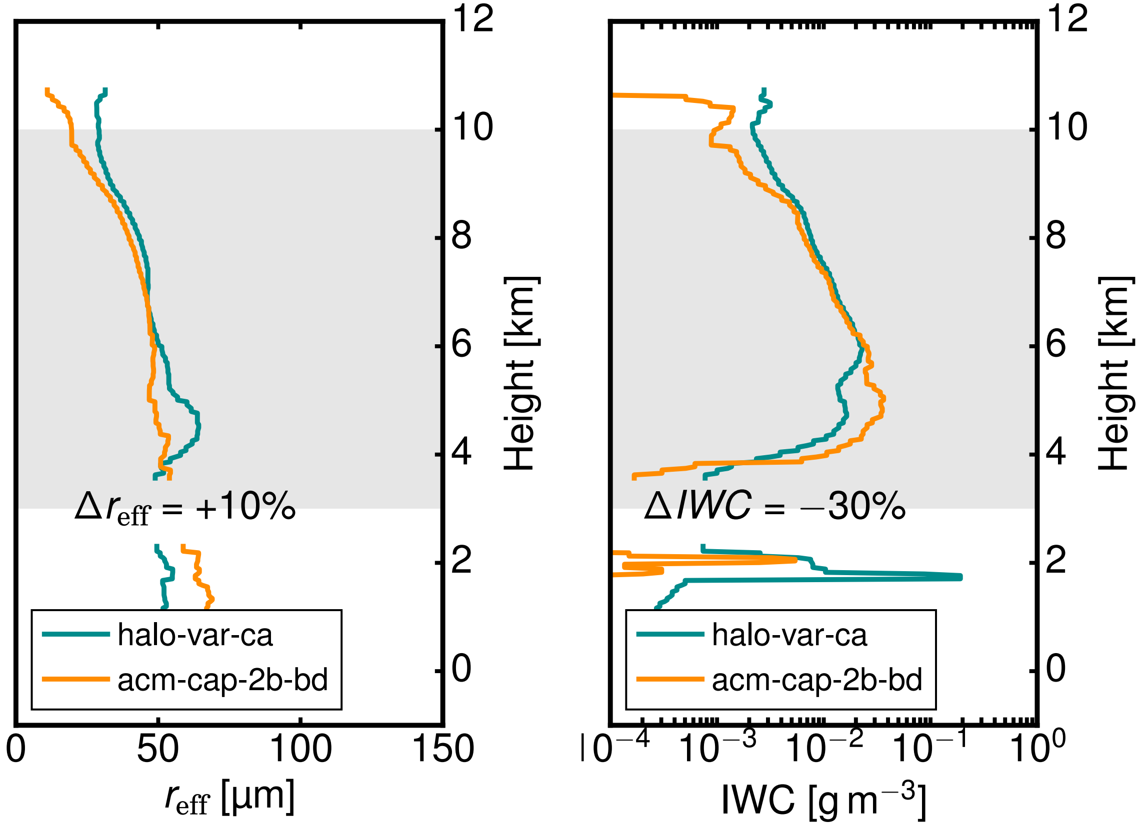
Using ice model from Aubry et al (2024), Heymsfield Composite (varpy-mix-ca)

Effective radius



Avg. Effective radius

Avg. Ice water content



→ *VarCloud with **slighly larger r_{eff}***

→ *VarCloud **lower IWC** at cloud base*

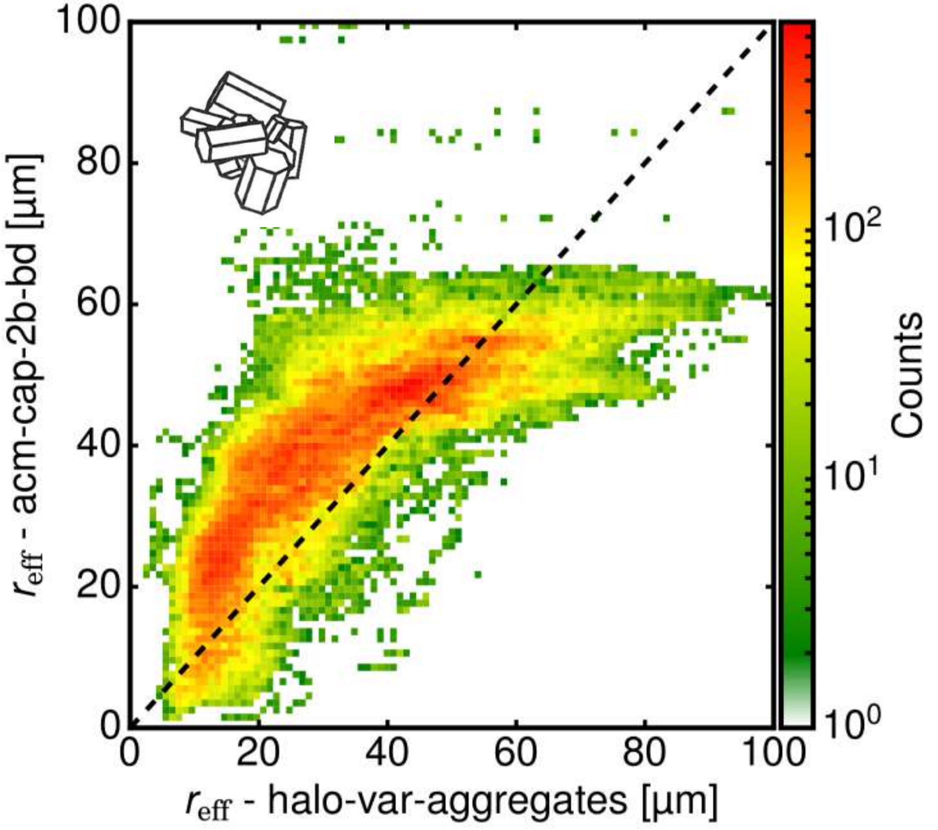
→ *+10% difference in r_{eff} to ACM-CAP-2B-BD*

→ *-30% difference in IWC to ACM-CAP-2B-BD*

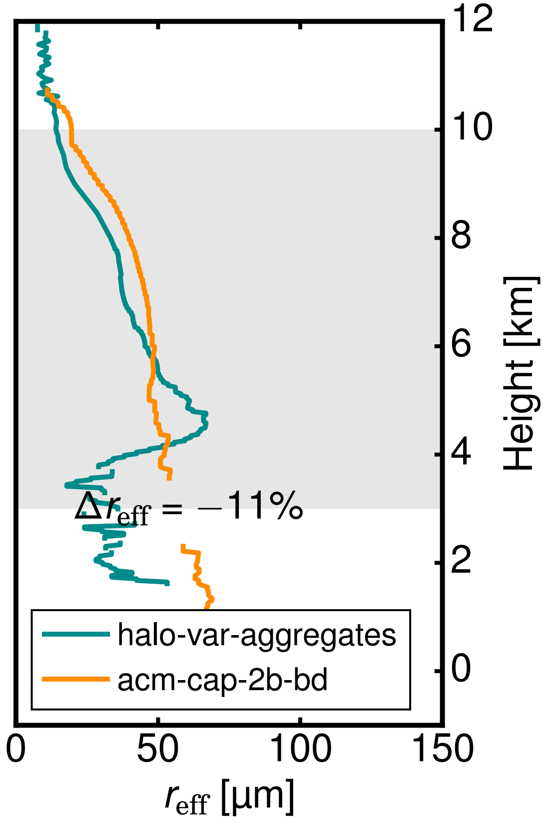
Retrieval comparison – VarCloud (HALO) and ACM-CAP-2B-BD

Using ice model from Yang et al (2013), Aggregates

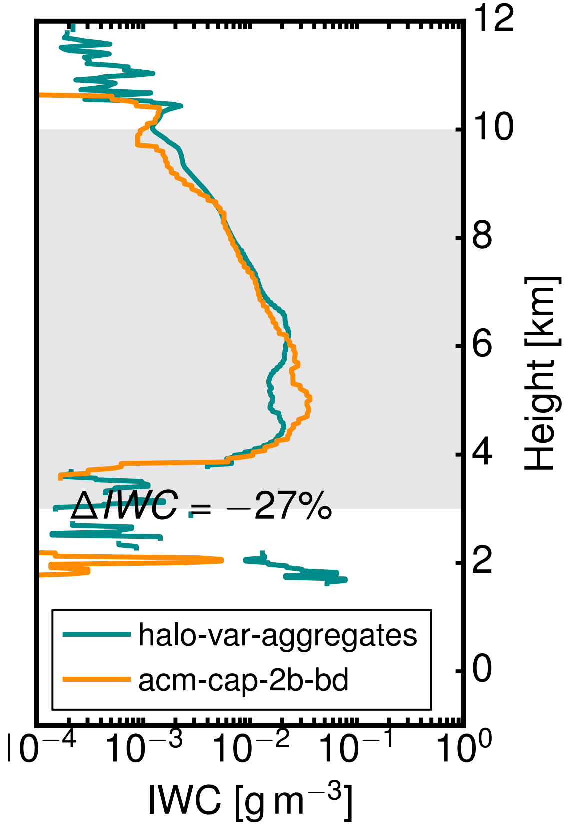
Effective radius



Avg. Effective radius



Avg. Ice water content



→ *VarCloud with **clearly lower r_{eff}***

→ *VarCloud **clearly lower IWC***

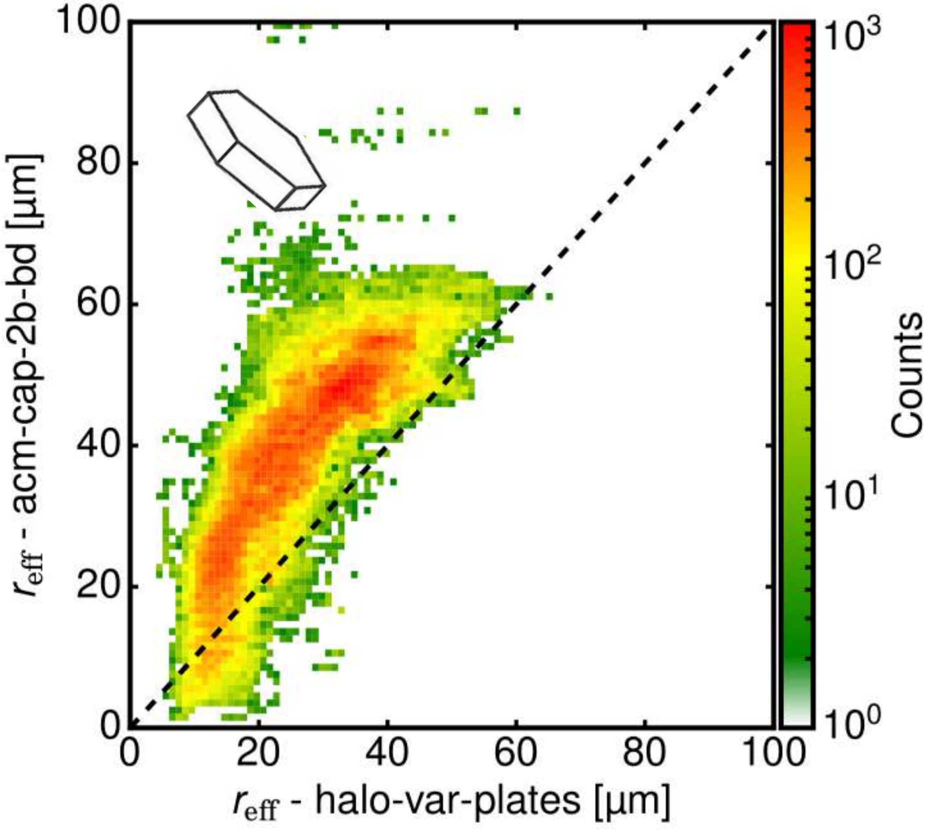
→ *-11% difference in r_{eff} to ACM-CAP-2B-BD*

→ *-27% difference in IWC to ACM-CAP-2B-BD*

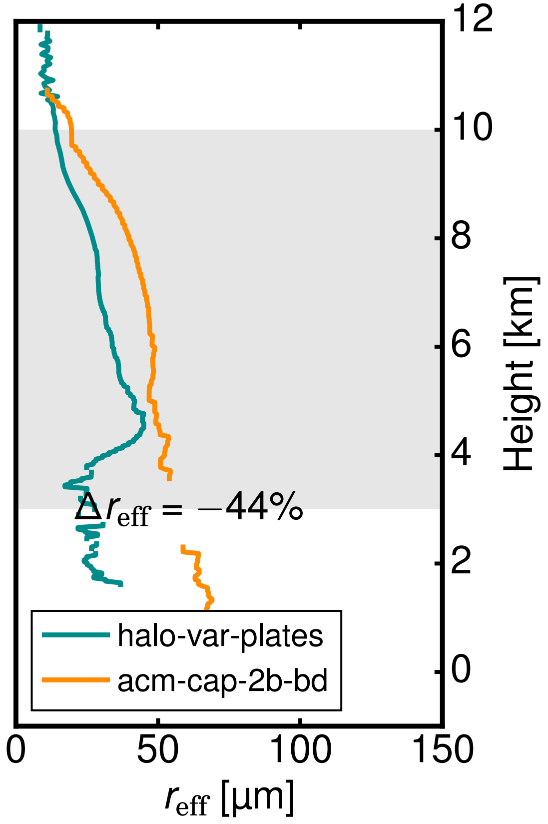
Retrieval comparison – VarCloud (HALO) and ACM-CAP-2B-BD

Using ice model from Yang et al (2013), Plates

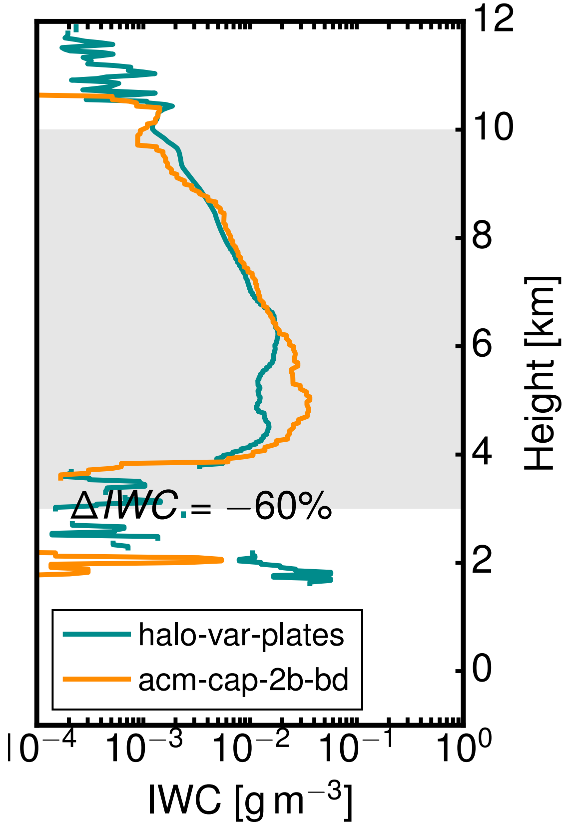
Effective radius



Avg. Effective radius



Avg. Ice water content



→ *VarCloud **half as large r_{eff}***
→ *VarCloud with **half the IWC***

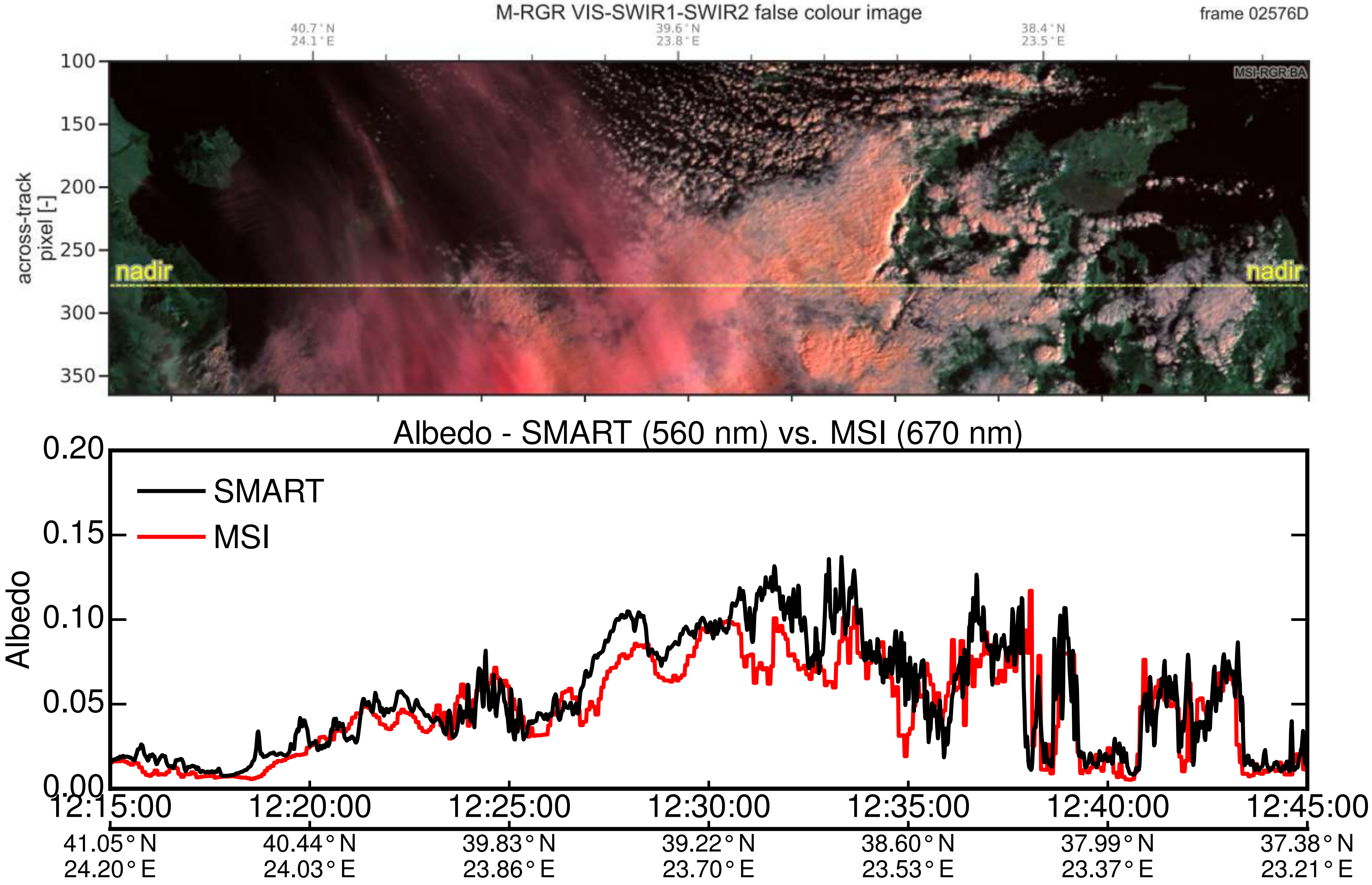
→ *-44% difference in r_{eff} to ACM-CAP-2B-BD*
→ *-60% difference in IWC to ACM-CAP-2B-BD*

Solar radiative closure

VarCloud vs CAPTIVATE

Solar radiative closure – MSI (670nm) vs SMART (560 nm)

Cloud albedo difference between both instruments

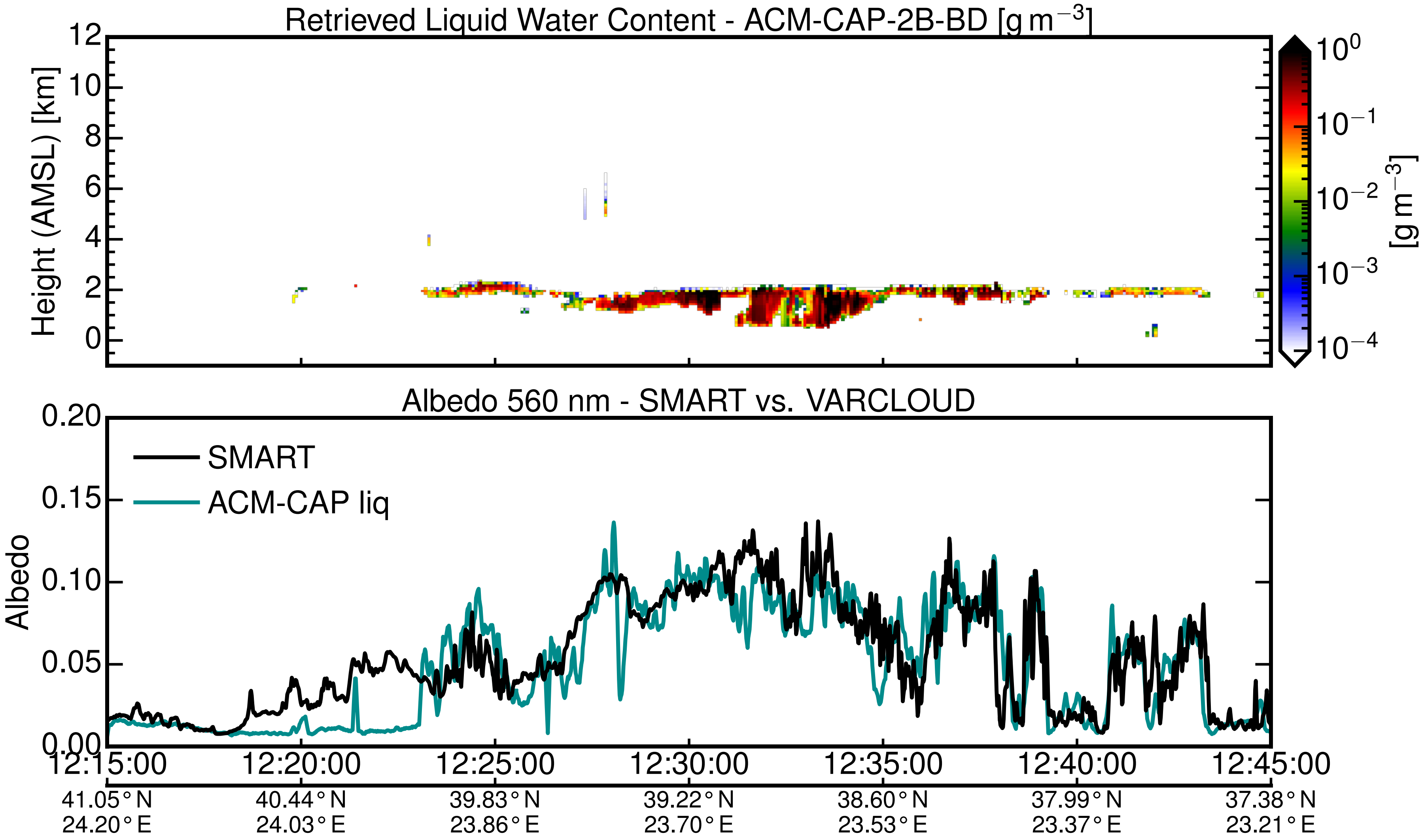


TWC
Total water content

Albedo
559 nm
670 nm

Solar radiative closure – ACM-CAP-2B-BD Liquid

Using ACM-CAP liquid as stand-in for the missing liquid from Varcloud

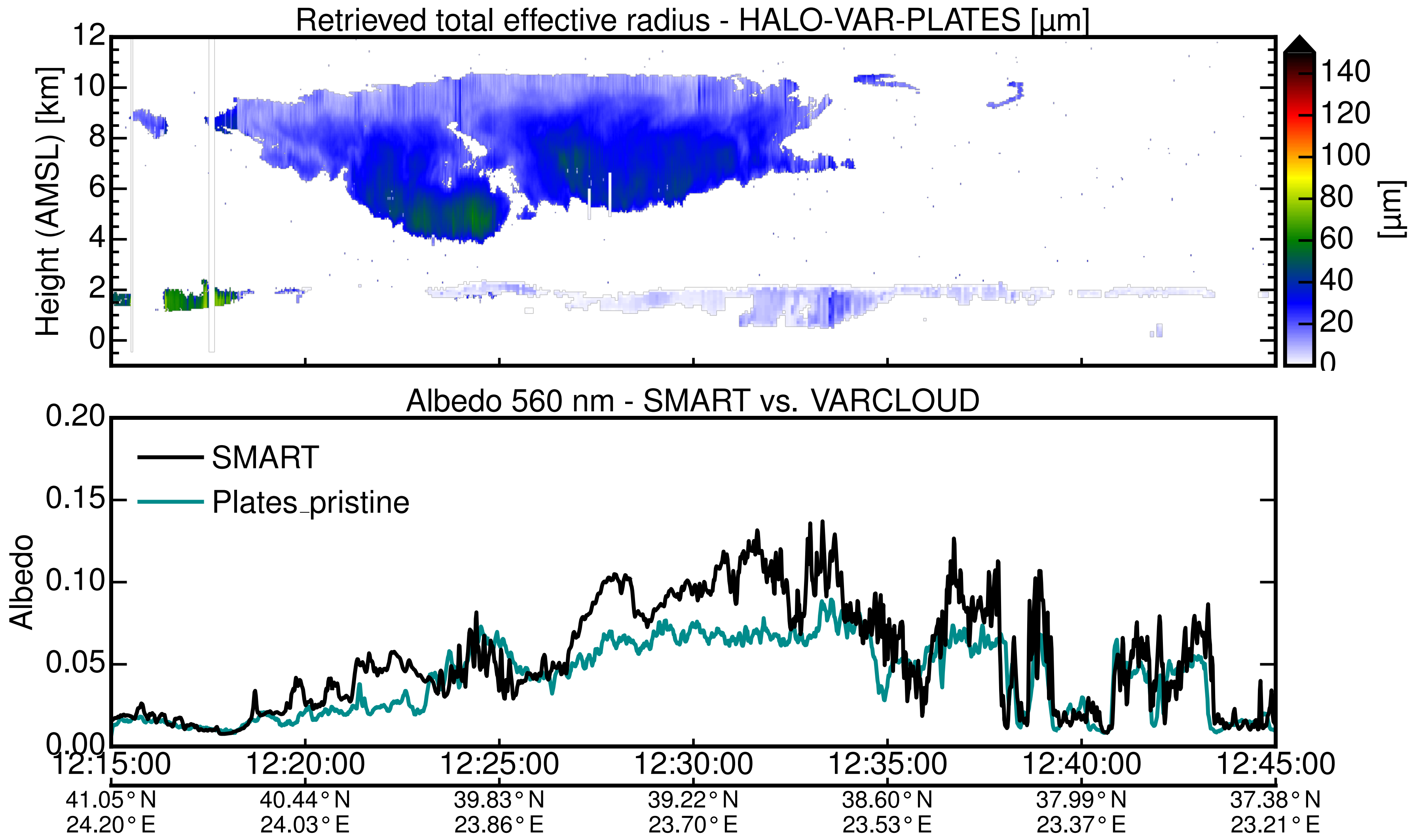


REFF
Ice effective radius

Albedo
559 nm

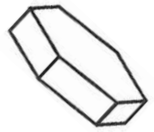
Solar radiative closure – VarCloud retrieval

Using ice model from Yang et al (2013), Plates (pristine)



Roughness
following
Yang et al (2013)

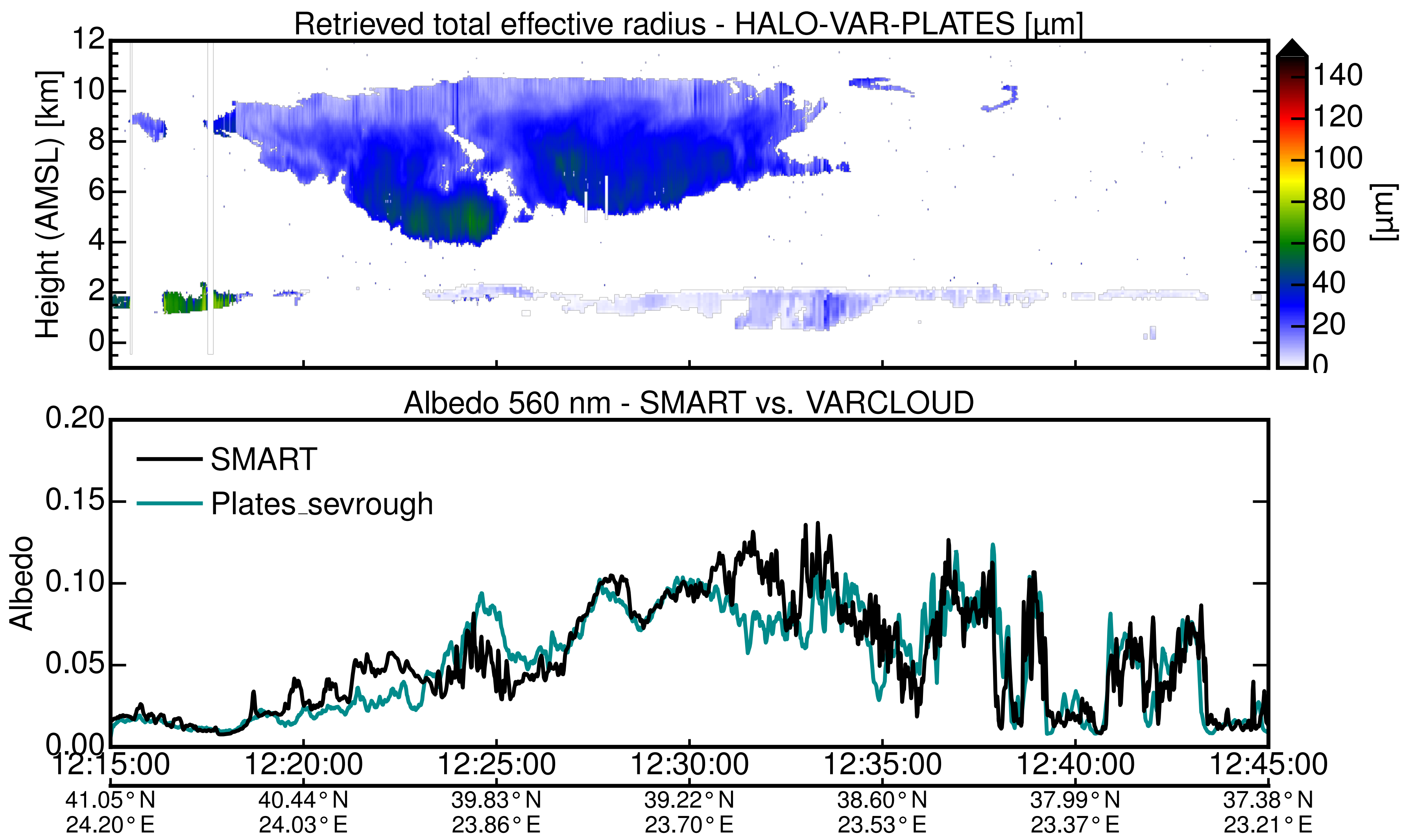
REFF
Ice effective radius



Albedo
559 nm

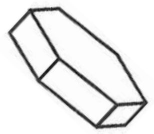
Solar radiative closure – VarCloud retrieval

Using ice model from Yang et al (2013), Plates (rough)



Roughness following Yang et al (2013)

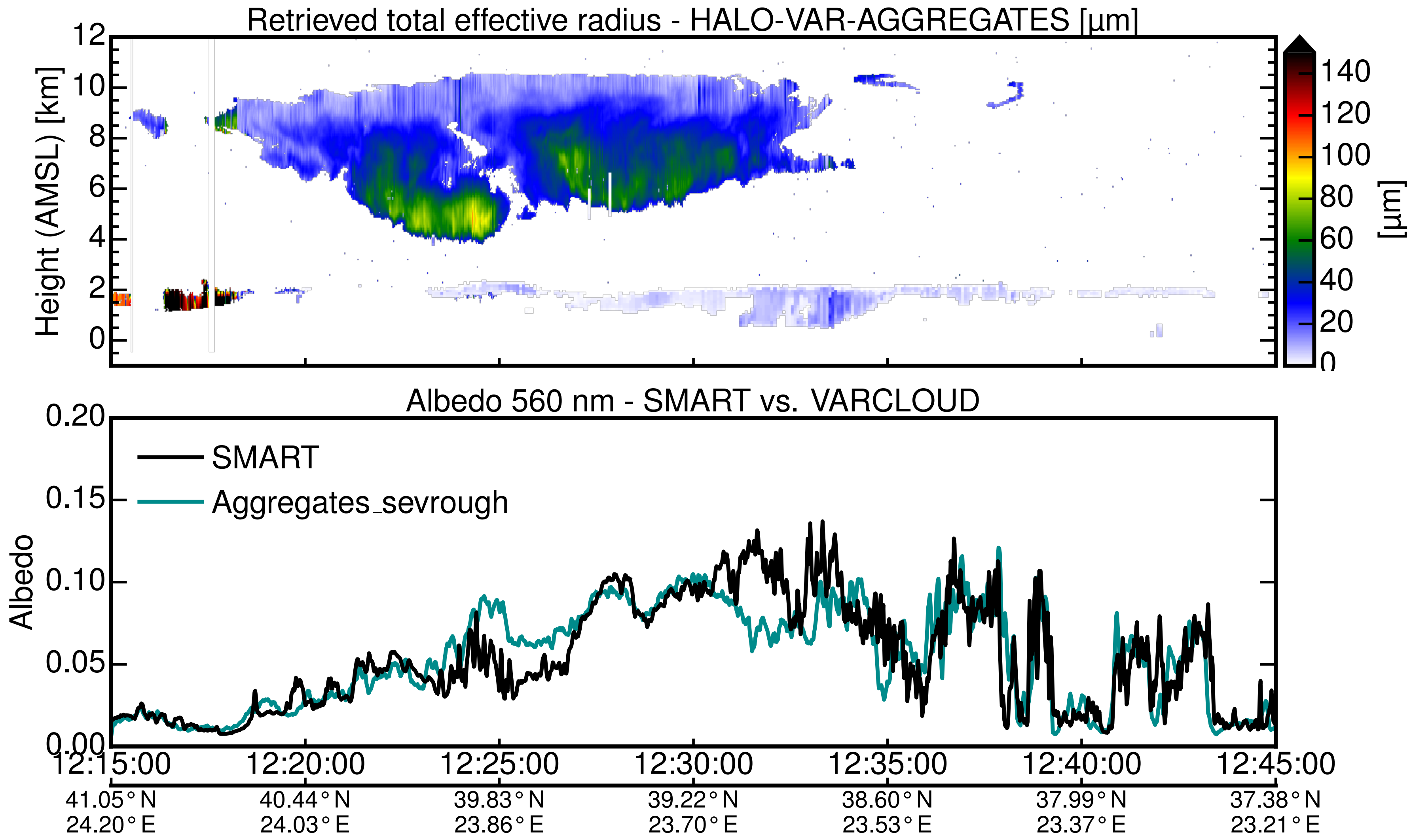
REFF
Ice effective radius



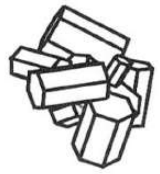
Albedo
559 nm

Solar radiative closure – VarCloud retrieval

Using ice model from Yang et al (2013), Aggregates



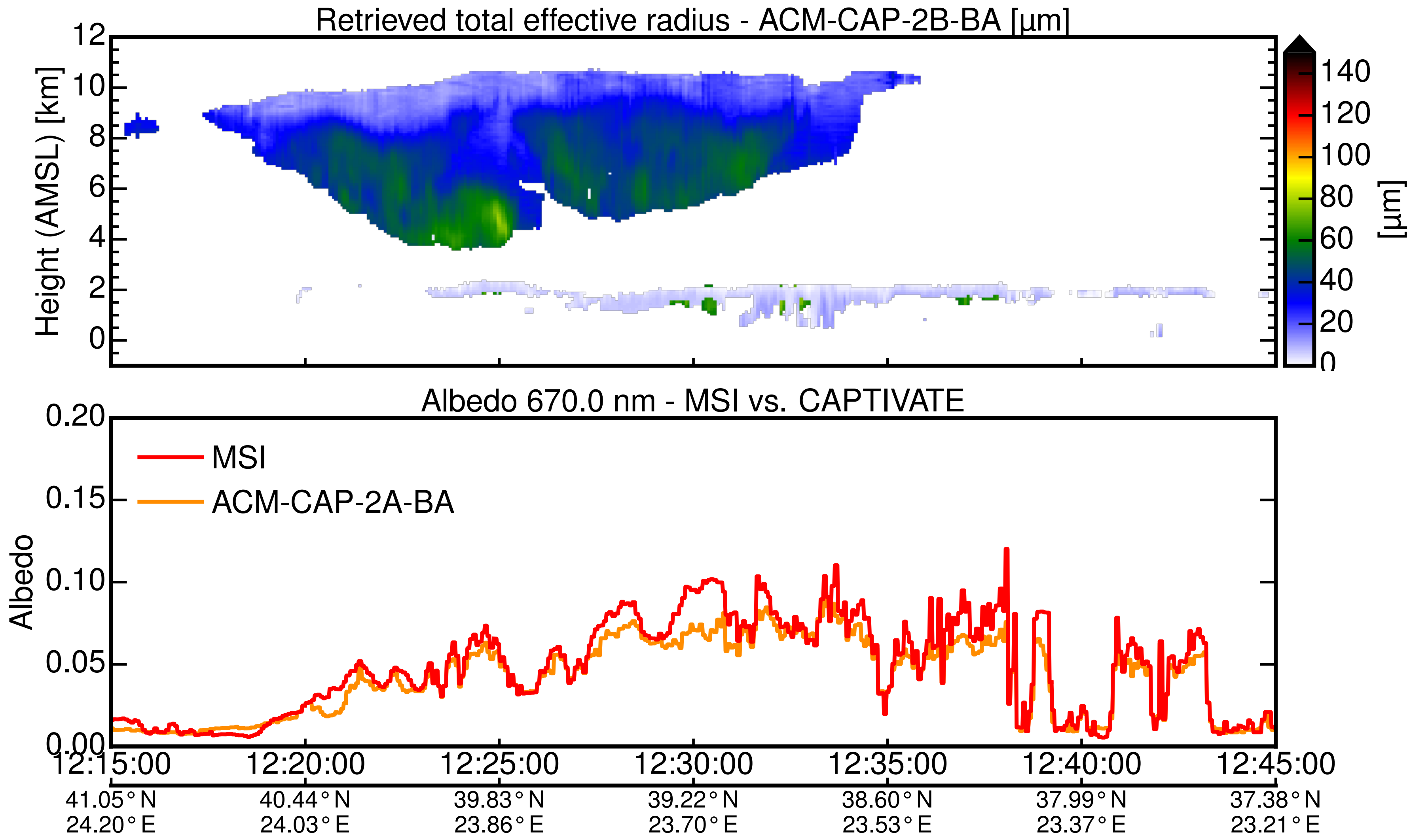
REFF
Ice effective radius



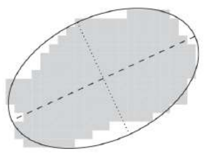
Albedo
559 nm

Solar radiative closure – ACM-CAP-2B-BA retrieval

Using ice model from Shannon et al (2023), Brown and Francis m(D)



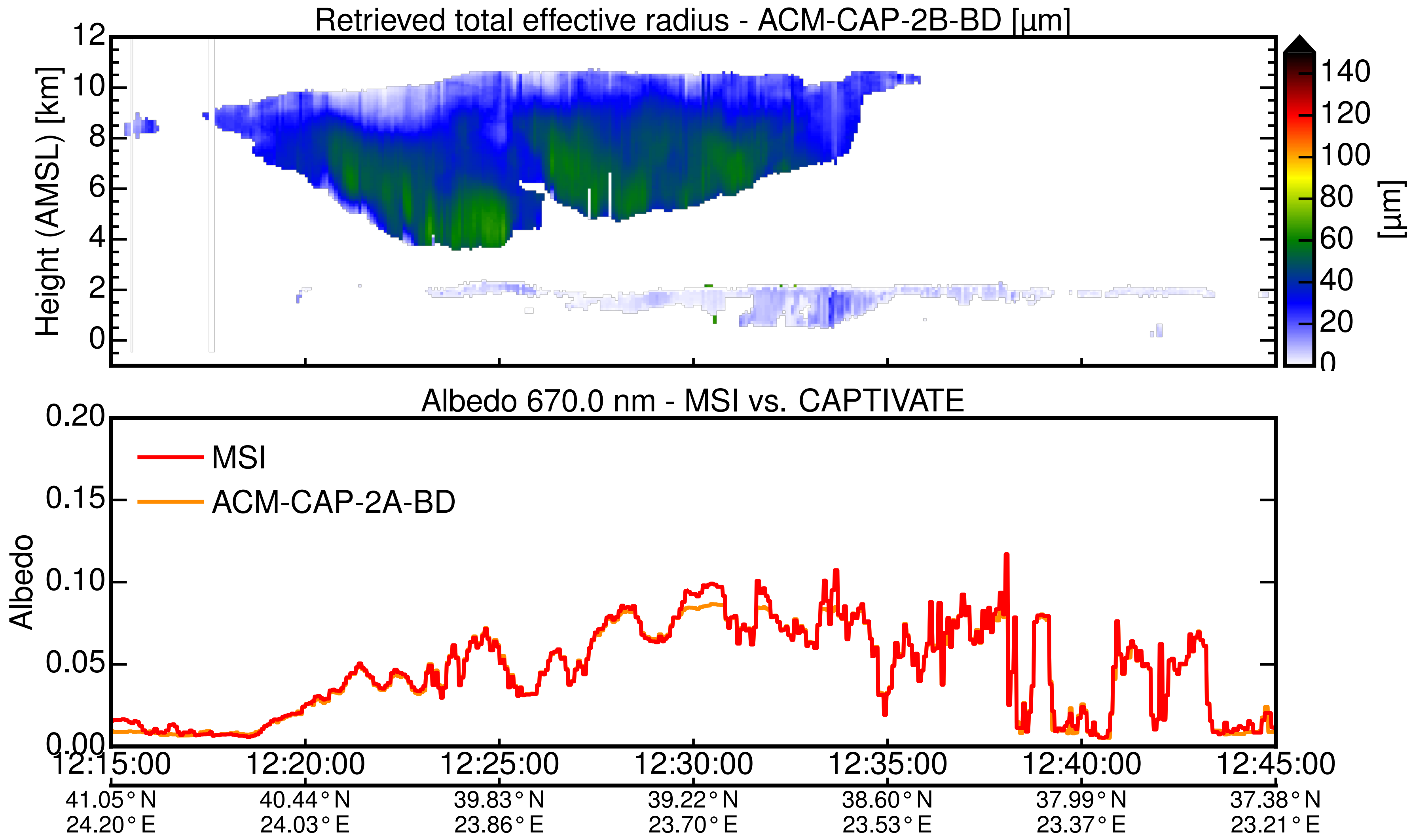
TWC
Total water content



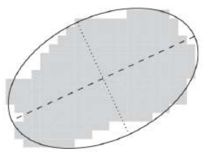
Albedo
670 nm

Solar radiative closure – ACM-CAP-2B-BD retrieval

Using ice model from Shannon et al (2023), Brown and Francis m(D)



TWC
Total water content

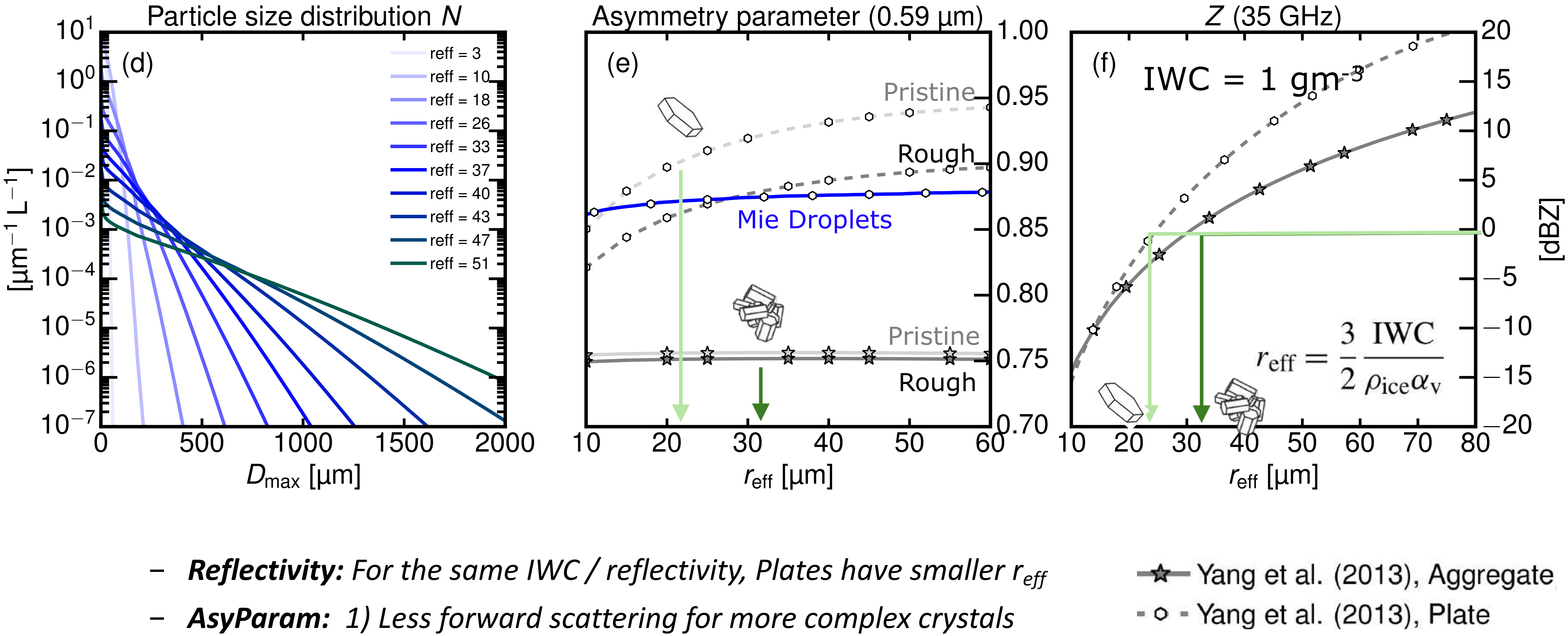


Albedo
670 nm

Discussion – Different bulk optical properties

Impact of crystal habit on asymmetry parameter and radar reflectivity

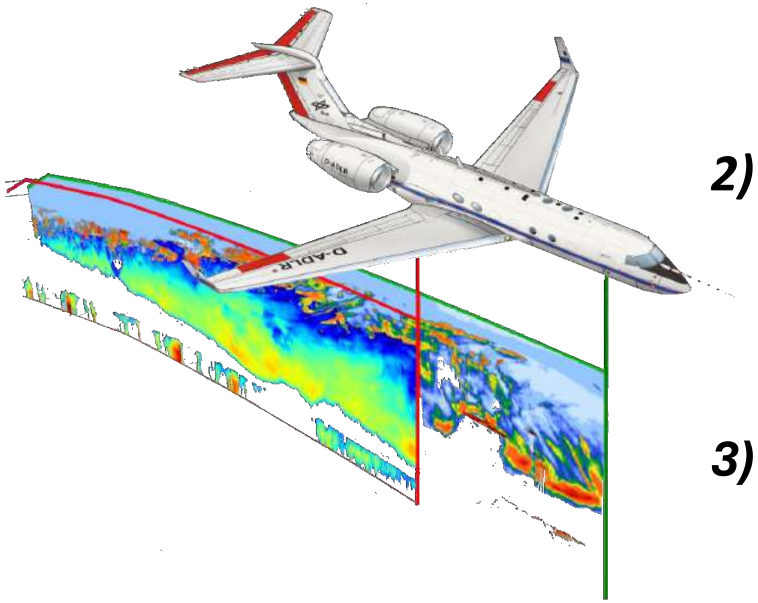
following Ewald et. al. (2021), AMT.



- ***Reflectivity:*** *For the same IWC / reflectivity, Plates have smaller r_{eff}*
- ***AsyParam:*** *1) Less forward scattering for more complex crystals*
  2) No strong connection with r_{eff} for more complex crystals

Summary – Overall findings during our retrieval comparison

… what we found so far and where to continue



1) **_ACM-CAP-2A-BD ice properties very similar to Varcloud (DARDAR-V3.10)_**

   → *“Used m(D) relationships are still very similar, larger differences when observed when explicit ice crystal shapes were used”*

2) **_Surface roughness partly more important than m(D) for radiative closure_**

   → *“Large influence of asymmetry parameter on radiation, so are we still underdetermined at cloud top when radar is missing?”*

3) **_Long term goal: Ice retrieval with variable but explicit ice particle shapes with consistent m(D), A(D) and scattering properties_**

   → *“Can lidar depolarization or BBR multi-angle measurements help to constrain the ice particle shape?”*