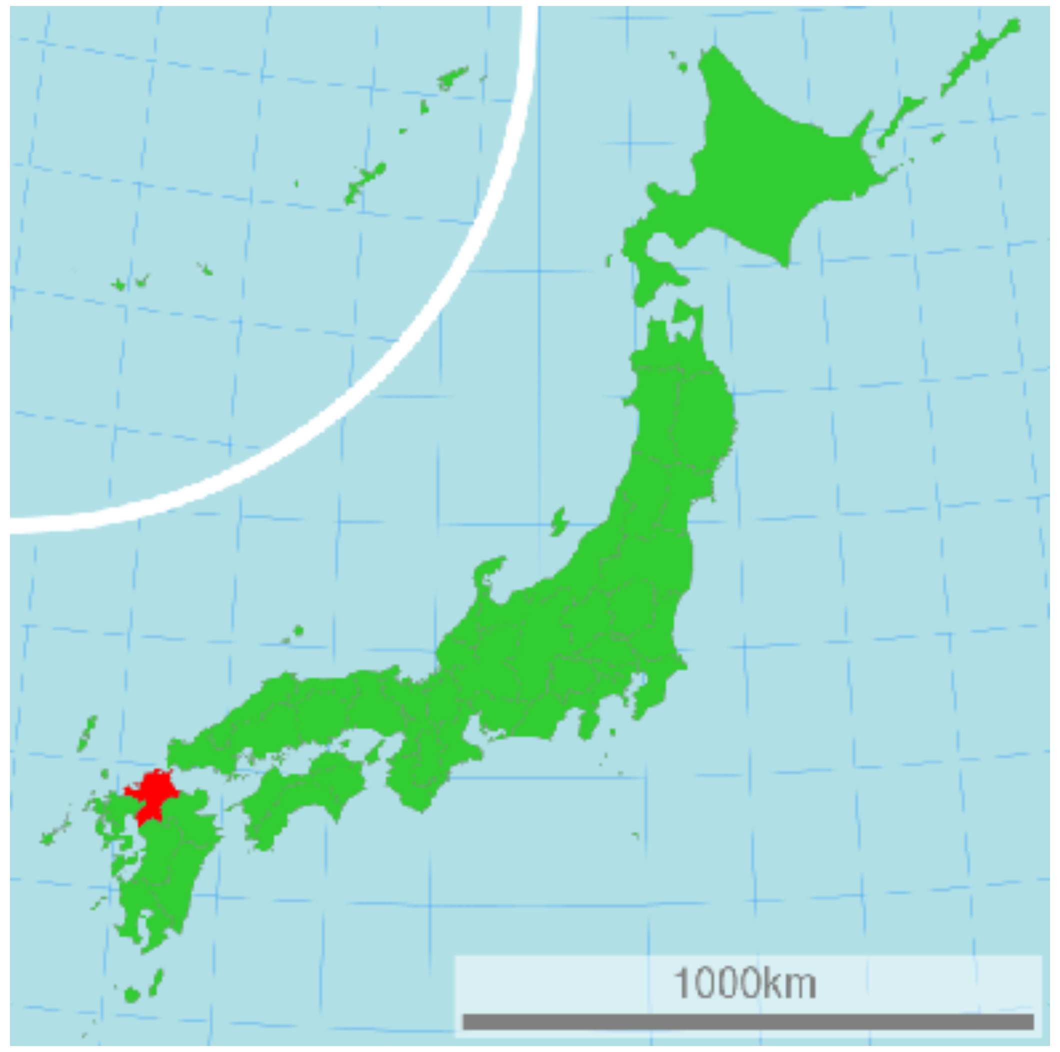
Development of algorithms for EarthCARE mission for improving the representation of clouds in the models

Hajime Okamoto
(Research Institute for Applied Mechanics, Kyushu University)



EarthCARE (Earth Clouds Aerosol Radiation Explorer): Advantage of CPR and ATLID

JAXA-ESA joint mission
launch date : 2023 FY
altitude : 400km

(Illingworth et al., 2015 BAMS)

1. **94GHz Doppler cloud radar (CPR); Ze, Vd (vertical)**

2. **355nm high spectral resolution lidar (ATLID); β, σ_{ext}, δ**

   Lidar ratio $S(355)=\sigma_{ext}(355)/\beta(355)$

3. **Multi-spectral imager (MSI) 7channels (0.69, 0.865, 1.65, 2.21,8.8, 10.8, 12.0µm)**

4. **Broad band radiometer (BBR) 3 views**

Co-chair: A. Illingworth/H. Okamoto

CPR : radar reflectivity factor Ze and Doppler velocity Vd

Higher sensitivity :-35dBZ; 7dB higher senstivity compared to CloudSat (-28dBZ)

Low and upper cloud detection will be improved.

Doppler velocity information: ~1m/s
Theoretical errors ~0.2 m/s for 16km mode with PRF of 7300Hz and ~0.5m/s for 20km mode (Hagihara et al., 2021 IEEE) with PRF~6200Hz
Phase discrimination for precipitation, i.e., snow or rain. Vertical motion, terminal velocity of particles

ATLID High spectral resolution lidar

HSRL will provide direct extinction information without assumption of lidar ratio and ice particle types will be inferred to reduce uncertainties in the retrieval of microphysics.
UV wavelength and HSRL will provide better estimate of aerosol microphysics.

CPR and synergetic algorithms (1): overview

CloudSat and CALIPSO algorithms

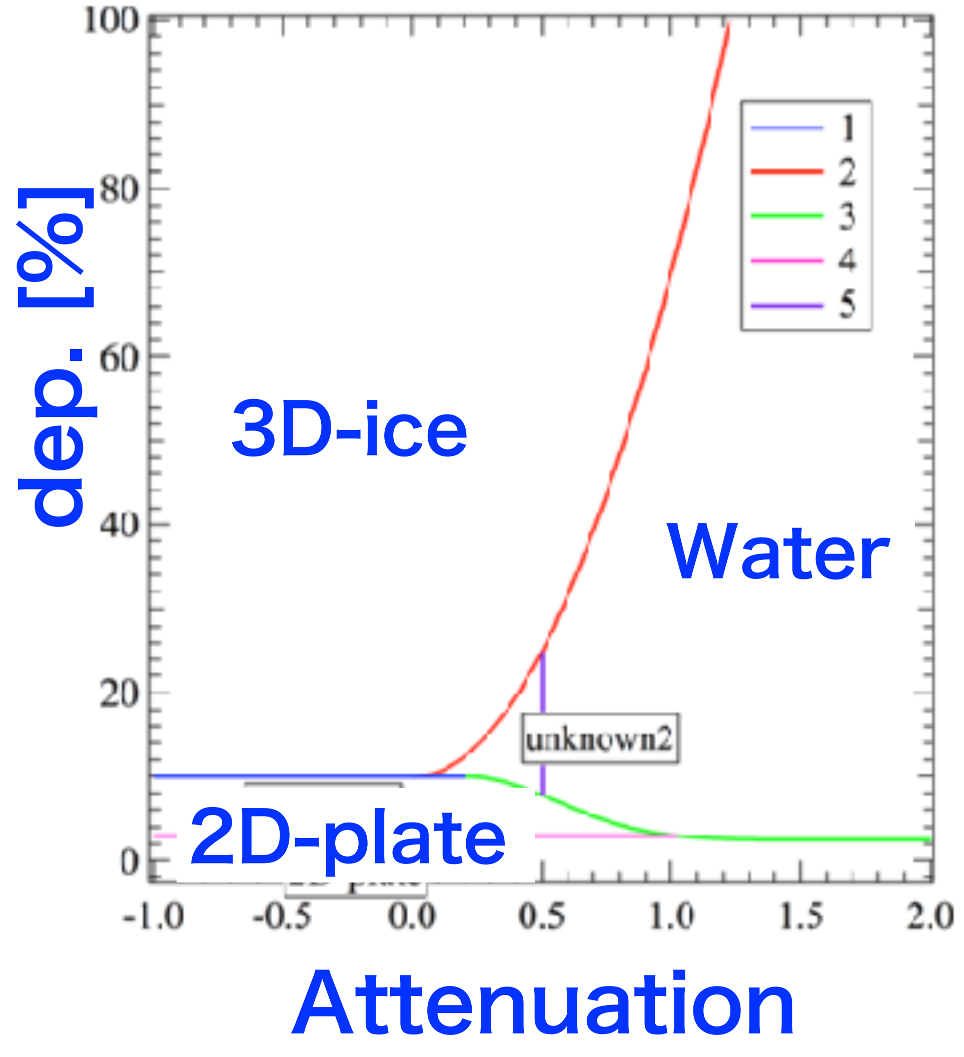
Cloud mask schemes : KU-mask
(Hagihara et al. 2010 JGR, 2014 JGR)
-based on ground-&ship-based conventional lidar algorithm
(Okamoto et al. 2007JGR, 2008 JGR)
C1: radar-only detected cloud
C2: lidar-only detected cloud
C3: radar-lidar overlapping cloud
C4: radar or lidar detected cloud

Cloud particle type: KU-type
Lidar-type (Yoshida et al. 2010 JGR)
- based on empirical/Monte Carlo simulations.

Cloud particle type-radar: C1
Cloud-particle type-synergy (Kikuchi et al., 2017 JGR)
Ice cloud type for CALIPSO (Okamoto et al., 2019 Opt. Express)
Ice particle type for ATLID and AOS lidar (Okamoto et al. 2020 Opt. Express)

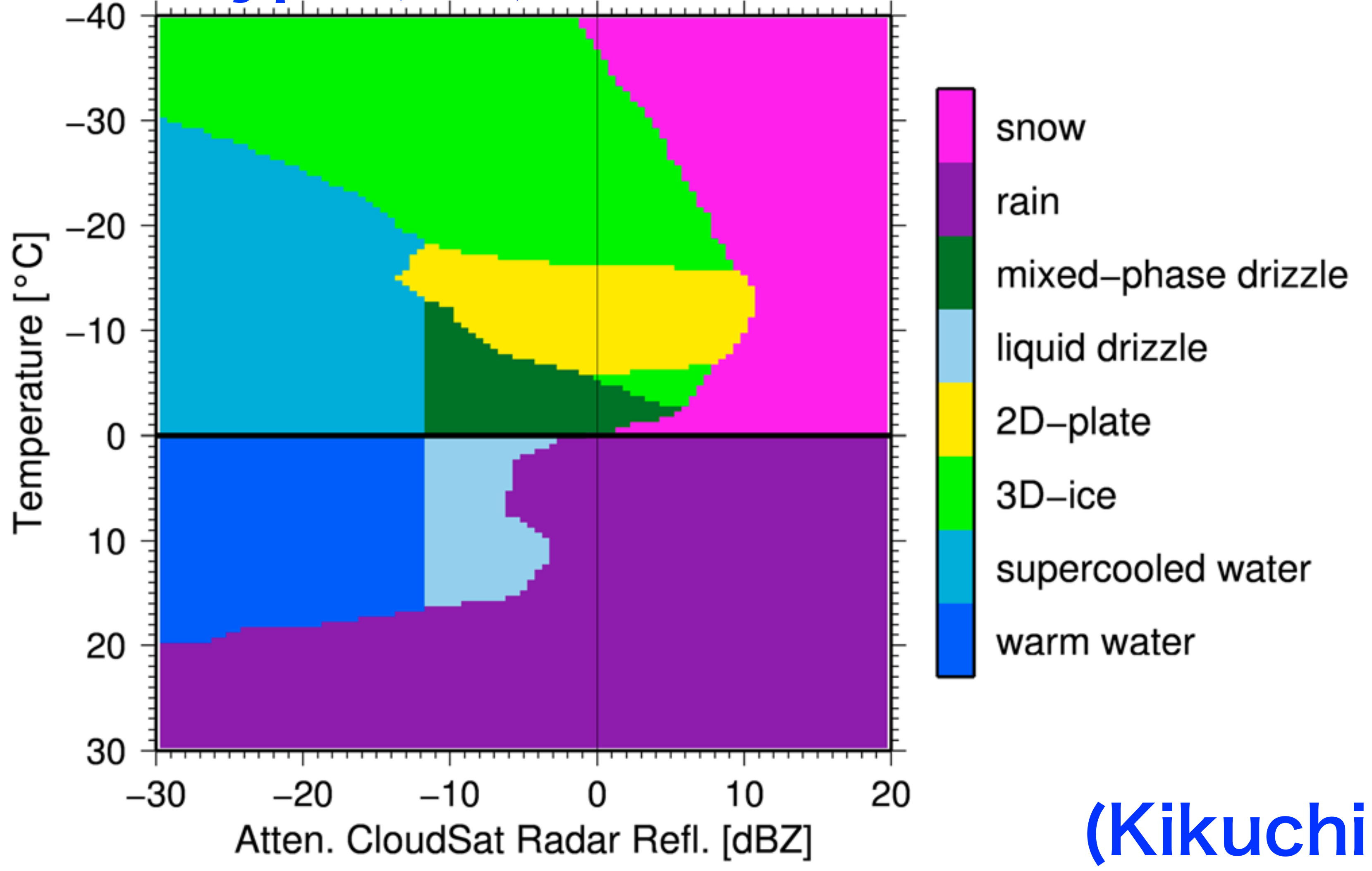
Cloud microphysics : KU-micro (for ice)
(Okamoto et al., 2010 JGR, Sato and Okamoto 2011JGR)
Vertical air-motion and terminal velocity of cloud particles
(Sato et al. 2009 JGR)

KU-type (C2) for CALIPSO



(Yoshida et al. 2010 JGR)

KU- type (C1) for CloudSat



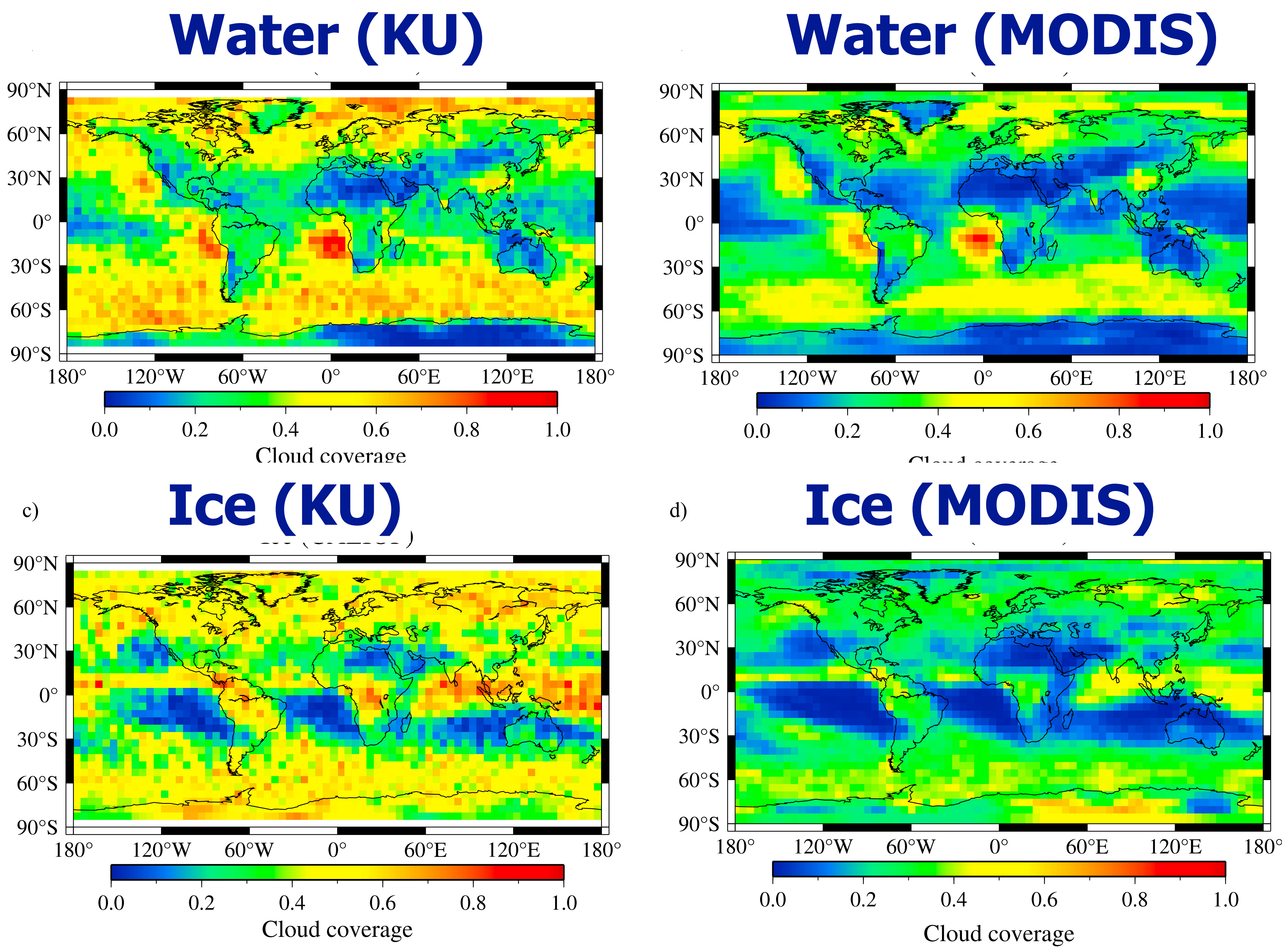
(Kikuchi et al. 2017 JGR)

There is a KU- type (C4) algorithm for CloudSat/CALIPSO

CPR and synergetic algorithms (2) mask and type for CALIPSO

Comparison of KU type and MODIS

Consistency in pattern with larger magnitude of ice and water fraction for KU compared with MODIS.



Water (KU)

Water (MODIS)

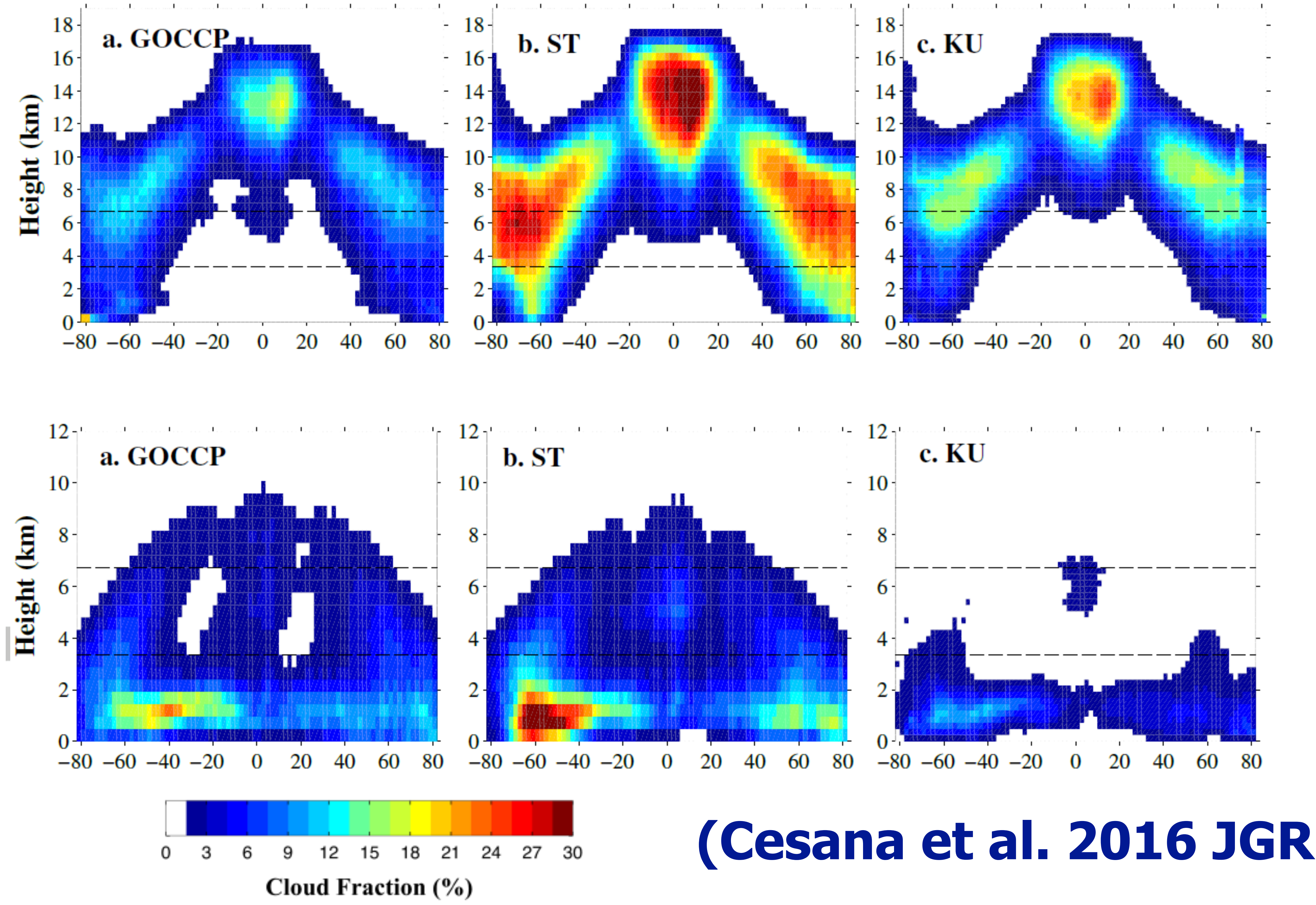
Ice (KU)

Ice (MODIS)

(Yoshida et al. 2010 JGR)

Comparison of CALIPSO-phase global products

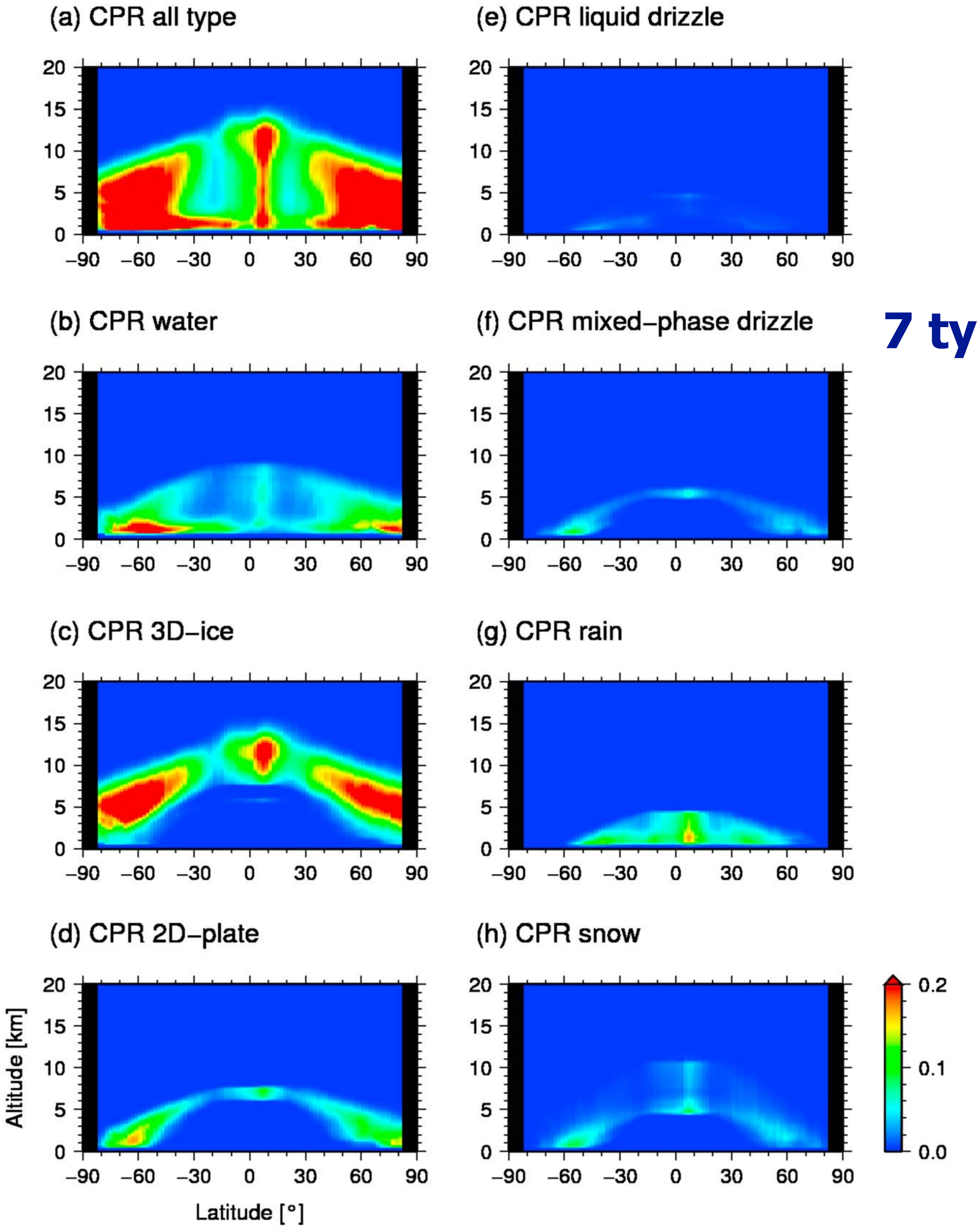
Large differences are identified among three products.
ST (NASA) >KU>GOCCP for ice
ST (NASA) >GOCCP> KU for water



(Cesana et al. 2016 JGR)

CPR and synergetic algorithms (3): Results from C1 type and C4 type

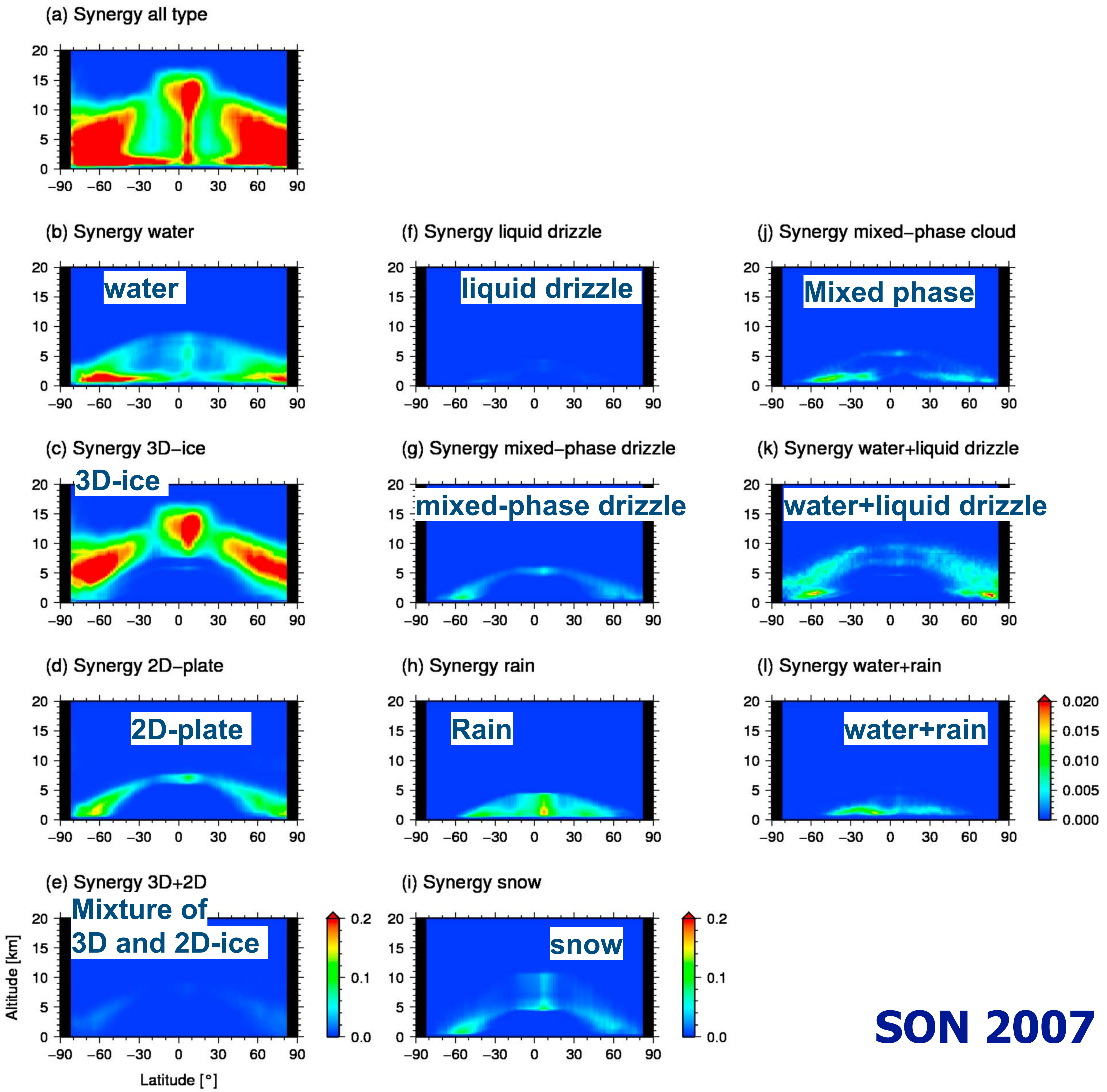
Cloud particle type for C1 clouds



7 types

SON 2007

Cloud particle type for C4 clouds by synergy-type algorithm



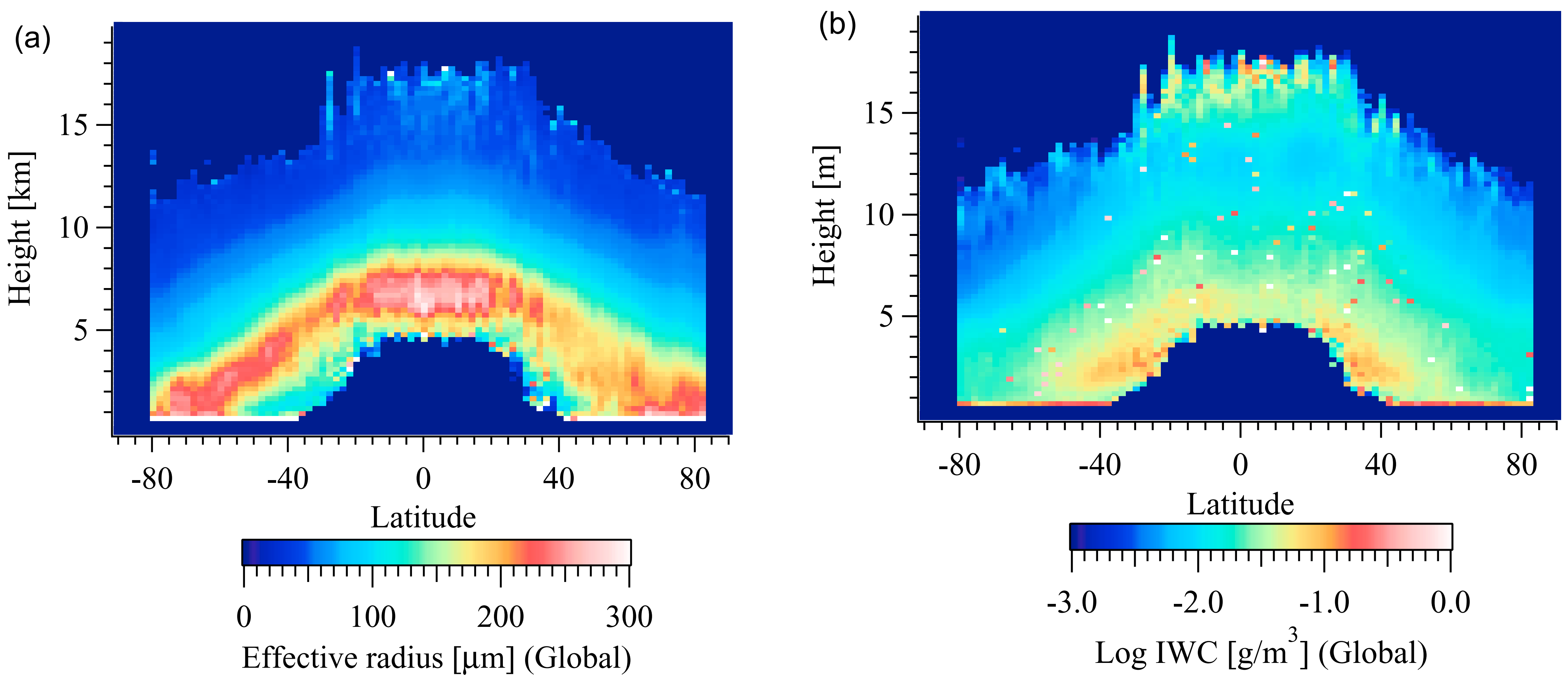
11 types

SON 2007

(Kikuchi et al. 2017 JGR)

CPR and synergetic algorithms (4): ice microphysics for C3 and C4

Ice cloud microphysics for C3 cloud from Synergetic algorithms

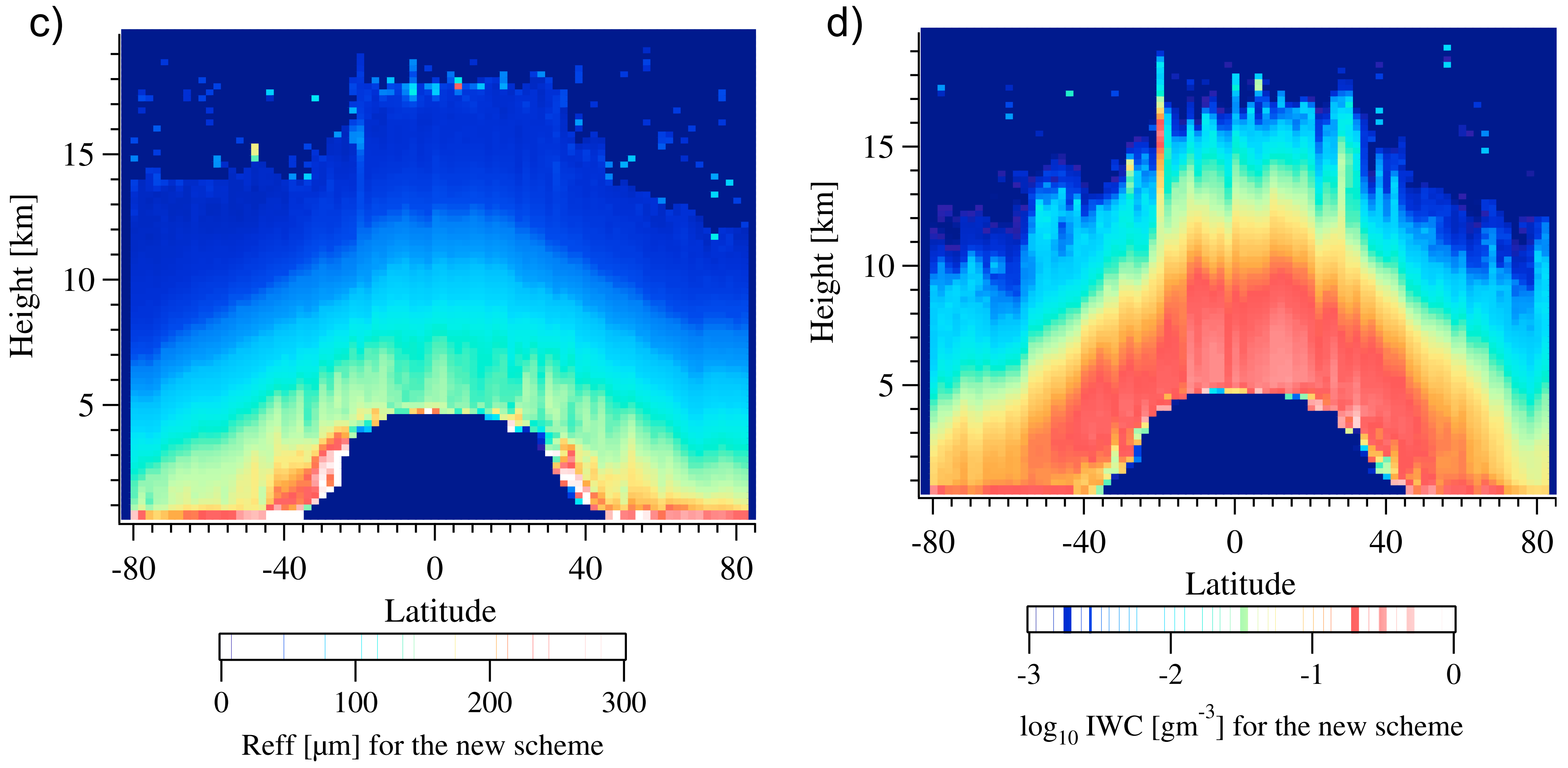


Reff for C3 cloud

IWC for C3 cloud

Okamoto et al. 2010 JGR

Ice cloud microphysics for C4 cloud from Synergetic algorithms



Reff for C4 cloud

IWC for C4 cloud

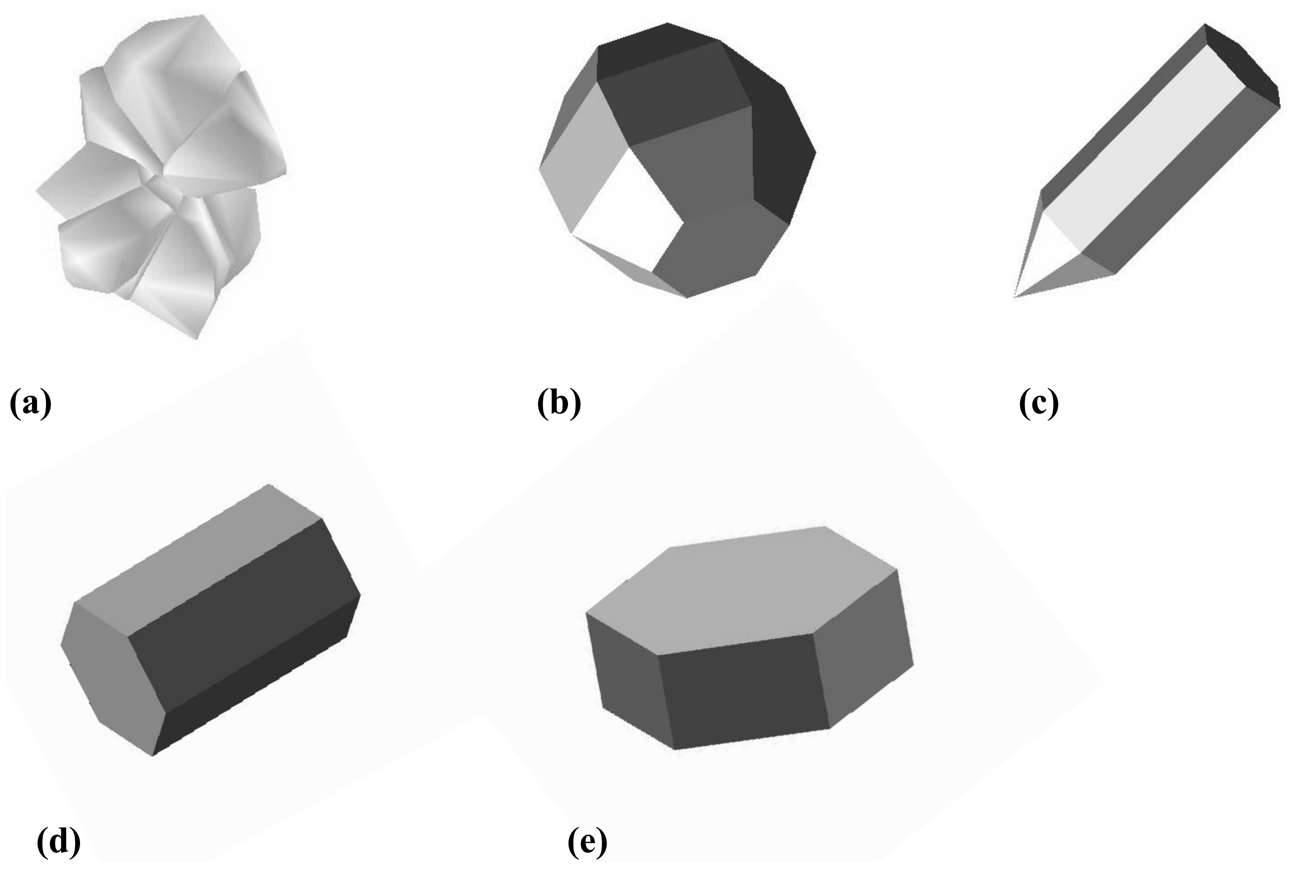
Sato and Okamoto 2011 JGR

Characteristics:
Ze, attenuated backscattering coefficient and depolarization ratio are used to retrieve effective radius and ice water content.
Mixture of 3D-ice and 2D-plates are taken into account where effects of specular reflection due to horizontally oriented ice plates are treated.

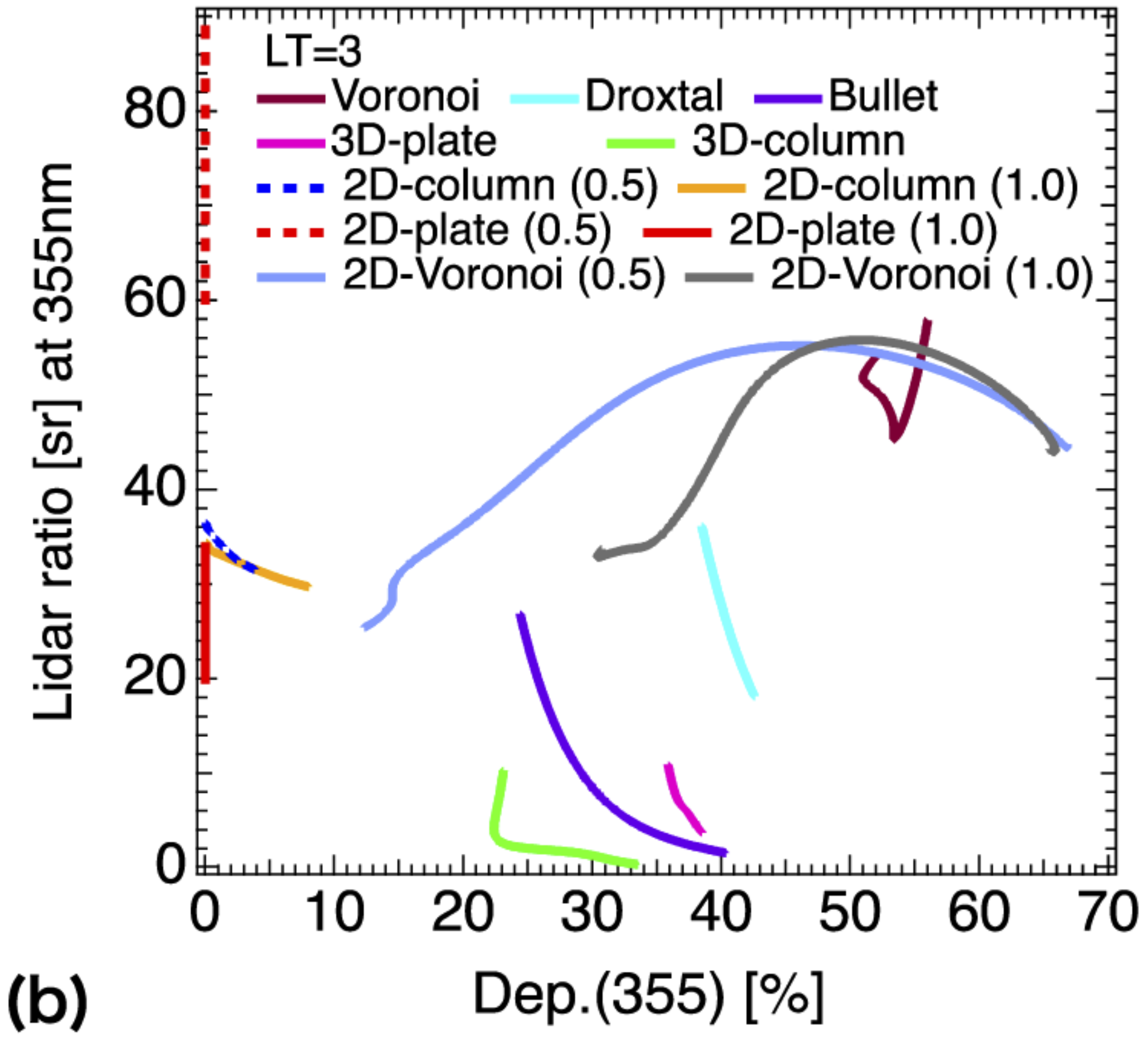
MSI products are also provided for wide swarth.
Algorithms for A-train are extended for EarthCARE CPR/ATLID/MSI.
Radiative flux for SW and LW as 4 sensor-products are also provided from the L2 outputs of retrieved microphysics.

Extension of algorithms (1) : ice particle type

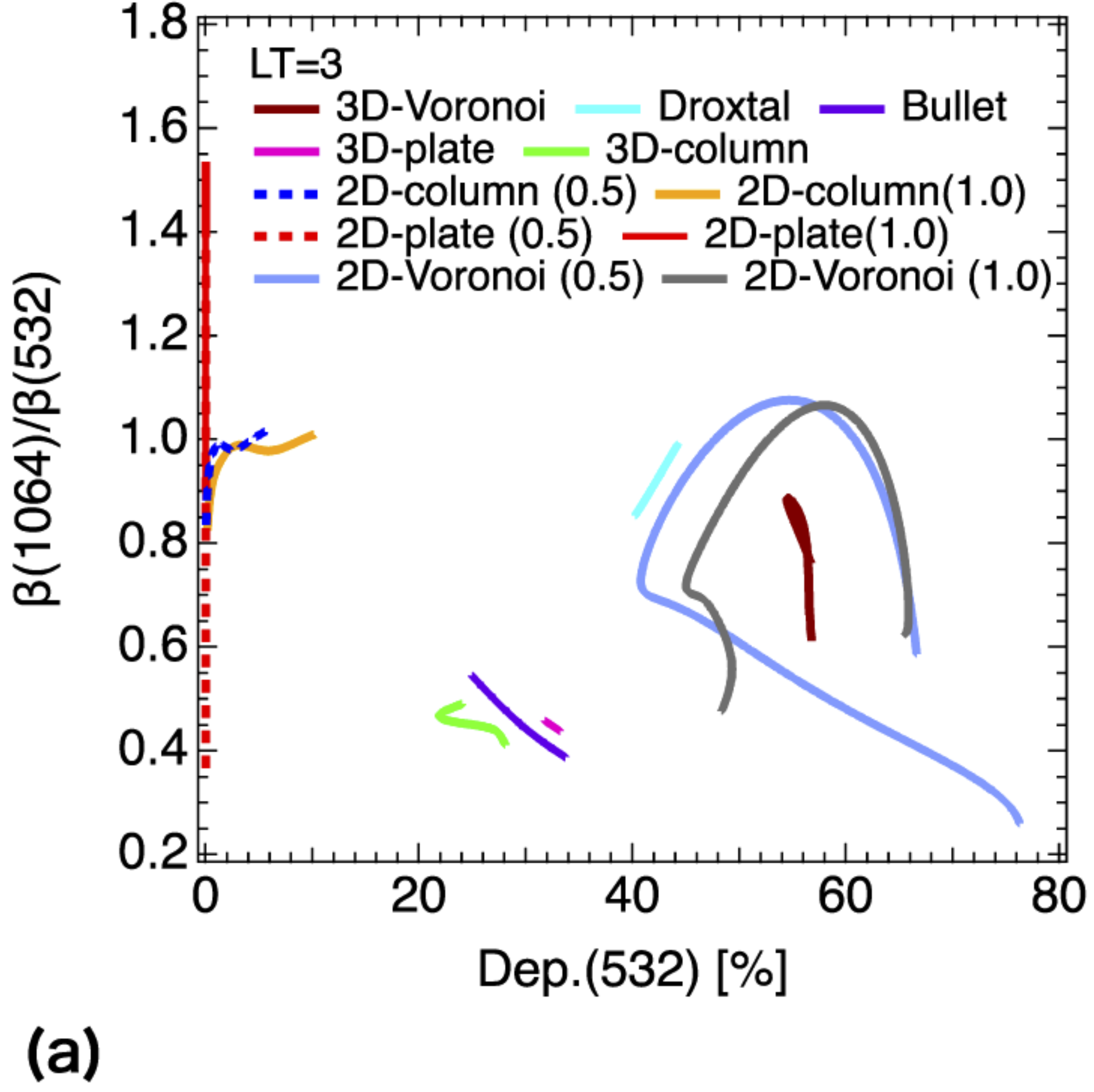
Backscattering properties depend on shapes, orientations, wavelength and laser tilt angle. Physical optics is developed and backscattering coefficient, extinction coefficient and depolarization ratio of ice particles have been computed.



Ice particle type for EarthCARE ATLID by using lidar ratio-depolarization diagram



Ice particle type for CALIPSO by using color ratio—depolarization diagram



Look up tables are prepared for 355nm, 532nm and 1064nm,
Laser tilt angles for 0.3 and 3 degrees off-nadir to cover ATLID and CALIPSO.
LUT is also made for 0 degree for ground-based lidars
LUTs for lidars are mostly compatible to those for CPR.

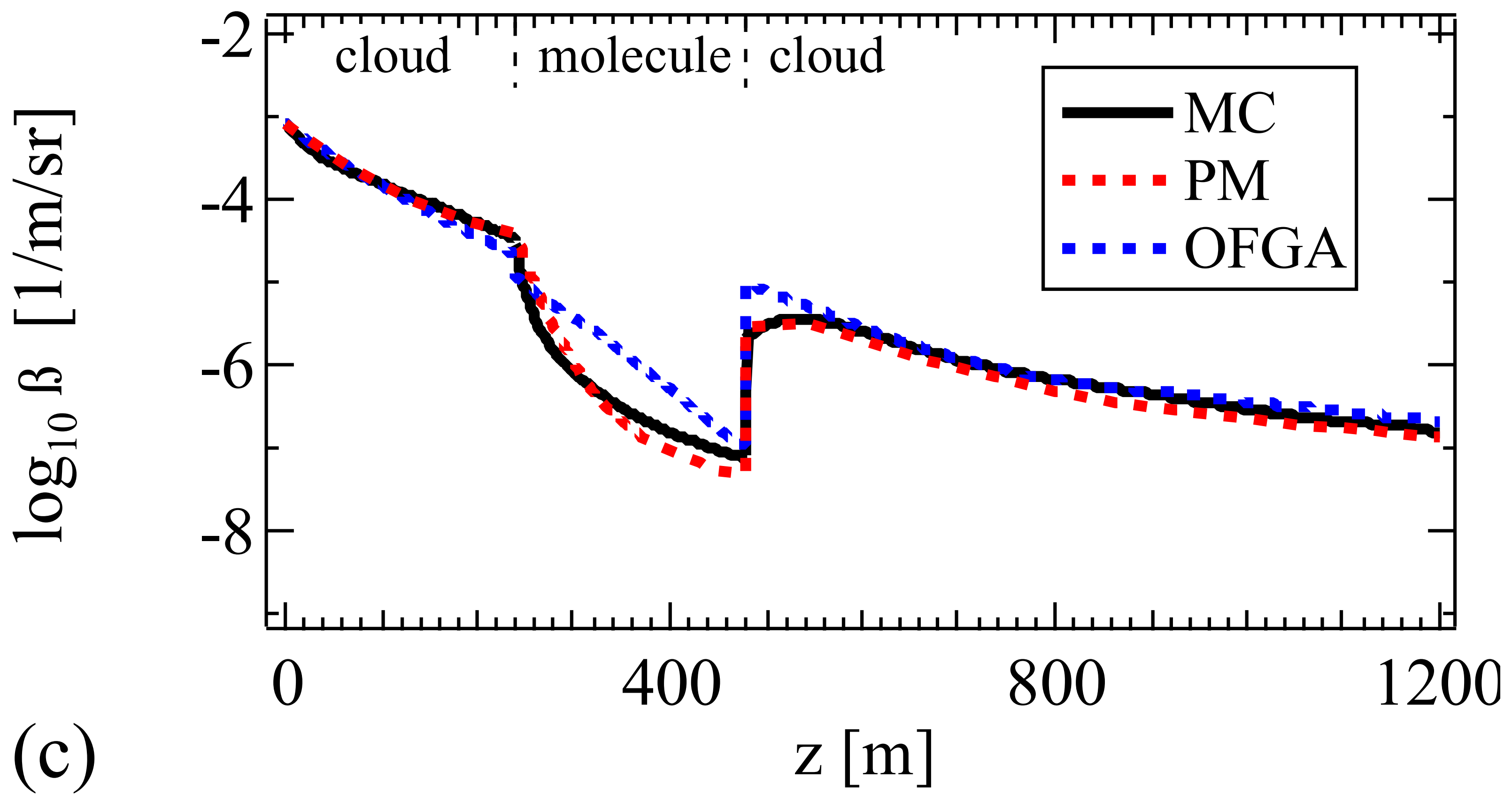
Okamoto et al. 2019 Opt. Express
Okamoto et al. 2020 Opt. Express

Extension of algorithms (2) : water clouds

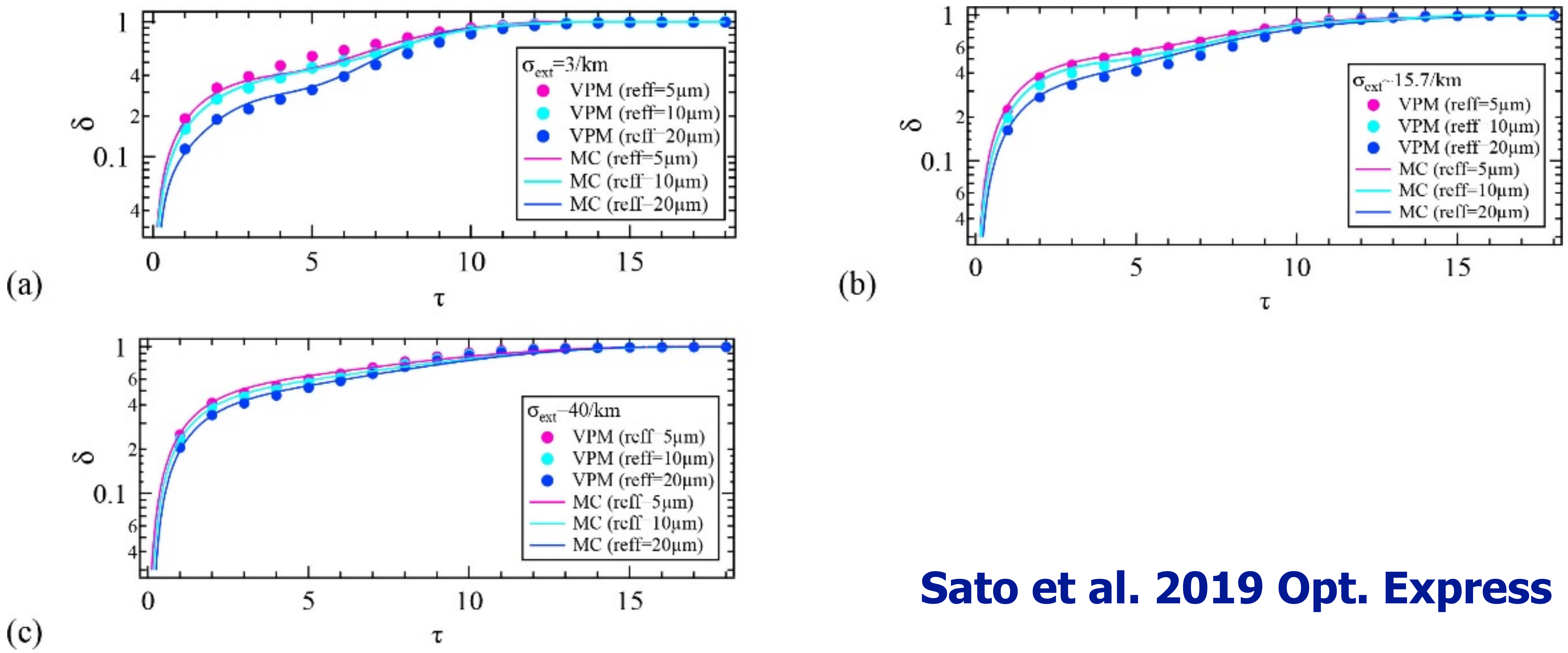
Fast multiple scattering computations in space-borne lidar signals are required to interpret optically thick clouds, e.g.,water cloud.

Physical Model (PM);
Analytical expression of N-th order phase function (Pn) is implemented instead of tracing each photon-paths.
Path integral formulation is also used to estimate effective extinction.

Vectorized Physical Model (VPM);
Analytical formula to estimate n-th order scattering matrix is implemented.
This is the first time to estimate depolarization due to multiple scattering with much less computing time compared with Monte Carlo method. PM/VPM show small errors. PM/VPM can be applied to space-borne polarization lidar application.



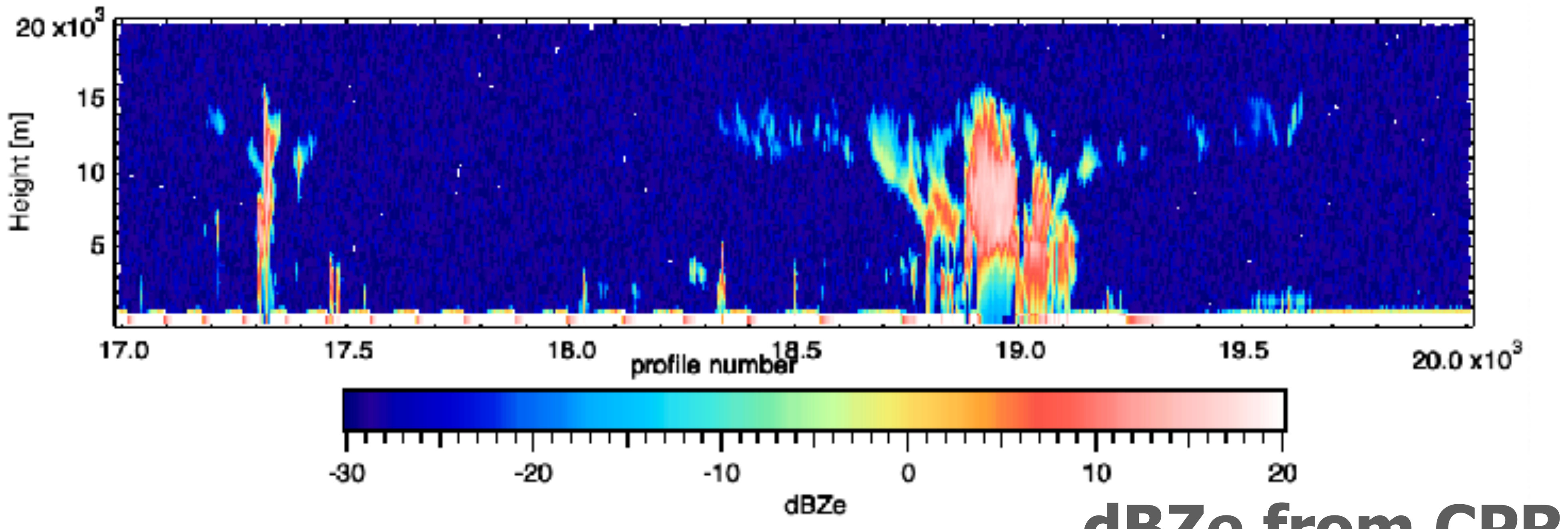
Sato et al. 2018 Opt. Express



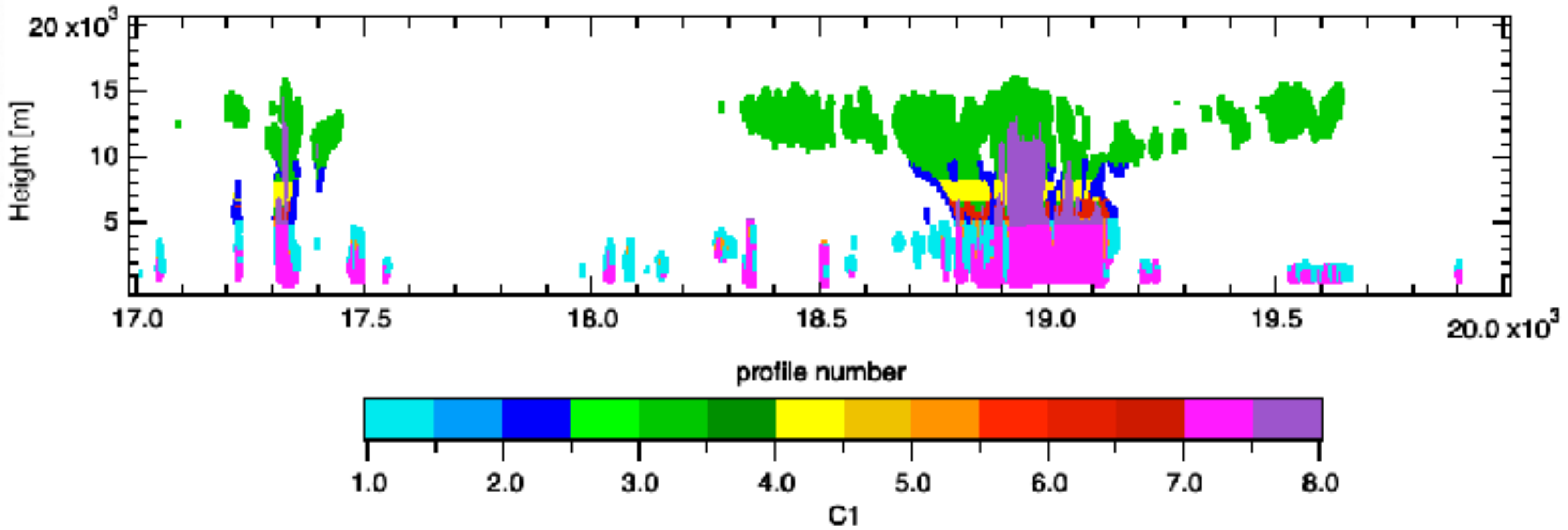
Sato et al. 2019 Opt. Express

Extension of algorithms (3) : quick look of retrieved particle types for A_train

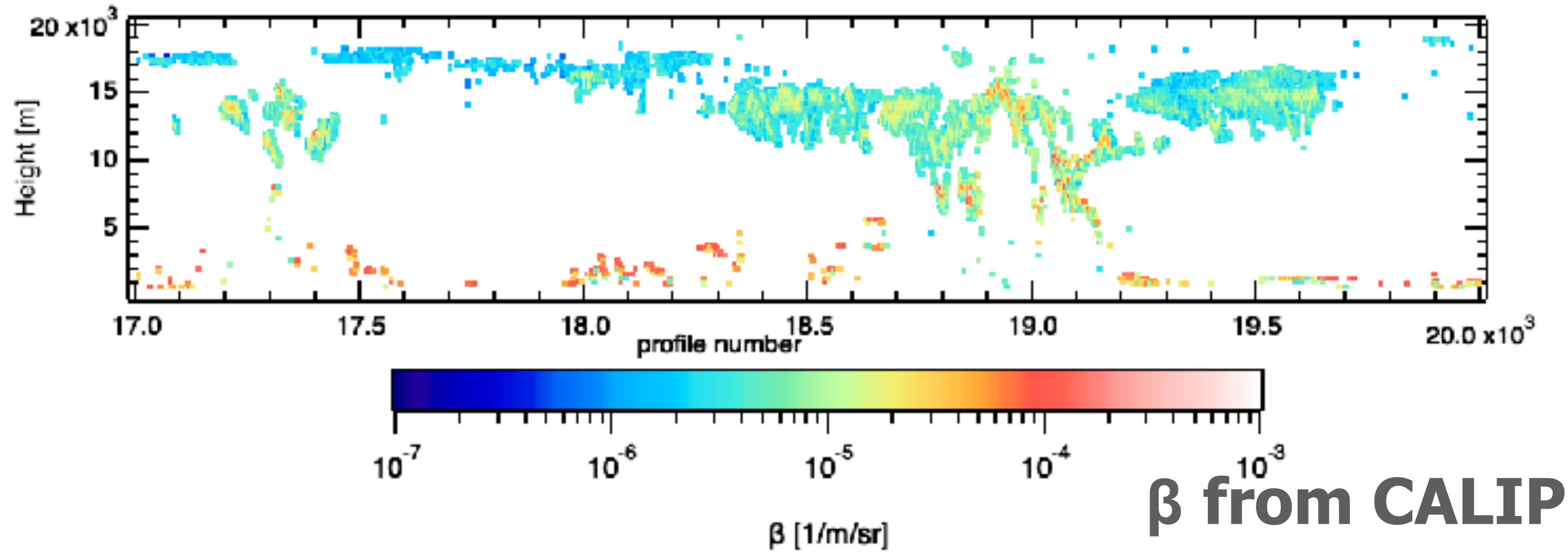
Algorithms for cloud particle types are extended.



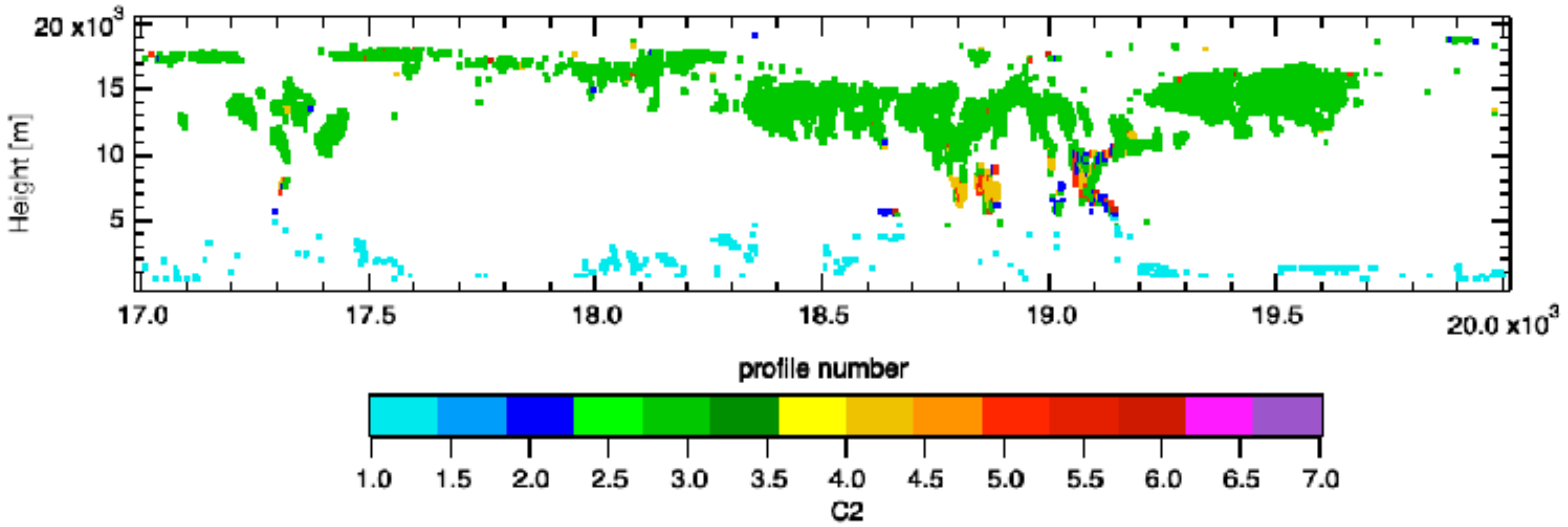
dBZe from CPR



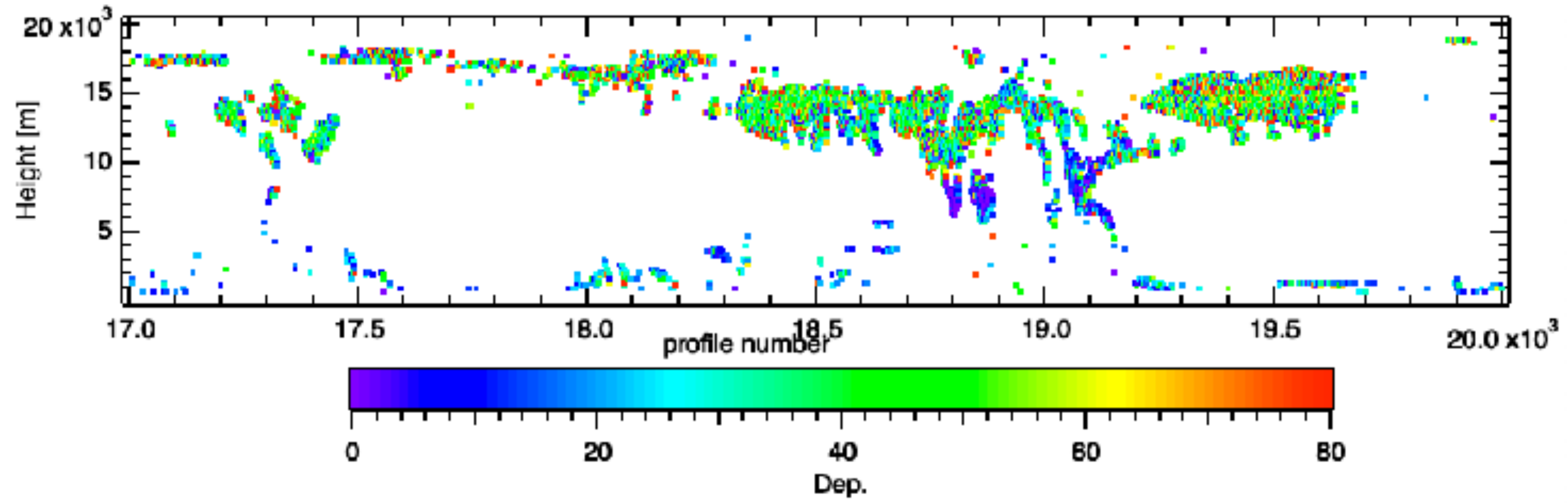
Cloud particle type for CPR



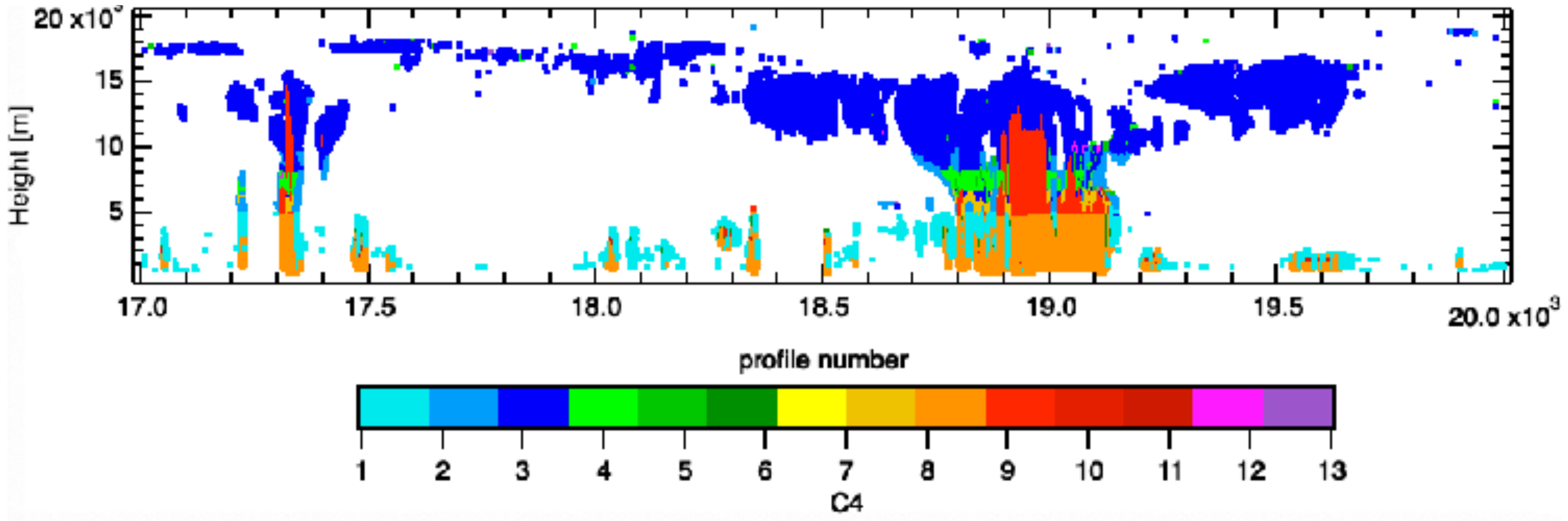
β from CALIPSO



Cloud particle type for Lidar



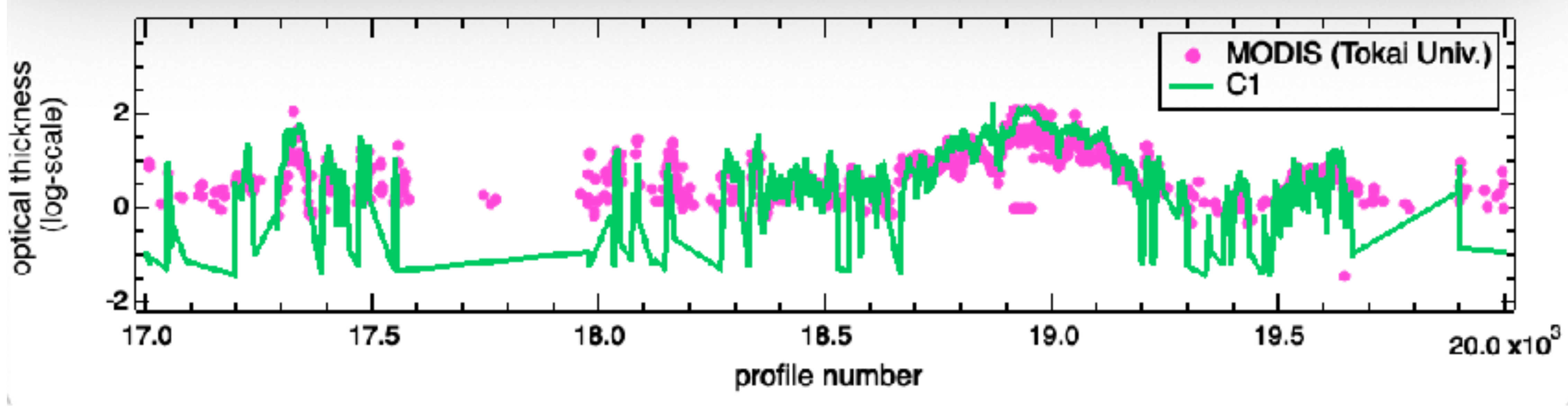
dep. from CALIPSO



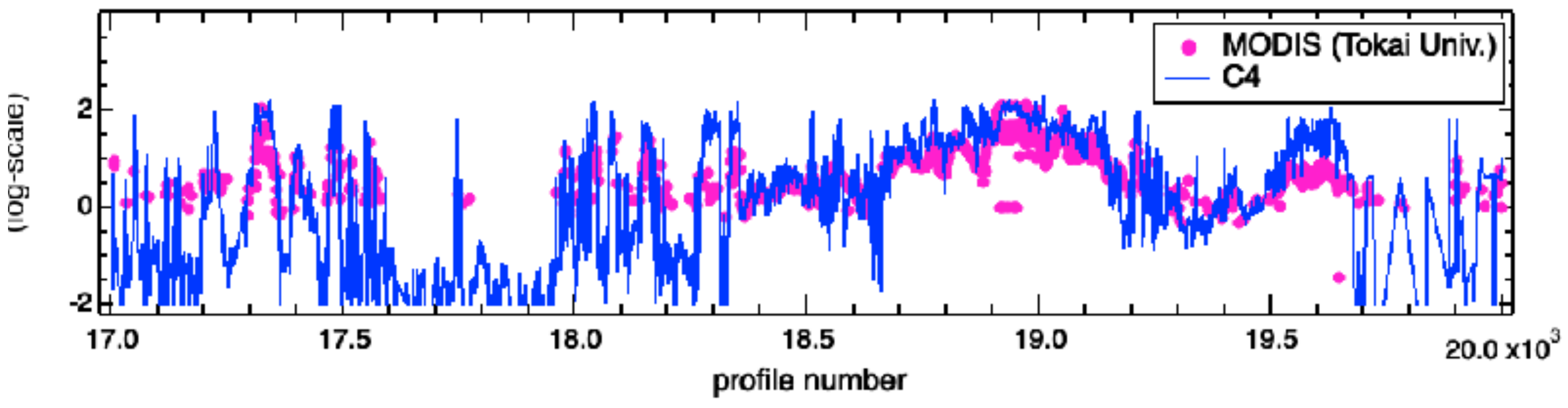
Cloud particle type for CPR-Lidar synergy

Extension of algorithms (4) : quick looks for retrieved cloud microphysics for A_train

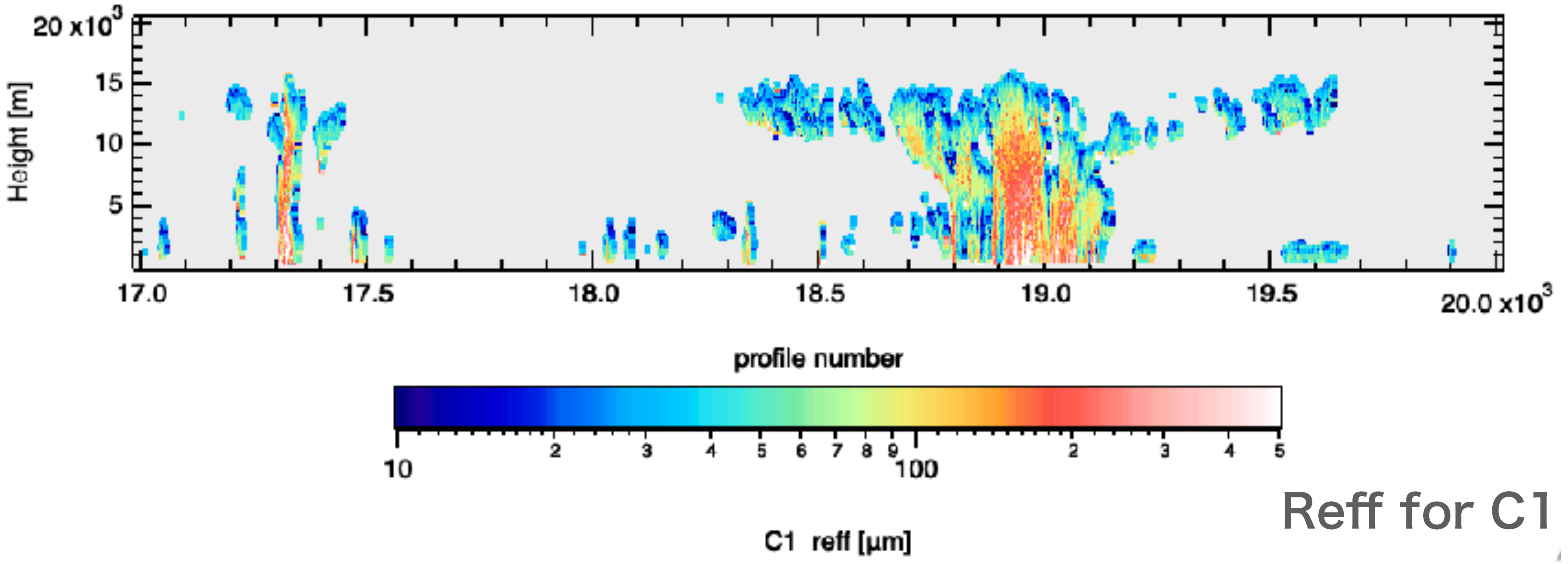
Retrieval algorithms are extended. Estimated optical thickness are compared with MODIS value from Tokai University. In general, agreement is found except for some two layers (ice and water). Extinction from ATLID can offer better characterization of ice particle type and Doppler information of CPR will provide more robust rain-snow classification.



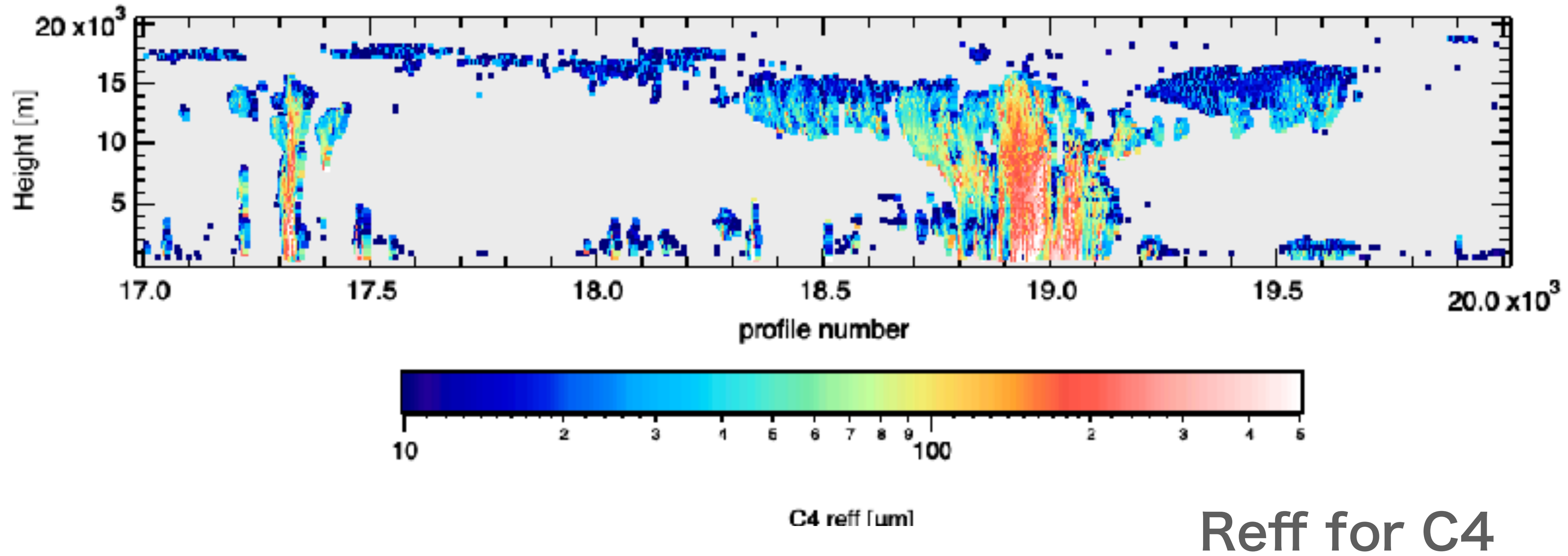
Tau for C1



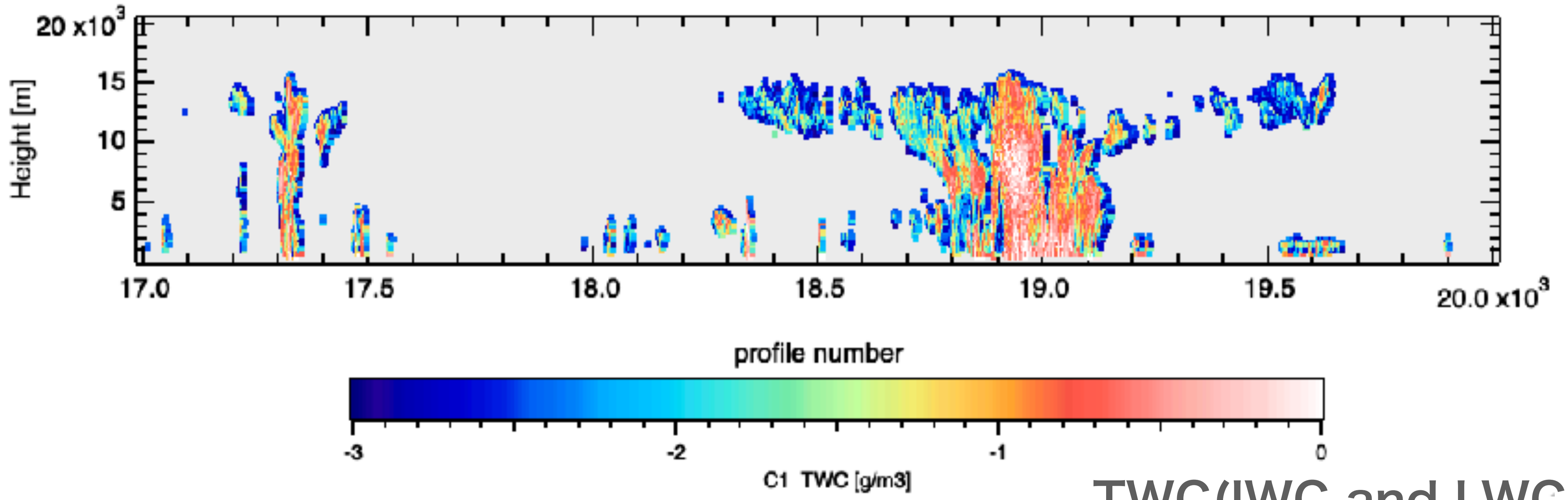
Tau for C4



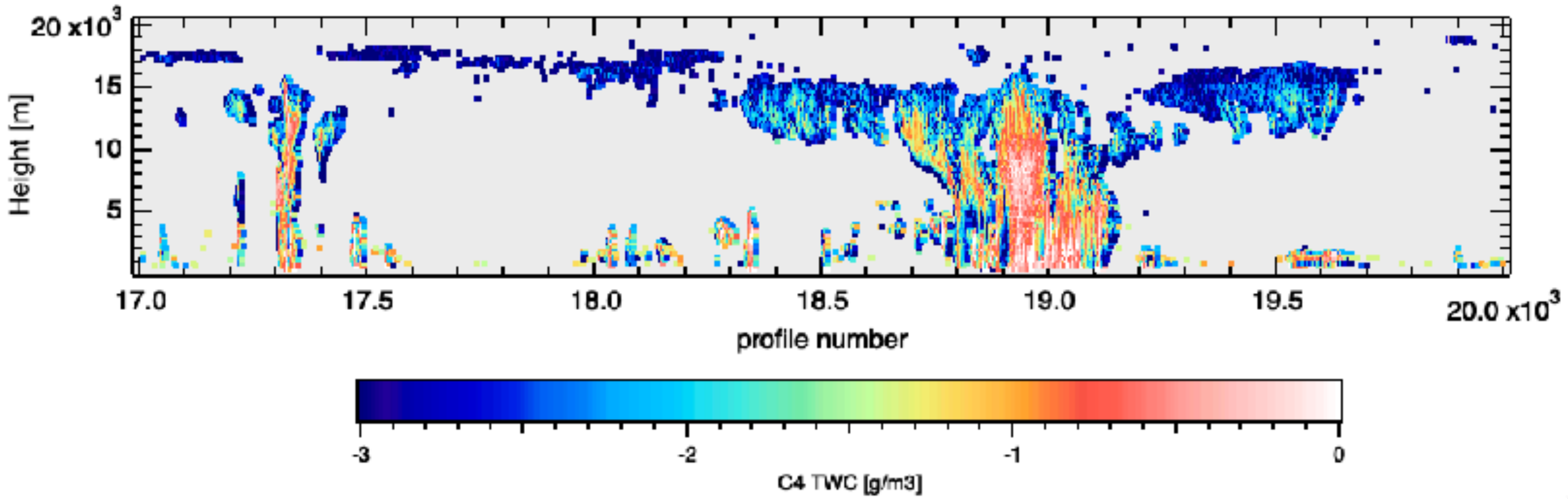
Reff for C1



Reff for C4



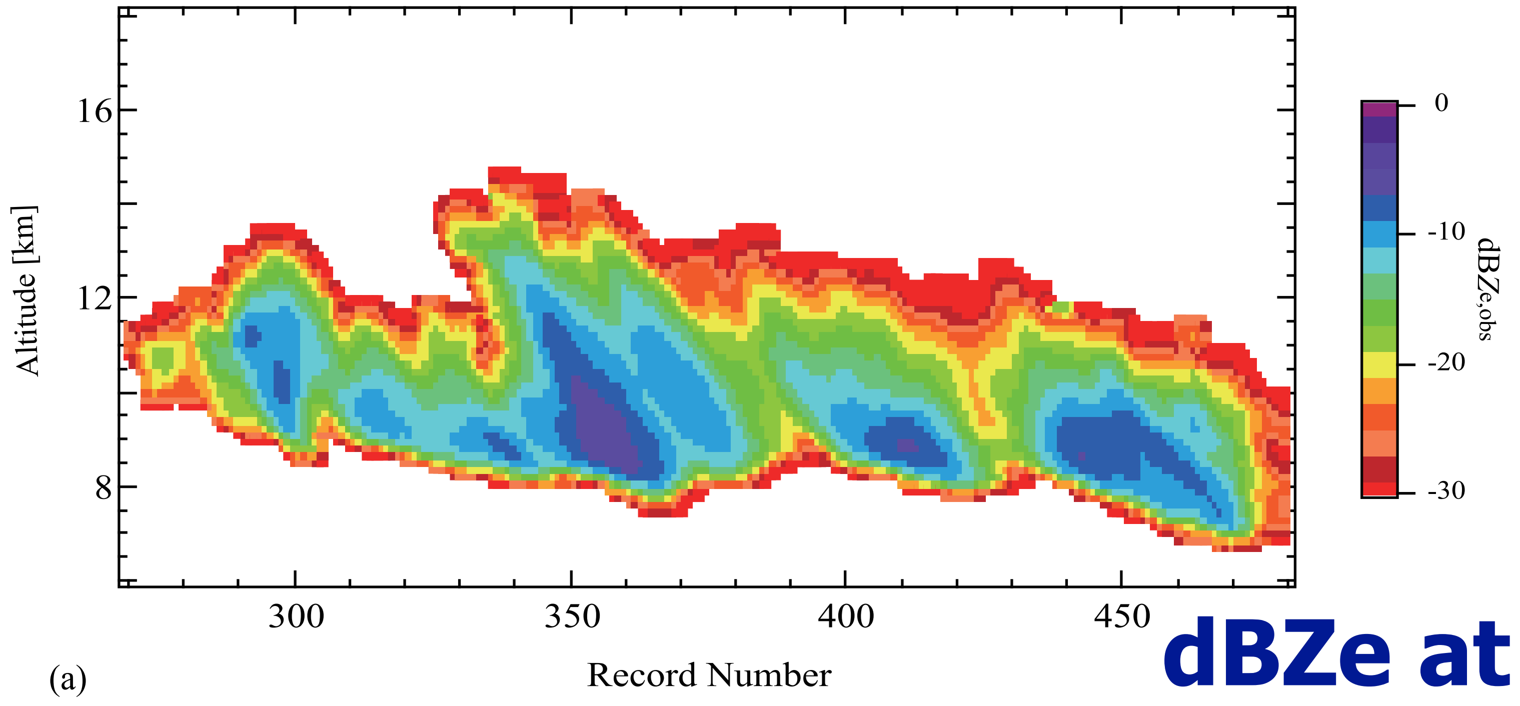
TWC(IWC and LWC) for C1



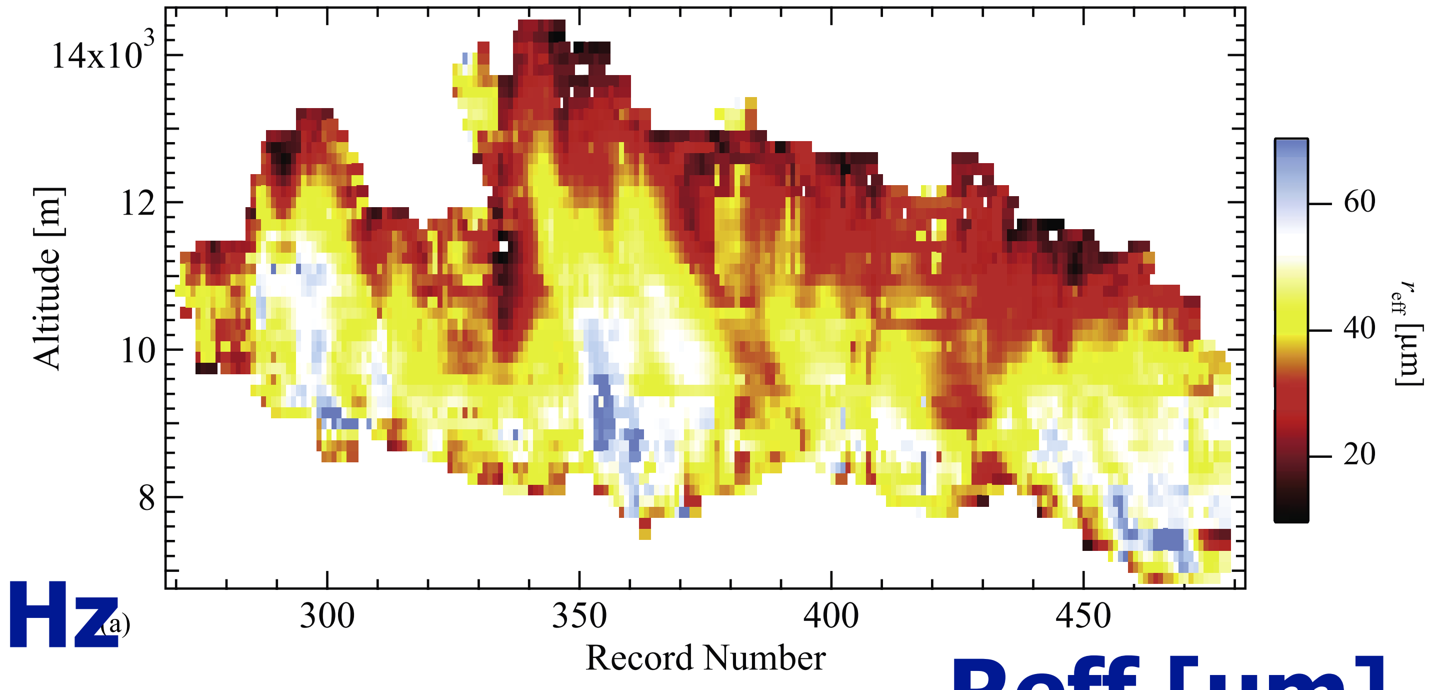
Total water content for C4

Extension of algorithms : using Doppler velocity

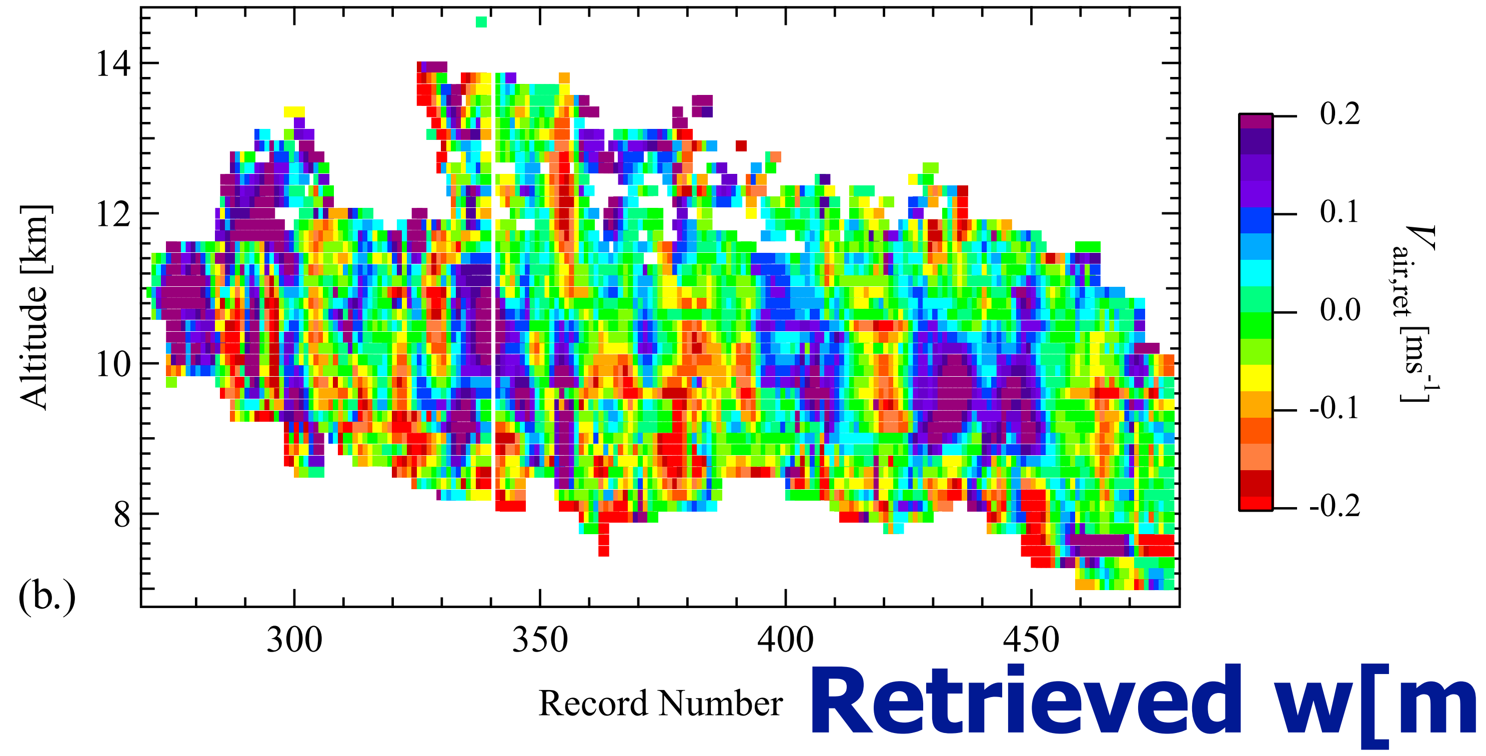
Doppler information is implemented into algorithms of CPR and lidar to retrieve microphysics, terminal velocity and air-motion. Retrieved air motion has been evaluated by EAR.



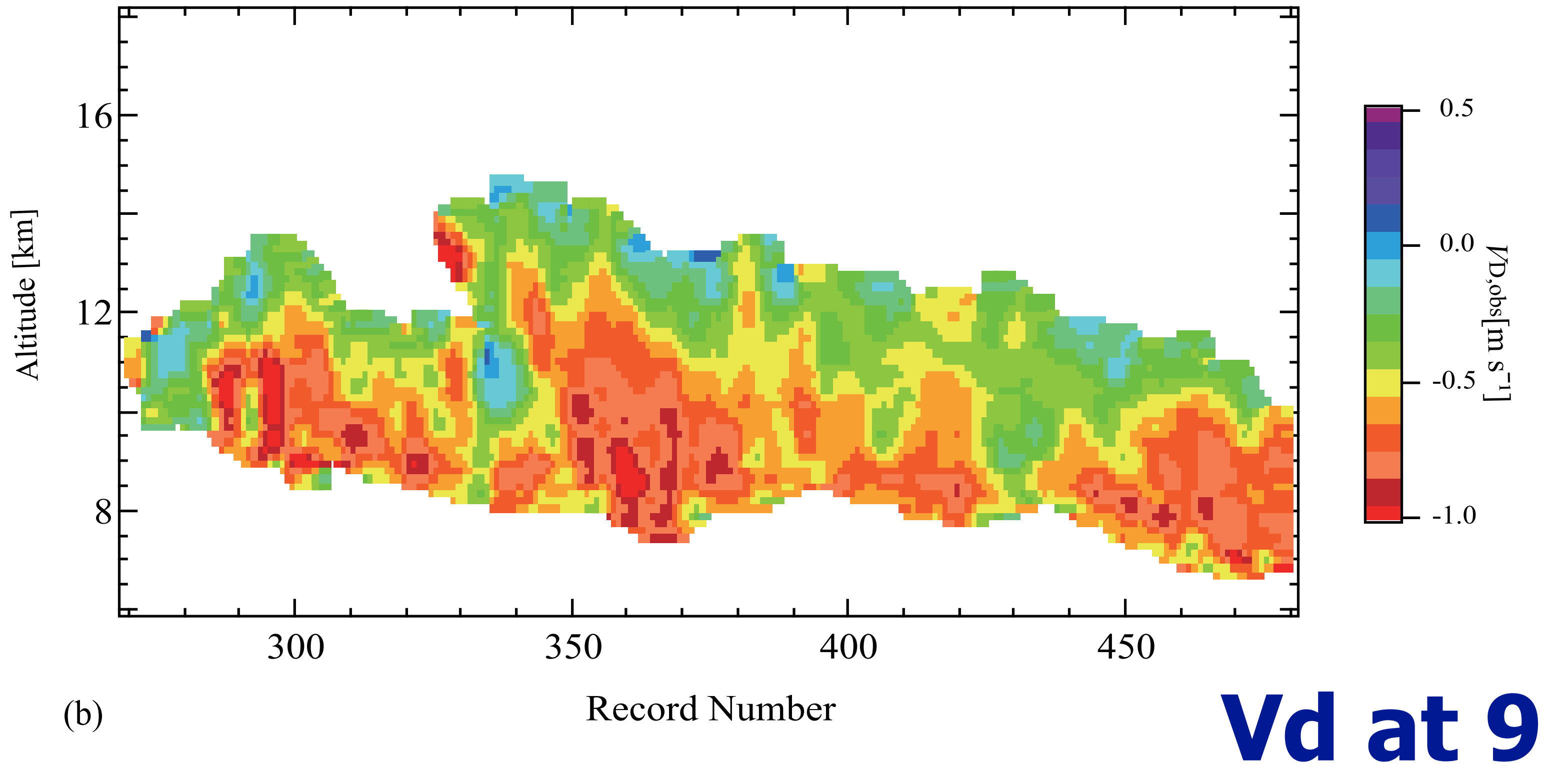
dBZe at 94GHz



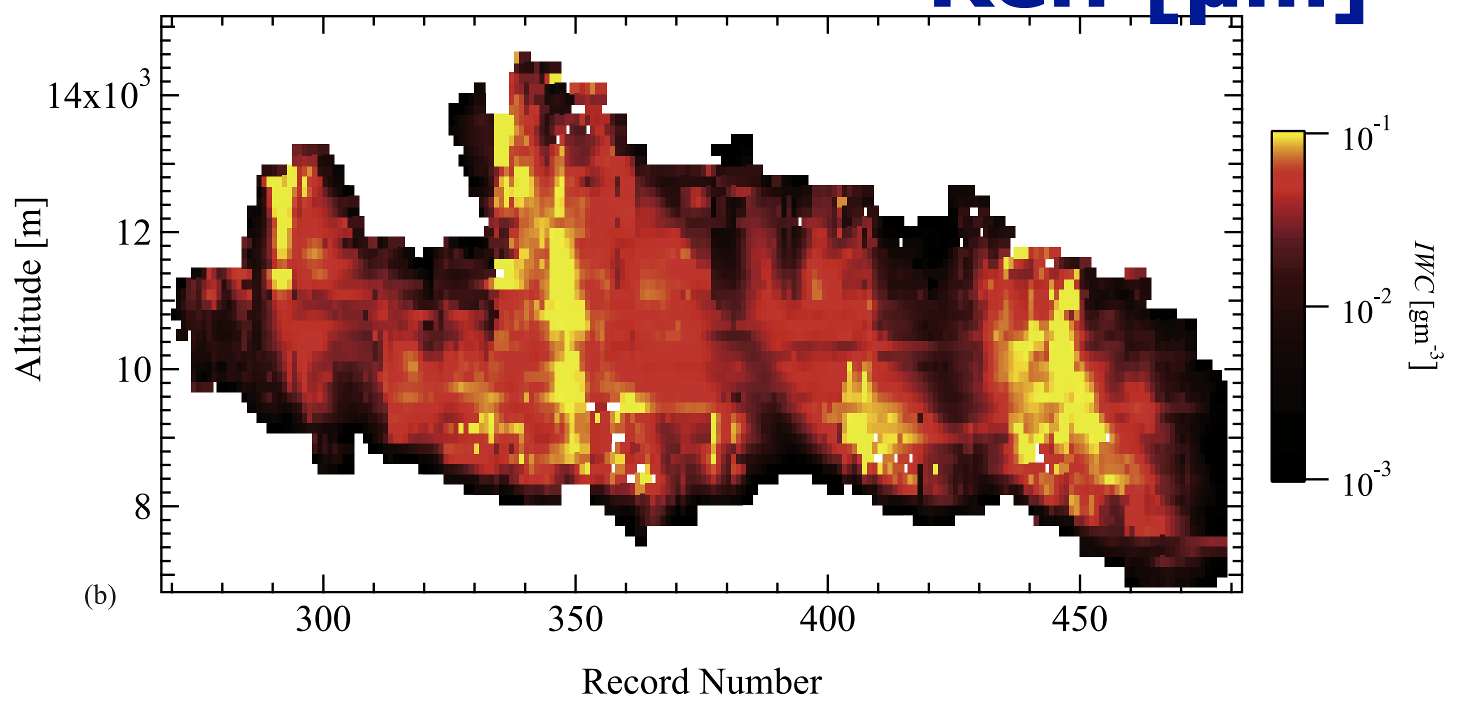
Reff [µm]



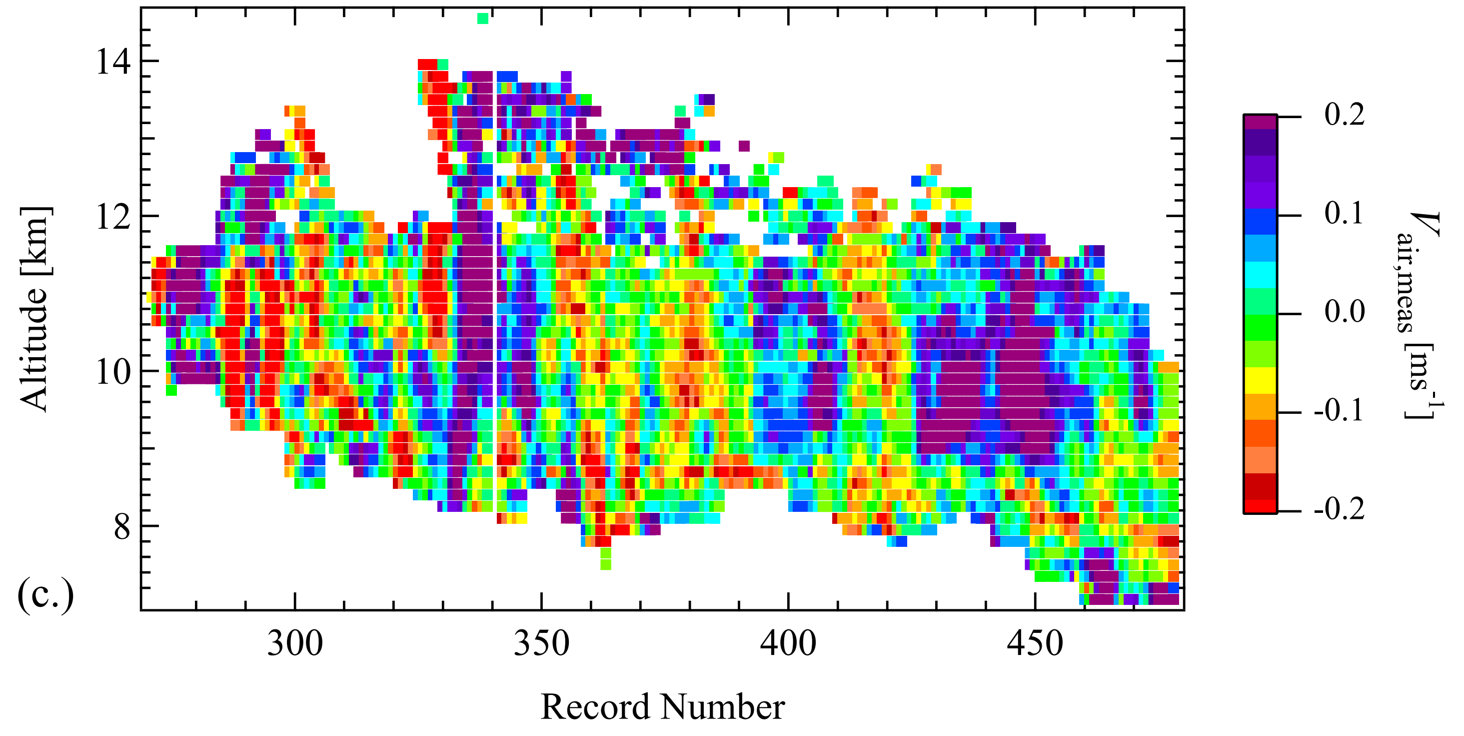
Retrieved w[m/s]



Vd at 94GHz

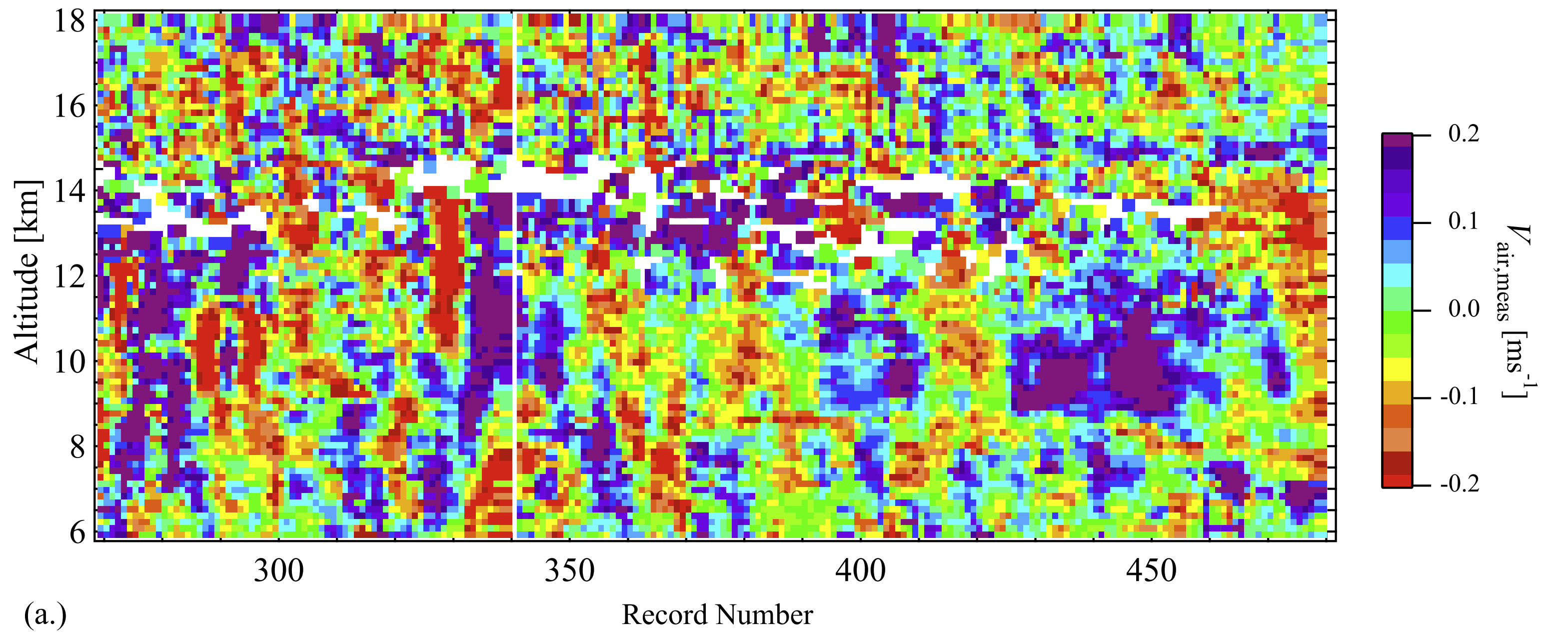


IWC [gm^{-3}]



Measured w[m/s]

Sato et al., 2009 JGR

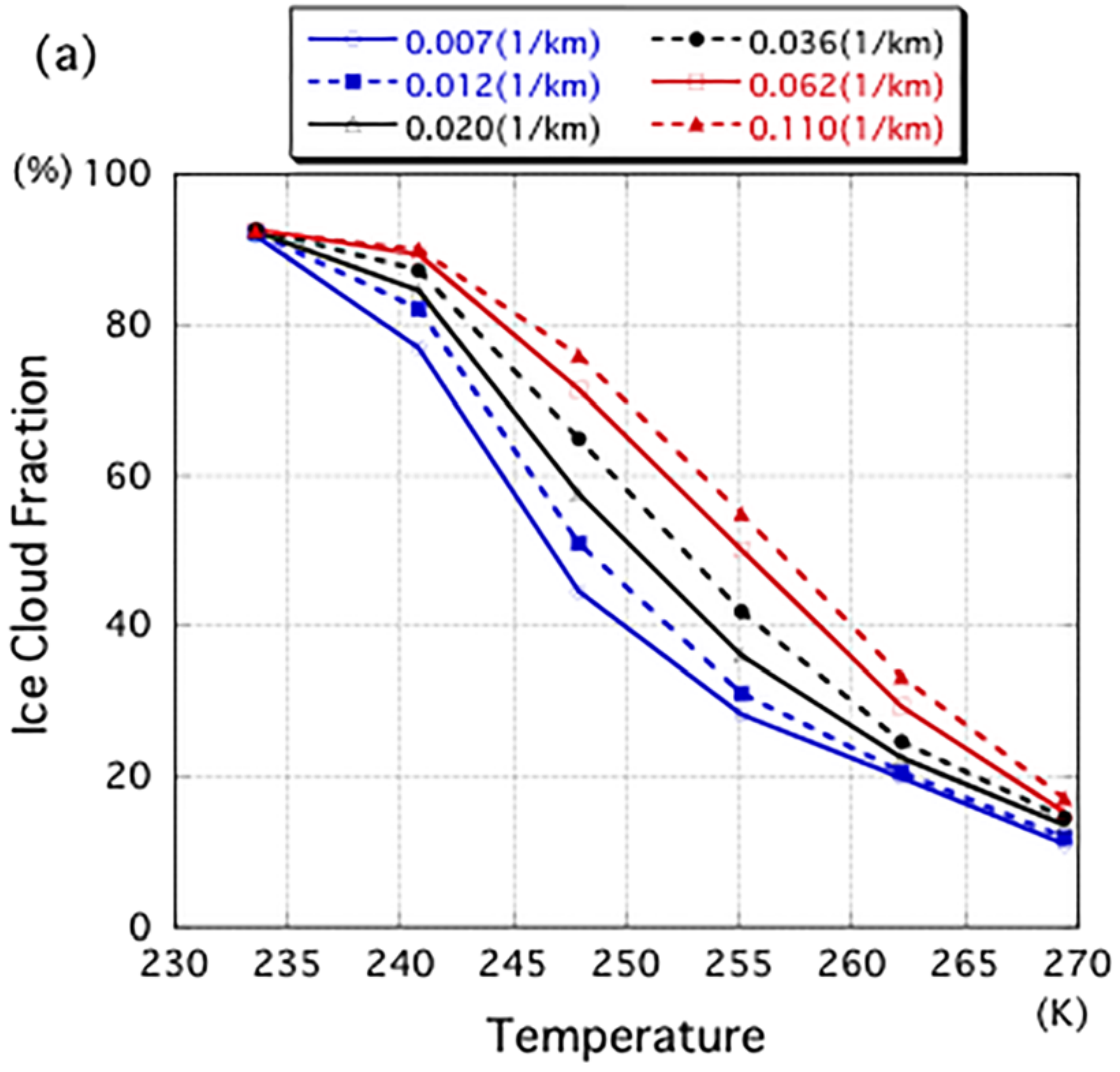


Clouds and air motion products are provided for 1km and 10km horizontal resolutions with 100m resolution in vertical.

Vertical air motion from VHF radar EAR(Equatorial Atmospheric Radar)

Lidar Ratio–Depolarization Ratio Relations of Atmospheric Dust Aerosols

Dust extinction affects temperature dependence of ice cloud fraction (Kawamoto et al., 2021 GRL) . Ice fraction increases as dust extinction increases. More sophisticated treatment of dust beyond simple spheroid approximation is needed for further analyses.



Kawamoto et al., 2021 GRL

Cloud particle phase from KU-type product.
Dust extinction is retrieved from CALIPSO (Nishizawa et al., 2007 JGR).

The super-spheroid model for computing the scattering matrix of dust aerosols is introduced

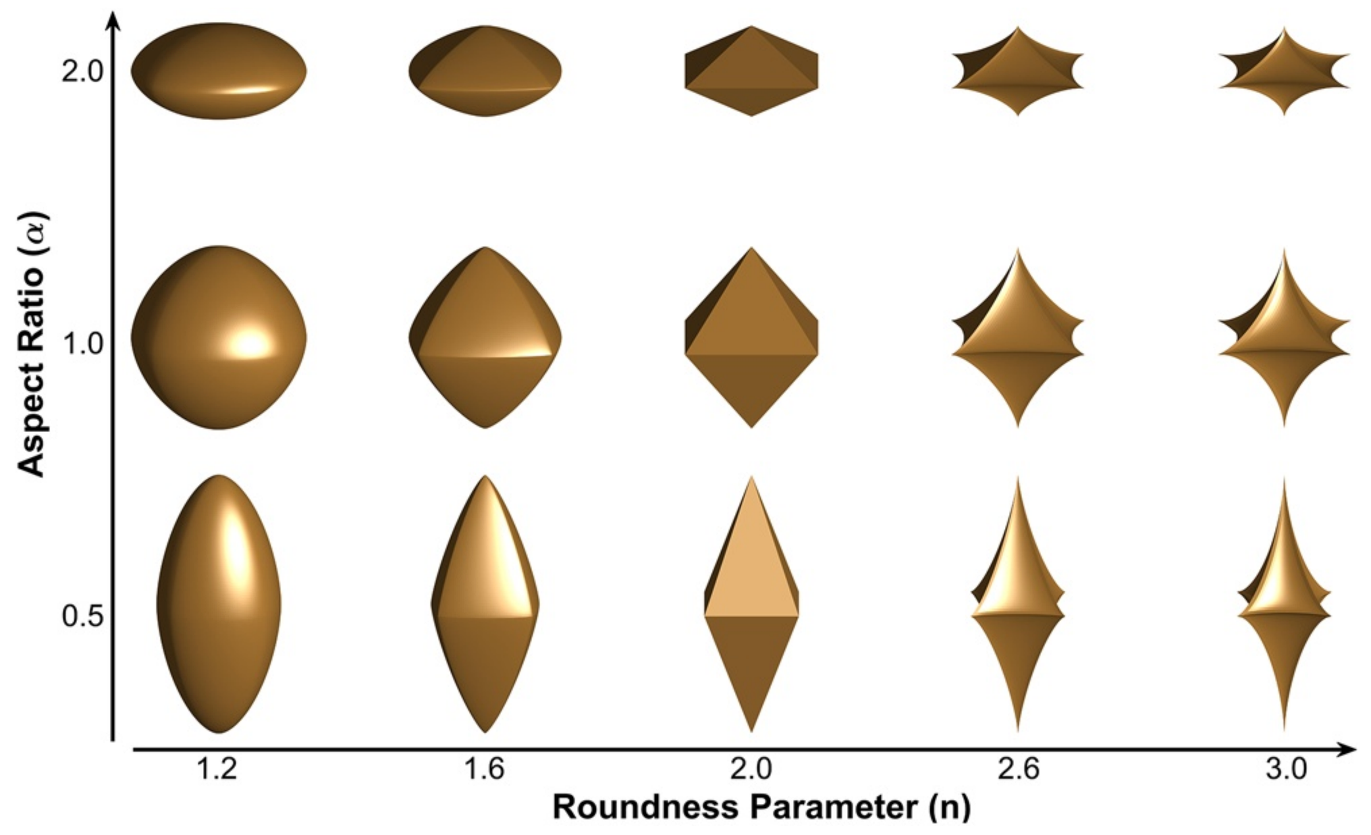
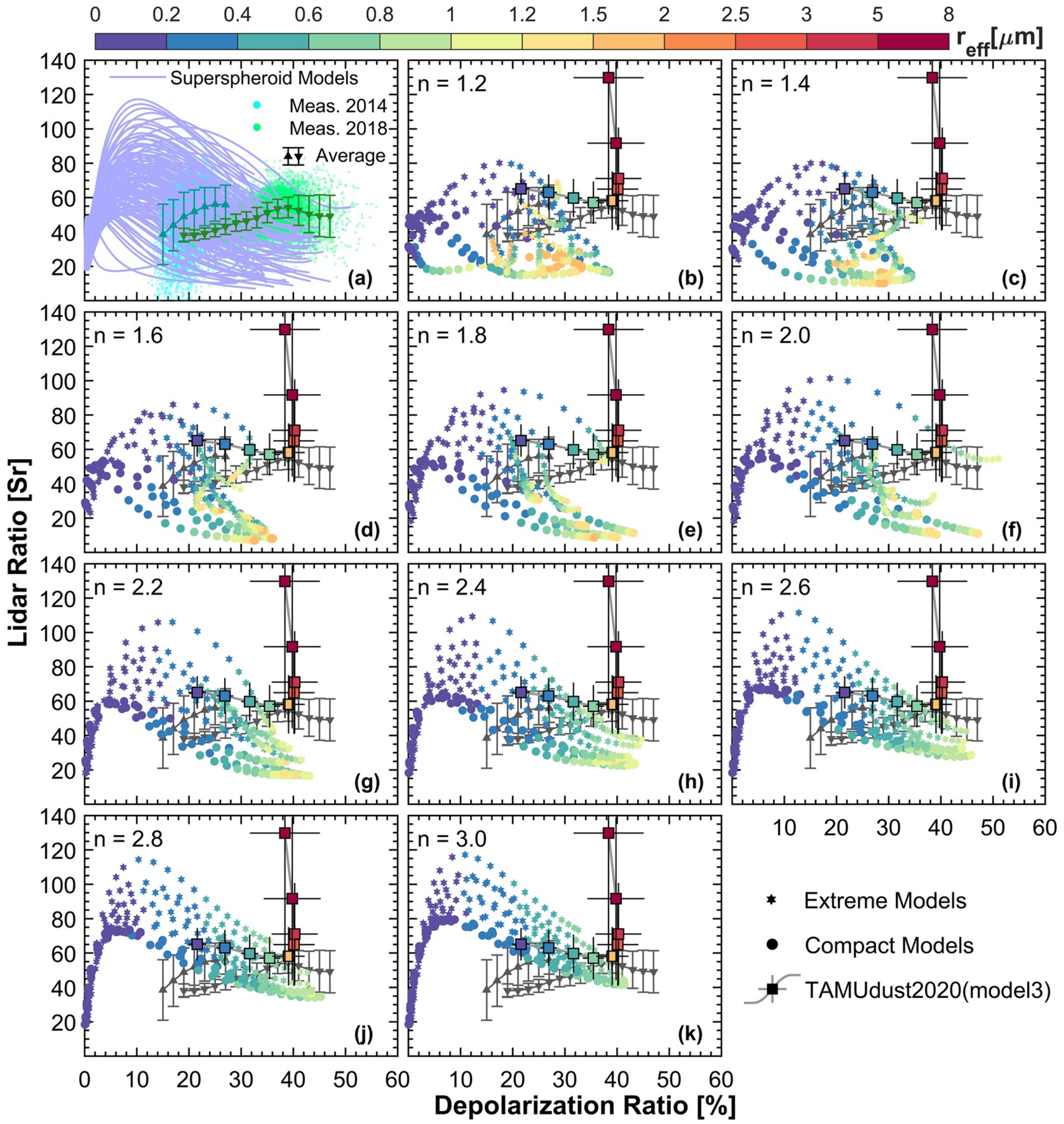


Figure 1. Super-spheroid models with different roundness parameters (n) and aspect ratios (α). Fifteen shapes (n = 1.2, 1.6, 2.0, 2.6, 3.0 and α = 0.5, 1.0, 2.0) were selected for illustration.

super-spheroid

$$\left(\frac{x}{a}\right)^{2/n} + \left(\frac{y}{a}\right)^{2/n} + \left(\frac{z}{c}\right)^{2/n} = 1.$$

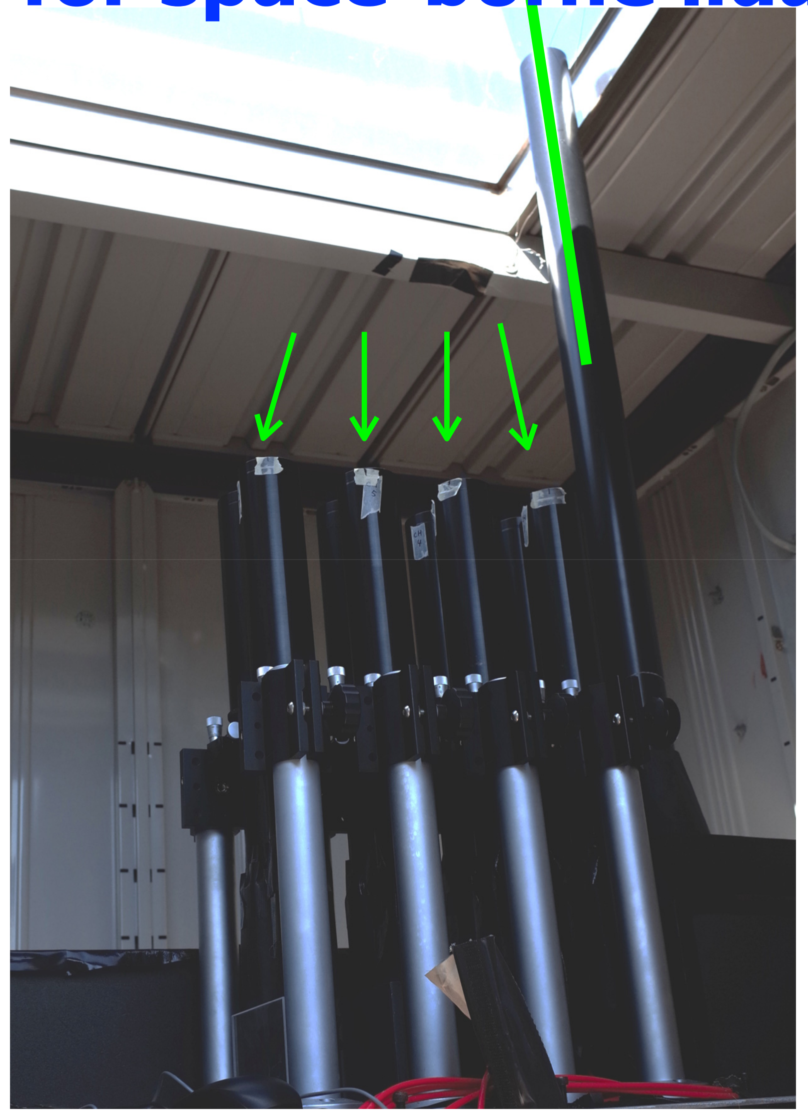


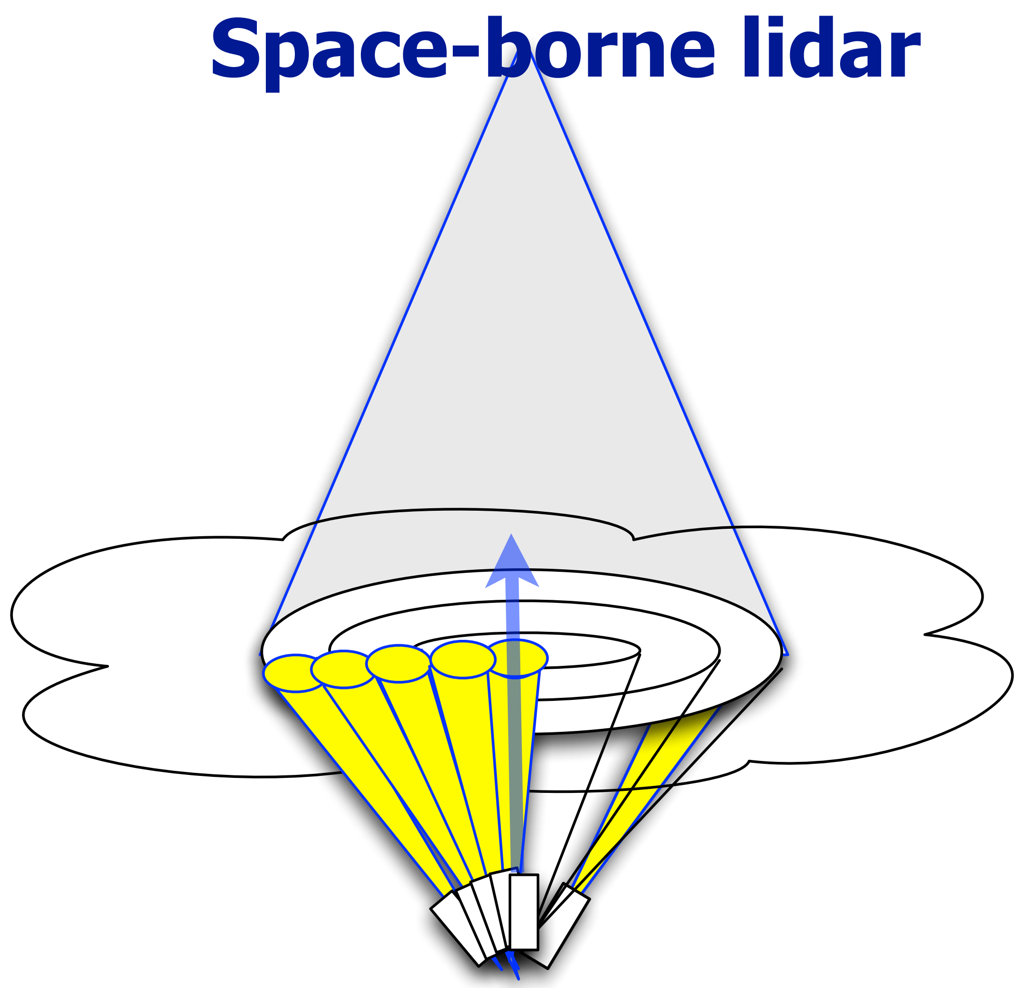
(Kong, S, Sato. K, Bi L., JGR, 2022)

- **The super-spheroid models with different sets of n and α were capable of simulating the entire $S - \delta$ range of HSRL measurement at 355 nm.**

Multi-Field-of-View Multiple-scattering polarization lidar to simulate space-borne lidar signals

Foot print size of space-borne lidar are much larger (~30m for ATLID and 90m for CALIPSO) than that of ground-based lidar so that larger multiple scattering for space-borne lidar is expected.





Lidar with large FOV can penetrate thick clouds : 8ch(4 co-pol.+4 cross-pol.) ~35mrad.

→can detect comparable multiple scattering to space-borne lidar and first depolarization.

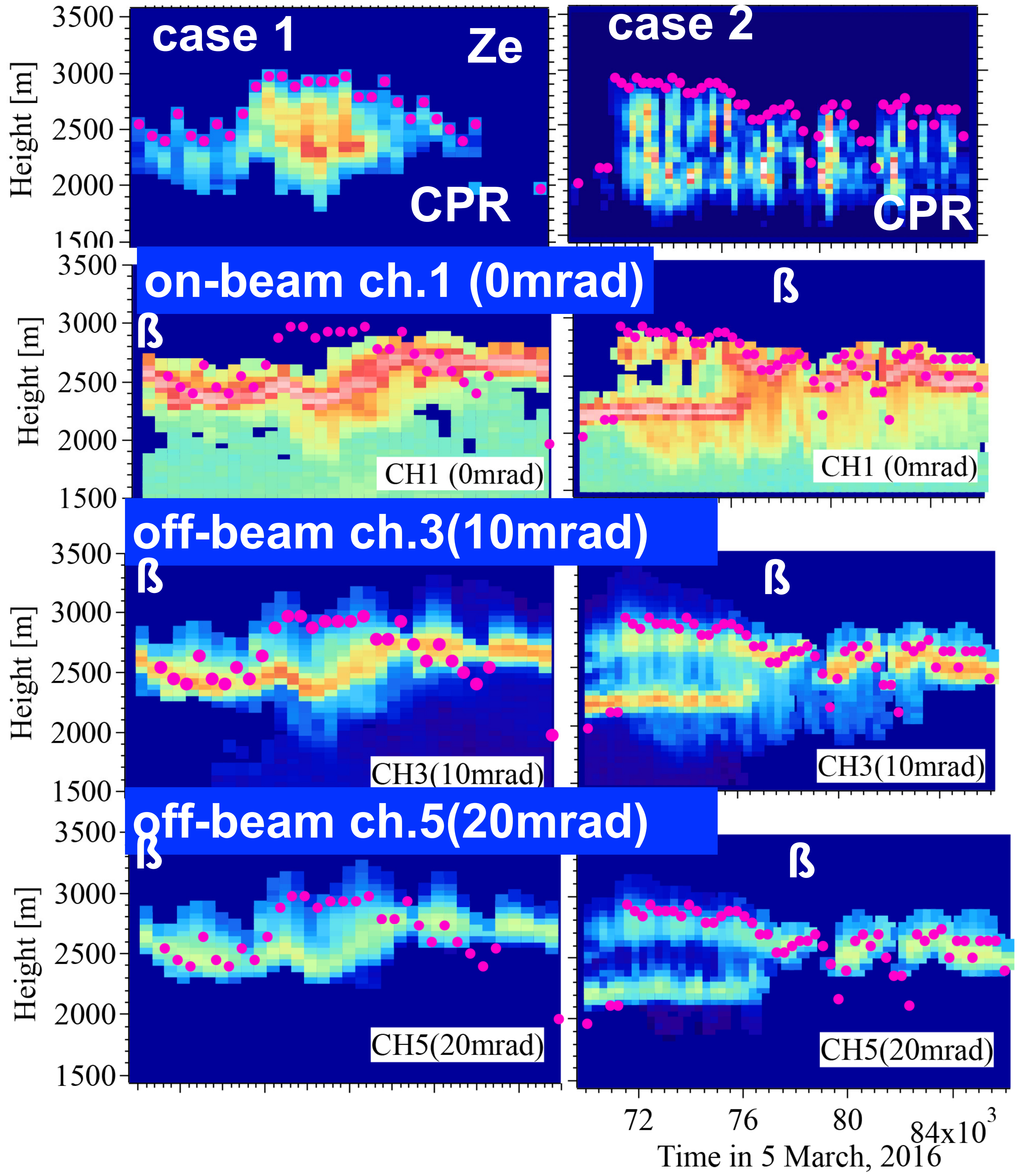
History of Multiple-scattering lidar

[Davis, 2008 JGR, Caharan et al., 2005 JTECH]

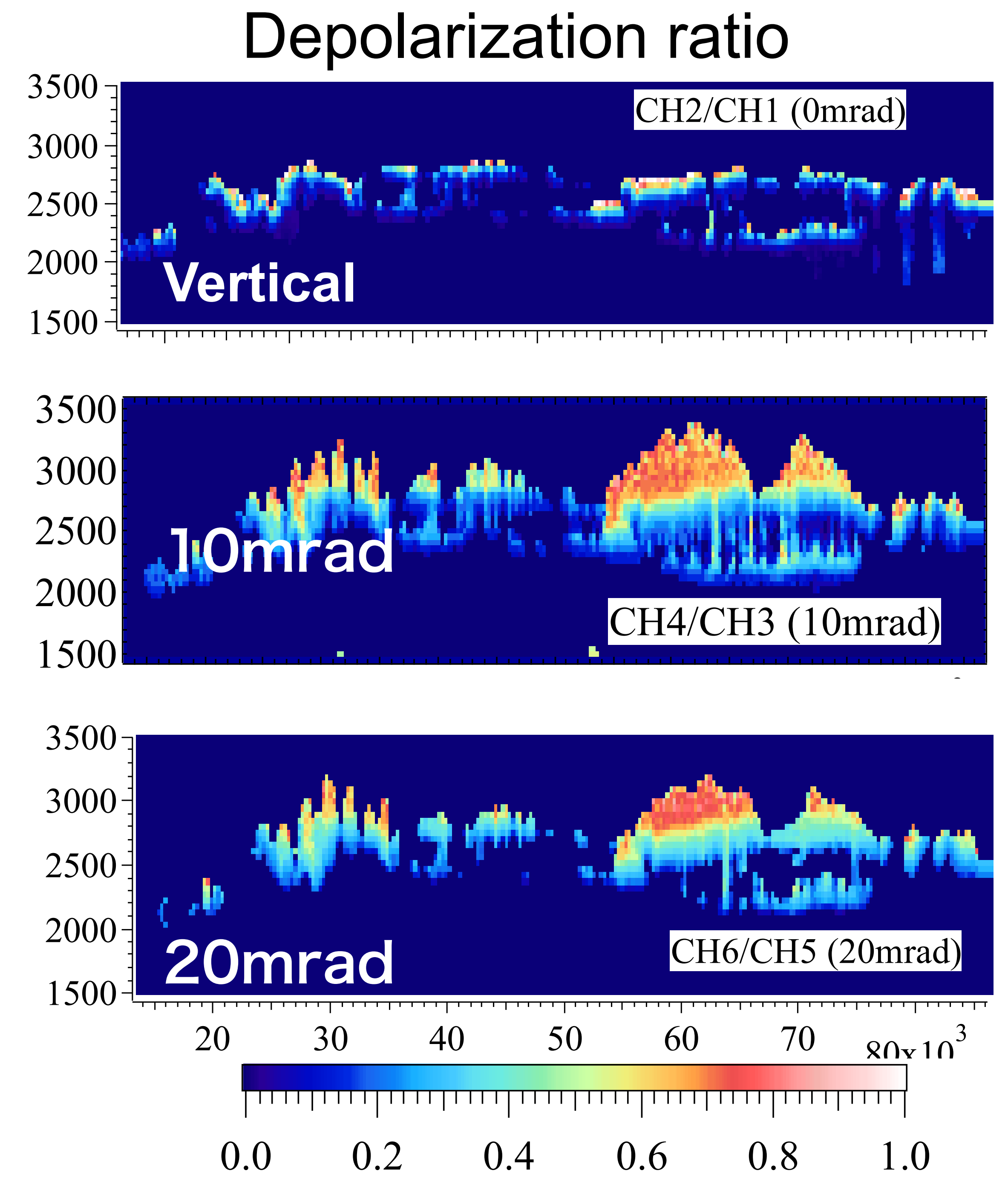
Multiple FOV lidar ~12mrad

[Bissonette and Hutt,1990 Appl. Opt., Roy et al.,1999 Appl. Opt.]

Comparison of Cloud top height by MFMSPL with Cloud Radar



Comparable depolarization of water cloud to CALIPSO has been observed by MFMSPL



(Okamoto et al., 2016 Opt. Express)

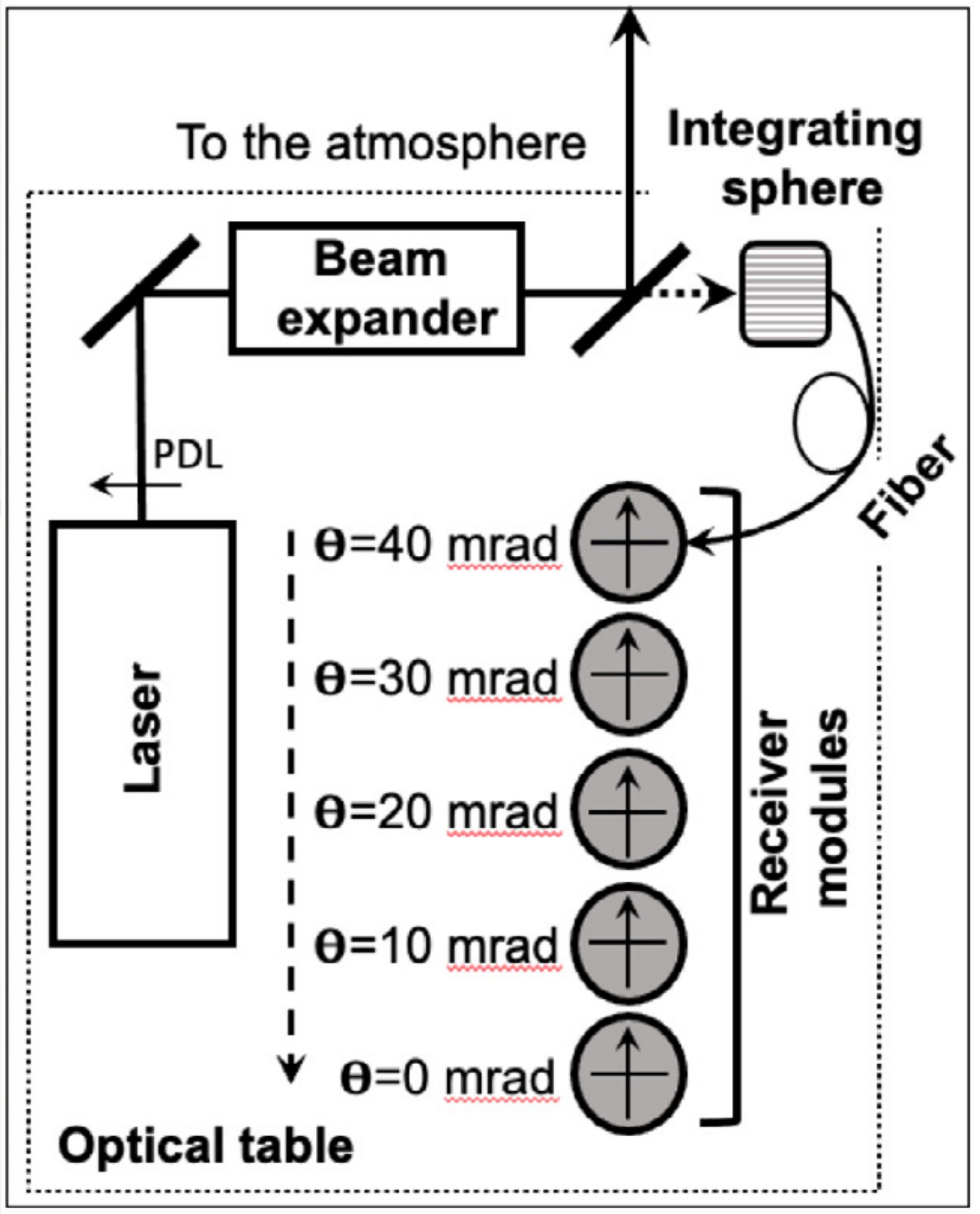
Ground-based validation instrumentations for EarthCARE products (I)

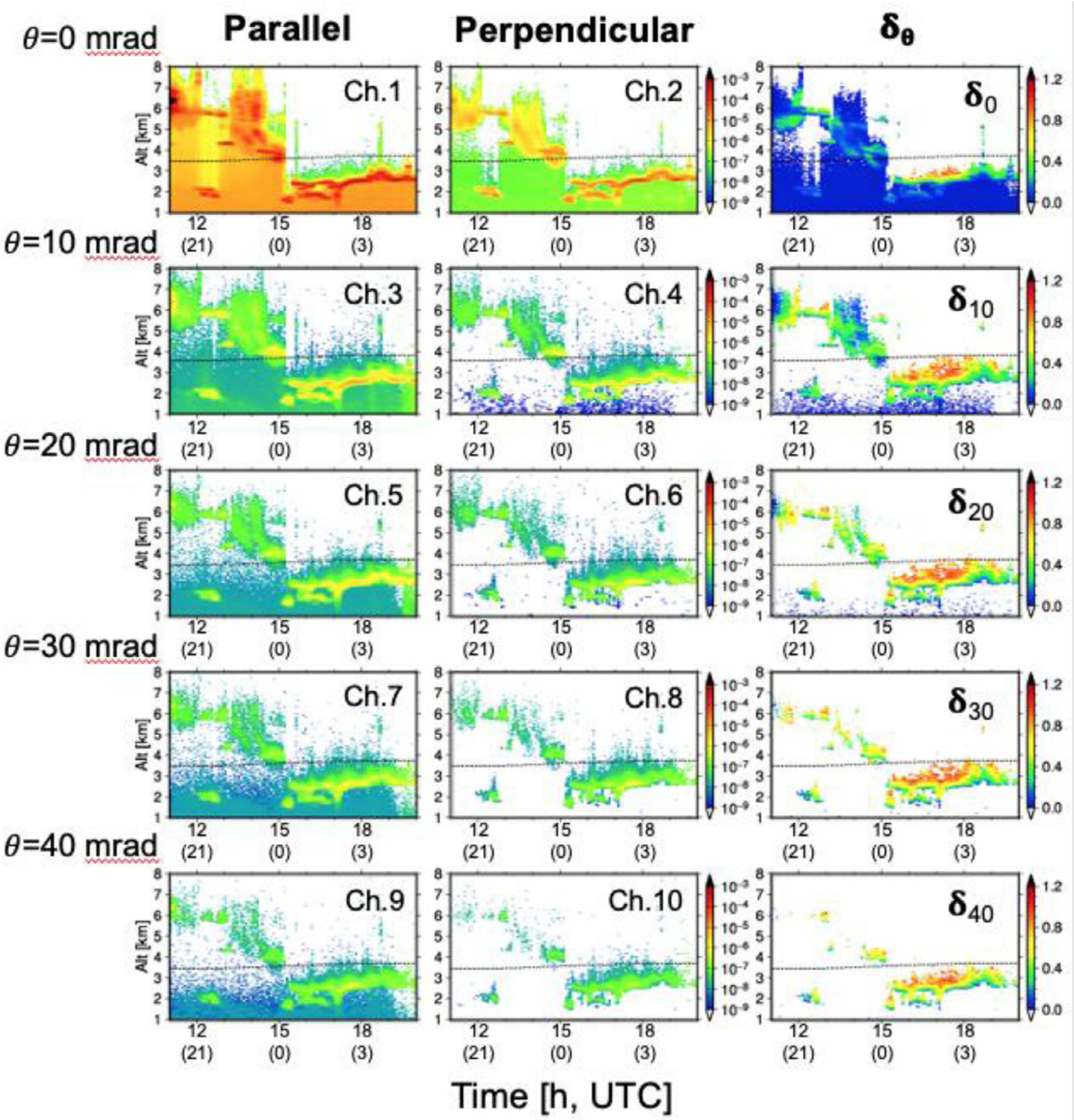
Synergistic-ground-based system are developed by Kyushu Univ., NIES, NICT and TMU to evaluate EarthCARE algorithms.

The observation system and collaboration will continue by a research collaboration agreement after 2022.

Ground-based validation instrumentations for EarthCARE products (I)

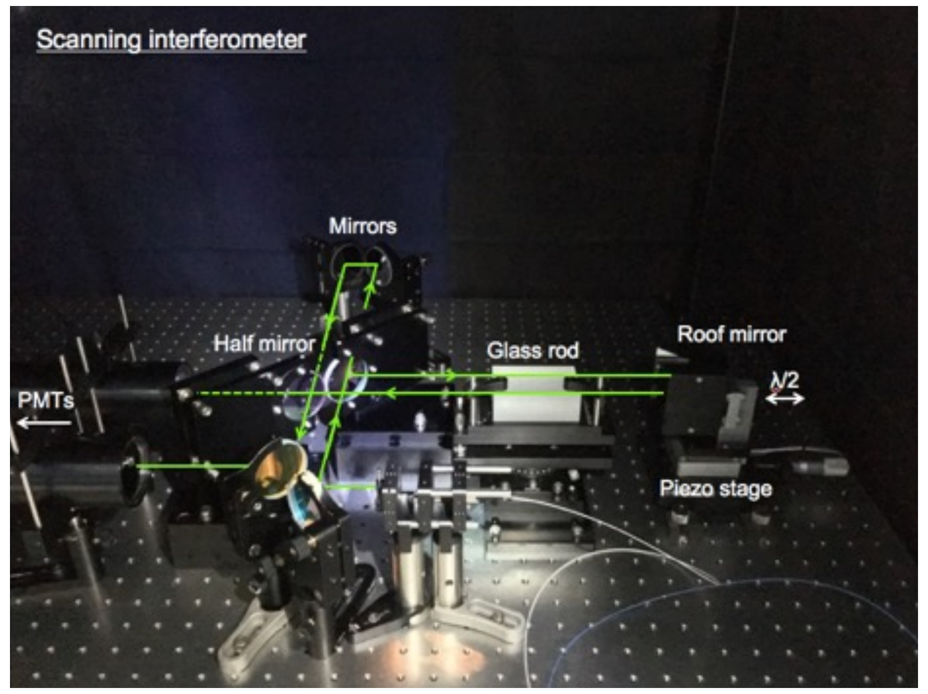
355nm-MFMSPL with 10 channels are developed (Nishizawa et al 2021 JQSRT)



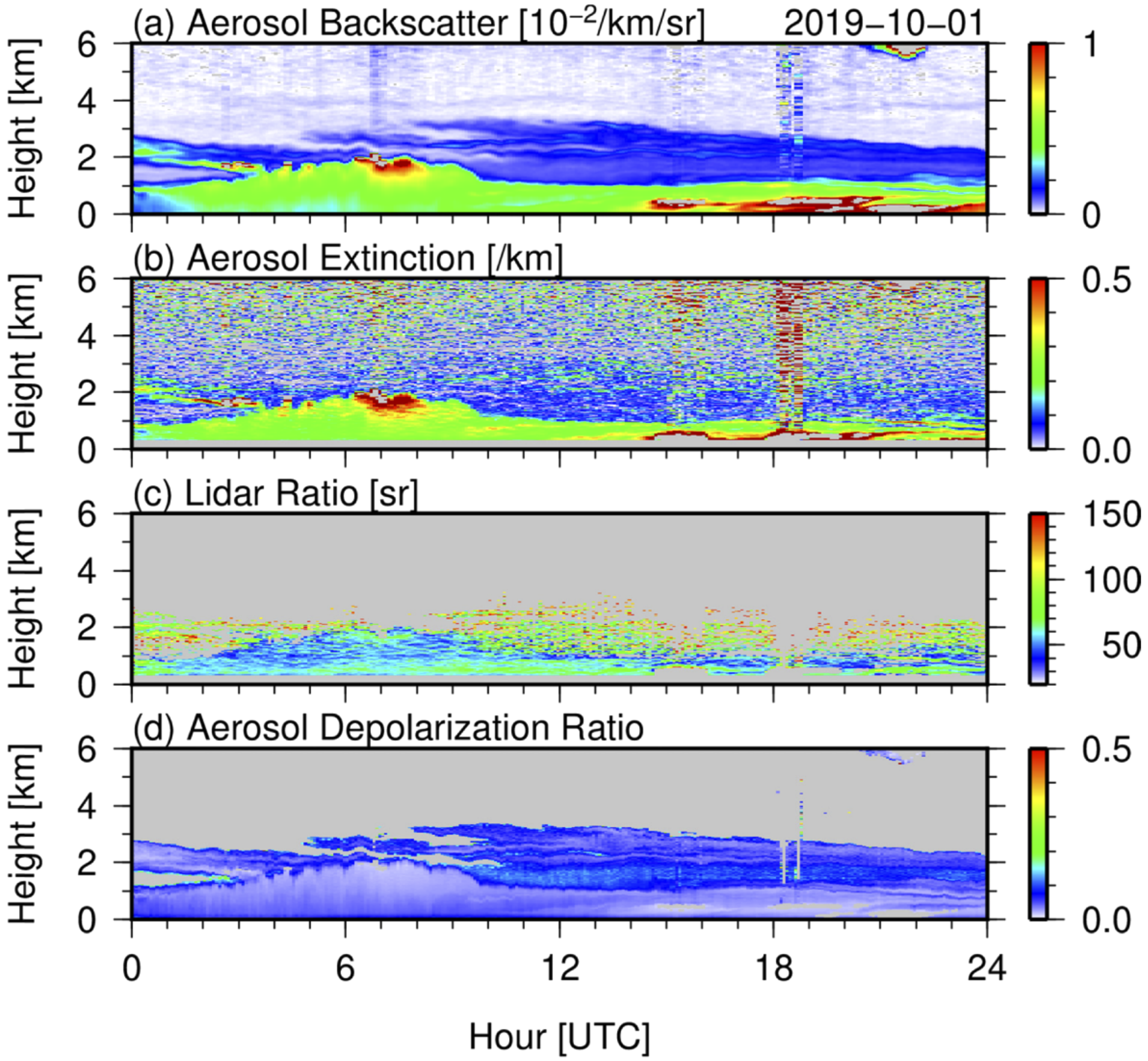


Ground-based validation instrumentations for EarthCARE products (II)

Long-term measurements of clouds, aerosols and vertical air motions have been carried out by new instruments HSRL and 355-MFMSPL with 94GHz Doppler radar and Doppler lidar. Analyses of cloud microphysics and vertical air motion from the algorithms are conducted.



355nm-HSRL with scanning interferometer



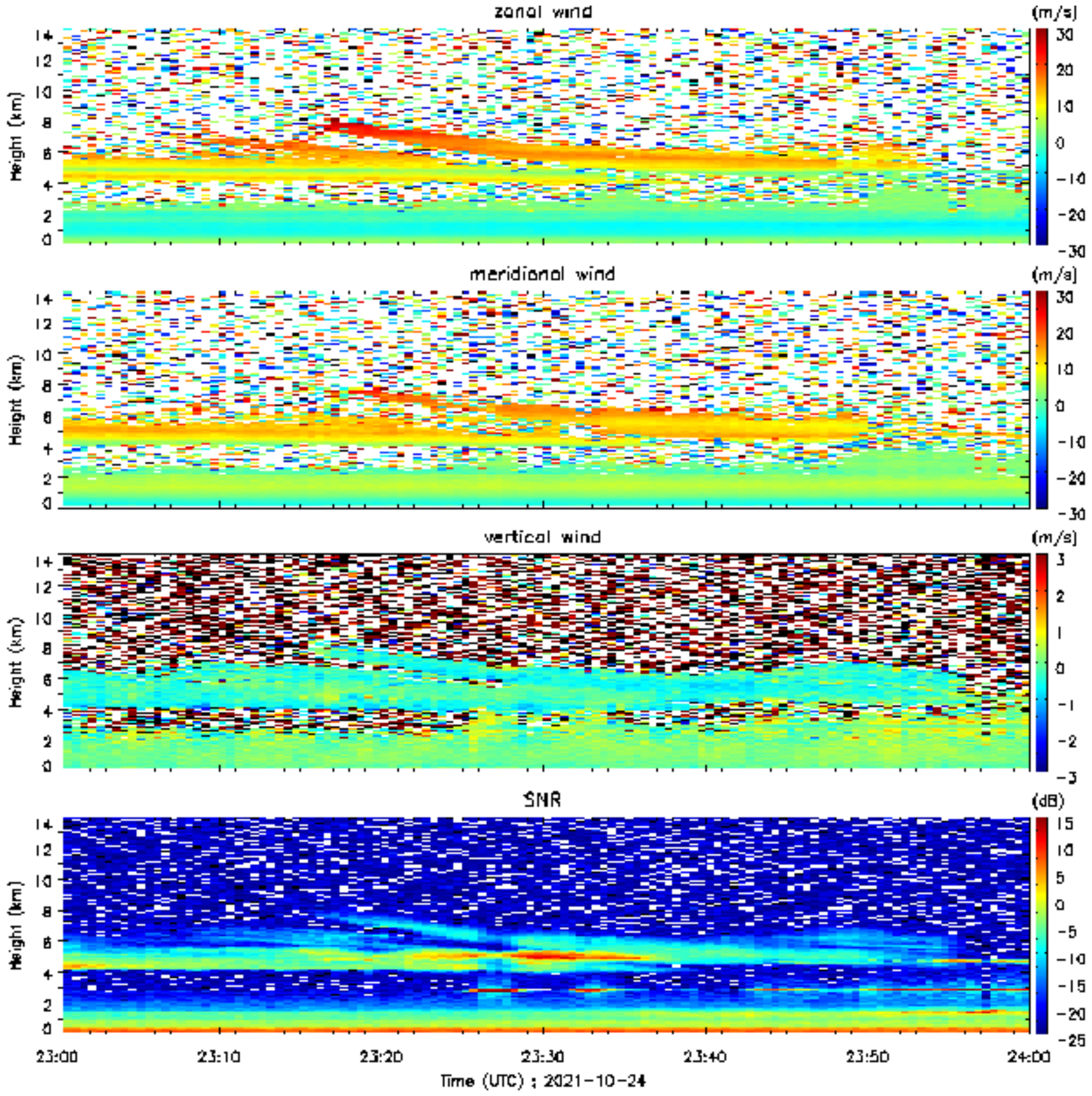
ß(355nm)

Extinction

Lidar ratio

Depolarization ratio

355nm-HSRL (Jin et al. 2020 Opt. Express)



U

V

W

SNR

Five angle-measurement of wind velocity has been carried out to derive U, V and W by the 2-µm Doppler lidar (Iwai et al., 2013 JTECH) to achieve 30sec resolution.

Summary

Algorithms for A-train and EarthCARE have been developed.

Global analyses of cloud phase and cloud microphysics were shown for A-train.

Continuity and some major improvements for EarthCARE and A-train observations are discussed. New input (extinction from ATLID and Doppler velocity from CPR) are expected to provide better characterization of cloud and precipitation particle phase and types and microphysics.

Synergistic observation systems have been developed. HSRL and Multiple scattering lidar at 355nm, high sensitivity 94GHz Doppler cloud radar and Doppler lidars correspond to the extended version of EarthCARE.

Cloud-, Precipitation- , Aerosol-microphysics and vertical motion from EarthCARE is crucial to constrain/improve the models.

Multiple-wavelength-observations and theoretical analyses to cover CALIPSO and EarthCARE ATLID are essential to bridge the gap between information content of A-train and EarthCARE.