Global identification of dominant ice microphysics in cirrus clouds using EarthCARE CPR observations

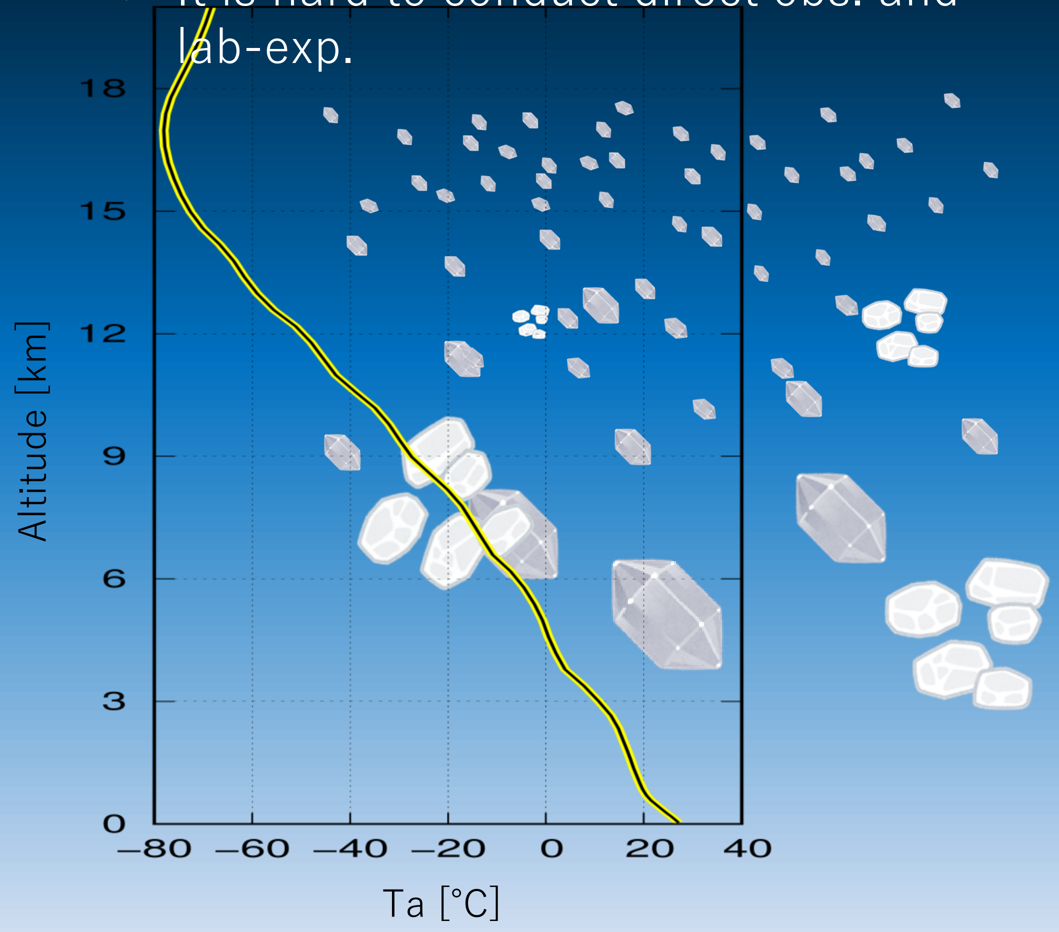
***Tatsuya Seiki (JAMSTEC)**
Akira Noda (JAMSTEC)
Yuichiro Hagihara (NICT), Hiroaki Horie(NICT),
Shunsuke Aoki (JAXA)

EarthCARE Science Workshop, Dec. 1^{th}-5^{th}, 2025

Introduction: crystal growth at very-low T_a

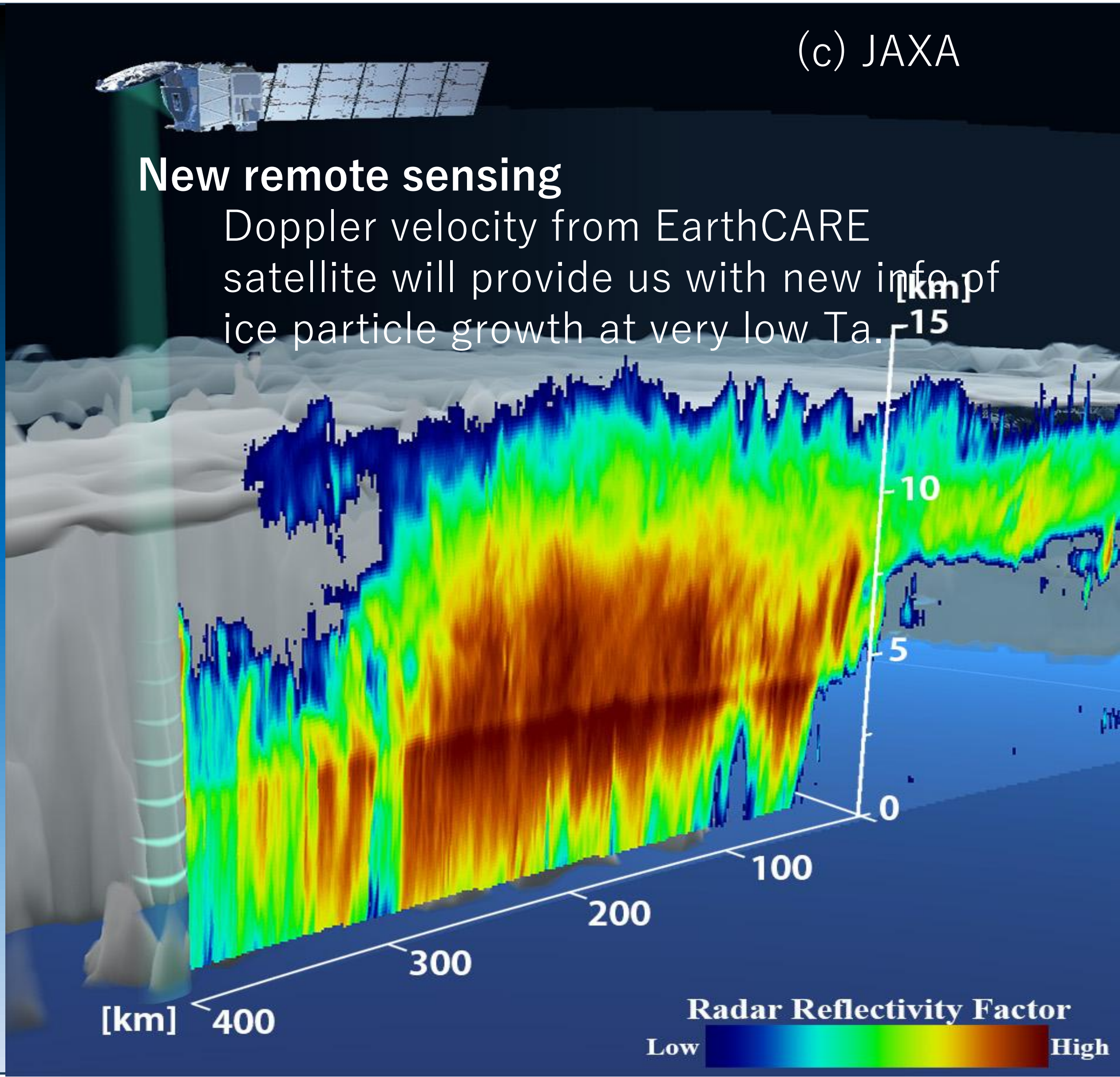
Falling Snow particles

- ✓ Their size and shape vary by Ta, RH, aerosols, and so on.
- ✓ It is hard to conduct direct obs. and lab-exp.



New remote sensing

Doppler velocity from EarthCARE satellite will provide us with new info of ice particle growth at very low Ta.



Analysis method：Ze-log10vd diagram

1) Dependence of Ze and vd

$$\begin{cases} Z = \int_0^\infty f(D) D^6 dD \sim N\overline{D}^6 \sim M\overline{D}^{6-b}. \\ v_d \sim v_t = \alpha \overline{D}^\beta. \end{cases}$$

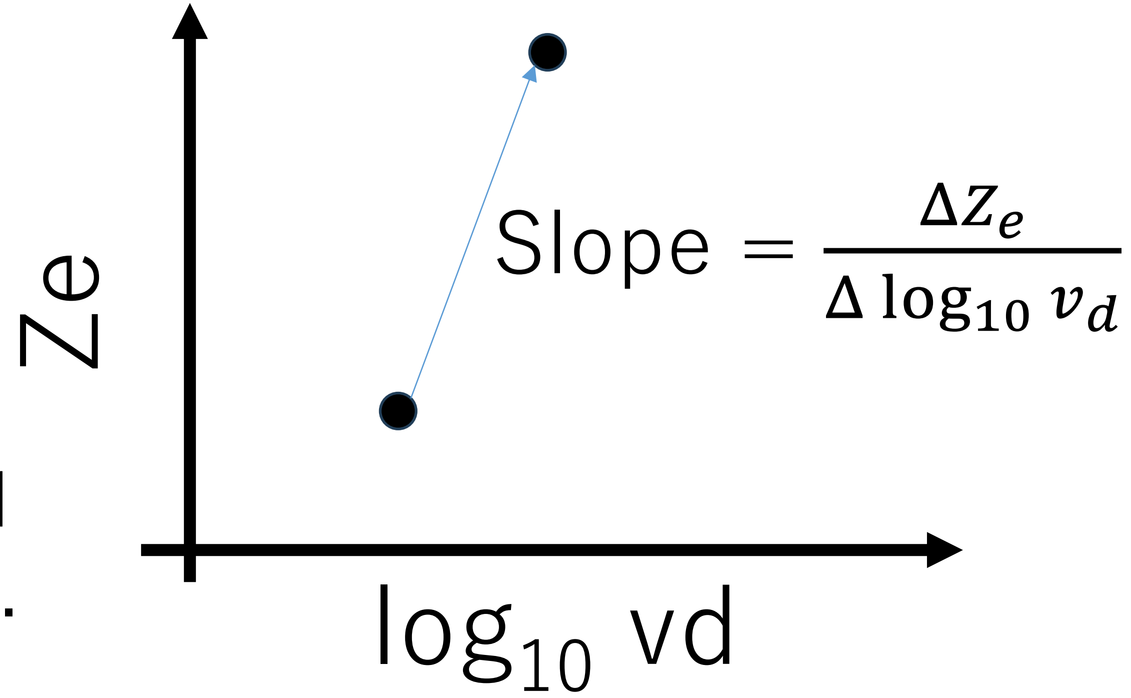
$M \propto \overline{D}^b$: mass-size relation

2) Z in decibel and vd in a common logarithmic scale

$$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{10}{\beta} \frac{\overline{D}}{M} \frac{\Delta M}{\Delta \overline{D}} + \frac{60 - 10b}{\beta}$$

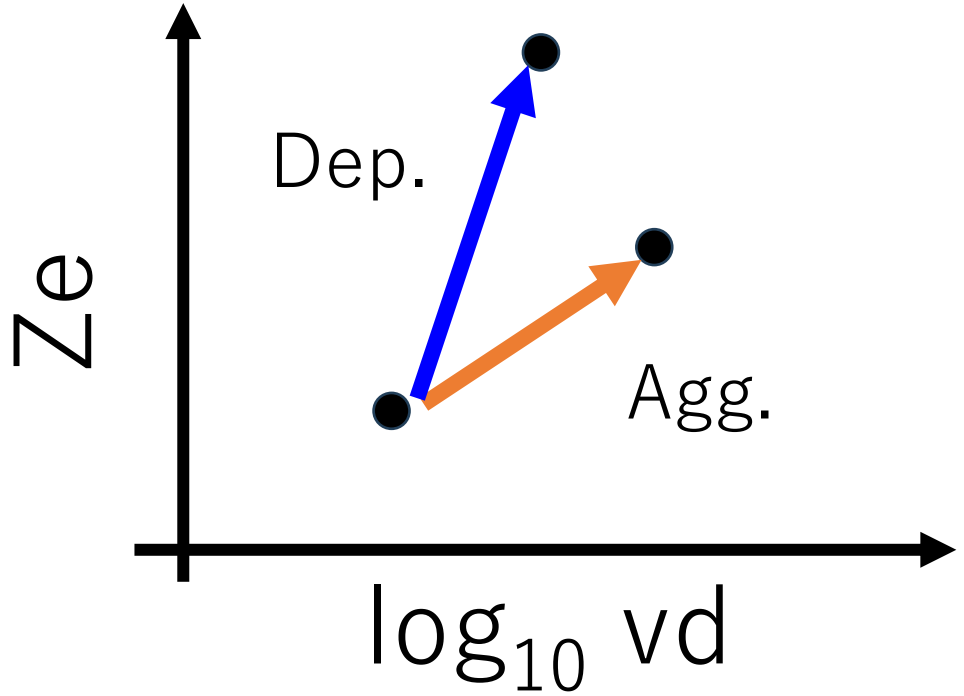
Microphysical sensitivity

Slope in the scatter plot of Ze and $\log_{10}$vd has info of particle growth.



Analysis method：interpretation of slope

$$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{10}{\beta}\frac{\bar{D}}{M}\frac{\Delta M}{\Delta \bar{D}} + \frac{60-10b}{\beta}$$



- Aggregational growth regime

  Total mass conserves. ($\frac{\Delta M}{\Delta \bar{D}} = 0$)

  $$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{60-10b}{\beta}$$

- Depositional growth regime

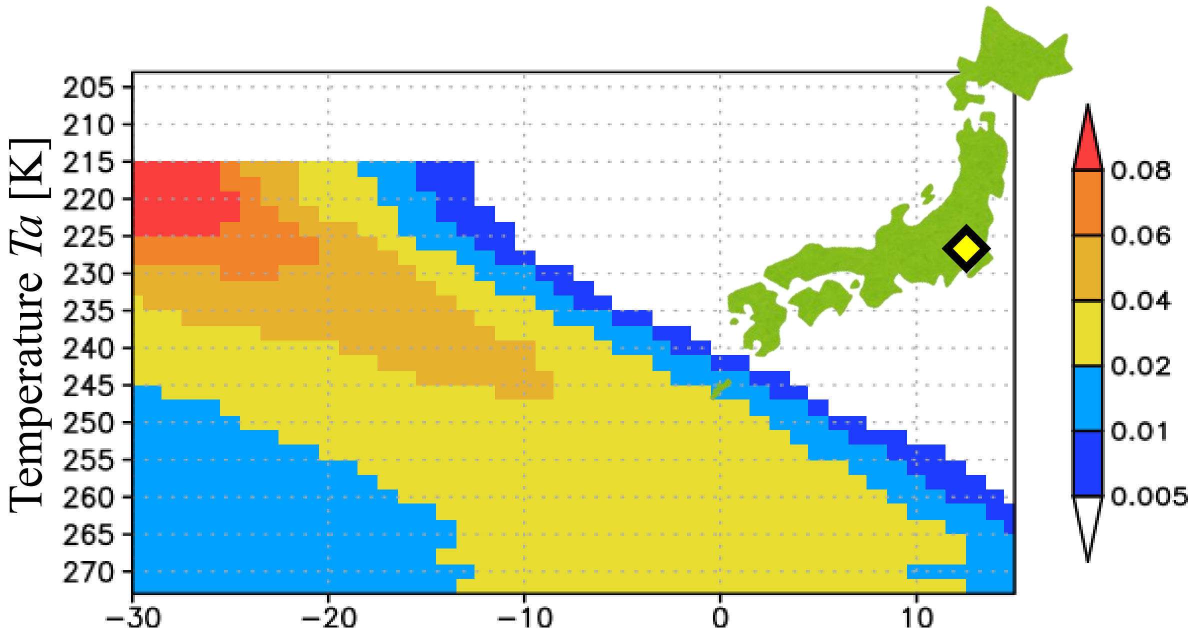
  Number does not change. $M = a\bar{D}^b$ $\quad \frac{\bar{D}}{M}\frac{\Delta M}{\Delta \bar{D}} = b$

  $$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{60}{\beta}$$

β and b depends on size and shape
$\beta \in [0.5: 2], b \in [2: 3]$

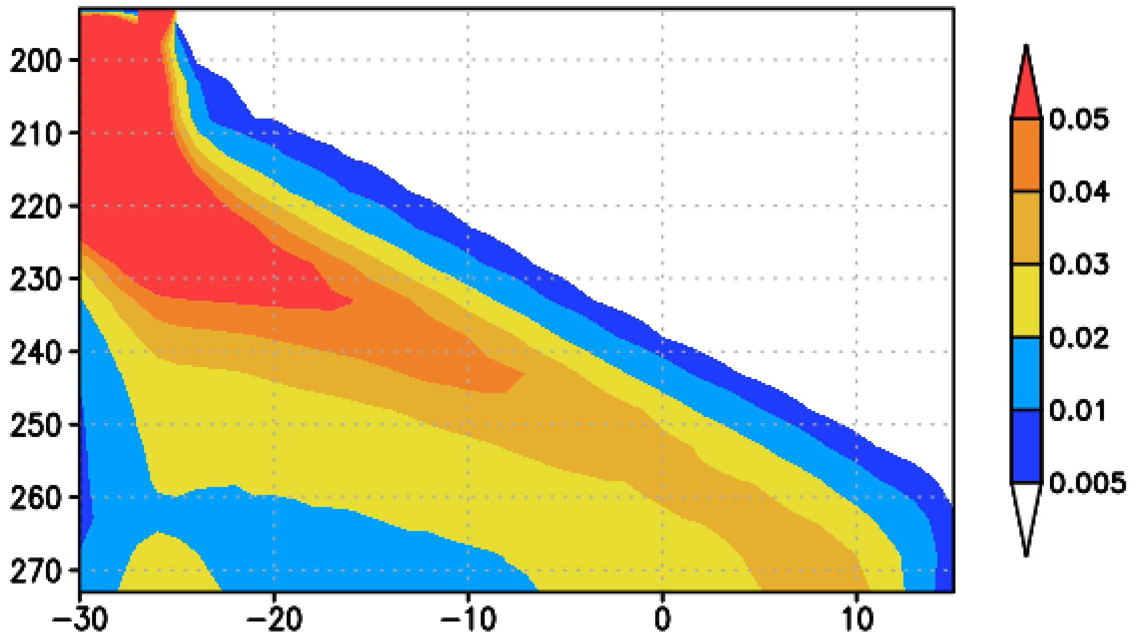
Use of in-situ observations for evaluation of Ze-log10vd diagram

CFAD from HG-SPIDER @ NICT in 2022



Ze [dBZ]

CFAD from CloudSat in 30N-45N



Ze [dBZ]

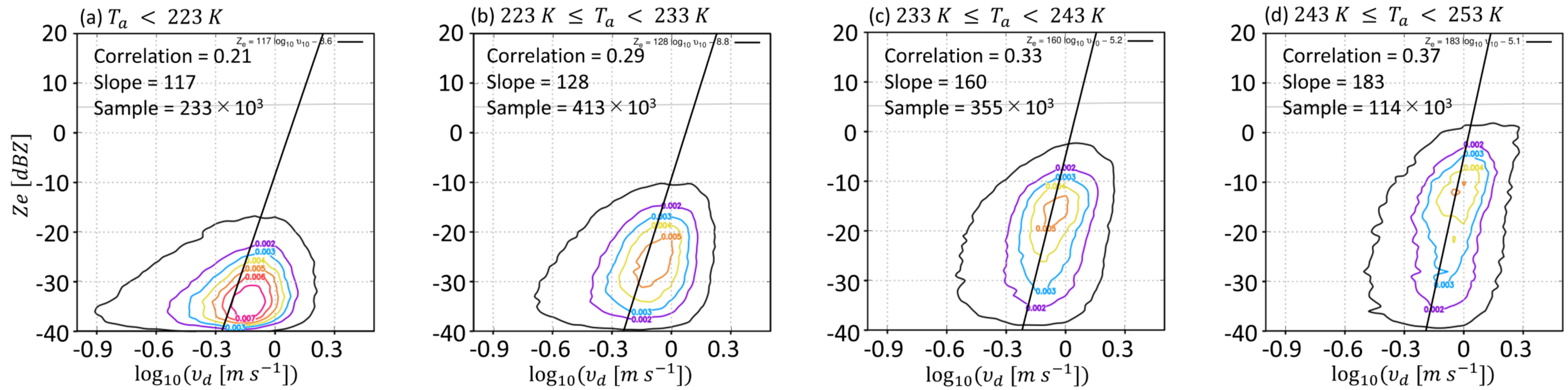
- ✓ Annual obs. @ single location represent general characteristics of the vertical profile of radar echo derived from CloudSat satellite observations.

Comparison of the Ze-$\log_{10}$vd diagram.

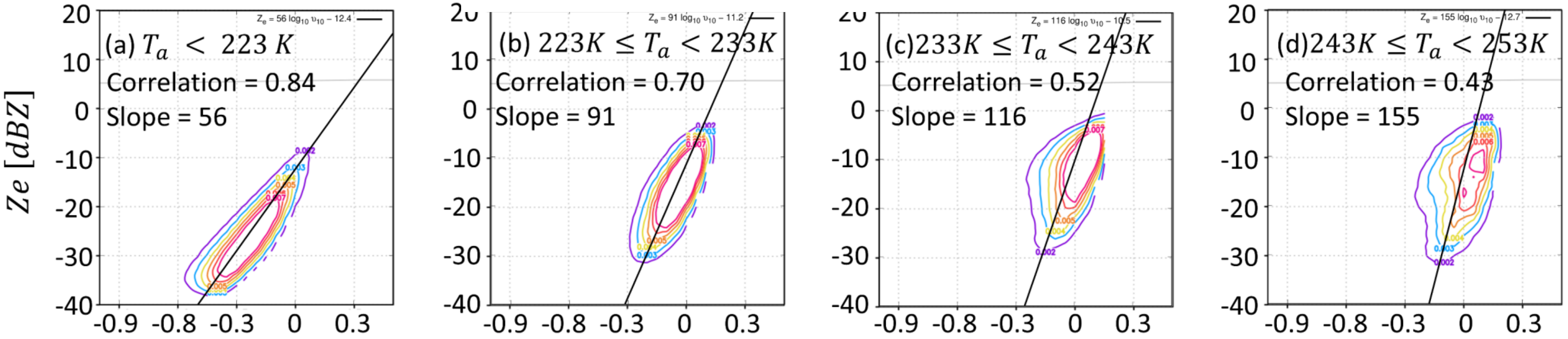
(Seiki, Horie, Hagihara, Noda, 2025, JAS, in press)

Colder ← Atmospheric Temperature → Warmer

In-situ observations @ NICT, Tokyo



Climate Model Simulations



Comparison of the Ze-log_{10}vd diagram.

(Seiki, Horie, Hagihara, Noda, Aoki, 2025, AMT-Preprint, under review)

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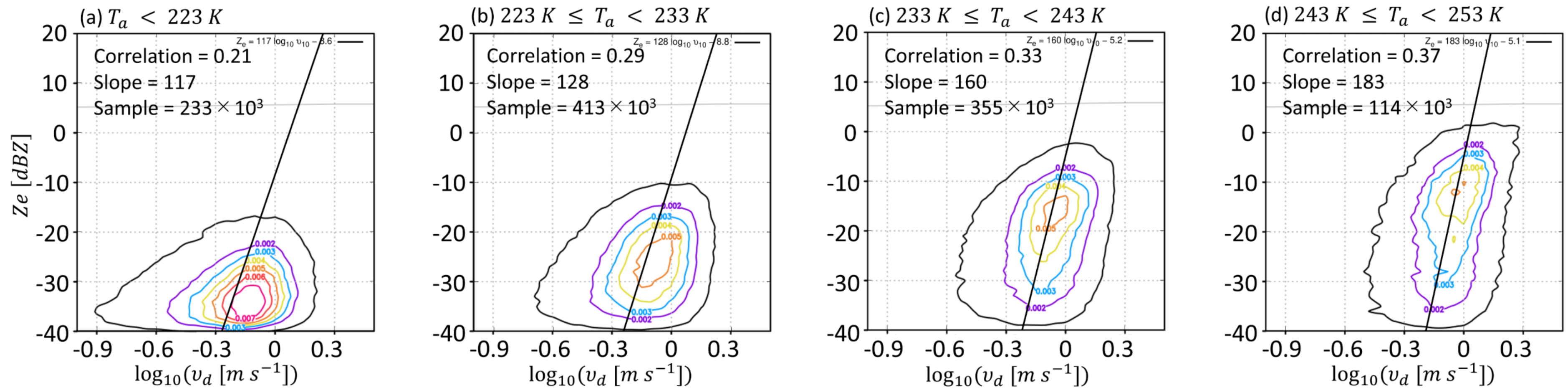
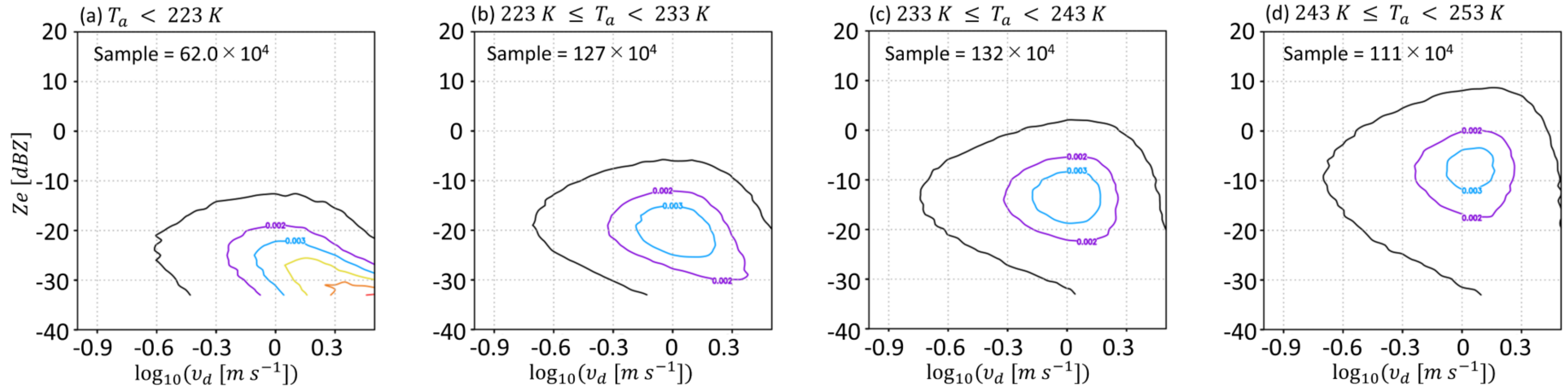
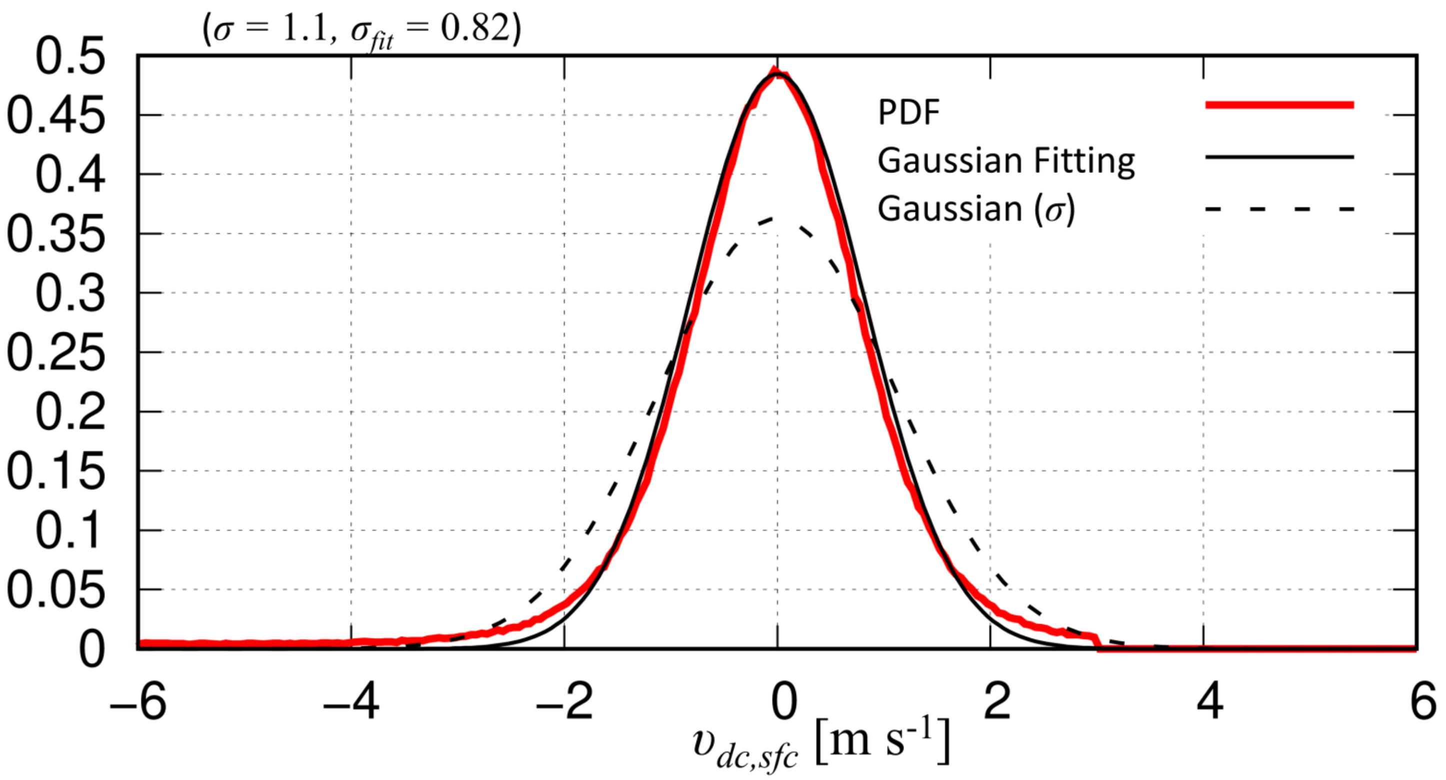


EarthCARE obs. in the northern mid-latitudes



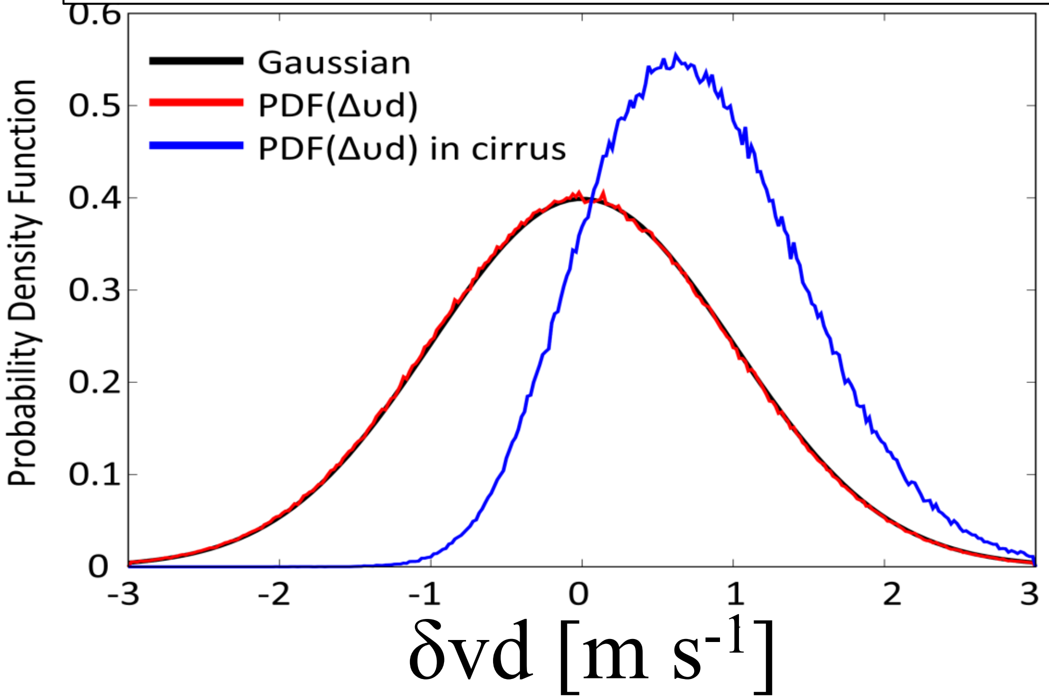
Random errors in Doppler obs. from EarthCARE

Doppler velocity is corrected so that moving-mean of vd@sfc = 0
➔vd@sfc is a measure of random error.



Error propagation of random error to the analysis

Synthetic satellite obs.
(in-situ obs.+Gaussian noise)



Positive sampling

$$\log_{10} v_d \rightarrow v_d > 0$$

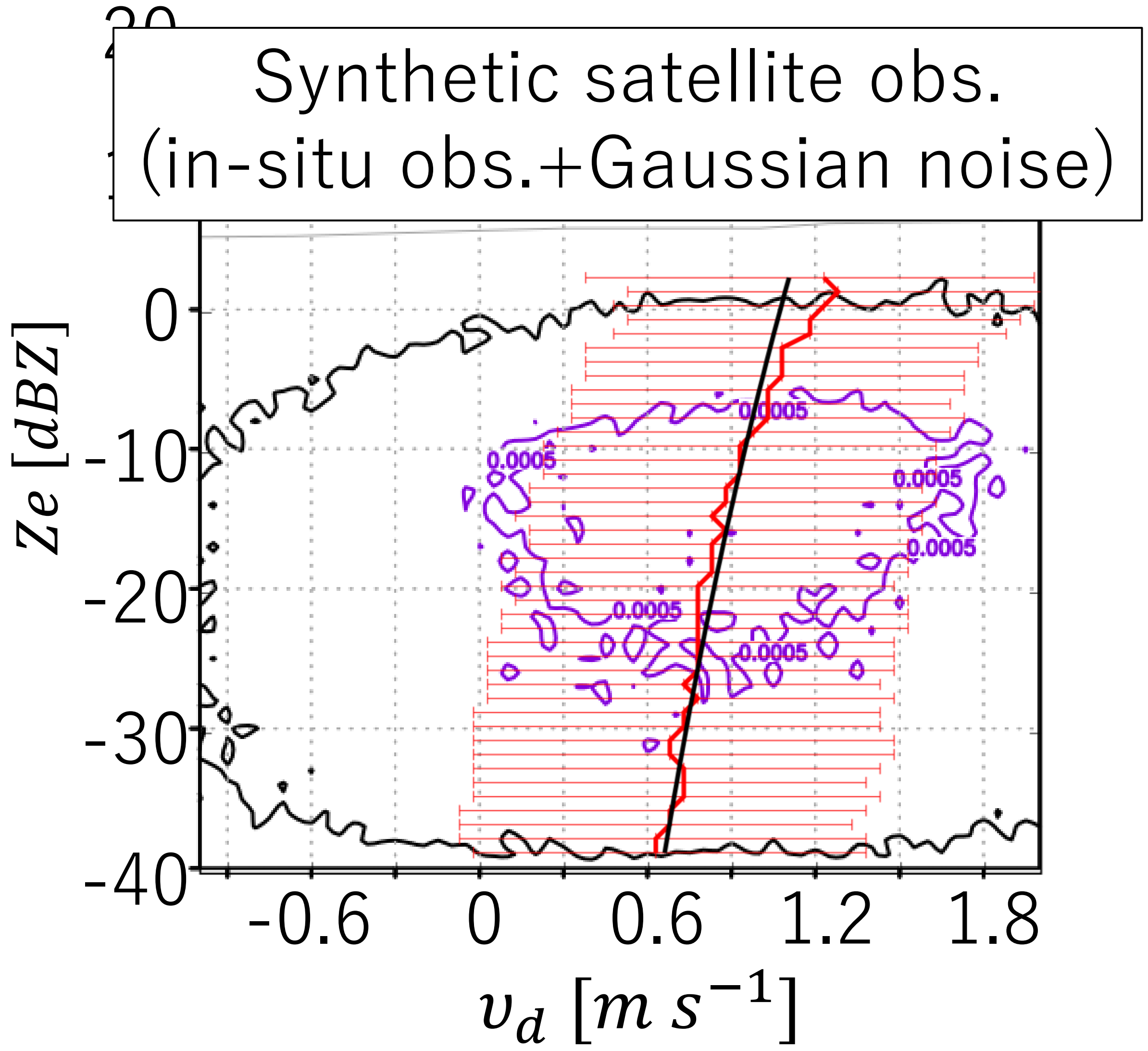
Error amplification

$$\log_{10}(v_d + \delta v_d) \sim \log_{10} v_d + \frac{1}{\ln(10)} \frac{\delta v_d}{v_d}$$

Log-transformation makes the error term ∝ 1/vd

➔ Error propagation is severe in cirrus or near cloud edge

Revision of the analysis method: use of median



✓Median is resistant to noise

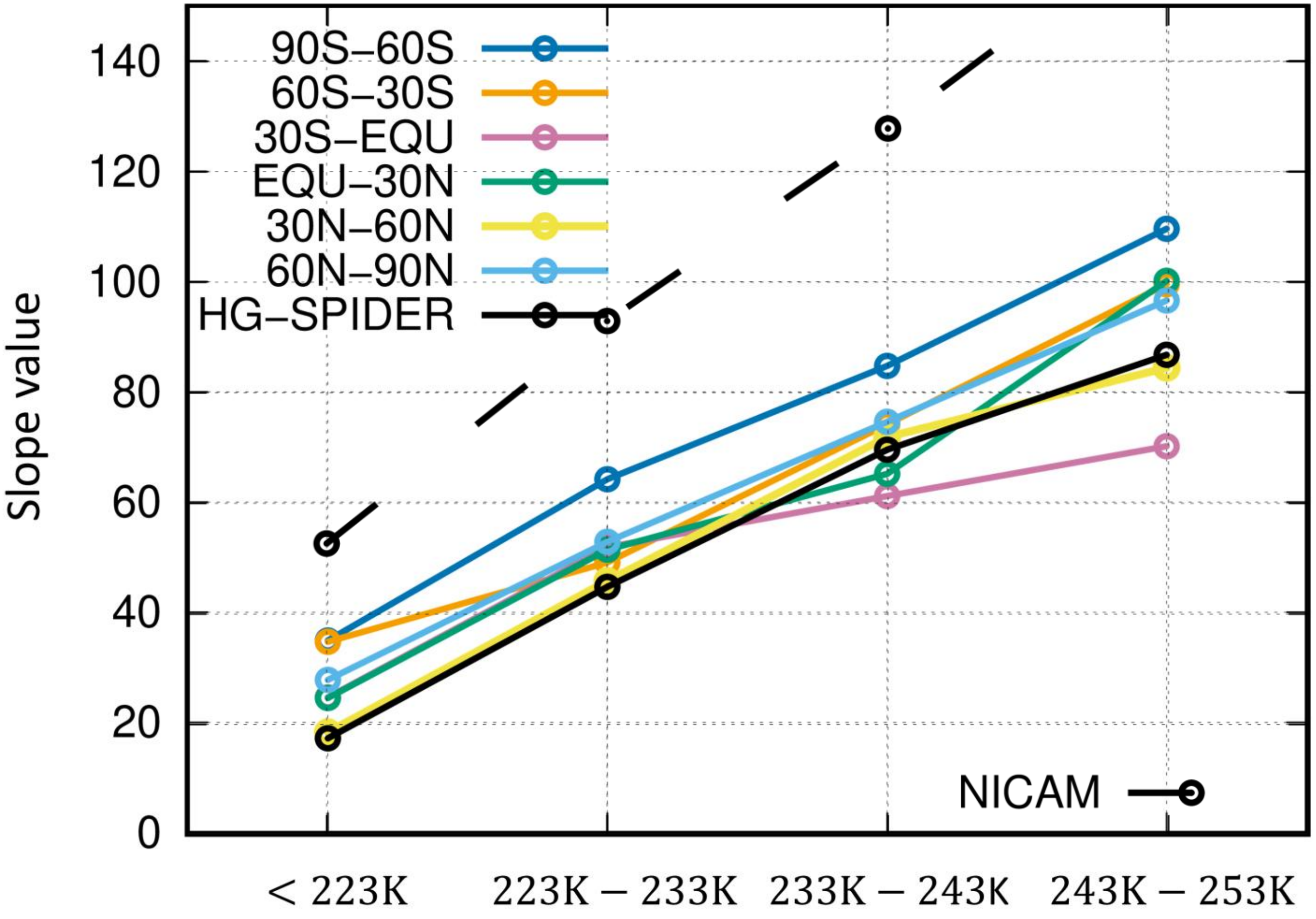
✓Log-transformation after calculating median of vd at each Ze bin

$$slope = \frac{\Delta Z_e}{\Delta \log_{10} \overline{v_d}}$$

Global meridional distribution of slope

$$\frac{\Delta Z_e}{\Delta \log_{10} v_d}$$

$$= \frac{10}{\beta}\frac{\overline{D}}{M}\frac{\Delta M}{\Delta \overline{D}} + \frac{30}{\beta}$$

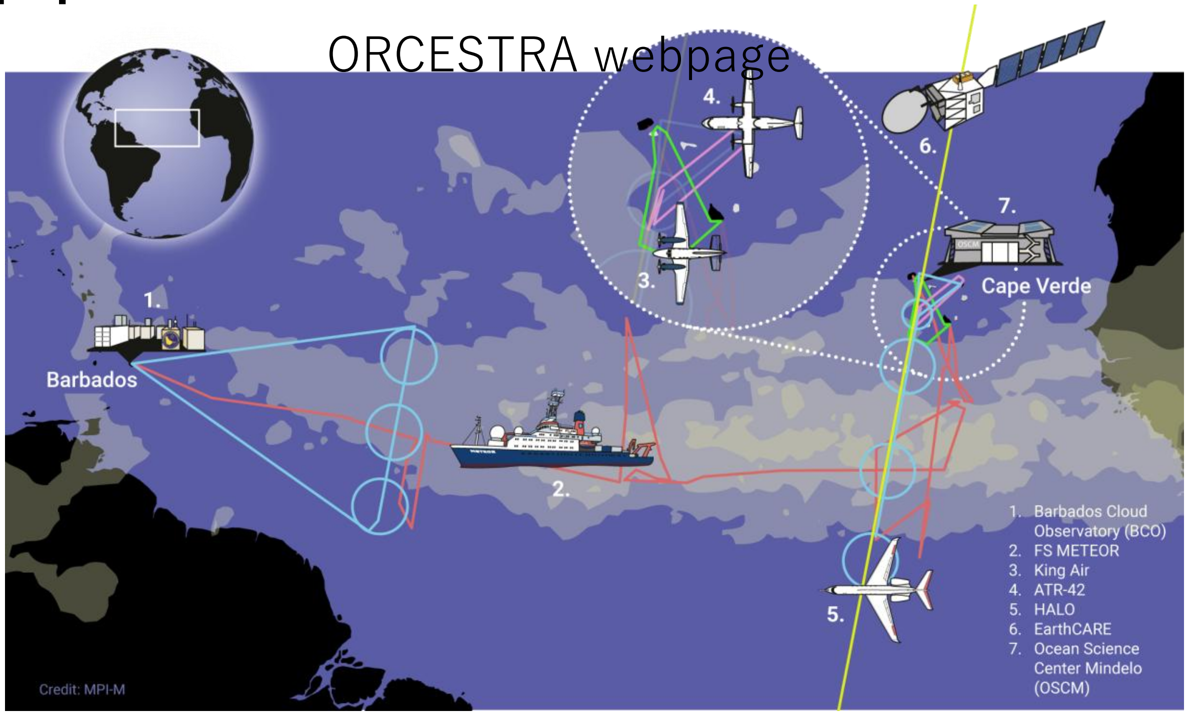


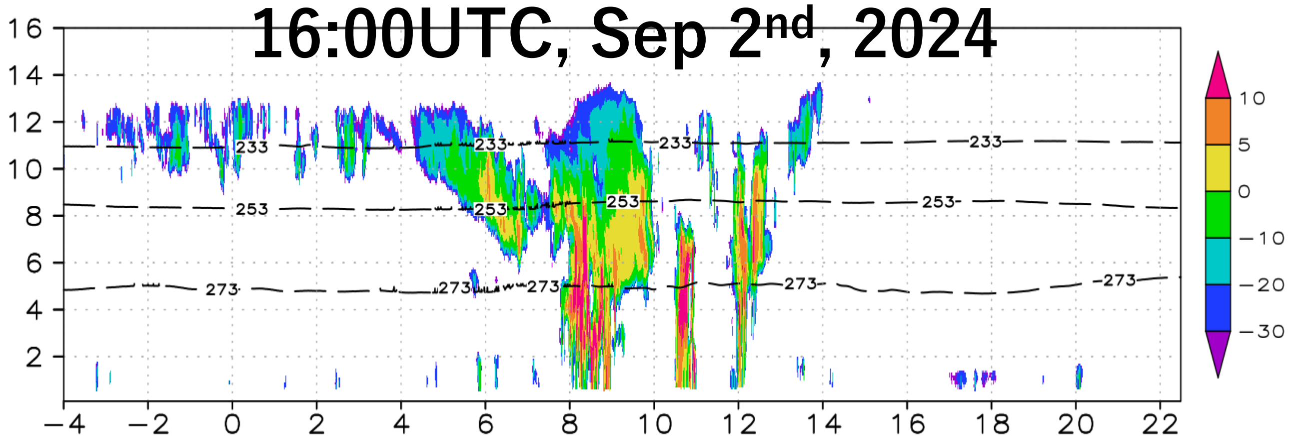
Deposition

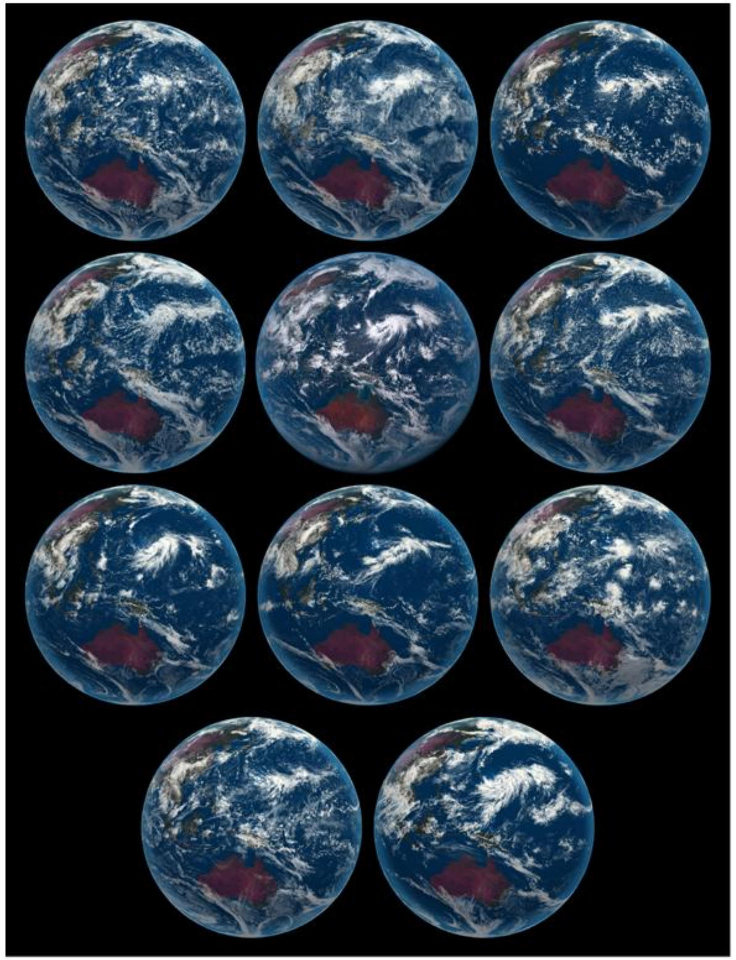
Aggregation

Cloud top ← Temperature range → Cloud base

Application to ECOMIP: evaluation of climate models







High-Resolution Climate Models
(Stevens et al., 2019)

Summary

Novel analysis method using Ze and log10vd

Seiki et al., (2025), JAS, in press.

- Slope (＝ΔZe/Δlog10vd) contains microphysical info.
- Error propagation from log-transformation is significant.
  - ➢ Median vd at each Ze is robust against random noise.

Global analysis

Seiki et al. submitted to AMT, preprint is available at egusphere

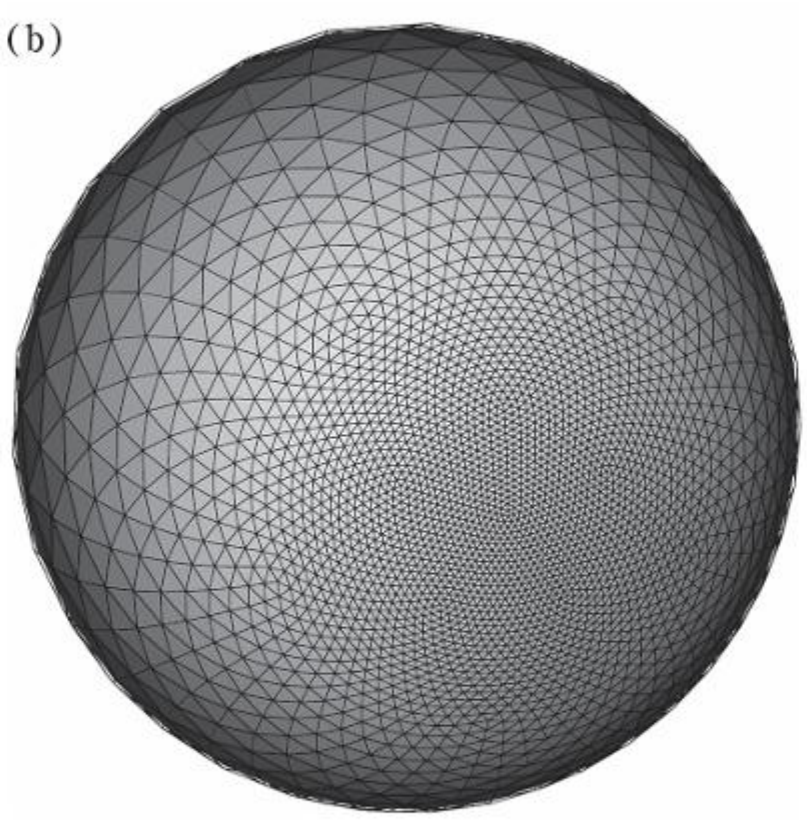
- Slope increases with Ta➔ Possibly universal
- Regional slope differences reflect unique microphysical characteristics

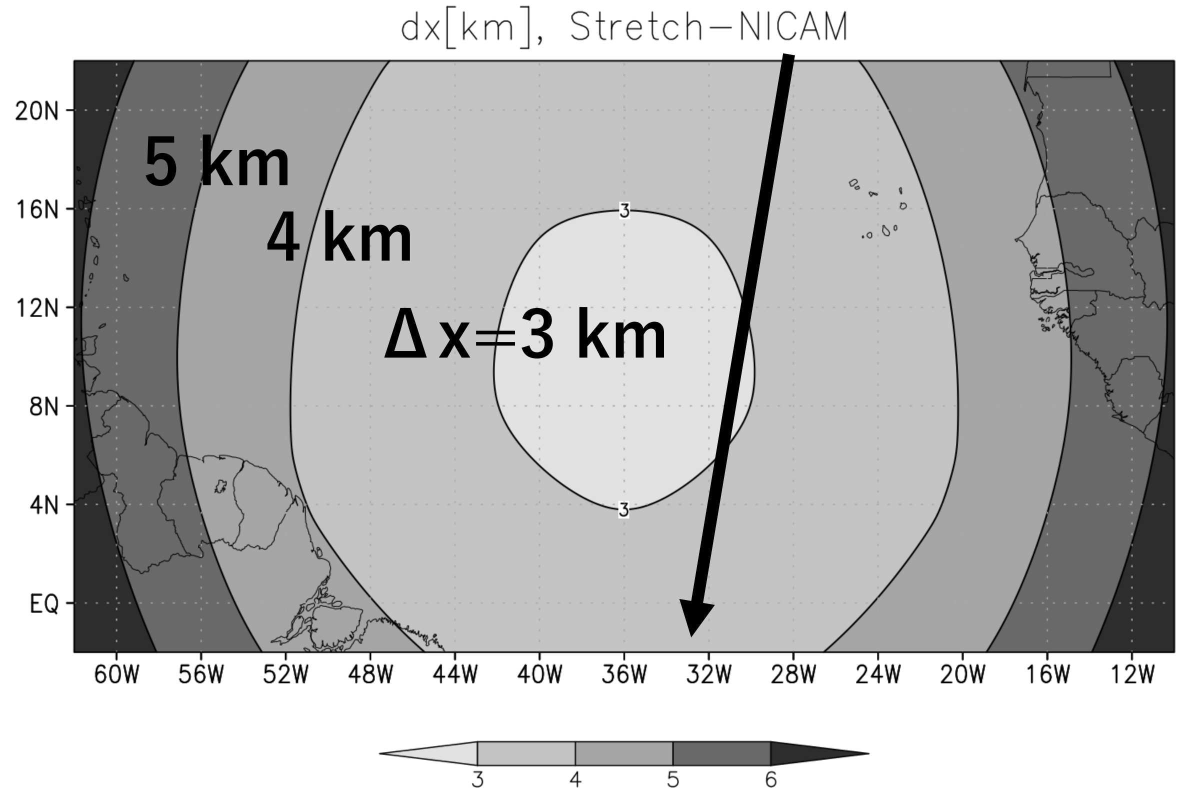
➢ Slope is useful as a quantitative metric for climate model evaluation (e.g., application to ECOMIP)

This work was supported by the 'Promotion of observation and analysis of radio wave propagation' fund of the Ministry of Internal Affairs and Communications, Japan.

Backup slides

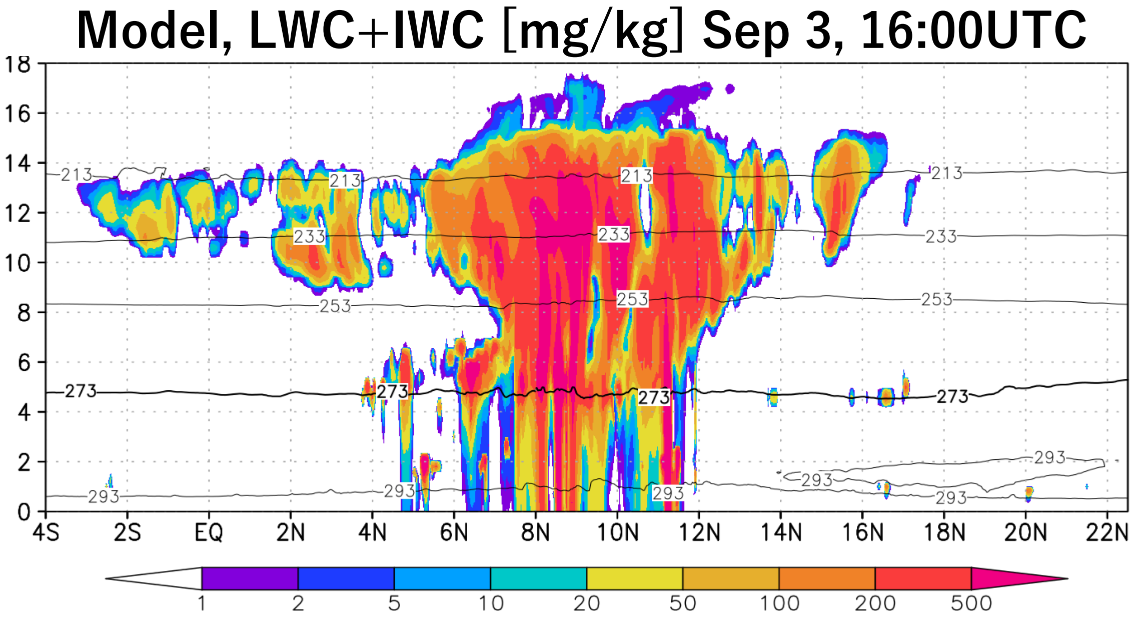
NICAM simulation for ECOMIP

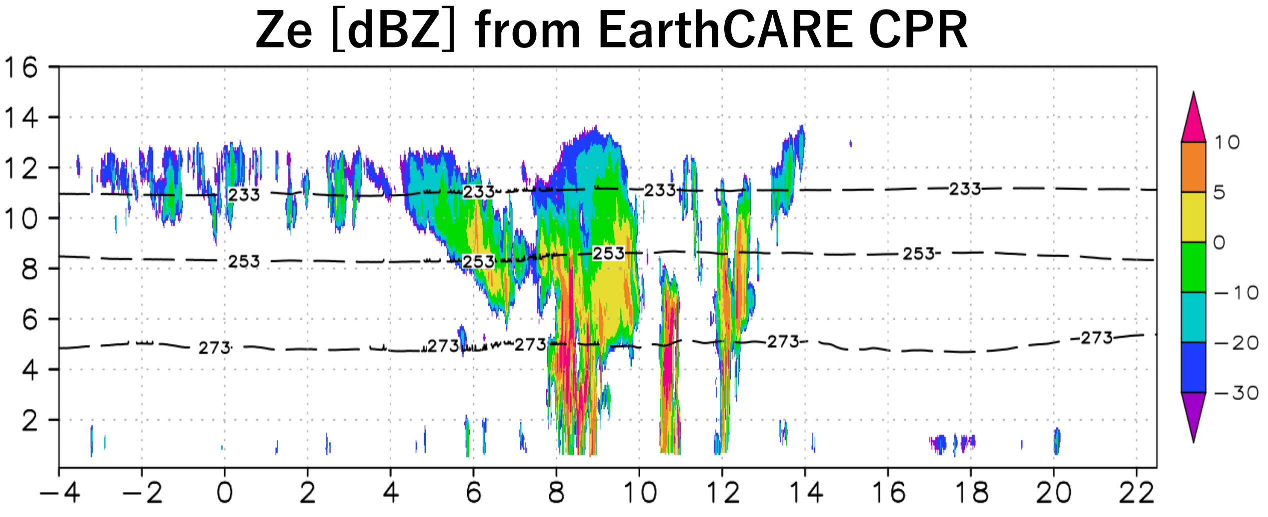


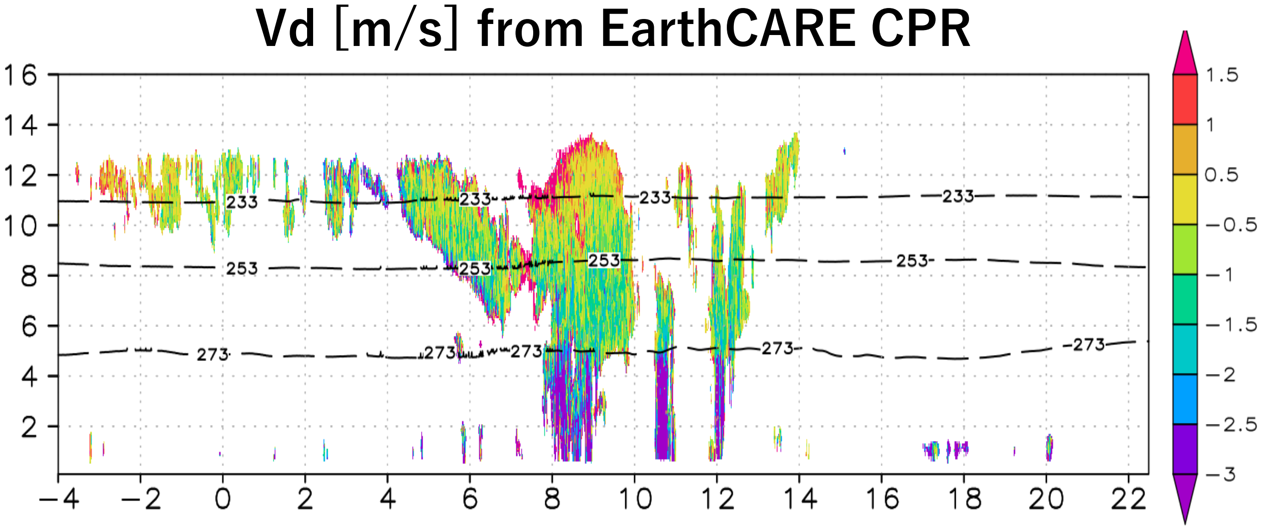


ECOMIP Phase 1 case (16:00UTC, Sep 2nd, 2024)
NICAM using 2-moment bulk cld. micro. with dx < 5km.

NICAM simulation for ECOMIP (dx<5km)



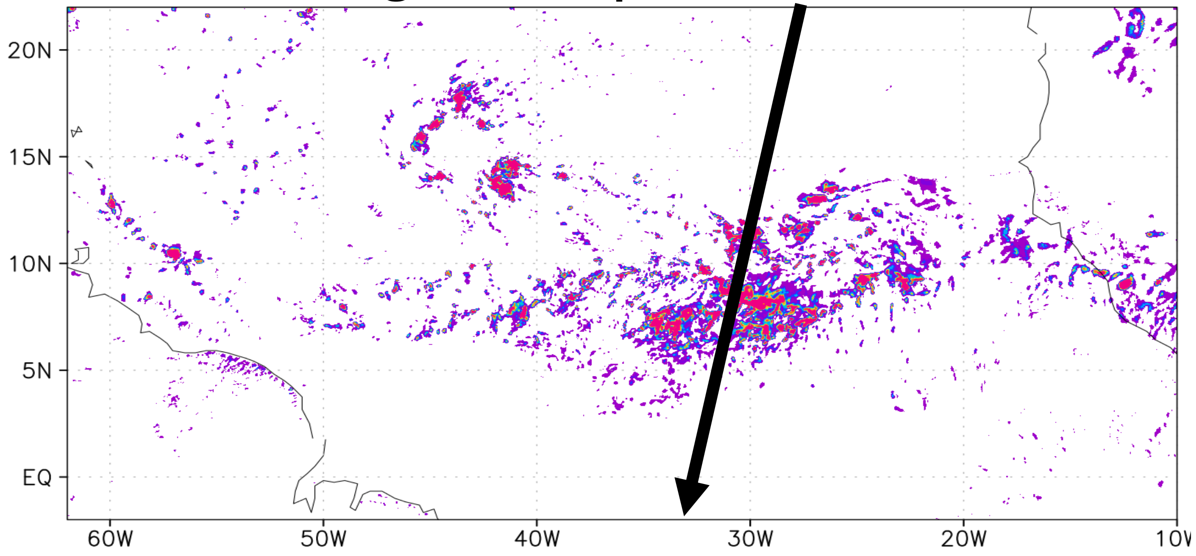




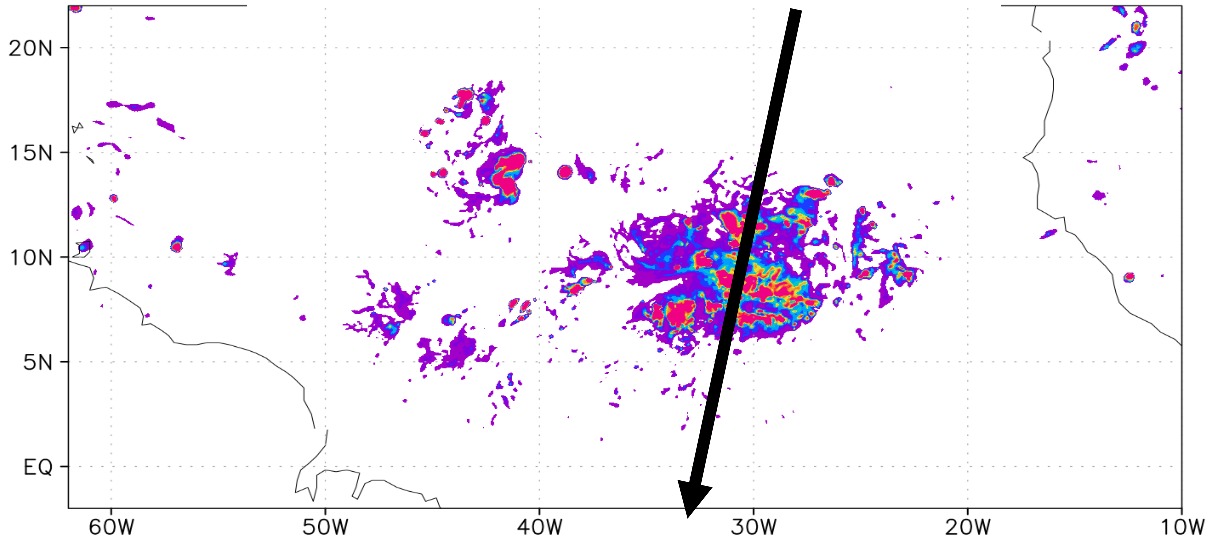
GrADS/COLA

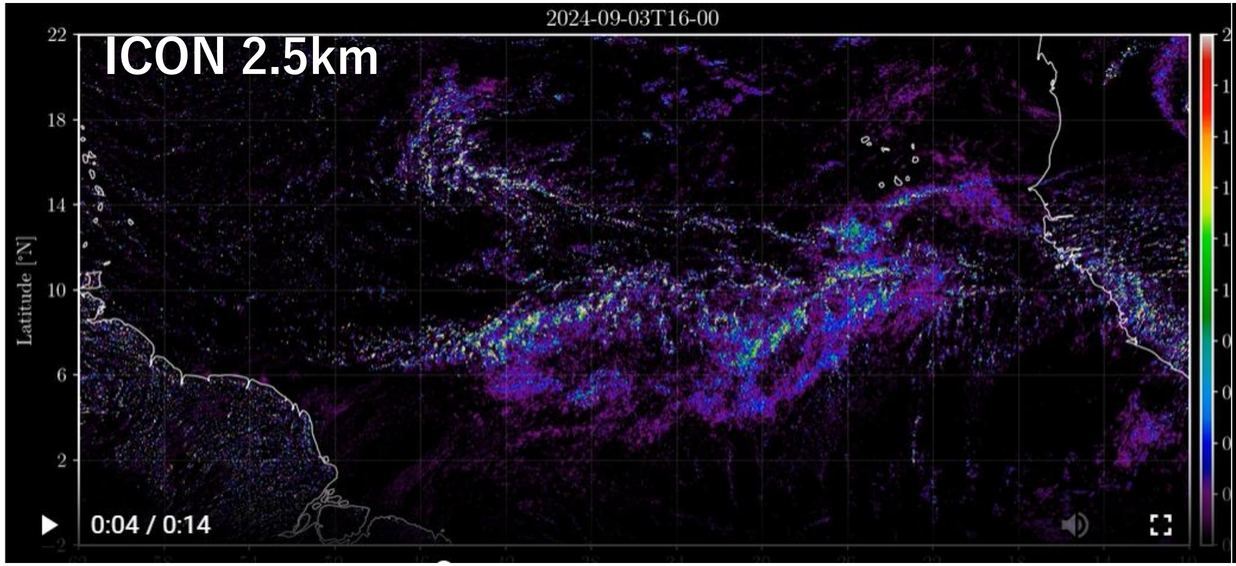
NICAM simulation for ECOMIP (dx<5km)

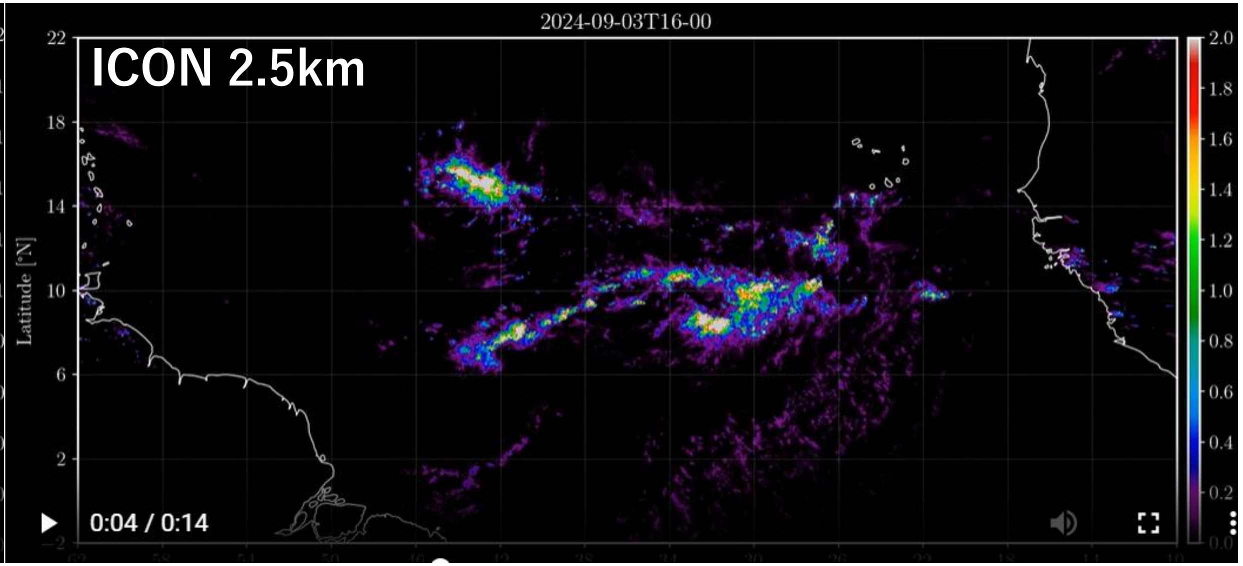
LWP[kg/m2], Sep 3, 16:00 UTC



IWP[kg/m2], Sep 3, 16:00 UTC

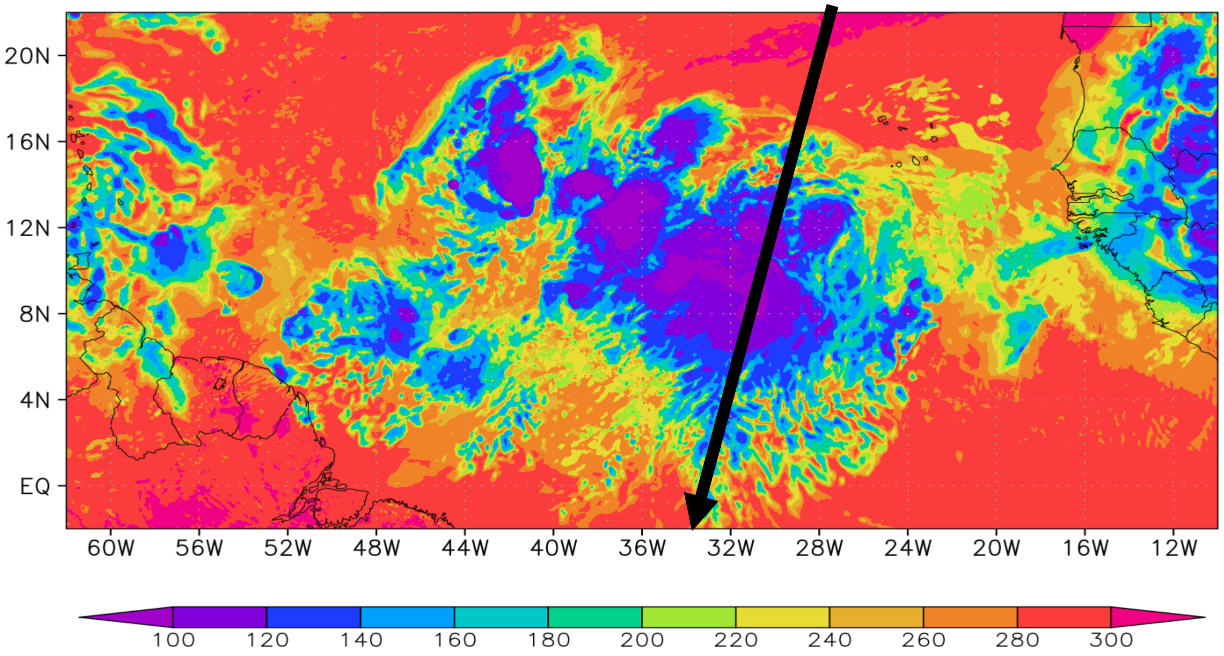


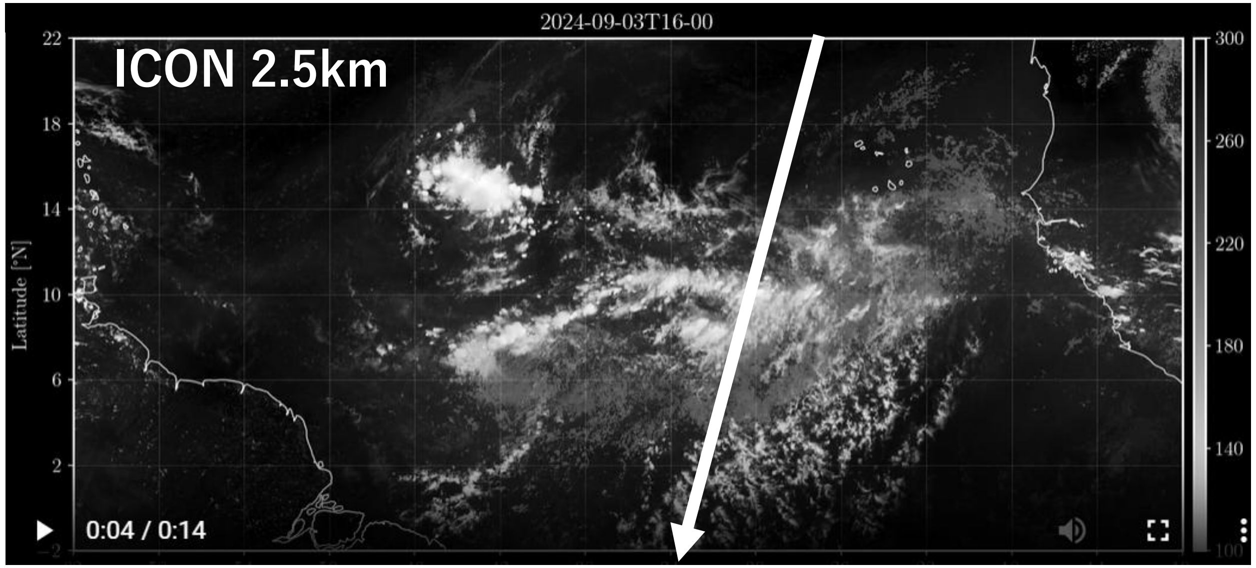




NICAM simulation for ECOMIP (dx<5km)

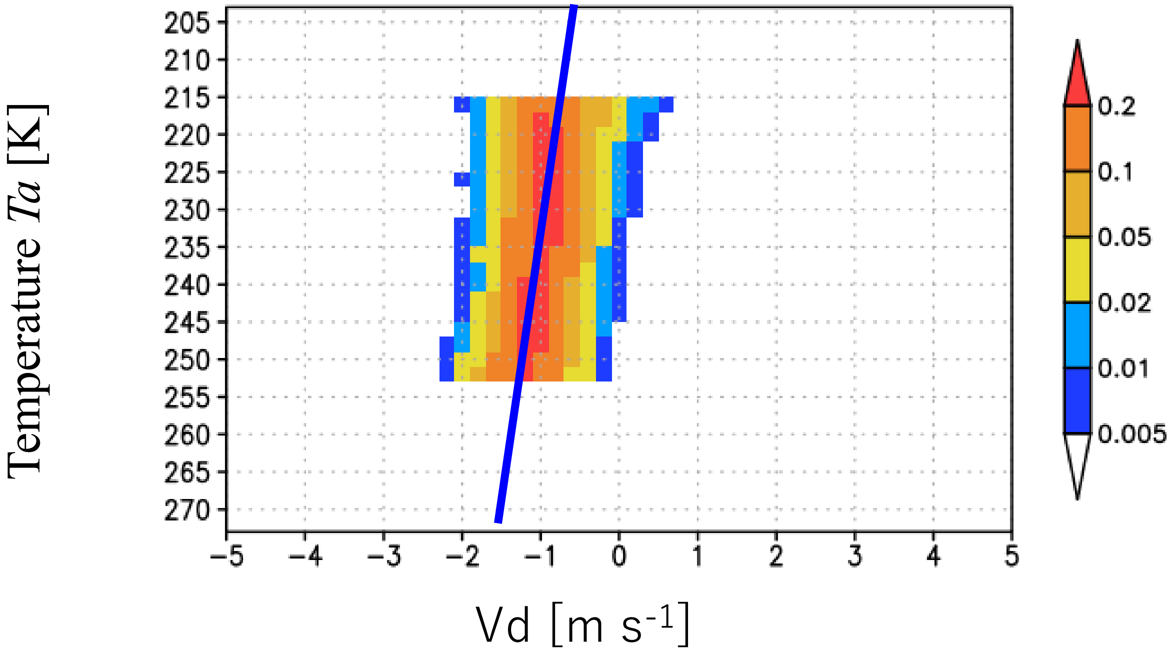
OLR[W/m2], Sep 3, 16:00 UTC





CFAD of doppler velocity

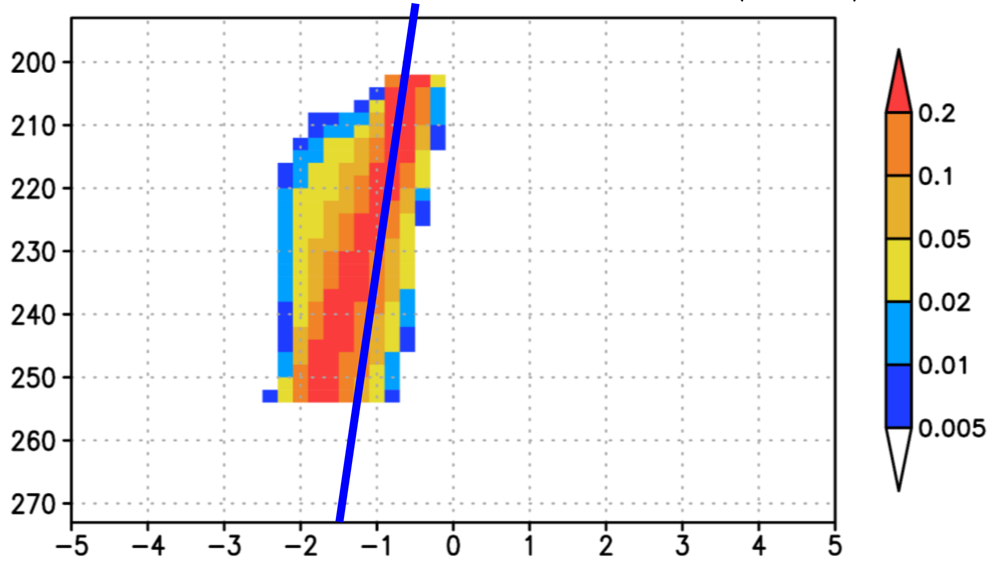
HG-SPIDER @ NICT in 2022



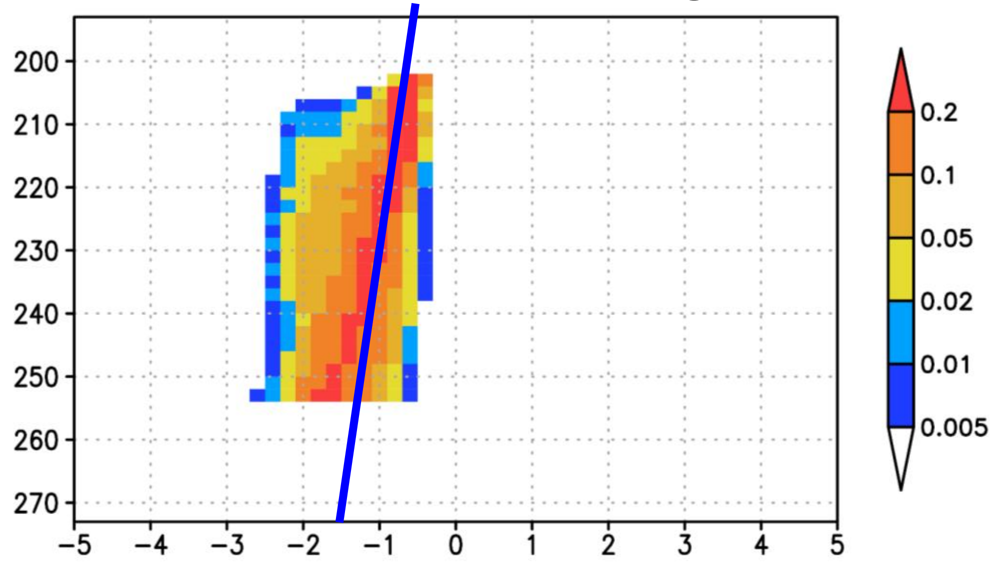
- Vd ~ -1 m s^{-1}
- Vd slightly decreases toward the cloud base
  - ➢ The v_d profile is improved by suppressing
    - aggregational growth (Seiki and Nagao, 2024)

✓ Doppler velocity is sufficiently sensitive to constrain ice cloud microphysics

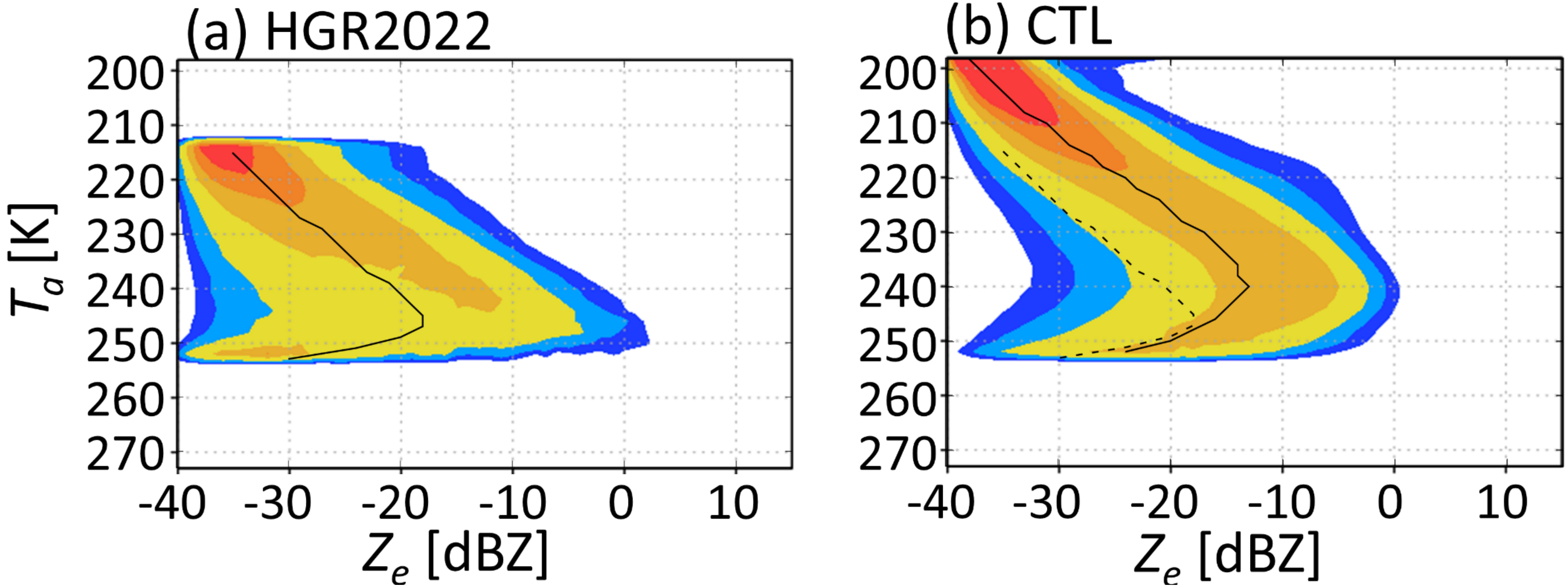
Simulation with Seiki and Ohno (2023)



Simulation with Seiki and Nagao(2024)



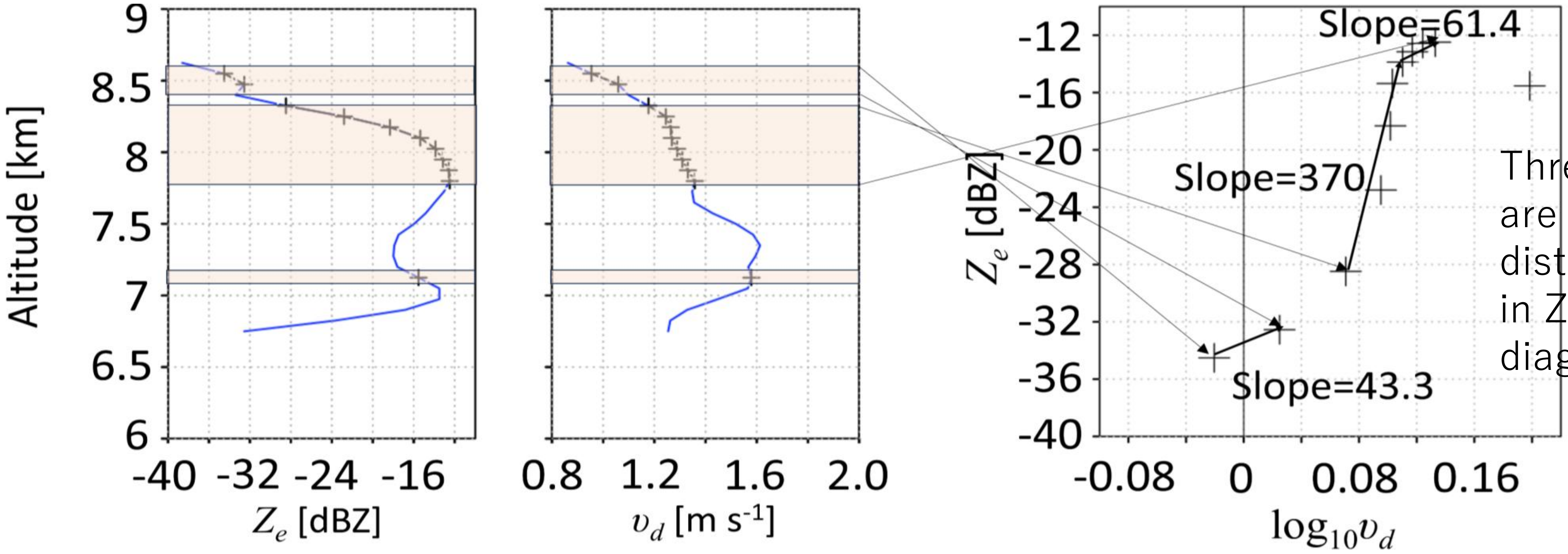
CFAD of Ze



(a) HGR2022
(b) CTL
200
210
220
230
240
250
260
270
T_a [K]
-40
-30
-20
-10
0
10
Z_e [dBZ]

From EORA3 Achievements to EORA4 Breakthroughs

In-situ measurements



Three regimes are clearly distinguished in Ze-$\log_{10}$vd diagram.

EC-CPR can reveal the global picture of the growth regimes

Seiki et al. (2025)

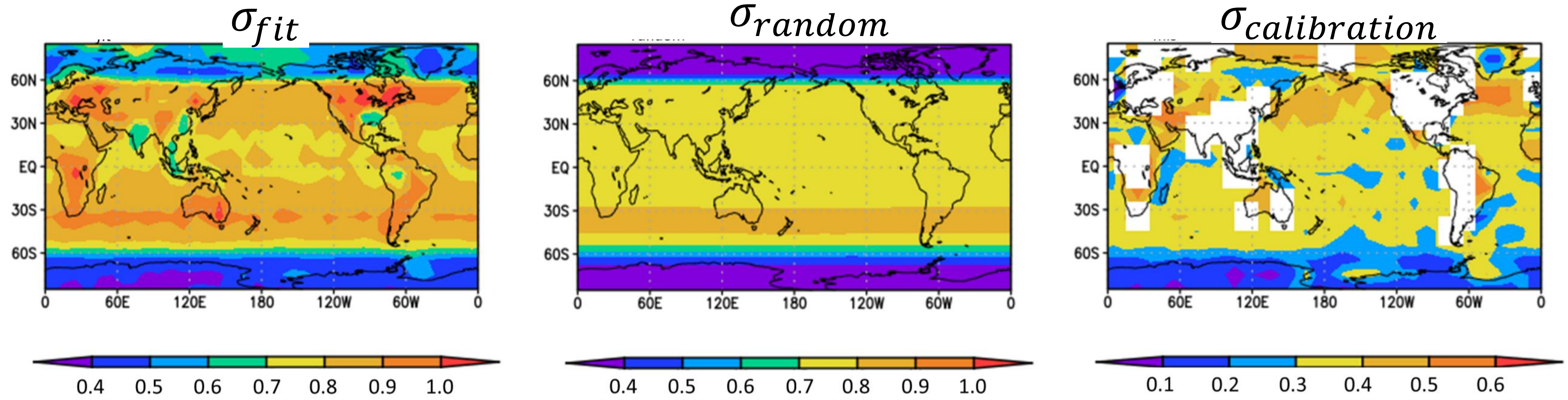
Random error in Doppler velocity measurements

(Seiki, Horie, Hagihara, Noda, Aoki, 2025, AMT-Preprint, under review)

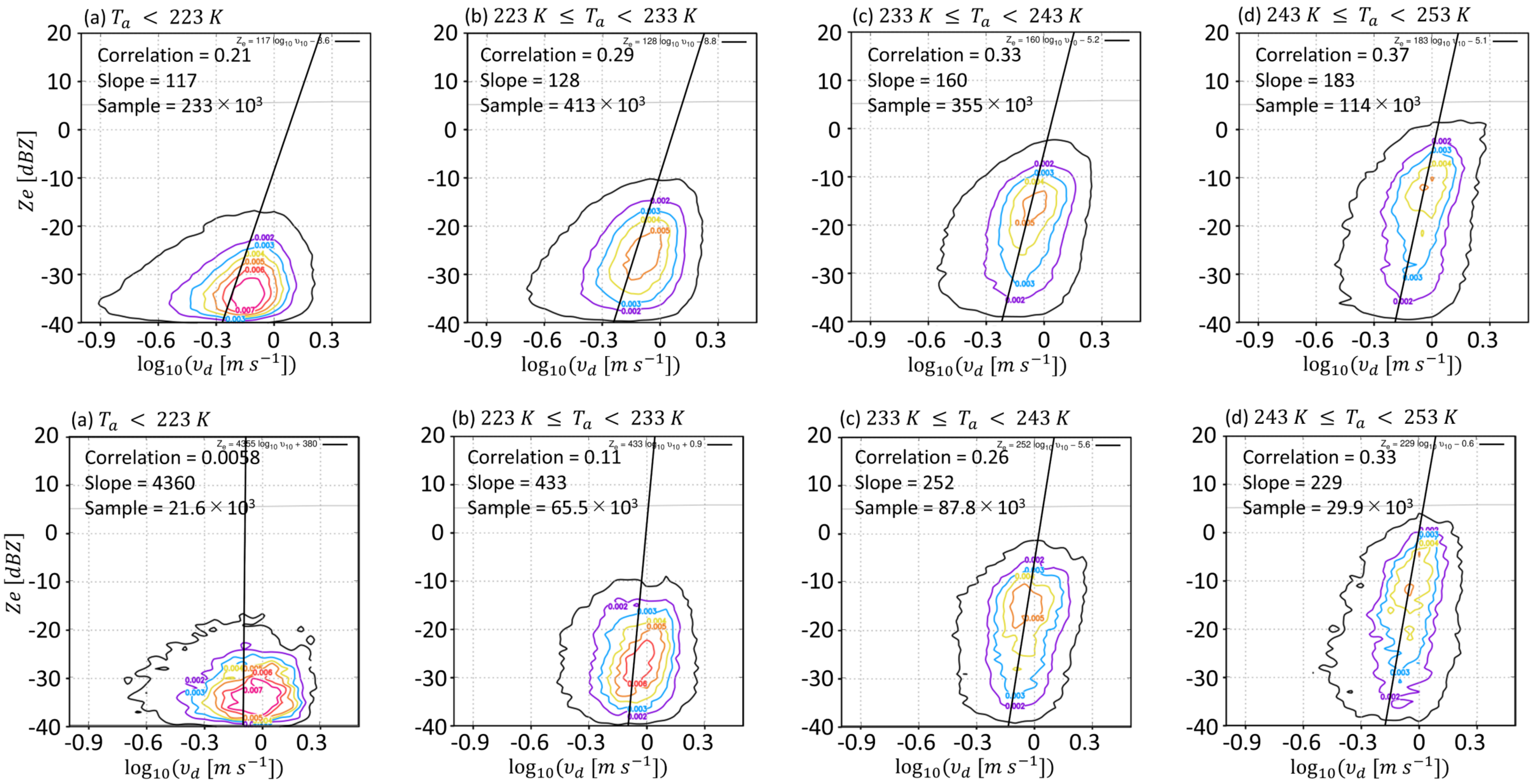
Measured Doppler velocity at surface $vd_{m,sfc}$ should be 0,

➔ Calibrated Doppler velocity at surface $vd_{c,sfc}$ is a measure of random error δv.

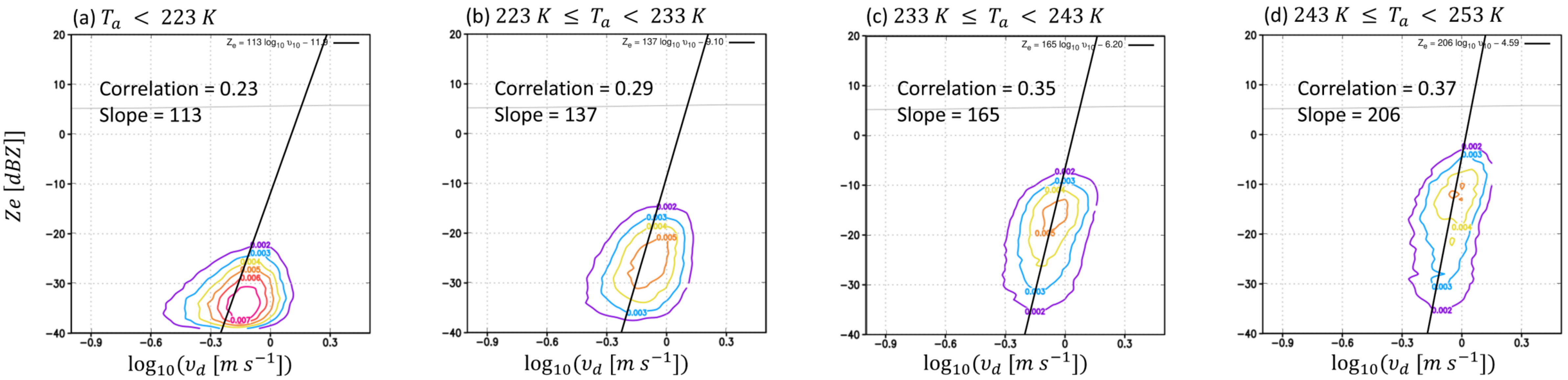
$$\sigma_{random} = C_{cor}\sqrt{\frac{\lambda^2}{32\pi^2 M_p \cdot \rho_{cor}^2 \cdot \left(\frac{1}{\mathrm{PRF}}\right)^2}\left\{\left(1+\frac{1}{S/N}\right)^2-\rho_{cor}^2\right\}},$$ (Hagihara et al., 2021)



Impact of Number of Samples on slope estimation



Joint PDF of Ze-$\log_{10} v_d$ across various temperatures

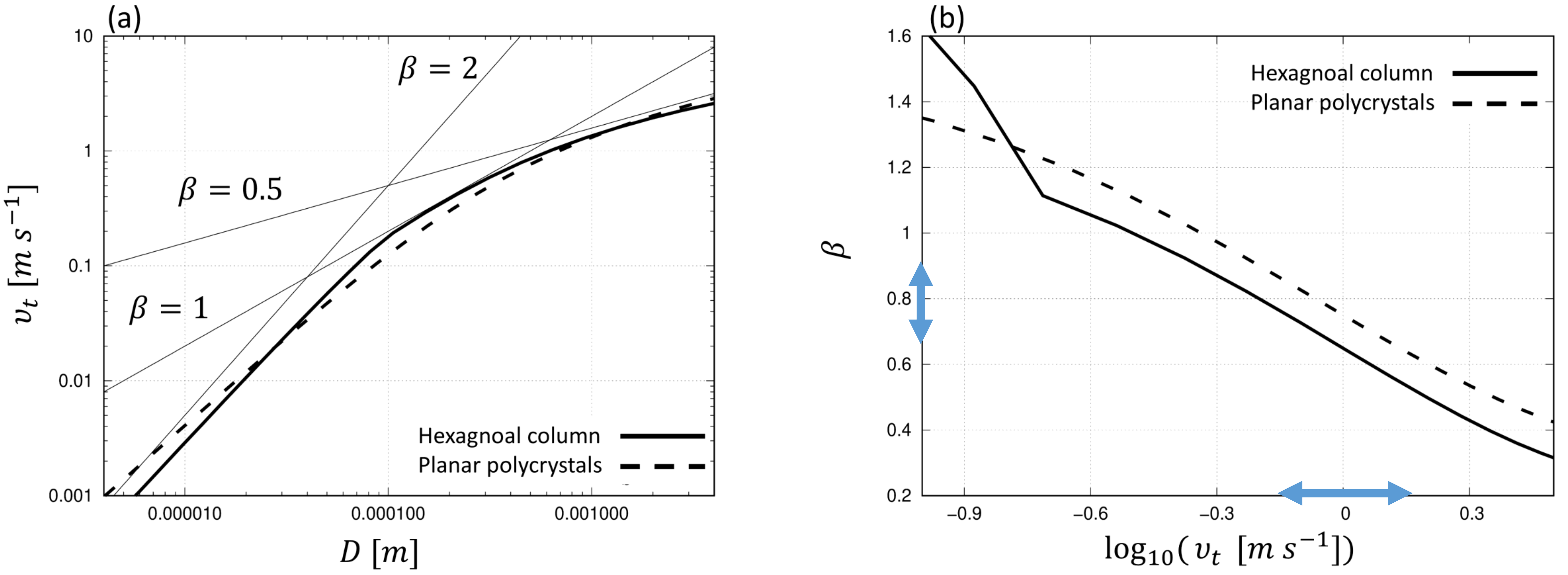


Representative slope is calculated by PCA of the Joint PDF.

✓ Slope steepens toward the cloud base.

1. Transition of the dominant growth modes
   - ➢ aggregation(30/ β) to vapor deposition(60/ β)
   - ➢ Is this related to a vapor rich condition in warm atmosphere?
2. Changes in β, related to a change in the particle size

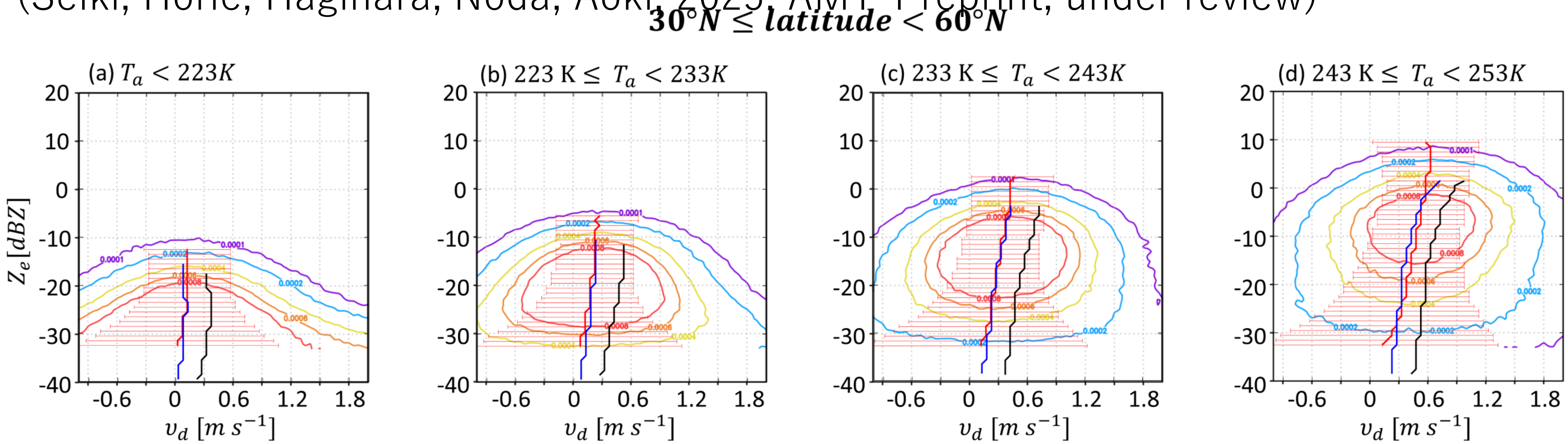
Changes in β, related to a change in the particle



In general, β ~2 in a smaller range and approaches 0.5 in a larger range.
Thus, β could change in the range from 0.7-0.9 in cirrus clouds.
➔ The significant changes in the slope (113-206) cannot be explained by only the change in β, indicating the change in the dominant microphysics.

Ze-vd diagram from EC-CPR

(Seiki, Horie, Hagihara, Noda, Aoki, 2025, AMT-Preprint, under review)



Evaluation of the method by sensitivity experiments using NICAM

CTL：Latest ver. (Seiki and Nagao, 2024)
AGG：Aggregation is overestimated. (Seiki and Ohno, 2023)
DEP：Vapor deposition is suppressed with the molecular effect.