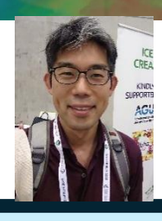
Dominant Ice cloud microphysical processes in cirrus clouds captured by ground Doppler radar observations

Tatsuya SEIKI[*1], Akira T. NODA[*1], Yuichiro HAGIHARA[*2], Hiroaki HORIE[*2]
*1Japan Agency for Marine-Earth Science and Technology
*2 National Institute of Information and Communications Technology



I have developed a double-moment bulk cloud microphysics scheme in a global climate model named NICAM
- Seiki and Ohno, 2023, JAS
- Seiki and Nagao, 2024, JAS

1. NEW Process Oriented Analysis

1-1. Ze-$\log_{10}\upsilon_d$ Diagram

Ze and $\log_{10}$ *ud* are linearly inter-related.

step1
$$Z = \int_0^\infty f(D)D^6 dD \propto N\overline{D^6} \propto M\overline{D^3}.$$
$$v_t \sim \alpha \overline{D}^{\beta}.$$

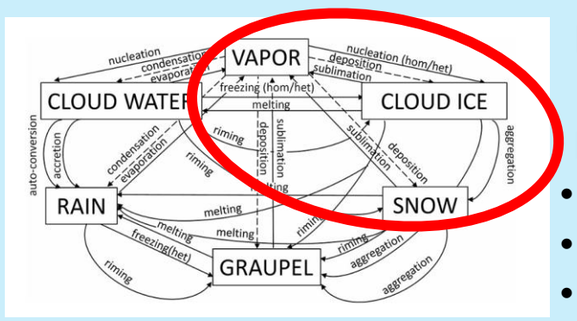
step2
$$Z_e[dBZ] = 10\log_{10} M + 30\log_{10}\overline{D} + c.$$
$$\log_{10} v_d \sim \log_{10} v_t \sim \beta \log_{10}\overline{D} + \alpha.$$

step3
$$\Delta Z_e[dBZ] \sim 10\log_{10} e \frac{\Delta M}{M} + 30\log_{10} e \frac{\Delta \overline{D}}{\overline{D}},$$
$$\Delta \log_{10} v_d \sim \log_{10} e\, \beta \frac{\Delta \overline{D}}{\overline{D}}.$$

Microphysical Sensitivity

GOAL
$$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{10}{\beta}\frac{\overline{D}}{M}\frac{\Delta M}{\Delta \overline{D}} + \frac{30}{\beta}$$

1-2. Identification of Ice Growth Mode



Major water substances in cirrus
Vapor, Cloud Ice, Aggregates

Major Microphysical Processes
- **Sublimation/Deposition**
- **Aggregation**
- Sedimentation

Aggregational Growth Mode

$$\frac{\Delta Z_e}{\Delta \log_{10} v_d} = \frac{30}{\beta}$$

The total mass concentration does not change while the mean particle size increases. ➔ The 1st term is negligible.

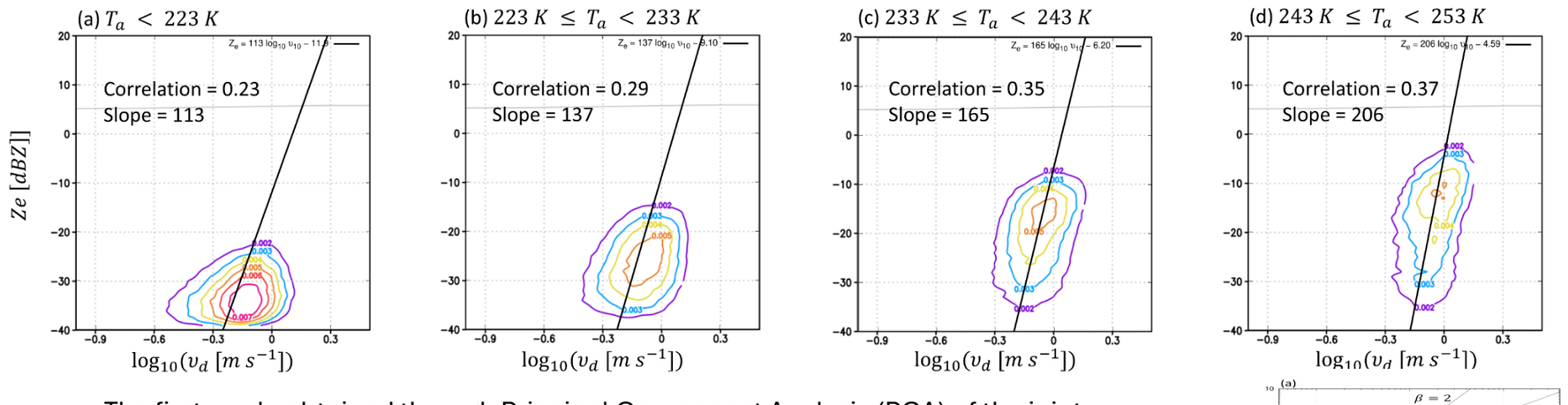
Depositional Growth Mode

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

The mass conc. increases as the particle size increases since the number conc. does not change.

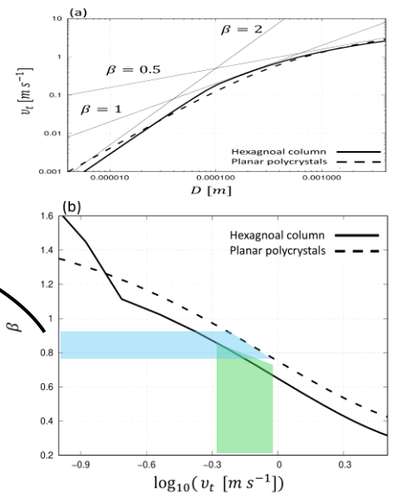
$M \sim \frac{\pi}{6}\overline{D}^3 \rho_i N \qquad \frac{\Delta M}{\Delta \overline{D}} \sim \frac{\pi}{2}\overline{D}^2 \rho_i N$

2. Examination using Ground Doppler Radar Observations



- The first mode obtained through Principal Component Analysis (PCA) of the joint probability density function corresponds to the slope.
- The slope gradually increases as the atmospheric temperature increases.
  ➔The dominant growth mode gradually changes from aggregation to vapor deposition as particles fall to the cloud base

ISSUES
1. β could increase by approximately 30 % in the typical range of $\log_{10}$υt.
   This transition of β cannot explain the large increment in the slope values from 113 to 206.
2. Non-spherical ice shape: Assuming $m \propto D^2$, ΔZ_e formulation is modified as follows:
   $\Delta Z_e = 10\log_{10} e \frac{\Delta M}{M} + 40\log_{10} e \frac{\Delta \overline{D}}{\overline{D}}$.
   This change has a minor impact on our interpretation.



Ground Doppler radar observations
HG-SPIDER has been operated by NICT (35.7° N, 139.5° E) for ground-based verification of EC-CPR. This study analyzed annual data for 2022 with a temporal integration of 1 minute. Cloudy pixels were identified using a radar reflectivity threshold greater than -40 dBZ.

Sampling Method
Ice particles in cirrus clouds are growing while falling. In this study, the atmospheric temperature is used as the vertical coordinate instead of the altitude. Therefore, the growth mode is defined as an increase in the equivalent radar reflectivity Z_e [dBZ] and Doppler velocity υ_d with an increase in the atmospheric temperature as follows:

$$\frac{\partial Z_e}{\partial T_a} > 0,\ \frac{\partial \log_{10}\upsilon_d}{\partial T_a} > 0,\ \upsilon_d > 0.$$

Here, υ_d is positive downward.

3. Evaluation using Numerical Simulations

3-1. Model Setup

NICAM with dx=14km. 9-day global simulations in four seasons were analyzed.
- CTL-EXP : The control experiment with the double-moment bulk MP scheme.
- AGG-EXP: Aggregation is significantly overestimated.
- DEP-EXP : Vapor deposition is significantly suppressed.

The theoretical basis of Ze-log10ud Diagram was validated.
1. A common feature:
   - An increase in slope with increasing atmospheric temperature.
2. Microphysical Sensitivity
   - The slope becomes smaller in AGG.
   - The reduction in vapor deposition (DEP) leads to a decreased slope.

3-2. Model Results

4. Summary

This study proposes an analysis method based on simultaneous observations of radar echo and Doppler velocity. The first mode obtained from PCA analysis of the joint probability density function of Z_e and $\log_{10}\upsilon_d$ ($\frac{\Delta Z_e}{\Delta \log_{10}\upsilon_d}$) is shown to effectively characterize the dominant microphysical processes in ice clouds.

Expectations for the EarthCARE Satellite
- Contrasting characteristics of cirrus clouds between the tropics and mid-latitudes may offer new insights into the microphysical processes governing high clouds.
- This method is to be applied to other non-convective cloud systems, as well.

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