Development of algorithms for air-motion, ice sedimentation and microphysics using lidar and radar

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ABSTRACT

Ice cloud microphysics and air motion ($V_{air}$) derived by lidar-radar technique and by single use of radar are compared at the same resolution pixel. Their drawbacks are the severe attenuation by precipitation and water clouds for the lidar-radar method (LRM) and $V_{air}$ effect for the radar-multi-parameter method (RMM). We developed an algorithm for radar and lidar where LRM and RMM are combined. In order to improve the accuracy of the retrieved microphysics for the whole part of clouds, effective radius ($r_{eff}$) from LRM is used to estimate the $V_{air}$ and then is incorporated in RMM to derive $r_{eff}$, ice water content ($IWC$), particle shape and $V_{air}$. The combined algorithm is applied to lidar and radar data onboard Research Vessel MIRAI (JAMSTEC) obtained in the Tropics, Mid-latitude and the Arctic to evaluate the vertical structure of ice cloud microphysics in GCM along the cruise tracks. From the comparisons of the observation and the model, it is found that the model’s cloud microphysics have narrow frequency distribution with large peak value, over-/under predicts the in-cloud $IWC$ at lower-/upper altitudes and over-/under predicts $r_{eff}$ at upper-/lower altitudes. Further analysis of the cause and effect of the simulated microphysics will be examined by information on the sedimentation velocities of ice particles.

1. INTRODUCTION

To understand how ice cloud vertical structure interacts with the climate, validation of the simulated ice clouds in global models is necessary. Recently, techniques for climate model validation by observation from active sensors has been studied for cloud macro-scale structure and its microphysics accumulated in the atmospheric column. For example, studies of [1], [2] used radar or radar and lidar to compare cloud occurrence and their amounts in ECMWF (European Center for Medium-Range Weather Forecasts) model over land. Similarly, in the study of [3], comparison between the observed and simulated radar reflectivity factor ($Z_r$) and lidar backscattering coefficient were performed for clouds over ocean in mid-latitude. These enabled estimates in the reproducibility of the $r_{eff}$ and grid scale $IWC$ in the model in an indirect way. In this study, we aim at validating model’s ice cloud microphysics directly.

For such purpose, reliable estimate in ice cloud microphysics and air motion ($V_{air}$) at various scales is necessary since they are both related to each other to the formation and maintenance mechanisms of ice clouds. It is shown that using multi-parameter, i.e., $Z_r$, Doppler velocity ($V_D$) and Linear depolarization ration (LDR), in 95-GHz Doppler radar has high potential in estimating microphysical properties of ice particles as well as their sedimentation velocities [4]. However, there exist some area of improvement to derive $V_{air}$ for the whole cloud. Therefore, LRM of Tohoku University [5] is used in combination with the developed RMM to improve the retrieval.

In section 2, procedure of the method is briefly described. In section 3, the retrieval results and validation of ice clouds in GCM are discussed. Finally, summary of our results is given in section 4.

2. PROCEDURE

In preparation to providing detail of the combined algorithm used in this study, performance in the microphysical properties and $V_{air}$ retrieval by RRM nd LRM are compared.

2.1 Microphysics and $V_{air}$ retrieval

Comparison between the retrieved microphysics for LRM and RMM are performed against the same in-situ dataset for $IWC$ in mid-latitude during APEX-E3/ECAV campaign and $r_{eff}$ and $IWC$ by applying them to ship-borne data [4]. It is noted that RMM can estimate the particle habit where co-existence of column and bullet rosette types is assumed and the mixing ratio of the two types (MX) vary. The results showed that both retrieval algorithms

Fig.1 Comparison between $r_{eff}$ obtained by RMM and LRM for ship-borne data.
perform comparatively well for a vast range of observed particle sizes, i.e., within ±20%.

### 2.1.1 RMM

Several methods for $V_{\text{air}}$ retrieval for ice clouds by cloud radar exist (e.g., method using Doppler width [6], method correcting $V_D$ by assuming the upward $V_D$ to be $V_{\text{air}}$ [7]), though reliable method seems to have not yet been established. Therefore, for the RMM algorithm, $V_{\text{air}}$ is retrieved by a simple iterative approach for each observation record similar to the study of [7]. The main concept is that, when $V_{\text{air}}$ is negligible, $V_D$ equals the reflectivity-weighted particle falling velocity ($V_{p}$) so that the observed $V_D$ should be negative (downward) velocity. Therefore, since positive part of $V_D$ should contain the information of upward $V_{\text{air}}$, the velocity of the ice particles in the same cloud and same time record is iteratively adjusted according to the mean value of the remaining upward velocities. Note that this is done only for particles that have $V_D$ smaller than the mean upward value in magnitude, which accounts for the inhomogeneity in $V_{\text{air}}$ as reported by wind profiler measurements. Fig. 2 shows the retrieved $V_{\text{air}}$ from RMM by using radar onboard vessel MIRAI in May 21, 2001 during two weeks cruise in mid-latitude (cruise MR01K02).

#### 2.1.2 Method for LRM

For the LRM, $V_{\text{air}}$ is derived by comparing the estimated $V_{p}$ from the derived $r_{\text{eff}}$ with $V_D$. It is noted that the same particle habit as the results from the RMM (MX) is used here, since LRM does not provide this information. This method has the advantage of directly deriving the positive and negative $V_{\text{air}}$. Fig. 3 is an example of the retrieved $V_{\text{air}}$ as a function of height for LRM observed by lidar and radar for the same cruise data as in subsection 2.1.1.

### 2.2 Comparison of $V_{\text{air}}$ by the two methods

Fig. 4a shows the comparison between the frequency distribution of the retrieved $V_{\text{air}}$ by RMM and LRM. The data is the same as in subsection 2.1. The result shows that RMM underestimates $V_{\text{air}}$ compared to that of LRM at most cases. In order to examine the sensitivity of the effects of particle habit in the retrieved $V_{\text{air}}$ for the LRM case, we considered two other habit types. Namely, plate (PL) and sphere (SP), which are expected to provide the minimum and maximum thresholds for the particle fall velocity for the same mass. In Fig. 4b, the mean ratio and its dispersion of $V_{\text{air}}$ for RMM to that for LRM are plotted for size bins retrieved by LRM for the same data in Fig. 4a. For relatively smaller to moderate size range, both methods estimate comparable $V_{\text{air}}$. It turns out that the underestimation of $V_{\text{air}}$ for RMM compared to that of LRM is found for large $r_{\text{eff}}$ despite the particle habit. When $V_{\text{air}}$ for RMM is smaller than that for LRM, $V_{\text{air}}$ for RMM is also smaller than that for LRM provided that $V_{\text{air}}$ is positive. Therefore, it is concluded that the underestimation in $V_{\text{air}}$ in RMM is primarily due to the large particles.

It should be noted that there is a deficiency in LRM where sphere is assumed in the look-up table (LUT) for the particle sizing and that uncertainty in the estimation of the multiple scattering effect on lidar signal may cause some difference between the two methods. In addition to the above discussion, the RMM cannot retrieve $V_{\text{air}}$ for records with no positive $V_D$ pixels. These indicate that combining lidar information with the radar-only approach will be effective to construct $V_{\text{air}}$ and microphysics for the entire clouds.

#### 2.3 Combined method for microphysics and $V_{\text{air}}$ retrieval

Here, the method combining LRM and RMM is briefly described. The method simultaneously retrieves four unknowns ($r_{\text{eff}}, IWC$, shape and $V_{\text{air}}$) by four observables from radar and lidar. The input data are the observed lidar and radar signals and the LUTs for the interpretation for lidar and radar observables. First, possible sets of $V_{\text{air}}$ and particle habit are determined from the LUT for LRM, while similarly, candidate of $r_{\text{eff}}, IWC$, particle type are
specified from the LUT for RMM at the same time. Then the solution will be the combination that satisfies both LUTs. The retrieved $V_{air}$ is further used for the analyses of the whole layers.

Example of the observed $V_D$ and the derived $V_z$ after $V_{air}$ correction is shown in the following figures (the retrieved microphysics are not shown). It can be seen that $V_D$ (Fig 5a) includes large portion of positive velocity, which is effectively removed after correction (Fig 5b).

Fig. 5 Time-height plots for the measured $V_D$ (a) and estimated $V_z$ after correction of $V_{air}$ (b) in Sep. 21, 2001 in mid-latitude.

3. APPLICATION

3.1 Latitudinal characteristic of retrieved ice cloud microphysics

The developed method is applied to Research Vessel MIRAI data obtained over the Tropical Western Pacific for three months in 2001 (cruise MR01K05), two weeks data in the North-East off shore Japan in 2001 (cruise MR01K02) and one month observation in the Arctic in 2002 (MR02K05). In all latitudes, ice cloud could be observed at least to altitudes near the tropopause. The $r_{eff}$ varies from few $\mu$m in all latitudes to 80 $\mu$m in the polar region and to over 100 $\mu$m in tropics and mid-latitude. The most frequent value for $r_{eff}$ is found at sizes around 30 $\mu$m despite the regions, but the mean $r_{eff}$ in the vertical and the dispersion of the frequency distribution for $r_{eff}$ are smallest in the polar region, and are largest in the mid-latitude. Most of the observed $IWC$ are between 10$^4$ and 1 g m$^{-3}$. Smaller/larger values in $IWC$ compared to other regions are frequently found in the polar region/tropics, while the broadest dispersion of the frequency distribution for $IWC$ is found in mid-latitude.

3.2 Validation of GCM

The cloud microphysics described in subsection 3.1 were compared with those estimated by SPRINTARS, which is an aerosol transport model on the basis of CCSR-NIES-FRCGC Atmospheric General Circulation Model along the cruise tracks in its prediction mode (temperature, pressure, and relative humidity estimated in SPRINTARS are nudged with NCEP/NCAR reanalysis data for each six hours, and $r_{eff}$ of ice clouds are fixed to 40 $\mu$m for radiation calculation). In order to compare the microphysics from the model, the radar signal is first estimated and then the model output is selected provided that the signal is beyond the radar sensitivity. We compared $r_{eff}$ in-cloud/grid-mean $IWC$ ($IWC_{IN}/IWC_{GM}$), and Cloud fraction ($CF_{inv}$). Fig. 6a shows the simulated and observed time-height cross section for $IWC_{IN}$ obtained for the whole period at mid-latitude.

Fig. 6 Time-height plots for observed (a.) and simulated (b.) $IWC_{IN}$ in logarithmic.

The cloud fields are relatively well reproduced, though rather overestimation near cloud boundaries are seen in SPRINTARS. For the microphysics, SPRINTARS seems to over/under-estimate the $IWC_{IN}$ at lower/higher altitudes. To further investigate the validity of the ice cloud scheme in SPRINTARS, comparisons are provided for their vertical structure and frequency distribution against observation (Fig. 7a and b, respectively).

Fig. 7 Observed and simulated mean vertical profile (a.) and frequency distribution (b.) for $IWC_{IN}$.
It is seen that the change in the over- and under-estimation in the mean IWC$_{\text{IN}}$ is bounded somewhere between 8 to 9 km. It may be possible that the mean IWC is affected by the large values and the comparison of the mean IWC may only reflect the validity of large IWC. Therefore in order to examine the validity of clouds with small IWC, we also performed the comparison on the frequency distribution of IWC$_{\text{IN}}$ between observation and the model. It is found that SPRINTARS tends to produce larger IWC$_{\text{IN}}$ with narrower dispersion compared to that observed. This feature is also found for the tropics case (Figures not shown). Tendency in the vertical distribution of the signs for under-over prediction of the IWC$_{\text{GM}}$ in SPRINTARS were similar among latitudes. Comparison in the macro-scale properties indicates that the features in the simulated cloud microphysics seemed to be related to the high frequency of occurrence of convection in the tropics, while it may be related to the problem in the generation mechanism of precipitating clouds in mid-latitude. Further investigation into how these discrepancies arise and how these affect the estimation in the cloud radiative properties, cloud formation and duration in the model will be a future target.

4. SUMMARY

Combined usage of the lidar-radar technique (LRM) and the radar-only method (RMM) was performed for effective retrieval of ice cloud microphysics, sedimentation velocity and $V_{\text{air}}$. Our findings are briefly summarized as follows:
1. Comparisons of the LRM and RMM derived $V_{\text{air}}$ showed that RMM may underestimate it for large $r_{\text{eff}}$. This is considered to be due to the small relative error in velocity for large particles and partly due to multiple scattering and non-sphericity effects in lidar.
2. Fraction of the $V_{\text{air}}$ retrieved pixels to the whole observed ones drastically increased by combining RMM with LRM compared with the previous algorithms.
3. Analyzed ice clouds observed by the ship-borne lidar and radar systems revealed the following features: the most frequent value of the retrieved $r_{\text{eff}}$ does not show much latitudinal dependence and lies around 30 μm: both frequency distribution and mean vertical profile for $r_{\text{eff}}$ show the existence of larger ice particles in mid-latitude among regions: number of large IWC is found in tropics compared with other two regions.
4. Simulated ice microphysics is validated against the retrieved one. Notable differences could be seen in the frequency distribution and mean vertical profile of the microphysical properties. The observed vertical profiles of the IWC$_{\text{IN}}$ show rather homogeneous structure compared with those of the model in both tropics and mid-latitude. The shape of the frequency distribution for simulated IWC$_{\text{IN}}$ is narrower than actual, suggesting the problem in the formation and dissipation mechanism of ice clouds simulated by SPRINTARS in both regions.

Further validation and analyses of the algorithm will be conducted by $V_{\text{air}}$ directly measured by the Equatorial Atmosphere Radar (EAR) in collaboration with the Research Institute for Sustainable Humanosphere (RISH) of Kyoto University. Also, characterization of lidar depolarization in relation to the retrieved microphysics, e.g., particle shape will be reported.

REFERENCES