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

Kaori Sato [(1)], Hajime Okamoto [(1)], Toshihiko Takemura [(2)], Nobuo Sugimoto [(3)], Hiroshi Kumagai [(4)]

[(1)] *Tohoku University, Aoba, Aramakiaza, Aoba-ku, Sendai 980-8578, Japan, ksato@caos-a.geophys.tohoku.ac.jp*
[(2)] *Kyusyu University, 6-1 Kasugakouen, kasuga, 816-8580, Japan, toshi@riam.kyushu-u.ac.jp*
[(3)] *National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 305-0052, Japan, nsugimoto@nies.go.jp*
[(4)] *National Institute of Information and Communications Technology, Koganei, Tokyo, 184-8794, Japan, kumagai@nict.go.jp*

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_e) 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_e, 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

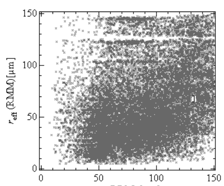


Fig.1 Comparison between r_{eff} obtained by RMM and LRM for ship-borne data.

perform comparatively well for a vast range of observed particle sizes, i.e., within ±20 %.

2.1.1 RMM

Several methods for V_{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_{air} [7]) though reliable method seems to have not yet been established. Therefore, for the RMM algorithm, V_{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_{air} is negligible, V_D equals the reflectivity-weighted particle falling velocity (V_{tz}) 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_{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_{air} as reported by wind profiler measurements. Fig. 2 shows the retrieved V_{air} from RMM by using radar onboard Vessel MIRAI in May 21, 2001 durring two weeks cruise in mid-latitude (cruise MR01K02).

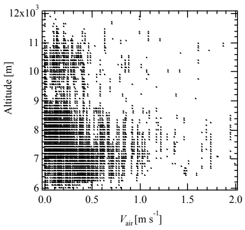


Fig. 2 Vertical distribution of V_{air} retrieved by radar. Positive denotes upward

2.1.2 Method for LRM

For the LRM, V_{air} is derived by comparing the estimated V_{tz} from the derived r_{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 the information. This method has the advantage of directly deriving the positive and negative V_{air}. Fig. 3 is an example of the retrieved V_{air} as a function of height for LRM observed by lidar and radar for the same cruise data as in subsection 2.1.1.

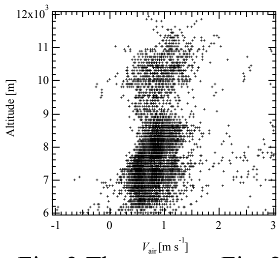
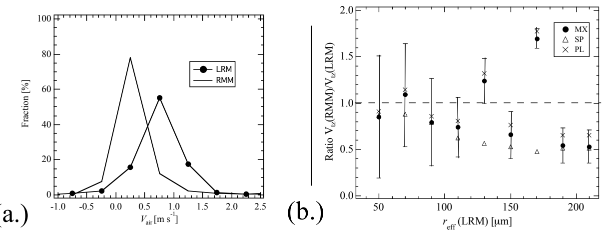


Fig. 3 The same as Fig. 2 but for LRM.

2.2 Comparison of V_{air} by the two methods

Fig. 4a shows the comparison between the frequency distribution of the retrieved V_{air} by RMM and LRM. The data is the same as in subsection 2.1. The result shows that RMM underestimates V_{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_{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_{tz} 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_{tz}. It turns out that the underestimation of V_{tz} for RMM compared to that of LRM is found for large r_{eff} despite the particle habit. When V_{tz} for RMM is smaller than that for LRM, V_{air} for RMM is also smaller than that for LRM provided that V_{air} is positive. Therefore, it is concluded that the underestimation in V_{air} in RMM is primarily due to the large particles.



(a.) (b.)

Fig. 4 Comparison of the frequency distribution for V_{air} (a.) and V_{tz} as a function of r_{eff} (b.) derived by RMM and LRM.

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_{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_{air} and microphysics for the entire clouds.

2.3 Combined method for microphysics and V_{air} retrieval.

Here, the method combining LRM and RMM is briefly described. The method simultaneously retrieves four unknowns (r_{eff}, *IWC*, shape and V_{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_{air} and particle habit are determined from the LUT for LRM, while similarly, candidate of r_{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_{tz} 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).

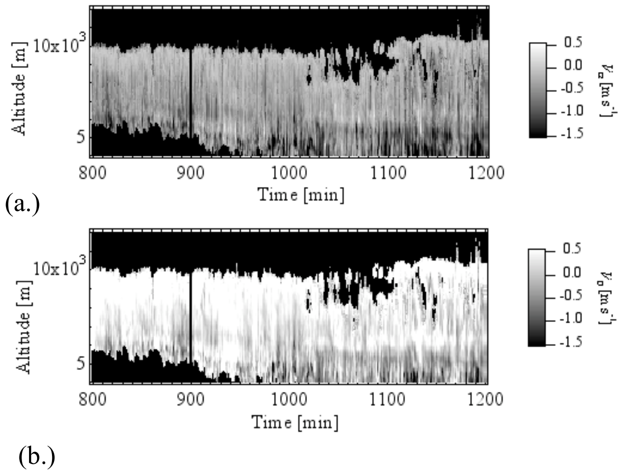


Fig. 5 Time-height plots for the measured V_D (a) and estimated V_{tz} after correction of V_{air} (b) in Sep. 21, 2001 in mid-latitude.

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 μm in all latitudes to 80 μm in the polar region and to over 100 μm in tropics and mid-latitude. The most frequent value for r_{eff} is found at sizes around 30 μm 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 μm 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_{ice}). Fig. 6ab shows the simulated and observed time-height cross section for IWC_{IN} obtained for the whole period at mid-latitude.

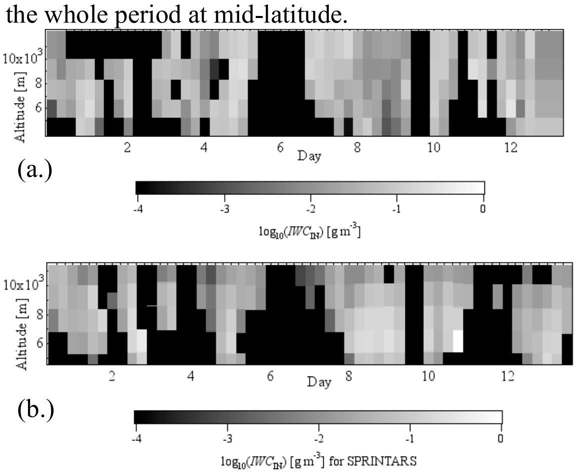


Fig. 6 Time-height plots for observed (a.) and simulated (b.) IWC_{IN} in logarithmic.

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).

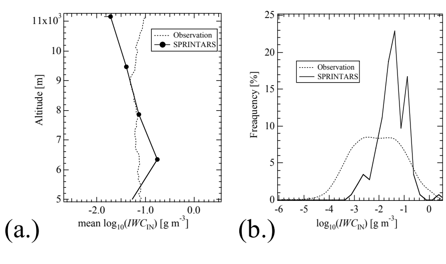


Fig.7 Observed and simulated mean vertical profile (a.)and frequency distribution (b.) for IWC_{IN}

It is seen that the change in the over- and under- estimation in the mean IWC_{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_{IN} between observation and the model. It is found that SPRINTARS tends to produce larger IWC_{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_{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_{air}. Our findings are briefly summarized as follows.

1. Comparisons of the LRM and RMM derived V_{air} showed that RMM may underestimate it for large r_{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_{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_{eff} does not show much latitudinal dependence and lies around 30 μm: both frequency distribution and mean vertical profile for r_{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_{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_{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_{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

[1] Mace, G. G., C. Jakob and K. P. Moran (), Validation of hydrometeor occurrence predicted by the ECMWF model using millimeter wave radar data, *Geophys. Res. Lett., 25,* 1645-1648, 1998

[2] Hogan R. J., C. Jakob, A. J. Illingworth, Comparison of ECMWF Winter-season cloud fraction with radar derived values, *J. Appl. Meteor., 40,* 513-525, 2002.

[3] Okamoto, H. et al., Cloud vertical structure obtained from the shipborne radar and lidar, : Part (I) Mid-latitude case study during Mirai MR01/K02 cruise of the R/V Mirai, submitted to *J. Geophys. Res*, 2005

[4] Sato. K, Ice cloud microphysics inferred from cloud profiling radar with multi-parameter functions, MS Thesis, Tohoku University, Center for Atmospheric and Oceanic Studies, 2006.

[5] Okamoto, H., et al., An algorithm for retrieval of cloud microphysics using 95-GHz cloud radar and lidar, *J. Geophys. Res., 108(D7), 4226,* doi:10 1029/2001JD001 225, 2003

[6] Gossard E. E, Measurement of cloud droplet size spectra by Doppler radar. J. *Atmos. Oceanic Technol*., **11**, 712-726, 1994

[7] Orr, B. W., and R. A. Kropfli, A method for estimating particle fall velocities from vertically pointing Doppler radar. *J. Atmos. Oceanic Technol*., 16, 29-37, 1999.

[8] Takemura, T., et al., Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model, *J. Geophys. Res., 110, D02202,* doi:10. 1029/2004JD005029, 2005.