MICROPHYSICS OF CLOUDS AND AEROSOLS BY COMBINED USE OF LIDAR AND CLOUD RADAR

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ABSTRACT

Active instruments such as lidar and cloud profiling radar are expected to provide new insights for the physical properties of clouds and aerosols and their roles in the climate system. These instruments can provide the detailed knowledge about the vertical structure of clouds and aerosols. In addition to the frequency of occurrence of clouds and aerosols, we also have developed several retrieval algorithms in oder to derive microphysics of clouds and aerosols: (1) radar-lidar algorithm for ice clouds, (2) radar-lidar algorithm for water clouds, (3) dual wavelength polarized lidar algorithm for aerosols, (4) dual wavelength lidar algorithm for ice clouds, (5) radar with multi-parameter method for ice clouds. We show the analyses of the observational data obtained by the Research Vessel Mirai from Tropical western Pacific to the arctic regions.

Together with the macro-scale properties of clouds and aerosols fields, these retrieved microphysics are used to validate climate models such as parcel model combined with cloud particle bin and SPRINTARS that can transport several aerosol species and is based on the CCSR-NIES-FRCGC General Circulation Model. The comparisons between the observations and the models indicate high/low cloud fractions are over-/under estimated in the models. For low clouds, the cloud top altitude is lower than the actual. These deficiencies illustrate the needs to improve the cloud schemes used in the models.

1. INTRODUCTION

One of the major uncertainties in the climate simulations is a treatment of cloud fields in climate models. Sensors on satellites can record the global distribution of cloud physical properties such as cloud cover, optical thickness and effective radius. Despite considerable effort using such satellite-borne sensors, however, uncertainties remain in the assessment of climate impacts due to clouds and aerosols. This is partly due to the presence of multi-layered clouds and also due to vertical inhomogeneity in cloud and aerosol microphysics. Active instruments such as cloud radar and lidar are powerful tools that can provide detailed vertical profiles of macroscale and microphysical properties and these instruments might overcome the current situations. One of our main aims is to validate the representation of clouds and aerosols in climate model. We conducted several ship-borne experiments involved the use of a 95GHz cloud profiling radar and a lidar onboard Research Vessel Mirai, which has been operated by the Japan Marine Science and Technology Center (JAMSTEC: Japanese Maritime Science and Technology Center) from 2001 to present. The first cruise was conducted in May 2001 in the northwest Pacific near Japan. The second cruise was mainly concentrated in the tropical western Pacific, from September to December 2001. We also conducted other cruises in mid-latitude and the Tropical western Pacific ocean in 2004, 2005 and 2006.

Cloud radar and lidar observation have been planned from two satellites that are scheduled to be launched in 2006 as part of the NASA Earth System Science Pathfinder (ESSP) program. CloudSAT will carry a 95-GHz radar. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) will include lidar [1]. ESA-JAXA mission, EarthCARE, will follow the two missions. It is therefore vital to understand the information latent in the combination of cloud radar and lidar.

2. RETRIEVAL ALGORITHMS

The received power of the radar or the lidar are affected by particle size such that the radar is sensitive to large particle and the lidar is sensitive to small particles. Furthermore, extinction due to clouds at lidar wavelengths is greater than extinction for radar. These differences affect how each sensor can be used and interpreted. With such knowledge, the cloud occurrence can be determined by the combination of the cloud radar and the lidar with the application of cloud mask schemes. The synergy of lidar and radar can also provide the information of cloud particle radius and liquid/ice water content (LWC/IWC). The lidar/radar algorithms (LRM) have been developed both for water and ice clouds. One unique feature of the algorithms is the attenuation-correction to the lidar signals according to the cloud microphysics determined by look-up tables backscattering and extinction for the radar and lidar signals[2]. The applicability of these algorithms is limited to the relatively small portions of total cloud areas. This is mainly due to the large attenuation by the thick clouds in the lidar signals and it is often the case for water clouds. In the analyses of microphysics of water clouds, it is important to assess the contribution of multiple scattering to the total lidar signals. We first applied the Backward Monte Carlo method (BMC) [3] to estimate the effect. In order to implement the effect into the look up tables used in radar/lidar algorithm, the effect is further formulated as a function of effective radius and LWC. It turns out the contribution of multiple scattering in the lidar backscattering is roughly proportional to the optical thickness and does not strongly depend on the details of microphysics for large particles (Fig. 1).

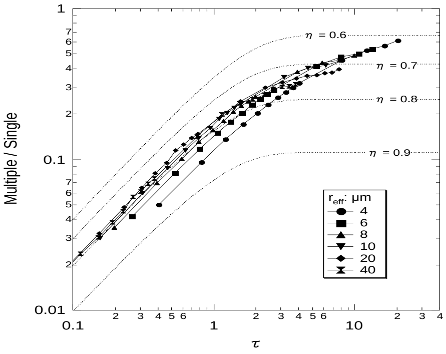


Fig.1. The ratio of multiple scattering to single one where the received signals are calculated as a function of optical thickness for varios combination of effective radius and LWC on the basis of Backward Monte Carlo method.

In order to increase the portion of clouds to be analyzed, we also developed the single use of lidar or radar algorithms for the retrieval of cloud microphysics. The lidar algorithm uses the lidar signals for the visible and infrared channels for ice clouds. The method is especially effective for tropical cirrus and anvil clouds including sub-visual clouds (SVC), where the radar often loses its sensitivity due to small cloud particles while the lidar still can detect them. For the radiatively important clouds, i.e., optically thick clouds, the information of radar with multiparameter functions (RMM), radar reflectivity factor, Doppler velocity and linear depolarization ratio (LDR), is considered to retrieve cloud microphysics. The advantage of the algorithm is the wide applicability. To separate contamination of vertical air motion in the measurement of Doppler velocity is an issue. Finally, the algorithm for aerosols are developed where the information of lidar signals at two wavelengths and depolarization ratio at visible wavelength are considered. The main feature is that it allows to retrieve vertical profiles of lidar ratio and type of aerosols and to be applicable to the aerosols below clouds. The information of aerosol properties below clouds together with the microphysics of clouds might lead to the understanding of cloud and aerosol interactions.

3. RESULTS FOR CLOUD MICROPHYSICS

First, the analyses of cirrus microphysics are shown in Fig. 2 as an example of the results from the synergy use of airborne radar and lidar.

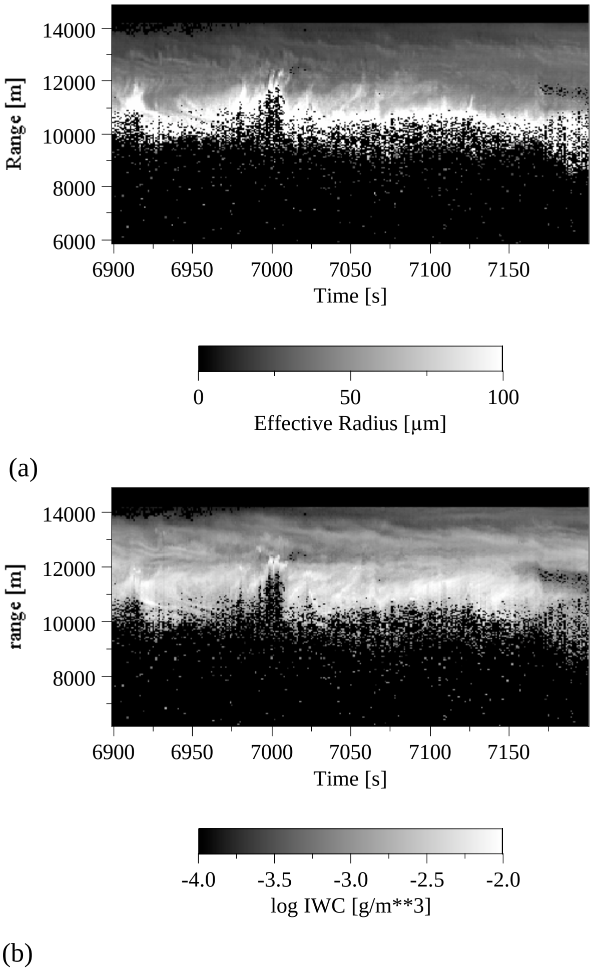


Fig. 2. Retrieved effective radius (a) and IWC (b) for cirrus clouds taken by the airborne cloud radar and lidar in March 27, 2003. Note that the altitude of air craft is expressed 15 km in the figures and actual clouds were found between the altitude of 7 to 11 km from sea- level.

The jet aircraft Gulf Stream-II equipped with 95GHz radar and lidar with wavelength of 355nm have been used for the extensive field campaign named APEX-E3/

ECAV in March- April, 2003. The main aim of the studies is to investigate the airborne radar/lidar data of clouds taken above cloud top in order to simulate EarthCARE mission which is planned by ESA and JAXA and will carry 95GHz radar with Doppler function and lidar with UV wavelength as well as depolarization channel. Both instruments were set to be nadir pointing so that the data were obtained from cloud top to bottom parts. The observational area was in East-China sea offshore Kyushu island. Thick cirrus clouds were observed for 11-12(JST) in March 27, 2003. Top part of the clouds consists of small particles, e.g., about 15 to 20 microns, and as the altitude of clouds decreases, the particle radius increases. It is noted that the actual cloud bottom part can not be analyzed by the LRM since the lidar could not penetrate the lower part of the clouds. IWC ranges from 0.001 to 0.01g/m^3.

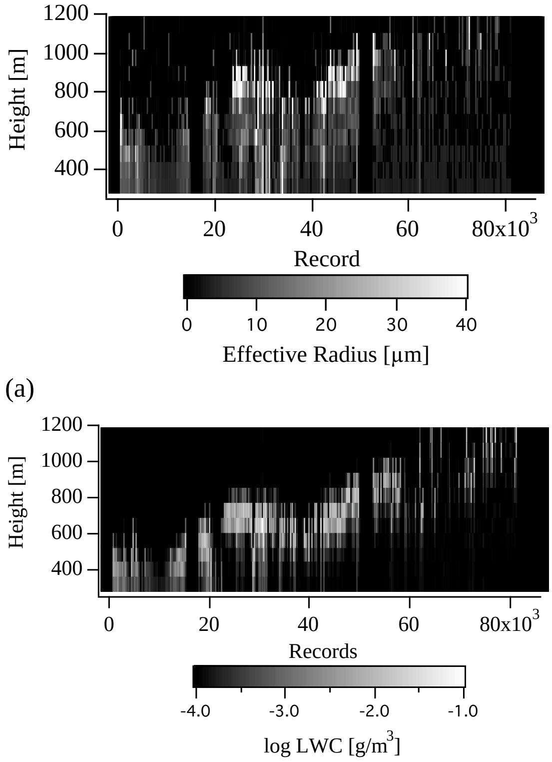


Fig.3. Retrieved microphysics of water clouds in May 17, 2001, during the R/V Mirai cruise MR01/K02. Effective radius (a) and LWC (b) by the LRM.

Fig. 3 shows an example of the analysis of water clouds observed by ship-born radar and lidar data taken during the Research Vessel Mirai MR01/K02 cruise. The radar and the lidar were installed in the same container and both instruments were vertically pointing. The LRM for water clouds was applied to the data. Therefore the cloud microphysics was retrieved from cloud bottom to the upper layer as long as the lidar signal is returned from the layer of interest. The effective radius ranging from 5 to 40 microns and the radius seems to increase as the cloud height increases. This can be naturally understood by the fact that the cloud formation actually started at cloud bottom with upward motion. The LWC turns to be between 0.01 to 0.1 g/m3. These values are relatively smaller compared with the typical value reported by the in-situ measurements. This may be due to the fact that the lidar signal are totally attenuated when the optical thickness exceeds around 1 and thus the retrieved microphysics corresponds to the relatively thin clouds.

Fig. 4 also shows the results from the R/V Mirai cruise but for Tropical western Pacific cruise conducted in Dec. 21, 2004. There are relatively thick cirrus clouds located at around 12-14 km, which may possibly be generated by the convective activity and also very thin clouds with geometrical thickness of around 200m were found. We used the lidar algorithm and found the effective radius of lower thick clouds was around 40 microns and maximum of IWC was 0.03g/m^3. Optical thickness reached 0.9 in the optically thick part. While, the values of the effective radius and IWC of upper layer, corresponding to SVC, were much smaller than the values for lower clouds, i.e., the former value is 12-25 microns and maximum value for the latter is 0.0025g/m^3.

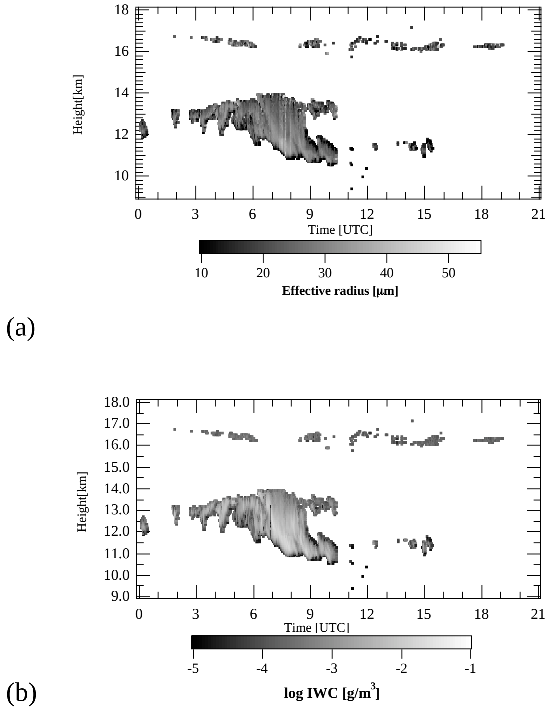
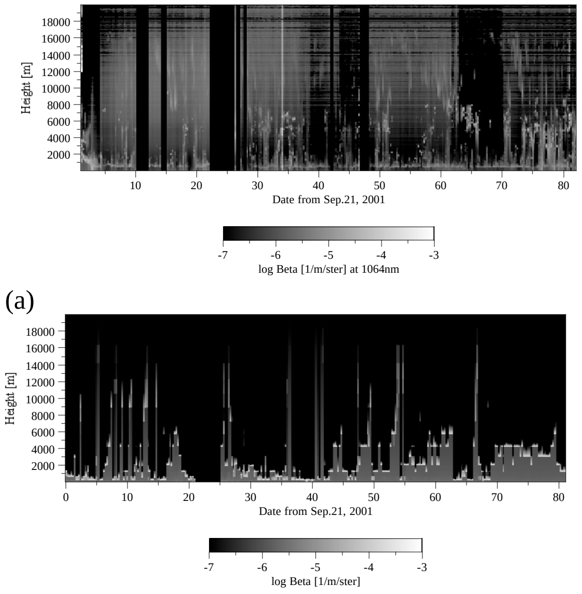


Fig.4. Microphysics of Tropical cirrus retrieved by the dual-wavelength lidar algorithm, during R/V Mirai MR04-08 cruise. Sub-visual cirrus clouds (SVC) were observed at 17 km in Dec. 21, 2004. Effective radius (a) and LWC (b).

The optical thickness estimated by the retrieved microphysics was compared with the values derived from the infrared radiometer with the knowledge of cloud bottom altitude. In general, good agreement is achieved when the optical thickness is less than one. However, the lidar method showed the underestimation of optical thickness when the value exceeds one. This may be explained by the attenuation due to clouds in lower altitude in lidar signals.

4. VALIDATION OF CLIMATE MODEL

We compared the results of the radar and the lidar data with those simulated by the general circulation model (GCM). Comparisons were done using SPRINTARS, a model based on the CCSR-NIES GCM [4]. The model in this study had T106 truncation, corresponding to a horizontal resolution of around 100 km and 20 vertical layers. Temperature, pressure, relative humidity estimated in SPRINTARS were nudged with 6 hour interval NCEP/NCAR reanalysis data. Clouds and aerosols were generated using SPRINTARS. In order to mimic the “observed” cloud fraction for the comparisons with the observations, we first estimated the radar and lidar signals from the model output using the radar/lidar simulator developed by us. Then the sensitivities of both instruments were taken into account to derive the cloud fraction for the cloud that can be observed in each model grid box. We compared the cloud frequency of occurrence between the observation and the simulations by the GCM in mid-latitude and the tropics. In both cases, the model underestimated low- and middle-level cloud occurrence, while significantly overestimated upper clouds and the over-prediction of upper cloud fraction in the GCM is more pronounced in the tropics. The similar findings were obtained for the comparison of the results of the parcel model. It is also found that a pattern of cloud fraction seems to be well reproduced in the mid-latitude, however, the model significantly over-predicted it in the tropics, especially in upper layer.



(a)

(b)

Fig. 5 Time-height cross section of observed lidar backscattering coefficient at 1064nm (a) and that simulated by the SPRINTARS (b). In the simulations, contributions of clouds and aerosols are taken into account.

There might be two approaches to assess the cloud and aerosol microphysics reproduced in the model. One is to use the retrieved microphysics by algorithms and to compare them with the outputs from the model. In the approach, similar to the comparison of cloud fraction, it is necessary taken into account the sensitivity of the instruments so that the optically thin clouds or clouds and aerosols above the very thick clouds may be excluded for the comparisons. Other is the direct comparisons of observables such as lidar backscattering coefficient or radar reflectivity factor. Fig. 5 shows the comparison of lidar backscattering at 1064nm between the observations and the simulations by the SPRINTARS. In the simulations of the lidar signals, the contribution of aerosols and clouds as well as the sensitivity of the instruments are considered. It is found that the model over-predicted the value of backscattering compared with the observations and the over-prediction leads to the too much attenuation for upper layers. These comparisons illustrate the needs for improvement of the cloud schemes in the model. We also will report the intensive comparison of microphysics, lidar and radar signals between the observations and the simulations for the cruises in the conference.

5. SUMMARY

Several retrieval algorithms for clouds and aerosols have been developed and tested. Then they have been applied to airborne and ship-borne radar/lidar data. Applicability of each algorithm turned out to be very different, e.g., radar only algorithm works fine for radiatively important clouds and single use of lidar algorithm is superior for the study of SVC. And there are some regions where several algorithm can be simultaneously applied and thus the inter-comparisons of the algorithms become possible. It is concluded that the products of the algorithms complement each other and should be combined to reproduce the whole picture of microphysics.

6. REFERENCES

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