EPJ Web of Conferences **119**, 21005 (2016) DOI: 10.1051/epjconf/201611921005
ILRC 27

Modeling lidar multiple scattering

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ABSTRACT

A practical model to simulate multiply scattered lidar returns from inhomogeneous cloud layers are developed based on Backward Monte Carlo (BMC) simulations. The estimated time delay of the backscattered intensities returning from different vertical grids by the developed model agreed well with that directly obtained from BMC calculations. The method was applied to the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite data to improve the synergetic retrieval of cloud microphysics with CloudSat radar data at optically thick cloud grids. Preliminary results for retrieving mass fraction of co-existing cloud particles and drizzle size particles within low-level clouds are demonstrated.

1. INTRODUCTION

The combined use of attenuated backscatter coefficient (β) and depolarization ratio (δ) is effective to reveal detailed microphysical structures within clouds. From space-borne lidars, they have been widely used to identify cloud phase [1][2], or further combined with cloud radar to determine mass concentration of non-spherical ice particles [3][4]. However, there are still areas of improvements in order to qualitatively retrieve vertically resolved cloud microphysics or to detect cloud base where multiple scattering effects are dominant as in optically thick low-level clouds [5]. In these situations, Monte Carlo methods are reliable for simulating the effects on lidar returns but are inefficient for inversion purposes [6]. The main objective of this paper is to improve lidar-only and radar-lidar synergy retrievals of cloud microphysics by updating the treatment for multiple scattering of depolarized lidar returns that are capable of handling global data.

2. METHODOLOGY

The concept of the method is to combine the parallel and perpendicular components of the backscattered intensities calculated by BMC for vertically homogeneous cloud cases to construct lidar returns from any inhomogeneous cloud layers (fig.1). To reflect the effect of inhomogeneity on the time delayed lidar returns, the excessive distances traveled within each vertical layer had been parameterized based on BMC simulation to determine the effective extinction σ_{eff} of the inhomogeneous media. Here, σ_{eff} is defined as the extinction including multiple scattering. In this way, repeated Monte Carlo simulations can be avoided for estimating the lidar returns in inversion schemes and the numerical cost in multiple scattering regimes can be reduced to that equivalent to assuming single scattering.

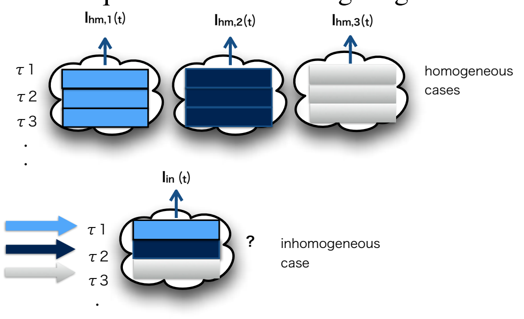

Fig.1 Basic concept. $I_{hm}(t)$ and $I_{in}(t)$ are the observed backscattered intensity at time t for homogenous and inhomogeneous cases, respectively, and τ_i is the optical thickness of the i-th layer from cloud top.

To test the validity of the developed method, BMC simulations were performed considering observation of liquid phase clouds with vertically varying microphysic from the CALIOP platform at 532 nm wavelength. For convenience, the microphysical properties were varied at 240m vertical resolutions corresponding to that of CloudSat radar, and result for an ideal cloud with three consecutive layers are provided as a representative case. The BMC method used in this study to simulate the lidar returns is known to compare well with other Monte Carlo codes tested against the same simulation settings [7].

3. RESULTS

Comparison between the estimated backscattered intensities for both parallel and perpendicular component and those obtained from direct BMC calculation had good agreement with each other. Figure 2 shows the result for the total backscatter coefficient. On the other hand, mere combination of the backscattered intensities estimated from BMC for homogeneous profiles and neglecting inhomogeneity effects largely deviated from the truth.

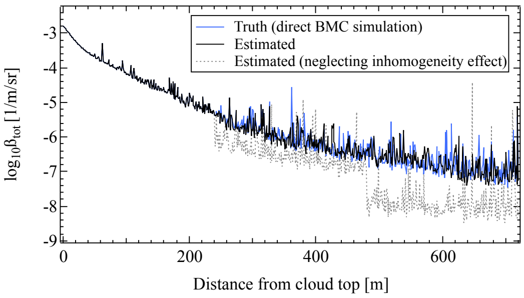

Fig. 2 Comparision between the estimated (black line) and simulated truth (blue line) of the total lidar backscatter coefficient for CALIOP at 532 nm wavelength. Extinction coefficients of the cloud layers were varied from 30.0, 15.0, 7.5 per kilometer at 240m resolutions from cloud top. Also shown are the estimated profile connecting BMC calculated backscattered intensities for homogeneous cases at layer boundaries without taking in to account the effect of inhomogeneity (gray dash line).

The backscattered intensities apparently returning from each vertical lidar grid were decomposed into the contributions from other grids. Comparison between those estimated and the truth implied that potentially the method is capable of determining the information the lidar returns contain about the microphysics of a particular cloud layer (Fig.3).

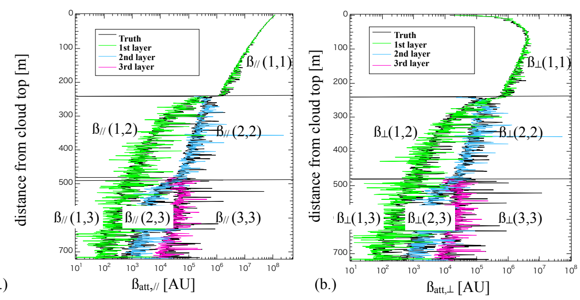

Fig. 3 (a.) Parallel and (b.) perpendicular component of the backscattered intensity for the same case as in fig.2. The estimated profile (colored line) and the truth via direct BMC simulation (black line) are compared. $\beta_{//\perp}(i,j)$ indicates the contribution of the microphysics at the i-th layer to the apparent backscattered intensity from the j-th layer.

4. APPLICATION

The developed lidar forward model was further tested against radar reflectivity (dBZ_e) obtained by CloudSat radar and β and δ obtained from CALIOP lidar to demonstrate its usability for cloud studies. Here, both sensors were combined to infer microphysical processes occurring within water clouds (Fig.4). To find solutions that satisfy each observable having different size dependence, the shape of the size distribution was assumed to be capable of detecting up to two different modes (i.e, mono-modal or bi-modal) within each vertical radar/lidar grid. The particle sizes and mass ratio were retrieved without fixing the mode radius. The retrieval results show that the synergy seems to be adequately functioning to separate drizzle (and precipitation) from cloud particles (Fig.5).

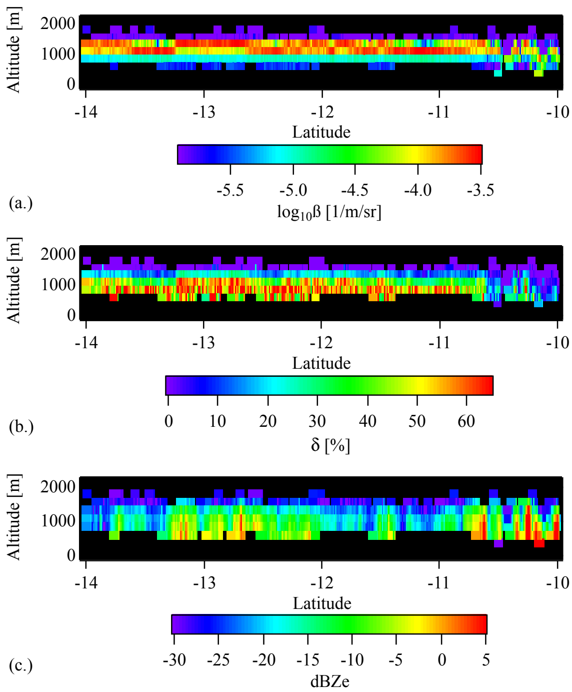

Fig.4 Latitude-height cross section of (a.) β and (b.) δ from CALIOP and (c.) dBZe from Cloudsat for low level cloud observed in October 2009. The CALIOP data are matched to the resolution of the CloudSat data and hydrometeor detection [4] has been performed.

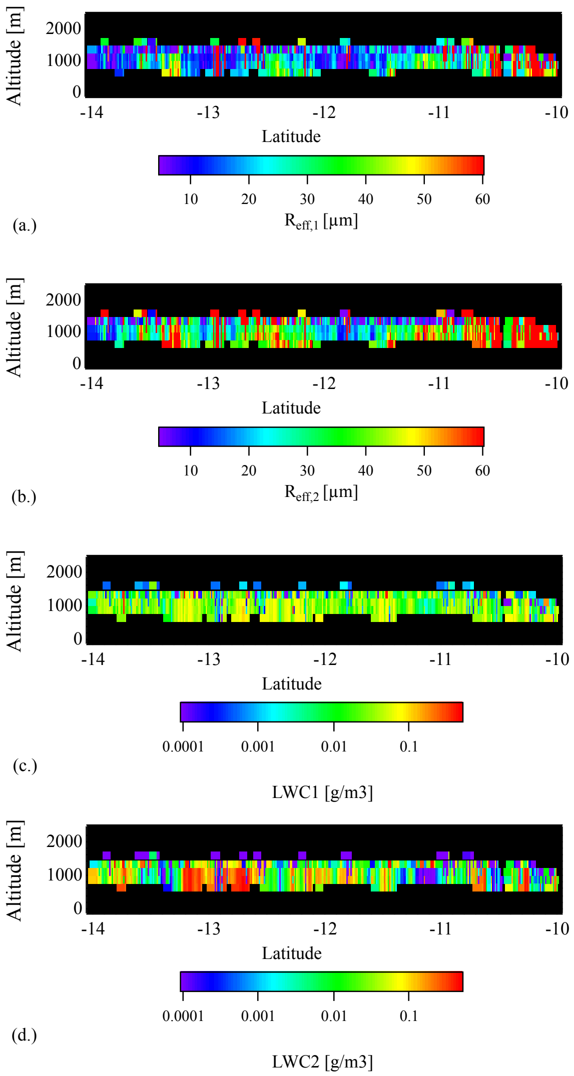

Fig.5 The same as fig. 4 but for the retrieved effective radius (R_{eff}) of (a.) mode 1 and (b.) mode 2, and (c.)/(d.) the liquid water contents (LWC) corresponding to (a.)/(b.). When the lidar/radar grid have bi-modal microphysical property, the smaller/larger mode is automatically identified as mode 1/mode 2, and therefore mode 1 and mode 2 does not necessarily correspond to cloud particle and drizzle (or precipitation), respectively.

5. CONCLUSIONS

Practical modeling of Monte Carlo simulations of multiple scattering effects from clouds was performed to analyze depolarized lidar returns from arbitral inhomogeneous cloud layers. For the cases tested, the method showed good performance. The developed forward model was used to inversely derive low-level cloud microphysics observed by CALIOP lidar. Especially, its potential for the synergy with CloudSat radar at heavily attenuated regions was focused. Preliminary results showed the effectiveness of the synergy to study the transition region, from cloud particles to drizzle and precipitation, which the representation in climate models is largely uncertain. In future, further validation of the methods is planned using collocated ground-base observation of Multiple Field of view Multiple Scattering Polarization Lidar (MFMSPL) and cloud radar, which realizes low-level cloud observations comparable to that of space-borne active sensors from ground.

ACKNOWLEDGEMENT

This study was supported by JSPS KAKENHI Grant Numbers 15K17762 and 25247078. K. Sato was also supported in part by the Kyushu University Interdisciplinary Programs in Education and Projects in Research Development, and by the program of Special Coordination Funds for Promoting Science and Technology, “Supporting positive activities for female researchers”.

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