RETRIEVING MICROPHYSICS OF CIRRUS CLOUDS FROM DATA MEASURED WITH RAMAN LIDAR RAMSES AND A TILTED CEILOMETER

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ABSTRACT

To develop a microphysical model of cirrus clouds, data obtained by Raman lidar RAMSES and a tilted ceilometer are studied synergistically. The measurements are interpreted by use of a data archive containing the backscattering matrixes as well as the depolarization, color and lidar ratios of ice crystals of different shapes, sizes and spatial orientations calculated within the physical-optics approximation.

1 INTRODUCTION

Retrieval of microphysical properties of cirrus clouds, i.e. sizes, shapes, and orientations of ice crystals, from lidar signals is a challenging problem for the lidar community that is not satisfactorily solved yet [1]. One of the problems in the lidar studies of cirrus clouds by means of the conventional vertically-pointing lidars is that appearance of even small fraction of quasi-horizontally oriented plate-like ice crystals in the clouds leads to strong variations of the lidar signals on the background of the signals formed by the randomly oriented fraction of the crystals. This phenomenon is easily explained by the specular reflection (or specular scattering) from the horizontally oriented plates [2, 3]. In particular, the space lidar CALIPSO was specially oriented at 3° off nadir to avoid the specular scattering. To retrieve the microphysical properties of the horizontally-oriented fraction of the ice crystals of cirrus clouds, the vertically-pointing Raman lidar RAMSES [4] has been supplemented with a ceilometer tilted at 5° off zenith.

In this contribution we show that joint use of signals from both RAMSES and the ceilometer allow us to retrieve the percentage of the quasi-horizontally oriented plate-like crystals and their effective tilts near the horizon.

2 METHODOLOGY

We assume that cirrus clouds are formed by two co-existing particle fractions. The main fraction consists of randomly oriented ice crystals of arbitrary shapes, while the minor fraction is an ensemble of quasi-horizontally oriented plate-like crystals. In general, if a crystal is illuminated by linearly polarized light, the backscattering cross section for a randomly oriented crystal consists of the parallel and perpendicular components:

$$\sigma = \sigma_{\parallel} + \sigma_{\perp}. \qquad (1)$$

However a quasi-horizontally oriented plate creates, with good accuracy [5], only the parallel component which is denoted as σ_{pl}. Hence two backscattering coefficients measured by RAMSES for a given height h are equal to

$$\beta_{\perp} = c\sigma_{\perp}, \qquad (2)$$

$$\beta_{\parallel} = c\sigma_{\parallel} + C\sigma_{pl}, \qquad (3)$$

where c and C are the number densities of the main and minor fractions, respectively. Their ratio

$$k = C / c \qquad (4)$$

is an important microphysical characteristics called the plate percentage.

Also, RAMSES measures the extinction coefficient

$$a = 2cs + 2CS, \qquad (5)$$

where s and S are average areas of the shadows produced by a randomly oriented crystal and a quasi-horizontally oriented hexagonal plate wavering about the horizontal plane, respectively.

The ceilometer does not detect polarization of light, it measures the total cross section of Eq. (1) σ_{ceil} at the wavelength of 1064 nm. Being tilted at 5° off zenith, it does not detect the minor fraction. Hence its signal is equal to

$$\beta_{ceil} = c\sigma_{ceil}. \tag{6}$$

In contrast to backscatter and extinction coefficients, the depolarization ratio (δ) and the lidar ratio (L) are two optical properties that do not depend on the number density of the cloud particles and thus are characteristics of the scattering behavior of the particle ensemble and, hence, more meaningful in the context of interpreting lidar data in terms of microphysics. If all crystals in clouds are randomly oriented, these properties are equal to

$$\delta_0 = \beta_{\perp}^0 / \beta_{\parallel}^0 = \sigma_{\perp} / \sigma_{\parallel}, \tag{7}$$

$$L_0 = \alpha_0 / (\beta_{\perp}^0 + \beta_{\parallel}^0) = 2s / \sigma. \tag{8}$$

For the mixture of the randomly oriented and quasi-horizontally oriented plates we have

$$\delta = \frac{\beta_{\perp}}{\beta_{\parallel}} = \frac{c\sigma_{\perp}}{c\sigma_{\parallel} + C\sigma_{pl}} = \frac{\delta_0}{1 + k\sigma_{pl} / \sigma_{\parallel}}, \tag{9}$$

$$L = \frac{\alpha}{\beta_{\perp} + \beta_{\parallel}} = \frac{L_0 + 2kS / \sigma}{1 + k\sigma_{pl} / \sigma}. \tag{10}$$

As experience shows, number densities c and C [Eqs. (2)-(6)] change much more rapidly with height h in natural clouds than the microphysical proxies δ and L.

Therefore, if horizontally oriented plates were absent, $C(h) = 0$, the four experimentally measured vertical profiles of Eq. (2), (3), (5) and (6), plotted with arbitrary constant factors, should exhibit similar curve shapes, reflecting the dependence $c(h)$.

Experimental data where aligned plates were absent are presented in Figs. 1 and 2. Indeed, in Fig. 1 we see that all four profiles are similar. In addition, we see in Fig. 2 that both the depolarization ratio and lidar ratio only weakly depend on the height unlike the quantities of Fig. 1. In the following, we refer to these data as 'Case 1'.

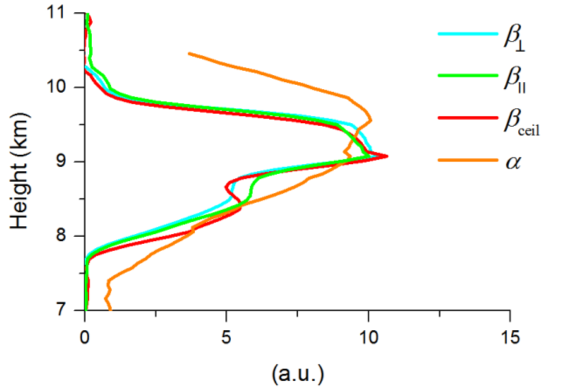

Figure 1. Case 1: Four simultaneously measured profiles of Eqs.(2), (3), (5), and (6). Profiles are scaled so that maxima have roughly the same magnitude

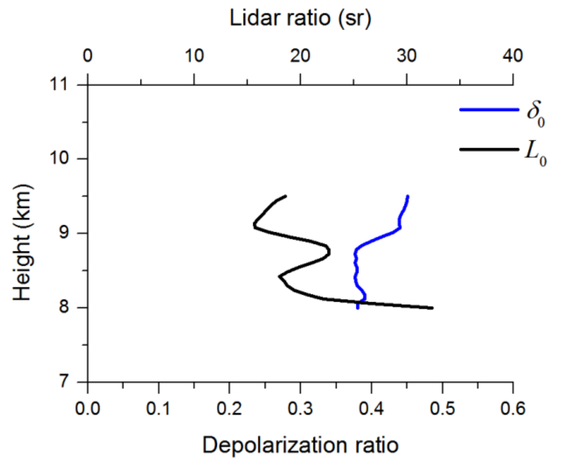

Figure 2. Case 1: Vertical profiles of the depolarization and lidar ratios

We note that the values $\delta_0 \approx 0.4$ and $L_0 \approx 20$ sr are rather typical values observed by RAMSES in cirrus clouds. According to our data archive with the backscattering matrixes of ice crystal particles [6], these values match best the results obtained for randomly oriented columns with distorted shapes.

3 RESULTS

Figures 3-5 showcase the experimental data referred to as Case 2. Here the appearance of horizontally oriented plates is revealed by the different shapes of the curves in Fig. 3. In addition, in Figs. 4 and 5, we see that the values of the depolarization and lidar ratios are close to those of Case 1 at a height of about 7 km. These observations indicate that there were only randomly oriented crystals at $h \approx 7$ km and that horizontally oriented plates appeared below.

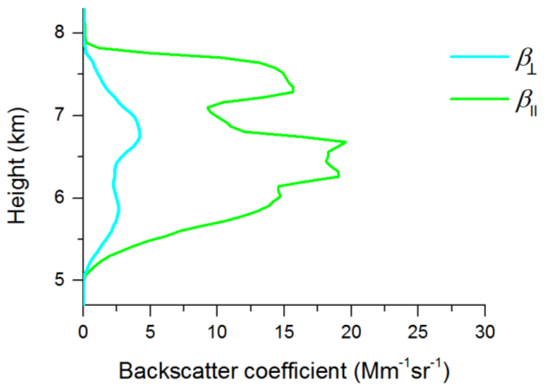

Figure 3. Case 2: Perpendicular and parallel backscattering coefficients measured simultaneously

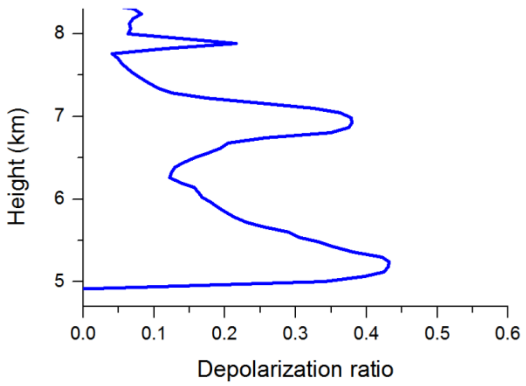

Figure 4. Case 2: Depolarization ratio

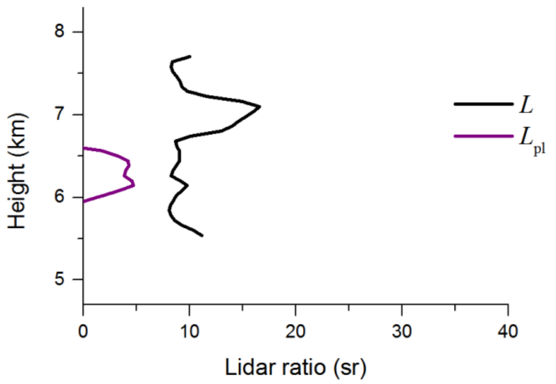

Figure 5. Case 2: Lidar ratios L and $L_{\rm pl}$, the lidar ratio of the horizontally oriented plates [see defining Eq. (11)]

We can now retrieve some new microphysical characteristics of the plates in Case 2. For the first, we use the following approximation. We suppose that the microphysical characteristics of the randomly oriented fraction change only negligibly with height. So their number-density independent optical properties are considered to be equal to the values measured at 7 km, $\delta_0 \approx 0.38$ and $L_0 = 15$ sr (Figs. 4 and 5). As a result, by applying Eqs. (7)-(10), we retrieve the ratio

$$L_{pl} = 2S / \sigma_{pl} , \qquad (11)$$

which is the lidar ratio of the oriented plates. The retrieved profile of $L_{\rm pl}$ is depicted in Fig. 5.

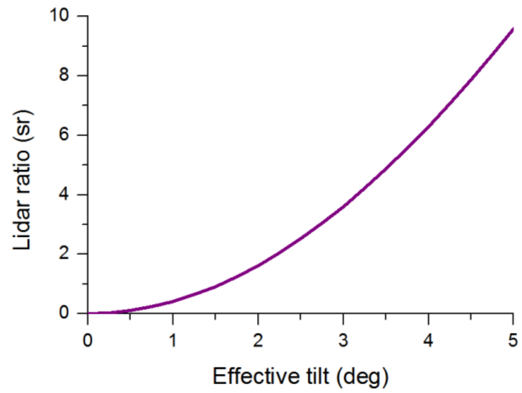

Figure 6. The lidar ratio of a quasi-horizontally oriented plate versus its effective tilt near the horizontal plane

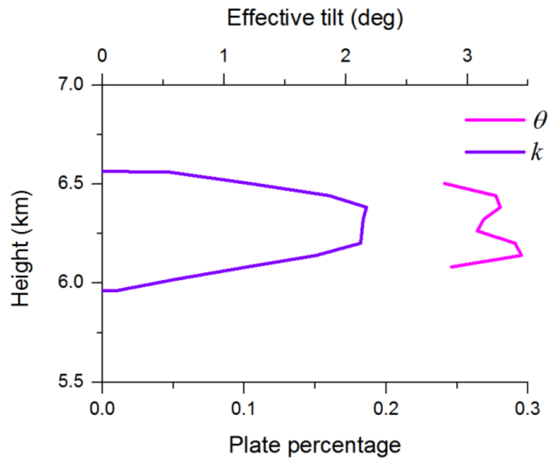

Figure 7. Effective tilt angle θ of the quasi-horizontally oriented plates and the plate percentage k retrieved from the experimental data of Figs. 3-5

The lidar ratio of Eq. (11) can be used to find the effective tilt (with respect to the horizon) of the quasi-horizontally oriented plates. For this purpose, we have calculated L_{pl} as a function of the effective tilt according to our papers [5, 7], the results are presented in Fig. 6. This relation converts the L_{pl} profile of Fig. 5 into the profile of the effective tilt θ (Fig. 7). The effective tilt angles were about 3°.

Finally, Eqs. (9) and (10) allow us to find also the quantity

$$B = 2kS / \sigma. \tag{12}$$

Here the first factor is the plate percentage k while the other factor corresponds to the ratio of plate and column sizes. This ratio should be assessed from either other experimental data or from model considerations. In our current work, we use the hypothesis that the sizes of the plates and columns are gamma-distributed [5] with their modal diameters being equal. Under this assumption, we are able to retrieve the plate percentage, which is depicted in Fig. 7 as well.

4 CONCLUSIONS

The joint use of the parallel and perpendicular backscattering coefficients together with the extinction coefficient measured by RAMSES in cirrus clouds allows us to detect and, to a certain degree, characterize the fraction of quasi-horizontally oriented plates. For such mixtures of randomly oriented crystals and quasi-horizontally oriented plates, we are able to retrieve approximately the plate percentage and the effective tilt angles for near-perfect horizontal alignment.

ACKNOWLEDGEMENTS

The work is partly supported by the grants 15-05-06100 and 16-35-60089 of the Russian Foundation for Basic Research and by the grant NS-8199.2016.5 of the President of the Russian Federation.

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