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INVESTIGATION OF THE MULTIPLE-SCATTERING INFLUENCE ON CLOUD DEPOLARIZATION-RATIO MEASUREMENTS BASED ON POLARIZATION-RAMAN-LIDAR EXPERIMENTS

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The polarization Raman lidar of GKSS allows to measure both the depolarization ratio of the elastically scattered light and the depolarization ratio of the light Raman scattered by nitrogen molecules (Wandinger et al. 1994a). While the depolarization of the elastically scattered radiation results from single scattering by nonspherical particles and from multiple scattering, the depolarization of the Raman signals is caused by a single Raman process — which yields to a depolarization ratio of 0.094 — and by additional elastic scattering processes, i.e., multiple scattering. The simultaneous measurement of the two different depolarization ratios gives additional information on scattering properties of clouds and supports the modeling of the multiple scattering influence on lidar measurements. This is demonstrated with the following measurement examples.

Fig. 1 shows a measurement of a water cloud at about 5.5 km height. The extinction coefficient, derived from the nitrogen signal, increases to values of about $10\,\mathrm{km}^{-1}$ in the center of the cloud, the optical depth is nearly 2.5 (Fig. 1a). The measured elastic and Raman depolarization ratios are shown in Fig. 1b and 1c, respectively. While for the elastic depolarization ratio the well-known steady increase with height is observed, the Raman depolarization ratio does not significantly deviate from the molecular value.

To simulate such depolarization effects two numerical models are used. The intensity of multiply scattered light is calculated from a radiative-transfer model (Shipley 1978). A double scattering model (Wandinger 1994b) is used to estimate the depolarization effect. Both models assume that multiple scattering is only caused by small-angle forward scattering processes close to the 0° direction before or after a backscattering event close to 180°.

For homogeneous water clouds (Cl-, Ns-cloud) the elastic depolarization ratio of the doubly scattered light $\Delta_0^{(2)}$ is found to be nearly height-independent with values between 0.15 and 0.3. With the assumption that multiply scattered light generally leads to a depolarization ratio Δ_0^{m} on the order of 0.1 to 0.4, the cloud depolarization ratio $\Delta_0 = \Delta_0^{\mathrm{s}} + \Delta_0^{\mathrm{m}}$ with the single-scattering depolarization ratio $\Delta_0^{\mathrm{s}} = 0$ can be estimated by the use of Δ_0^{m} from the double-scattering model and the contribution of multiple scattering to the totally backscattered light calculated with the radiative-transfer model. The comparison of the measured and the calculated depolarization ratios, shown in Fig. 1b, indicates that the actual depolarization ratio Δ_0^{m} is between 0.3 and 0.4 in the lower part of the cloud. A complete depolarization ($\Delta^{\mathrm{m}} = 1$) by multiple scattering as often assumed for the estimation of the multiple-scattering effect in water clouds appears to be unrealistic.

The different behavior of the elastic and the Raman depolarization ratio in Fig. 1 results from the different backscatter processes. From Mie theory one can find that droplet forward

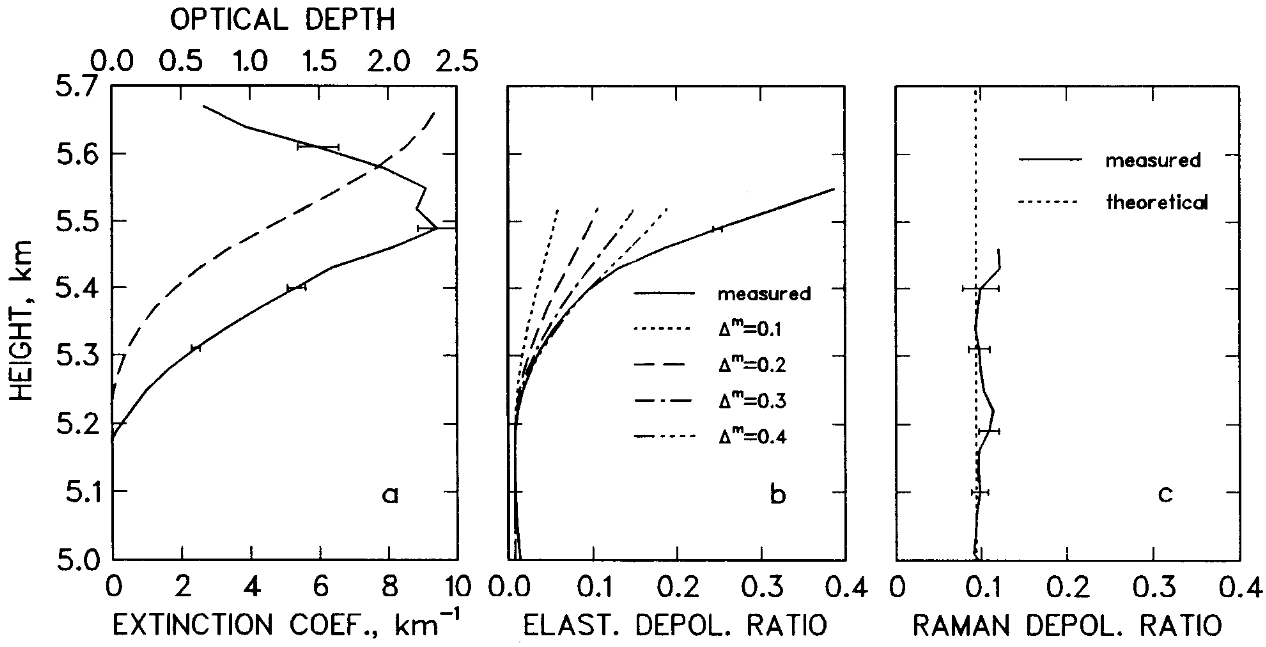

Fig. 1: a. Extinction coefficient (solid) and optical depth (dashed), b. measured and calculated elastic depolarization ratios, c. measured and calculated Raman depolarization ratios of a water cloud. Time resolution is 10 min, range resolution 180 m, calculation step width 30 m. Error bars are due to signal noise.

scattering does not depolarize the light. The Raman backward process is angle-independent near 180°, so that the depolarization ratio does not vary if multiple scattering leads to a variation of the backscatter angle, and the observed Raman depolarization ratio is range-independent. The depolarization of light by droplet backscattering, on the other hand, increases strongly with the deviation of the backscatter angle from 180°. For a C1-cloud the depolarization ratio increases from 0 to 0.65 if the backscatter angle decreases from 180° to 179°, for a Ns-cloud a value of 0.55 is reached at 179.5°. As a result of the extended depolarization measurements and model calculations, one can state that the measurements indicate that the consideration of small-angle forward and backward scattering processes for the model calculations is sufficient to obtain realistic results in terms of the multiple-scattering effect on cloud lidar measurements.

Fig. 2 shows a measurement of a cirrus cloud. The extinction coefficient, the optical depth, and the two depolarization ratios are given for two successive time intervals of about 7 minutes. During the first period an increase of the Raman depolarization ratio was obtained above 6 km that disappeared in the next time interval. The observed radiative properties of the cloud — extinction, optical depth, and backscattering — did not significantly change. The different Raman depolarization ratios are obviously caused by microphysical properties of the cloud. An increase of the Raman depolarization ratio can only be explained by elastic forward-scattering processes. Numerical simulations with scattering phase matrices for regularly-shaped, randomly-oriented hexagonal ice crystals (Takano et al. 1985) show, however, that these particles do not lead to a depolarization of the forward scattered light. On the other hand, one can expect that irregularly shaped crystals do cause such a depolarization. Scattering phase matrices to verify this statement are not available yet. The Raman depolarization ratio may thus be used to investigate the forward-scattering behavior of ice crystals and to identify cloud layers with irregularly shaped crystals.

If forward scattering leads to an increase of the Raman depolarization ratio, the elastic depolarization ratio is also affected. The Raman signal, however, is more sensitive to forward-scattering effects. Because of the isotropic phase function at 180° all forward scattered photons are backscattered with the same intensity. For ice crystals the phase function is peaked at 180°, so that the backscattering efficiency decreases rapidly with increasing forward scattering angles. From this point of view, the Raman depolarization ratio indicates whether or not multiple scattering must be taken into account in the interpretation of elastic-depolarization-ratio data.

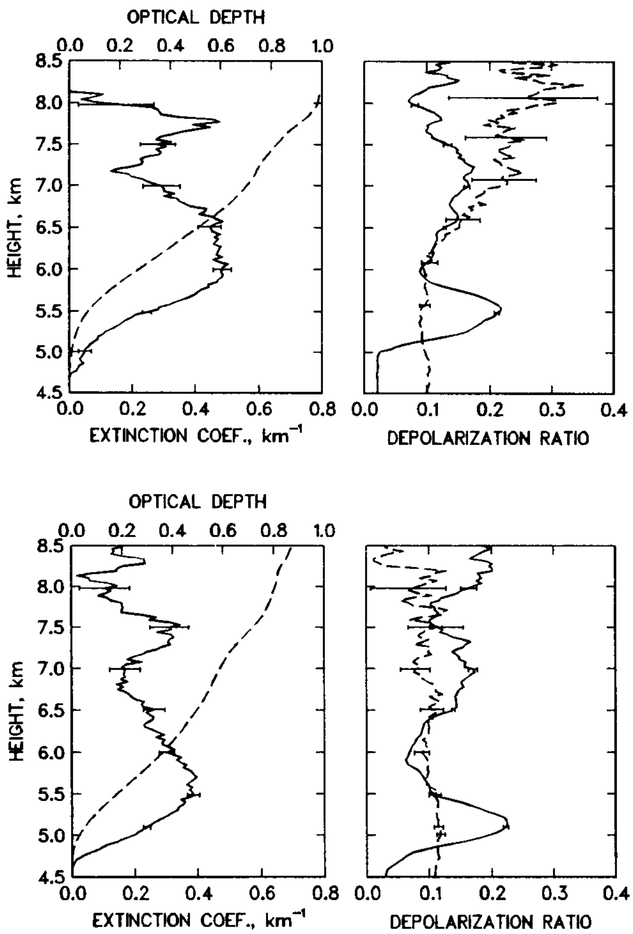

Fig. 2: Extinction coefficient (left, solid), optical depth (left, dashed), elastic depolarization ratio (right, solid), and Raman depolarization ratio (right, dashed) measured in a cirrus cloud during two successive time intervals (upper and lower graphs). Time resolution is 7 min. Smoothing length is 120 m for the elastic depolarization ratio and 600 m for the other quantities with a calculation step width of 30 m. Error bars are due to signal noise.

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