Backscattering linear depolarization ratio of laboratory generated ice clouds composed of pristine and complex-shaped ice crystals

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Abstract

Artificial ice clouds have been generated in the laboratory by using the large cloud simulation chamber AIDA of Forschungszentrum Karlsruhe. Experiments have been conducted in the 0C to -30C temperature range. Temperature and saturation ratio regimes with distinct predominating ice crystal habits in a varying ice crystal complexity could be identified by probing the ice clouds with a contact-free, single particle imaging device developed in our institute. Backscattering linear depolarization ratio measurements have been performed on the overall ice cloud simultaneously to single ice crystal characterization. A clear dependence of the linear backscattering depolarization ratio on the ice crystal habit was observed. Ice clouds composed predominantly of compact columnar crystals exhibit a higher depolarization ratio than clouds composed of thin plate-like crystals. Ice crystal growth at high ice saturation ratios increases the particle complexity and lowers the depolarization ratio.

1 Introduction

Quantifying the role of cirrus clouds in the climate system requires the determination of the microphysical properties like size and habit of cirrus ice particles and their radiative properties in the infrared and visible region [1]. Fundamental knowledge of scattering, absorption, and polarization properties of ice crystals is also required for reliably retrieving the microphysical particle properties of visible and subvisible cirrus clouds from remote sensing data. Especially the knowledge of the link between the backscattering depolarization ratio δ of ice crystals and their size and habit is a prerequisite for the interpretation of LIDAR remote sensing measurements of cirrus clouds. Interpretations of LIDAR depolarization data usually rely on results from ray tracing models that calculate laser depolarization ratios for large pristine ice crystals, i.e. hexagonal columns and plates [2]. These models predict backscatter depolarization ratios in the range from 0.1 to 0.65, depending on the size and shape (aspect ratio) of the crystals [2, 3]. Depolarization generally becomes larger for larger ice crystals and is larger for columns compared to plates [3]. Moreover, it was found that the depolarization ratio of columns will be significantly reduced, if the basal facets become distorted, e.g. by the formation of pyramidal inversions (like in “hollow” columns) [4]. Although thin plates and “hollow” columns are also not very effective in depolarizing laser light, low depolarization ratios ($0.1<\delta<0.3$) frequently observed in cirrus clouds by *Sassen and Benson* [5] were attributed to the existence of supercooled water droplets and to crystal orientation due to gravitational sedimentation. However, the authors concluded that the linear depolarization ratio of more realistic, complex-shaped ice crystals might differ significantly from that of pristine and simplified crystal geometries modeled so far.

In order to shed some light on the depolarization capabilities of ice clouds with ice crystal shapes that closely resemble those found in natural ice clouds, we started to run well-defined ice crystal growth and characterization campaigns at the large cloud simulation chamber AIDA of Forschungszentrum Karlsruhe. Such campaigns became feasible after the development and installation of two new instruments at the chamber in 2006, namely the in situ laser scattering and depolarization device

SIMONE and the contact-free single particle imaging probe PHIPS. A brief introduction of these instruments is given in section 2. Experimental results are discussed in section 3.

2 Experimental methods

The experiments were conducted at the cloud simulation chamber AIDA [6] in the temperature range of 0C to -30C and at initially ambient pressure. The chamber was humidified to near ice saturated conditions prior to the experiments. Water vapor concentration within the chamber is determined by a long-path tunable diode laser spectrometer. Small seed ice crystals with sizes of a few micrometers were generated outside of AIDA by mixing a cold gas stream containing crystalline ammonium sulfate aerosol particles with warm and moist air in a turbulent mixing chamber with a temperature maintained at -60C. By directing the resulting ice particle/air flow into the AIDA chamber an ice crystal number concentration of about 1 to 10 cm^{-3} can be generated within 10 minutes in the huge AIDA volume of 84 m^3. Ice saturated or supersaturated conditions can be achieved by a controlled expansion of the chamber gas and, thus, a controlled cooling of the chamber volume. Overall homogeneous conditions within the chamber are assured by a mixing fan at the bottom of the chamber.

Light scattering measurements

The laser light scattering and depolarization instrument SIMONE uses a cw semiconductor laser with an emission wavelength of λ=488 nm to generate a polarized and collimated light beam which is directed horizontally along the 4 meter diameter of the cylindrically shaped AIDA chamber. The polarization vector of the light beam can be arbitrarily changed by using a liquid crystal polarization rotator in front of the laser head, but is usually aligned parallel to the scattering plane. The latter is defined by the light beam and the overlapping detection apertures of two telescope optics that probe scattered light from the chamber interior from the 1.8° and 178.2° directions. The intersection between the laser beam and the detection apertures defines a detection volume of 7 cm^3 in the center of the chamber. The intensity of light scattered in forward direction is measured by a photomultiplier. The backscattered light is decomposed by a Glan-Laser prism according to the parallel and perpendicular components with respect to the incident laser polarization. The corresponding intensity components $I_\perp$ and $I_\parallel$ are measured by two photomultipliers. From these measurements the backscattering linear depolarization ratio δ is determined by

$$\delta = I_\perp - I_\perp^{bg} / I_\parallel - I_\parallel^{bg} ,$$

with $I_\perp^{bg}$ and $I_\parallel^{bg}$ the background intensities of the particle-free chamber.

Ice particle habit characterization

Bright field microscopic imaging of single ice crystals was conducted online using the novel PHIPS imaging instrument. The PHIPS instrument is installed underneath the aluminum chamber within the temperature controlled housing of AIDA. It vertically extracts chamber air via a 10 mm in diameter stainless steel flow tube that extents to about 200 mm into the chamber volume. A stable sampling flow of 10 SLM is maintained by a flow controller backed by a vacuum pump. When a cloud particle passes the detection volume of the instrument, which is defined by the intersection of the laser beam cross section and the field of view of an optical detector, scattered light generates a trigger pulse that opens the shutter of the microscopy unit and fires – with a short delay – the flash lamp. The half width of the flash is only 10 ns. In this way an 8 times magnified bright field image of the moving ice crystal is generated without any motion blurring. The system has an optical resolving power of about 2 µm and a depth of field of about 150 µm. The magnified image of the particle is captured by a 1392×1024 pixel CCD camera with 6.45×6.45 μm^2 pixel size. This results in a field of view of about 1.1×0.8 mm^2 with a pixel resolution of 0.8 µm in the object plane. Image processing algorithms have been developed for automated analysis of the geometric properties of the particles, like projected area, sphere equivalent diameter, roundness and aspect ratio.

3 Results

An example of an ice growth experiment is shown in Figure 1. The experiment was started at a temperature of -5C. Ice crystals with columnar shapes are expected in this temperature range [7]; pristine habits for a growth near ice saturation and complex shapes (like "hollow" columns or needles) for a growth at intermediate and high saturation ratios. Within the first 300 sec experiment time supercooled water droplets were sprayed by a two-component nozzle directly into the chamber to gradually increase the ice saturation ratio by droplet evaporation. Ice saturated conditions were eventually achieved at about 300 sec experiment time.

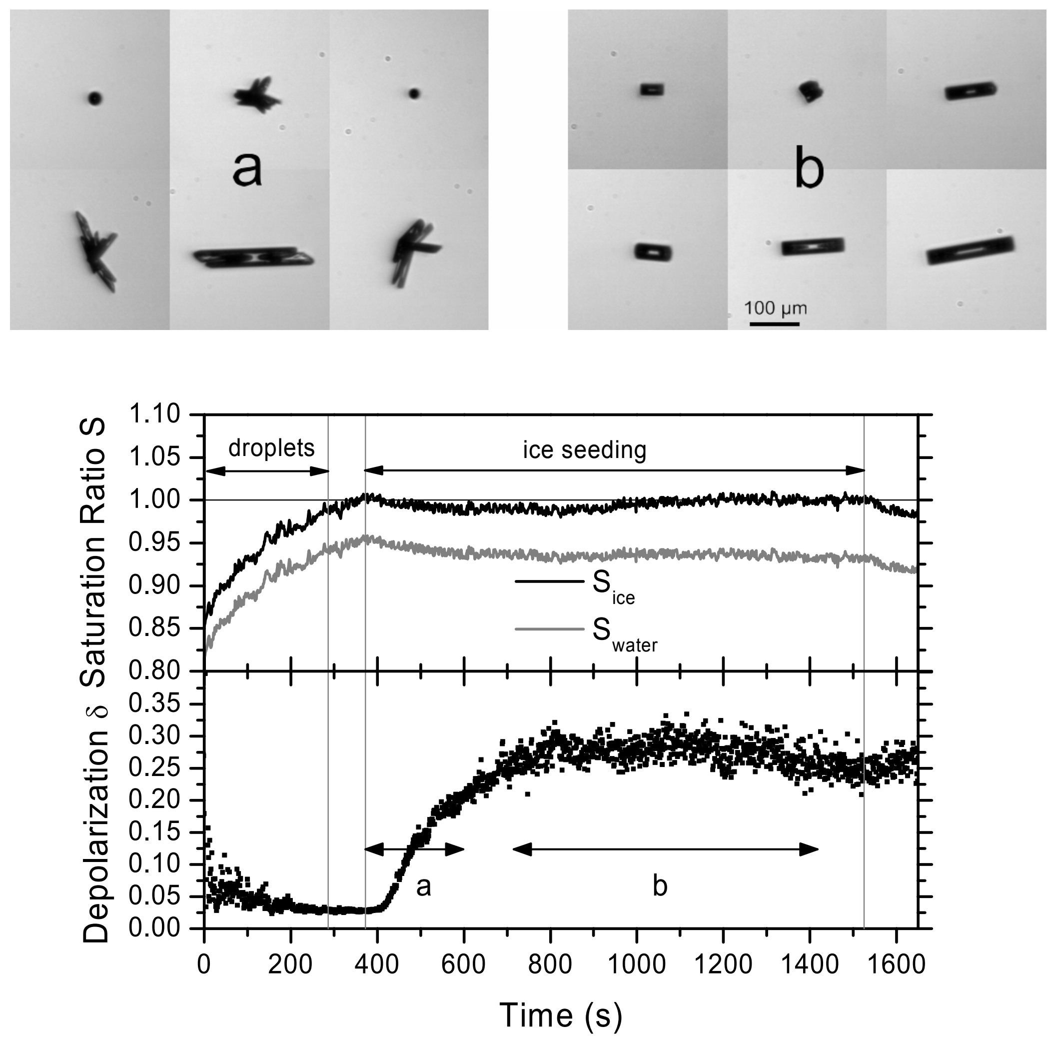

Figure 1: Ice growth experiment conducted at an initial temperature of -5C. See text for details.

Note that the saturation ratios given in Figure 1 are mean values. Locally, the saturation ratios might differ from these values due to temperature and water vapor inhomogeneities, especially near the injection positions of the water droplets and the seed ice crystals. The presence of a droplet cloud is reflected by a low depolarization ratio δ in Figure 1. Ice seeding was started roughly 1 minute after the water droplet injection has been stopped. Thus, small seed ice crystals were added to an evaporating water cloud. To maintain ice saturated conditions in the chamber during ice seeding, the chamber gas was slowly expanded by pumping, resulting in a temperature drop to -7.5C during 300 to 1500 sec experiment time. Immediately after the beginning of the seed ice addition a mixed phase cloud was observed for a short time period of about 60 to 100 sec by PHIPS (first row of plate (a) in Figure 1). Needles and almost "hollow" columns were indeed observed in this period of high saturation ratio as expected from [7]. After the water droplets have been evaporated the remaining ice cloud was predominantly composed of "hollow" columns and bundles of needles (shown in the second row of plate (a)), which results in a low depolarization ratio of only about 0.1 to 0.15. Newly added seed ice crystals then grew at lower saturation ratios which resulted in a gradual change of the cloud composition between 500 and 700 sec experiment time. An uniform cloud predominantly composed of rather solid columns with less structural complexity was eventually achieved at about 700 sec experiment time. By keeping the saturation ratio at about ice saturation while continuously feeding new seed ice crystals, a stable cloud could be maintained over about 900 sec (plate (b) of Figure 1). A significantly higher depolarization ratio of about 0.3 was measured during this time period of compact, solid crystals. In further experiments, conducted in temperature regions where the ice crystals grow into plate-like shapes (-12C and -25C), we measured very low depolarization ratios of 0.1 or even less. Such ice clouds cannot easily be distinguished from supercooled water clouds by LIDAR applications. Our experimental results confirm, at least qualitatively, the trends in the ray tracing modeling results by *Takano and Liou* [4] and *Noel et al.* [2], i.e. very low δ values in case of very thin plates and a strong decrease of δ by the formation of basal inversions in case of columns. However, for the distorted ice crystals shown in plate (a) of Figure 1, we measured a significantly lower depolarization ratio of $0.1<\delta<0.15$ than modeled so far for columns with deep inversions in the basal facets ($\delta=0.24$).

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