10 YEARS OF LIDAR OBSERVATIONS OF MIXED-PHASE CLOUDS WITH FOCUS ON TEMPERATURE AND AEROSOL PROPERTIES

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1. ABSTRACT

Based on more than 10 years of regular observations of aerosols and clouds with a three-wavelength depolarization Raman lidar at the Leibniz Institute for Tropospheric Research (IfT) Leipzig, studies on heterogeneous ice formation in free tropospheric clouds are performed. The focus is set on clouds showing cloud top temperatures between -40 °C and 0 °C. Cloud top height and temperature, respectively, are taken as the primary parameters determining the initiation of cloud glaciation. The cloud phase is determined from the depolarization ratio measured with the lidar. Until the end of 2006, 400 cloud cases were found in the defined range of temperature. The primary goal of the study is to establish a statistic regarding the relationship between cloud top temperature and the percentage of ice-containing clouds with respect to all observed clouds. First results of the data analysis indicate that at temperatures below -15 °C already 50% of the observed clouds contain ice. With decreasing temperature the fraction of ice-containing clouds increases, reaching 80% at -25 °C and almost 100% at -35 °C. Besides temperature, the properties of aerosol particles acting as ice nuclei are an important parameter for heterogeneous freezing processes. Thus a further goal is to extend the study by including information about the presence or absence of aerosol layers and the type of aerosol in the vicinity of the clouds observed with the lidar.

2. INTRODUCTION

The process of heterogeneous ice formation in the free troposphere currently is an important topic of atmospheric science. Heterogeneous ice formation plays a major role for an accurate precipitation forecast in meteorological models and influences optical properties of clouds because ice and water have different radiative properties (Yoshida and Asano, 2005). This proceeding describes the approach to setup a lidar-based study of the temperature- and aerosol-type dependence of heterogeneous ice formation in free-tropospheric clouds. The work is done in the scope of the project DRIFT (Dust related ice formation in the troposphere). The description of the applied instrumentation is given in Section 3. Section 4 presents the methodology. First, preliminary results are shown in Sec. 5.

3. INSTRUMENTATION

The described study is based on data acquired with the zenith-pointing three-wavelength Raman depolarization lidar of the Leibniz Institute for Tropospheric Research Leipzig, Germany. Aerosol and cloud optical properties can be retrieved at 355, 532 and 1064 nm. The depolarization ratio, indicating cloud phase, is measured at 532 nm.

Since 1997 regular lidar measurements have been performed in the scope of GERLIN (German Lidar Network; 1997–2000) and EARLINET (European Aerosol Research Lidar Network, since 2000). In addition to the...
regular measurements observations have been performed during Saharan dust outbreaks and episodes with long–range transport of forest fire smoke, Arctic haze, and urban pollution from North America to Central Europe. Since the beginning of 2006 additional measurements have been performed with special emphasis on thin mid–tropospheric clouds (mostly altocumulus clouds). Currently, the database contains more than 1000 measurements.

4. METHODOLOGY

In the first step of the statistical analysis, all available lidar measurements performed since 1997 were examined for the occurrence of suitable cloud cases. For each cloud case the following information was compiled:

(a) Geometrical cloud properties (Cloud top and base height and time of occurrence)
(b) Cloud phase
(c) Meteorological cloud properties (Temperature, humidity, and wind at the cloud boundaries)
(d) Aerosol properties (10 day backward trajectories, backscatter coefficient at 532 nm)

A. Geometrical Cloud Properties

Heterogeneous ice formation is known to occur at temperatures between approximately -40 °C and -10 °C. Therefore, as a first step in the data analysis process a database was created containing the geometrical properties, i.e. cloud top height and cloud base height, and the time of occurrence of all clouds observed during the measurements performed since 1997 that had top heights of below 10 km height (> -40 °C).

In the case of opaque clouds with optical depths larger than approx. 3 the cloud top can not be determined directly from the averaged signal because no information is returned from altitudes above the cloud. Instead, the cloud top is retrieved from measurements in cloud holes or from the cloud and aerosol structures after the passage of the cloud field. If also this approach gives no information about the cloud top, the cloud is removed from the database. For less than 3% of all clouds no cloud top could be determined.

B. Cloud Phase

The determination of the phase of the observed clouds is based on the depolarization ratio at 532 nm wavelength. The laser emits parallel polarized light. The receiver detects the parallel and cross–polarized components of the backscattered light separately. The volume depolarization ratio is now defined as the ratio of the volume backscatter coefficient measured with the cross–polarized channel to the respective backscatter coefficient measured with the parallel polarized channel.

During scattering events at aerosol and cloud particles the polarization of a fraction of the scattered light is modified. The strength of this depolarization primarily depends on the deviation of the shape of the scattering particle from a sphere. Thus, liquid water droplets cause no depolarization whereas ice crystals cause significant depolarization to the returned laser light.

Besides particle shape two masking effects alter the depolarization of the detected signal. Multiple scattering of light in optically thick water clouds causes additional depolarization that increases linearly with cloud penetration depth of the laser beam. Many clouds show depolarization ratios of up to 10% at cloud top. This behavior is in agreement with modelling results. The second effect is caused when measurements are performed with a zenith–pointing lidar and horizontally oriented ice crystals are present and produce specular reflections which result in the detection of strong lidar signals and low depolarization ratios close to those of water clouds.

Extensive lidar observations with Doppler, Raman, and depolarization lidar have been done to study the relationship between the depolarization ratio and the dynamical behavior of ice crystals (Seifert et al., 2008). In conclusion, we found clear signatures of water, mixed-phase and ice cloud layers in terms of depolarization ratio, so that an unambiguous separation of cloud layers containing liquid drops...
only or a mixture of drops and ice crystals or ice crystals only became possible.

A water cloud always shows no depolarization at cloud base and a weak to considerable multiple scattering effect in the depolarization ratio at cloud top. Layers containing ice crystals always cause a non-monotonic, inhomogeneous vertical profile of the depolarization ratio. By applying these features, we were able to group the cloud cases found during the last 10 years into two different cloud classes (liquid, ice, mixed-phase).

C. Meteorological Cloud Properties

Between September of 2000 and September 2006 two radiosondes were launched per day (00 UTC, 12 UTC) at Oppin, 40 km west of Leipzig, by the German Meteorological Service. The sondes measured temperature, humidity, and wind speed and direction. During special events additional radiosondes were launched at the lidar station. For times not covered by the radiosonde data the meteorological properties are obtained from model reanalyses based on the Global Data Assimilation System (GDAS) of the U.S. National Weather Service’s National Center for Environmental Prediction (NCEP) that can be accessed via http://www.arl.noaa.gov/NOAAServer/.

D. Aerosol Properties

Laboratory and modeling studies show that besides temperature the efficiency of heterogeneous freezing strongly depends on the type of aerosol that acts as an ice nuclei (Diehl et al., 2006). Thus as a final step of the presented study it is planned to investigate the impact of the aerosol type on cloud glaciation. We use the backscatter coefficient calculated at 532 nm wavelength to determine if there was aerosol observed at cloud level. To obtain the type of aerosol that was present during the observation of a cloud we use, if available, the analyzed aerosol optical data of the multiwavelength Raman lidar (Müller et al., 2007) and 10 day backward trajectory calculations. The focus is basically set on the discrimination between scenarios with and without Saharan dust. However, it is also possible to identify anthropogenic haze and forest fire smoke but cases with mid–tropospheric clouds in such aerosol layers are rare.
5. RESULTS

A. Case Study

Figure 1 presents height–time plots of range–corrected lidar signal and depolarization ratio measured on 16 September and 17 September 2006. The 120–hour backward trajectories shown in Fig. 2 all passed the Sahara before they arrived at Leipzig at altitudes of 3000, 5000, and 7000 m. Thus the aerosol type that was present during the time of the measurement is classified as Saharan dust.

The dust plume is clearly visible up to heights of 4 km in the range corrected signal in Fig. 1. Traces of dust are found up to 8 km height. The volume depolarization ratio also identifies the dust at lower heights. However, the volume depolarization ratio depends on Rayleigh and particle depolarization. Rayleigh scattering at air molecules produces very low depolarization ratios so that the volume depolarization ratio is low if the particle signal is low and Rayleigh scattering dominates.

Above heights of about 4 km several cloud layers are visible extending up to heights of 12 km. They were separated into different cloud cases according to Sec. 4-A and Sec. 4-B.

B. Statistics

In the scope of the presented study more than 600 cloud cases were found in the height range between the ground and 10 km. 400 cloud cases could be classified in the temperature range between -40 °C and 0 °C.

Figure 3 shows the number of analyzed cloud cases as a function of cloud top temperature binned into intervals of 5 K. The three histograms show the data separately for all clouds(a), ice–containing clouds(b) and water clouds(c).

The dataset is well distributed over the
temperature range with approximately 40 cases per 5 K temperature interval. Only around -40 °C less cloud cases were found, suggesting that the region of around -40 °C separates the temperature range dominated by homogeneous freezing (Cirrus; T < -40 °C) from the temperature range dominated by heterogeneous freezing (Altocumulus; T > -40 °C).

Figure 3(b) shows that ice–containing clouds spread homogeneously over a wide vertical range, probably caused by the concurrence of homogeneous and heterogeneous freezing, falling ice crystals and cloud seeding effects.

An interesting feature of Fig. 3(c) is that pure water clouds with cloud top temperatures ≤ -25 °C are rare. This is further illustrated in Fig. 4 that shows the fraction of ice–containing clouds with respect to all observed clouds as a function of cloud top temperature. The relative amount of ice-containing clouds is a strong function of temperature in the range from about -12 °C to about -27 °C. This is the range of temperatures where the efficiencies of the different heterogeneous ice formation mechanisms rapidly increase with decreasing temperature. Whereas heterogeneous ice formation is comparably inefficient at temperatures above -15 °C, heterogeneous ice formation has almost a 100% probability at temperatures lower than -30 °C. This finding was recently confirmed by lidar measurements in southern Morocco during the SAMUM (Saharan Mineral Dust Experiment) campaign (Ansmann et al., 2008). At temperatures < -35 °C homogeneous ice formation is initiated and dominates ice production. At temperatures below -40 °C cirrus is the only remaining cloud type.

6. BIBLIOGRAPHY