The electric field alignment of ice crystals in thunderstorms

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Abstract

The re-orientation of ice crystals in cirrus anvils following a lightning stroke is often visible from the ground with a sudden change in cloud brightness. Vonnegut suggested that this effect was due to electric field orientated ice crystals relaxing their orientation upon the removal of the field. Laboratory measurements of the electric field strength required to orientate ice crystals typical of those in thunderstorm anvils have now been made. The particular distribution of visible laser light scattered by a cloud of ice crystals orientated in an electric field is used to identify the types of ice crystal present. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Vonnegut (1965) suggested that the orientation of ice crystals falling in thunderstorm anvil regions would be affected by the local electric field and that following a lightning discharge the rapid re-orientation of the reflecting crystals would lead to a change in cloud brightness visible from the ground. Mendez (1969) studied the polarization of light scattered by anvil crystals in New Mexico thunderstorms and noted a rapid change at the time of a lightning stroke. Hendry and McCormick (1976) used a polarization diversity radar and reported abrupt changes in orientation of ice particles in the anvil regions associated with lightning discharges. Shao and Krehbiel (1996) used a dual

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circular-polarization radar in a remote study of storm electrification and are currently using the information to map out the electrical alignment directions in storms.

Evidently, electric fields in the electrified regions of thunderstorms are sufficient to orientate ice crystals and the release of electric tension following a lightning stroke leads to the observation of a rapid re-orientation of the crystals. The detection and identification of ice crystals in clouds by remote means such as radar and lidar is influenced by the orientation of the ice crystals so that a knowledge of the critical field required to orientate crystals will be a useful tool both as a help in identifying the types of ice crystals in the cloud and as a remote indication of the strength of the electric field present before lightning.

The anvil regions of thunderstorms contain ice crystals which extend in size to a few hundred micrometres. Arnott et al. (1994) measured crystal sizes in cirrus using a replicator designed by Hallett (1976) and confirmed this size range but were surprised to find a crystal distribution with a maximum crystal size below 50 μm; they concluded that the optical scattering properties of such clouds are influenced significantly by these smaller crystal sizes. Vonnegut's suggestion was that the reflection of light from the faces of crystals produces the observed change of cloud brightness following lightning, and this will be the dominant cause of the visual observations. However, the laboratory technique makes use of the refraction of light by ice crystals in order to determine their orientation in an electric field. The ice crystals scatter visible radiation in all directions and also act as prisms and so refract light most efficiently at angles close to their angle of minimum deviation. For light entering a prism face of a hexagonal plate ice crystal and leaving via another prism face, the ice crystal acts like a 60° prism for which the angle of minimum deviation is 22°. In the atmosphere, horizontally orientated plate crystals cause sun-dogs visible at 22° on either side of the sun when fairly low in the sky, while a random orientation of ice crystal plates or columns produces the complete 22° halo around the sun. A randomly orientated array of thick plate or columnar crystals produces a 46° halo when light enters a basal face and leaves through a prism face with the crystal acting like a 90° prism; occasionally 46° sun dogs are visible indicating the presence of horizontally orientated columnar crystals. In this work a laboratory study of the scattering properties of ice crystals has been adapted to permit study of the orientational effect of an electric field.

2. Experimental details

The experiments are conducted in a cloud chamber located inside a walk-in cold room capable of operating down to −40°C, as shown in Fig. 1. A vapour source drives moisture directly into the chamber to form a supercooled cloud of water droplets. Ice crystals are nucleated by the action of pulses of compressed air expelled directly into the cloud; the adiabatic expansion cools a local volume of cloud sufficiently to initiate the crystals. The vapour source and the nucleating pulses of compressed moist air are continued in order to provide a constant source of ice crystals. The air pulse frequency and duration can be varied to give some degree of control over the size distribution and concentration of the crystals.
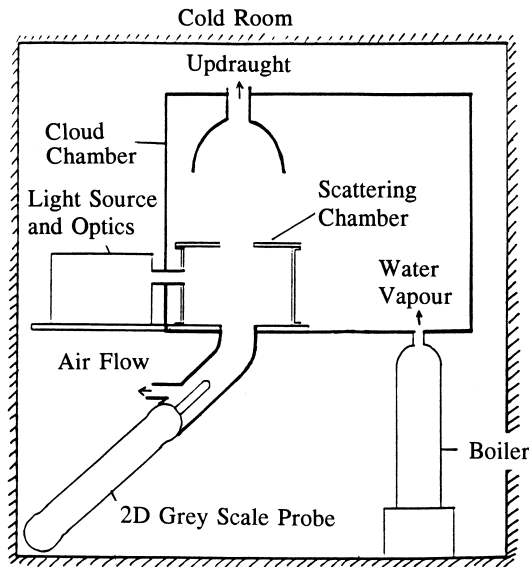
Fig. 1. The cold room containing the ice crystal cloud chamber and the light scattering chamber.

Within the cloud chamber is a cylindrical chamber through which the cloud is drawn down by an air flow which passes through the imaging optics of a PMS 2 D grey scale probe. The ice crystals passing through the scattering chamber are thus continuously sampled allowing the acquisition of size and concentration data. A He–Ne laser beam (0.63 μm) enters the scattering chamber horizontally, Fig. 2, and the radiation scattered in the horizontal plane is monitored by a Silicon–Germanium photodiode detector which moves smoothly round the chamber on a motor driven rotating table under computer control and scans through the scattering range 10° to 170°. The phase function, which is a measure of the angular scattering intensity, is determined from the scattering data
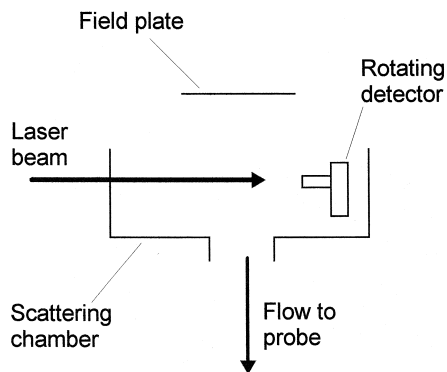

Fig. 2. Schematic of the experimental arrangement.

following the method outlined by Sassen and Liou (1979) and described by Rimmer and Saunders (1997).

In order to determine the effect of a vertical electric field on the crystal orientation, an electric field plate is located 32 cm above the floor of the metal scattering chamber. The electric field plate can be raised to a potential up to 20 kV to provide a non-uniform field in the chamber. However, in the small active light-scattering volume in the centre of the chamber, the field is vertical with a maximum value in the region of 62.5 kV m^{-1} which is of the order of typical breakdown electric field strengths in thunderstorms (100 kV m^{-1}) according to Winn et al. (1981).

3. Results

Fig. 3 shows the ice crystal size distribution for the cloud used in our experiment. The cloud chamber temperature varied from $-8.5°C$ at the top to $-20°C$ at the bottom giving a mixture of columnar and plate type ice crystals. In Fig. 4 we show the phase functions (normalised intensity distribution) as a function of angle of scatter for field plate voltages of 15 kV and 20 kV corresponding to vertical electric fields in the centre of the scattering volume of 47 and 62.5 kV m^{-1}. It is apparent from the figure that the phase functions are significantly different in the forward scattering regions, particularly around the 22° and 46° halo scattering angles. At field strengths up to 15 kV, the 22° halo is relatively weak and the 46° halo is absent, however at 20 kV, both haloes are prominent. This result can be explained by the field-induced charges in the ice crystals
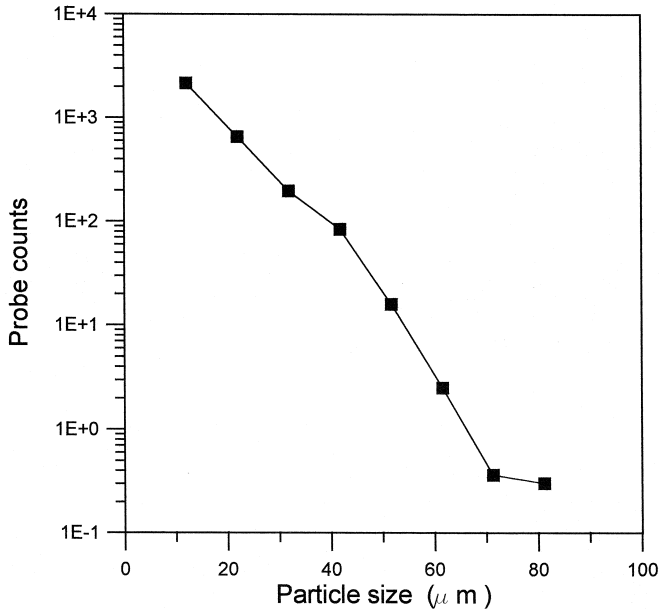

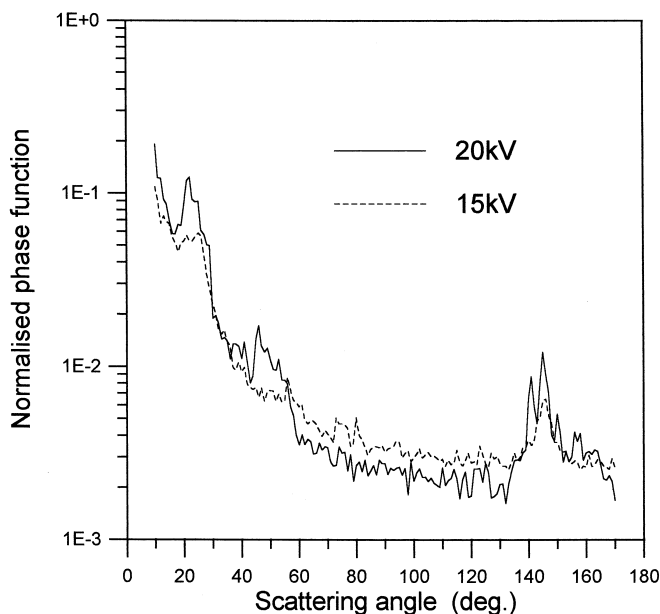Fig. 3. Ice crystal size distribution in the cloud.

Fig. 4. Scattering phase functions for field plate voltages of 15 kV and 20 kV.

causing them to align their major axes with the field. Orientated columns, which become orientated vertically with the longer axis (c-axis) parallel to the vertical electric field, will lead to an enhancement of the 22° halo in the scattering plane whilst vertically orientated plates, with an a-axis parallel to the field, will enhance the 46° halo. The field strength in the sampling volume is not uniform because the scattering chamber walls and the detector casing affect the field configuration. However, in the small active scattering volume in the centre of the scattering chamber the field strength is a maximum and the direction is vertical, so the upper limit to the critical field strength required to orientate the crystals must lie between 47 and 62.5 kV m^{-1}.

4. Discussion

Thunderstorm electrification processes, as discussed by Vonnegut (1963, 1994), result in a vertical distribution of charged particles throughout the cloud giving rise to sufficiently high electric fields to initiate lightning discharges. Vonnegut (1991) pointed out that the high charges in the anvil, confirmed by the observed orientation effect of the field, attract negative ions from above the cloud resulting in the typical thunderstorm current flow, which is of the order of 1 A. Because of the shielding charges found on the cloud particles at the edges of the cloud, the determination of field strengths inside thunderstorms is possible only by internal measurements, such as rockets and balloons (Marshall et al., 1996), and aircraft (Dye et al., 1986) or by measuring the external field changes produced by lightning (Wilson, 1916; Krehbiel et al., 1979). In many cases, the

thunderstorm charges are concentrated in such a way as to produce a vertical tripole with the anvil and lower cloud regions carrying net positive charges with an extensive negative charge region at intermediate levels, although recent work by Marshall et al. (1996) shows a more complicated charge distribution.

The present work deals with a remote method by which the electric field value in thunderstorm cirrus anvils may be estimated. Visual observations of changes in reflectivity have provided qualitative information in the past, in the future, data will be available from dual circular-polarization radar observations (Shao and Krehbiel, 1996). The sudden change in cloud optical reflectivity, when the electric field relaxes immediately following a lightning flash, indicates the presence of non-spherical cloud particles whose field-induced dipoles orientate the crystals so that the longer axis of the crystals becomes aligned with the pre-lightning field direction. These particles are most likely to be positively charged ice crystals which have been carried into the anvil region. Cho et al. (1981) analysed the influence of turbulent eddies on the orientation of ice crystals falling in cumulonimbus clouds and showed that turbulence is not able to destroy the preferred orientation of columnar crystals, with their long axis horizontal, and hexagonal plates with their broad face horizontal. Weinheimer and Few (1987) calculated the required electrical torque to overcome aerodynamic forces on typical cirrus type ice crystals and found that crystals over 200 μm dimension required orientational fields in excess of 100 kV m^{-1}, while smaller crystals could be orientated in fields of order 10 kV m^{-1}. In the present work, the predominant ice crystal size is below 50 μm and the required orientational field is around 50 kV m^{-1}, which appears to be consistent with the theoretical work. The observation of orientational effects shows that turbulence is not a significant influence on the falling behaviour of ice crystals in our laboratory cloud.

The crystal re-orientation observed in these experiments and in nature, indicates the existence of a pre-lightning electric field of around 50 kV m^{-1} or more. That such high fields are present in the anvil regions of thunderstorms, when the charging regions are usually assumed to be at lower altitudes, is of relevance to the processes involved in thunderstorm electrification.

Acknowledgements

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