Atmospheric halos provide means to estimate shapes and orientations of airborne ice crystals

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The shapes of ice crystals in tropospheric clouds have been examined with various techniques. An efficient addition to the methods is provided by halo phenomena arising from reflection and refraction of sun light in airborne ice crystals. This paper describes the extent to which conclusions of ice crystal properties can be drawn based on analysis of visible halos. The associations of ice-crystal orientations and shapes with halo forms can be examined with a Monte-Carlo simulation algorithm using geometrical optics.

INTRODUCTION

The problem of determining microphysical properties of cirrus and cirrostratus clouds has received scientific interest due to the role of upper tropospheric clouds in Earth's radiation budget and climate. The issue has been approached from many different angles. Ice-crystal nucleation has been extensively examined and numerous laboratory experiments have been conducted. The ice-crystal content of cirrus clouds has been studied with spaceborne and ground-based remote-sensing methods with frequencies ranging from millimeter waves up to visible light [1]. Also various ice crystal probes and cloud-particle imagers have been flown in aircrafts [2]. Understanding the conditions of the upper troposphere is a demanding task and despite all the results achieved so far, inconsistencies between theories and practical measurements arise constantly [3].

Atmospheric halos offer an additional tool for determination of ice-crystal properties in tropospheric clouds. By looking at the halos visible in a cloud under examination, one can make fairly accurate estimates of the orientations and shapes of the ice crystals, since there exists a well established association between halos and ice crystal orientations [4]. Furthermore, some attributes of a halo display give insight into aspect ratio of ice crystals as well as to possible imperfectness of certain crystal faces. A few authors have dealt with halo phenomena in this context, but their approaches have not exploited the full potential of atmospheric halos as one element in determining the microphysical properties of tropospheric clouds. In this paper some methods for halo - ice crystal associations are described.

COMPUTER SIMULATIONS OF HALOS

Reflection and refraction of sunlight by hexagonal ice crystals (Ice Ih, see Fig. 1) gives rise to about 35 halo forms, and when sometimes these hexagons have also pyramidal $\{10\bar{1}1\}$ faces, a group of about 25 additional halo forms are possible. Earlier scholars used pencil and paper as well as clever geometrical techniques to solve the light ray paths responsible

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for different halo forms and to derive their appearence at different sun elevations. Now we can harness the computer to do all these calculations. The size parameters of halo-making ice crystals are large enough to justify the use of a geometrical-optics-based Monte-Carlo algorithm for simulations of halo phenomena.

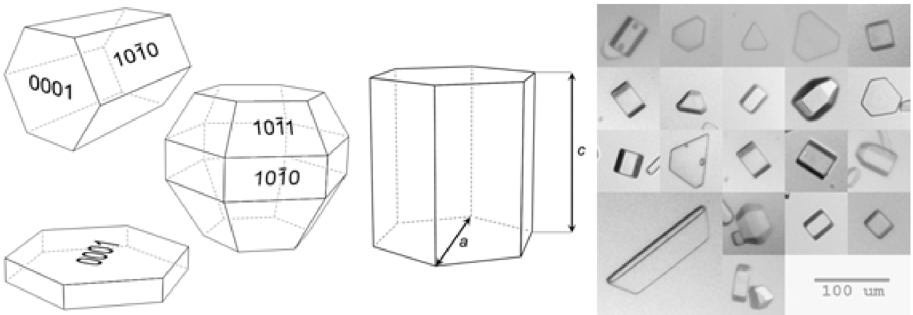

Figure 1. Hexagonal column-, plate- and pyramidal ice crystal on the left. The aspect ratio is the ratio of the length of the prism in c-axis direction to the width in a-axis direction. On the right, examples of real crystals collected in diamond dust near ground.

In a halo-simulation program [5], a ray from the sun's disk is traced through an ice crystal according to the laws of geometrical optics until it leaves the crystal and creates a pixel of light, a halo point, on a celestial sphere. Ice crystals are defined for the computer as an intersection of half-spaces. At each face the light is split into reflected and refracted components, whose intensities are governed by Fresnel equations. These intensities are interpreted as probabilities based on which the decision of plotting is made. After one cycle a new ray is taken under consideration and the process is repeated for as many rays as needed, even millions. Each variable controlling crystal dimensions, shape and orientation can be set to vary according to uniform or normal distribution with a desired standard deviation. Monte-Carlo halo simulation procedure was first implemented by Greenler and Mallman [6], and further elaborated by Pattloch and Tränkle [7].

Faint halos and the sometimes encountered lack of halos in high clouds [8] is a clear indication of the presence of poor halo makers. The program can be expanded to handle also non-convex polyhedra, such as rosettes, capped columns or twinned plates. Also internal impurities, face deficiencies and air bubbles can be modelled. These modifications may be needed in order to evaluate the degradation in halos when the ice crystals are not perfect.

WHAT CAN BE LEARNED BY LOOKING AT A HALO DISPLAY?

Halo displays can be seen regularly – over 100 days a year in most locations worldwide. Typical displays include only a few halo forms, which come from the group of about ten most common ones. Compared to ordinary halos complex displays provide more versatile features from which ice crystal properties can be deduced, but they occur less often. The properties of ice crystals that can be seen from halos are the following:

Main axis orientation. The orientation of the crystal main axis is readily seen; plate crystal halos, such as parhelia and circumzenith arc, arise from crystals with their c-axis vertical, and column crystal halos, such as 22° tangent arcs, arise from crystals with their c-axis horizontal. In cases of circular halos, the crystals do not have a preferred orientation but are more or less randomly oriented. Birefringence of ice provides another method to determine the main axis direction, since the deviation of the extraordinary component reaches a maximum when the light path is perpendicular to the main (optical) axis of the crystal [9]. The angular separation of the two components is, however, very small. This poses a challenge for detection of this separation, especially since the exact location of the inner edge of a halo is not easy to see.

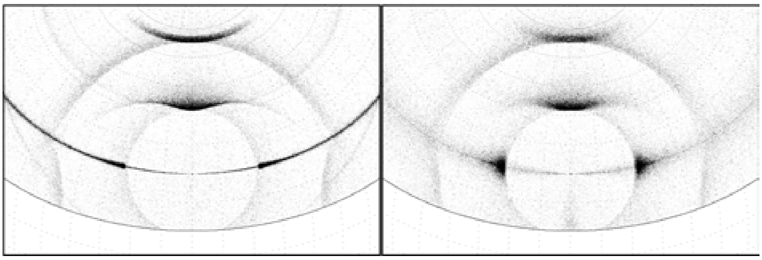

Figure 2. Two simulations showing the effect of different crystal tilts. The standard deviations of normally distributed tilts for plate crystal populations were 3° (left) and 6° (right), and for column populations 0.3° and 3°, respectively. It should be noted that the outer halo touching the circumzenith arc is not a 46° halo, but rather a combination of infralateral and supralateral arcs.

Tilting angles of the crystals. Well developed halos are a sign of very small tilting angles of the main axis of crystals. In some good-quality displays, the crystal tilts of the order of just a few tenths of a degree are needed to attain a good match between a halo photograph and a simulation. The appearence of halos is sensitive to the tilting angle; an increase of a few degrees can result in a considerable change in the halos (Fig 2). This parameter can be fairly accurately estimated by comparing photographs with a simulation, thus opening an interesting possibility for comparison between halo observations and e.g. lidar measurements.

Crystal aspect ratios. The orientations of ice crystals in the air are partially dictated by their aspect ratio and cross section in a plane perpendicular to the main axis. The intensity profiles of halos and their respective definitions give indications of the shape of ice crystals that made the halos. Different aspect ratios and profiles have an effect on relative surface areas of crystal faces, which has a direct impact on the probabilities of occurence of halo-making raypaths. In addition, some raypaths may become more favoured than others when the crystal dimensions change and in some cases part of the raypaths may be completely shut off. These effects are most prominent in pyramid crystal halos and halos with a raypath involving internal reflections, i.e. less frequently seen halos, see Fig 3.

CONCLUSION

Atmospheric halos provide a tool to estimate airborne ice-crystal properties. When halos are seen, the information that can be extracted from their appearence can be combined with the data obtained with other means. Ice crystal - halo associations can be modelled with a Monte-Carlo-simulation algorithm using geometrical optics. With the aid of computer simulations a good match between observed halos and the model can be obtained, giving values for the shapes and orientations of ice crystals responsible for the halos. There is no direct way to figure out the crystal sizes from the halos, but for that one may use optical phenomena produced by the diffraction, e.g. coronae, which are practically always seen when particles come between the sun and the observer.

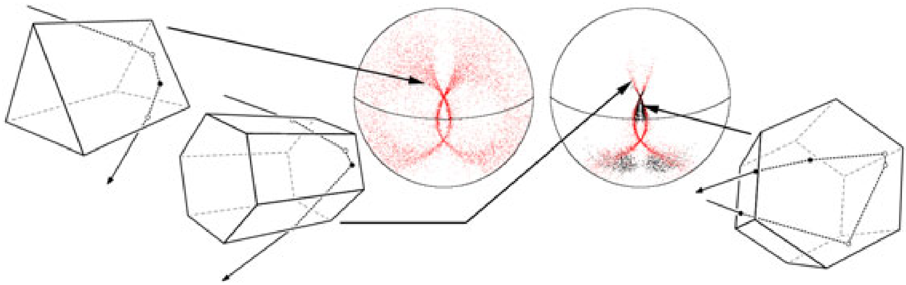

Figure 3. An example of the effect of crystal shape on the formation of halos. Simulations showing two components of diffuse anthelic arcs with a regular hexagonal column (right) and a triangular one (left). With a triangular column the component B spreads wider than with a regular hexagon, since within the crystal there is more room for the raypath. The raypath of the A component (black dots) includes internal reflections from adjacent faces of the hexagon, which is the reason it is completely missing from the leftmost simulation since it can not be formed at all when the crystal profile is triangular.

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