

NOTES AND CORRESPONDENCE

On the Occurrence of Hollow Bullet Rosette- and Column-Shaped Ice Crystals in Midlatitude Cirrus

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(Manuscript received 12 October 2006, in final form 7 February 2007)

ABSTRACT

Cirrus clouds in mid- and high latitudes are frequently composed of bullet rosette- and column-shaped ice crystals, which can have hollow ends. Bullet rosette-shaped ice crystals are composed of a number of bullets radiating from a central point. Research has shown that the light-scattering properties of ice particles with hollow ends are different from the scattering properties of solid ice particles. Knowledge of the frequency of occurrence of hollow particles is important to more accurately calculate the radiative properties of cirrus clouds.

This note presents the results of a survey of cirrus cloud ice crystal replicas imaged from balloon-borne Formvar (polyvinyl formal) replicators. Fifty percent to 80% of the replicated bullet rosette- and column-shaped particles had hollow ends. In bullets longer than 150 μm in length, the length of the hollows of the bullets averaged 88% of the total length of the bullet. The combined length of both hollow portions of column-shaped ice crystals varied from 50% of the length of the column for 30- μm -long columns to 80% of the length of the columns longer than 200 μm . Asymmetry parameter values estimated from cirrus cloud aircraft particle size distributions are higher by 0.014 when hollow crystals are considered. This difference leads to a 2.5 W m^{-2} increase for hollow crystals at the surface for a 0.5 optical depth cloud, demonstrating the importance of the incorporation of hollow particle scattering characteristics into radiative transfer calculations.

1. Introduction

At any give time, 30% of the midlatitudes are covered with high-altitude cirrus clouds (Wylie and Menzel 1999). Cirrus clouds have been identified as one of the most uncertain components regulating the earth's climate system (Lynch et al. 2002; Liou 1986). Midlatitude cirrus clouds are often composed of bullet rosette- and column-shaped ice crystals (Heymsfield et al. 2002). Lawson et al. (2006) showed that bullet rosette- and column-shaped ice crystals are responsible for more than 50% of the cloud extinction for midlatitude cirrus clouds, while convectively generated cirrus clouds usually contain highly irregular particles [contrast the cirrus particle images by Heymsfield et al. (2002) to anvil cirrus particles shown by Garrett et al. (2005)]. While

bullet rosette-shaped ice crystals are commonly observed in aircraft microphysical data, current aircraft image probes do not have sufficient resolution or optical quality to determine the frequency of occurrence of hollow particles.

Hollow particles have been mentioned in the literature, although their frequency of occurrence has not been quantified. Bailey and Hallett (2004) showed that bullet rosette- and column-shaped ice crystals can grow to be hollow under high ice super saturation conditions in a laboratory diffusion chamber. Walden et al. (2003) stated that bullet-shaped ice crystals collected at the South Pole are always hollow and that columns were frequently hollow. Grenfell et al. (2005) questioned whether or not bullet rosette crystals in cirrus cloud are hollow. High-resolution images of bullet rosette-shaped crystals collected on the ground at the Mt. Hachimantai Observatory of Akita University, Japan, clearly showed high occurrence of hollow bullets (Heymsfield et al. 2002). Heymsfield (1986) showed im-

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ages of hollow column-shaped ice crystals imaged with an aircraft Formvar replicator taken at 190 K in high-altitude tropical subvisual cirrus.

Hollow crystals have been implied by imaging atmospheric bullets and measuring the diameter of the resulting melted drops. The expected mass of the particle can be calculated from measurements, which can then be compared to the actual mass. Using this technique, Heymsfield and Knollenberg (1972) showed that bullets have effective densities as low as 0.7 g cm^{-3} with an average of 0.81 g cm^{-3} , where a value of 0.91 g cm^{-3} would be expected for solid crystals. An effective density of 0.7 g cm^{-3} is achieved when a pyramid that is equal in length to the bullet is removed from the bullet, whereas a density of 0.81 g cm^{-3} would imply that the average length of the hollows was half of the length of the bullet. Heymsfield et al. (2002) further investigated the occurrence of hollow crystals by estimating the density of bullets by directly measuring crystal images of bullet rosette-shaped crystals photographed in Siberia. The total volume of crystals as well as the volume of the hollow was estimated for the bullets of 180 imaged bullet rosettes and the average bullet effective density was calculated to be 0.82 g cm^{-3} .

Ray-tracing results have shown that the scattering properties of hollow bullet rosettes are substantially different from those of solid bullet rosettes at visible wavelengths (Schmitt et al. 2006). For hollow crystals the asymmetry parameter was lower (0.84 versus 0.87) for rosettes with skinny bullets, but the trend reversed for rosettes with squat bullets (0.80 versus 0.73). Takano and Liou (1995) used ray-tracing techniques to show similar differences between the scattering properties of solid and hollow columns (0.84 solid, 0.86 hollow), although their modeled columns had smaller hollows than those observed in this study.

Datasets of the scattering properties of cirrus particles have recently become available to the modeling community. Baum et al. (2005) used size distributions from aircraft data and ray-tracing results to estimate the bulk-scattering properties of ice clouds. Their calculations included the scattering properties of solid bullet rosettes as well as those of other crystal types. Baran (2005) used solid column-shaped crystals and aggregates of circular cylinders to calculate the scattering properties of ensembles of particles for use in climate models. Inclusion of the scattering properties of hollow crystals would make the Baum and Baran datasets more realistic.

In this note we will report the results of an analysis of the frequency of occurrence of hollow bullet rosette- and column-shaped ice crystals. The data were gathered from balloon-borne replicator ascents through

midlatitude cirrus and wave clouds. In section 2 a description of the replicator data will be presented along with the meteorological conditions present during the ascents studied. Section 3 discusses the data analysis technique. In section 4 the results of the study will be presented. Section 5 will include a summary of the results and implications.

2. Data description

a. Replicator data

The National Center for Atmospheric Research (NCAR) continuous Formvar replicator system was developed to measure vertical profiles of the microphysical properties of clouds. The operation of the balloon-borne replicator system is described in detail by Miloshevich and Heymsfield (1997). The replicator assembly piggybacks with a standard RS-80H radio-sonde. A length of clear video film is precoated with a layer of Formvar before the ascent. During the ascent, before the replicator film is exposed to the ambient air, the Formvar is softened with trichloromethane. When ice crystals hit the liquid Formvar, it flows around the crystal and solidifies as the solvent evaporates, leaving a detailed replica of the crystal. The low viscosity of Formvar allows it to flow easily into hollow ends of particles enabling easy identification. Use of the Formvar replication technique to capture and preserve detailed features of crystals was developed by Schaefer (1941).

Figure 1 shows examples of crystal replica images from the Formvar replicator. The hollows of the bullet rosette- and column-shaped particles are clearly visible. The hollows of some bullet rosette-shaped particles can be difficult to identify when the bullets do not lay flat in the Formvar. The hollow ends from small ($\sim 25 \mu\text{m}$) columns are clearly visible showing that hollow ends are present throughout crystal development. The numerous small spots on the replicator images are droplets that form when the Formvar rapidly evaporatively cools (Miloshevich and Heymsfield 1997).

b. Ambient conditions during ascents

Throughout the 1990s the NCAR balloon-borne replicator system was used to sample the microphysical properties of cirrus clouds in conjunction with various field projects. In this study, data from three replicator ascents through cloud layers containing high concentrations of bullet rosette- and column-shaped ice crystals were analyzed. Profiles of the relative humidity with respect to water as well as ice saturation values for the three ascents are shown in Fig. 2. The humidity profiles

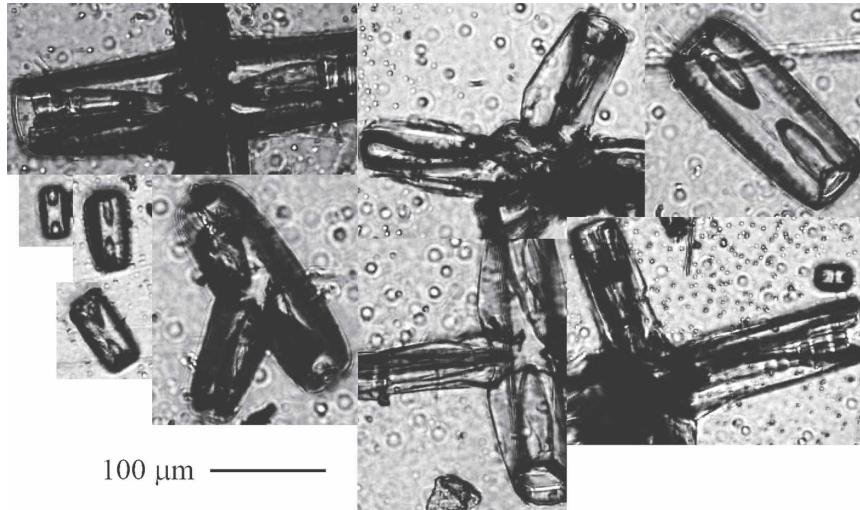


FIG. 1. Images of hollow bullet rosette- and column-shaped ice crystals.

were corrected for known calibration and time constant errors using techniques developed by Miloshevich et al. (2004). The three humidity profiles show that cloudy regions used in this study were not in highly supersaturated regions with respect to ice. Bailey and Hallett (2004) showed that bullet rosette-shaped ice crystals do not nucleate at supersaturations less than 25%, indicating that these particles were formed elsewhere.

The first replicator ascent used in this study was from the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment, Phase II (FIRE-II) on 25 November 1991 in Coffeyville, Kansas. The replicator was launched into a low-level cloud at

2000 m with overlying cirrus layers between 8000 and 10 000 m. High concentrations of bullet rosette- and column-shaped ice crystals were encountered as the replicator passed through a cirrus layer between 8400 and 8800 m (-42° and -45°C), where a peak supersaturation of 7.6% was measured.

The second replicator ascent analyzed in this study was launched from Cottonwood, Arizona, on 2 March 1995. The atmosphere was highly saturated with a thick cloud layer at 6000 m composed mostly of plate- and irregularly shaped ice crystals. Another thick cloud layer containing bullet rosette-shaped ice crystals was encountered between 8.6 and 9.4 km (-37° to -45°C).

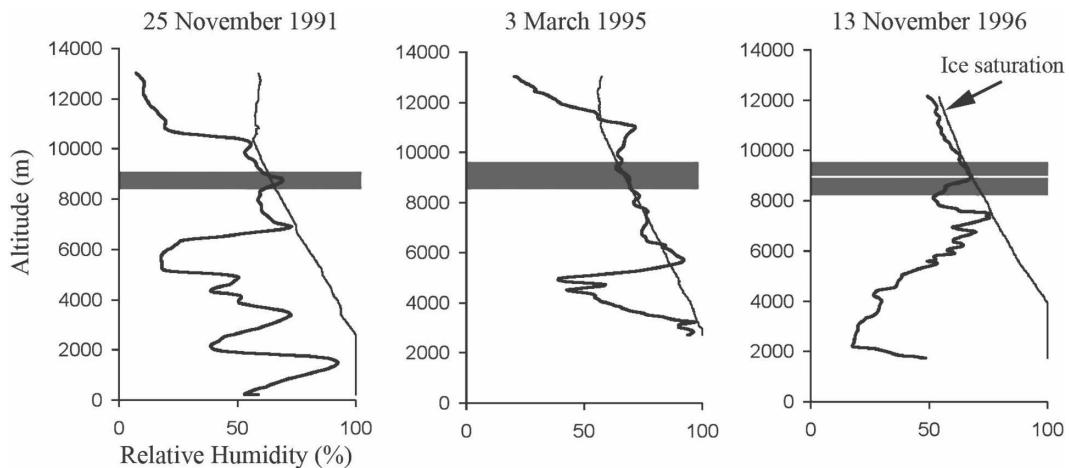


FIG. 2. Vertical profiles of the temperature and dewpoint temperature for the three ascents studied. The thick lines show the corrected relative humidity with respect to water values. The thin lines represent saturation with respect to ice. The gray bars indicate the regions studied. The upper bar on the 13 Nov 1996 sounding is the column region.

TABLE 1. Detailed cloud properties for each of the clouds analyzed.

Date	25 Nov 1991	2 Mar 1995	13 Nov 1996	13 Nov 1996*
Location	Kansas	Arizona	Colorado (wave)	Colorado (column)
% of crystals hollow in top 20% of cloud	60%	59%	67%	61%
% of crystals hollow in bottom 20% of cloud	47%	46%	89%	67%
% of crystals hollow in entire cloud	58%	52%	80%	64%
Total replicas counted	506	451	264	457
No. of solid crystals	214	214	53	163
No. of hollow crystals	292	237	211	294
Cloud-top temperature (°C)	−45	−44	−37	−44
Cloud-base temperature (°C)	−42	−37	−33	−40

* The two clouds studied from the 13 Nov 1996 launch were distinctly separated by a cloud-free region and are therefore listed separately here.

At 11 000 m, the supersaturation with respect to ice peaked at 25%.

The third replicator ascent analyzed in this project was launched on 13 November 1996 from the Marshall test site near Boulder, Colorado. A midlevel optically thick wave cloud was present with optically thin overlying cirrus. The balloon encountered high relative concentrations of bullet rosette-shaped ice crystals in the wave cloud between 8.3 and 8.6 km (−33° to −38°C). The sounding shows that the atmosphere was unsaturated at this level, indicating that the balloon intersected the wave cloud in a sublimation zone. The balloon then ascended through the optically thin though geometrically thick cirrus layer, which was composed mostly of small column-, budding rosette-, and droxtal-shaped (Yang et al. 2003; Zhang et al. 2004) ice crystals. The cloud thinned out at 9500 m at a temperature of −46°C.

3. Data analysis

Digital images of the ice crystal replicas for this project were taken using a Nikon Labophot-2 microscope with a Scalar USBshot-2 camera attached. The Scalar camera transmitted continuous video of the magnified replicator film directly to a computer monitor. As the replicator film was moved, new crystals came into view and were carefully inspected at up to three different magnifications yielding fields of view ranging from $710 \times 530 \mu\text{m}$ to $75 \times 56 \mu\text{m}$. Crystal replicas were classified as having been created by obviously hollow or solid crystals. It was immediately apparent whether or not column-shaped crystals contained hollows, as columns generally were oriented flat in the Formvar. Hollow ends were not always immediately apparent in bullet rosette-shaped crystals as the bullets were not always flat in the Formvar. To better determine the length of the hollows of the bullets, the microscope focus was adjusted so that the focal plane

passed through the crystal, which more readily facilitated the identification of hollows. A bullet rosette-shaped crystal was considered hollow if at least one bullet could be confirmed as hollow. A bullet rosette-shaped crystal was considered to have solid bullets if at least one bullet could be confirmed as solid. A mixture of hollow and solid bullets was rarely seen in the same bullet rosette-shaped crystal. Bullet rosette-shaped crystals that were obscured by artifacts or were indeterminable were omitted.

Crystals that impacted near the edge of the film may not have been fully replicated. Likely causes were that the Formvar was not liquid enough near the edges, or that the crystals did not impact at a high enough velocity to penetrate into the Formvar. This effect was most obvious for the later two ascents, which could explain why the percentage of hollow particles was lower for those ascents than for the earlier ascent. Particles in areas of the film where complete replication did not occur were ignored. Because of the philosophy used in this analysis and the possible biases in the data, the results presented in this note should be considered to be lower limits of the frequency of occurrence of hollow particles. It was more likely that hollow particles might erroneously have been classified as solid, and solid crystals were unlikely to have been classified as hollow.

4. Results

A total of 1687 replicas of bullet rosette- and column-shaped crystals were classified for this project. Of the 1687 crystals, 62% were observed to be hollow. The frequency of occurrence of hollow particles was calculated for the radiationally important top and base of each of the cloud layers analyzed. Table 1 summarizes the statistics from each of the layers analyzed. The cirrus layers from Kansas and Arizona were similar in that the cloud tops had higher occurrences of hollow par-

ticles than the cloud bases. The Colorado wave cloud, by contrast, had higher relative concentrations of hollow particles at the base than at the cloud top. The Colorado wave cloud had the highest relative concentration (80%) of hollow particles of the three observed clouds, due likely to the high super saturations found upwind of wave clouds. The more stable cirrus layers (Arizona, Kansas, and the Colorado column layer) all had overall relative concentrations of hollow crystals between 50% and 65%.

For a subset of the analyzed particles, the length of the hollow was compared to the total length of the crystal. A 90% hollow bullet was characterized by the hollow portion being 90% of the length of the total bullet length. For columns, a 90% hollow column was characterized by the combined length of the hollows at both ends of the column totaling 90% of the total length of the c axis of the column. In nearly all cases, the hollows on both sides of the column were the same length. The length of the hollows for each component bullet of a bullet rosette-shaped crystal was generally the same as well. For bullet rosette-shaped crystals, the hollows were generally at least 60% and up to 100% of the length of the individual bullets with an average of $88\% \pm 10\%$. The length of the hollow portion (or portions in the case of columns) of the crystal divided by the total length of the crystal component is hereafter referred to as the hollowness factor. Column-shaped crystals that were longer than $100 \mu\text{m}$ had hollowness factors that ranged from 70% to 90% and averaged $83\% \pm 6\%$. There was a dependence on size for the small column-shaped crystals observed in the column cloud in Colorado. The hollowness factor ranged from $50\% \pm 10\%$ for $30\text{-}\mu\text{m}$ particles and approached $80\% \pm 5\%$ for $80\text{-}\mu\text{m}$ particles. Figure 3 shows the size dependence for columns smaller than $100 \mu\text{m}$. A linear fit to the points in Fig. 3 is given by $H = 0.52L + 38$, where H is the hollowness factor expressed as a percent and L is the column length in microns. Limitations in resolution precluded the investigation of a trend in hollowness for small bullet rosette-shaped crystals.

Two additional datasets were analyzed in an effort to include properties from more diverse atmospheric conditions. Bullet rosette images from Mt. Hachimantai Observatory (a subset of which is shown in Heymsfield et al. 2002) were analyzed. Ninety-seven percent of the bullet rosettes had hollow bullets in this dataset. Weickmann (1948) showed many images of bullet rosette- and column-shaped ice crystals imaged during flights between -30° and -50°C . In the cloud regions where bullet rosette- and column-shaped ice crystals were

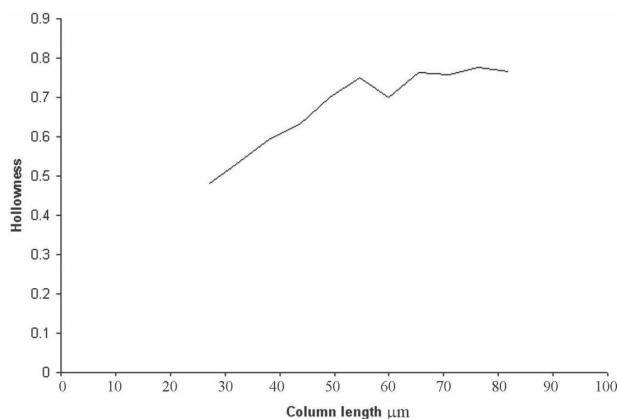


FIG. 3. The dependence of hollowness on crystal length for small columns observed on 13 Nov 1996.

common, hollow ends were identified in 80% of the ice crystals.

To investigate the effect of hollow particles on the radiative properties of cirrus clouds, the asymmetry parameter was calculated for cirrus clouds sampled during the Atmospheric Radiation Measurement Program (ARM) in March 2000. For brevity of this note, we refer the reader to Schmitt et al. (2006) for a discussion of the aircraft microphysical data and the ray-tracing calculations for hollow bullet rosette-shaped ice crystals. Cloud-integrated asymmetry parameter estimates from the aircraft microphysical results were calculated using the ray-tracing asymmetry parameter results from Schmitt et al. (2006) and the hollowness factor was determined from the current study. For the calculation of the asymmetry parameter, including hollow particles, it was assumed that 70% of the particles were hollow. Smaller bullet rosettes were assumed to have lower hollowness factors similar to the trends observed for columns in this study. For this study the smallest crystals were assumed to be a mixture of 50% columns and 50% droxtals. The resulting average asymmetry parameter calculated for the dataset was 0.801 for solid crystals and 0.815 when the hollowness factor was considered. Following the same calculation as Schmitt et al. (2006), consideration of the scattering properties of hollow crystals would yield a surface radiation increase of 2.5 W m^{-2} for a cirrus cloud with an optical depth of 0.5 for the wavelength range between 380 and 780 nm.

5. Summary and conclusions

In this note we have reported the investigation of the frequency of hollows in the ends of bullet rosette- and column-shaped ice crystals. By analyzing balloon-borne replicator data from three ascents, we have shown that

50%–80% of these ice crystals have hollow ends. Ice particle properties from other particle image datasets (Heymsfield et al. 2002; Weickmann 1948) showed 80%–97% of bullet rosette- and column-shaped ice crystals had hollow ends, indicating that the replicator results are reasonable. The depth of the hollows of columns was shown to increase with size for small particles and levels off at $80\% \pm 6\%$ for large particles, while the length of the hollows of rosette-shaped crystals was found to average $88\% \pm 10\%$ of the length of the component bullets. While the conditions present for the three ascents analyzed here do not represent all cirrus clouds, these data, presented here in combination with the results from the articles cited in the introduction, provide strong evidence that hollow crystals are common in cirrus clouds composed of bullet rosette- and column-shaped ice crystals.

When the results of this study are applied to aircraft microphysical data, the result is an increase of 2.5 W m^{-2} of radiation at the surface for the visible wavelengths. These findings suggest that changes are necessary in the way scattering properties are calculated for ice crystals in cirrus clouds. Scattering parameterizations should include the scattering properties of hollow particles.

Acknowledgments. The authors thank Larry Miloshevich for his work in collecting the replicator data and for his efforts correcting the radiosonde data. This work was supported by NASA through SAIC Subcontract 4400107161.

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