NOTES AND CORRESPONDENCE

Ice Crystal Shapes in Midlatitude Cirrus Clouds Derived from Hydrometeor Videoonde (HYVIS) Observations

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Abstract

This study investigates the frequency of the occurrence of ice crystal habits in midlatitude cirrus clouds that were primarily associated with warm or stationary fronts within synoptic-scale lows. The measurements were performed with a balloonborne hydrometeor videoonde (HYVIS). The predominant types were single bullets at temperatures ranging from –60°C to –20°C. Plate-type crystals were dominant at temperatures warmer than –20°C, whereas column or bullet rosette crystals became dominant at temperatures colder than –60°C. The distributions of the ice crystal habits derived from the HYVIS observations were consistent with the results of recent laboratory and field experiments, although the dependency of the ice crystal habits on ice supersaturation was not characterized in this study because only limited accurate humidity data were available under low temperature conditions.

The size dependency of the distributions of the axis ratios of column and bullet crystals tended to decrease with increasing crystal dimension. We found no clear temperature dependency of the axis ratios of columnar crystal shapes. The area ratios of the six classified crystal habits were found to be comparable with previously reported ratios. The fact that the area ratio decreased with increasing dimension was apparent for all the crystal types. Polynomial curves fit to plots of area ratio versus maximum crystal dimension for each crystal type evidenced patterns different from those reported in previous studies. When the conventional power–law relationships between cross-sectional area and dimension reported in a previous study were applied to the HYVIS data, we found that the power–law relationships could overestimate the measured cross-sectional area integrated over the 250 m height interval between the cloud base and the cloud top by 10 %–80 %. The degree of overestimation was highly variable between individual cases.

Keywords ice crystal habit; midlatitude cirrus cloud; area ratio of ice crystals

1. Introduction

Cirrus clouds, which cover over 20 % of the earth, have an important influence on the earth’s radiation budget and climate (Liou 1986). The net effect of cirrus clouds on surface depends on both the macro-

physical properties (cloud height, geometrical thickness, and temperature) and microphysical properties (ice crystal size, shape, and density). The habit of ice crystals, in particular, is one of the least known but most complicated factors that are required to quantify the impact of cirrus clouds on climate, because the crystal shape determines the terminal velocity, projected cross-sectional area, and ice water content of ice particles. Moreover, the distribution of ice particles of different shapes affects the lifetime, scattering properties, and growth rates of precipitation in ice clouds.

Cirrus clouds consist of ice particles with a variety
of shapes and sizes; the sizes of the particles range from < 10 µm to a few millimeters. The distribution of ice crystal shapes and sizes in cirrus clouds could have a significant impact on the sign (warming or cooling) of cirrus cloud net radiative forcing (Zhang et al. 1999). To improve parameterizations for cirrus radiative properties in climate models, it is important to accurately quantify the single scattering properties of the individual particles with a given size and shape. Kristjánsson et al. (2000) have demonstrated that ice crystal size and shape may have a significant influence on climate changes projected by global climate models.

Many studies have focused on the radiative impact of nonspherical ice crystal habits on the solar part of the electromagnetic spectrum (Mitchell and Arnott 1994, hereafter MA94). Wendisch et al. (2005) concluded that the impact of cirrus ice crystal shape on solar spectral irradiance was important with respect to reflected irradiance above an optically thin cirrus cloud, especially for small solar zenith angles. Few studies have been conducted about the thermal IR part of the spectrum to evaluate the influence of ice crystal habits on thermal IR cirrus radiative properties (Francis et al. 1999). Wendisch et al. (2007) concluded that the effects of cirrus ice crystal shapes on thermal IR irradiance were substantial for high, optically thin cirrus clouds, especially with respect to upwelling irradiance above the clouds.

An early study of in situ observations of cirrus clouds was conducted by Weickmann (1947), who revealed that, in convective cirrus clouds, the primary ice crystal type was a bullet rosette consisting of hollow prismatic crystals in three-dimensional clusters, and in cirrostratus clouds, the primary ice crystal types were single bullets, columns, and thick plates. Heymsfield and Platt (1984) collected replicator data from cirrus clouds and determined the predominant crystal types in several temperature ranges. At temperatures between −20° and −40°C, they observed spatial or polycrystalline forms with some columns, plates, and bullets. At temperatures between −40° and −50°C, the predominant crystal types were hollow columns and spatial forms in stable and convective cirrus clouds, respectively. At temperatures below −50°C, the predominant types were hollow or solid columns with some hexagonal plates although bullet rosettes were occasionally observed.

Recent field observations have advanced our knowledge of ice crystal shapes in clouds. Extensive observations with the cloud particle imager (CPI) have been conducted in several field campaigns (Lawson et al. 2001; Baker and Lawson 2006; Lawson et al. 2006a, b) and have targeted several types of clouds: wave clouds, midlatitude and high-latitude cirrus clouds, tropical anvil and cirrus clouds, and arctic clouds. These studies suggest that midlatitude and high-latitude cirrus clouds may be comprised of more “rosette-shaped” crystals (polycrystals with a rose shape, including budding rosettes with short arms, mixed-habit rosettes, or rosettes with plate-like/side-plane features) than previously reported.

Laboratory experiments reveal that the ice crystal habit and its size are governed by temperature and ice supersaturation. Recent laboratory studies have provided a comprehensive description of ice crystal habits in the atmosphere at temperatures ranging from 0° to −70°C (Bailey and Hallett 2004, 2009, hereafter BH04 and BH09). These results, supported by recent observational studies, have confirmed that the crystal habit in the atmosphere at temperatures between −20° and −40°C is dominated by plate-like polycrystalline forms. In the lower temperature ranges (< −40°C), the crystal habit regime is shifted to columnar polycrystalline forms.

The terminal velocity, extinction coefficient, and effective radius of ice particle are related to the projected cross-sectional area that depends on particle size and shape. Most studies have used habit-dependent relationships between ice particle diameters (maximum dimensions) and cross-sectional areas to estimate the total area of a population of particles (Mitchell 1996; Mitchell et al. 1996, hereafter M96 and Me96, respectively). However, the appropriateness of such empirical equations is uncertain, and the estimation error should be examined on a case-by-case basis. Heymsfield et al. (2002) proposed a general approach for improving the derivation of microphysical properties (bulk density and mass of ice particles) of ice clouds on the basis of two parameters: the maximum dimension and the projected cross-sectional area of the ice particle. Recently, cross-sectional area data from past studies have been evaluated and parameterized for each crystal shape by introducing a shape-sensitive parameter, the area ratio (Heymsfield and Miloshevich 2003, hereafter HM03).

Most microphysical, in situ data from previous studies have been obtained from aircraft observations. Balloonborne hydrometeor videosonde (HYVIS) (Murakami and Matsuo 1990; Orikasa and Murakami 1997) has some advantages over aircraft observations.
for cirrus cloud observations. A HYVIS can easily reach the highest clouds—up to the top of cirrus clouds—and has sufficient resolution to distinguish the shapes of ice particles smaller than 100 µm. The HYVIS can obtain the vertical distributions of hydrometeors at fine spatial resolutions and with relatively few artifacts such as shattering and breakup compared with aircraft observations (Orikasa et al. 2013). The datasets from in situ observations are still limited although a variety of microphysical instruments have been developed and used for many years.

In this study, we report the frequency of the occurrence of ice crystal habits in midlatitude cirrus clouds that were generated primarily by synoptic-scale systems. The measurements were performed using a balloonborne HYVIS. The distributions of the axis and area ratios of ice particles in our dataset are presented for comparison with results of previous studies. The characteristics of ice crystal habits and shape-sensitive parameters are discussed, and the results are compared with other observational datasets and laboratory studies.

2. Instrument and dataset

The cirrus cloud microphysical dataset was obtained from HYVIS observations at Tsukuba (36.0°N, 140.1°E), Japan, during the period 1994–2007. We analyzed the images of cirrus cloud particles from 37 launches of the HYVIS, during which it was accompanied by a rawinsonde or GPS sonde. Ambient temperature and relative humidity of ice particles in cirrus cloud were simultaneously measured; however, we have yet to develop the correction algorithm for the humidity sensor. We presented the uncorrected data of humidity measurements in Orikasa et al. (2013), which were widely distributed from ice-subsaturated to water-subsaturated regions. In most cases, the cirrus clouds in the dataset were associated with a midlatitude warm front within a synoptic-scale low, stationary (Baiu) front, or strong jet stream during spring to early summer. The study included neither precipitating clouds nor anvil clouds formed by deep convection.

The HYVIS has two video cameras (close-up and microscopic) with different magnifications. After the launch of the HYVIS, the particle images were relayed in real time via a 1687 MHz microwave transmitter to a ground station. The crystal habit of each particle was derived from the images of both cameras. The images were evaluated and processed on the basis of visual inspection. Orikasa et al. (2013) have provided a description of the HYVIS instrument and the dataset obtained from the ground-based cirrus cloud observations in Tsukuba.

Automatic image processing was also utilized to obtain the cross-sectional area (A), maximum dimension (D), major axis length (a), and minor axis length (b) of each particle in the microscopic camera images. The particle size ranged from about 10 to 200 µm. The particle images recorded by the close-up camera, however, were not processed because the image quality was inadequate for estimation of shape parameters.

In this study, we examined shape-sensitive parameters in terms of aspect ratio and area ratio (Ar). We defined the aspect ratio of each ice particle to be the axis ratio (= b/a), i.e., the ratio of the lengths of the minor and major axes. We defined Ar to be the ratio of the cross-sectional area of the particle (A) to the area of a circumscribed circle with diameter equal to the maximum dimension of the particle, i.e., Ar = A/(πD^2/4), where D is the maximum dimension of the particle. Compact particles with nearly circular shapes have an Ar nearly 1.0, whereas elongated, flat, or stellar particles have a lower Ar.

3. Results

3.1 Crystal habit frequency

In this study, the cirrus particle images measured with the HYVIS were classified into six major habit categories according to Magono and Lee (1966): column, bullet, plate, side planes, bullet rosette, and combinations (or aggregations) of columns and plates. A great majority (> 80 %) of ice crystals smaller than 50 µm was unclassified owing to shape recognition being less reliable and the ice crystals being frequently quasi-spherical in shape; whereas over 80 % of ice crystals larger than 100 µm were classified.

In this study, the unclassified type is not included in the statistics of the ice crystal habits, as noted below. Examples of microscopic images in cirrus clouds obtained with the HYVIS are shown in Fig. 1; each classified type of ice crystals is accompanied with unclassified ice particles.

Figure 2 shows the frequency of the occurrence of ice crystal habits as a function of ambient temperature. It is apparent from Fig. 2 that the most prevalent habit was a single bullet crystal at temperatures ranging from –60° to –20°C. At temperatures between –60° and –35°C, the single bullet type was the most prevalent crystal type in the whole dataset (Fig. 2b). The plate type was dominant
Fig. 1. Examples of the HYVIS microscopic images observed in cirrus clouds in each classified type (two pictures in a row) of ice crystals (white arrows) accompanied with unclassified ice particles (black arrows). The ambient temperatures of each of two pictures in a classified type are indicated on the right-hand side.
at temperatures warmer than –20°C, whereas the column or bullet rosette type became dominant at temperatures colder than –60°C (Fig. 2a). At temperatures colder than –40°C, the frequency of the bullet rosette and column crystals had a significant tendency to increase with decreasing temperature. At temperatures warmer than –40°C, the plate type had a discernible tendency to increase with increasing temperature. Side planes were more frequent at temperatures ranging from –45° to –25°C compared with other temperatures. The fact that there was a transition in the habit distribution observed in this study at a temperature of about –40°C is consistent with a recent laboratory study in which measurements were made with a static diffusion chamber (BH04).

The percent frequency of ice crystal habits is plotted as a function of distance from the top of the cirrus clouds ($D_{top}$) in Fig. 3. The panels in Fig. 3 are arranged according to the cloud top temperature ($T_{top}$). According to the cirrus observational dataset by Lawson et al. (2006a), the combination of $D_{top}$ and $T_{top}$ is not always a good indicator of particle shape and size, suggesting that new ice particles can nucleate and grow or sublimate at all levels in clouds. This behavior is generally similar to that of our cirrus dataset. However, there were some trends in the percent frequencies of ice crystal habits for $T_{top}$s colder than –55°C in spite of few cases of $T_{top}$s warmer than –55°C: the frequency of the plates tended to increase with increasing $D_{top}$, whereas that of bullets tended to decrease. Regardless of the $T_{top}$, bullet rosettes were most prevalent near cloud tops, the prevalence of side planes increased in the middle of the clouds, and the prevalence of plates had a tendency to increase with increasing $D_{top}$. In contrast, the frequency of the columns was greatest near cloud tops, and in some cases (Figs. 3b, e) the frequency of the columns tended to increase with increasing $D_{top}$.

### 3.2 Shape parameters

The axis ratio of column, bullet, and bullet rosette crystals measured with the HYVIS is shown in Fig. 4 as a function of dimension and temperature. The axis ratios of the column and bullet crystals had a tendency to decrease with increasing crystal dimension. However, there was little apparent correlation between the axis ratios of bullet rosettes and crystal dimension, suggesting that the growth of bullet rosettes tends to be isotropic. We found no clear temperature dependence of the axis ratio of the three crystal shapes. Similar to the axis ratios of the bullet rosettes, the axis ratios of the other three crystal shapes (plates, side planes, and combinations of columns and plates) were not strongly dependent on...
Fig. 3. Same as Fig. 2, but as a function of distance from cirrus cloud tops. The frequencies have been normalized within a 1 km cloud depth interval. The plots have been sorted on the basis of the cloud top temperature.
The area ratio of various types of ice crystal habits has been investigated in several field projects and has been found a useful parameter for characterizing particle shapes in previous studies (M96, HM03). As in Fig. 4, the area ratios of the six crystal habits are plotted in Fig. 5, where they are compared with the analogous area ratios reported in previous studies. The size dependency of the area ratio decreases with increasing dimension for all crystal types at a decreasing rate with increasing dimension. The implications are that ice crystals have a more open geometry as they grow and that the area ratio gradually approaches a limit for the largest particle measured in the cloud. The general trend of the relationship between area ratio and crystal dimension for columnar crystals (Figs. 5a, b) in this study showed higher or similar trend compared with that in the HM03 study. The M96 curves in Figs. 5a and 5b predict a higher area ratio throughout the range of crystal dimensions than that apparent in the data, possibly due to differences in sampling conditions (e.g., the M96 data were generally sampled at warmer temperatures). The size dependencies of the area ratios of plates and side planes apparent in Figs. 5c and 5d were weak compared with the size dependencies of the other area ratios. A similar pattern is apparent in the results of other studies (M96, Me96, Heymsfield and Kajikawa 1987 (HK87 in Fig. 5d), and HM03). In contrast, the decrease of the area ratio of bullet rosette crystals (Fig. 5e) with increasing crystal dimension was a stronger trend in this study than in previous one. Further investigation will be needed to identify the cause of this difference.

A significant trend was found in the relationship between the area ratio measured with the HYVIS and maximum dimension (Fig. 6a), its temperature (Fig. 6b), and normalized height (Fig. 6c) although the data points in Fig. 6 are widely scattered. A second-order polynomial fit to the mean area ratios in each 30 µm interval is shown in Fig. 6a. The value of the polynomial decreased from about 0.6 to 0.3 for 50 and 400 µm particles, respectively. These area ratios are smaller than the cirrus particle replicator data reported by HM03, but they evidence a trend that is generally similar to their results. Figure 6b shows a plot of area ratios for each temperature range in 10°C intervals. The slope of the trend curve of area ratio versus maximum dimension was smaller in magnitude at warmer versus colder temperatures. Figure 6c shows plots of area ratios categorized according to cloud layer, each cloud is divided into five layers.
Fig. 5. Same as Fig. 4, but for area ratios of crystal habits in the form of (a) columns, (b) bullets, (c) plates, (d) side planes, (e) bullet rosettes, and (f) combinations of columns and plates. The analogous curves from M96 (dots), Me96 (dots), HK87 (solid curve), and HM03 (long dashes) are shown for comparison.
of equal thickness, from the cloud top to the cloud base. The slopes of the trend lines were steeper in the upper cloud layers than in the lower half of the clouds although the area ratios were highly variable. The height dependence in Fig. 6c is consistent with the temperature trends in Fig. 6b, which shows similar dependence to that in the HM03 study.

We applied the power–law relationships between particle dimensions and cross-sectional areas reported by M96 to the HYVIS data. Figure 7 shows the ratio of areas calculated from the empirical power–law equations \( A_c \) to areas measured from the image analysis \( A_m \) in each cirrus cloud layer (250 m height interval) whose temperature is assigned at mid-level in the layer. We found that the integral of \( A_c \) over the vertical column of a cloud could overestimate the integral of \( A_m \) by 10%–80%; the extent of overestimation was highly variable, irrespective of \( T_{\text{top}} \) or cloud depth (not shown). Although several different crystal habits contributed to the overestimation, this discrepancy was mainly due to the power laws (from M96) for columnar and bullet rosette types, as shown in Fig. 5.

4. Comparison with other datasets

During the past several decades, a variety of ice crystal habit diagrams have been drawn from laboratory studies, in situ observations (mainly on the ground), or combinations of the two. One of the most famous diagrams is the snow crystal morphology diagram (Nakaya 1954), which depicts a columnar habit at temperatures below –22°C. However, recent laboratory and field studies (BH09; Baker and Lawson 2006; Lawson et al. 2006a, 2006b) have both firmly established that the ice crystal habit at temperatures between –40° to –20°C is plate-like and dominated by polycrystalline forms. This habit regime is consistent with our dataset, which evidenced significant frequencies of plates and side planes within this temperature range. The single bullet was also the dominant crystal habit in this temperature range in our dataset and was deemed to result from sedimentation of ice particles from colder regions aloft.

A significant difference in the present study and previous studies (Heymsfield et al. 2002; Lawson et al. 2006a, b) is the abundance of single bullets. Single bullets originate from rosettes that break up. Gow (1965) reports that single bullets result from disintegration of bullet rosettes from sublimation. The disintegration is attributed to a gross weakening of the structure caused by sublimation at the center of the

![Fig. 6. Relationship between area ratios and maximum dimensions. The curves are second-order polynomials fit to the HYVIS data points grouped on the basis of (a) the mean values (squares) within 30 µm intervals (excluding an outlier point, which corresponds to the 340–370 µm interval); (b) the indicated temperature intervals; or (c) five cloud layers, each cloud is divided into layers of equal thickness between the cloud base and the cloud top.](image-url)
Fig. 7. Ratio of cross-sectional areas ($A_c$) calculated from the empirical power laws reported by Mitchell (1996) to the measured cross-sectional areas ($A_m$) determined from analyses of the images in each cirrus cloud layer (250 m height intervals).
bullet clusters. One possibility of the high frequency of single bullets in our dataset is the difference of ice supersaturation compared with previous studies of in situ observations. The heads or apices of single bullets in the HYVIS images generally have a rounded shape. According to our simultaneous observations using the Snow White (chilled-mirror dewpoint sensor) during the 2004 and 2007 field campaigns, we had mostly near ice saturation to low ice supersaturation (−5 % to < 10 %) in cloud layers, sometimes moderate to high ice supersaturation (10 % to 30 %), and sometimes ice subsaturation in the humidity profile. On the other hand, most studies by aircraft observations were typically made in vigorous clouds (with rather strong updraft) such as anvils, wave clouds, or precipitating frontal clouds. For a simplified comparison, all single bullet crystals in this study would be assumed to occur as a result of sublimation of bullet rosettes whose arms were 3 to 6 per bullet rosette on average; the averaged occurrence frequency of bullet rosettes would increase from 12 % in the original dataset to 39 %−32 % in the assumed dataset, which is comparable with the observational result of Lawson et al. (2006a). Another possibility is high frequency of breakup of bullet rosettes during sampling with the HYVIS, but this reasoning should be excluded by image analysis on a frame-by-frame basis. The fragmented ice particles breaking up upon impact were excluded from the frequency of the ice crystal habit.

The ice particle images in our dataset consist of the great majority (> 80 %) of unclassified crystal habit type in particles smaller than 50 µm, as stated in section 3.1. We did not have the irregular type in our classification. The definition of irregular type remains unclear and varies in different studies, which makes it difficult to compare with previous studies in terms of the abundance of small irregular particles. Ice particles classified as the “rosette-shaped” type in the study by Lawson et al. (2006a) were classified mostly as bullet rosette or combination of columns and plates in this study. According to the findings of Baker and Lawson (2006) from the wave cloud observations, side planes were mostly observed on crystals that had exceeded their riming threshold size, suggesting that the side-plane growth may occur at a riming site via subsequent vapor deposition. In our cirrus dataset, there was no riming sign on ice particles, which is consistent with the laboratory study by BH04 that side planes can be observed even below water saturation conditions.

According to the study by BH04, ice crystal growth is influenced by factors such as defects, stress, and dislocations in a crystal, in addition to the main factors of temperature and ice supersaturation. The variability of growth rates causes the variability of the aspect (axis) ratios of columns or bullets commonly observed in cirrus clouds.

Figure 4 compares the axis ratios of columns and bullets in cirrus clouds measured with the HYVIS to the analogous ratios reported in previous studies (Heymsfield 1972 (H72 in Fig. 4b) and MA94). In this study, we found wide variability of crystal axis ratios. On average, the size dependency of the axis ratio of columnar crystals was similar to the size dependency reported in previous studies. Further analysis of aspect ratio data in our dataset has yet to be performed for other types of ice crystals. For instance, the aspect ratios of each element of a bullet rosette crystal can be compared with those reported in other studies and with those of single bullets or other elements in this study. BH04 states that component crystals of bullet rosettes often have nonuniform aspect ratios in the laboratory and that aspect ratios reported from in situ observations may be affected by vapor competition among neighboring component bullets and/or orientation during the fall of the crystal.

Figure 5 provides a comparison of the area ratios of several crystal types from HYVIS observations and previous studies. Another size dependency of the area ratio was apparent in the HYVIS dataset although there was wide variability for each crystal type. The M96 dataset was obtained from clouds with higher cloud top temperatures, the result perhaps being area ratios of columnar crystals larger than those in this study. Other reasons could be differences among microphysical instruments. The curves of single bullet crystals in the HM03 study were similar to the curves in this study, although the curves of the side planes differed between the two studies. These comparisons should be analyzed cautiously, because the area ratio is not simply determined by local temperatures and supersaturations in clouds but may also be influenced by other environmental factors (such as vertical velocity or relative humidity profiles) and by cloud macrophysical properties (such as cloud top temperature and/or cloud thickness).

The aspect (or axis) ratio or area ratio from 2D imaging probe data is subject to errors resulting from the rather coarse digitization (e.g., 25 µm resolution for the 2DC probe) of the particle images as well as to errors that depend on the orientation of the falling particle when it is imaged. The balloonborne videoonde (or ice crystal replicator) data have the advantage of being more finely resolved in addition.
to the CPI, although the latter errors are similarly included.

5. Summary

In this study, we used a HYVIS to measure the frequency of the occurrence of ice crystal habits in midlatitude cirrus clouds. These clouds were generally associated with synoptic-scale depressions. The bullet type crystal was predominant at temperatures between −60° and −20°C. The possibility of high frequency of single bullets in this study is related to the sampling humidity conditions—near ice saturation to low ice supersaturation. At temperatures colder than −40°C, the average frequency of bullet rosette and column types increased with decreasing temperature, whereas at temperatures warmer than −40°C, the frequency of the plate types increased with increasing temperature. These results are consistent with recent laboratory studies. Plots of habit frequency versus cloud depth, sorted by cloud top temperature, revealed that the habit frequency distribution was influenced mainly by ambient temperature, with some effects caused by sedimentation. It should be noted, however, that there is no information in the HYVIS dataset that could be used to isolate effects of other factors, such as ice supersaturation, updraft velocity, and ice nucleation onto aerosols.

Shape-sensitive parameters, such as the area ratio or aspect (axis) ratio, can facilitate deduction of more accurate information about the microphysical and optical properties of ice clouds. We examined the size and temperature dependencies of area ratios and axis ratios determined from the HYVIS measurements and compared those dependencies with results from previous studies. Similarities were generally found in the size and temperature dependencies; however, further studies are required to analyze the differences between our results and those from previous studies and to explain the large variability within the same dataset. A large error in the total cross-sectional area of the population of ice particles (and in the extinction coefficient of clouds) might be introduced using the conventional power–law relationships between area and dimension. These uncertainties can be attributed to the differences in relationships from one dataset to another and to the substantial natural variability in the relationships. Normalized cloud height, as well as the temperature and crystal shape, can influence the relationship between the area ratio and size.

The characteristics of ice crystal habits and shape-sensitive parameters obtained in this study are basic information about natural cirrus clouds and can be used to assess differences between datasets and/or between individual cases. However, the characteristics are not well known. Laboratory and theoretical studies of ice particle growth and evaporation are required to better understand the distribution of crystal shapes and the substantial variability in the vertical distributions and size dependency of shape-sensitive parameters derived from the HYVIS dataset.

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