Article

Shape Dependence of Falling Snow Crystals' Microphysical Properties Using an Updated Shape Classification

Sandra Vázquez-Martín ^{1,*} , Thomas Kuhn ¹ and Salomon Eliasson ² ¹ Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology (LTU), 98 128 Kiruna, Sweden; thomas.kuhn@ltu.se² Swedish Meteorological and Hydrological Institute (SMHI), 601 76 Norrköping, Sweden; salomon.eliasson@smhi.se

* Correspondence: sandra.vazquez.martin@ltu.se

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Abstract: We present ground-based in situ snow measurements in Kiruna, Sweden, using the ground-based in situ instrument Dual Ice Crystal Imager (D-ICI). D-ICI records dual high-resolution images from above and from the side of falling natural snow crystals and other hydrometeors with particle sizes ranging from 50 μm to 4 mm. The images are from multiple snowfall seasons during the winters of 2014/2015 to 2018/2019, which span from the beginning of November to the middle of May. From our images, the microphysical properties of individual particles, such as particle size, cross-sectional area, area ratio, aspect ratio, and shape, can be determined. We present an updated classification scheme, which comprises a total of 135 unique shapes, including 34 new snow crystal shapes. This is useful for other studies that are using previous shape classification schemes, in particular the widely used Magono–Lee classification. To facilitate the study of the shape dependence of the microphysical properties, we further sort these individual particle shapes into 15 different shape groups. Relationships between the microphysical properties are determined for each of these shape groups.

Keywords: natural snow crystals; hydrometeors; classification; shape; microphysical properties

1. Introduction

The shape of ice particles is an important characteristic that affects the radiative impact of clouds. Accurate knowledge of the microphysical properties of clouds, including particle shape, is important in order to assure accurate cloud parameterizations in climate and meteorological forecast models, e.g., that presented in References [1,2]. Realistic cloud microphysical parameterizations are also essential for most cloud retrievals from satellite measurements. For instance, in order to retrieve quantities such as cloud water path or cloud effective radius, the underlying assumptions of particle shape, size, and distribution have a massive impact on the retrieval itself [3,4]. The unavoidable sensitivity of satellite retrievals to assumptions on ice particle properties, such as particle size, area, and the shape of snow crystals, is one of the dominating sources of uncertainties in cloud retrievals [5]. Although satellite observations of clouds are important validation sources for models, the role of clouds still poses one of the most substantial uncertainties in modeling the climate [6].

The shape of the snow crystals, which this paper primarily concerns, is formed by deposition, riming, aggregation, or a combination of these mechanisms [7]. Deposition refers to the process of water vapor freezing (depositing) onto ice nuclei or an existing ice crystal. If the ice crystals are in an environment with supercooled water droplets, these droplets may collide with and freeze onto the

crystals, forming an icy surface layer and riming the crystal. As the snow crystals grow, they are more likely to collide with one another and to join together in a process called aggregation. The snowflake typically encounters several different temperature and humidity environments as they grow, resulting in a great variety of shapes, such as needles, stellar, plates, and graupel [8–17].

Nakaya and Sekido [8] developed a snow crystal morphology diagram (“Nakaya Diagram”) tying the growth conditions of snow crystals to water vapor supersaturation (relative to ice) and temperature. This diagram has been adapted and translated into English by Libbrecht [16].

In 1951, the International Commission of Snow and Ice (ICSI) and the International Association of Cryospheric Sciences (IACS) characterized snow crystals into ten main shapes: plates, stellar crystals, columns, needles, spatial dendrites, capped columns, irregular particles, graupel, ice pellets, and hail. This classification, called the “Abstract of the International Classification for Snow” [18], is still used to distinguish different types of snow, including snow on the ground [19].

However, for some purposes, a more detailed classification is desirable. Magono–Lee [20] published a categorization scheme, still widely used, that catalogs snow and crystals into 80 categories. This classification scheme will, from now on, be referred to as the Magono–Lee classification. It divides shapes into categories and subcategories, allowing a logical shape labeling. For example, the shape “C1f” is a hollow, simple, columnar crystal, where C is columnar crystal, 1 is simple, and f is hollow.

More recently, Kikuchi et al. [21] presented an extensive revision of the Magono–Lee classification which catalogs snow crystals and other solid precipitation particles into 121 categories. This revised classification uses levels and sublevels in a similar way to Magono–Lee. However, Kikuchi et al. [21] merged the two main levels *N* (needles) and *C* (columns), and consequently, some shapes that already existed in Magono–Lee received new labels.

There are also situations where a less detailed classification with only a few shapes is more desirable to use. For instance, the Abstract of the International Classification for Snow by ICSI and IACS provides a less detailed classification. However, instead of using two completely different classification schemes depending on how much detail one needs, it may be more practical to use one scheme, which allows for more or less detail. The Magono–Lee classification is such a scheme since it has different levels, and the main level with its eight categories could constitute one such coarse classification with less detail. Using Magono–Lee enables comparison with many previous studies that have used this classification. Additionally, using a less detailed classification defined by a few shape groups, which are based on the detailed Magono–Lee scheme, results in a classification method that is both flexible and compatible with previous classifications. On the one hand, updating the highly detailed underlying classification of Magono–Lee by only adding new shapes would guarantee compatibility with previous studies. On the other hand, grouping the shapes into shape groups would make it possible to accommodate the needs of studies that do not require or desire such a high level of detail. Regrouping for specific studies is very easy since the underlying shapes use the same classification, and the eight main-level categories of Magono–Lee would only define one of many possible ways of grouping.

Therefore, this study aims to first update the previous snow shape classification scheme of Magono–Lee by adding newly found shapes, then to sort particles into different shape groups, and finally to study the average microphysical properties of these shape groups. Hence, the study effectively aims to analyze the shape dependence of the snow particles’ microphysical properties. For this, we present a dataset of falling snow particles that have been collected in Kiruna in northern Sweden with the new ground-based instrument Dual Ice Crystal Imager (D-ICI) [22] in Section 2. Section 3 describes how to classify these particles into shapes by updating the Magono–Lee classification scheme with shapes found by Kikuchi et al. [21] and Libbrecht [23] as well as shapes found in Kiruna as part of this study. The shape groups are defined in Section 4. Section 5 investigates the shape dependence of microphysical properties by using these shape groups. Finally, this study is summarized and concluded in Section 6.

2. Site and Measurements

2.1. Measurement Site

Our measurements have been carried out in Kiruna, Sweden (67.8° N, 20.4° E) using the D-ICI, the ground-based in situ instrument described in Kuhn and Vázquez-Martín [22]. Most of the measurements took place on the roof of the main building of the Swedish Institute of Space Physics (IRF) on the space campus at the height of about 15 m above the ground at an altitude of 425 m above mean sea level. The remaining measurements were done from the roof of the IRF Lidar laboratory located 950 m away from the space campus at the height of 5 m above ground. We consider these two locations close to each other and thus can further regard them as the same Kiruna measurement site.

Our dataset is from multiple snowfall seasons during the winters of 2014/2015 to 2018/2019. At the Kiruna site, each season lasts from about the beginning of November to the middle of May. Surface temperatures in Kiruna can reach down to $-43.3\text{ }^{\circ}\text{C}$ [24], and our data include temperatures down to $-27\text{ }^{\circ}\text{C}$. The IRF weather database [25], based on instruments 1.7 km away from the space campus and 2.44 km from our current measurement location, provides temperature and relative humidity used in this study.

2.2. Instrument

The D-ICI recorded images of falling snow crystals and other hydrometeors. After falling through the inlet, in-focus particles are detected and then imaged twice, simultaneously from above and from the side. These dual images are taken using two high-resolution imaging systems (resolution of about $10\text{ }\mu\text{m}$ with a pixel resolution of $3.7\text{ }\mu\text{m}/\text{px}$; for a detailed description, see [22]). The additional information provided by a second image improves the shape classification.

An inlet camera is mounted to monitor the D-ICI inlet, such that it is viewing the inlet without obstructing the path of the falling particles. The camera is used to detect inlet blockage in order to exclude, in post-processing, any data affected by this.

2.3. Image Processing

Top-view images are used to determine particle size, cross-sectional area, area ratio, and aspect ratio by the automated process presented in detail in Kuhn and Vázquez-Martín [22]. The first steps are to remove the background features from uneven illumination and to remove out-of-focus particles. The particles then have their boundaries traced. These particle boundaries are further used to determine the properties of the particle.

The maximum dimension, $D_{\max}$, is used to describe particle size. Here, it is determined by the smallest diameter that completely encircles the particle on the image. The cross-sectional area, A , is the area enclosed by the particle boundary on the image, determined from the number of enclosed pixels. Equation (1) defines the area ratio, A_r , as follows:

$$A_r = \frac{A}{\frac{\pi}{4} \cdot D_{\max}^2}. \quad (1)$$

Equation (2) defines the aspect ratio, A_s , as follows:

$$A_s = \frac{X}{Y}, \quad (2)$$

where X is the width perpendicular to Y , the longest distance between any two points of the particle boundary.

3. Particle Shape Classification

3.1. Classification Method

The particle shape classification is carried out manually by looking at both top- and side-view images simultaneously since these provide complementary information about the shape. The images provide enough detail so that they can be classified according to the Magono–Lee scheme.

Figure 1 shows a few examples of successfully classified snow particles. In some cases, classification is relatively simple with one image only, for example, the top view of the stellar crystal of example (a). However, looking at the side view of the same example, the ice particle's shape may be mistaken for a needle type, as it looks similar to example case (b), which is of needle shape. Thus, determining the shape from one image is challenging even when using high-resolution images due to ambiguities arising in the case of unfavorable orientation in that image.

Cases (c) and (d) are more examples, which, in the side view, appear to have a similar shape. However, from the top-view images, we can distinguish two different shapes: (c) has a dendritic crystal or stellar shape, and (d) is a bullet capped with a dendrite. Similarly, particles in (e) and (f) appear to have similar shapes in the side view, i.e., hexagonal plate shape, however, from the top-view images, we can distinguish two different shapes: (e) is a capped column, and (f) is a hexagonal plate capped on one side with a thin plate. In a few cases, it is difficult to specify the shape despite the availability of top- and side-view images. For instance, we cannot distinguish if (g), (h), or (i) are the same shape, i.e., if they are graupel-like snow or densely rimed ice crystals. For such cases, we determine that they have a graupel shape.

Figure 1. Shape classification is less ambiguous with dual images. Panels (a–i) show nine examples of different particles with side views (*right*) and top views (*left*). Discussion of these examples is in the text.

3.2. Recent Updates

When classifying snow particles using the shape classes from the Magono–Lee classification, for some particles, a suitable shape class is missing. To these particles, we have either assigned a shape found in more recent literature or a new shape class. In both cases, we have chosen shape labels that are consistent with the Magono–Lee nomenclature. Thus, this new classification is an update of the Magono–Lee classification, which is only an extension of this original classification scheme, so that the many previous studies or datasets that have been using Magono–Lee may still be used as a reference.

Some new shapes appear in the study of Kikuchi et al. [21], which uses labels that are different from Magono–Lee. Therefore, we include these shapes with new labels consistent with Magono–Lee.

Other shapes are added but keep the same labels as in Kikuchi et al. [21], as they are not conflicting with Magono–Lee.

We also add some shapes observed by Libbrecht [23] as an extension of the Magono–Lee classification. Since shapes by Libbrecht [23] do not have any labels, only a shape name, they are added by assigning compatible labels that are consistent with the Magono–Lee nomenclature.

Table 1 shows the shapes added from Libbrecht [23] and Kikuchi et al. [21].

Table 1. Added shapes from Libbrecht [23] and Kikuchi et al. [21].

Particle Shape Name (Old Label)	New Label
Kikuchi et al. [21]:	
Combination of bullets with plates (CP2c)	CP2f
Combination of bullet with dendrites (CP2d)	CP2g
Seagull-type crystals (CP9a–CP9e)	CP4a
Bullet with plate	CP2a
Plate with needles	CP3d
Plate with columns	CP3e
Aggregation of combinations of columns and bullets	A1a
Aggregation of combinations of plates and dendrites	A2a
Aggregation of combinations of columns, planes and crossed plates	A3a
Frozen cloud particle	H1a
Chained frozen cloud particles	H1b
Frozen small raindrop	H1c
Sleet particle	H2a
Ice pellet	H3a
Libbrecht [23]:	
Twin columns	C1j
Triangular form/plate	P1g
Hollow plate	P1i
Split plate	P1k
Split stellar crystal	P1l
Double plate	P1o
Arrowhead twins	S4
Crossed plates	S5

3.3. New Shapes from Kiruna

New shapes only found in Kiruna and not yet described are also included as an extension of the Magono–Lee classification with labels compatible with Magono–Lee. These 34 new shapes are named as shown in Table 2.

Table 2. The 34 new shapes found in Kiruna: Figure 2 shows example images of all these new shapes.

Particle Shape Name	New Label
Rectangular plate	P1h
Plate with a central hole	P1j
Irregular split plate	P1m
Irregular split stellar crystal	P1n
Double stellar crystal	P1p
Stellar over plate	P1q
Triangular form with plates at ends	P2h
Triangular form with dendrites at ends	P2i
Concentric plates with sector-like extensions	P2j
Concentric plates with stellar or dendritic extensions	P2k
Column with plate and dendrite	CP1d
Asymmetric capped column (with plates)	CP1e
Multiple capped column with dendrites	CP1f
Asymmetric column with dendrites	CP1g
Bullet with plate and dendrite	CP2c
Bullet with two plates	CP2d
Bullet with two dendrites	CP2e
Combination of bullets (capped bullets)	CP2f
Asymmetric combination of bullets	CP2i
Aggregation of multiple capped columns	A4a
Aggregation of needles and sheaths	A5a
Aggregation of stellar crystals	A6a
Aggregation of dendrite crystals	A7a
Aggregation of plates	A8a
Aggregation of bullets	A9a
Aggregation of bullet rosettes and capped bullets	A9b
Aggregation of branches	A10a
Aggregation of seagull	A11a
Aggregation of malformed crystals	A12a
Aggregation of irregular particles	A13a
Aggregation of frozen small raindrops and snow crystals	A14a
Rimed bundle	R1e
Rimed capped bullet	R1f
Raindrop	H4a

Figure 2 shows example images of all the new shapes found in Kiruna. In some cases, more images of the same shape are shown in order to show the small differences that can be found within the same shape, i.e., the accepted variability within the shape classification. In other cases, side- and top-view images of the particle shape are shown for better shape description. For instance, in shape CP2d, only by looking at the side view of the first particle can we see the bullet with two plates.

Figure 2. The 34 new shapes found in Kiruna: Table 2 shows their completed name. The same scaling is applied to all images; a 1.0-mm scale bar is shown as reference. In some cases, more images of the same shape are shown to indicate possible differences found in the same shape. In other cases, side- and top-view images of the particle shape are shown for better shape description.

The resulting updated classification of Magono–Lee has 135 shapes, including the 34 new shapes from Kiruna. In Appendix A, Table A1 shows the complete names of all these shapes. Figures A1 and A2 show images of all the particle shapes taken by D-ICI. The 34 new shapes found in Kiruna are highlighted by thick gray frames.

4. Shape Groups

The microphysical properties (particle size, cross-sectional area, and area ratio) are determined from the particle images taken with D-ICI. After classifying the particles, one can study these properties for specific shapes or how the properties depend on them. It is challenging to study the characteristics of all 135 shapes since most particle shapes infrequently appear so that statistically significant results are hard to achieve.

Furthermore, even if we had found enough examples of every single shape to achieve statistical significance, it may be hard for the models to utilize this level of detail. Additionally, due to natural variability, the encountered variation in microphysical properties of one shape would, in many cases, be larger than shape-to-shape variations.

Therefore, to analyze the shape properties, it seemed to be more useful to use a classification based on only a small number of shape groups, instead of the 135 individual shapes. In the following section, we describe how we gather the 135 shapes into 15 shape groups, which are then used to study shape dependencies. However, these shape groups can be assembled differently into, for instance, less than 15 groups, depending on the needs of the study. In this case, 15 shape groups were defined in an attempt to simplify shape description while still maintaining some level of detail.

In a similar approach to Magono–Lee [20], we gather the shapes into 15 groups with comparable morphological characteristics. Magono–Lee’s main level $P = \text{Plane crystal}$ contains both plate-like shapes and stellar shapes; however, we wish to separate the two for this study and, hence, group them somewhat differently. Therefore, the groups used here do not exactly follow the main levels of Magono–Lee. This is not seen as incompatible to the Magono–Lee classification scheme. Rather,

the detailed classification using the updated Magono–Lee shapes from Section 3 allows one to group shapes according to the needs or interests, which may differ from study to study. In this sense, the grouping used here is not seen as rigid and definitive but as a first useful attempt to study snow particle characteristics depending on shape. These 15 shape groups are listed in Table 3.

Table 3. Shape groups (1–15).

Shape Groups (1–15)
(1) <i>Needles and thin or long columns</i>
(2) <i>Crossed needles and crossed columns</i>
(3) <i>Thick columns and bullets</i>
(4) <i>Capped columns and capped bullets</i>
(5) <i>Plates</i>
(6) <i>Stellar crystals</i>
(7) <i>Bullet rosettes</i>
(8) <i>Branches</i>
(9) <i>Side planes</i>
(10) <i>Spatial plates</i>
(11) <i>Spatial stellar crystals</i>
(12) <i>Graupel</i>
(13) <i>Ice and melting or sublimating particles</i>
(14) <i>Irregulars and aggregates</i>
(15) <i>Spherical particles</i>

Thus, we sort particle shapes that look similar, such as particles with needle-like shapes and thin columns, into groups of shared morphology. Therefore, even rimed particles can be included in such a group, as long as they appear to have the same type of morphology. Graupel particles, which do not appear to have a particular shape, are grouped separately as *Graupel*. Tables 4–7 provide detailed descriptions of the 15 shape groups. For each group, particle images of all the shapes that define that group are shown. In Appendix B, Table A2 lists for each shape group all shapes with their labels and names.

Table 4. Shape groups and their descriptions (part 1): For each of the 15 groups, images of all included shapes are shown. The complete names of these shapes are shown in Table A2 in Appendix B.

Shape Groups (1–15) and their Descriptions	Images
(1) <i>Needles and thin or long columns</i> : Includes needles, other snow crystals with elongated features (i.e., needle-like shape), and thin or long columns, including rimed needles and rimed thin columnar crystals.
(2) <i>Crossed needles and crossed columns</i> : Combination of crossed needles and a combination of crossed thin or long columns.
(3) <i>Thick columns and bullets</i> : Thick columnar, minute columns, bullet shape, scroll, pyramid, and cup shapes.
(4) <i>Capped columns and capped bullets</i> : Columns and bullets with plates at one end or both ends.
(5) <i>Plates</i> : Hexagonal plates including solid and hollow plates, skeletal surfaces, sector plates, plates with scrolls at the end, rimed plates, split plates, double plates, concentric plates, minute hexagonal plate, plate ice crystal, and triangular and rectangular plates.

Table 5. Shape groups and their descriptions (part 2): For caption, see Table 4.

Shape Groups (1–15) and their Descriptions	Images
<p>(6) Stellar crystals: Stellar and dendrite shapes including simple stars, stellar with plates or sector-like ends, dendritic crystal with plates or sector-like ends, plate with simple, sector-like or dendritic extensions, broad branch or dendritic crystal with 12 branches, stellar crystal with scrolls at ends, rimed stellar crystal, split stellar crystals, double stellar crystal, concentric plates with extensions of different forms, minute stellar crystal, dendrite ice crystal, and triangular form with extensions of different forms.</p>	<p>P1d P1e P1f P1l P1n P1p</p> <p>P2a P2b P2c P2d P2e P2f</p> <p>P2g P2h P2i P2j P2k P4a</p> <p>P4b CP3c R1d G4 1.0</p>
<p>(7) Bullet rosettes: Combination of bullets or columns, bullet rosette shapes including bullet with plates or dendrites.</p>	<p>C2a C2b CP2g CP2h CP2i R1f 1.0</p>
<p>(8) Branches: Arm-extension-like shape, malformed dendritic crystal, and seagull-type crystal.</p>	<p>P3a P3b P3c P5 P7b</p> <p>CP4a I3a I3b 1.0</p>

Table 6. Shape groups and their descriptions (part 3): For caption, see Table 4.

Shape Groups (1–15) and their Descriptions	Images
(9) <i>Side planes</i> : Snow crystals composed of several crossed hexagonal plates including radiating plates, side planes, scale-like side planes, combination of side planes with bullets and columns, assemblage of plates, arrowhead twins, and crossed plates shape.
(10) <i>Spatial plates</i> : Snow crystals composed of a plate with spatially attached plates or dendrites including densely rimed plate and columns on plates.
(11) <i>Spatial stellar crystals</i> : Stellar crystal or dendrites with spatial plates or with dendrites, including densely rimed stellar crystal, stellar crystal with rimed spatial branches, graupel-like snow of hexagonal type or lump type, and graupel-like snow with non-rimed extensions.
(12) <i>Graupel</i> : Soft hail shape considering that perceptions and definitions of soft hail can vary.

Table 7. Shape groups and their descriptions (part 4): For caption, see Table 4.

Shape Groups (1–15) and their Descriptions	Images
<p>(13) Ice and melting or sublimating particles: Minute ice crystals, i.e., particles that grow in cirrus clouds from minute frozen cloud droplets, such as frozen cloud particles, and ice pellets.</p>
<p>(14) Irregulars and aggregates: Particles that cannot be classified into any other shape group in addition of the agglomeration of snow crystals.</p>
<p>(15) Spherical particles: Frozen small raindrops and liquid raindrops.</p>

5. Properties of Shape Groups

In this section, we analyze the properties of the shape groups defined in Section 4. More than 10,000 images were taken during snowfall events from 2014 to 2019. As mentioned in Kuhn and Vázquez-Martín [22], we only consider particles that are completely in the field of view for analysis. In total, we found 3165 particles from 67 days that fulfilled these criteria and they make up the dataset further referred to in this study.

5.1. Occurrence and Properties

Figure 3 shows the frequency of occurrence of each shape group. We note that, in our dataset, shape group (8) *Branches* is the most common, occurring 20% of the time, followed by groups (14) *Irregulars and aggregates*, (9) *Side planes*, and (1) *Needles and thin or long columns* occurring 17%, 14%, and 11% of the time, respectively. The other shape groups have frequencies below 7.5%.

Figure 3. Occurrence of shape groups (1–15).

Figure 4a–c shows the particle size, $D_{\max}$; cross-sectional area, A ; and area ratio, A_r , respectively, for each shape group. These quantities are shown by their median, represented as a point. The data spread is given by the percentiles 84.1% and 15.9%, which together correspond to $\pm 1\sigma$ (standard deviation) if the distribution was normal (or Gaussian). The same data are shown in Table 8.

In Figure 4a, we note that shape group (6) *Stellar crystals* has the largest particle size with median $D_{\max} = 1450 \mu\text{m}$, followed by shape groups (2) *Crossed needles and crossed columns*, (7) *Bullet rosettes*, (8) *Branches*, (9) *Side planes*, and (11) *Spatial stellar crystals* with $D_{\max} > 1000 \mu\text{m}$. Shape groups (3) *Thick columns and bullets*, (5) *Plates*, (13) *Ice and melting or sublimating particles*, and (15) *Spherical particles* have the smallest sizes with median $D_{\max} < 500 \mu\text{m}$. Shape groups (11) *Spatial stellar crystals* and (14) *Irregulars and aggregates* have the widest spread ranging over $1000 \mu\text{m}$, whereas shape groups (13) *Ice and melting or sublimating particles* and (15) *Spherical particles* have the smallest data spread with less than $300 \mu\text{m}$.

Figure 4b illustrates that shape group (6) *Stellar crystals* with the largest particle size also has the largest cross-sectional area, with median $A = 6.34 \times 10^{-7} \text{ m}^2$, followed by shape groups (7) *Bullet rosettes*, (8) *Branches*, (9) *Side planes*, and (11) *Spatial stellar crystals* with median $A > 3.0 \times 10^{-7} \text{ m}^2$. In general, groups with large $D_{\max}$ also have large areas. However, there are exceptions, such as shape group (2) *Crossed needles and crossed columns*. While this shape group is among the groups with the largest $D_{\max}$, it is also among the shape groups with smaller areas. This is due to its shape leading to a

minimal area ratio, as can be seen in Figure 4c. We note that shape groups (1) *Needles and thin or long columns* and (2) *Crossed needles and crossed columns* have the smallest area ratios with $A_r < 0.2$. Shape group (15) *Spherical particles* has an area ratio close to one, as expected.

Figure 4. Microphysical properties of snow crystals for each shape group are shown in solid lines. The median and the spread corresponding to (a) particle size, D_{max} ; (b) cross-sectional area, A ; and (c) area ratio, A_r , are shown. Values of the median are represented as points. Lower and upper ends of the vertical bars are given by the percentiles 15.9% and 84.1%, respectively, representing the data spread. For comparison, median and the spread corresponding to all data (regardless of shape) are also shown in black dashed lines.

Table 8. The total number of particles, #; particle size, D_{max} ; cross-sectional area, A ; and area ratio, A_r , for the shape groups. The median and percentiles 15.9% and 84.1% are displayed. For comparison, results for all the data, i.e., all the shape groups together regardless of shape, are also shown.

Shape Groups (1–15)	#	$D_{max}/\mu\text{m}$			$A/10^{-9} \text{ m}^2$			A_r		
		Median	15.9%	84.1%	Median	15.9%	84.1%	Median	15.9%	84.1%
(1) Needles/long columns	350	956	555	1485	142	81.3	232	0.195	0.119	0.363
(2) Crossed needles/col.	72	1267	910	1737	233	148	357	0.181	0.124	0.282
(3) Thick columns	124	473	283	659	69.0	34.1	105	0.411	0.281	0.654
(4) Capped columns/bull.	221	662	476	1084	175	89.1	393	0.498	0.332	0.666
(5) Plates	213	504	336	856	143	65.7	387	0.748	0.596	0.823
(6) Stellar crystals	57	1450	864	1876	634	235	1260	0.443	0.315	0.561
(7) Bullet rosettes	55	1040	724	1305	348	194	570	0.430	0.326	0.561
(8) Branches	629	1078	714	1589	360	170	748	0.415	0.313	0.526
(9) Side planes	428	1105	856	1470	432	255	773	0.462	0.368	0.573
(10) Spatial plates	51	699	500	978	239	131	422	0.659	0.544	0.758
(11) Spatial stellar cryst.	235	1032	621	1683	420	168	1040	0.521	0.431	0.599
(12) Graupel	74	571	390	912	156	75.6	435	0.646	0.597	0.719
(13) Ice/melting particles	96	279	212	509	40.2	21.2	95.5	0.596	0.384	0.765
(14) Irregulars/aggregates	518	821	503	1452	247	97.6	619	0.488	0.337	0.618
(15) Spherical particles	42	181	108	236	24.8	8.60	48.7	0.961	0.924	0.976
All shape groups together (regardless of shape)	3165	899	489	1454	244	89.7	614	0.461	0.286	0.640

5.2. Relationships between Microphysical Properties

5.2.1. Cross-Sectional Area and Area Ratio

The cross-sectional area versus particle size (A vs. $D_{\max}$) and area ratio versus particle size (A_r vs. $D_{\max}$) relationships for the shape groups are analyzed in this section. The A vs. $D_{\max}$ relationship is fitted to a power law given by Kuhn and Gultepe [26]:

$$A = C_1 \cdot \left(\frac{D_{\max}}{1\mu\text{m}} \right)^{C_2}. \quad (3)$$

Equation (3) yields straight lines on a logarithmic plot; therefore, the parameters C_1 and C_2 are determined from linear fits to the data expressed as $\log(A)$ versus $\log(D_{\max})$, so that if all particles were spherical (i.e., they would appear circular in the images), C_1 and C_2 would be equal to $\frac{\pi}{4} \times 10^{-12} \text{ m}^2$ and 2, respectively.

The area ratio is calculated according to Equation (1) but can also be expressed as a power law function:

$$A_r = C_3 \cdot \left(\frac{D_{\max}}{1\mu\text{m}} \right)^{C_4}, \quad (4)$$

where parameters C_3 and C_4 can be obtained from Equations (3) and (1) so that $C_3 = C_1 \times \frac{4}{\pi} \times 10^{12} \text{ m}^{-2}$ and $C_4 = C_2 - 2$.

Figure 5 shows the fitted A vs. $D_{\max}$ (left) and A_r vs. $D_{\max}$ (right) relationships as lines for each shape group. The point on each line represents the median of the distribution of $D_{\max}$, the lines' endpoints correspond to the percentiles 15.9% and 84.1%, and hence, the spread of data is illustrated by the length of the line. The fit parameters C_1 and C_2 as well as the corresponding correlation coefficients, R^2 , which are used to analyze correlation, are shown in Table 9. In general, judging from the correlation coefficient, R_a^2 , in all shape groups, there is a good correlation ($R_a^2 \geq 0.73$) in the A vs. $D_{\max}$ relationship. The shape groups (5) *Plates*, (11) *Spatial stellar crystals*, (12) *Graupel*, (13) *Ice and melting or sublimating particles*, (14) *Irregulars and aggregates*, and (15) *Spherical particles* have $R_a^2 > 0.9$.

For most shape groups, area ratio decreases with increasing particle size, as can be seen in Figure 5. Clearly, group (15) *Spherical particles* is an exception, and its area ratio is almost constant, i.e., size independent. A nearly constant A_r means that $C_4 \simeq 0$ and $C_2 \simeq 2$ (see Equations (3) and (4)), which is the case for this group. Two more groups have values of C_2 close to 2. In group (12) *Graupel*, many particles have a close to spheroidal shape, and this appears to be similar over all sizes encountered, so that the area ratio is again size independent. The other group with C_2 fairly close to 2 and an almost constant A_r is (6) *Stellar crystals*. Apparently, the stellar particles in this group also remain similar at different sizes, so that A_r hardly varies. While A_r for group (15) *Spherical particles* is close to 1, A_r for (6) *Stellar crystals* is much smaller, approximately 0.4, as one would expect.

Particles in shape groups (1) *Needles and thin or long columns*, (2) *Crossed needles and crossed columns*, and (3) *Thick columns and bullets*, which are highly nonspherical, have C_2 values furthest from 2. As a consequence, C_4 values are furthest from zero and these groups have the steepest size dependence of A_r , as can be seen in Figure 5.

Figure 5. Area versus particle size (A vs. D_{max}) and area ratio versus particle size (A_r vs. D_{max}) relationships for each shape group (solid lines) and for all data regardless of shape (black dashed lines) are shown. For a legend, see Figure 4. Fits of A versus D_{max} and A_r versus D_{max} relationships are shown in logarithmic scale. The median D_{max} of the data is represented as a single point on each line. The length of the fit lines are defined by percentiles 15.9% and 84.1% of D_{max} . Top: A vs. D_{max} relationship given by Equation (3). For comparison, the area of spheres given by $(\pi/4) \cdot D_{\text{max}}^2$ is shown as a gray dashed line. Bottom: A_r vs. D_{max} relationship given by Equation (4). The corresponding data are shown in Table 9.

Tables 8 and 9 as well as Figures 4 and 5 show, in addition to the results for each shape group described above, also the results of A vs. D_{max} and A_r vs. D_{max} fits to all data (regardless of shape). These are provided as references and for situations where one might need average relationships instead of shape-dependent ones.

Table 9. Area versus particle size (A vs. $D_{\max}$) and area ratio versus aspect ratio (A_r vs. A_s) relationships fitted to Equations (3) and (4) for each shape group and for all data, i.e., for all the shape groups regardless of shape. The parameters C_1 , C_2 , C_5 , and C_6 and the correlation coefficients R_a^2 and R_b^2 are shown.

Shape Groups (1–15)	A vs. $D_{\max}$			A_r vs. A_s		
	$C_1/10^{-12} \text{ m}^2$	C_2	R_a^2	C_5	C_6	R_b^2
(1) Needles and thin or long columns	108	1.05	0.76	0.0183	0.698	0.90
(2) Crossed needles and crossed columns	128	1.05	0.73	0.0591	0.252	0.32
(3) Thick columns and bullets	31.6	1.25	0.85	0.0415	0.756	0.89
(4) Capped columns and capped bullets	5.31	1.59	0.79	0.0120	0.654	0.46
(5) Plates	3.17	1.72	0.94	−0.00869	0.894	0.80
(6) Stellar crystals	0.531	1.93	0.86	0.123	0.395	0.25
(7) Bullet rosettes	5.35	1.60	0.82	0.0991	0.450	0.25
(8) Branches	2.11	1.73	0.84	0.0845	0.483	0.47
(9) Side planes	1.88	1.76	0.88	0.124	0.457	0.32
(10) Spatial plates	4.64	1.66	0.86	0.0718	0.698	0.61
(11) Spatial stellar crystals	1.88	1.78	0.95	0.0736	0.556	0.55
(12) Graupel	0.324	1.97	0.98	0.201	0.518	0.45
(13) Ice and melting or sublimating particles	5.87	1.54	0.91	0.0351	0.769	0.68
(14) Irregulars and aggregates	3.54	1.66	0.90	0.0158	0.648	0.52
(15) Spherical particles	0.795	1.99	0.99	−0.168	1.14	0.93
All shape groups together (regardless of shape)	5.66	1.58	0.83	−0.451	0.900	0.71

5.2.2. Area Ratio and Aspect Ratio

Area ratio versus aspect ratio (A_r vs. A_s) data can be fitted to the linear relationship:

$$A_r = C_5 + C_6 \cdot A_s, \quad (5)$$

where C_5 and C_6 are the fit parameters.

Figure 6 shows the A_r vs. A_s relationship for each shape group. For comparison, the equality $A_r = A_s$ is displayed as a gray dashed line. We note that particles in shape groups (3) *Thick columns and bullets*, (5) *Plates*, (13) *Ice and melting or sublimating particles*, and (15) *Spherical particles* are closest to this line. As can be seen in Table 9, these groups, together with group (1) *Needles and thin or long columns*, have a good correlation between area and aspect ratio ($R_b^2 \geq 0.7$). On the other hand, shape groups (2) *Crossed needles and crossed columns*, (6) *Stellar crystals*, (7) *Bullet rosettes*, and (9) *Side planes* have a low correlation ($R_b^2 < 0.5$). For instance, in the case of the shape group (6) *Stellar crystals*, this might be due to several factors: the empty space between their branches resulting in low A_r values and/or significant variations in A_s due to particle orientation. Shape groups (1) *Needles and thin or long columns*, (3) *Thick columns and bullets*, (5) *Plates*, and (15) *Spherical particles* have the highest correlation ($R_b^2 > 0.8$).

Figure 6. Area ratio versus aspect ratio (A_r vs. A_s) relationships for each shape group (solid lines) and for all data regardless of shape (black dashed lines) are shown. Fits for the A_r vs. A_s relationship are given by Equation (5). The median A_s is represented as a single point on each line. The lengths of the fit lines are defined by the percentiles 15.9% and 84.1% of A_s . For comparison, spherical particles are shown ($A_r = A_s$) as dashed gray line. For a legend, see Figure 4. Data are shown in Table 9.

6. Summary and Conclusions

This paper presents data and images of falling snow and other hydrometeors in the size range from 50 μm to 4 mm by the D-ICI during snowfall events in Kiruna, Sweden from 2014 to 2019. The D-ICI takes dual high-resolution images (side and top view) that enable a better shape classification than if there was only one image per particle. From these images, we were able to determine the particle size, cross-sectional area, area ratio, and aspect ratio of individual particles.

We separated the particles into many different shapes following largely the Magono–Lee classification scheme. This resulted in an updated classification with 135 shapes, including 34 new shapes found in Kiruna during this period, which are shown in Figures A1 and A2. The new shapes are highlighted by gray frames. Table A1 (Appendix A) lists the full names of all the shapes, and the new shapes are denoted [KRN].

This study sought to find some characteristic microphysical properties, particle size, cross-sectional area, area ratio, aspect ratio, and frequency of occurrence of similar shapes. To facilitate this, we further sorted the 135 shapes into 15 shape groups based on morphological similarity. Naturally, it is also possible and, for some applications, more suitable to choose fewer groups.

Tables 4–7 (Section 4) show detailed descriptions of each of these groups, and a list with the complete names of the particle shapes sorted into the shape groups is given in Table A2 (Appendix B).

The main conclusions of this study can be summarized as follows:

- The dual images provides more information about the particle shape.
- We found 34 snow particles that are not yet described and that warrant their own shape in the updated shape classification.
- In our dataset, shape groups (1) *Needles and thin or long columns*, (8) *Branches*, (9) *Side planes*, and (14) *Irregulars and aggregates* are the most common, occurring more often than 10% of the time.
- Shape group (6) *Stellar crystals* has the largest median particle size, $D_{\text{max}} = 1450 \mu\text{m}$, followed by shape groups (2) *Crossed needles and crossed columns*, (7) *Bullet rosettes*, (8) *Branches*, (9) *Side planes*, and (11) *Spatial stellar crystals* with $D_{\text{max}} > 1000 \mu\text{m}$. Shape groups (3) *Thick columns and bullets*,

- (5) *Plates*, (13) *Ice and melting or sublimating particles*, and (15) *Spherical particles* have the smallest $D_{\max} < 500 \mu\text{m}$ (see Figure 4a).
- Shape group (6) *Stellar crystals* also has the largest median cross-sectional area, $A = 6.34 \times 10^{-7} \text{ m}^2$, followed by shape groups (7) *Bullet rosettes*, (8) *Branches*, (9) *Side planes*, and (11) *Spatial stellar crystals* with $A > 3.0 \times 10^{-7} \text{ m}^2$ (see Figure 4b).
 - In general, groups with large particle sizes also have large areas. However, there are exceptional shape groups with the largest particle sizes but with smaller areas, as it is in the case of shape group (2) *Crossed needles and crossed columns*. We can see in Figure 4c, in which we note that shape groups (1) *Needles and thin or long columns*, (2) *Crossed needles and crossed columns*, and (3) *Thick columns and bullets* have the smallest area ratios, $A_r < 0.4$.
 - In general, there is a good correlation of the A vs. $D_{\max}$ relationship for the shape groups, with correlation coefficients varying from 0.73 for shape group (2) *Crossed needles and crossed columns* to over 0.9 for shape groups (5) *Plates*, (11) *Spatial stellar crystals*, (12) *Graupel*, (13) *Ice and melting or sublimating particles*, (14) *Irregulars and aggregates*, and (15) *Spherical particles* (see Table 9).
 - In most shape groups, area ratio decreases with increasing particle size. This is strongest for the shape groups with the lowest area ratios: (1) *Needles and thin or long columns*, (2) *Crossed needles and crossed columns*, and (3) *Thick columns and bullets*, which consequently also have the lowest values of C_2 . The shape groups (15) *Spherical particles*, (14) *Graupel*, and (6) *Stellar crystals* are exceptions and have area ratios that are almost constant.
 - Shape groups (1) *Needles and thin or long columns*, (3) *Thick columns and bullets*, (5) *Plates*, and (15) *Spherical particles* have the highest correlation in the A_r vs. A_s relationship, with R_b^2 larger than 0.8 (see Table 9). On the other hand, shape groups (2) *Crossed needles and crossed columns*, (6) *Stellar crystals*, (7) *Bullet rosettes*, and (9) *Side planes* have correlation coefficients lower than 0.5. Shape groups (6) *Stellar crystals* and (7) *Bullet rosettes* have a particularly low A_r vs. A_s correlation of 0.25 despite a A vs. $D_{\max}$ correlation larger than 0.82. For instance, in the case of the shape group (6) *Stellar crystals*, this might be due to several factors; the empty space between their branches resulting in low A_r values and/or variations in A_s due to particle orientation.

This shows that, with the D-ICI and the classification in shapes and shape groups, particle characteristics can be studied for groups of similar shapes. Since fall speed can be measured by analyzing side-view images taken by the D-ICI [22], the shape dependence of fall speed can also be studied. The resulting parameterizations of the snow microphysical properties may be useful for improving our understanding of precipitation in cold climates in addition to helping improve the cloud microphysical parameterizations in the climate and forecast models.

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Appendix A. Shapes

Table A1 shows the updated classification of natural snow crystals and other hydrometeors. Original particle shapes are from the Magono–Lee classification. Added shapes from Libbrecht [23] are marked as [Li] and from Kikuchi et al. [21] are marked as [Ki]. Gray background and [KRN] mark the new particle shapes found in Kiruna.

Figure A1. Updated shape classification (part 1): The 34 new shapes found in Kiruna are highlighted by thick gray frames. A list with the complete names of these shapes is shown in Table A1. Same scaling for all images: 1.0-mm scale bar is shown.

Figure A2. Updated shape classification with 135 different shapes (part 2): For caption, see Figure A1.

Table A1. Updated classification.

Level (N, C, ...), Sublevel (1, 2, ...), Name	Label
N = Needle crystal	
1. Simple needle	
a. Elementary needle	N1a
b. Bundle of elementary needles	N1b
c. Elementary sheath	N1c
d. Bundle of elementary sheaths	N1d
e. Long solid column	N1e
2. Combination of needle crystals	
a. Combination of needles	N2a
b. Combination of sheaths	N2b
c. Combination of long solid columns	N2c
C = Columnar crystal	
1. Simple column	

Table A1. Cont.

Level (N, C, ...), Sublevel (1, 2, ...), Name	Label
a. Pyramid	C1a
b. Cup	C1b
c. Solid bullet	C1c
d. Hollow bullet	C1d
e. Solid column	C1e
f. Hollow column	C1f
g. Solid thick plate	C1g
h. Thick plate of skeleton form	C1h
i. Scroll	C1i
j. Twin columns	C1j [Li]
2. Combination of columns	
a. Combination of bullets (bullet rosettes)	C2a
b. Combination of columns (column rosettes)	C2b
P = Plane crystal	
1. Regular crystal developed in one plane	
a. Hexagonal plate	P1a
b. Crystal with sector-like branches	P1b
c. Crystal with broad branches	P1c
d. Stellar crystal	P1d
e. Ordinary dendritic crystal	P1e
f. Fernlike crystal	P1f
g. Triangular form/plate	P1g [Li]
h. Rectangular plate	P1h [KRN]
i. Hollow plate	P1i [Li]
j. Plate with a central hole	P1j [KRN]
k. Split plate	P1k [Li]
l. Split stellar crystal	P1l [Li]
m. Irregular split plate	P1m [KRN]
n. Irregular split stellar crystal	P1n [KRN]
o. Double plate	P1o [Li]
p. Double stellar crystal	P1p [KRN]
q. Stellar over plate	P1q [KRN]
2. Plane crystal with extensions of different form	
a. Stellar crystal with plates at ends	P2a
b. Stellar crystal with sector-like ends	P2b
c. Dendritic crystal with plates at ends	P2c
d. Dendritic crystal with sector-like ends	P2d
e. Plate with simple extensions	P2e
f. Plate with sector-like extensions	P2f
g. Plate with dendritic extensions	P2g
h. Triangular form with plates at ends	P2h [KRN]
i. Triangular form with dendrites at ends	P2i [KRN]
j. Concentric plates with sector-like extensions	P2j [KRN]
k. Concentric plates with stellar or dendritic extensions	P2k [KRN]
3. Crystals with irregular number of branches	
a. Two-branched crystal	P3a

Table A1. Cont.

Level (N, C, ...), Sublevel (1, 2, ...), Name	Label
b. Three-branched crystal	P3b
c. Four-branched crystal	P3c
4. Crystal with 12 branches	
a. Broad branch crystal with 12 branches	P4a
b. Dendritic crystal with 12 branches	P4b
5. Malformed crystal	
Many varieties	P5
6. Spatial assemblage of plane branches	
a. Plate with spatial plates	P6a
b. Plate with spatial dendrites	P6b
c. Stellar crystal with spatial plates	P6c
d. Stellar crystal with spatial dendrites	P6d
7. Radiating assemblage of plane branches	
a. Radiating assemblage of plates	P7a
b. Radiating assemblage of dendrites	P7b
CP = Combination of column and plane crystals	
1. Column with plane crystals at both ends	
a. Column with plates (capped column)	CP1a
b. Column with dendrites	CP1b
c. Multiple capped column	CP1c
d. Column with plate and dendrite	CP1d [KRN]
e. Asymmetric capped column (with plates)	CP1e [KRN]
f. Multiple capped column with dendrites	CP1f [KRN]
g. Asymmetric column with dendrites	CP1g [KRN]
2. Bullet with plane crystals	
a. Bullet with plate	CP2a [Ki]
b. Bullet with dendrite	CP2b
c. Bullet with plate and dendrite	CP2c [KRN]
d. Bullet with two plates	CP2d [KRN]
e. Bullet with two dendrites	CP2e [KRN]
f. Combination of bullets (capped bullets)	CP2f [KRN]
g. Combination of bullets with plates	CP2g [Ki]
h. Combination of bullets with dendrites	CP2h [Ki]
i. Asymmetric combination of bullets	CP2i [KRN]
3. Plane crystal with spatial extensions at ends	
a. Stellar crystal (dendrite) with needles	CP3a
b. Stellar crystal (dendrite) with columns	CP3b
c. Stellar crystal (dendrite) with scrolls at ends	CP3c
d. Plate with needles	CP3d [Ki]
e. Plate with columns	CP3e [Ki]
f. Plate with scrolls at ends	CP3f
4. Seagull-type crystal	
a. Seagull crystal	CP4a [Ki]
S = Columnar crystals with extended side planes	
1. Side planes	S1
2. Scale-like side planes	S2

Table A1. Cont.

Level (N, C, ...), Sublevel (1, 2, ...), Name	Label
3. Combination of side planes, bullets, and columns	S3
4. Arrowhead twins	S4 [Li]
5. Crossed plates	S5 [Li]
A = Aggregates of snow crystals	
1. Aggregation of column-type crystals	
a. Aggregation of combinations of columns and bullets	A1a [Ki]
2. Aggregation of plane-type crystals	
a. Aggregation of combinations of plates and dendrites	A2a [Ki]
3. Aggregation of column- and plane-type crystals	
a. Aggregation of combinations of columns, planes and crossed plates	A3a [Ki]
4. Aggregation of multiple capped columns	
a. Aggregation of multiple capped columns	A4a [KRN]
5. Aggregation of needle- and sheath-type crystals	
a. Aggregation of needles and sheaths	A5a [KRN]
6. Aggregation of stellar-type crystals	
a. Aggregation of stellar crystals	A6a [KRN]
7. Aggregation of dendrite-type crystals	
a. Aggregation of dendrite crystals	A7a [KRN]
8. Aggregation of plate-type crystals	
a. Aggregation of plates	A8a [KRN]
9. Aggregation of bullet-type crystals	
a. Aggregation of bullets	A9a [KRN]
b. Aggregation of bullet rosettes and capped bullets	A9b [KRN]
10. Aggregation of branch-type crystals	
a. Aggregation of branches	A10a [KRN]
11. Aggregation of seagull-type crystals	
a. Aggregation of seagull	A11a [KRN]
12. Aggregation of malformed-type crystals	
a. Aggregation of malformed crystals	A12a [KRN]
13. Aggregation of irregular-type crystals	
a. Aggregation of irregular particles	A13a [KRN]
14. Aggregation of frozen small raindrops and snow crystals	
a. Aggregation of frozen small raindrops and snow crystals	A14a [KRN]
R = Rimed crystal (crystal with cloud droplets attached)	
1. Rimed crystal	
a. Rimed needle crystal	R1a
b. Rimed columnar crystal	R1b
c. Rimed plate or sector	R1c
d. Rimed stellar crystal	R1d
e. Rimed bundle	R1e [KRN]
f. Rimed capped bullet	R1f [KRN]
2. Densely rimed crystal	
a. Densely rimed plate or sector	R2a

Table A1. Cont.

Level (N, C, ...), Sublevel (1, 2, ...), Name	Label
b. Densely rimed stellar crystal	R2b
c. Stellar crystal with rimed spatial branches	R2c
3. Graupel-like snow	
a. Graupel-like snow of hexagonal type	R3a
b. Graupel-like snow of lump type	R3b
c. Graupel-like snow with non-rimed extensions	R3c
4. Graupel	
a. Hexagonal graupel	R4a
b. Lump graupel	R4b
c. Cone-like graupel	R4c
I = Irregular snow crystal	
1. Ice particle	I1
2. Rimed particle	I2
3. Broken piece from a crystal	
a. Broken branch	I3a
b. Rimed broken branch	I3b
4. Miscellaneous	I4
G = Germ of snow crystal (ice crystal)	
1. Minute column	G1
2. Germ of skeleton form	G2
3. Minute hexagonal plate	G3
4. Minute stellar crystal	G4
5. Minute assemblage of plates	G5
6. Irregular germ	G6
H = Other solid precipitation particles	
1. Frozen hydrometeor particle	
a. Frozen cloud particle	H1a [Ki]
b. Chained frozen cloud particles	H1b [Ki]
c. Frozen small raindrop	H1c [Ki]
2. Sleet particle	
a. Sleet particle	H2a [Ki]
3. Ice pellet	
a. Ice pellet	H3a [Ki]
4. Droplets of water	
a. Raindrop	H4a [KRN]

Appendix B. Shape Groups

Table A2 shows the shapes of the updated classification of natural snow crystals and other hydrometeors sorted into shape groups. Original particle shapes are from the Magono–Lee classification. Shapes from Libbrecht [23] are marked as [Li], and shapes from Kikuchi et al. [21] are marked as [Ki]. Gray background and [KRN] mark the new particle shapes found in Kiruna.

Table A2. Shapes of the updated classification sorted into shape groups.

Shape Groups (1–15), Name	Label
(1) Needles and thin or long column	
Elementary needle	N1a
Bundle of elementary needles	N1b
Elementary sheath	N1c
Bundle of elementary sheaths	N1d
Long solid column	N1e
Rimed needle crystal	R1a
Rimed columnar crystal	R1b
Rimed bundle	R1e [KRN]
(2) Crossed needles and crossed columns	
Combination of needles	N2a
Combination of sheaths	N2b
Combination of long solid columns	N2c
(3) Thick columns and bullets	
Pyramid	C1a
Cup	C1b
Solid bullet	C1c
Hollow bullet	C1d
Solid column	C1e
Hollow column	C1f
Solid thick plate	C1g
Scroll	C1i
Twin columns	C1j [Li]
Minute column	G1
(4) Capped columns and capped bullets	
Column with plates (capped column)	CP1a
Column with dendrites	CP1b
Multiple capped column	CP1c
Column with plate and dendrite	CP1d [KRN]
Asymmetric capped column (with plates)	P1e [KRN]
Multiple capped column with dendrites	CP1f [KRN]
Asymmetric column with dendrites	CP1g [KRN]
Bullet with plate	CP2a [Ki]
Bullet with dendrite	CP2b
Bullet with plate and dendrite	CP2c [KRN]
Bullet with two plates	CP2d [KRN]
Bullet with two dendrites	CP2e [KRN]
Combination of bullets (capped bullets)	CP2f [KRN]
(5) Plates	
Thick plate of skeleton form	C1h
Hexagonal plate	P1a
Crystal with sector-like branches	P1b
Crystal with broad branches	P1c
Triangular form/plate	P1g [Li]

Table A2. Cont.

Shape Groups (1–15), Name	Label
Rectangular plate	P1h [KRN]
Hollow plate	P1i [Li]
Plate with a central hole	P1j [KRN]
Split plate	P1k [Li]
Irregular split plate	P1m [KRN]
Double plate	P1o [Li]
Stellar crystal over plate	P1q [KRN]
Plate with scrolls at ends	CP3f
Rimed plate or sector	R1c
Germ of skeleton from	G2
Minute hexagonal plate	G3
(6) Stellar crystals	
Stellar crystal	P1d
Ordinary dendritic crystal	P1e
Fernlike crystal	P1f
Split stellar crystal	P1l [Li]
Irregular split stellar crystal	P1n [KRN]
Double stellar crystal	P1p [KRN]
Stellar crystal with plates at ends	P2a
Stellar crystal with sector-like ends	P2b
Dendritic crystal with plates at ends	P2c
Dendritic crystal with sector-like ends	P2d
Plate with simple extensions	P2e
Plate with sector-like extensions	P2f
Plate with dendritic extensions	P2g
Triangular form with plates at ends	P2h [KRN]
Triangular form with dendrites at ends	P2i [KRN]
Concentric plates with sector-like extensions	P2j [KRN]
Concentric plates with stellar or dendritic extensions	P2k [KRN]
Broad branch crystal with 12 branches	P4a
Dendritic crystal with 12 branches	P4b
Stellar crystal with scrolls at ends	CP3c
Rimed stellar crystal	R1d
Minute stellar crystal	G4
(7) Bullet rosettes	
Combination of bullets (bullet rosettes)	C2a
Combination of columns (column rosettes)	C2b
Combination of bullets with plates	CP2g [Ki]
Combination of bullets with dendrites	CP2h [Ki]
Asymmetric combination of bullets	CP2i [KRN]
Rimed capped bullet	R1f [KRN]
(8) Branches	
Two-branched crystal	P3a
Three-branched crystal	P3b
Four-branched crystal	P3c
Malformed crystal	P5

Table A2. Cont.

Shape Groups (1–15), Name	Label
Radiating assemblage of dendrites	P7b
Seagull crystal	CP4a [Ki]
Broken branch	I3a
Rimed broken branch	I3b
(9) Side planes	
Radiating assemblage plates	P7a
Side planes	S1
Scale-like side planes	S2
Combination of side planes, bullets, and columns	S3
Arrowhead twins	S4 [Li]
Crossed plates	S5 [Li]
Minute assemblage of plates	G5
(10) Spatial plates	
Plate with spatial plates	P6a
Plate with spatial dendrites	P6b
Plate with needles	CP3d [Ki]
Plate with columns	CP3e [Ki]
Densely rimed plate or sector	R2a
(11) Spatial stellar crystals	
Stellar crystal with spatial plates	P6c
Stellar crystal with spatial dendrites	P6d
Stellar crystal with needles	CP3a
Stellar crystal with columns	CP3b
Densely rimed stellar crystal	R2b
Stellar crystal with rimed spatial branches	R2c
Graupel-like snow of hexagonal type	R3a
Graupel-like snow of lump type	R3b
Graupel-like snow with non-rimed extensions	R3c
(12) Graupel	
Hexagonal graupel	R4a
Lump graupel	R4b
Cone-like graupel	R4c
(13) Ice and melting or sublimating particles	
Ice particle	I1
Frozen cloud particle	H1a [Ki]
Chained frozen cloud particles	H1b [Ki]
Sleet particle	H2a [Ki]
Ice pellet	H3a [Ki]
(14) Irregulars and aggregates	
Aggregation of combinations of columns and bullets	A1a [Ki]
Aggregation of combinations of plates and dendrites	A2a [Ki]
Aggregation of combinations of columns, planes and crossed plates	A3a [Ki]
Aggregation of multiple capped columns	A4a [KRN]

Table A2. Cont.

Shape Groups (1–15), Name	Label
Aggregation of needles and sheaths	A5a [KRN]
Aggregation of stellar crystals	A6a [KRN]
Aggregation of dendrite crystals	A7a [KRN]
Aggregation of plates	A8a [KRN]
Aggregation of bullets	A9a [KRN]
Aggregation of bullet rosettes and capped bullets	A9b [KRN]
Aggregation of branches	A10a [KRN]
Aggregation of seagull	A11a [KRN]
Aggregation of malformed crystals	A12a [KRN]
Aggregation of irregular particles	A13a [KRN]
Aggregation of frozen small raindrops and snow crystals	A14a [KRN]
Rimed particle	I2
Miscellaneous	I4
Irregular germ	G6
(15) Spherical particles	
Frozen small raindrop	H1c [Ki]
Raindrop	H4a [KRN]

References

1. Stoelinga, M.; Hobbs, P.V.; Mass, C.F.; Locatelli, J.; Colle, B.; Houze, R.; Rangno, A.L.; Bond, N.A.; Smull, B.F.; Rasmussen, R.M.; et al. Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE). *Bull. Am. Met. Soc.* **2003**, *84*, 1807–1826. [\[CrossRef\]](#)
2. Tao, W.K.; Simpson, J.; Baker, D.; Braun, S.; Chou, M.D.; Ferrier, B.; Johnson, D.; Khain, A.; Lang, S.; Lynn, B.; et al. Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model. *Meteorol. Atmos. Phys.* **2003**, *82*, 97–137. [\[CrossRef\]](#)
3. Posselt, D.J.; L'Ecuyer, T.S.; Stephens, G.L. Exploring the error characteristics of thin ice cloud property retrievals using a Markov chain Monte Carlo algorithm. *J. Geophys. Res.* **2008**, *113*. [\[CrossRef\]](#)
4. Zhang, Z.; Yang, P.; Kattawar, G.; Riedi, J.; Labonnote, L.C.; Baum, B.A.; Platnick, S.; Huang, H.L. Influence of ice particle model on satellite ice cloud retrieval: lessons learned from MODIS and POLDER cloud product comparison. *Atmos. Chem. Phys.* **2009**, *9*, 7115–7129. [\[CrossRef\]](#)
5. Cooper, S.J.; Garrett, T.J. Identification of small ice cloud particles using passive radiometric observations. *J. Appl. Meteorol.* **2010**, *49*, 2334–2347. [\[CrossRef\]](#)
6. IPCC. Clouds and Aerosols. In *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 571–658. [\[CrossRef\]](#)
7. Pruppacher, H.R.; Klett, J.D. *Microphysics of Clouds and Precipitation*, 2nd ed.; Dordrecht: Kluwer Academic Publishers: Dordrecht, The Netherlands, 1997.
8. Nakaya, U.; Sekido, Y. General Classification of Snow Crystals and their Frequency of Occurrence. *J. Fac. Sci. Hokkaido Imp. Univ. Ser. II* **1936**, *1*, 243–264.
9. Hanajima, M. On the conditions for the formation of snow crystals. *J. Meteorol. Soc. Jpn. Ser. II* **1942**, *20*, 238–251. [\[CrossRef\]](#)
10. Nakaya, U. Snow Crystal Growth: Electron Microscope Study of Snow Crystal Nuclei (Advance communication). *J. Glaciol.* **1951**, *1*, 550. [\[CrossRef\]](#)
11. Nakaya, U. *The Formation of Ice Crystals*; American Meteorological Society: Boston, MA, USA, 1951; pp. 207–220. [\[CrossRef\]](#)
12. Itoo, K. On the Growth of Ice Crystals in the Air. *Pap. Meteor. Geophys.* **1951**, *2*, 315–316. [\[CrossRef\]](#)

13. Isono, K. An Electron–Microscope Study of Ice Crystal Formation – A Preliminary Report. *J. Meteorol. Soc. Jpn. Ser. II* **1953**, *31*, 318–322. [CrossRef]
14. Isono, K. On the Growth of Ice-Crystals in the Air. *J. Meteorol. Soc. Jpn. Ser. II* **1957**, *35A*, 31–37. [CrossRef]
15. Ukitiro, N.; Masando, H.; Jiro, M. Physical Investigations on the Growth of Snow Crystals. *J. Fac. Sci. Hokkaido Univ. Ser. II* **1958**, *5*, 88–118.
16. Libbrecht, K.G. Morphogenesis on Ice: The Physics of Snow Crystals. *Eng. Sci.* **2001**, *1*, 10–19.
17. Libbrecht, K.G. The physics of snow crystals. *Rep. Prog. Phys.* **2005**, *68*, 855–895. [CrossRef]
18. Seasonal Snow Cover: a guide for measurement compilation and assemblage of data. Unesco/IASH/WMO, 1970. Available online: https://globalcryospherewatch.org/bestpractices/docs/UNESCO_snow_cover_1970.pdf (accessed on 4 December 2019).
19. Fierz, C.; Armstrong, R.; Durand, Y.; Etchevers, P.; Greene, E.; McClung, D.; Nishimura, K.; Satyawali, P.; Sokratov, S. *The International Classification for Seasonal Snow on the Ground (UNESCO, IHP (International Hydrological Programme)—VII, Technical Documents in Hydrology, No 83); IACS (International Association of Cryospheric Sciences) Contribution No 1; UNESCO/Division of Water Sciences: Paris, France, 2009.*
20. Magono, C.; Lee, C.W. Meteorological classification of natural snow crystals. *J. Fac. Sci. Hokkaido Univ.* **1966**, *II*, 321–335.
21. Kikuchi, K.; Kameda, T.; Higuchi, K.; Yamashita, A. A global classification of snow crystals, ice crystals, and solid precipitation based on observations from middle latitudes to polar regions. *Atmos. Res.* **2013**, *132–133*, 460–472. [CrossRef]
22. Kuhn, T.; Vázquez-Martín, S. Microphysical properties and fall speed measurements of snow ice crystals using the Dual Ice Crystal Imager (D-ICI). *Atmos. Meas. Tech. Discuss.* **2019**, 1–24. [CrossRef]
23. Libbrecht, K.G. *Ken Libbrecht's Field Guide to Snowflakes*; Voyageur Press: Minneapolis, MN, USA, 2006.
24. SMHI. Januari 2018—Lufttemperatur och vind, SMHI_vov_temperature_wind_jan18. Available online: <https://www.ce.se/smhi-sveriges-meteorologiska-och-hydrologiska-institut/> (accessed on 4 December 2019).
25. IRF. Weather at IRF. Available online: <http://www2.irf.se/weather/> (accessed on 4 December 2019).
26. Kuhn, T.; Gultepe, I. Ice Fog and Light Snow Measurements Using a High-Resolution Camera System. *Pure Appl. Geophys.* **2016**, *173*, 3049–3064. [CrossRef]

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