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A global classification of snow crystals, ice crystals, and solid precipitation based on observations from middle latitudes to polar regions

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ABSTRACT

This paper presents an extensive revision of Magono and Lee's (1966) classification of natural snow crystals, which has been widely used in snow and ice studies to describe snow crystal shapes. The new classification catalogs snow crystals and other solid precipitation particles into 121 categories, in contrast to Magono and Lee's 80 categories. Of these, 28 categories were created to classify new types of snow crystals that have been discovered in polar regions since 1968, seven were created after reconsidering the original categories, and six categories were created to classify solid precipitation particles such as frozen cloud particles and small raindrops. Because our observational area extended from middle latitudes (Japan) to polar regions, we refer to our new classification scheme as 'global-scale classification' or 'global classification'. The global classification consists of three levels – general, intermediate, and elementary – which are composed of 8, 39, and 121 categories, respectively. This paper describes the characteristics of each type of snow crystal, ice crystal, and solid precipitation particle.

1. Introduction

Researchers have identified many types of snow crystals, which have been classified into various categories. Nakaya and Sekido (1938) classified natural snow crystals into 21 categories based on their shape, and Nakaya (1954) classified snow crystals into 42 categories. This is called 'general classification of snow crystals'. Schaefer (1951) provided a practical classification of natural solid particles using 10 categories based on their size (very small, small, medium, large, and very large) and additional characteristics (broken, rimed, flake, and wet). This classification was also described by Mason (1957, 1971). Magono and Lee (1966) classified natural snow crystals into 80 categories based on their shape; their classification scheme is widely used by scientists to describe snow crystal shapes. However, it was based mainly on observations in Japan and did not include several types of snow crystals that are observed only in Arctic and Antarctic regions.

Kikuchi proposed a 'peculiar type' category of snow crystals in 1969 (Kikuchi, 1969; 1970; 1974) based on his observations at Syowa Station, Antarctica between February 1968 and January 1969. However, this category has not been widely used. Recently, Fierz et al. (2009) proposed a classification of snow on the ground. Precipitation particles including snow

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crystals and solid precipitation are classified into 9 categories for visual observation purpose in their Appendix A. This is basically the same as practical classification by Schaefer (1951) and Mason (1957, 1971).

On the other hand, Заморский (1955) introduced a new classification system for snow and ice crystals that he observed in Siberia in his book "Атмосферный Лед (Ice in the atmosphere)", and Клинов (1960) introduced a similar classification system for crystals that he observed in Siberia in his book "Вода в Атмосфере при Низких Температурах (Water in the atmosphere at lower temperatures)". However, neither of these authors classified crystals systematically.

Since the publication of Magono and Lee's (1966) classification system, snow crystal observations have expanded to include polar regions (Kikuchi and Hogan, 1976, 1979; Magono, 1978; Kikuchi and Kajikawa, 1979; Kajikawa et al., 1980; Higuchi et al., 1981; Kikuchi, 1987, 1989; Kikuchi and Asuma, 1999; Walden et al., 2003), and artificial snow crystal formation experiments and analyses have been widely conducted (e.g., Yamashita, 1979; Gonda, 1980; Kikuchi and Sato, 1984; Yamashita and Ohno, 1984; Sato and Kikuchi, 1985; Takahashi et al., 1991; Fukuta and Takahashi, 1999; Bailey and Hallett, 2004, 2009; Aburakawa, 2005; Hiramatsu and Sturm, 2005; Takahashi and Mori, 2006; Murai et al., 2012). These new observations and experiments have revealed several types of new snow crystals, such as the Gohei twin, seagull-type, and skeletal-type, which have not yet been classified.

Recently, Bailey and Hallett (2004) examined the growth rates and crystal habits of ice and snow crystals that form at temperatures between −20 °C and −70 °C, and in 2009 they presented a crystal habit diagram of snow crystals (Bailey and Hallett, 2009), but they did not classify snow and ice crystals systematically. Libbrecht (2003) presented beautiful natural and artificial snow crystals, but he used the classification provided by Magono and Lee (1966).

Many other recent papers also refer to Magono and Lee (1966) for describing snow and ice crystal shapes, for example Nelson (2005), Lawson et al. (2006), and Teschl et al. (2013). Evidently, a new classification scheme is needed to include every type of snow crystal and ice crystal.

In 2012, we published a new classification of snow crystals, ice crystals, and solid precipitation particles in Japanese, which we referred to as a 'global classification' (Kikuchi et al., 2012). Our data included observations of these particles from middle latitudes to polar regions since 1968. The global classification consists of three levels: general, intermediate, and elementary. The general level has 8 categories, the intermediate level has 39 categories, and the elementary level has 121 categories.

This paper extends on our previous report and includes more detailed descriptions, in English, of each of the 121 types of snow crystals, ice crystals, and solid precipitation particles. It also includes drawings of the 121 particle types.

2. A description of snow crystals and other solid precipitation particles in the global classification

Table 1 presents the locations where the 121 types of snow crystals, ice crystals, and other solid precipitation particles were observed, and Table 2 presents each particle type's global classification. Fig. 1 presents the photographs of the 121 particle types, and Fig. 2 schematically summarizes the shape of each particle. In this chapter, we briefly describe the characteristics of each particle.

Table 1
Main observation sites of snow crystals, ice crystals, and other solid precipitation.

Number	Locations	Latitude and longitude
Observation sites in Japan		
1	Cloud Physics Observatory of Hokkaido University at Mt. Teine, Sapporo, Hokkaido	43°04′N, 141°11′E
2	Wind Wave Observation Site, Hokkaido Developing Bureau, Yokomachi, Ishikari, Hokkaido	43°15′N, 141°21′E
3	Yukomambetsu Spa, Higashikawa, Hokkaido	43°41′N, 142°47′E
4	Hachimantai Ski Slope, Kazuno, Akita	39°59′N, 140°48′E
5	Sand Dune Farming Experimental Station, Kahoku, Ishikawa	36°43′N, 136°42′E
Observation sites in polar regions in northern hemisphere		
6	Science Research Center, Inuvik, Canada	67°22′N, 133°42′W
7	Yellowknife Airport, Yellowknife, Canada	62°28′N, 114°27′W
8	Barrow, Alaska, USA	71°18′N, 156°44′W
9	Peters Lake, Alaska, USA	69°N, 145°W
10	Alta River Camping Site, Alta, Norway	69°56′N, 23°16′E
11	Kautokeino, Norway	69°01′N, 23°03′E
12	Ny-Ålesund, Svalbard, Norway	78°55′N, 11°56′E
13	Longyearbyen, Svalbard, Norway	78°13′N, 15°38′E
14	Space Physics Institute, Kiruna, Sweden	68°56′N, 21°04′E
15	Arctic Research Center, Sodankyla, Finland	67°22′N, 26°38′E
16	Arctic Station, Godhavn, Greenland	69°15′N, 53°34′W
17	Godthåb, Greenland	64°10′N, 51°45′W
Observation sites in polar regions in southern hemisphere		
18	Syowa Station, Antarctica	68°00′S, 39°35′E
19	Dome Fuji Station, Antarctica	77°19′S, 39°42′E
20	McMurdo Station, Antarctica	77°51′S, 166°40′E
21	Amundsen–Scott South Pole Station, Antarctica	90°00′S

2.1. Column crystal group (C)

'Column crystal group' includes snow crystals with characteristics similar to columns. This group is divided into four types: C1–C4.

2.1.1. Needle-type crystal (C1)

'Needle-type' refers to snow crystals shaped like needles, with tops shaped like knife-edges. This crystal type is subdivided into three categories: needle (C1a), needle bundle (C1b), and combination of needles (C1c). Crystals in C1a have a simple form, crystals in C1b have two or more needle crystals,

Table 2
Global classification of snow crystals, ice crystals, and other solid precipitation.

General level	Intermediate level	Elementary level
C Column crystal group	1. Needle-type crystal	a. Needle
		b. Bundle of needles
		c. combination of needles
	2. Sheath-type crystal	a. Sheath
		b. Bundle of sheaths
		c. Combination of sheaths
	3. Column-type crystal	a. Solid column
		b. Skeletal column
		c. Skeletal column with scrolls
		d. Long solid column
		e. Combination of columns (Column rosettes)
	4. Bullet-type crystal	a. Pyramid
		b. Solid bullet
		c. Skeletal bullet
		d. Combination of bullets (Bullet rosettes)
P Plane crystal	1. Plate-type crystal	a. Plate
		b. Thick solid plate
		c. Skeletal plate
	2.Sector-type crystal	a. Sector
		b. Broad branches
	3. Dendrite-type crystal	a. Stellar
		b. Dendrite
		c. Fern
	4. Composite plane-type crystal	a. Stellar with plates
		b. Stellar with sectors
		c. Dendrite with plates
		d. Dendrite with sectors
		e. Plate with branches
		f. Plate with sectors
		g. Plate with dendrites
	5. Separated and multiple dendrite-type crystals	a. Two branches
		b. Three branches
		c. Four branches
		d. 12-branches
		e. 18-branches
		f. 24-branches
	6. Spatial assemblage of plane-type crystal	a. Plate with spatial sectors
		b. Plate with spatial dendrites
		c. Dendrite with spatial sectors
		d. Dendrite with spatial dendrites
	7. Radiating assemblage of plane-type crystal	a. Radiating assemblage of plates
		b. Radiating assemblage of dendrites
	8. Asymmetrical plane-type crystal	a. Asymmetrical plane
		b. Complex multiple plates
CP Combination of column and plane crystals group	1. Column with plane-type crystals (Capped column)	a. Column with plates
		b. Column with dendrites
		c. Column with multiple planes
	2. Combination of bullets with plane-type crystal	a. Bullet with plate
		b. Bullet with dendrite
		c. Combination of bullets with plates
		d. Combination of bullets with dendrites
	3. Plane crystals with column-type crystal	a. Dendrite with needles
		b. Dendrite with columns
		c. Dendrite with scrolls
		d. Plate with needles
		e. Plate with columns
		f. Plate with scrolls
	4. Crossed plate-type crystal	a. Crossed plates
		b. Chained crossed plates
		c. Radiating assemblage of crossed plates
	5. Irregular combination of column- and plane-type crystals	a. Irregular combination of columns, bullets and crossed plates
	6. Skeletal-type crystal	a. Skeletal tetragon
		b. Polycrystalline skeletal tetragon
		c. Multiple skeletal tetragon
		d. Complex skeletal polygon
		e. Combination of skeletal columns and crossed plates
		f. Combination of skeletal bullets and tetragon
		g. Combination of skeletal polygons
		h. Complex prism plane structures
	7. Gohei twin-type crystal	a. Gohei twin
		b. Gohei twin with combination of bullets
		c. Gohei twin with crossed plates
		d. Gohei twin composed of multiple columns
		e. Double symmetrical gohei twin
		f. Iciclelike gohei twin
		g. Multiple lozenge gohei twin
	8. Spearhead-type crystal	a. Spearhead
		b. Spearhead with combination of bullets
		c. Spearhead with crossed plates
		d. Multiple spearhead
	9. Seagull-type crystal	a. Seagull with attached plates inside wings
		b. Seagull with attached plates outside wings
		c. Seagull with attached plates on both sides of wings
		d. Seagull with attached serrate crystals inside wings
		e. Seagull with attached serrate crystals outside wings
A Aggregation of snow crystals group	1. Aggregation of column-type crystals	a. Aggregation of combinations of columns and bullets
	2. Aggregation of plane-type crystals	a. Aggregation of combinations of plates and dendrites
	3. Aggregation of column- and plane-type crystals	a. Aggregation of combinations of columns, planes and crossed plates
R Rimed snow crystal group	1. Rimed crystal	a. Rimed column
		b. Rimed plate
		c. Rimed dendrite
		d. Rimed spatial branches
	2. Densely rimed crystal	a. Densely rimed column
		b. Densely rimed plate
		c. Densely rimed dendrite
		d. Densely rimed spatial branches
	3. Graupel-like snow	a. Graupel-like snow of hexagonal shape
		b. Graupel-like snow of lump shape
		c. Graupel-like snow with non-rimed branches
	4. Graupel	a. Hexagonal graupel
		b. Lump graupel
		c. Cone graupel
G Germ of ice crystal group	1. Column-type ice crystal	a. Column ice crystal
		b. Tabular column ice crystal
	2. Plane-type ice crystal	a. Plate ice crystal
		b. Non-hexagonal ice crystal
		c. Dendrite ice crystal
	3. Polyhedral-type ice crystal	a. 14-face polyhedral ice crystal
		b. 20-face polyhedral ice crystal
	4. Polycrystalline-type ice crystal	a. Assemblage of hexagonal ice crystals
		b. Complex crossed plates ice crystal
		c. Irregular ice crystal
I Irregular snow particle group	1. Ice particle	a. Ice particle
	2. Rimed snow particle	a. Rimed snow particle
	3. Broken snow particle	a. Broken snow particle
H Other solid precipitation group	1. Frozen hydrometeor particle	a. Frozen cloud particle
		b. Chained frozen cloud particles
		c. Frozen small rain drop
	2. Sleet particle	a. Sleet particle
	3. Ice pellet	a. Ice pellet
	4. Hailstone	a. Hailstone

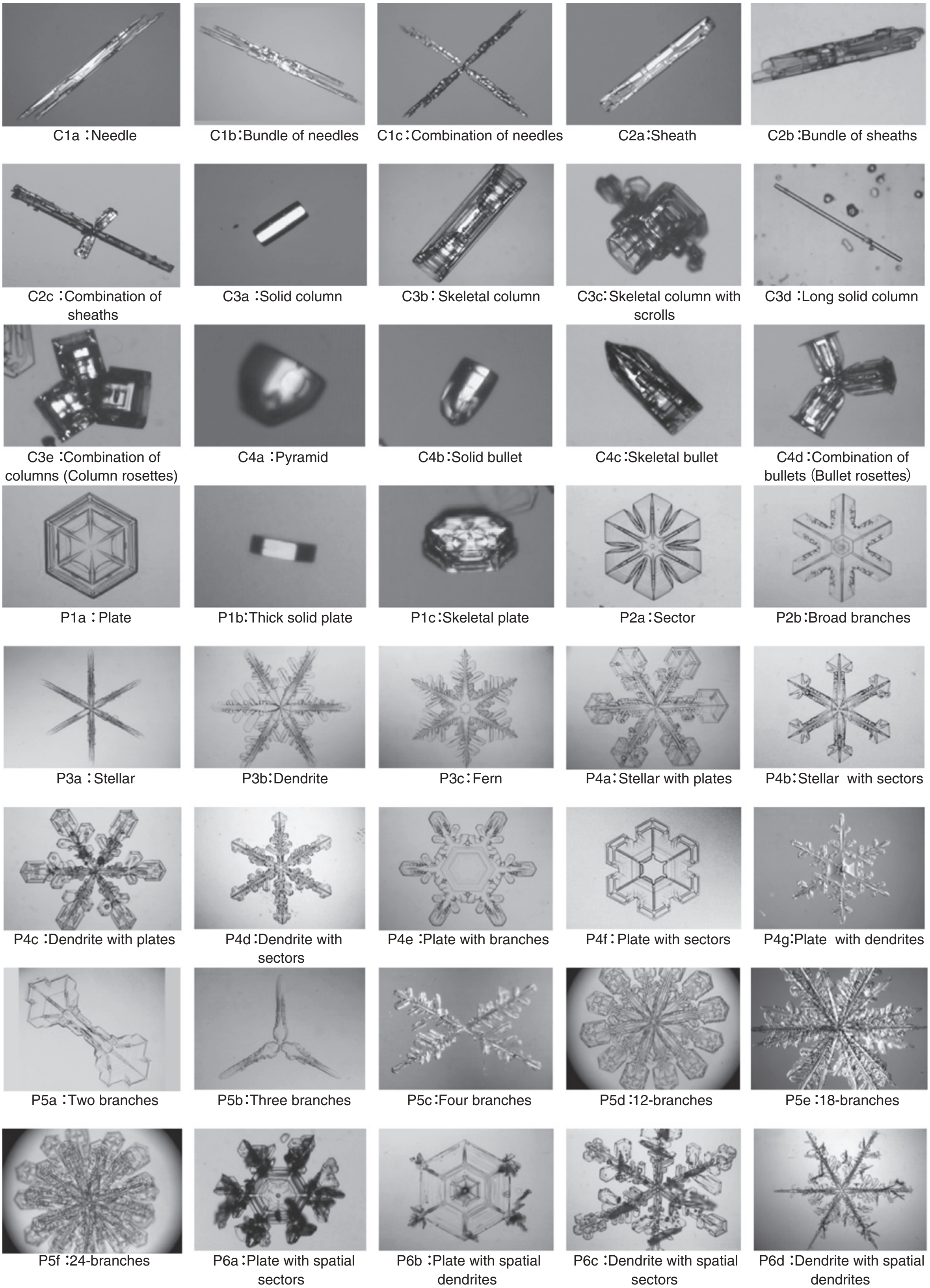

Fig. 1. 1-1. Microscopic photographs of snow crystals from C1a to P6d. 1-2. Microscopic photographs of snow crystals from P7a to CP8d. 1-3. Microscopic photographs of snow crystals, ice crystals, and other solid precipitation from CP9a to H3a. H4a is a photograph of hailstones.

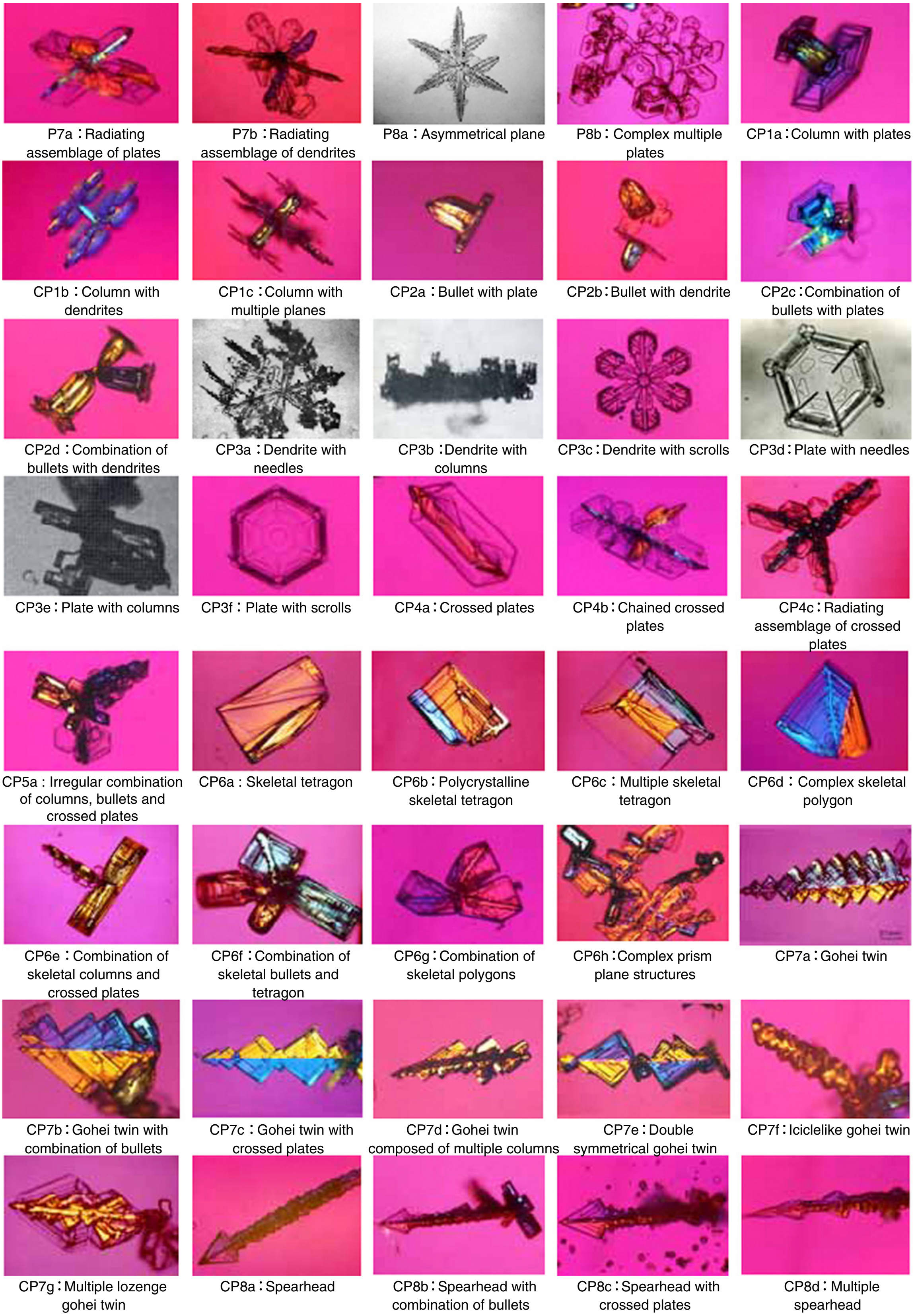

Fig. 1 (*continued*).

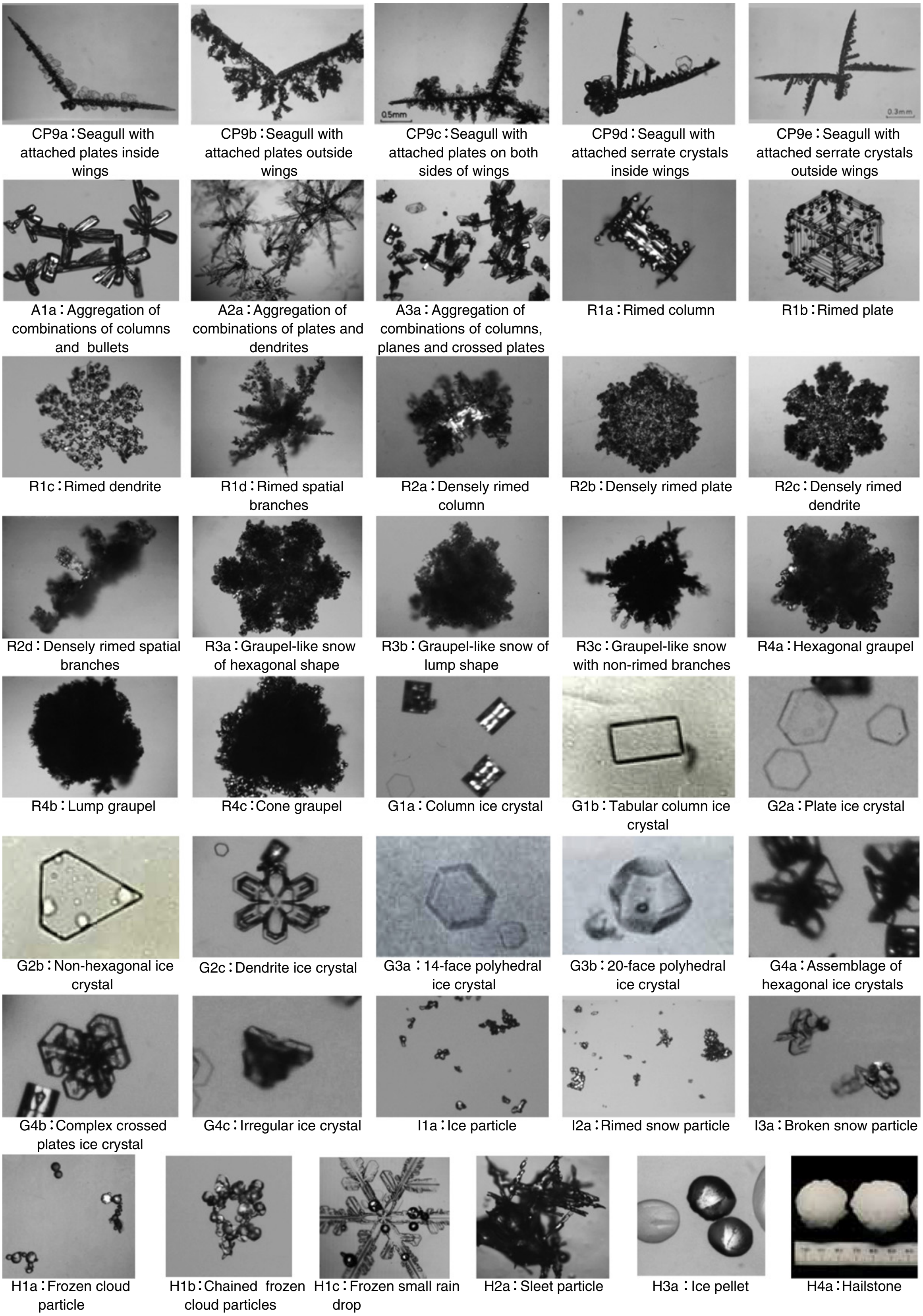

Fig. 1 (*continued*).

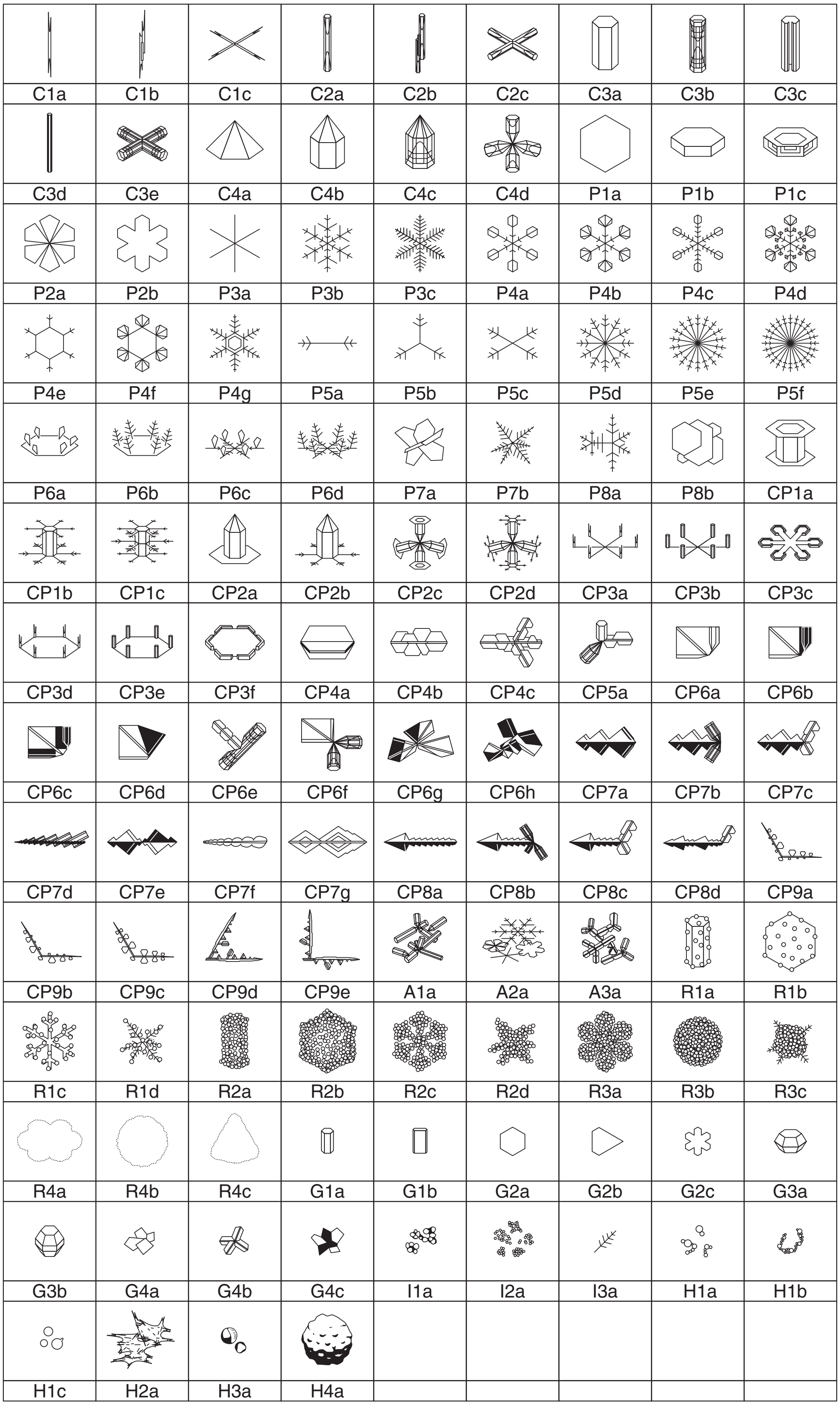

Fig. 2. Schematic drawings of 121 types of snow crystals, ice crystals, and other solid precipitation.

and crystals in C1c consist of needles that are radially oriented. The average length of crystals in C1 is 2 mm.

2.1.2. Sheath-type crystal (C2)

'Sheath-type' refers to snow crystals that are extremely thin hollow columns. This crystal type is subdivided into three categories: sheath (C2a), sheath bundle (C2b), and combination of sheath (C2c). Crystals in C2a have a simple form, crystals in C2b consist of two or more sheath crystals, and crystals in C2c consist of sheaths that are radially oriented. Crystals in C2 are on average slightly longer than crystals in C1.

2.1.3. Column-type crystal (C3)

'Column-type' refers to snow crystals that are columnar in shape. This crystal type is subdivided into five categories: solid column (C3a), skeletal column (C3b), skeletal column with scrolls (C3c), long solid column (C3d), and combination of columns (C3e). The term 'column rosettes' is also used to describe C3e crystals. Crystals in C3a are shaped like a simple solid column, crystals in C3b are simple hollow columns, crystals in C3c have scrolls at the ends of their columns, and crystals in C3d are long solid column. The ratio of length to radius for C3d is over 20, and generally ranges between 40 and 50. The C3d snow crystal was discovered by Shimizu (1963) during observations at Byrd Station, Antarctica in 1961. He originally named this crystal type 'Long prism. Kobayashi (1965) artificially produced the C3d crystals at temperature range between −45 and −50° C at low supersaturation. Crystals in C3e consist of columns that are radially oriented. The average lengths of crystals in C3 are 0.2–0.3 mm for C3a, 0.5 mm for C3b and C3c, 1 mm for C3e, and >1 mm for C3d.

2.1.4. Bullet-type crystal (C4)

'Bullet-type' refers to snow crystals that are bullet shaped. This crystal type is subdivided into four categories: pyramid (C4a), solid bullet (C4b), skeletal bullet (C4c), and combination of bullets (C4d). The term 'bullet rosettes' is also used to describe C4d crystals. Crystals in C4a, C4b, and C4c have simple forms similar to a pyramid, solid bullet, and skeletal bullet, respectively. Crystals in C4d consist of skeletal bullets that are radially oriented. This type of snow crystal is often observed in polar regions (Walden et al., 2003; Kameda et al., 2007). The average lengths of crystals in C4 are 0.1 mm for C4a, 0.5 mm for C4b and C4c, and 1 mm for C4d.

2.2. Plane crystal group (P)

'Plane crystal group' refers to snow crystals that are planar shaped. This crystal group is divided into eight types: P1–P8.

2.2.1. Plate-type crystal (P1)

'Plate-type' refers to snow crystals that are shaped similar to a hexagonal plate. This crystal type is subdivided into three categories: plate (P1a), thick solid plate (P1b), and skeletal plate (P1c). Crystals in P1a have a simple form similar to a hexagonal plate. Crystals in P1b are thicker than those in P1a. Crystals in P1c consist of a hexagonal plate with skeletal surfaces. The average diameter of crystals in P1 is between 0.1 and 1 mm.

2.2.2. Sector-type crystal (P2)

'Sector-type' refers to snow crystals shaped similarly to a sector plate. This crystal type is subdivided into two categories: sector (P2a) and broad branches (P2b). Crystals in P2a have a simple form similar to a sector plate. Crystals in P2b have six wide branches. The average diameter of crystals in P2 is between 0.5 and 2 mm.

2.2.3. Dendrite-type crystal (P3)

'Dendrite-type' refers to snow crystals similar in shape to dendrites. This crystal type is the most typical shape of crystals found in the mid-latitudes. It is subdivided into three categories: stellar (P3a), dendrite (P3b), and fern (P3c). Crystals in P3a are shaped like simple stars. Crystals in P3b have sub-branches extending from each branch, and are frequently shown in common literature. Crystals in P3c have more complex sub-branches than those in P3b. The typical average diameter of P3 crystals is between 1 and 3 mm, and is sometimes equal to or greater than 10 mm.

2.2.4. Composite plane-type crystal (P4)

'Composite plane-type' refers to snow crystals similar in shape to dendrites, but composed of two or more types of dendrite-type crystals. This crystal type is subdivided into seven categories: stellar with plates (P4a), stellar with sectors (P4b), dendrite with plates (P4c), dendrite with sectors (P4d), plate with branches (P4e), plate with sectors (P4f), and plate with dendrites (P4g). Crystals in P4a and P4b consist of stellar branches with ends that form plates and sectors, and crystals in P4c and P4d consist of dendritic branches with ends that form plates and sectors. Crystals in P4e, P4f, and P4g consist of plates that have branches, sectors, and dendrites growing from each plate corner. The typical average diameter of P4 crystals is between 1 and 3 mm, and is sometimes equal to or greater than 10 mm.

2.2.5. Separated and multiple dendrite-type crystals (P5)

'Separated and multiple dendrite-type' refers to snow crystals similar to dendrites, but separated or multiplied. This crystal type is subdivided into six categories; two branches (P5a), three branches (P5b), four branches (P5c), 12-branches (P5d), 18-branches (P5e), and 24-branches (P5f). The crystals in P5a, P5b, and P5c are separated from dendrites, and the crystals in P5d, P5e, and P5f are multiples of dendrites. The average diameter of crystals in P5 is between 1 and 3 mm. Subgroups P5e and P5f are new categories that were not included in the classification by Magono and Lee (1966).

2.2.6. Spatial assemblage of plane-type crystal (P6)

'Spatial assemblage of plane-type' refers to snow crystals composed of a plate with spatially attached dendrites. This crystal type is subdivided into four categories: plate with spatial sectors (P6a), plate with spatial dendrites (P6b), dendrite with spatial sectors (P6c), and dendrite with spatial dendrites (P6d). Crystals in P6a are composed of a hexagonal plate with spatially attached sectors. Crystals in P6b are composed of a hexagonal plate with spatially attached dendrites. Crystals in P6c are composed of a dendrite with spatially attached sectors. Crystals in P6d are composed of a dendrite with spatially attached dendrites. The average diameter of crystals in P6 is between 1 and 3 mm.

2.2.7. Radiating assemblage of plane-type crystal (P7)

'Radiating assemblage of plane-type' refers to a snow crystal composed of a plate with radially attached plates or dendrites. This crystal type is subdivided into two categories: radiating assemblage of plates (P7a) and radiating assemblage of dendrites (P7b). The average diameter of crystals in P7 is between 1 and 3 mm.

2.2.8. Asymmetrical plane-type crystal (P8)

'Asymmetrical plane-type' refers to a snow crystal structured like an asymmetrical plane. This crystal type is subdivided into two categories: asymmetrical plane (P8a) and complex multiple plates (P8b). Crystals in P8a are composed of a plate-type crystal that has asymmetrically oriented branches. Crystals in P8b were not included in the classification by Magono and Lee (1966). Crystals in P8b consist of a central plate and several or sometimes several tenths of plates that grow from each corner of the central plate. The average diameter of crystals in P8 ranges is between 1 and 5 mm.

2.3. Combination of column and plane crystals group (CP)

'Combination of column and plane crystals group' refers to snow crystals composed of columns and planes. This group is subdivided into nine types: CP1–CP9.

2.3.1. Column with plane-type crystals (or capped column) (CP1)

'Column with plane-type' refers to snow crystals composed of a column with a plane at both ends. This crystal type is subdivided into three categories: column with plates (CP1a), column with dendrites (CP1b), and column with multiple planes (CP1c). Crystals in CP1a are composed of column-type crystals with plates at both ends, crystals in CP1b are composed of column-type crystals with dendrites at both ends, and crystals in CP1c are composed of column-type crystals with multiple planes. The average length of crystals in CP1 is approximately 1 mm.

2.3.2. Combination of bullets with plane-type crystal (CP2)

'Combination of bullets with plane-type' refers to snow crystals composed of bullets with planes at each end. This type of crystal is subdivided into four categories: bullet with plate (CP2a), bullet with dendrite (CP2b), combination of bullets with plates (CP2c), and combination of bullets with dendrites (CP2d). Crystals in CP2a are composed of bullet type crystal with plates at each end, crystals in CP1b are composed of bullet type crystal with dendrites at the end, crystals in CP2c are composed of combination of bullets with plates at the end, and crystals in CP2d are composed of a combination of bullets with dendrites at the end. The average length of crystals in CP2 is between 0.5 and 1 mm.

2.3.3. Plane crystals with column-type crystal (CP3)

'Plane crystals with column-type' refers to snow crystals composed of a plane crystal with columns. This crystal type is subdivided into six categories: dendrite with needles (CP3a), dendrite with columns (CP3b, side view), dendrite with scrolls (CP3c), plate with needles (CP3d), plate with columns (CP3e), and plate with scrolls (CP3f). Crystals in CP3a are composed of a dendrite with needles, crystals in CP3b are composed of a plate with columns, crystals in CP3c are composed of a dendrite with a scroll at each tip, crystals in CP3d are composed of a plate type crystal with needles, crystals in CP3e are composed of a hexagonal plate with needles, and crystals in CP3f are composed of a plate with a scroll at each edge. This type of crystal is very rare, and the average length or diameter of crystals in CP3 is approximately 0.5 mm.

2.3.4. Crossed plate-type crystal (CP4)

'Crossed plate-type' refers to snow crystals composed of several hexagonal plates. This crystal type is subdivided into three categories: crossed plates (CP4a), chained crossed plates (CP4b), and radiating assemblage of crossed plates (CP4c). Crystals in CP4a consist of a simple form of crossed plates composed of several hexagonal plates, crystals in CP4b are composed of several hexagonal plates continuously arranged in one direction, and crystals in CP4c are composed of several CP4b crystals arranged radially. "Columnar crystals with extended side planes" in Magono and Lee (1966) is renamed to crossed plate-type (CP4) in this study. The average length of crystals in CP4 is approximately 0.5 mm.

2.3.5. Irregular combination of column- and plane-type crystals (CP5)

'Irregular combination of column- and plane-type' refers to snow crystals that are a combination of columns, bullets, and crossed plates (CP5a). The average length of CP5 crystals is approximately 2 mm.

2.3.6. Skeletal-type crystal (CP6)

'Skeletal-type' refers to snow crystals composed of a tetragon. This crystal type is subdivided into eight categories: skeletal tetragon (CP6a), polycrystalline skeletal tetragon (CP6b), multiple skeletal tetragon (CP6c), complex skeletal polygon (CP6d), combination of skeletal columns and crossed plates (CP6e), combination of skeletal bullets and tetragon (CP6f), combination of skeletal polygons (CP6g), and complex prism plane structures (CP6h). Crystals in CP6 have been observed at air temperatures below −25 °C. Crystals in CP6a are mono-crystals of a skeletal tetragon composed of a prism plane $(10\bar{1}0)$. Crystals in CP6b consist of a polycrystalline skeletal tetragon similar to CP6a crystals in external shape and structure. A polarizing microscope reveals that these crystals are polycrystalline crystals with two colors. Crystals in CP6c consist of a multiple skeletal tetragon, similar to CP6a and CP6b. A polarizing microscope reveals that CP6c crystals are poly-crystals. CP6c crystals are characterized by their growth stage; they grow as a single crystal and the c-axis direction changes to 90°. CP6d crystals consist of a complex skeletal polygon constituted from two crystals with skeletal structures. Crystals in CP6d have a pentagonal shape, crystals in CP6e consist of a combination of skeletal columns and crossed plates, crystals in CP6f consist of a combination of skeletal bullets and tetragons, crystals in CP6g consist of a combination of skeletal polygons that are radiantly oriented, similar to crystals in CP6d, and crystals in CP6h have complex prism plane structures. The average length of crystals in CP6 is between 0.2 and 5 mm.

2.3.7. Gohei twin-type crystal (CP7)

'Gohei twin-type' refers to snow crystals that contain symmetrical growths of columnar or bullet types crystals in one direction. This crystal type is subdivided into seven categories: Gohei twin (CP7a), Gohei twin with combination of bullets (CP7b), Gohei twin with crossed plates (CP7c), Gohei twin composed of multiple columns (CP7d), double symmetrical Gohei twin (CP7e), icicle-like Gohei twin (CP7f), and multiple lozenge Gohei twin (CP7g). 'Gohei' is a Japanese word that refers to the pendant paper strips that hang from a sacred rope at a Shinto shrine (Kikuchi and Sato, 1984). The CP7 crystal type was discovered by Kikuchi (1969, 1970) at Syowa Station, Antarctica between 1968 and 1969. CP7 crystals have also been observed in Arctic regions (Norway, Sweden, Canada, and Greenland) (Magono, 1978; Kikuchi, 1987) and at the South Pole (Kikuchi and Hogan, 1976). CP7 crystals have been observed only when surface temperatures were below −25 °C. The tip angles of the Gohei twin of CP7a, CP7b, and CP7c crystals are approximately 80°. CP7a crystals have a bilateral plate symmetry, CP7b crystals are a combination of CP7a crystals and bullets, CP7c crystals are a combination of CP7a crystals, bullets, and crossed plates, CP7d crystals consist of a Gohei twin composed of multiple columns or bullets in the same direction as the c-axis, and CP7e crystals are shaped like a symmetrical Gohei twin. CP7f crystals are shaped like an icicle-like Gohei twin, and grow columns, bullets, and dumpling shaped crystals, making the crystal appear like a continuously connecting icicle. CP7g crystals consist of a multiple lozenge Gohei twin characterized by a lozenge growth, and the tip of the crystal has various forms depending on its growth stage. Some CP7 crystals have been artificially formed in cloud chambers at temperatures between −20 and −35 °C (Kikuchi and Sato, 1984; Sato and Kikuchi, 1985; Asano et al., 1989; Nakata et al., 1992). Similar shapes of snow crystals using a pyrotechnic method with silver iodide are also reported (Schaefer and Cheng, 1968). The average length of CP7 crystals is between 0.2 and 5 mm.

2.3.8. Spearhead-type crystal (CP8)

The external shape of CP8 crystals is similar to the CP7 crystals described above. However, the tip angle of CP8 crystals is 60°, as opposed to 80° for CP7 crystals. Furthermore, the prism planes of columns and bullets are not as defined as CP8 crystals as they are in CP7 crystals. The characteristic feature of CP8 crystals is their continuous teeth, which appear like a jigsaw between crystals of columns and bullets growing at both sides. CP8 crystals have been observed at temperatures below −25 °C. CP8a crystals are the simplest form of the CP8 series. CP8b crystals are a combination of CP8a crystals and bullets. CP8c crystals are a combination of CP8a crystals, bullets, and crossed plates; the bullets and crossed plates grow toward the side opposite the direction of the spearhead. CP8d crystals are characterized by the continual growth of their tip, usually repeated two or three times to the growth direction of the spearhead. The average length of CP8 crystals is between 2 and 5 mm.

2.3.9. Seagull-type crystal (CP9)

'Seagull-type' refers to a snow crystal composed of two wings; it resembles a flying seagull with spread wings. At low temperatures below −25 °C, crystals such as Gohei twin and spearhead crystals appear at a frequency of 1–5% (Kajikawa et al., 1980), but seagull-type crystals tend to fall continuously during a short time interval. This crystal type is subdivided into five categories: seagull with attached plates inside wings (CP9a), seagull with attached plates outside wings (CP9b), seagull with attached plates on both sides of wings (CP9c), seagull with attached serrate crystals inside wings (CP9d), and seagull with attached serrate crystals outside wings (CP9e). Plate-type crystals grow inside the wings of CP9a crystals, and outside the wings of CP9b crystals. Plates grow inside and outside the wings of CP9c crystals. Serrate-type crystals grow inside CP9d crystal wings, and outside CP9e crystal wings. Seagull crystals with attached serrate crystals on the inside and outside, such as for CP9c crystals, have never been observed. The length of both ends of the crystal wing is between 2 and 8 mm.

Because crystals in the subgroups CP6 through CP9 have generally been observed in Arctic and Antarctic regions, they were not included in previous systems such as the general classification by Nakaya (1954) or the meteorological classification by Magono and Lee (1966).

2.4. Aggregation of snow crystals group (A)

'Aggregation of snow crystals group' refers to snow crystals that coalesce to form an aggregate of snow crystals. This group is subdivided into three types: A1, A2, and A3.

2.4.1. Aggregation of column-type crystals (A1)

An A1 crystal aggregate refers to a coalescence of snow crystals from groups C1 through C4 (column-type crystals). The average diameter of A1 crystals is several times that of a single column-type crystal.

2.4.2. Aggregation of plane-type crystals (A2)

An A2 crystal aggregate refers to the coalescence of crystals from categories P1 through P8 (plane-type crystals). The average diameter of A2 crystals is several times that of a single plane-type crystal.

2.4.3. Aggregation of column- and plane-type crystals (A3)

An A3 crystal aggregate refers to a coalescence of crystals from CP1 to CP9 (column- and plane-type crystals). The average diameter of A3 crystals is several times that of a single column- or plane-type crystal.

2.5. Rimed snow crystal group (R)

'Rimed snow crystal group' refers to snow crystals that are rimed. This group is subdivided into four types, R1 through R4, based on the level of riming.

2.5.1. Rimed crystal (R1)

'Rimed crystal' refers to a snow crystal that is rimed, with an easily identifiable original crystal. This crystal type is subdivided into four categories: rimed column (R1a), rimed plate (R1b), rimed dendrite (R1c), and rimed spatial branches (R1d). R1a crystals are rimed crystals of types C1 through C4, R1b crystals are rimed crystals of type P1, R1c crystals are rimed crystals of types P2 through P5, and R1d crystals are rimed crystals of types P6 and P7. The average length or diameter of an R1 crystal is nearly the same as that of original snow crystals that are not rimed.

2.5.2. Densely rimed crystal (R2)

'Densely rimed crystal' refers to a snow crystal that is densely rimed, with an identifiable original crystal. This crystal type is subdivided into four categories: densely rimed column (R2a), densely rimed plate (R2b), densely rimed dendrite (R2c), and densely rimed spatial branches (R2d). These categories are the same as those used for R1 crystals, but each type has a different degree of riming. The average length or diameter of R2 crystals is slightly larger than that of the original snow crystals because of the dense riming.

2.5.3. Graupel-like snow (R3)

'Graupel' is a German word that is frequently used to refer to soft hail. 'Graupel-like snow' refers to a snow crystal that is more densely rimed than an R2 crystal, but is not a graupel (R4). This crystal type is subdivided into three categories: graupel-like snow with a hexagonal shape (R3a), graupel-like snow with a lump shape (R3b), and graupel-like snow with non-rimed branches (R3c). The original hexagonal shape of R3a crystals can be identified with careful examination. R3b crystals are shaped like a lump of graupel-like snow, and R3c crystals are shaped like a lump of graupel-like snow or cloud droplets that grow non-rimed branches (Fujiyoshi and Wakahama, 1985) or only the ends of branches can be seen from the droplets. The average diameter of R3 crystals is greater than the diameters of the original snow crystals because of the dense riming.

2.5.4. Graupel (R4)

'Graupel' refers to a rimed particle in which original snow crystals are no longer identifiable. This crystal type is subdivided into three categories based on their shape: hexagonal graupel (R4a), lump graupel (R4b), and cone graupel (R4c). The average diameter of R4 crystals is between 1 and 3 mm.

2.6. Germ of ice crystal group (G)

'Germ of ice crystal group' refers to minute ice crystals (less than 0.1 mm) that are often observed at middle latitudes and polar regions. Because ice crystals are also located in cirrus cloud and play an important role in the energy balance of the earth-atmosphere system, extensive studies on microphysical and optical properties of ice crystals have been carried out (ex. Liou, 1986; Labonnote et al., 2000; Baran, 2004).

This crystal group is subdivided into four types: G1–G4. Ice crystals are classified into this group based on extensive observations of snow and ice crystals in polar regions since 1968 (e.g., Kikuchi, 1970, 1987, 1989; Higuchi et al., 1981; Kikuchi and Uyeda, 1992; Kikuchi and Asuma, 1999).

2.6.1. Column-type ice crystal (G1)

'Column-type ice crystal' refers to a minute snow crystal that grows in clouds from minute frozen cloud droplets. It is the typical particle that creates 'diamond dust' conditions in the middle latitudes, and is also called an 'ice prism.' This crystal type is subdivided into two categories: column ice crystal (G1a) and tabular ice crystal (G1b). G1a crystals are very common in the middle latitudes and also in polar regions. The shape of these crystals changes as they grow. In the early stages, as frozen supercooled cloud droplets, the crystals are shaped as a solid column. As they grow, they become sheath-shaped, and as a result their columns are grooved. G1b crystals have two large opposite prism planes and four extremely thin prism planes. G1b crystals are quadrilateral in shape, and were first identified by Higuchi (1968). The average length of G1 crystals is about 50 μm.

2.6.2. Plane-type ice crystal (G2)

'Plane-type ice crystal' refers to a minute plate-type of ice crystal. It is the second most common crystal type in G2. This crystal type is subdivided into three categories: plate ice crystal (G2a), non-hexagonal ice crystal (G2b), and dendrite ice crystal (G2c). G2a crystals have no surface patterns in their early stages of the formation; their skeletal structure appears at their surfaces when the crystals grow. Because G2b crystals are shaped like triangles, quadrilaterals, and pentagons, non-hexagonal features appear. G2b crystals do not have many surface patterns. G2c is a minute dendrite ice crystal. The average diameter of G2 crystals is between several tenths of a micrometer and 100 μm.

2.6.3. Polyhedral-type ice crystal (G3)

'Polyhedral-type ice' refers to a minute polyhedral-type of ice crystal. This type of ice crystal is very rare in nature; photomicrographs of these crystals (see Fig. 2) were taken in Fairbanks, Alaska (Ohtake, 1970). This crystal type is subdivided into two categories: 14-face polyhedral ice crystal (G3a) and 20-face polyhedral ice crystal (G3b). G3a crystals are formed from 2 basal faces (0001) to 12 pyramidal faces $(10\overline{1}1)$, and G3b crystals are formed from 2 basal faces, 12 pyramidal faces, and 6 prism faces $(10\overline{1}0)$. The average diameter of G3 crystals is between several tenths of a micrometer and 100 μm. G3 crystals are a new category that Magono and Lee (1966) did not include in their classification system.

2.6.4. Polycrystalline-type ice crystal (G4)

'Polycrystalline-type ice' refers to a minute polycrystalline-type of ice crystal. This type of ice crystal is also very rare in nature. This crystal type is subdivided into three categories: assemblage of hexagonal ice crystals (G4a), complex crossed plates ice crystal (G4b), and irregular ice crystal (G4c). The average diameter of G4 crystals is between several tenths of a micrometer and 100 μm.

2.7. Irregular snow particle group (I)

'Irregular snow particle group' refers to particles raised from a snow cover by strong winds. The group is subdivided into three types: I1–I3.

2.7.1. Ice particle (I1)

Most of these particles are raised from a snow cover by strong winds. The average diameter of I1 particles is between several tenths of a micrometer and 100 μm.

2.7.2. Rimed snow particle (I2)

Most of these particles are R1 type snow crystals that have been raised from a snow cover by strong winds. The average diameter of I2 particles is between about 30 μm and 100 μm.

2.7.3. Broken snow particle (I3)

Most of these particles are snow crystals that have been raised from a snow cover by strong winds. Only parts of the original crystal shapes are preserved. The average diameter of I3 particles is between about 30 μm and 100 μm.

2.8. Other solid precipitation group (H)

'Other solid precipitation group' refers to solid precipitation particles that are not snow crystals or ice crystals. Previous snow particle classifications (Nakaya, 1954; Magono and Lee, 1966) did not include other types of solid precipitation, but a practical classification of solid precipitation (Schaefer, 1951; Mason, 1957, 1971) categorized other particles into ten codes, including ice pellets (or sleet in America) and hail. Therefore, we have added these solid precipitation classifications to our global classification. The capital letter "H" comes from the first letter of "hydrometeor". This group is subdivided into four types: H1–H4.

2.8.1. Frozen hydrometeor particle (H1)

'Frozen hydrometeor particle' refers to a frozen particle. These particles are often observed in polar regions. Their diameter is larger than a cloud droplet but smaller than a raindrop. This particle type is subdivided into three categories: frozen cloud particles (H1a), chained frozen cloud particles (H1b), and frozen small rain drop (H1c). H1a particles are often observed at temperatures below −25 °C (Kikuchi, 1969, 1970). H1b particles are chained frozen cloud particles consisting of frozen cloud particles chained together with several to several tens of particles. H1c particles are frozen small raindrops with a diameter of 100–150 μm. They can be observed independently, but have often been observed with other types of snow crystals. Spicules or spikes are sometimes observed protruding from the surfaces of H1c particles. The average diameter of H1 particles is between 10 and 200 μm.

2.8.2. Sleet particle (H2)

'Sleet particle' refers to a particle that is a mixture of rain and snow. Although these particles can be classified by their degree of melting, it is difficult to identify the degree of melting during field observations (Fujiyoshi, 1986). Thus, these particles are not classified in more detail. The average diameter of H2a particles is between 1 and 10 mm.

2.8.3. Ice pellet (H3)

'Ice pellet' refers to a transparent or translucent ice particle. The average diameter of H3 particles is between 0.2 and 5 mm.

2.8.4. Hailstone (H4)

'Hailstone' refers to transparent or translucent ice particles. The average diameter of H4 particles is between 5 and 50 mm, but sometimes larger hail stones are observed with diameters larger than 50 mm. Hailstone particles can be classified by size (e.g., very small, small, medium, large, very large) or by shape (e.g., spherical, protrusions, and shape changes). However, our classification system does not categorize these particles by size or shape.

3. Conclusions

Three types of snow crystal classification have been published to date: general classifications of snow crystals (Nakaya and Sekido, 1938; Nakaya, 1954), practical classifications of solid particles (Schaefer, 1951; Mason, 1957, 1971; Fierz et al., 2009), and a meteorological classification of snow crystals (Magono and Lee, 1966). The classification by Magono and Lee (1966) has been widely used to describe snow crystal shapes in snow and ice studies. However, their classification system was based mainly on observations in Japan and did not include some types of snow crystals that have been discovered in the Arctic and Antarctic since 1968. Additionally, their system did not include commonly observed solid precipitation such as sleet, ice pellets, and hail.

This paper presented a new classification system for snow crystals, ice crystals, and other solid precipitation, based on the work done by Japanese scientists from middle latitudes to polar regions since 1968. It is an extension of our original article, which we published in Japanese (Kikuchi et al., 2012). Because our system is based on global observations, we refer to it as the 'global scale classification' or 'global classification' system. It consists of three levels: general, intermediate, and elementary. The general level has 8 categories, the intermediate level has 39 categories, and the elementary level has 121 categories. This paper presents the characteristics of each type of snow crystal, ice crystal, and solid precipitation particle.

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