SNOW CRYSTAL FORMS AND THEIR RELATIONSHIP TO SNOWSTORMS

Helmut K. Weickmann

Atmospheric Physics and Chemistry Laboratory
Environmental Research Laboratories
National Oceanic and Atmospheric Administration
Boulder, Colorado 80302

Several typical snow crystal forms are discussed and it is shown how they are related to the large scale storm structure. The formation of specific forms, for instance, dendritic stars and spatial crystals are discussed in more detail.

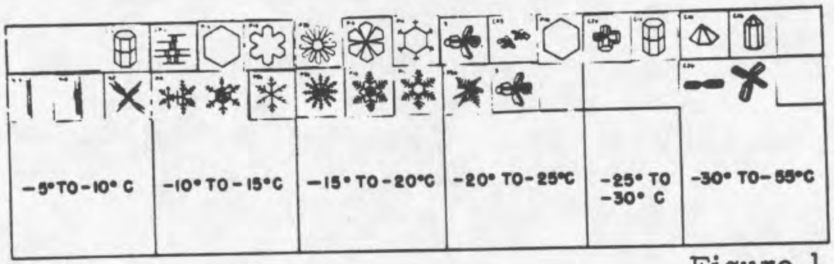
In the past years we have studied precipitation systems that occur during winter in the Great Lakes Basin. We have observed the occurrence of three basic precipitation systems which can be clearly separated due to the particle type that they discharge as well as due to the typical cloud system in which these originate. Fig. 1, which shows the dependence of major crystal forms on temperature in a water-saturated environment, will assist the reader in the following discussion.

The Precipitation Systems

System No. 1: System 1 occurred typically on February 13, 1971. It is a synoptic scale precipitation system whose center moved north-eastward and was located east of the Great Lakes region. Overriding warm air over the cold air on the back side of the large depression caused the formation of a deep altostratus layer which continuously discharged very fine snow crystals. A typical radiosonde cross section is shown on Fig. 2. The overriding warm air is clearly shown from the inversion (temperature increase at 900 mb); in the shallow layer below the inversion clouds may form but no ice crystals as the temperature is not sufficiently low. Lake Erie being frozen did not introduce warm convection. Yet from the homogeneously overcast sky fine snow fell whose crystals have the typical shapes of low temperature origin which are typical of Cirrus and Altostratus. The ice character of the cloud follows from the dewpoint which represents ice saturation for the environmental temperature. The following log entries testify to the Cirrostratus character of the crystals.

Buffalo, New York - 13/14 February 1971:

> 0810 EST. Small flakes of small rimed prism bundles; individual crystal sizes about 0.1 mm diameter, flakes 1 to 2 mm, 20 to 30 crystals per flake. Note from Fig. 2 that the occurrence of a thin sc-layer at the inversion is possible due to the steep gradient and the high humidity. The temperature however is too warm for the formation of crystals therefore only riming of the high level crystals occurs. As the Buffalo region remains on the edge of the large scale depression as it moves north-eastward the crystal shape does not change all day.



SNOW CRYSTAL FORMS

VERSUS

TEMPERATURE OF FORMATION

Figure 1.

Figure 1. Major snow crystal forms and their dependence on temperature when growing at water saturation (lower line of crystals) or below water saturation and above ice saturation (upper line of crystals).

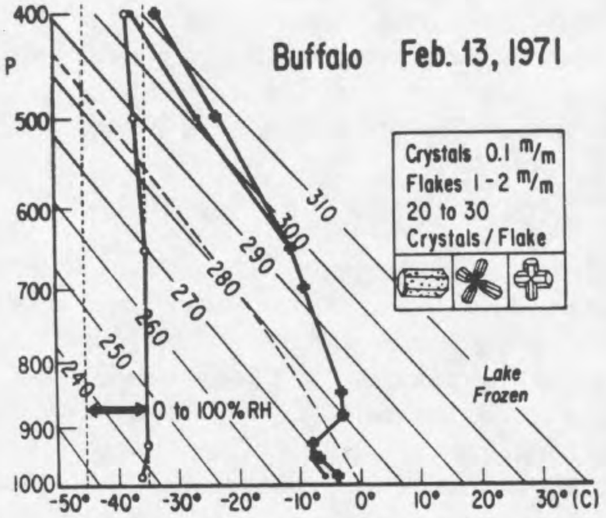


Figure 2.

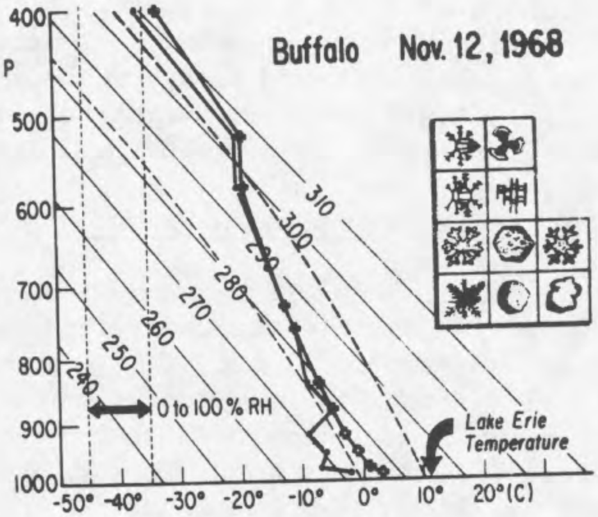


Figure 3.

Figure 2. Atmospheric temperature and humidity profile connected with the precipitation of high level Altostratus crystals. Note that water saturation exists up to about 650 mb air pressure (ordinate) but temperature at this point is below $-10^{O}C$ which is too warm for crystal formation.

Figure 3. Temperature and humidity profile on Nov. 12, 1968, over Buffalo, N. Y., a.m. Prism forms indicate the existence of a deep moist layer reaching above 400 millibar (ordinate). Dotted line from lake temperature crossing temperature profile at about 550 millibar indicate approximate temperature profile of convective clouds forming over the warm lake surface. In these clouds dendrites, spatial aggregates and graupel form in agreement with Fig. 1.

Niagara, New York:

0955 EST. Still typical As, Cs particles now unrimed in small flakes, less than 10 individual crystals consisting of hollow prism bundles with numerous individual crystals, 0.1 to 0.2 mm, some crystals indicate the beginning of the formation of end plates. (The formation of end plates on prisms indicates the existence of layers of higher humidity at the temperature range where normally plates would form.)

On road between Niagara and Buffalo:

1455 EST. Still same type of snowfall, essentially unflaked As particles, prisms, on and off rimed (were rimed at 1430 EST, not now), but have acquired thick plates.

Buffalo, New York:

1600 EST. Still the same fine prism bundles. As the low pressure area moved northward, the lower cold air layer became deeper, while the altostratus layer dried up. Consequently, during the night the particle habit changed, as was observed the next morning.

Buffalo, New York:

0750 EST. Light snowfall from clear sector plates and stars. On car are sector stars with droplet in center, and sector spatial stars, partially very lightly rimed; there are also a few graupel in between.

The total snow accumulation in 24 hours in the Buffalo area was light and not more than 2 to 3 inches; traffic problems were caused by icy roads and drifting snow. In Bergeron's terminology (1947), the snowfall was characterized by the existence of a "releaser cloud" but the absence of a low level "spender-cloud". More toward the center of the storm where the latter was present 12 inches and more accumulated. Note that at this time Lake Ontario was unfrozen, while Lake Erie was frozen.

System No. 2: The synoptic situation of this system is very similar as before, again northerly winds prevail, but we are located closer to the center of the depression, the lakes are warm (Lake Erie temperature is 11°C!) which increases the tendency for the formation of low level convective clouds. The observation was made on November 12, 1968, along the south shore of Lake Erie while driving from Dunkirk back to Buffalo, along a 20 mile stretch near Hamburg, New York.

1505 EST. Heavily rimed prisms with little rimed plates and dendritic branches or appendices, also stars and graupel. Snowfall intensity light to moderate.

1513 EST. Forms are now very difficult to distinguish: all are rimed consisting of dendritic and sector stars, prisms with side plates, and graupel. Moderate snowfall intensity mixed with showers, visibility less than one kilometer.

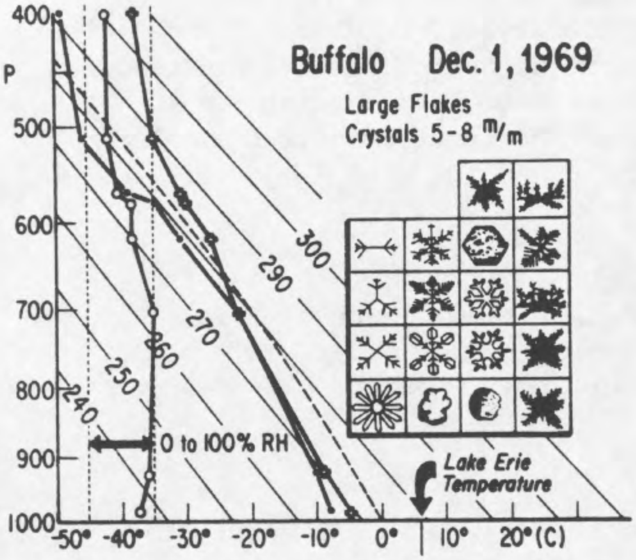


Figure 4.

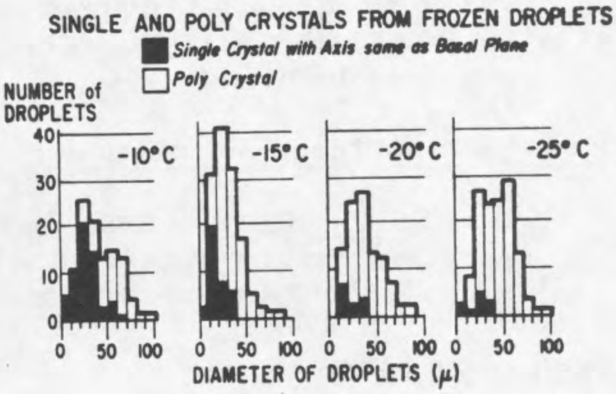
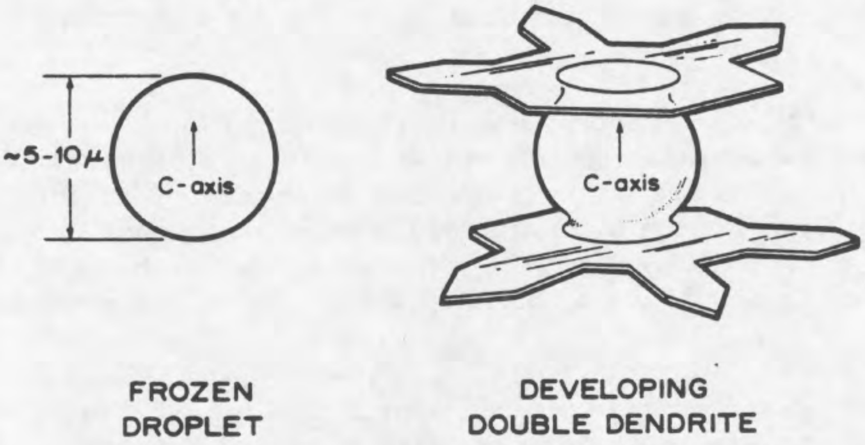


Figure 5.

Figure 4. Temperature and humidity profile on Dec. 1, 1969, over Buffalo, N. Y., Dotted line emerging from surface at 0°C and crossing temperature profile at 650 millibar (ordinate) indicates the approximate temperature profile of the convective lake clouds. Crystal forms are in agreement with this profile.

Figure 5. Development of single and polycrystals from supercooled droplets on crystallization (acc. to Magono and Aburakawa, 1968).



FROZEN DROPLET

DEVELOPING DOUBLE DENDRITE

Figure 6.

Figure 6. Schematic drawing indicating the development of a double dendrite from a droplet frozen to a unit crystal. Note that due to competition for water vapor the upper and the lower crystal may develop alternate branches.

1520 EST. Moderate snowfall, visibility less than 1 km snow consisting of all possible forms, graupel, spatial dendrites, prism bundles with side plates completely and partially rimed.

1535 EST. Now rimed spatial plate crystals, small prisms with end plates, dendrites, but no graupel.

These forms are consistent with the temperature and humidity profile of this day. (Fig. 3, note legend). The warm lake temperature explains the formation of low convective clouds with some graupel formation. The morning radiosonde indicates the existence of a deep moist layer which is ice saturated in its upper parts and has caused the formation of the prismatic crystals, while the evening radiosonde showed drying out from above, but saturation up to -20°C, which accounts for the formation of spatial dendrites. With the presence of a lower "spender cloud" the precipitation efficiency is increased compared with the case of System No. 1, as is qualitatively evident from the low visibility.

System No. 3: This system is a typical moderate lake storm which formed over Lake Ontario on 1 December 1969. The airflow was from the northwest turning north and as the morning as well as the evening radiosonde indicate the lapse rate was nearly moist adiabatic. The lake was still warm (+6°C) causing the formation of a convective Stratocumulus layer whose tops must have reached the 650 mb level. A survey of the precipitation particles was made from the edge of the band to its center along an east-western direction on driving from downtown Buffalo to Batavia about 30 miles east of Buffalo. Every 2 to 3 miles we stopped the car and investigated the snow crystals using a hand-held microscope (Fig. 4.).

1525 EST. 0 miles, downtown Buffalo: Snow flurries consisting of sector stars, dendrites, and spatial sector stars and spatial dendrites, partly flaked, no riming.

1534 EST. 2.9 miles. After driving through a locally heavier shower, the particles are now the same as before and fall in flurries.

1539 EST. 5.7 miles. Same forms but indicating a more intensive precipitation process through heavier riming. Sector stars are rimed essentially along their periphery.

1549 EST. 8.1 miles. Small concentration of snow crystals, sector stars again rimed at periphery.

1555 EST. 12.0 miles. Snow flurries, again consisting of rimed sector stars.

1601 EST. 15.1 miles. Snow flurries, sector stars in all riming stages, mostly double stars.

1611 EST. 19.0 miles. Light to moderate snowfall; sector stars spatial sector branches, all in flakes, little riming.

1617 EST. 21. 1 miles. Moderate snowfall of large dendritic stars (diameter, larger than 5 mm), bi-level sector stars, few spatial sector or dendritic crystals, unrimed or slightly rimed, moderate flaking.

1620 EST. 23. 1 miles. Moderate snowfall, flakes or large dendritic stars (larger than 5 mm), some spatial dendrites, visibility 1 to 2 miles.

1635 EST. 26. 4 miles. City Batavia. Light snowfall, spatial dendrites, rimed.

1655 EST. 31. 2 miles. Moderate to heavy snowfall; large flakes from large dendrites and spatial dendrites, diameter of dendrites 7-8 mm, moderate riming; fall velocity more than 1 m/sec.

1705 EST. 36. 9 miles. Moderate to heavy snowfall; large rimed dendrites and spatial dendrites in flakes, riming considerably, causing new branches to grow from crystal surfaces. Fall velocity more than 1 m/sec.

1716 EST. 41. 5 miles. Moderate to heavy snowfall. Heavily rimed dendrites and spatial dendrites, large individual crystals, higher fall velocities than before.

Return trip:

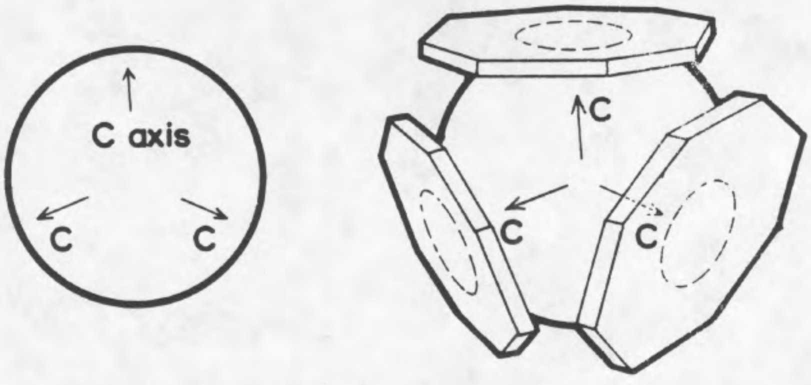
1735 EST. 31. 2 miles from downtown Buffalo. Dendrites and spatial dendrites, all moderately rimed, large crystals.

1745 EST. 26. 4 miles from downtown Buffalo. Heavy snowfall or large flakes (> 1 cm) consisting of large dendrites and spatial dendrites, with branches emerging from rimed droplets, all moderately rimed, sizes of individual crystals 5-7 mm diameter. The flakes are loosely aggregated causing a very moderate fall velocity.

1811 EST. 16. 7 miles from downtown Buffalo. Moderate snowfall, spatial dendrites rimed, individual crystals smaller than before.

1841 EST. 6. 2 miles from downtown Buffalo. Snowfall slowly diminishing. There could be no question that this snowfall originated in a squall from Lake Ontario.

Fig. 4 gives the temperature lapse rate of the Buffalo radiosonde for this day and the schematic drawings of the crystal forms in Nakaya's classification. Note that the humidity decreases above the 700 mb level. The arrow indicates the water temperature, and we have shown an intermediate moist-adiabate line which may have been caused by the heat transfer from the warm water surface. Convective clouds may have formed along this moist adiabate, causing some of the cloud tops to reach beyond the 700 mb level.



DEVELOPING SPATIAL DENDRITE

Figure 7.

Figure 7. Dendrite development from polycrystal. Form of macroscopic crystal is that of a spatial dendrite.

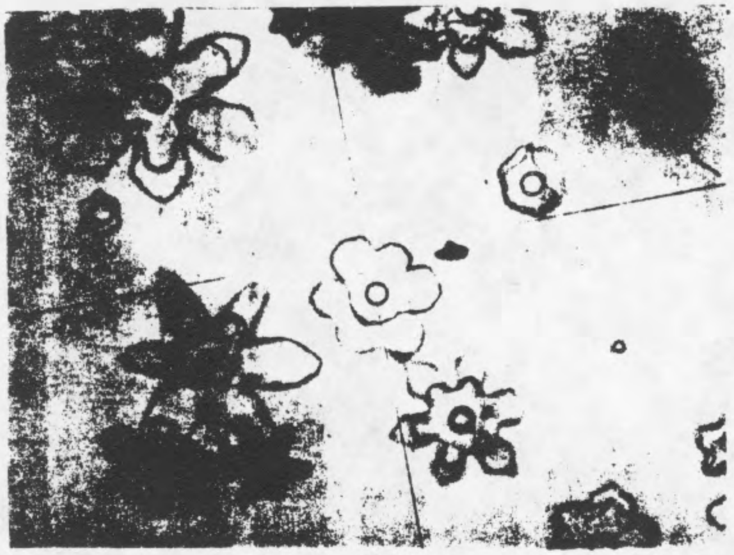


Figure 8a.

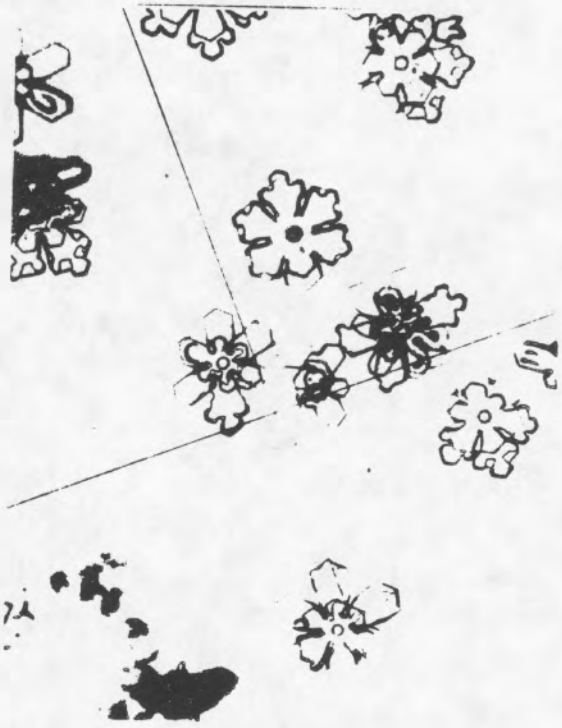


Figure 8b.

Figure 8a. Double dendrites formed in cloud chamber at -15.5°C after seeding with AgI evaporated from hot plate.

Figure 8b. Double dendrites formed in cloud chamber at -17°C after seeding with 2% AgI - isopropylamine mixture.

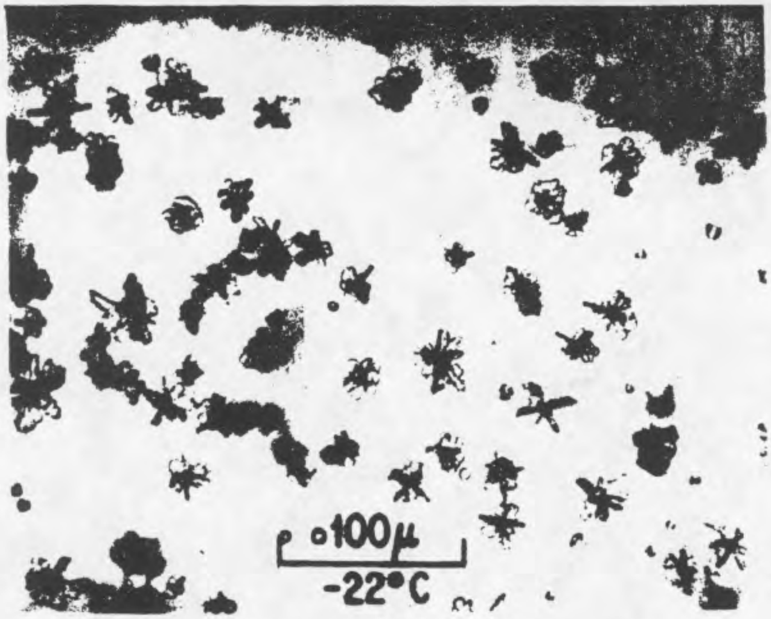


Figure 9.

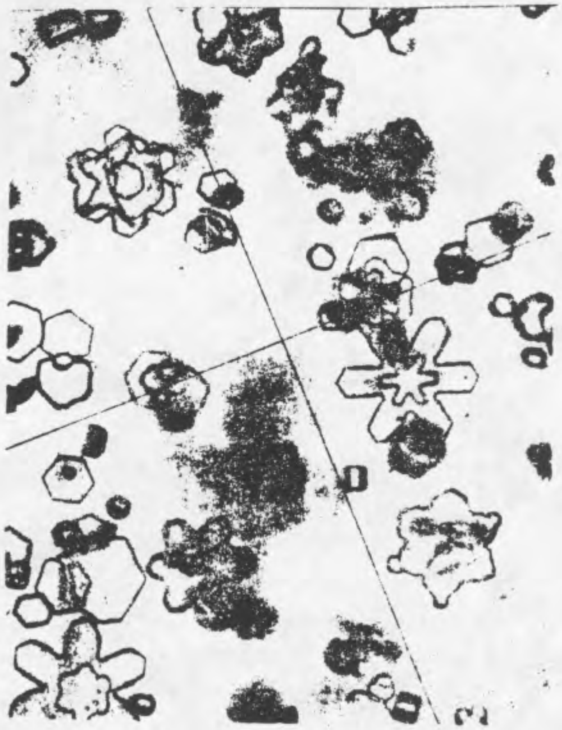


Figure 10.

Figure 9. Spatial dendrites formed in cloud chamber after seeding with AgI.

Figure 10. Crystals formed in cloud chamber at -17.5°C after seeding with dry ice. Crystallization process is due to homogeneous nucleation and not due to droplet freezing.

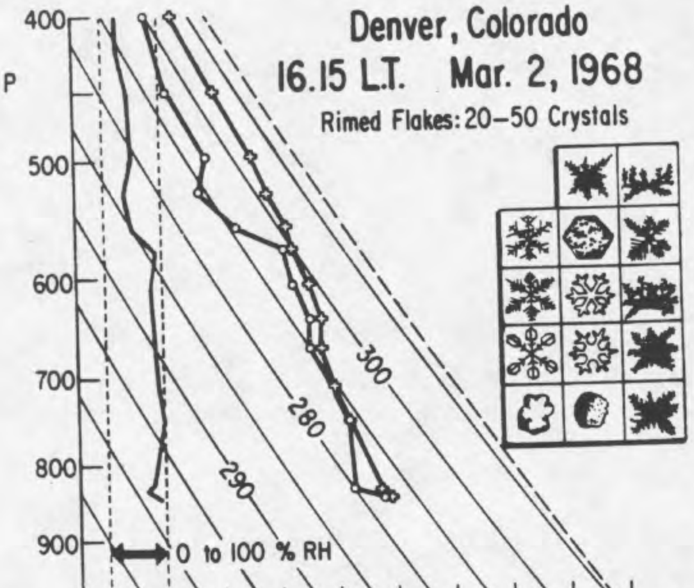


Figure 11.

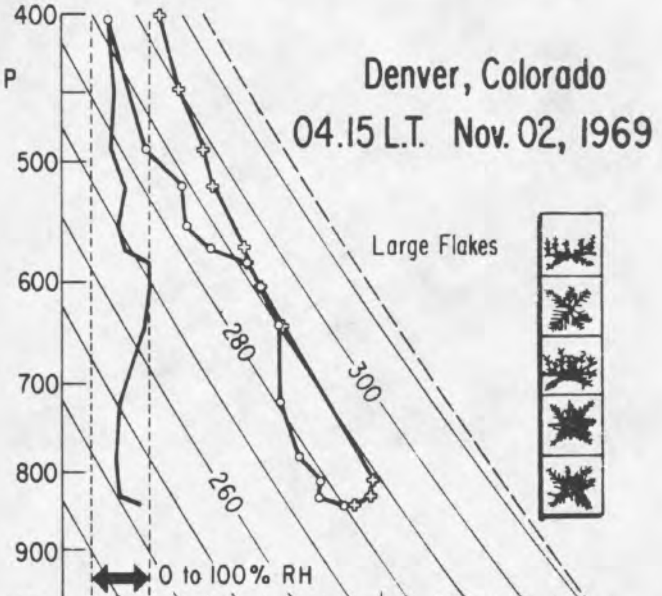


Figure 12.

Figure 11. Temperature and humidity profile on 2 March 1968, Denver, Colo. Crystal forms agree with diagram of Fig. 1.

Figure 12. Temperature and humidity profile on 2 November 1969, Denver, Colo.

The precipitation process that is active in this cloud system is no longer compatible with the Bergeron mechanism of a spender and releaser cloud. Apparently here the releaser cloud is missing and the release of precipitation has to be accomplished by the spender cloud. While the precipitation intensity is always light when the releaser cloud is present and the spender cloud missing, this is not necessarily true as long as only the spender cloud is available since the rate of condensation in the convective cloud system is high, therefore, as long as the temperature is low enough, heavy precipitation from even shallow systems may fall. As this important precipitation mechanism has not as yet been described in the literature, it shall be accomplished subsequently.

Microphysics of Crystal Habit Formation.

The ice forming mechanism in these cloud systems is as follows:

The cloud droplets which rise with the cloud have a freezing nucleus embedded or come into contact with one. When the threshold temperature of the nucleus is reached, the droplet freezes. The subsequently developing crystal habit is a function of the temperature at which the droplet froze, of its size, and of the temperature and humidity of the atmospheric layers which it passes through. The temperature and size determine whether it will form a single crystal or a polycrystal and this determines whether a plane star or a spatial star will form. This process depends on temperature and size of the frozen cloud drop in a way which has been explored by Magono and Aburakawa (1968). These authors used as nucleant an ice surface whose C-axis was perpendicular to the surface orientation, and sprayed on that surface droplets of various sizes and temperatures. Using polarized light they then studied the crystalline structure of the frozen droplet. Their results for various temperatures and droplet sizes are shown in Fig. 4. Different hatching of the block diagrams indicate whether the droplets on impact formed single crystals or polycrystals. In the case of a freezing nucleus embedded into the droplet it will replace the ice surface of the experiment. As long as the nucleus has one active nucleation site, a unit crystal will grow as in the Magono and Aburakawa experiment. Whether this is indeed just one site or whether one site wins in the competition of a number of sites is immaterial. Furthermore, the formation of a unit or of a polycrystalline crystal when a drop freezes is not only a function of the threshold temperature, i.e., of the nucleus, but also a function of drop size, consequently a function of the post-nucleation crystallization process. At lower temperatures, it would be possible that several nucleation sites become active, but it can also occur that dendritic growth emerging from one nucleation site on the nucleus causes the polycrystalline structure of the drop. This latter process has been observed for large drops (1 mm diameter) as the reason for polycrystallinity (Brownscomb and Hallett, 1967). It is conceivable that droplets which have crystallized into a single crystal form double stars or dendrites as shown schematically in Fig. 6 (Weickmann, Katz, and Steele, 1970), while polycrystals will accordingly initiate the formation of spatially arranged dendritic branches (Fig. 7). Figs. 8a and 8b show all double crystals which have formed in a cloud chamber after seeding with differently prepared AgI crystals. The temperatures were between -15.5 and -17.5°C. Fig. 9 shows spatial aggregates which have formed after freezing nuclei seeding with AgI in a supercooled cloud at -22°C (aufm Kampe et al. 1951) according to the scheme of Fig. 7.

Fig. 10 shows for comparison the ice crystals which form after dry ice seeding due to homogeneous nucleation. Note that none has a frozen droplet in the center. Cloud temperature was -17.5°C.

We can now make an important statement related to the origin of various crystal types in conventive cloud systems: Planar double dendrites and spatial dendrites form through freezing of cloud droplets which are carried in the water saturated updraft to their threshold temperature; their size and the temperature at crystallization will determine whether a planar double dendrite or a spatial multi-branch dendrite will form. The lower the temperature the more likely becomes the formation of a polycrystal for any droplet size. The great importance of these irregular type of snow crystals, which nevertheless are found in a number of typical varieties (reference Magono and Lee, 1966), for the efficient formation of precipitation follows from the fact that they offer a large surface area. We have planimetered the surface area of dendritic stars from the collection of Magono and Lee (1966) and have found that expressed in terms of effective surface area their equivalent radius as hexagonal plate crystal is about 1/2 of the circumscribed circle. At the same time, they have a great riming efficiency and the frozen droplets can again form centers of new branches (Magono and Lee, 1966). This explains why deep cloud systems can effectively be snowed out by crystals as few as 1 to 10 per liter - - concentrations which can in nature be expected to form in the temperature range -20 to -25°C.

We like to emphasize here an important mechanism that determines, as we will see later, the efficiency of the precipitation mechanism. This mechanism is the self-cleaning process of the clouds; they free themselves from the ice crystals generated within them during their active stage. These ice crystals, because of their small fall velocity, are taken with the updraft to the cloud top, leaving the cloud beneath ice-free, and on top they are dispersed horizontally in a shallow layer and away from the cloud in a Stratocumulus cumulo-genitus mechanism. The ice crystals which have formed throughout the depth of the cloud are now concentrated in a shallow layer in and around the cloud top and are ready to snow-out a neighboring cloud whose updraft has ceased. We believe that this concentration process of the ice crystals is an important mechanism for the effective snow-out of these cloud systems whose releaser cloud is missing. From there they may fall into another cloud which has ceased to be active, and whose internal structure is determined by large energy consuming eddies. In the meantime, the original cloud has become inactive also, air no longer ascends through it and the organized updraft is decaying into eddies and turbulence. Ice crystals that fall into these clouds have excellent conditions for growth because their fall velocities are well within the velocities of the turbulent eddies. The precipitation process described in our case study No. 3 and those which are related to the typical lake storm cloud systems (Fig. 4), resemble most nearly the "generating cell" mechanism which has been described by Marshall (1953), Langleben (1954), Gunn et al. (1954), Gunn and Marshall (1955).

It appears that the primitive equipment, usually a vertically pointing antenna whose return signal was recorded on a simple paper recorder, was superior in displaying the profile of the precipitation structure than presently used in modern equipment. It would be desirable to resume this research with present day sophisticated equipment and under due consideration of the effects on radar pattern of rising and falling precipitation particles. It is conceivable that the vertical echo pattern of the generating cells proper is due to the presence of both rising and falling snow crystals. It is interesting that this possibility is mentioned only in Marshall's original paper on that subject, while in later publications this important echo characteristic is no longer considered.

The interrelating, comparative snow crystal analysis.

After having described the system of snow crystals which are discharged from shallow lake storms, we only have to study the snow precipitation at other locations in order to be able to draw conclusions about the occurrence or non-occurrence of similar systems. Of course, it is known from the extensive snow crystal observations made by Japanese scientists on the peninsula Hokkaido that the same storms occur there when the air is moving from the warm Japan Sea over Hokkaido. We have, however, also frequently observed that orographic systems in Colorado and Bavaria north of the Alps occur also as shallow storms. Before we describe some of the precipitation systems related to this problem we will show how snow crystal observations can be used to determine similarities in the cloud structure. It must be admitted that to date no numerical snow crystal model exists which is able to describe satisfactorily the infinite variety of natural snow crystal habit and its modifications in the riming process. Numerical models have been proposed by Koenig (1971) and Cotton (1971), but the forms modeled are simple elementary crystal form which do not occur in nature except in seeded clouds. In the cases where overseeding is effective so that simple forms occur and riming is excluded, the models probably describe quite well the precipitation efficiency of the cloud. When compared with the so-called natural conditions using the same crystal forms, the natural efficiency turns out to be much less. In natural conditions of crystal growth and riming, nature has however infinite possibilities of increasing the collecting surface for both vapor through diffusion and cloud water through riming so that the natural efficiencies must be greatly underestimated in existing numerical models. This deficiency should always be kept in mind when such simplified numerical models of crystal habit are being used for the evaluation of precipitation efficiency in seeded and unseeded clouds.

The great sensitivity of the crystal habit to temperature and humidity conditions follows clearly from the fundamental work of Nakaya on crystal growth and from the Magono and Lee (1966) crystal classifications. The diagrams of these investigators show that for instance in the temperature range from -15 to -20°C any habit from solid columns to dendrites can form depending on the humidity conditions. This has been confirmed for natural conditions in our seeding experiments where the seeding rate caused the formation of 1000 crystals per liter. These effectively overseeded the cloud causing crystal growth at ice saturation and consequently the formation of columns. The crystal habit in a natural cloud is related sensitively to dynamic cloud parameters such as temperature, humidity and liquid water content, which in turn depend on other cloud parameters like updraft velocity etc., but also to microphysical parameters like concentration of freezing nuclei. In winterly cloud systems with identical nuclei concentrations, the crystal habit depends on the cloud dynamics; consequently, identical crystal habits point to the action of identical cloud systems.

Description of crystal habits in other types of shallow winter snow storms.

Subsequently, we bring a few examples of snow storms which have produced identical crystal habits as lake winter storms:

Boulder, Colorado, 2 March 1968, up-slope condition: Radiosonde data (Fig. 11):

1615 MST: Continuous moderate snowfall since A. M. Snow crystals 6 miles east of Foothill range are flaked and slightly rimed, not all crystals in a flake are rimed. Most forms are dendritic stellars, or a

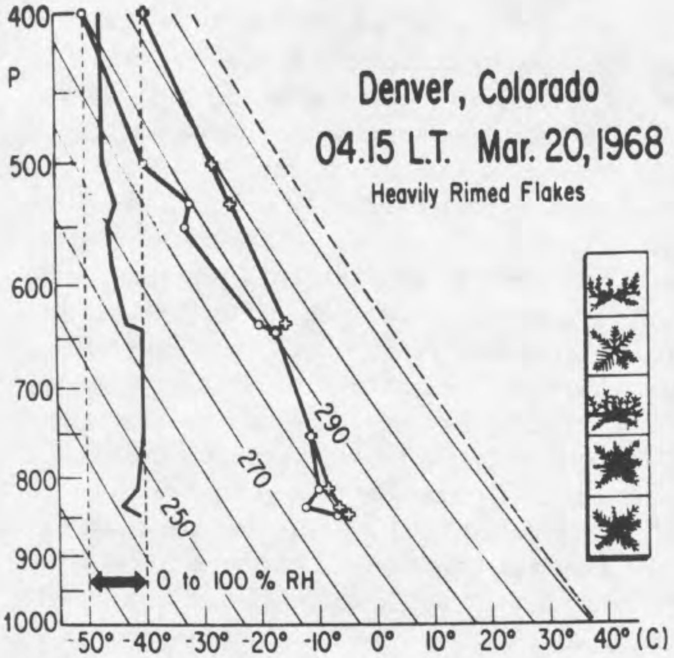


Figure 13.

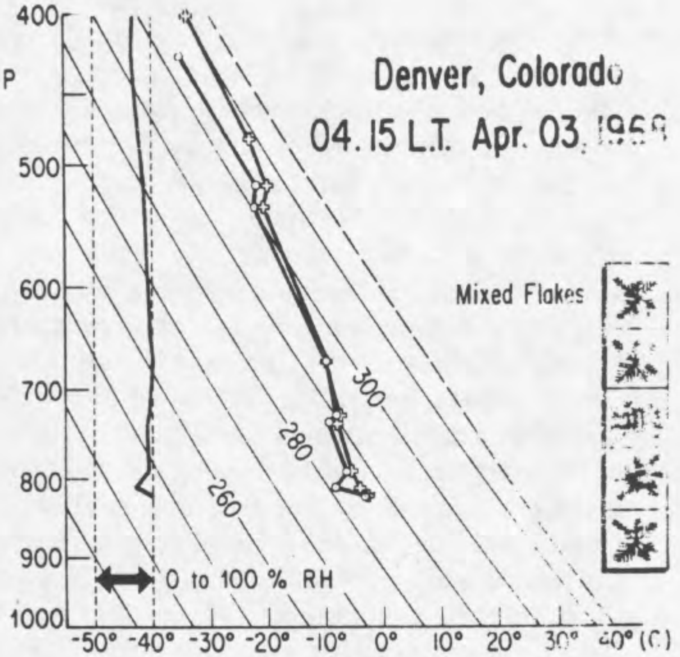


Figure 14.

Figure 13. Temperature and humidity profile on 20 March 1968, Denver, Colo.

Figure 14. Temperature and humidity profile on 3 April 1968, Denver, Colo.

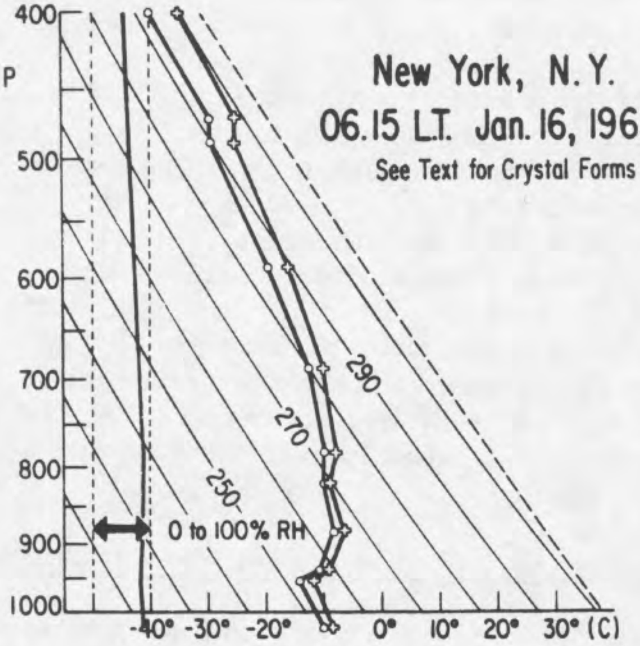


Figure 15a.

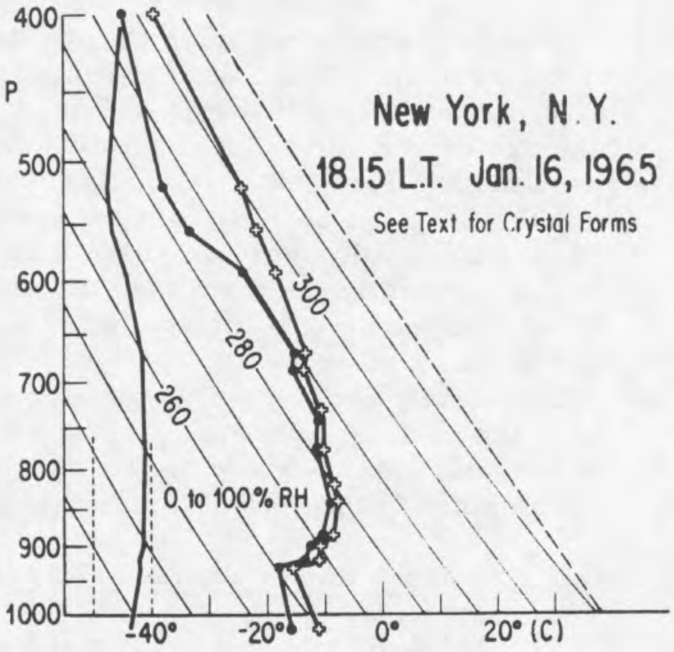


Figure 15b.

Figure 15a. Temperature and humidity profile on 16 January 1965, New York City, N. Y., 06. 15 local time.

Figure 15b. Temperature and humidity profile on 16 January 1965, New York City, N. Y., 18. 15 local time.

mean habit between sectors and dendrites. Original habits are spatial dendrites, spatial sector stars, but no prisms.

1625 MST: Intensification of snowfall. Both, flakes and individual crystals are larger, rimed as before, no prism forms.

1630 MST: The flakes consist of about 20 to 50 single crystals. The individual crystals are between large (diameter about 5 mm) sector stars with few rimed droplets to small spatial plate particles. (One big sector star contains perhaps as much ice as one small spatial dendrite).

1700 MST: Continuously heavy snowfall. Particles are flakes, but now consisting of many small spatial plate aggregates, small sector or dendritic stars, but more numerous flakes and crystals. It seems as if either the generating level or the freezing nuclei concentration has increased with altitude; for either one of these reasons more particles are generated and all remain smaller without reducing or increasing overall rate of snowfall.

1720 MST at base of Foothills, Boulder, Colorado: Heavy snowfall, large flakes consisting of spatial dendrites, partly heavily rimed, one graupel (snow pellet). Stars are dendrites rather than sectors. The most intensive riming is in the center of the spatial aggregates.

Boulder, Colorado, November 2, 1969; Radiosonde data (Fig. 12):

1200 MST: Snowfall with rimed flakes changes to snowfall with very large flakes. Before the change the forms were spatial plate aggregates rimed and flaked together. After the intensification to large flakes the forms were: spatial aggregates of large dendrites, rimed and flaked. The only basic difference was that the fundamental habit had changed from spatial plate and sector aggregates to large spatial dendrites. Large flake precipitation lasted for about 5 minutes.

Boulder, Colorado, March 20, 1968; Radiosonde data (Fig. 13):

1800 MST: Very dense intensive snowfall. Snowflakes consist of heavily rimed spatial dendrites.

Boulder, Colorado, April 3, 1968; Radiosonde data (Fig. 14):

0700 MST: Heavy snow storm from north. Flakes consisting of spatial dendrites which are slightly rimed. 10 - 15 crystals fall in 10 seconds per cm^2. They are large spatial dendrites; flakes have about 1/2 inch diameter and consist of 10 - 20 single dendrites.

Other similar log entries are from snow observations in New Jersey, in Northern Main, in Bavaria (Germany), in Alaska. Quite often the shallow storm type constitutes the main body of a typical front, then the crystal sequence is as described by Grunow (1960) and Weickmann (1957). The storm begins with high level low temperature prism bundles and ends with the typical shallow storm crystals, such as spatial dendrites in flakes and rimed and mostly mixed with sector or dendritic stars.

Subsequently we would like to quote one observation sequence of such a storm, as observed on January 16, 1965, in Asbury Park, New Jersey; Radiosonde data are from New York, New York, Fig. 15a, b,.

Figs. 15a, b, present the typical As-Ns (Altostratus-Nimbostratus) phase of the storm during which high-level prism forms are predominant. Fig. 17 indicates that an inversion has formed just above the 700-mb level, and that the typical convective Sc (Strato-cumulus) particles are being discharged through many hours as described subsequently:

> 1350 EST: Particles are now crystalline and small and numerous, reaching from a few plates over many plate aggregates to prisms.
>
> Same forms fell for hours; but in the morning they were rimed, larger, and partly in flakes. During the forenoon sometimes large stars fell also.
>
> 1445 EST: Renewed intensification of snowfall. All particles are larger and rimed and form flakes. Sector stars, not heavily rimed, fall also. Most particles are spatial aggregates.
>
> 1520 EST: Snowfall intensified. Large rimed dendrites and large rimed dendritic spatial aggregates. Dendrites and spatial dendrites fall, single and in small flakes. Double stars also.
>
> 1545 EST: Heavily rimed dendrites in greater frequency than spatial aggregates. The dendrites are homogeneously rimed over the whole surface. Sometimes the rimed drops have grown into crystals (prisms).
>
> 1930 MST: Still considerable snowfall (-10°C) from flakes. Particles are dendrites as stars and as spatial dendrites, both rimed and unrimed.
>
> Here for the whole afternoon the shallow storm character was in progress.

We have called attention to these observations because they permit the conclusion that the non-precipitating shallow cloud systems will occur as well in other places, though probably less frequently, than over the Great Lakes Basin. They may present a seeding potential which is hitherto unexploited.

General common features of shallow winter snow storms.

It appears that shallow winter storms originate within the boundary layer flow in connection with a moisture source. Preferably the flow becomes established before condensation occurs. This permits the establishment of neutral stability in the boundary layer, which leads to convective instability as condensation occurs. A cloud thickness of 1500 meters is sufficient to cause moderate to heavy snow falls according to our experiences in the Great Lakes region. Condensation in the boundary layer flow occurs for several reasons: in the Great Lakes and related areas due to the flow of the air over a warm lake surface; in orographic precipitation, as per example, for easterly flow from Kansas to Colorado against the Rocky Mountains due to the lifting of the airmass by several thousands of feet, and finally in synoptic cyclonic systems due to the cyclonic vorticity present in the storm.

The artificial beneficial exploitation of these storm systems is particularly desirable in regions where the upslope flow occurs over normally downslope or dry areas, such as in the United States, in Colorado, Wyoming, and New Mexico. Exploitation of these systems, which occur according to our observations between 2 to 5 times per season, depends largely on our ability to forecast and recognize the systems early enough, so that seeding plans can be initiated.

REFERENCES

aufm Kampe, H. J., H. K. Weickmann and J. J. Kelly (1951), The influence of temperature on the shape of ice crystals growing at water saturation, J. of Meteorology, 8, pp. 168-174

Bergeron, T., (1949), The problem of artificial control of rainfall on the globe. 1. General effect of ice nucleii on clouds, Tellus, 1, (1) pp. 32-43.

Brownscombe, J. L., and J. Hallett (1967), Experimental and field studies of precipitation particles formed by the freezing of supercooled water, Quart. J. Roy. Met. Soc., 93, pp. 455-473.

Cotton, William R., (1970), A numerical simulation of precipitation development in supercooled cumuli, NSF Grant GA-13818, Report No. 17 to NSF.

Grunow, J., (1960), Snow crystal analysis as a method of indirect aerology, AGU Geophys. Monograph No. 5, Physics of Precipitation, Waverly Press, Inc., Baltimore, Md. pp. 130-141.

Gunn, K. L. S., M. P. Langleben, and A. S. Dennis (1954), Radar evidences of a generating level for snow, J. Met. 11, pp. 20-26.

Koenig, L. R. (1971), Numerical modeling of ice deposition, JAS, 28, 2, pp. 226-237.

Langleben, M. P., (1954), The terminal velocity of snowflakes, Quart. J. Roy. Met. Soc., 80, pp. 174-181.

Magono, Ch. and Ch. W. Lee (1966), Meteorological classification of natural snow crystals. J. Faculty of Science, Hokkaido Univ., Series VII, Geophysics, Vol. 2, pp. 321-335.

Magono, Ch. and H. Aburakawa (1968), Experimental studies on snow crystals of plane type with spatial branches, J. Faculty of Science, Hokkaido Univ., of Japan, Series VII, 3, pp. 85-97.

Marshall, J. S. (1953), Precipitation trajectories and patterns, J. Met. 10, pp. 25-29.

Weickmann, H. K. (1957), The snowcrystal as aerological sonde, Artificial stimulation of rain, Proc., First Conference, Physics of Cloud and Precipitation Particles, Woods Hole Oceanographic Institution, Woods Hole, Mass., pp. 315-326.

Weickmann, H. K., U. Katz and R. Steele (1970), AgI - Sublimation or contact nucleus, Second National Conf. on Weather Modification, Santa Barbara, Calif., pp. 332-336