Formation of Graupel[1]

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ABSTRACT

Measurements were made of the sizes and concentrations of graupel and snow crystals occurring in seeded and untreated winter storms of the Sierra Nevada. The amounts of rime on individual snow crystals were also determined. The observations show that crystal riming, and formation and precipitation of graupel, are common to all stages of Sierran snowstorms. Graupel occurs simultaneously with all types of snow crystals, but individual crystal types do not consistently occur with or serve as kernels for particles of graupel.

Graupel particles do not develop predominantly on kernel snow crystals that grow to relatively large sizes over relatively long periods by deposition and accretion. Graupel often forms instead on a select few small crystals, when it forms utilizing regular crystals as kernels. Graupel frequently develops without kernels, by alternate riming processes. One possible alternative is a mechanism that produces graupel from rime accumulated at localized points on parent snow crystals.

1. Introduction

Graupel consists of white, opaque, granular snow pellets. These precipitation elements occur in hexagonal, conical and lump forms, according to classifications by Schaefer (1951), Nakaya (1954), and Magono and Lee (1966). Graupel is formed by the accretion and freezing of cloud droplets on parent ice particles. Whether graupel forms by rime enveloping the parent particles, or by the breaking off of rime accumulations from a parent, is not completely understood.

The concensus has been that most graupel represents the extreme, prehail stage of the riming of snow crystals (Arenberg, 1941; Nakaya, 1951, 1954; Schaefer, 1951; List, 1958; Magono and Lee, 1966). Magono (1953) also suggests that riming of irregular ice particles could lead to graupel formation. Weickmann (1953) proposes that graupel could form as heavily rimed, frozen cloud droplets. Knight and Knight (1973) suggest that lump graupel, in particular, may be rimed spatial or radiating dendrites or any other snow crystals that rime while tumbling. These observations and hypotheses are all based on the contention that each graupel particle is developed by accretion on some type of ice particle that serves as a core or "kernel." Hindman and Johnson (1972) have applied this concept in their numerical model of ice particle growth. The model is designed to simulate growth by simultaneous vapor deposition and droplet accretion. The model appropriately allows for variability in the final mass of water accreted if the rate of growth by accretion is calculated to be greater than that by deposition, the snow crystal is assumed to develop into a spherical graupel particle, given sufficient growth time. If the converse exists, the crystal is assumed to remain lightly or moderately rime. This approach of modeling continuous growth of single crystals is limited. All crystals of each type are treated alike in each given case. There is no allowance for the stochastic nature of snow crystal interaction with cloud water, nor for the consequent simultaneous generation of some graupel and some crystals with less rime or no rime at all. In addition, according to such models and most theories, graupel forms only by droplets accreting at a smoothly progressing rate, on kernel crystals. This concept can mislead one to believe that graupel forms primarily on those crystals that can maintain growth by deposition and accretion for the longest times. This concept is subject to improvement, and the universality of graupel formation by rime buildup around kernels is open to question.

Hexagonal graupel particles are heavily rimed, hexagonal types of snow crystals (Knight and Knight, 1973), but the kernels are not necessarily the crystals that have achieved the greatest or even the average depositional growth times and sizes.

Conical and lump graupel might form with no kernel ice particles at all. Conical graupel may result from the buildup of rime at localized sites on the undersides of settling, planar snow crystals. Cones of rime, attached by their tips to parent snow crystals, may form at these sites. Forces due to crystal collisions may break off the cones. The cones could then gather further rime

[1] Expanded from portions of a Ph.D. dissertation, Colorado State University (Reinking, 1973).

during free fall as separate graupel particles. Knight and Knight (1973) have postulated and provided some empirical evidence for this alternate mechanism of graupel formation. Apparently this process could also produce lump graupel.

The hypotheses for the formation of graupel on kernel snow crystals with short periods of depositional growth, and the development of graupel without snow crystals as kernels, are supported by evidence presented in this paper. Other alternatives are also discussed. The study is based on snow crystal data collected in the field during orogenic winter storms of the central Sierra Nevada.

2. Data and methods

The data for this study were collected in conjunction with the field weather modification experiments of Project CENSARE (CENtral SierrA REsearch). The project was designed to study snow formation processes and the corresponding potential for precipitation enhancement by cloud seeding. Some 14,500 snow crystals were analyzed from 260 individual samples collected during nine synoptically diverse Sierra Nevada snowstorms of the 1971–72 and 1972–73 seasons. Eight of the storms were seeded, one was not. Rawinsonde data were used to determine tops and temperatures of the clouds in which crystals could nucleate and grow. The rawinsondes were launched from Jackson and Tamarack, California. Jackson (1711 ft MSL) is in the foothills where orogenic lifting initially becomes significant. Tamarack (6918 ft MSL) is located on the windward slope of the Sierra Nevada near the mean elevation of maximum snowfall. The crystal sampling site was Tamarack. At this site, a hooded deep freeze was used to ensure crystal data acquisition even when surface temperatures warmed to very near 0°C. The freezer was positioned in a clearing during snowfall. Crystals settled through collection ports into the freezer where they were replicated in plastic (1.5% polyvinylformal in ethylene dichloride) on large glass slides. Replicas were obtained at 15–45 min intervals during snowfall.

Data reduction was accomplished by projecting the replicas onto a screen with standard overhead equipment. Magnification of the crystal images was set at 100×. The replicated crystals were examined for detail with a microscope prior to projection. Axis size measurements and identifications of individual crystals were then made on the screen. A computerized number system equivalent to the Magono and Lee (1966) crystal classification was used to identify diffusional growth habits. A separate category was used to represent graupel.

The extent of accretion has normally been empirically classified by simply categorizing snow crystals as rimed or unrimed (Ono, 1969; Zikmunda and Vali, 1972). Measurements of the amounts of accretion on individual crystals comprising a large field sample were applied to more accurately describe the accretion process. The onset and the progression of the amount of riming for entire crystal populations were thus depicted. It was possible to bypass the impracticality of counting and measuring individual droplets on individual crystals because the crystal sample was large. Studies by Hobbs *et al.* (1971) and Reinking (1973) demonstrated that semi-quantitative estimates of rime coverage on individual crystals can be obtained on a percent-of-area-covered basis. Amounts of accumulated rime can be visually rated from most to least on a scale of four or five, with reasonable confidence. For this study, individual snow crystals that formed according to any of the primary, regular growth habits were classified according to rime coverage on their collecting surfaces by using the scale; 1) unrimed, and areal coverages of 2) 1–25%, 3) 25–50%, 4) 50–75%, 5) 75–100%, and 6) 100% plus.

Single percentages representative of each interval of areal rime coverage were utilized in the analyses. The zero rime category, and its separation from the 1–25% category are, of course, absolute. The 25–50% and 50–75% intervals were weighted at the respective medians. The 1–25% interval was weighted slightly below its median, at 10%; the 75–100% interval was weighted slightly above the median, at 90%. The latter two weights do not produce results substantially different from those based on medians, but do serve as indicators of the following factors:

(i) Crystals in the light rime category frequently have just encountered the onset of riming and have collected only a few droplets. The weight at 10% indicates this phenomenon.

(ii) Rime coverage on heavily rimed crystals is particularly uneven. For example, rime near the center of a planar crystal in the 75–100% category may be light, while that near the edges, if visualized to spread out evenly, may more than cover the whole collecting surface. The weight at 90% indicates that many of the crystals in this category have collected rime sufficient to cover their surfaces, even though the surfaces were not totally obscured.

Graupel is represented in the 100% plus category. Also included in this category are the few snow crystals that remain recognizable by growth habit despite very heavy riming; these particles are very near the graupel stage.

Estimates of the in-cloud concentrations of the various types of snow crystals and graupel were computed from samples that included all appropriate data. Required information included the exposure time t(s) of each slide replica, the number density nA^{-1} (cm^{-2}) of each type of crystal on each slide, and the terminal velocity V (cm s^{-1}) corresponding to the average crystal size for each type. The average crystal sizes were computed for selected precipitation episodes within the storms. The concentrations were estimated using the

Table 1.
Growth habits and occurrence of snow crystals at Tamarack.

	HABIT GROUP	SAMPLE SIZE	PERCENT OF TOTAL SAMPLE
N	NEEDLES AND SHEATHS (N1a–d; N2a,b)*	6925	47.7
C	HOLLOW COLUMNS (C1f)	1345	9.3
P1A	HEXAGONAL PLATES (P1a)	706	4.9
P1B	BRANCHED PLANAR CRYSTALS (P1b–f, P2a–g; P3a–c; P4a,b; CP3a d)	1256	8.6
P1C	FRAGMENTS OF BRANCHED PLANAR CRYSTALS (fP1b–f; fP2a–g; fP3a–c; fP4a,b; fCP3a–d; I3.)	1584	10.9
P2	RADIATING ASSEMBLAGES OF PLATES AND DENDRITES (P7a,b)	276	1.9
CP	CAPPED COLUMNS (CP1a–c)	220	1.5
O	OTHER REGULAR CRYSTALS	66	0.4
R	GRAUPEL (R4a–c)	1061	7.3
I	MISCELLANEOUS ICE PARTICLES (I1)	1082	7.5
	TOTAL SAMPLE SIZE	14521	100.0

*MAGONO AND LEE CLASSIFICATION; CODES PRECEDED BY "f" INDICATE CRYSTAL FRAGMENTS

equation

$$N\,[\ell^{-1}] = (nA^{-1}t^{-1}V^{-1}) \times 10^3.$$

Unrimed or lightly rimed crystals (less than 25% surface area rime coverage) were included in one category for determination of the necessary terminal velocities. Crystals which were more heavily rimed were included in a second category. Terminal velocity data exist only for unrimed and heavily rimed snow crystals; thus the division into two categories was necessary. The equations that were used to compute V are presented by Reinking (1973). They are based on curves and equations published by Bashkirova and Pershina (1964), Heymsfield (1972), and Zikmunda and Vali (1972). These fallspeeds could be moderately improved, or at least substantiated further, by incorporating the more recent data on heavily rimed snow particles from Locatelli and Hobbs (1974).

Precipitation episodes were separated according to synoptic front and 500 mb trough positions relative to the locale of the collection site.

3. Graupel occurrence

The observed snow crystals of the various growth habits were grouped according to similarities in formation temperatures, shape and fallspeed (for details, see Reinking, 1973). The grouped samples are summarized in Table 1. Graupel is presented as habit group R. Lump and hexagonal graupel, and smaller numbers of conical graupel contributed to the sample. The graupel particles represent 7.3% of the total snow particle sample.

Graupel fell during 19 of the 25 observed precipitation episodes (Table 2). No preferential association of the graupel occurrence with front or 500 mb trough positions is apparent. Graupel occurrence is well represented in storm episodes relative to all front and trough positions. This is probably to be expected. Graupel formation is normally expected to be associated with convection. Convection in Sierran storms is not isolated to periods of front or trough passage. Banded convection and precipitation occur frequently in these storms, especially in advance of fronts (Elliott and Hovind, 1964; Peace, 1971). Imbedded convection during frontal periods is normal, and is apparently somewhat enhanced when a trough aloft reinforces the wave front. Post-frontal and/or post-trough imbedded convection is common, but can be relatively shallow due to capping

Table 2.
Precipitation episodes and graupel occurrence.

PRECIPITATION EPISODE	DATE	PRE-FRONTAL	FRONTAL PASSAGE	POST-FRONTAL	PRE-TROUGH	TROUGH PASSAGE	POST-TROUGH	NO FRONT OR TROUGH ±6 HR	GRAUPEL
	1971								
1	2 DEC			X	X				YES
2	3 DEC	X			X				NO
3	21 DEC	X							NO
	1972								
4	23 JAN			X		X			YES
5	23 JAN						X		YES
6	25 JAN	X							YES
7	25 JAN		X						YES
8	25 JAN			X	X				YES
9	26 JAN						X		YES
10	27 JAN				X				YES
11	27 JAN					X			YES
12	22 MAR	X							YES
13	22 MAR		X						YES
14	22 MAR			X	X				YES
15	22 MAR					X			YES
16	5 APR	X							YES
17	5 APR	X							YES
18	5 APR		X	X					NO
19	11 APR							X	NO
20	12 APR	X							YES
21	12 APR	X							YES
22	12 APR	X			X				YES
23	12 APR			X			X		NO
	1973								
24	29 JAN	X							NO
25	29 JAN			X	X				YES

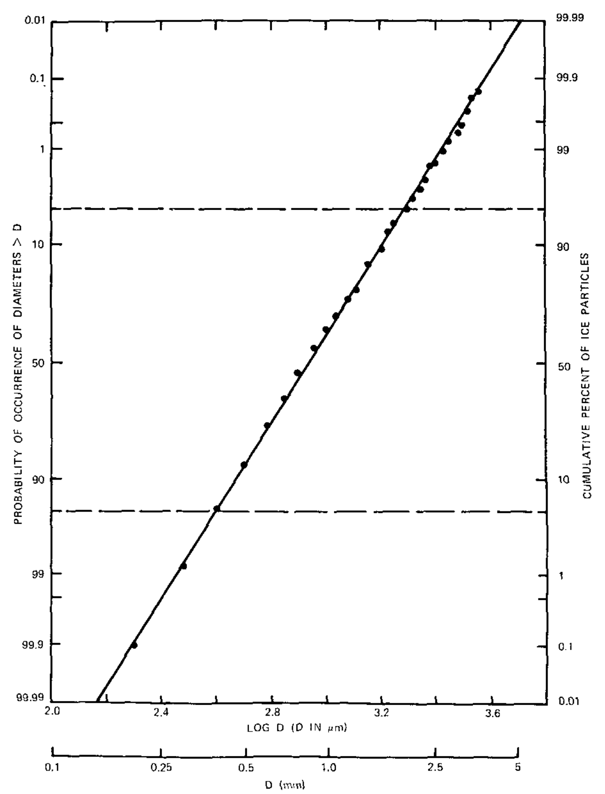

FIG. 1. Cumulative size distribution of graupel.

Table 3.
Snow particle concentrations (liter^{-1}) by crystal habit group*.

	N(−6°C)**			C(−8°C)			P1A(−12°C)			P1B(−15°C)		
PRECIP. EPISODE	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL
3	8.8	2.3	11.1	0.0	0.0	0.0	0.3	0.2	0.5	8.8	0.6	9.4
6	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.3	0.3	0.6
7	11.5	3.3	14.8	0.2	0.0	0.2	0.4	0.0	0.4	0.2	0.3	0.5
8	9.9	1.8	11.7	0.4	0.1	0.5	0.2	0.0	0.2	0.1	0.2	0.3
10	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.9	3.0	0.6	3.6
11	0.1	0.0	0.1	0.4	0.0	0.4	4.9	0.0	4.9	2.4	1.0	3.4
12	10.7	4.3	15.0	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.4	0.5
13	0.1	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.4	2.8	0.5	3.3
14	60.6	5.7	66.3	–	–	–	–	–	–	0.0	0.0	0.0
15	0.3	0.0	0.3	0.0	0.0	0.0	1.0	0.1	1.1	0.0	0.5	0.5
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.4
17	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0
18	3.0	0.4	3.4	0.1	0.0	0.1	11.2	0.0	11.2	0.5	0.0	0.5
19	72.4	4.5	76.9	0.3	0.0	0.3	0.3	0.0	0.3	0.5	0.1	0.6
20	19.6	3.8	23.4	1.9	1.2	3.1	0.0	0.0	0.0	0.1	0.2	0.3
21	123.2	28.5	151.7	2.5	1.7	4.2	0.0	0.0	0.0	0.0	0.7	0.7
22	43.8	17.1	60.9	2.5	0.5	3.0	2.3	0.0	2.3	1.5	5.1	6.6
24	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2	1.1	0.3	1.4
25	3.4	2.1	5.5	0.1	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0

	P1C(−15°C)			P2(−20°C)			CP(−25°C)			I			R
PRECIP. EPISODE	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	UNRIMED OR LIGHT RIME	HEAVY RIME	TOTAL	TOTAL
3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	0.8	0.0	0.0	0.0	0.0
6	0.7	0.3	1.0	0.1	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.2	0.0
7	0.4	0.3	0.7	–	–	–	–	–	–	0.5	0.1	0.6	0.2
8	0.6	0.2	0.8	0.0	0.0	0.0	0.0	0.3	0.3	1.1	0.2	1.3	0.3
10	2.1	0.7	2.8	0.2	0.4	0.6	0.1	0.0	0.1	1.1	0.0	1.1	0.1
11	3.0	0.5	3.5	0.3	0.1	0.4	–	–	–	0.8	0.0	0.8	0.2
12	0.0	0.1	0.1	–	–	–	–	–	–	0.0	0.4	0.4	0.3
13	0.2	1.2	1.4	0.1	0.0	0.1	–	–	–	1.1	0.1	1.2	0.7
14	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.1
15	0.4	0.4	0.8	–	–	–	–	–	–	0.0	0.0	0.0	1.1
16	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.3	0.2	0.5	0.1
17	1.1	0.1	1.2	0.2	1.1	1.3	0.0	0.0	0.0	0.1	0.7	0.8	0.3
18	0.1	0.1	0.2	1.6	0.2	1.8	0.0	0.0	0.0	0.4	0.0	0.4	0.0
19	0.9	0.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0
20	0.3	0.4	0.7	–	–	–	–	–	–	0.4	1.2	1.6	0.2
21	0.1	0.2	0.3	–	–	–	–	–	–	0.7	0.0	0.7	0.4
22	1.1	0.8	1.9	–	–	–	–	–	–	0.6	0.0	0.6	0.6
24	0.8	0.2	1.0	0.0	0.1	0.1	0.0	0.0	0.0	0.3	0.1	0.4	0.0
25	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.9	0.2

*ZEROS IN THE TABLE INDICATE CRYSTAL CONCENTRATIONS LESS THAN 0.1 PER LITER; DASHES (–) INDICATE CASES WITH NO CLOUD AVAILABLE FOR CRYSTAL FORMATION AT APPROPRIATE TEMPERATURES.
**TEMPERATURES INDICATE APPROXIMATE CENTERS OF FORMATION TEMPERATURE RANGES.

by subsidence aloft. Thus convection, and graupel, occur in all phases of Sierran snowstorms.

This convection is weak or moderate in comparison, for example, to the circulations in the intense convective cloud systems of the High Plains. Corresponding effects on graupel size are indicated. Graupel produced by the High Plains storms is most frequently in the diameter range from less than 1 mm to 3 mm, but does develop diameters as large as 8–12 mm (Auer, 1972). Only about 10% of the graupel that falls from Sierran snowstorms is larger than 1.7 mm; a practical maximum diameter is approximately 5 mm. The size distribution of observed graupel is almost perfectly log-normal with respective mean, median and modal diameters of 1.00, 0.85 and 0.80 mm (Fig. 1).

All of the Sierran precipitation periods except episodes 24 and 25 (Tables 2 and 3) were seeded. Effective seeding increases ice crystal concentrations and total depositional crystal growth when sufficient cloud water is available. Increased deposition may have reduced accretion and graupel size; or latent heat releases caused by the seeding may have moderately increased convection, accretion and graupel size. The amount of riming could have thus been affected by the seeding. However, the nature of the riming process, rather than the absolute amounts of occurring rime, is being examined here, and this nature should not be altered by seeding. In any case, the amounts of rime composing graupel, as inferred from the size of graupel, did not differ between the untreated sample and the seeded cases. The water vapor density in the observed storms normally remained at or near the liquid saturation level during sufficient portions of crystal growth to maintain an abundance of liquid droplets, and to thus cause the accretion process to remain important throughout the life of both unseeded and seeded storms (Reinking, 1973).

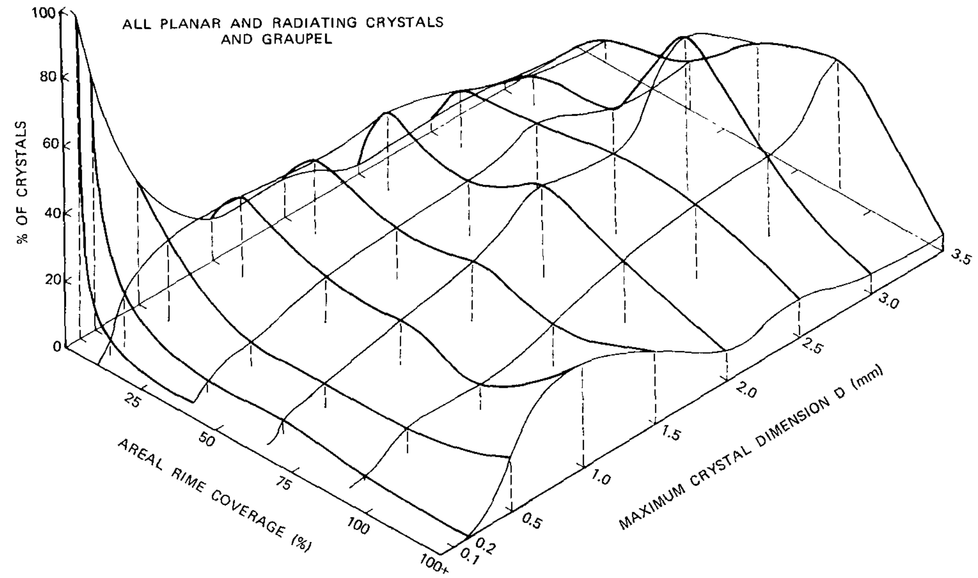

Fig. 2. Distribution of the amounts of accretion, given as areal rime coverage, on planar and radiating crystals (Groups P1A, B, C, and P2 in Table 1); graupel (Group R) is added to the 100% plus rime coverage category.

Estimated concentrations of graupel and associated snow crystals are shown in Table 3 along with cloud temperatures. Details of cloud conditions and seeding operations are given by Reinking (1973).

Graupel concentrations were primarily of the order of a few tenths per liter. These concentrations are comparable to the average graupel concentration of approximately 0.5 per liter observed by Auer (1972) in the untreated High Plains storms.

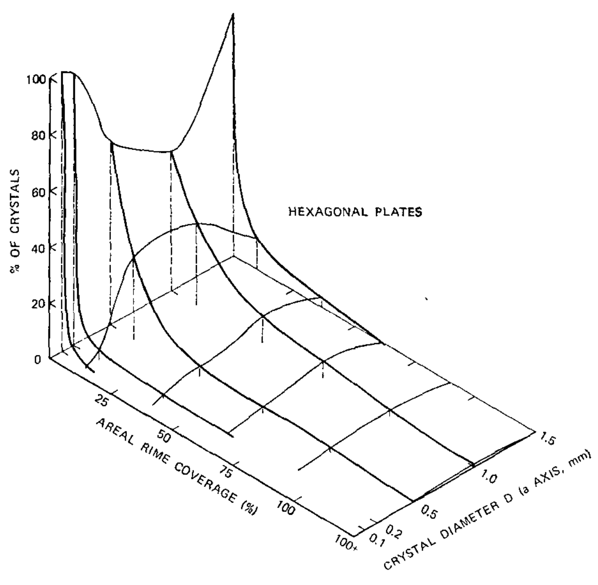

Fig. 3. Distribution of the amounts of accretion on hexagonal plates (Group P1A, Table 1).

Needles and sheaths (crystal group N, Table 3) provide the strongest evidence for enhanced ice nucleation due to seeding. These crystals, which characterize nucleation and growth at relatively warm temperatures (−4 to −8°C), would typically be expected to occur in concentrations well below 0.1 per liter. Much larger concentrations occurred in most seeded cases. However, the large average concentration that occurred in the second of the untreated cases suggests that crystal multiplication or enhanced natural nucleation also contributed to the totals. Further discussion of these aspects is given by Reinking (1973). The relationship of the graupel concentrations to seeding cannot be discerned.

Graupel fell along with columnar and planar crystals during most precipitation periods. However, graupel was accompanied by only needles, sheaths and hollow columns during episode 14 (Table 3). These same columnar types of crystals, some irregular ice particles, and only a few unrimed and lightly rimed fragments of planar crystals fell with graupel during episode 25. Individual crystal types occurred with varied degrees of rime in all samples from specific points in time, so some significantly rimed but still recognizable planar crystals would be expected in these cases if these types were serving as kernels. These occurrences indicate that the availability of planar crystals to serve as kernels is not prerequisite for graupel formation.

4. Graupel formation

Information regarding the formation of graupel may be gained by comparing size distributions of the regular snow crystals, as functions of amounts of rime accreted,

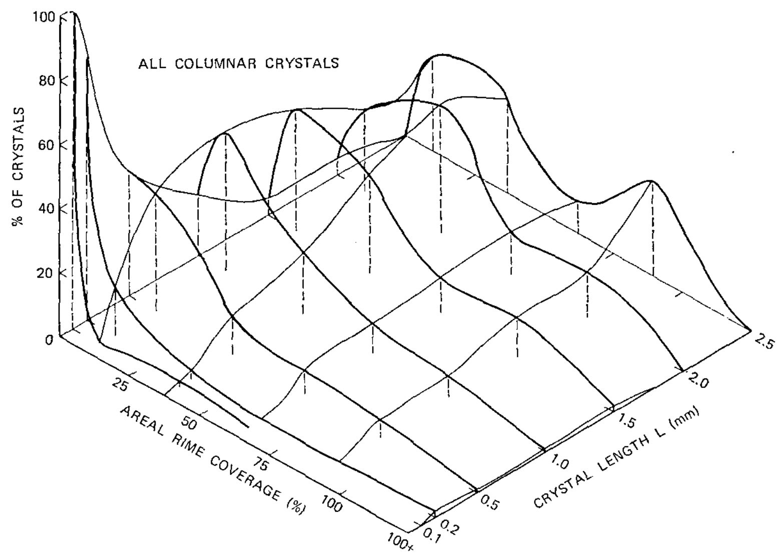

FIG. 4. Distribution of the amounts of accretion on branched planar crystals (Group P1B, Table 1).

to the size distribution of graupel. Three-dimensional distributions of the areal rime coverage have been devised to graphically illustrate the sampled populations of planar and columnar crystals (Figs. 2–7). This was accomplished for each sample by first determining the percentage of crystals in a specific size interval as a function of the percentage of areal rime coverage. These two-dimensional distributions were then plotted as a function of crystal size. The plotted crystal sizes correspond to the mid-points of the size intervals of the maximum dimension[2] of planar crystals and the length[3] of columnar crystals. Illustration of the areal rime coverage at and following the onset of accretion on the smallest crystals has been enhanced by the use of size intervals for the smallest crystals that are narrower than those used for the larger sizes. Each of the three-dimensional distributions defines a surface which shows 1) the size distribution of crystals with any given rime coverage, 2) the dispersion and mode in the amounts of rime on the crystals of any given size, and 3) the trends of both the dispersion and the modes with increasing crystal size (or equivalent depositional growth time, assuming reasonable correlation between time and size).

The accretion distributions of areal rime coverage in Figs. 2–7 are composites representing crystals from

[2] Length along the a axis when crystal is symmetrical; largest dimension when crystal is asymmetrical or irregular in shape.

[3] Length along the c axis for regular single crystals; total length for crystals such as bundles of needles.

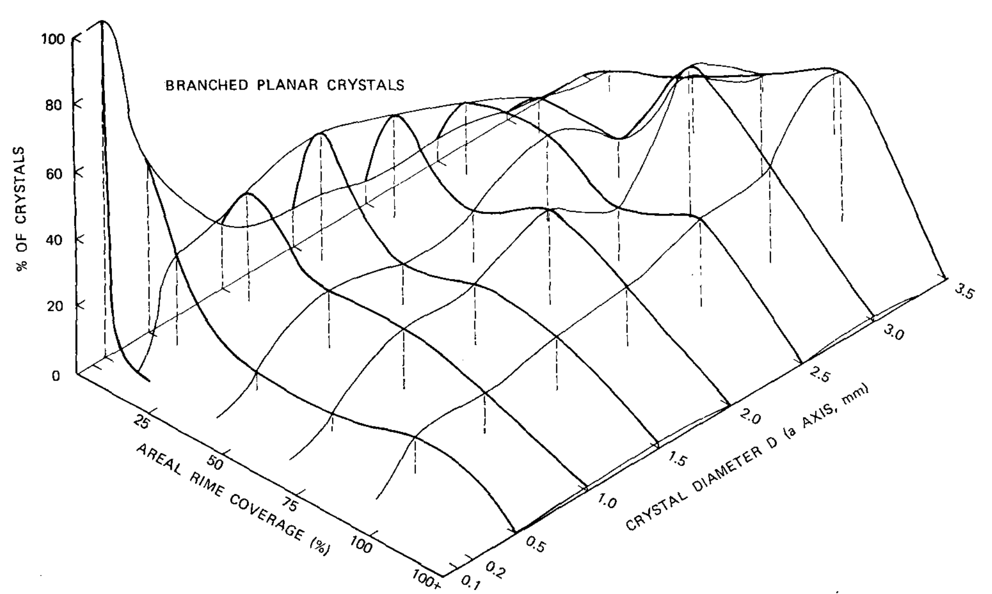

FIG. 5. Distribution of the amounts of accretion on all columnar crystals, in terms of crystal length (Groups N, C and CP, Table 1).

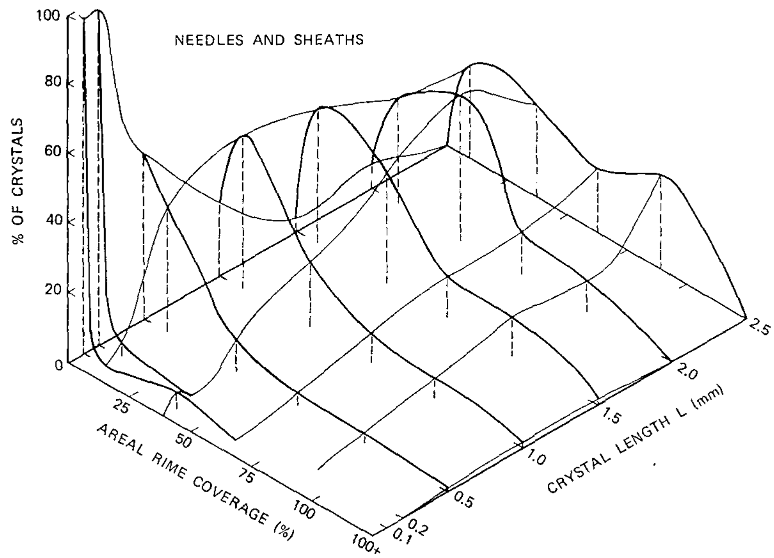

Fig. 6. Distribution of the amounts of accretion on needlelike crystals, in terms of crystal length (Group N, Table 1).

all storm periods, except episodes 24 and 25, which contributed 3.3% of the total sample and were collected after initial analyses of the other data.

The general patterns and magnitudes of dispersion in these distributions are common to the crystals sampled in individual precipitation periods; they are not the results of scatter due to differences among individual precipitation periods with crystal populations having narrow dispersions of rime (Reinking, 1973).

The composites do, of course, smooth the data from individual periods, and are therefore more readily interpreted. Snow crystals larger than those indicated in Figs. 2–7 did occur, but were too few to contribute significantly to the analyses.

Each distribution includes a few crystals that rimed to the 100% plus stage but still remained recognizable

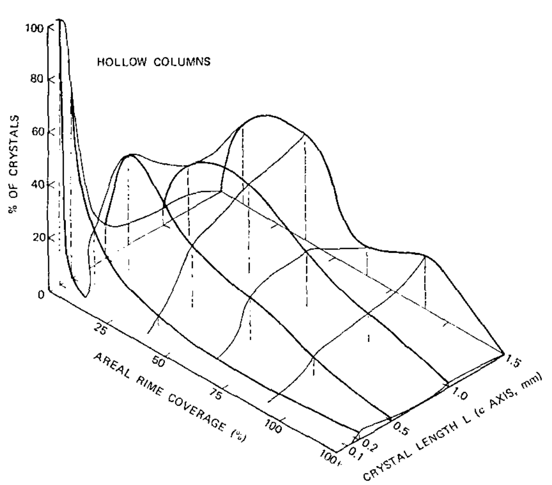

Fig. 7. Distribution of the amounts of accretion on hollow columns, in terms of crystal length (Group C, Table 1).

by specific habit or habit group. These crystals contribute less than 0.7% of the total snow particle sample. Approximately half of this percentage is represented by needles and sheaths (Fig. 6). The remainder is well divided among the other crystal groups.

Graupel is included only in Fig. 2 with the distribution for all planar and radiating crystals (Groups P1A, B, C and P2 in Table 1). The graupel dominates the 100% plus rime category.

For each crystal size in each of Figs. 2–7, consider the dispersion in the observed areal rime coverage about the amount of rime corresponding to the modal percentage of crystals. This dispersion is small and concentrated in the no-rime category for the smallest crystals. The dispersion widens and reaches maximum ranges at intermediate crystal sizes, then narrows again for larger crystals but centers on heavier rime categories. The trend of the modal percentages of each crystal group reveals a gradual migration with increasing crystal size from the no-rime to the moderate or heavy rime categories. These characteristic trends represent the continued accumulation of rime throughout all but the initial diffusional growth periods of the crystals.

We now examine Fig. 2, and consider the sizes of the graupel (100% plus rimed particles) relative to the degree of riming of other crystals of the same sizes. From a point representing 100% of the crystals, minimal size and zero rime, the modes of the three-dimensional distribution should migrate directly outward to the mode in the graupel distribution, if the graupel is generated by kernel crystals that grow for the longest times, to the largest sizes, by continued deposition plus accretion. This is not the case. In Fig. 2, the migration of the peak percentage of all planar and radiating crystals through increasing degrees of rime does not

Table 4.
Average degree of riming on snow crystals of average size.

	CRYSTAL DIMENSION*	AVERAGE CRYSTAL SIZE, μm	RIME COVERAGE ON AVERAGE CRYSTAL, %
ALL PLANAR CRYSTALS	(D)	1034	24
ALL COLUMNAR CRYSTALS	(L,W)	689,112	20
NEEDLES, N1a	(c,a)	799,77	16
SHEATHS, N1c	(c,a)	668,97	24
HOLLOW COLUMNS, C1f	(c,a)	477,149	26
HEXAGONAL PLATES, P1a	(a)	447	8
BRANCHED PLANAR CRYSTALS, P1B	(a)	1825	42

*THE a AXIS, c AXIS, LENGTH L, WIDTH W, OR MAXIMUM DIMENSION D ARE REPRESENTED AS APPROPRIATE

lead to the peak in the graupel size distribution. The graupel mode is at 0.8 mm, but the planar and radiating crystal mode at this same size, which migrates out from the smallest sizes of crystals that collect rime, is in the category of lightest rime coverage. The migration of the planar and radiating crystal modes may be traced out to the 75–100% rime category at 3.5 mm; it bypasses the graupel peak.

The graupel distribution can be compared, with the same result, to the distributions for any of the other crystal habit groups. This is shown by the progressions of riming with crystal size for hexagonal plates, branched planar crystals, the composite of all columnar crystals (groups N, C and CP), hollow columns, and needle-like crystals (Figs. 3–7).

The average areal rime coverage on crystals of average size is given in Table 4 for crystals of the habit groups represented in Figs. 2–7. The average dimensions of the planar and the columnar types are within the size range of the predominance of the graupel. The corresponding average rime coverages, however, are all less than 30%, and much too low to qualify the average crystals as kernels for graupel of the observed sizes.

Hexagonal graupel was observed. However, the sampled hexagonal plates were so lightly rimed that they could not have contributed significantly to the graupel population, as shown by Fig. 3.

The surface representing the accretion distribution for all of the planar and radiating crystals, which includes the six-branched crystals, shows a distinct minimum within the 75–100% rime category at 1 mm and adjacent sizes (Fig. 2). This minimum separates the main body of the distribution from the graupel distribution. The minimum is also evident if the graupel distribution is superimposed on Figs. 3–7 and related to crystals of the other habit groups. With the graupel included, surfaces of consistent slope from modal to maximum rime coverages would be found if the graupel distributions and the distributions of areal rime coverages on crystals were completely interdependent. These surfaces would result from the microphysical process of elimination, whereby some modal percentage of crystals that reach a given size collects a given amount of rime, a smaller percentage collects more rime, and still fewer collect enough rime to become graupel. Thus the percentage of crystals of a given size in the 100% plus category would be less than or equal to the percentages of crystals with less rime. There would be no upswing in the percentage of crystals as the graupel category is reached, and the minimum observed in each case would not occur.

The analyses to this point show that the graupel distribution and the distributions of areal rime coverage on crystals are at least partially independent.

This partial independence can be further substantiated. Graupel particles with "feather-like" extensions that suggest formation on radiating dendrites were observed. Most radiating assemblages of dendrites (group P2) were quite heavily rimed, but 96% of the crystals in this relatively small sample were larger than the 1 mm mean for graupel. The sizes of radiating assemblages of plates (also group P2) were comparable to the graupel dimensions, but only five crystals of this type with more than 75% rime coverage were observed; these crystals, and capped columns (group CP) did not occur with enough consistency or in large enough concentrations to account as kernels for the graupel, as shown in Table 3. Individual needle-like crystals (Fig. 6) so obviously retained their elongated, roughly cylindrical forms, even when heavily rimed, that they could hardly be confused with graupel.

Collectively the data validate the separation of the graupel size distribution from the distributions that describe size and rime coverage of the various crystal types. Any process of graupel formation on kernels, acting alone, would produce the hypothetical distribution with the consistent slope and no separating minimum, as discussed above. Explanation of the observed separation must be based on processes of graupel formation other than that of accretion on kernel crystals. In particular, the explanation must depart from any concept of graupel forming mainly on those kernel crystals that maintain growth for relatively long times and attain relatively large sizes.

Some graupel undoubtedly does form by utilizing kernel crystals. However, the data show that graupel particles that develop with crystals as kernels must form predominantly on a select few relatively small crystals that rapidly gather heavy rime. The size comparisons show that these graupel and their kernels are small relative to the larger crystals of all types precipitated. These small kernels must be a small portion of any given crystal population because many more crystals are observed to continue depositional growth to become larger crystals instead of graupel. Also, of the total number of graupel observed, the graupel formed on kernels can provide only that small portion that contributes to an unseparated distribution of areal rime coverage such as hypothesized above. This portion of the graupel is represented by a fraction of the area under the 100% plus curve for graupel in Fig. 2. This portion can be very crudely estimated by examining the slope of the surface in Fig. 2, and visualizing an extension of the surface from a rime coverage of about 85% to the maximum coverage, with no slope change from negative or zero to positive. The portion of the graupel that accounts for the upswing in the percentage of crystals at 100% plus is thus excluded, and the remaining fraction only accounts for 25% of the total or less.

The selection of a few, relatively small crystals as kernels has at least one plausible explanation. The accumulation of crystal mass by accretion can be an accelerating process. Graupel formation on a few of the smaller crystals requires only that such accelerations and relatively large accretional growth rates be realized by small fractions of the total crystal population during early stages of depositional growth. This selective generation of graupel is indeed possible because natural clouds have non-uniform liquid water contents along the trajectory of any crystal. Those crystals that enter a zone of high liquid water content early in growth are likely to have the greatest opportunity to become graupel, provided they have attained sufficient size to be reasonably efficient collectors of droplets. At later stages of depositional growth, accelerations to the same or even larger rates of mass gain by accretion do not necessarily produce graupel, because much larger total masses of rime must be collected to form graupel from the larger crystals.

Another possible contributor is the aggregate kernel. Holroyd (1964) suggested that conical graupel particles are aggregations of rimed needles or sheaths that collect more rime after aggregation. Needles and sheaths contributed heavily to the total sample, and a small portion of the graupel observed was conical. The needle-like crystals, with respective mean, median and modal lengths of 0.73, 0.65 and 0.60 mm, were generally somewhat smaller than the diameters of the observed graupel, and therefore were apparently compatible with the idea of further growth by aggregation and accretion to form graupel. Drawbacks are immediately evident, however. Aggregates of needles and sheaths observed falling from the Sierran storms were very loosely compacted and randomly structured. Very large accumulations of rime would have been required to fill the open spaces, and graupel particles much larger than observed would have resulted. It is also difficult to visualize how the conical form could have developed.

The question remains as to whether all graupel consistently forms with crystals as kernels. The data indicate that this is not the case. The alternate mechanism postulated by Knight and Knight (1973) for conical graupel formation, and extended to lump graupel development, has been explained above. This process of localized riming on crystals, and subsequent break-off of the rime accumulations to form graupel, does not require graupel particles to be as large as the parent crystals. Also, it permits graupel to occur in greater numbers than the parent particles. Thus, for example, the numbers of 0.5–2 mm graupel in Fig. 2 can significantly exceed the numbers of 2 mm and smaller crystals with 50 or 70 or 90% rime coverage, as observed. This process may therefore logically account for the smaller of the observed graupel particles and the partial independence of the graupel distribution from the accretion distributions of the snow crystals.

Limitations to general acceptance of this process, as discussed in part by Knight and Knight (1973), must be weighed properly. The obscure role of the small, indescribable bits and pieces of ice particles (group I) present in most snow crystal samples must be considered, although many of the irregular particles observed during this study were composed of clear rather than opaque ice. In any case, some of the observed graupel must have developed without kernel crystals, and the localized riming process offers one realistic explanation.

5. Conclusions

Formation and precipitation of graupel are common during all stages of Sierran snowstorms. The significant occurrences of graupel and heavily rimed crystals throughout treated storms show that accretion remains important even with competition from seeding-enhanced growth of ice by deposition.

Graupel occurs with all types of snow crystals. It also occurs when particular types of crystals that could otherwise serve as kernels are either absent from the snowfall, or are occurring with only minor accumulations of rime. There is no one-to-one association of graupel with any particular crystal type, or with either planar or columnar crystals in general. However, branched planar crystals and needle-like crystals occurred most consistently, with heavy rime, during falls of graupel. Thus these types are the most probable candidates for parent crystals for graupel in the observed storms. These and other parent crystals may serve either as graupel kernels, or as temporary carriers of rime accumulations that break off to subsequently develop into graupel.

The shapes of heavily rimed crystals reveal that planar and radiating crystals are more likely kernels than needle-like crystals, as normally assumed. However, the generally hypothesized graupel development by continued accumulation of rime, leading to envelopment of kernel crystals, can explain only a portion of graupel occurrences.

The size distribution of graupel is at least partially independent of the regular snow crystal distributions of size and amount of collected rime. The comparisons of distributions show that graupel does not develop predominantly from snow crystals with the relatively long time periods of growth by deposition and accretion. When graupel does form by utilizing regular crystals as kernels, it forms predominantly on a select few, relatively small crystals that accrete droplets at comparatively rapid rates. Graupel frequently develops without kernels, by alternate riming processes such as the suggested mechanism of localized riming. More convincing theories and evidence for alternatives must be sought. One key approach is to deal quantitatively in models and measurements with the nonuniformities rather than the averages of liquid water contents and other cloud parameters affecting accretion.

Interpretations of related aspects of the accretion process are provided by Reinking (1973; 1974a, b).

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