The Climatology of Hailstone Embryos[1]

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ABSTRACT

Data on hailstone embryo types, using a broad classification as graupel or frozen drops, are presented from several geographical areas representing distinctly different storm "climatologies." The relative frequency of the two embryo types varies greatly from area to area, in a way that correlates rather well with average cloud-base temperature. The warmer based clouds produce hail with more frozen drop embryos. The correlation may be explainable either in terms of the dominant precipitation growth process—liquid coalescence or the ice process—or in terms of recycling of embryos, or both. In light of these results, the transferability of any hail suppression technology from one area to another should not be considered to be automatic.

1. Introduction

Several years of hail collection and embryo classification in northeastern Colorado have revealed that the embryos of the hailstones of that region are predominately graupel. This fact was used as partial support for the case that the ice process is the primary mechanism of precipitation formation in convective storms in that area (Knight *et al.*, 1974; Dye *et al.*, 1974). Data taken from seeding days in the National Hail Research Experiment (NHRE) have been presented and analyzed in relation to the seeding (Knight and Knight, 1979). The present paper records the northeastern Colorado results from all hailstones examined from that area with subsequent, similar studies from climatologically different hail areas. These further studies were undertaken in part from curiosity and in part under the aegis of NHRE because of arguments that embryo type may correlate with the potential for hail suppression by cloud seeding. The initial finding that different climates do produce hail with different embryo-type frequencies has motivated further study because an explanation of the differences is of fundamental interest and of possible fundamental importance in understanding hail growth.

2. Techniques and procedures

Chasing hailstorms to obtain hailstones as they fell was usually done with the aid of radio communication with a radar site. The hailstones were caught in a large, mosquito net funnel and immediately "quenched" in hexane at dry ice temperature (Knight and Knight, 1968). The quenched hailstones were stored in dry ice and transported to a cold laboratory. Hailstones were also collected from the ground in those instances where the vehicle arrived too late to catch them as they fell. For the collections reported outside of northeastern Colorado, the majority of the hailstones were collected from the ground by volunteers recruited by the author or by others. The hailstone embryos were classified from thin sections and photographs made in the cold laboratory and, except where noted, were all done by the author.

None of the samples of embryo types are quantitative in the sense of sectioning and classifying all the stones that fell on a given area. Such a procedure would either give a small sample of the large stones or involve a prohibitive amount of work sectioning the small ones. The procedure used was to have the hailstone size spectrum represented fairly evenly: to section at least 30 or 40 stones from each collection, selected to contain approximately the same number of the smallest sizes as of the largest, and several sizes in between.

Hailstone embryo types were first described in detail from thin-section analysis by List (1958), and have since been described by several other investigators. The results reported here use the rather coarse classification of Knight and Knight (1974): graupel, frozen drop, and everything left over or doubtful. There is undeniably some subjectivity in any classification, but this one is useful because it is unequivocal most of the time. Eighty-eight percent of the hailstones in the author's collection have been classified as containing either graupel

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or frozen drop embryos. The graupel embryos are conical in symmetry and more or less bubbly throughout, whereas the frozen drop embryos are spherically symmetrical (or oblate), with a ring of clear ice surrounding a central, disorganized patch of air bubbles, often containing an expansion crack through the center. One example of each embryo type is shown in Fig. 1. Embryo size cannot be assigned in any but an arbitrary way, as Fig. 1 will reveal, and it is therefore not part of the routinely tabulated data—hailstone size (the maximum linear dimension), however, is.

3. Results

Table 1 contains most of the results of the present hail embryo climatology study in addition to the available, published results from other investigators. The number of storm days is noted in Table 1 because the hailstones from a given storm tend to have some common characteristics so that the number of *storms* sampled is more important for any one area than the number of stones and, in general, is a rough measure of how representative the entire collection may be. The number of stones collected from any one storm is often a reflection of the severity of that storm. To reduce any bias introduced by having analyzed a disproportionately large number of stones from a few storms, all of the author's collections have been normalized to 25 stones from each storm day. Storm day was used rather than storm because of the difficulty encountered in distinguishing one storm from another. As the table shows, the percentages obtained from the normalized collections do not differ greatly from those obtained using the raw data.

The author's results given in Table 1 are also stratified according to hailstone size with 25 mm in longest linear dimension as the separation between large and small stones. Because only hailstone embryos clearly defined as graupel or frozen drops are included in the results reported, the percentages do not add to 100.

The data show that there exist strong differences in predominant embryo type depending upon the geographical area. The largest percentages (87 and 80) of graupel embryos are found in the NHRE area and in the areas of Colorado and Wyoming that surround the NHRE operational area. The smallest percentages of graupel embryos (17 and 23) are found in Oklahoma and the South African Lowveld. The major finding of this study is that the difference in embryo type is so large that, despite sources of subjectivity and bias, it is certainly a real phenomenon.

The size stratification in Table 1 shows a striking consistency in the relationship between hailstone size and embryo type in collections from many different areas. Table 2 is extracted from Table 1 and contains the results from every collection examined by the present author. In each collection the larger hailstones (>25 mm in longest dimension) contained a greater percentage of frozen drop embryos than did the smaller hailstones (≤25 mm) in the same collection. Although the results reported by Carte and Kidder in 1970 for hailstones from the South African Highfeld given in Table 1 are ex-

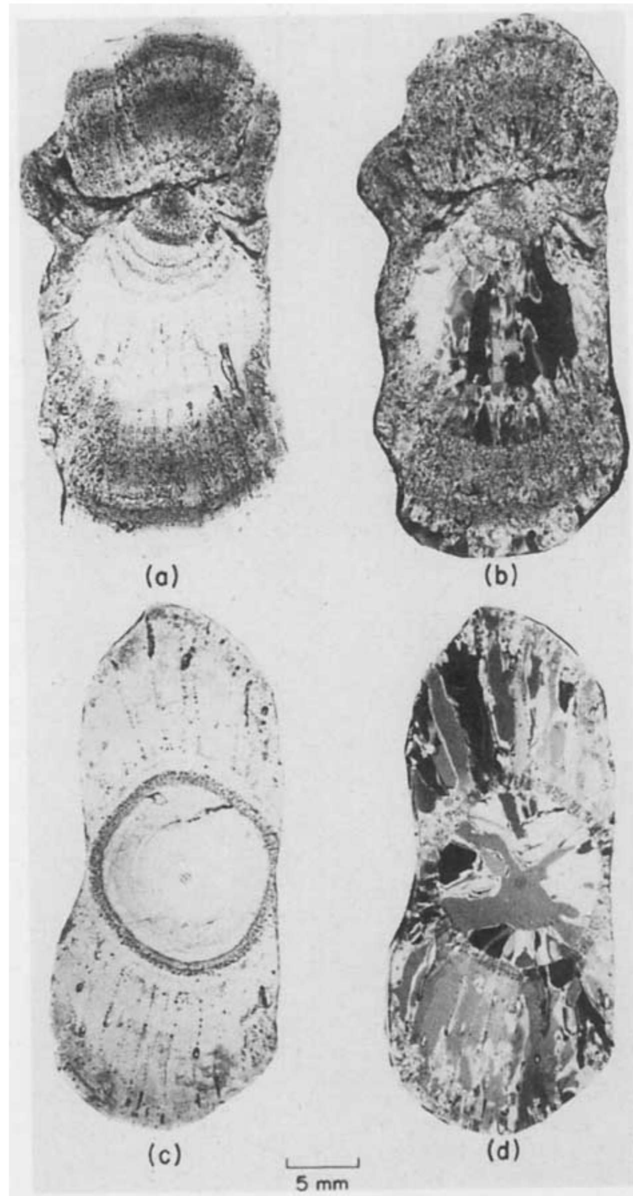

FIG. 1a. Thin section of a hailstone containing a graupel embryo in ordinary transmitted light. Red Deer, Alberta, 1979.

FIG. 1b. Same thin section as in Fig. 1a, in polarized light.

FIG. 1c. Thin section of a hailstone containing a frozen drop embryo, in ordinary transmitted light. Red Deer, Alberta, 1979.

FIG. 1d. As in Fig. 1c except in polarized light.

TABLE 1. Percent of graupel and frozen drop embryos in hailstones from different geographical areas.

Area	Longest dimension (mm)	Number of storm days	Number of stones	Graupel embryos (%)	Frozen drops (%)	Normalized per storm day: Graupel embryos (%)	Normalized per storm day: Frozen drops (%)
NHRE		58	3660	87	9	79	12
	≤25		3478	88	8	83	9
	>25		182	57	27	43	35
Colorado		35	800	80	12	76	12
Wyoming (except NHRE)	≤25		629	89	7	87	10
	>25		171	51	29	38	23
Caucasus[1]		15	210	65	35		
Alberta		23	2110	61	26	74	17
	≤25*		1610*	72	20	79	13
	>25		371	26	56	24	55
Switzerland (Knight)		12	404	49	43	46	45
	≤25		341	51	42	48	45
	>25		63	37	49	37	47
South Africa (Highveld)[2]			1718				
	<10			44	54		
	10–30			60	38		
	30–50			64	35		
	>50			80	18		
Switzerland (Federer)[3]		5	1220	37	63		
Midwest, USA		20	496	29	54	27	62
	≤25		54	41	44	39	53
	>25		442	28	55	23	65
South Africa (Lowveld)		18	1318	23	62	29	54
	≤25		960	29	54	31	52
	>25		358	6	83	6	83
Oklahoma		27	1124	17	62	15	67
	≤25		752	18	58	30	61
	>25		372	13	69	9	65

* Less 129 stones of unknown size.
[1] Khorguani and Tlisov (1976).
[2] Carte and Kidder (1970).
[3] Federer and Waldvogel (1978).

ceptions to the author's observations, more recent results from that group (Roos, 1980) agree with the present author's findings and Roos has concluded that "Evidently, spheroidal glassy embryos . . . were favoured to develop into large hailstones." (Spheroidal, glassy embryos in Roos' classification system are equivalent to frozen drop embryos.) The other exception to this relationship is reported by Khorguani and Tlisov (1976) in hailstones from eleven storms in the northern Caucasus in which the authors state that ". . . the grauple embryo ratio increases with . . . increasing . . . hailstone diameter." In the absence of better documented data from this area it is unprofitable to speculate on possible explanations for the differences.

4. Discussion

a. Origins of the embryos

The water drops that freeze to become frozen drop embryos may originate through a liquid coalescence process or they may be melted ice particles caught in an updraft below the 0°C level and recycled into the storm. Graupel embryos evidently form by the accretion of supercooled droplets onto ice particles in the dry-growth regime. The initial ice particles may be snow crystals, aggregates, frozen drops too small to be recognized later, or ice fragments. The initial ice particle of a graupel hailstone embryo is usually not recognizable in thin section.

TABLE 2. Percent of embryo type by hailstone size.

Area	Number of stones	Longest dimension (mm)	Percent of graupel embryos	Percent of frozen drop embryos
NHRE	3478	≤25	88	8
	182	>25	57	27
Colorado, Wyoming	629	≤25	89	7
	171	>25	51	29
Alberta	1610	≤25	72	20
	371	>25	26	56
Switzerland	341	≤25	51	42
	63	>25	37	49
Midwest	54	≤25	41	44
	442	>25	28	55
South Africa (Lowveld)	960	≤25	29	54
	358	>25	6	83
Oklahoma	752	≤25	18	58
	372	>25	13	69

It seems remarkable that virtually all of the collections of hailstones from single storms from which 50 or more stones were sectioned contain some representatives of both embryo types. As an example, Fig. 2 shows a number of stones from a single collection which arrived at the same place at approximately the same time and which contain two kinds of embryos. This might be taken to suggest that both liquid coalescence and the ice process act to form precipitation in almost all hailstorms, although to differing extents. [One might appeal to giant aerosol particles for the initiation of coalescence (Rosinski *et al.*, 1979) in the storms with especially cold cloud bases.] Another explanation of mixed embryo types can be made in terms of recycling of stones. Ludlam (1958) first argued clearly that hail formation has to be a two-stage process, because updrafts strong enough to support the final hailstone growth are too strong to allow time for embryo formation. English (1973) modeled hail growth from embryos "injected" into the strong updraft and Young (1977), has idealized this for numerical models by considering that any storm contains an embryo formation region, a hail growth zone, and an appropriate delivery of particles between the two. Since the updrafts of most hailstorms do cross the freezing level, one might anticipate that embryo delivery in the form of precipitation particles falling or mixing into the updraft could often span the 0°C level, leading to a mixture of drop and graupel embryos, even in clouds that initially only form precipitation through the ice process.

These two fundamentally different origins for the drop embryos offer competing explanations for the relationships found in the present analysis, as is discussed below.

b. Relation between embryo type and cloud-base temperature

Average cloud-base temperatures have been calculated from lifted condensation levels (LCL) and cloud condensation level (CCL) taken from soundings on hail days in various areas. Fig. 3 gives the

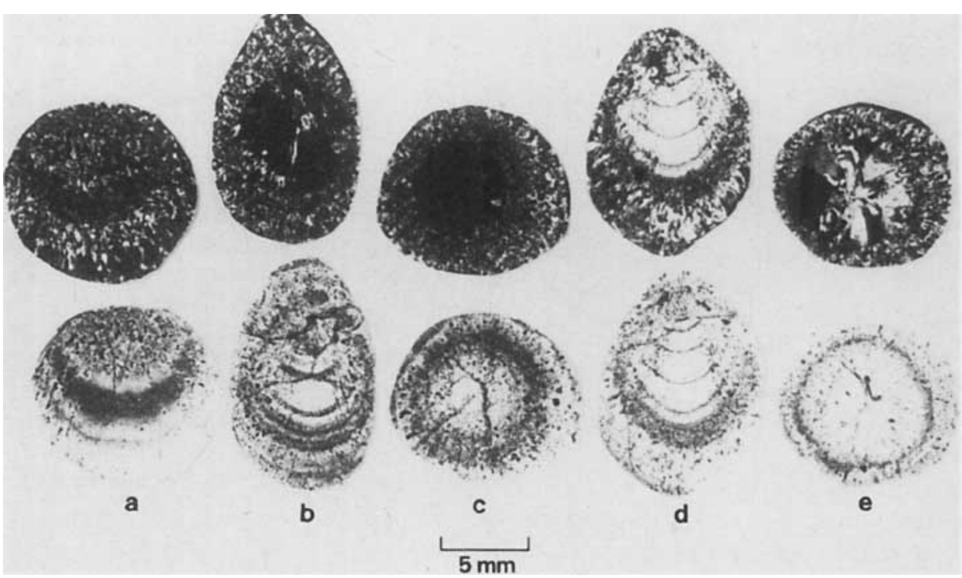

FIG. 2. Thin sections of five hailstones from the same collection in NHRE, 1974, in ordinary transmitted and polarized light. (c) and (e) contain frozen drop embryos; (a), (b) and (d) graupel embryos.

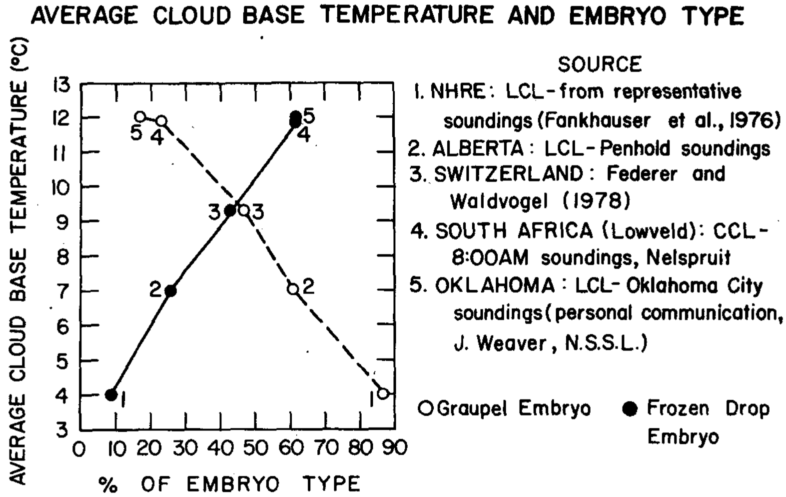

FIG. 3. Percent of graupel and frozen drop embryos as a function of *average* cloud-base temperatures.

sources for these geographical averages and shows a quite systematic relationship between them: the percentage of frozen drop embryos increases with increasing average cloud-base temperature and there is a corresponding decrease in the percentage of graupel embryos. Obviously, warmer cloud bases favor both the suggested origins for the drop embryos, so the existence of the relationship cannot be used as an argument for one over the other.

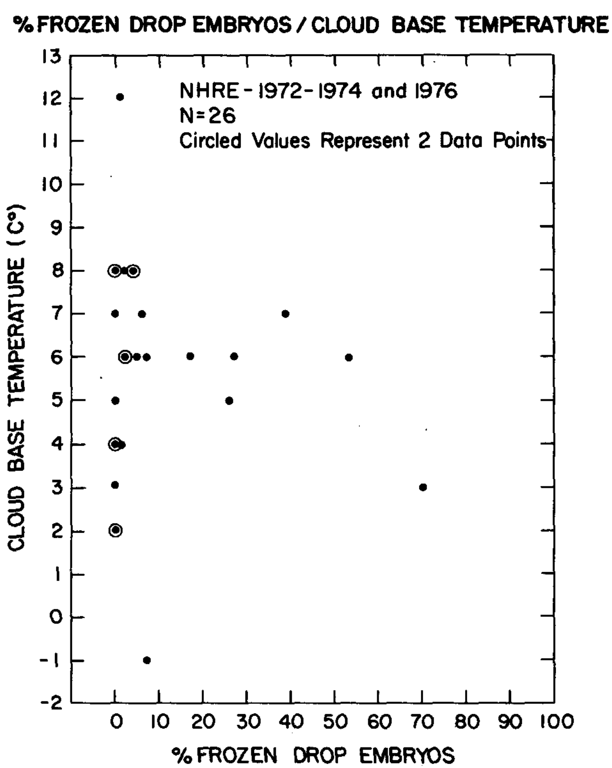

FIG. 4. Percent of frozen drop embryos as a function of cloud base temperature for NHRE, 1972, 1974 and 1976.

It was interesting and surprising that no relationship between embryo type and cloud-base temperature was observed when the largest single data set, that from NHRE, was examined on a day-by-day basis. Fig. 4 shows these results. (The average cloud-base temperature in this figure is ~2°C warmer than the average of +4°C used in Fig. 3 because only the days on which hail actually was collected are included.) One might use the lack of any relationship in Fig. 4 as an argument for the recycling concept, since the strength of the liquid coalescence process should be more highly dependent upon cloud-base temperature; however, the argument is not very compelling.

There are obviously other differences between hailstorms of the various sampled areas than cloud base temperature. These differences range from the average synoptic setting (e.g., frontal versus air mass storm) or the average local sounding (shear or potential instability), to possible consistent microphysical differences (ice nuclei or CCN spectra). Any or all of these factors may be important contributors to the observed differences of hailstone embryos, but the cloud-base temperature is both the only easily quantified factor that could be used for correlation purposes and the one factor that by itself would be expected to relate to embryo type, through either of the mechanisms suggested above.

c. Embryo type versus hailstone size

The relationship between embryo type and hailstone size shown in Table 2 appears only in data averaged over entire groups of collections. Even the large, single storm collections fail to show a clear relation between size and embryo type. Thinking of hail as a two-stage process, one might rationalize the correlation by assuming different average fall velocities for frozen drop and graupel embryos, and, consequently, different average growth histories. However, without embryo size information one cannot carry such speculations very far.

d. Implications for hail suppression

Too little is known about either hail formation or the physical reason for the consistent differences in embryo type between different areas to draw specific implications of these results to hail suppression theories or techniques. One general implication does seem clear, however. The strong embryo type differences suggest that hail suppression techniques cannot be transferred from one geographical area to another without consideration of the predominant embryo type in the area of interest, among other factors. To the extent that embryos form in different ways, a seeding technique reported to be effective in mitigating hail in one area could have a very different effect in a different area. Atlas (1977) has already raised this point, which the present data further support.

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