Results of a Randomized Hail Suppression Experiment in Northeast Colorado. Part V: Hailstone Embryo Types[1]

CHARLES A. KNIGHT AND NANCY C. KNIGHT

National Center for Atmospheric Research, Boulder, CO 80307

(Manuscript received 7 September 1978, in final form 2 January 1979)

ABSTRACT

Hailstones collected within or near the National Hail Research Experiment (NHRE) target area on 23 days of the randomized seeding experiment were sectioned and classified as to embryo type. No significant correlations were found between embryo type and hail size, hail amount or cloud base temperature, but a suggestive relation between seeding and embryo type does exist. The seeded storms had a substantially greater tendency to produce hail with "frozen drop" embryos than did non-seeded storms. Two simple tests give probabilities of obtaining the results by chance of 0.13 and 0.22. The result is suggestive enough to be worth investigating in a future experiment.

1. Introduction

During the hail seasons of 1972–74, hailstone collections were made by mobile chase teams from the National Center for Atmospheric Research (NCAR), the University of Wyoming, and the Desert Research Institute of the University of Nevada. The teams were directed by radio from Grover headquarters and occasionally from aircraft. When possible, freshly fallen stones were picked up from the ground or from a net and quenched in liquid hexane at dry-ice temperature (Knight and Knight, 1968) but about half of the collections were obtained from the ground some 10 to 30 min after fall. Collections were made on 23 of the 57 declared "hail days" [see Part I Foote and Knight (1979): a "hail day" is defined by a radar criterion] and on other days as well, although those do not enter into this analysis. Twenty of the 34 hail days without collections also had no hail measured from pads or separators. Thus in one sense the collections were on 23 of the 37 days, or 62%; but it should be noted that three of the collections were made outside but near the target area on days with zero recorded hail in the target area.

Size distributions were not made from the collections because in nearly all cases the samples were not an unbiased sampling of the total size spectrum of hail that fell at the point of collection. As a general rule, between 10 and 50 stones were sectioned and photographed from each collection, and the embryos were classified as graupel, frozen drop or other, according to criteria given by Knight and Knight (1970). Stones were selected for sectioning so that the entire size range was more or less uniformly represented. This procedure biases the observations toward larger stones in the sample. The largest size therefore is meaningful. The collection sites were always along roads and at times were undoubtedly at an edge of a hail swath or streak.

2. Results

Table 1 gives the collated results from all of the sectioned hailstones. The S or NS beside the data indicates seed and control (non-seed) days. The times given are either a time during the actual hailfall for the fresh collections, or the time of picking the hail from the ground for the others. In cases where the number of stones sectioned is less than 10, it is an indication of the size of the total collection. It was not uncommon to be chasing a storm, to hear an occasional hail impact on the automobile, and to stop and only be able to find 2–10 hailstones on the ground. If a distinct precipitation shaft was in sight and the object of pursuit, the chasers would usually not even stop to look for hail in such circumstances. According to WMO convention (Huschke, 1959), hail is defined as ice particles greater than 5 mm in diameter. This artificial size limitation has no generic significance here, and it is disregarded throughout Table 1.

Not all hail collections on seed days are listed as seeded (Column 6). In this column, "yes" means that seeding could have affected the collection, and

[1] This research was performed as part of the National Hail Research Experiment, managed by the National Center for Atmospheric Research and sponsored by the Weather Modification Program, Research Applications Directorate, National Science Foundation.

0021-8952/79/121583-06$05.50

TABLE 1. Hail collection data for declared hail days.

Date	Location magnetic azimuth, nautical miles from Gill	Time	Number of Collections	Number of Stones	Seed	Percent Drop Embryos	Percent Graupel Embryos	Maximum Hailstone Dimension (cm)	L.C.L. From Representative Sounding (meters, MSL)	Cloud Base Temperature °C	Total Hail Mass in Target Area (10^{10} g) Separator	Pads
1972												
10 June (s)	37.5° — 29 mi	19:30	1	63	yes	41	51	2.3	3478	5.7	0	0
16 June (ns)	88° — 45 mi	16:45	1	8	no	0	88	1.3	2939	8.4	0	0
17 June (s)	2° — 37 mi	15:15	1	14	no	0	93	1.4	3295	7.1	5.21	2.71
	3° — 36 mi	15:27	1	16	no	0	100	1.4				
	59° — 26 mi	15:40	1	46	no	0	100	1.1				
	78° — 56 mi	17:45	1	27	yes	30	70	1.4				
	358° — 43 mi	15:02	1	16	no	0	100	1.3				
	359° — 42 mi	15:00	1	8	no	0	100	1.3				
22 June (ns)	12.5° — 36.5 mi	16:47	1	19	no	32	68	1.4	3653	4.9	0	0
	10° — 35 mi	16:43	3	22	no	27	73	1.7				
23 June (s)	55° — 34 mi	18:33	1	9	yes	78	22	1.6	3881	2.8	5.70	7.92
	53° — 34 mi	19:00	1	11	yes	64	0	1.7				
26 June (s)	33° — 57 mi	16:40	1	7	no	0	100	1.6	3706	1.6	0.03	0.24
6 July (ns)	62° — 26 mi	15:45	1	6	no	0	100	2.3	3753	3.8	4.98	6.43
	57° — 42.5 mi	16:20	1	8	no	0	100	2.3				
7 July (s)	47° — 47 mi	18:10	1	16	yes	12	81	1.4	3268	8.0	32.66	19.68
	71° — 61 mi	19:18	1	29	yes	0	97	1.2				
24 July (s)	65° — 33 mi	15:40	1	14	yes	50	50	2.0	3842	5.6	4.99	6.09
	67° — 38 mi	16:00	1	6	yes	33	67	1.0				
	67° — 36 mi	16:10	1	11	yes	18	82	1.2				
	33° — 47 mi	16:35	1	10	yes	0	100	1.5				
26 July (s)	51° — 36 mi	17:55	1	11	yes	27	27	1.1	3749	6.1	37.75	10.53
	350° — 40 mi	14:50	1	21	no	5	95	1.3				
27 July (ns)	21° — 27 mi	14:55	2	19	no	31	68	1.1	3544	5.7	9.55	3.15
	15° — 17.5 mi	15:08	1	12	no	0	100	1.0				
	22° — 50 mi	17:30	2	65	no	9	89	1.1				
	37° — 53 mi	17:55	1	6	no	50	33	1.1				
1973												
21 May (ns)	332° — 43 mi	13:20	1	23	no	0	100	3.3	3203	3.8	111.93	39.85
	54° — 43 mi	15:52	1	4	no	0	100	2.1				
	61° — 41 mi	16:00	1	8	no	0	100	1.6				
	58° — 42 mi	15:55	1	43	no	0	100	1.8				
	50° — 44 mi	16:30	1	2	no	0	100	1.6				
28 June (s)	50° — 18 mi	17:07	1	31	no	3	97	1.9	3438	7.9	12.10	1.91
	27.5° — 16 mi	17:58	1	26	no	0	92	1.2				

TABLE 1. (*Continued*)

Date	Location magnetic azimuth, nautical miles from Gill	Time	Number of Collections	Number of Stones	Seed	Percent Drop Embryos	Percent Graupel Embryos	Maximum Hailstone Dimension (cm)	L.C.L. From Representative Sounding (meters, MSL)	Cloud Base Temperature °C	Total Hail Mass in Target Area (10^{10}g) Separator	Pads
1973 (Contd.)												
9 July (NS)	39.5° — 45 mi	16:30	1	24	NO	0	100	0.8	3842	5.7	1.59	1.17
	58.5° — 42 mi	16:58	1	4	NO	0	100	0.9				
	67.5° — 42 mi	17:30	1	29	NO	14	76	1.4				
21 July (NS)	21° — 27 mi	16:50	2	68	NO	2	80	1.4	2474	12.0	41.79	13.12
	34° — 25 mi	16:50	1	34	NO	0	100	1.4				
28 July (NS)	51° — 45 mi	16:45	1	3	NO	0	100	0.7	4002	2.1	1.10	0.32
	350° — 15 mi	15:30	1	15	NO	0	100	1.2				
1974												
17 May (S)	68° — 45 mi	19:00	1	3	YES	0	100	0.4	2158	8.5	0.23	0
19 May (NS)	72° — 68 mi	17:30	2	27	NO	20	80	1.6	4542	-0.8	0.23	0.32
12 July (S)	10° — 40 mi	16:40	1	57	NO	2	88	0.9	4220	5.6	1.73	0.43
21 July (S)	57° — 51 mi	17:08	1	54	YES	39	37	2.3	3479	7.5	1.69	1.32
24 July (NS)	63° — 65 mi	14:00	1	42	NO	0	88	1.6	3633	7.2	2.55	0.03
7 August (S)	42° — 57 mi	15:51	1	54	YES	2	96	1.0	3618	5.7	44.45	15.96
	34° — 56 mi	14:53	1	38	YES	0	100	0.8				
9 August (NS)	9° — 42.5 mi	16:42	1	26	NO	12	42	1.4	2503	9.0	23.98	0.39
	13° — 44 mi	16:59	1	13	NO	100*	0	1.5				

*This percent of drop embryos is badly biased. Hemispherical stones were selected for collection and sectioning because of their odd shapes, and they were all broken halves of small stones with drop embryos.

"no" that it definitely could not have, as for instance when the collection was made before seeding commenced on that day. The percent drop and graupel embryos often do not add up to 100, because some embryos were not classifiable.

It is particularly interesting to note, when comparing the present results with results from other areas, that the hail in this sample is small. The maximum diameter of hail collected was greater than 1 inch (2.4 cm) on only one of the 23 hail-day collections.

The lifting condensation level and corresponding cloud-base temperatures are taken from Fankhauser *et al.* (1976) and the total hail amounts are from Dye *et al.* (1976).

3. Discussion

While the observations were not made with the idea of seeking seeding effects (if that had been the motive, a much better sample could have been obtained), this brief resumé of results is given because the collections were extensive enough that it is possible that the results might be relevant to the seeding effect analysis. The relevance might be of two forms: an indication of a direct seeding effect or an indication of an unrepresentative draw, a chance imbalance in the selection of seed and control days.

At the present state of knowledge of both the processes within thunderstorms and the interpretation of hailstone features, discussion of either of these possibilities must be very speculative. Briefly, graupel embryos are thought to originate by riming of snow crystals or *small* frozen drops. If a frozen drop larger than about 400 or 500 μm diameter started the graupel, then it would be recognizable as such (Knight and Knight, 1970) and the embryo would be called a drop embryo. The complications become apparent when it is realized that the drop embryos might be the result of an entirely liquid coalescence process (aided or not by giant nuclei) or they may be recirculated, melted graupel or small hail or they might arise from coalescence triggered by drops shed from melting hail. Still other possibilities may exist and the fact is that there is insufficient evidence for deciding the actual embryo origin in all of these cases. Attempting to elucidate the origin of the drop embryos is a subject for further work.

Some model treatments (e.g., Nelson, 1976; see also Atlas, 1977) have also shown a great influence of the presence or absence of large supercooled drops on the efficiency of seeding with ice nuclei for hail suppression. Unfortunately, whether the models apply to natural clouds in the kind of detail that would be required for these results to be meaningful is also unknown. However, the models are suggestive, and it does stand to reason from very general arguments that the presence or absence of substantial concentrations of large supercooled drops might strongly influence seeding effects. The scientific rationale underlying the allegedly successful Soviet hail-prevention technique is based on the existence of large supercooled drops in an accumulation zone of restricted volume.

A serious problem in using these hail embryo-type data at all is the question of representativeness of the samples. Many of the samples are small, and on some days there is only one collection. However, the data do give a little confidence that a hailstorm tends to be rather consistent in its embryo types when sampled at different places. In Table 1, 21 May 1973 is probably the best example; but see also 17 June 1972, in which the only unusual collection, with regard to embryo type, was taken more than 2 h later than the rest, and 24 July 1972, for which the odd sample was collected far from the others. More extensive data on this question, from analysis of the extensive 1975 and 1976 collections, confirm this consistency of embryo type over time and space scales that correspond to single storms.

The correlations that might be sought in these data are between maximum stone size, embryo type, cloud-base temperature, total hail mass and seeded versus control days. Fig. 1 shows the hail mass, in grams, estimated for the entire target area from hail network data, plotted against percentage of drop embryos for the 23 hail-day collections. Each point is labeled S (seeded), NS (non-seeded), or NS(SD), the last referring to a collection from a definitely non-seeded storm on a seed day. The four points along the ordinate at 10^9 g are in reality three 0's and one estimate of 3×10^8.

No relation is seen between hail mass and embryo type, and there is no strong, obvious relation in this sample of 23 days between seededness and hail mass. It is remarkable, however, that there is a strong tendency for days with the most drop embryos to be seed days. With the exception of the one point marked by an asterisk (9 August 1974, see footnote to Table 1), which is too high in percentage of drop embryos but by an unknown amount, six of the seven highest percentages of drop embryos were on seed days. On the one of these days with 41% drop embryos but no hail within the target area (10 June 1972), the hailfall was outside the target area and was quite heavy: it was actually one of the most severe hailstorms sampled, and it was seeded. Total hail mass restricted to the target area is a misleading index of storm severity.

This curious bias toward seed days having more drop embryos was the only correlation found in these data that appeared even suggestive. It is even more suggestive when the two of the 23 days with both S and NS(SD) collections are examined. In both cases the S collection has a much higher drop

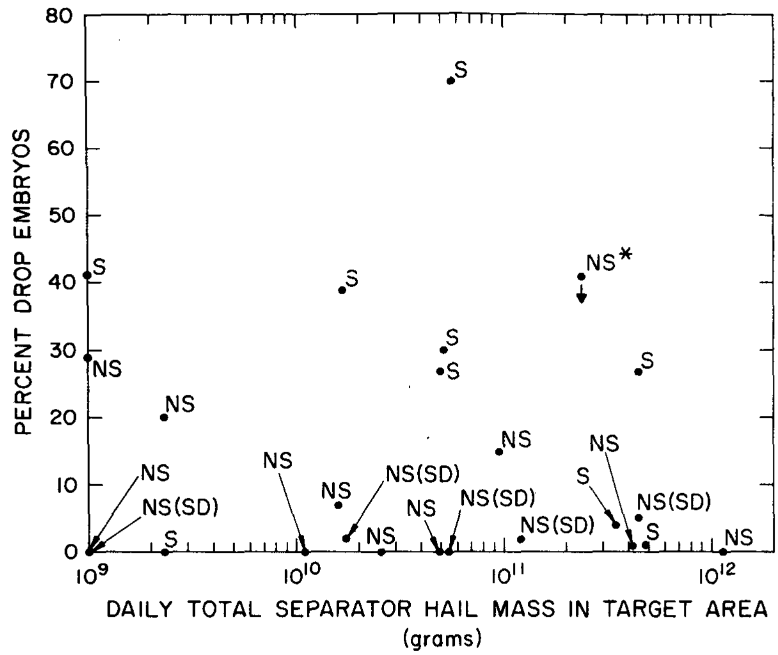

FIG. 1. Each point represents a collection or group of collections from a single storm, and is located to indicate the percentage of drop embryos found and the total hail mass in the target area. Only data on declared hail days are included, but the collections are not necessarily made inside the target area. S designates a seed day, with the collection from a cell that might have been seeded; NS(SD) a seed day but a definitely unseeded collection; and NS a non-seed day. See text for further discussion. The asterisk represents an overestimate of the percentage of drop embryos (see Table 1).

embryo percentage than the NS(SD) collection, but a close examination of 26 July 1972 (Sanborn *et al.*, 1976) indicates that here it appears very unlikely that the S collection actually was affected by seeding. We reiterate that the NS(SD) designation implies *definitely* non-seeded; S implies only that the hail may have fallen from a seeded cell. There is no way of establishing that AgI really did reach supercooled parts of any given cell.

The two contingency tables (Table 2) were used to derive probabilities of the results coming from a homogeneous population. The two unbiased divisions are, first, 0% drop embryos versus >0% drop embryos; and second, <3% drop embryos versus >3% drop embryos, the division that most nearly divides the sample in half. By selecting the best percentage of drop embryos (~25%) as the separation, a more significant result could be found, but such a procedure hardly seems valid, without an independent, physical reason for splitting the population at that value.

This relationship between embryo type and seeding could be the object of nearly limitless speculation, but it is perhaps the best course here to leave such speculation at a minimum. If this relation is significant and not just a happenstance, then a direct effect of seeding upon embryo type would be a natural explanation except for the apparent absence of any straightforward reason why seeding with ice nuclei should produce frozen drop embryos rather than more graupel embryos. If the relation is just due to chance, then it is indeed a suggestion of an unrepresentative draw.

These results are not relevant in evaluating the NHRE seeding experiment, except insofar as the predominance of graupel embryos already reported (Knight *et al.*, 1974) contributes to the conclusion

TABLE 2. Two contingency tables of the probability of obtaining the correlation between embryo types and presence or absence of seeding. The two divisions of the sample are discussed in the text.

	0% drop embryos	>0% drop embryos		<3% drop embryos	>3% drop embryos
S	1	8	S	2	7
NS	5	6	NS	6	5
NS(SD)	2	3	NS(SD)	4	1
Total NS	7	9	Total NS	10	6
	$P = 0.22$				$P = 0.13$

that accumulation zones of large supercooled water drops are not a source of hail embryos in northeastern Colorado hailstorms. As is discussed somewhat more fully in Part IX (Knight *et al.*, 1979), this in turn contributes to the conclusion that the NHRE seeding method, modeled after Soviet techniques, was inappropriate for suppressing hail in northeast Colorado.

The relation between seeding and embryo type is strong enough, however, to suggest that a future hail suppression test might include the gathering of more data of this kind, to see if the correlation is meaningful or not. If, for instance, a tracer experiment (Browning and Atlas, 1977) necessitated extensive hail collection, embryo analysis could be done at the same time with little extra expense.

Acknowledgments. Special thanks are due to the many people who participated in obtaining the hailstone collections, and to those at the Grover operations center and in research aircraft who helped in directing the chase vehicles into the paths of storms.

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