"REVIEWED"

SOME HISTORIC OPERATIONAL HAIL SUPPRESSION PROGRAMS DATING TO 1957

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Abstract. Operational (non-experimental) programs designed to reduce hail damage by various cloud seeding techniques using artificial ice nuclei have been conducted for more than 30 years. Six of these historic programs operated in quality fashion are summarized. Each was designed around the application of silver iodide by aircraft flying at cloud base and/or near cloud tops. In a few cases, the airborne application of seeding material was supplemented by a network of ground generators. In each case, ground-based radar systems were used to direct project operations. The reviewed programs include operational areas in the states of New York, Colorado, Texas and Utah, plus the countries of Kenya and Greece. Various methods of evaluation are discussed and results suggest reductions in hailfall within a broad range of probabilities.

1.0 INTRODUCTION

The modern era of weather modification has lasted four decades. November 13, 1946, the date of Dr. Vincent J. Schaefer's discovery of artificial ice crystal production by solid carbon dioxide (dry ice), marked the beginning of a meaningful understanding of this science and technology. The technology has been largely applied to rain and snow enhancement, hail suppression and local fog dissipation. Like any evolving technology, each of these areas of modification continues in various stages of development and improvement. Efforts to suppress hail by cloud seeding began within the United States in the mid-1950's. Since that time, the technology of hail suppression has been applied in many countries of the world.

Calculated on the basis of 1975 dollars, the average annual hail damage to property and agriculture in the United States exceeded $800 million (Changnon, et al 1977). At present values, the U.S. losses probably exceed two billions dollars. The average annual loss figure covering global scale hail damage is not easily computed but can be conservatively estimated from a variety of international reports at well over four billion dollars. It may actually be much higher (Lloyds 1986).

Both laboratory and field experiments have suggested the possibility of reducing hail damage by artificially converting large amounts of supercooled liquid water to ice crystals in potential hail clouds, thereby inhibiting or eliminating hailstone growth. This view has lead to theoretical investigations which suggest the apparent results may be strongly related to delivery techniques of the nucleating material, the type and form of nucleating material delivered, and the physical characteristics of the treated storms.

Optimism among operators and program sponsors has produced the resources necessary to sustain several operational programs. However, there presently exists a difference in viewpoint between those individuals who accept the statistical results from a few operational programs with improved design features, and those individuals who require both physical and statistical evaluations from field experiments.

Six examples of operational hail suppression programs are summarized in the following sections of this paper. The ones chosen were designed around the airborne application of silver iodide ice nuclei, with two exceptions where extensive networks of ground generators served as major sources of nuclei. The programs selected for assessment are limited to those which had major design, operation and evaluation inputs by the author. They are listed in Table 1.

2.0 FEATURES OF REVIEWED OPERATIONAL PROGRAMS

2.1 The Hudson Valley Program, New York

Organized in 1956 with funds supplied by voluntary contributions from apple orchard farmers in the Hudson Valley upstate from New York City, this program was operated for a two-year period during the summer months of 1956 and 1957. Operations were designed around a network of about 75 ground generators which contained a solution of 4% silver iodide by weight complexed with sodium iodide in acetone and burned in a propane flame. This network was supplemented by a P-40 aircraft equipped with two airborne liquid-fuel silver iodide generators. A 3cm radar system was located near the center of the target area and served as the field headquarters for all operations. The total target area was approximately 4,000 km^2.

TABLE 1.

SUMMARY INFORMATION FOR SIX HAIL SUPPRESSION PROGRAMS 1956-1985

Program	Period of Operations	Aircraft	Ground Generators	Radar	Number of Storm Days
1. Hudson Valley, N.Y.	01 Jul-30 Sep 1956	1 (P-40)	77	3cm	29
	15 May-30 Sep 1957	1 (P-40)	75	3cm	40
2. Northeast Colorado	15 May-15 Sep 1959	2 (P-40) 3 (T-28)	135	3cm	52
3. Kenya, Africa	01 Oct-30 Sep 1968	1 (T.C.)	0	3cm	184
	01 Oct-30 Sep 1969	2 (T.C.)	0	3cm	210
	01 Oct-30 Sep 1970	2 (T.C.)	0	3cm	200
	01 Oct-30 Sep 1971	3 (T.C.)	0	3cm	232
	01 Oct-30 Sep 1972	3 (T.C.)	0	3cm	222
	01 Oct-30 Sep 1973	3 (T.C.) 1 (T-206)	0	3cm	185
	01 Oct-30 Sep 1974	3 (T.C.) 1 (T-206)	0	3cm	126
	01 Oct-31 Jan 1975	3 (T.C.) 1 (T-206)	0	3cm	23
4. Western Texas	14 May-09 Sep 1970	3 (T.C.)	0	3cm	30
	10 May-10 Oct 1971	3 (T.C.)	0	3cm	26
	10 May-31 Oct 1972	3 (T.C.)	0	3cm	39
	01 May-31 Oct 1973	5 (T.C.)	0	3cm	19
	01 May-31 Oct 1974	3 (T.C.)	0	5cm	35
	01 May-31 Oct 1975	3 (T.C.)	0	5cm	43
5. Northern Utah	15 May-15 Sep 1976	2 (TC/AZ)	5	5cm	23
	15 Mar-15 Sep 1977	2 (TC,AZ)	10	5cm	54
	16 May-30 Sep 1978	2 (TC,AZ)	0	5cm	12
	15 May-15 Sep 1979	2 (TC,AZ)	0	5cm	44
	15 May-31 Aug 1980	2 (TC,AZ)	0	5cm	11
	15 May-15 Aug 1981	2 (TC,AZ)	0	5cm	13
6. Northern Greece	01 Sep-31 Oct 1981	2 (AZ)	0	5/10cm	2
	15 Apr-15 Oct 1982	2 (AZ)	0	5/10cm	25
	01 May-30 Sep 1984	5 (AZ)	0	5/10cm	21
	01 May-30 Sep 1985	5 (AZ)	0	5/10cm	21

Severe storms associated with frontal passages moving from west to east, plus local airmass thunderstorms developing within the target area, were responsible for the severe hail at ground level. Operations covered three months in 1956 and four months in 1957. An average of 10 storm periods per month was recorded during this two-season period. Within these storm days in 1956 and 1957, the radar meteorologist recorded 282 and 418 individual precipitation echoes (cells) respectively. Some 3,693 ground generator hours and 51 aircraft seeding flights were logged within these two seasons (Henderson 1956, 1957).

2.2 Northeast Colorado

The largest single-area hail suppression operations program ever organized in the United States was conducted during the 15 May - 15 September period in 1959. This historic program was operated over an area of approximately 9,000 km^2 in the extreme northeast corner of Colorado and included a 3cm radar system, 5 aircraft, and 135 silver iodide ground generators. A total of 14 persons were involved in the actual conduct of the program, not considering the residents of the area who operated the individual ground generators on command from the radar field headquarters. Funding for the program was supplied by voluntary contributions from dry-land farmers, cattle ranchers and various businesses within the region.

The five cloud seeding aircraft (three T-6, and two T-28) were each equipped with two airborne liquid-fuel generators. The ground generators and the airborne generators utilized a solution of 2% silver iodide by weight, complexed with sodium iodide in acetone and burned in combination with propane. Severe hail at ground level was produced by both squall lines associated with frontal passages and individual thunderstorms associated with local unstable air conditions.

During the four-month period in 1959, a total of 630 potential hail cells was noted by radar within the target area. Approximately 94% of these were identified as producing hail either aloft or at ground level at some time during their life cycle. Within the actual 52 seeding days more than 7,400 hours of ground generator time and 219 cloud seeding flights were logged (Henderson, 1960; Schleusener 1959, 1960, 1962).

2.3 Kenya, East Africa

The Kenya Hail Suppression Project was organized in October 1967 and continued for more than seven years through 31 January 1975. The operation area was located some 80 km easterly from Lake Victoria, and about 190 km northwest of Nairobi. Funding for the program was developed by tea interests in Kenya, largely the African Highlands Produce Company (James Finlay Company, Ltd.) and the Kenya Tea Company (Brooke Bond Ltd.). Kenya is one of the only areas in the world where the tea plant does not go dormant at least during some portion of the year. The area also produces an unusual number of days with hail noted at ground level somewhere within or near the growing tea. This average is nearly 200 days per year! Hailfall has been logged during every month of the year in this area.

The operations program actually included two target areas of about 900 km^2 each. Within these two areas some 20,000 hectares of select tea were in production. During the early stages, a single aircraft equipped with pyrotechnic cloud seeding devices was the only method of dispensing silver iodide. A second aircraft was added in the second year, another followed in 1970, and in 1972 a fourth aircraft was added to the full operations. Silver iodide pyrotechnic devices, both ejectable and end-burning units, were the only means of nuclei dispersal used during the total operation. Storm cells were primarily seeded at cloud base, but occasionally this was supplemented by cloud-top seeding near the -10^{o}C level. A ground-based 3cm radar system always served as the supervisory equipment at the field headquarters.

During the full 88-month operational period, a total of 1,382 operational days were logged with one or more seeding flights. Some 3,173 seeding flights were launched plus an additional 1,980 cloud observation flights conducted when potential hailstorms were anticipated but none occurred. More than 5,700 storm cells were seeded during the 88 months of operations (Henderson 1972, 1975).

2.4 Texas Program

The Texas Hail Suppression Program was another effort funded by voluntary contributions from farmers, ranchers, and a few businesses in west Texas. Each year portions or all of four different counties were included in the target area of approximately 6,000 km^2. The program was initiated on 14 May 1970 and remained operational for four or five months each year until 31 October 1975.

The program began with field supervision from a 3cm radar system. In 1974 a 5cm weather radar system was substituted and was used during the final two years of the program. Three aircraft were assigned to the program each year, except when the target area was expanded in 1973 and an additional two aircraft were operational over the total area. Each aircraft was fitted with two airborne liquid-fuel silver iodide generators and racks for mounting pyrotechnic seeding devices. Application of silver iodide seeding material was primarily accomplished within the strong inflow areas near cloud base, although occasionally some flights were conducted near the tops of growing cloud turrets near -10^{o}C. The airborne generators utilized 4% silver iodide by weight in a complexed solution of sodium iodide and acetone.

During these six operational periods from 1970 through 1975 the aircraft conducted 554 seeding flights, logging nearly 1,000 hours of flight time. More than 430,800 grams of silver iodide were dispensed into 1,212 storm cells (Changnon, 1974; Henderson 1971, 1972, 1974; Schickedanz 1974).

2.5 Utah-Idaho Program

Operations of this program began on 15 May 1976 and continued through 15 August 1981. The operational periods each year ranged from two to six months. During the first four years, the total operational area was approximately 26,000 km^2. A 2,600 km^2 portion of the target area in Idaho was deleted during the 1980 and 1981 seasons, leaving some 23,400 km^2 for operations in these final two years. This was one of the first programs in the United States which was funded through a political process involving state/county cooperative efforts.

The operations were designed around a 5cm ground based radar system and two aircraft equipped with both liquid-fuel generators and special holding racks for pyrotechnic cloud seeding devices. During the 1976 and 1977 operations, the aircraft seeding capability was supplemented by 5 and 10 ground generators respectively. No ground generators were used during the subsequent four years.

Within these six operational periods from 1976 through 1981, the aircraft conducted 350 cloud seeding flights, logging some 802 hours of flight time. Nearly 102,800 grams of silver iodide were dispensed into 762 storm cells (Henderson 1979, 1981).

2.6 Program in Greece

Following a number of administrative requirements, the hail suppression program in Greece was activated for a two-month period from 1 October through 31 November in 1981. In the following year of 1982 a full operational period was activated between 15 April through 15 October. No program was initiated in 1983. However, the program was reactivated and expanded in the following season and was active during periods from 1 May through 30 September in 1984 and 1985. The program was been funded by the Greek Government.

Operations were designed around the use of five aircraft and the dispersal of silver iodide ice nuclei generated by pyrotechnic cloud seeding devices. The application of seeding material was accomplished at both cloud base and at cloud tops near the -10 C^{o} level. One 5cm radar and two 10cm radar systems were used for storm detection and supervision of the program as operated over three target areas in the northern section of the country. Within major agricultural areas, two of the targets had areas of 1,000 km^2 each and the third occupied an area of 2,000 km^2.

Within the four operational seasons, a total of 136 seeding flights were logged during the 69 seeding days. Observations flights totaled 119 on other days when clouds were present but no seeding was required. A total of 101,300 grams of silver iodide were dispensed by pyrotechnic devices over the four season period (Flueck 1985, 1986; Henderson 1985; Solak 1985).

3.0 EVALUATIONS OF RESULTS

3.1 Introduction

During the 30-year period 1956-1985, many statistical and physical evaluations of hail suppression programs have been conducted. These have caused discussion and debate at both the operational and scientific levels (Henderson, 1971; Changnon 1974; Sonka 1977).

Operational programs have been numerous and extensive (Todd, Clement J. and Wallace E. Howell, 1985.) Scientific experiments have been limited to only a very few areas of the world (Foote, G. Brant and Charles A. Knight, 1977). Most operational programs have included only minimal design criteria as compared to scientific experiments and the rigid program analyses which follow. As a result, operational hail suppression programs have been slow in producing the kinds of physical and statistical results acceptable to the scientific community. Nonetheless, some hail suppression programs operated over this past 30 year period have been well designed and operated, producing information worthy of assessment. Most of these have indicated beneficial hail reductions (Changnon, 1974; Henderson, 1972, 1975, 1979, 1985).

Data from the six programs summarized in this paper have been examined at considerable depth and the results from these investigations are listed in Table 2. With the exception of the program in Greece conducted during the 1984 and 1985 seasons, none of the program designs included randomization within the operations. These assessments of non-randomized programs have largely consisted of statistical comparisons of seeded and non-seeded periods and/or areas. Further details and brief comments on these evaluations are presented in the following sub-sections.

3.2 Hudson Valley, New York

At the time this program was designed and conducted, very little was known about clouds which produce hail, the hailstone birth and growth mechanisms, or a most appropriate statistical methodology which might be applied to collected data. At the operational level, the general attitude seemed to be, "If there is considerable hail damage within the protected area, the operations must be unsuccessful. If there was very little hail damage, the program surely was responsible for a positive result."

In the case of the Hudson Valley Program, only some minimal Target-Control hail damage relationships, plus a few radar echo seed/no-seed comparisons, were developed following program operations (Henderson, 1956, 1957). In the case of Target-Control investigations, hail damage was examined both within and beyond the target boundaries. There was evidence that hail damage to apples was somewhat more severe in the areas beyond these boundaries than within the protected area. The data did not lend themselves to a strong statistical treatment. Radar echo data logged for storm cells within and beyond the target boundaries also suggested higher reflectivities outside the protected area during and following the seeding events. Once again, the data did not receive a rigorous statistical treatment.

TABLE 2

RESULTS FROM EVALUATIONS OF SIX HAIL SUPPRESSION PROGRAMS, 1956-1985

Program	Total Seasons	Type of Evaluation	Data Source*	Results (averages) Change in Hailfall	Results (averages) Change in Rainfall	Significance Level (Hail)
1. Hudson Valley, N.Y. (1956-1957)	2	T-C	C,R	A weak suggestion of less hail with no effect on rainfall		Not Sig.
2. Northeast Colorado (1959)	1	T-C	HP,R	Decrease	Increase	Not Sig.
3. Kenya, East Africa (1968-1975)	8	S/N-S	C,R	-28%	+12%	0.05
4. Western Texas (1970-1975)	6	T-C	I,R	-48%	+5%	0.05
5. Northern Utah (1976-1981)	6	T-C	I,R	-69%	+11%	0.10
6. Northern Greece (1981/82 - 1984-85)	2 2	T-C S/N-S	C,R HP,R	-52% -75%	+6% +9%	0.10 0.03

* C = Damage to crops
R = Radar data (reflectivities)
I = Insurance data
HP = Hailpad data

A cursory examination of rainfall data was also conducted and the Target-Control comparisons during historic and operations periods indicated neither a positive nor negative effect on total rainfall during either of the operational seasons. At the end of the two-season program, both hailfall and rainfall results appeared uncertain although both radar data and Target-Control hailfall comparisons provided a modest suggestion of less hail within the protected area.

3.3 Northeast Colorado

As noted in many previous publications, a hail suppression program operated for only one year has little chance of accumulating enough data which will indicate results at a reasonably high significance level. This is particularly true in the case of operational programs which are not usually designed with all the necessary features of a scientific field experiment.

In the case of the Northeast Colorado Program conducted in 1959, the program did have an independent analysis by personnel from Colorado State University. This independent research was conducted at the request of the program's sponsor, Northeast Colorado Hail Suppression Association. The research had three goals:

1. To attempt to determine if the cloud seeding program was effective in reducing hail intensity.
2. To attempt to determine the effect of the cloud seeding program on precipitation amounts.
3. To gain a better understanding of the physical processes involved in hail occurrences.

The independent field research effort focused on reports of hail occurrences by mail (389 reports received) from observers both within and beyond the protected area boundary, information from 250 hailpads located within and near the protected area, and precipitation data from U.S. Weather Bureau sources. The evidence from these independent investigations (Schleusner, 1959, 1960) suggested the following:

(1) Cloud seeding probably was associated with decreases in hail intensity and areal extent in some cases during the summer of 1959 in northeast Colorado.
(2) A comparison of hail events from 15 May through 15 September 1959 indicates a reduction in hail impact energy associated with the seeding.
(3) A target-control analysis of rainfall indicates a positive precipitation anomaly for the area included in the cloud seeding program.

3.4 Kenya, East Africa

Even though the hail suppression program in Kenya was not designed as a randomized experiment, it did offer excellent evaluation opportunities for the following three reasons:

(1) The average number of hail days per year was near 200.
(2) The rapid nature of the tea growth and the harvest (each 10-15 days).
(3) The long-term experience of tea estate managers in assessment of tea production against crop losses due to individual hailstorms.

From an operational viewpoint, not all hail producing storms could be treated with silver iodide because of the large numbers and rapid growth of individual cells, plus the logistics of aircraft flights during each day's relatively short period of cloud growth and hail production.

Utilizing the radar system to identify all individual potential hail producing cells, plus the rather precise independent assessment of damage to the tea plants over various sections of the protected area, the tea estates administrative staff were able to provide a separation of damage which resulted from seeded and not-seeded hail cells. Over the eight year period from 1967/68 through 1974/75, the average damage to tea per hail instance from 3,464 hail instances was 3,082 Kg in the seeded cases and 4,280 Kg per hail instance for the not-seeded cases (Henderson 1972, 1975). The analysis suggested a reduction in hail damage of about 28%, significant at the 0.05 level. This appeared to be a relatively large reduction when one considers that the operational design called for aircraft to seed the highest intensity (radar reflectivity) cells first, then move down the intensity scale as more potential hail cells developed during each period. Such an operational criterion tends to leave the weaker cells in the not-seeded category, suggesting that the apparent 28% reduction is probably conservative.

Additionally, an investigation was conducted on precipitation data obtained from some 16 stations within and adjacent to the protected area. Annual rainfall amounts were statistically compared using target-control relationships developed from data obtained during the historic period prior to the start of this hail suppression program. The results from this analysis indicated a surprising 12% average annual increase in rainfall within the protected area, statistically significant at the 0.10 level.

3.5 Western Texas

The six years of hail suppression operations in Texas were conducted concurrently with the final six years of the program in Kenya. In fact, many of the design and operational features accumulated during the first two years of the Kenya program were applied to the early hail suppression efforts in Texas. However, hailstorms were more severe but far less frequent in Texas and the damage to various crops did not lend itself to the same level of evaluation.

Data from the Crop Hail Insurance Actuarial Association in Chicago has provided the primary input to evaluations of the hail suppression program in Texas. Radar operations from both 3cm systems in the early years and 5cm systems in later years have provided supplemental data on the differences between seeded and not-seeded severe storms within and beyond the boundaries of the protected areas. In addition, precipitation records from the National Weather Service sources have served as the support information in regards possible changes in rainfall. Several investigators have assumed the task of examining a broad range of both hail and rainfall data for application to the hail suppression program in Texas (Henderson, 1971, 1974; Henderson and Changnon, 1972; Schickedanz, 1974; and Changnon, 1974).

In regards the analyses of hail, loss-cost insurance data from 12 counties including both protected and surrounding areas were used in a statistical comparison with historic periods as well as target-control relationships. These analyses suggest at a rather high significance level that hail damage within the protected area was reduced by about 48% during the six-year operational period from 1970 through 1975.

A similar degree of investigation was applied to the rainfall figures from areas within these same 12 counties. Multiple regression equations were developed which produced correlation coefficients in the range from 0.89 to 0.93, indicating that more than 80% of the variability can be explained by the equations. The application of the "t" test to the differences from expectation revealed that precipitation in the protected area did depart from expectation in a positive direction by about 5%.

3.6 Northern Utah

As in the case of the West Texas Program, data for use in the evaluations came from figures supplied by the Crop-Hail Insurance Actuarial Association, plus rainfall records supplied by the National Weather Service. In the case of hail damage, statistical techniques were applied to four different target-control relationships (Henderson, 1979, 1981). These control areas came from agricultural areas in the nearby states of Wyoming and Idaho, as well as areas in Utah adjacent to the protected area. From these analyses, the change in hailfall within the protected area during the six-year operational period ranged from -60% to -81%, with correlation coefficients from 0.51 to 0.72.

All rainfall figures from both the previous historic period and the operational period itself were examined in much the same manner. Multiple regression equations were developed for several target-control relationships with correlation coefficients ranging from 0.78 to 0.86, surprisingly high for periods of summer precipitation. The average change in rainfall within the protected area during the six-year period appears to be on the order of +11%, but statistical significance is rather low.

3.7 Northern Greece

The program in Greece, as conducted during the 1984 and 1985 seasons, may be one of the only operational hail suppression operations in the world where strict randomization was applied to a portion of the field effort. A network of hailpads (Henderson, 1985) supplied data from both seeded and not-seeded days. Statistical techniques were applied to these data. Additionally, an independent investigation was conducted by Dr. John Flueck, statistician, and the results included in a rather lengthy summary report (Solak, et al, 1985, Henderson, 1985).

The independent analysis (Flueck, 1985) strongly suggests that the hail suppression effect (1) reduces the number of hailstones, (2) reduces the size of the maximum hailstones, (3) reduces the size of the area over which hailstones fell, and (4) reduces the hailfall mass flux within the protected areas where hail was measured. The typical reduction of these four variables is about -75%, within the range from -58% to -85%. Statistical significance is at the 0.03 level!

Long-term historic rainfall data are sparse within the various areas of northern Greece. However, data from several stations in the area were examined and statistical methods applied to the higher quality sources. These analyses suggest increases of +6% (1981-1982), and +9% (1984-1985) within the protected areas during the operational periods, but these rainfall results do not appear statistically significant after only two years of operations.

4.0 CONCLUSION

The target/control statistical comparisons of six operational hail suppression projects conducted over the past 30 years in varying climates and with different approaches have been assessed. Independent analyses of two of these (Texas and Greece) provide strong statistical support for reduction in hail accompanied by a small increase in rainfall.

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