Texas Cloud Seeding Experiments using Electrically Charged Droplets: 2017-2022

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ABSTRACT

Research operations, using electrostatically charged water droplets as a seeding agent, were conducted in convective clouds over West Texas as an exploratory experiment in 2017. Research continued later in its confirmatory phase through 2022. The initial research flights were conducted using an Air Tractor 402B provided by the USDA, and later both a Piper Comanche and 502B were equipped to extend those operations. For the assessments of possible impacts, radar data and TITAN software were used, following the same protocols established for the evaluations of long-running operational cloud-seeding programs in Texas. A total of 18 small and isolated seeded clouds were compared with similar control (unseeded) cases provided by the TITAN software. Such a comparison indicated significant increases in lifetime, area, precipitation flux, and precipitation mass among other variables of interest, and the average increases appeared to be larger than those obtained with glaciogenic (silver iodide) flares used in the legacy rain-enhancement projects in Texas (1996-2023). In this paper, we summarize the approach taken in the research and results from the analysis of data, both of which led the U. S. Department of Agriculture to request a U. S. patent which has since been issued.

1. Introduction: Physical Foundations

1.1 The use of water droplets for weather modification purposes preceded the experiments carried out by I. Langmuir, V.J. Schaefer, and B. Vonnegut using glaciogenic agents (dry ice and silver iodide) to target supercooled water within the clouds (late 1940's). In 1938, H.G. Houghton and W.H. Bradford reported the successful dissipation of warm fogs using sprays of hygroscopic solutions, particularly those of calcium chloride. Their experiments were done at the M.I.T. field station in South Dartmouth, Massachusetts, and they demonstrated that fog droplets could be removed by using large electrically charged particles (water drops or sand). They found the most difficult challenge to be producing large particles with sufficiently uniform size distribution (Houghton and Radford, 1938).

1.2 In the 1950s, the Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) implemented cloud seeding operations using water droplets.÷ In 1952, eleven experiments were done in which small water droplets of median radius 25 microns were sprayed at a rate of about 1.9 liters per second (~30 gallons per minute) at some 300 meters above the cloud base. Most of the seeded clouds (ten of eleven cases, ~91%) were reported to have developed rain signatures, whereas nearby unseeded clouds did not. In four cases, when the cloud thickness was larger than 1,500 meters, the modification signal was vigorous (Mason, 1975). Similar experiments were conducted in the Caribbean by Wallace E. Howell with similarly promising results, but the extension of the technique to large-scale applications was then considered extremely costly and in need of more research (Fenn and Weickmann, 1959; see also Mason, ibid, and Cotton, 1982). It is important to emphasize that those experiments were made before a clear explanation of the collision-coalescence mechanism was known.

1.3 The first model demonstrating rain production as a consequence of a chain reaction was presented by Irving Langmuir (1948) when he wrote:

> "…These droplets, under favorable conditions, would grow to such a size that they
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> will break up into two or more large drops and also produce a relatively large number
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> of small droplets which, however, would be larger than the cloud droplets."

It was a move away from the original work of Houghton and Radford at MIT and from the three-phase process of precipitation formation (Bergeron-Findeisen). In the mind of Langmuir, the target may be not only fogs but clouds aloft, with or without supercooled water.

In the early 1950s, F. H. Ludlam (1951) followed Langmuir's ideas by modeling how a collector droplet will move in an updraft, growing at the expense~~s~~ of smaller droplets. Ludlam calculated the minimum vertical extent in a cloud necessary for the formation of showers by accretion: the final raindrop radius as a function of updraft speed. Ludlam's model considers a large droplet (a collector) entering the base of a cloud and being carried upward by an updraft of velocity V. Because the terminal velocity is a function of the droplet size, the raindrop radius becomes a function of the updraft. Further simplifications lead to the following:

$$H = \int_{h_0}^{h_{top}} dz = \frac{4\rho}{\varepsilon w} \int_{r_1}^{r_{top}} \frac{U - V_T(r)}{V_T(r)}\, dr;\ \Delta t = \frac{4\rho}{\varepsilon w} \int_{r_1}^{r_{final}} \frac{1}{V_T(r)}\, dr$$

By assuming an accretion efficiency $\varepsilon = 0.85$, Ludlam found a minimum height H was necessary for droplets to grow to rain-embryo sizes. Higher values of efficiencies can also be assumed.

1.4 In the 1970s, a sound scientific explanation was reached about how cloud droplets grow up to precipitation sizes by the collision-coalescence mechanism. Succinctly stated, droplet growth occurs from both small and large droplets, a consequence of large droplets having larger fall velocities, allowing them to collide and collect small droplets (the minority of large droplets, the collectors, grow at the expense of the small droplets, the collected). The whole process is described by two coefficients, the collision efficiency $E_{collision}$ and the coalescence efficiency $E_{coalescence}$, (Bartlett, 1972; Klett and Davis, 1973; Lin and Lee, 1975; Schlamp et al, 1976). The mechanism works as follows: (1) collision efficiency is negligible unless the collectors have radii of at least 20 microns; (2) for collected droplets with radii of about 10 microns and collectors with 40-micron radii or larger, the collision efficiencies approach unity; and (3) for larger collector radii, the collision efficiency may exceed unity by wake capture.

1.5 Uncertainties and caveats about the previous statements can be attributed to turbulence, the amount of available water vapor, the temperature field, and particular electrical conditions. Multiple observations show more rapid droplet growth takes place under enhanced turbulence, whereas the presence of electric fields enhances coalescence efficiency due to the presence of induced dipoles in these droplets. Other, more detailed observations suggest that adding collector droplets of proper size (radii ~ 40 microns) with electric charges of about 50 picocoulombs may trigger the collision-coalescence mechanism. Modeling has shown that the collision efficiency between charged and neutral droplets and/or charges of opposite sign can be drastically enhanced even if the electric charges are well below the Rayleigh limit of disruption (Khain et al, 2004; visit also Pruppacher and Klett, 1997). Thus, it can be hypothesized that operational seeding of vigorous convective clouds in a continental environment, using electrically charged droplets with radii of about 40 microns, should enhance the collision-coalescence mechanism in the seeded clouds, leading to noticeable increases in precipitation.

2. Conceptual Model and its operational implementation

2.1 The conceptual model was developed as input was gathered from the earliest experimental flights. It is the main pillar for future actions and should be modified if needed. The sequence of events outlined by the model follows:

CM1: a continental cloud with a quasi-uniform droplet size distribution (high colloidal stability) is seeded at its base within the inflow with 40-micron radius electrically charged water droplets (collectors).

2.3

CM2: the collectors grow at the expense of the background smaller droplets by collision and coalescence. With time, these collectors in the updraft should become precipitation drops. The minimum depth needed for a collector to reach precipitation sizes is roughly proportional to the updraft velocity.

CM3: base seeding operations with electrically charged collectors may be extended to mesoscale convective systems and stratiform clouds. For layered clouds, top seeding might be used.

2.2 An agricultural aircraft was equipped with a spraying system that was outfitted with a series of spray nozzles. This produced an atomized spray at proprietary and tested droplet size and distributions. The spray nozzles were surrounded by an electrically charged stainless steel electrode designed to induce a polar opposite charge to the fluid sprayed from the nozzle, as seen in figure X (Martin et al. 2022). In this study, only water was used as the seeding agent. The equipped aircraft took off and received direction to a candidate cloud with measurable updraft by a licensed meteorologist. The pilot then flew 500 feet below the target cloud and turned on the spraying system so that charged pressurized water was sprayed out of the nozzle when specific inflows were found using the aircrafts vertical speed indicator. The inflow then carried the electrically charged droplets up into the cloud to invigorate the droplet growth through collision and coalescence of the warm rain process.

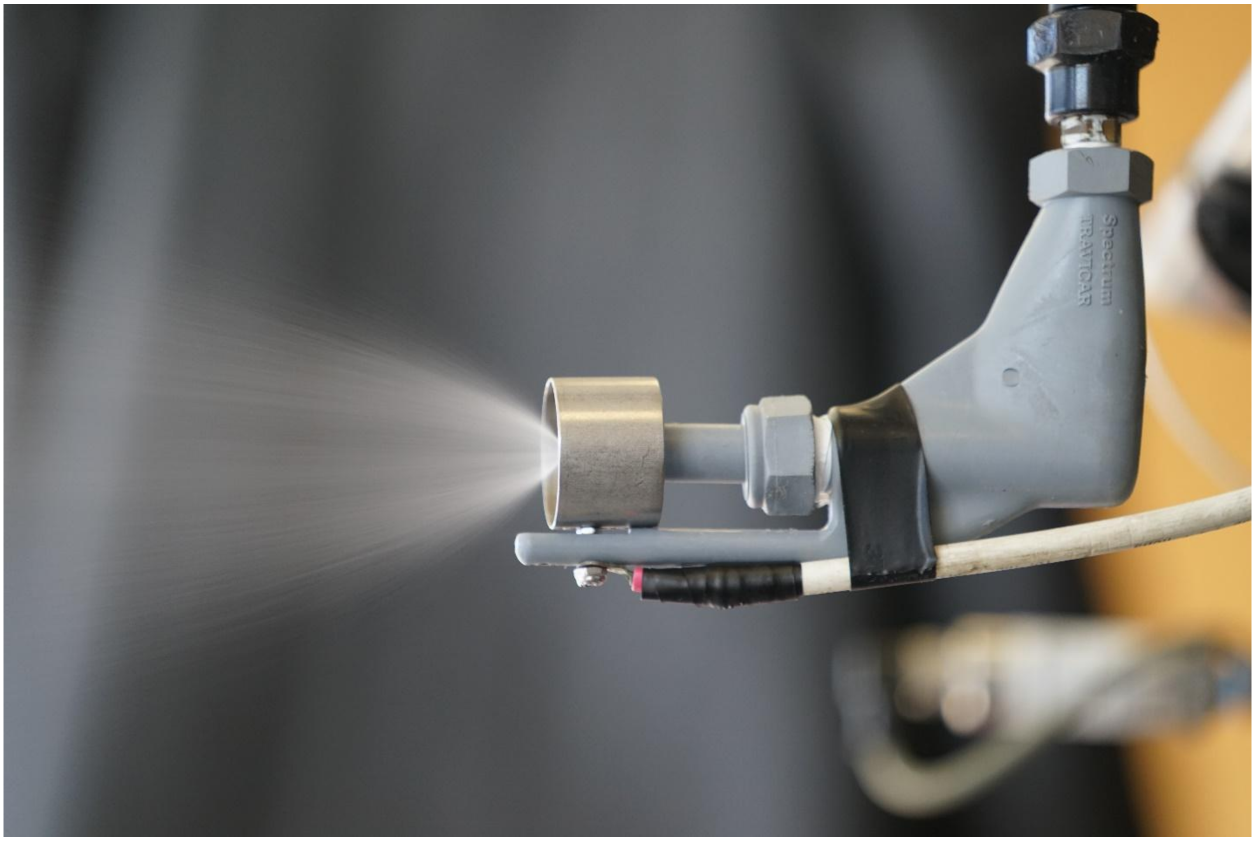

Figure 1. An electrostatic nozzle encased within the electrode to induce an electrostatic charge on the spray cloud emitted from the nozzle tip.

2.4 Research operations were directed from the West Texas Weather Modification Association Office in San Angelo, Texas. The Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) software program was used for operational decision-making and later for the assessments (Bates and Ruiz-Columbie, 2002). As mentioned before, these research operations followed the same protocol already established for weather modification operations in the local project. The research study using electrically charged droplets began in June 2017.

2.5 Importantly, to preserve the integrity of the local operational program, the–spray seeding approach embraced the same operational focus (non-randomized seeding), although some random-like criterium took place when considering where to locate the seeding aircraft. In short, locations of the seeding aircraft were decided by available resources and seeding operations using flares and water droplets occurred generally on opposite sides of the target area. This design enabled comparisons between the two types of seeding.

Figure 2. (a) USDA-ARS Air Tractor 402b used in the 2017 Texas pilot project and (b) a close-up view of the nozzles.

3. Results and Assessments

3.1 Comparisons between clouds seeded with electrically charged droplets and similar control (unseeded) cases, as well as quasi-synchronous seeded clouds using glaciogenic flares and correspondingly similar control (unseeded) clouds, were made to determine possible seeding effects. In both comparisons, the control cases were determined using TITAN software (TrackMatch.test utility). The results are presented here in the same format as used for operational assessments in Texas. The two tables are below:

Table 1. Small-seeded clouds with electrostatically charged droplets compared to control~~s~~ clouds (18 couples).

Variable	Charged Sample	Unseeded Sample	Simple Ratio	Increase (%)
Lifetime	55 min	40 min	1.38	38 (31)
Area	72.3 km^2	40.7 km^2	1.78	78 (62)
Volume	267.2 km^3	129.6 km^3	2.06	106 (84)
Top Height	9.1 km	8.5 km	1.07	7 (4)
Max dBz	53.2	4.2	1.06	6 (3)
Top Height of Max dBz	4.1 km	4.2 km	0.98	-2 (-3)
Volume Above 6km	83.5 km^3	38.3 km^3	2.18	118 (107)
Precip. Flux	524.2 m^3/s	281.3 m^3/s	1.86	86 (116)
Precip. Mass	2078.9 kton	699.8 kton	2.97	197 (208)
Cloud Mass	187 kton	82.7 kton	2.26	126 (126)
N	11.1	8.5	1.31	31 (35)
Average timing: 0.7. Average seeding duration: 9.3 minutes. Average Dose: 23.5 gallons of Water. Notice the increase in precipitation mass of 208%.				

Table 2. Small-seeded clouds with electrostatically charged droplets compared to dual seeded clouds (glaciogenic and hygroscopic, 24 samples).

Variable	Dual Sample	Unseeded Sample	Simple Ratio	Increase (%)
Lifetime	65 min	40 min	1.63	63 (48)
Area	73.6 km^2	55.4 km^2	1.33	33 (24)
Volume	247.6 km^3	153.4 km^3	1.61	61 (38)
Top Height	9.0 km	8.3 km	1.07	7 (4)
Max dBz	53.3	50.1	1.06	6 (3)
Top Height of Max dBz	4.1 km	4.2 km	0.95	-5 (-2)
Volume Above 6km	188.5 km^3	60.3 km^3	3.13	213 (130)
Precip. Flux	534.5 m^3/s	295.8 m^3/s	1.81	81 (54)
Precip. Mass	176.8 kton	949.7 kton	2.41	141 (90)
Cloud Mass	176.8 kton	86.7 kton	2.05	105 (27)
N	13.0	11.0	1.18	18/51
Average timing: 0.88. Average seeding duration: 9.2 minutes. Average Dose: 40 in/L (180 AgI flares, 3 hygroscopic flares (24 samples). Notice the increase in precipitation mass of 90%.				

3.2 Conclusions:

First: In terms of precipitation production, seeding operations with electrically charged water seemed to be more efficient (208 % versus 90 %) using 18 data samples. However, other storm radar variables appeared to be more impacted by the flare seeding using 24 sample pairs. Note that the increase in volume above 6 km, where supercooled water is observed, is 130% versus 107%, a possible indication that although electrically charged water droplets can reach supercooled levels depending on the updraft intensity, they primarily affected the warm region of a storm~~.~~

Second: The cost of operations may also be a consideration since current estimations indicate that using water droplets as a seeding agent appears to be nearly seven times more expensive than using flares. Additional considerations about environmental impacts may influence future actions.

Third: Due to limited resources, the actions herein described were done in an operational-oriented manner. Gathering detailed data describing microphysical changes in seeded and control cases should be an objective of future experiments to provide insight into how various seeding techniques impact the evolution, and productivity, of storms.

Fourth: The USDA, which conducts research for technology transfer, was confident enough in the results to request a patent in the technology which was approved as US 11,116,150 and pending continuation-in-part application 17/387,348 both entitled "Aerial Electrostatic System for Weather Modification."

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