Weather Modification Scientific Management in Texas: The extensive and intensive uses of TITAN

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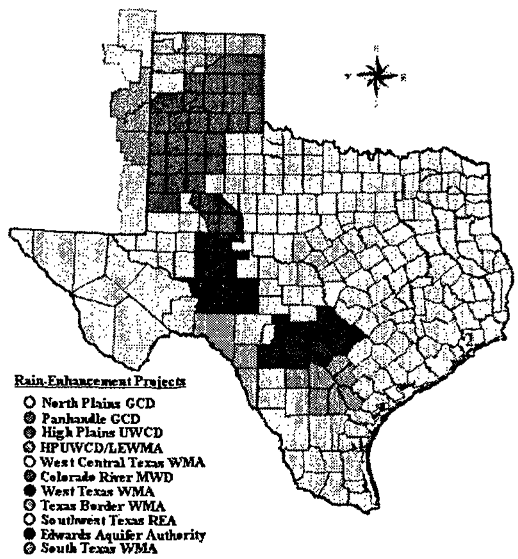
Abstract. Nowadays Texas already has ten working operational rain-enhancement projects, which are focused to diminish the impact of periodic severe droughts by using cloud seeding techniques. These programs use TITAN and telemetry to perform and improve the operations and the TITAN analysis software to assess the performance and evaluate the results. This paper describes these uses.

1. Introduction

The use of the Thunderstorm Identification Tracking Analysis and Nowcasting software package (TITAN) in Texas began timidly in San Angelo in 1997. Originally conceived in South Africa (Mittermaier and Dixon, 2000) the package was introduced in Texas to help meteorologists and pilots in cloud seeding operations. Two years later, in 1999, the Texas Weather Modification Association decided it would be mandatory to use **TITAN** in all the local projects. In short, **TITAN** is a collection of programs, working systematically, that permits the interaction between the radar information and the meteorologist as a **G**raphic **U**ser **I**nterface (**GUI**). At the beginner level one can understand and use TITAN in an easy windows style, but the system possesses many more features that empower it enormously. This software package uses volume-scan radar data as its primary source of information and displays it in six possible windows, which can be handled using the mouse. The prior extensive use of this tool in Texas required eventually a deeper and intensive use, because **TITAN** can be coupled to a telemetry system, becoming then an invaluable tool during the cloud seeding operations. TITAN also has an evaluation software package that allows us to match seeded clouds with similar unseeded clouds (control clouds), calculate radar features of these clouds, and compare properties to obtain an evaluation of the operations. Last year (2001) each local project in Texas received an annual evaluation report, and most of the projects were aided by daily and monthly evaluation reports (Bates and Ruiz, 2001). The reports consisted of tables of comparison between seeded and control samples of clouds. Different radar variables displayed together with the radar estimation of increases gave us performance information. Before TITAN the enormous amount of information generated in operational programs was practically unmanageable, and all the technical figures came from randomized experiments with very small samples of cloud. The success of our results is that we have now the opportunity to handle any amount of information to obtain similar figures than those obtained during randomized experiments. We like to say that **Weather Modification has two periods in Texas and probably worldwide: before and after TITAN.**

2. Scientific Management

Last year, the State of Texas had ten local projects in operations during a period that extended from March to November 2001.



The radars in use were WSR-74 C (Bomar et al, 1999). Local meteorologists used the **File** Transfer Protocol (**FTP**) to send TITAN data to the server at San Angelo where the evaluations were made. A very strong feedback of information took place between the evaluation office and the local TITAN projects, a relationship that allowed us to help meteorologists and pilots to improve their performances. Advice about appropriate dosages and correct timing for seeding operations accompanied the calculations about possible increases using nine radar variables. The variables used were: Lifetime, Area, Volume, Top height, Maximum reflectivity, Top height of maximum reflectivity, Volume above 6 km, Precipitation Flux, and Precipitation

Mass. Values of these variables for the seeded and control clouds permitted the calculation of simple ratios and their corresponding increases.

The experience accumulated in Texas during randomized experiments and previous operational programs has given us good insights to build **a conceptual model** for the cloud seeding operations in the State. Texas projects use **glaciogenic seeding** to modify the natural regime of seedable clouds, the real target is the supercooled water in these clouds. The agent in use is **silver iodide**, which is released in clouds **to empower the formation of ice aggregates.** The maximum efficiency for aggregation occurs **around –5 °C**. Seedable clouds must have top heights around this temperature but warmer than **–15 °C** (Finnegan and Pitter, 1988).

i) The Silver Iodide should be released in the clouds during their **early stages of development**, let's say the first half-lifetime. Mature storms that have reached a quasi-steady stage with the environment are considered too old to obtain results from seeding.

ii) **Dosages** should reach the dynamic mode of seeding, i.e. around **100 ice-nuclei per liter of supercooled volume.**

These principal features of the conceptual model, together with the TITAN evaluation software package constitute the main components of the scientific management of cloud seeding in Texas. This is a way of looking for knowledge that is very similar to engineering, where we follow numbers supported on knowledge-based conceptual ideas to assess the results and to overcome technical problems in a safe and economical fashion.

In this paper we present the results obtained for the whole state of Texas after averaging the results of the local projects. The technical reports for the local projects are available upon request.

3. Results and Analyses

A total of 1031 clouds were seeded and identified for **TITAN** in Texas during the year 2001, although 174 seeded clouds did not have the data necessary to run the evaluation software package or were seeded too late to be considered in the evaluations. A subtotal of 857 seeded clouds was available for evaluation from the different projects. For each one of these clouds TITAN was capable of finding a similar unseeded cloud that we used as control cloud in order to make the evaluations. The program gave numerous candidates for the control role, and the user needs to be patient in the selection of the best candidate. Each control cloud was selected from a list of unbiased candidates, but the human interaction is vital to take into account both radar and TITAN limitations. A control cloud must be always an unseeded cloud that lives in the same environment as its partner, in similar synoptic conditions, at similar distance to the radar. We decided to find the control cloud from the same day that the target cloud was seeded.

TITAN uses a space of four radar variables to model the clouds before matching. These variables (area, volume, mass, and precipitation flux) are followed from the time of track origin. In fact, TITAN proceeds to identify the best storm track matches from the data based on one of the maximum rate of increase of these four variables (they are strong correlated, therefore using one is enough). Because TITAN uses the derivatives, a problem about initial size is very frequent. This problem is connected with the initial bias in the selection of clouds for seeding in operational projects when it is mandatory to seed the best clouds. We designed a model to deal with this problem (the H model) which is instrumental model in solving the size problem by giving the selected control cloud the same seeded cloud's initial condition (Ruiz et al, 2002). Nevertheless, the comparisons presented here illustrate raw and modeled data.

Table S1 shows the results for the whole sample of seeded clouds and their control clouds. The table is an average of the results of the ten local projects.

In table S1, bold values in parenthesis are modeled values.

A total of 7717 flares of different types and about 136 hours of generator time were used to modify the natural regime of the seeded clouds. An average dose of about 286 g of silver iodide was used which dropped to around 197 g after timing considerations ($\varepsilon = 0.69$, the fraction of the amount of seeding material that is seeded during the first half lifetime of the cloud). The corresponding ice-nuclei concentration in the supercooled region of the clouds averaged about **30 ice-nuclei per liter, a quasi-static dose.**

Possible overestimations may be associated with the singular events present in the whole sample (126 couples have at least one component with Precipitation Mass greater than 10 000 kton). However, the modeled increases in table S1 are in approximately the same ranges as increases reported in previous randomized experiments in the region (Rosenfeld and Woodley, 1993). To obtain a better comparison with these randomized experiments, additional calculations for only small clouds and clusters (731 couples) were done and are shown in table S2.

Table S1. The Global Comparison between Seeded and Control clouds
Seeded Sample versus Control Sample (857 couples, arithmetic means)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	109 min	58 min (**64**)	1.88 (**1.70**)	88 (**70**)
Area	98.7 km2	50.6 km2 (**61.5**)	1.95 (**1.60**)	95 (**60**)
Volume	400.7 km3	175.6 km3 (**224.3**)	2.28 (**1.79**)	128 (**79**)
Top Height	8.8 km	8.0 km (**8.4**)	1.10 (**1.05**)	10 (5)
Max dBz	50.4	48.0 (**48.9**	1.05 (**1.03**)	5 (3)
Top Height of max dBz	**4.6 km**	**4.6 km** (4.5)	**1.00** (1.02)	0 (2)
Volume Above 6 km	203.1 km3	70.1 km3 (**99.7**)	2.90 (**2.04**)	190 (**104**)
Prec.Flux	831.4 m3/s	362.6 m3/s (**469.4**)	2.29 (**1.77**)	129 (**77**)
Prec.Mass	4116.7 kton	1512.3 kton (**1782.3**)	2.72 (**2.31**)	172 (**131**)

Table S2 shows the results for the sample of small seeded clouds and their control. The table is an average of the results of the ten local projects.

In table S2, bold values in parenthesis are modeled values. A total of 5351 flares and about 67 hours of generator time were used to seed this sub-sample, for an average dose of around 281 g of silver iodide, which dropped to 201 after timing considerations, giving a concentration of about **50 ice-nuclei per liter, an intermediate dose.** Raw and modeled increases are certainly between those reported in randomized experiments with static mode of seeding (Israeli experiments, HIPLEX) and the results from randomized experiments with dynamic mode of seeding (FACE, TEXARC).

Table S2. The Comparison for Small Clouds and Small Cluster
Seeded Sample versus Control Sample (731 couples, arithmetic means for small clouds and clusters)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	83 min	51 min (**56**)	1.62 (**1.48**)	62 (**48**)
Area	54.5 km2	41.1 km2 (**44.6**)	1.33 (**1.22**)	33 (**22**)
Volume	175.3 km3	127.0 km3 (**143.2**)	1.38 (**1.22**)	38 (**22**)
Top Height	8.1 km	7.7 km (**7.9**)	1.05 (**1.03**)	5 (**3**)
Max dBz	49.2	47.9 (**48.7**)	1.03 (**1.01**)	3 (**1**)
Top Height of max dBz	**4.4 km**	**4.5 km** (4.4)	**0.98** (1.00)	**-2** (0)
Volume Above 6 km	54.1 km3	37.3 km3 (**43.1**)	1.45 (**1.26**)	45 (**26**)
Prec.Flux	375.8 m3/s	260.5 m3/s (**300.5**)	1.44 (**1.25**)	44 (**25**)
Prec.Mass	1731.0 kton	827.2 kton (**969.7**)	2.09 (**1.79**)	109 (**79**)

Further analyses have been made to clarify the responses of seeding operations in different sub-samples. One important option is to analyze the result by restricting the comparison to single cells versus single cells, where both the seeded and the control components are single cells. This strong distinction artificially limits the possible dynamic extension of the seeded clouds but allows the analysis of the differences between the smallest units. Table S3 shows the corresponding results.

Table S3. The Comparison for Single-cell Clouds
Seeded Sample versus Control Sample (302 couples, arithmetic means for single clouds)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	45 min	36 min (**39**)	1.25 (**1.15**)	25 (**15**)
Area	30.2 km2	26.8 km2 (**28.3**)	1.13 (**1.07**)	13 (7)
Volume	91.6 km3	80.3 km3 (**87.0**)	1.14 (**1.05**)	14 (5)
Top Height	7.5 km	7.3 km (**7.6**)	1.03 (**0.99**)	3 (**-1**)
Max dBz	48.3	47.4 (**47.9**)	1.02 (**1.01**)	2 (**1**)
Top Height of max dBz	**4.2 km**	**4.3 km** (4.2)	**0.98** (1.00)	**-2** (0)
Volume Above 6 km	22.1 km3	18.6 km3 (**20.2**)	1.19 (**1.09**)	19 (9)
Prec.Flux	208.3 m3/s	173.5 m3/s (**194.5**)	1.20 (**1.07**)	20 (7)
Prec.Mass	611.1 kton	384.4 kton (**422.5**)	1.59 (**1.45**)	59 (**45**)

A total of 1709 flares and about 23.5 hours of generator time were used to seed this sub-sample, for an average dose of around 185 g of Silver Iodide that dropped to 134 g after timing considerations, giving an average concentration of about **90 ice-nuclei per liter, a quasi-dynamic dose.** Results in table 3 are intermediate between static and dynamic results but very close to those corresponding to a static mode of seeding, which indicate that the dynamical limitation in place is penalizing the results excessively. This latter is an indirect indication that dynamic seeding should be promoting the formation of additional cells in the seeded clouds. Not all the single seeded clouds evolved to a multi-cell cloud stage, but some of them did. The natural extension of the analysis to multi-cell clouds gave the results shown in table S4.

A total of 1727 flares and 38.5 hours of generator time were used to seed this sub-sample, for an average dose of 338 g, which dropped to 234 g after timing considerations, giving an average concentration of about **50 ice-nuclei per liter, an intermediate dose.**

Now, without dynamical restrictions, the results correspond to the used doses: **They are intermediate between expected results with static and dynamic doses.**

Table S4. The Comparison for Multi-cell Clouds
Seeded Sample versus Control Sample (191 couples, arithmetic means for multi-cell clouds)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	110 min	82 min (85)	1.34 (1.29)	34 (29)
Area	87.4 km2	70.2 km2 (73.5)	1.25 (1.19)	25 (19)
Volume	284.2 km3	218.0 km3 (233.6)	1.30 (1.22)	30 (22)
Top Height	8.7 km	8.2 km (8.6)	1.06 (1.01)	6 (1)
Max dBz	49.8	48.3 (49.3)	1.03 (1.01)	3 (1)
Top Height of max dBz	4.5 km	4.6 km (4.5)	0.98 (1.00	2 (0)
Volume Above 6 km	78.5 km3	59.0 km3 (66.1)	1.33 (1.19)	33 (19)
Prec.Flux	554.6 m3/s	397.9 m3/s (441.9)	1.39 (1.26)	39 (26)
Prec.Mass	3007.4 kton	1653.3 kton (1891.5)	1.82 (1.59)	82 (59)

The superposition of increases from tables S3 and S4 can offer a clear insight of resultant effects:

Table S5: The Superposition of Results from Couples of the Same Gender
Superposed Effects in Lifetime, Area, Volume, Prec.Flux, and Prec.Mass

ΔLifetime	ΔArea	ΔVolume	ΔPrec.Flux	ΔPrec.Mass
20%	12%	12%	14%	50%

Results in table S5 seem to be intermediate although increases in Area and Volume look to be associated to a static mode of seeding. The dynamical restriction for the sub-sample of "single/single" couples appears to affect the superposed effects by eliminating synergetic issues.

Coming back to the sub-sample of 191 multi-cell/multicell couples, a further analysis of multiplicity using the information about the amount of cells in each volume scan for every case, shows very interesting features. Table S6 summarizes these new insights:

Table S6. The Comparison of Multiplicity (proliferation of cells)
Analysis of multiplicity using the amount of cells (n)

	<n>	Abs. Maximum	<max. occurrence>	<transition>
Seeded Sample	3.46	9	28 min	13 min
Control Sample	3.07	10	20 min	13 min

Missed Opportunities

The analysis of results ends with the account of seedable clouds that were not seeded in every target area. This account serves to evaluate approximately the quality of the meteorological vigilance of seedable conditions, and also the ability of using these seedable conditions (aircraft, meteorologists and pilots readiness...). We write "approximately" since we worked with TITAN data and we did not have control of "seedable missed days". In the future this control should be developed. In general, we counted as a missed opportunity every seedable unseeded cloud in every target area with lifetime longer than 45 minutes (shorter lifetime clouds were not considered in this occasion, but the boundary might be eventually dropped). Table S8 shows the results that include timing and doses for each target area and for the whole State of Texas. These four variables represent the fields where we can exert actions to improve the performances in the future.

Table S8: An Analysis of Performance
Missed Opportunities (M.O), Efficiency using Seedable Conditions, Timing, and Dosages used.

Project	M.O	Efficiency(%	Timing(%)	Dosage (IN/ l)
EAA (Hondo)	22	80	64	13
CRMWD (Big Spring)	11	82	50	5
HPUWCD (Littlefield)	22	91	85	50
NPWMA (Dumas)	8	85	66	16
PREP (White Deer)	9	75	73	9
STWMA (Pleasanton)	13	89	68	46
SWTREA (Cotulla)	28	84	51	30
TBWMA (Del Río)	15	81	46	10
WCTWMA (Abilene)	21	82	75	31
WTWMA (San Angelo)	18	92	79	50
TEXAS	**167**	**86**	**69**	**30**

A total of 167 seedable clouds (14%) were missed during the operations over the whole state, giving an efficiency of 86%. The timing was 0.69, which means that 69% of the seeding material went, in average, to the seeded clouds in the first half lifetime. The average dose of **30 ice-nuclei per liter** indicates that the mode of seeding was, in average, quasi-static.

A heuristic figure

An important factor in an operational program of weather modification is the necessity of satisfying client questions. One heuristic consideration may illustrate the aforementioned potentialities of the results. Using the value of Precipitation mass in table S2 for "the average control cloud" (827 kton) as the expected value, an increase of 79% (in the same table) means that from "the average seeded cloud" we received an additional amount of water of

$$\mathbf{q = 827 * 0.79 = 653\ kton}$$

and for the sub-sample of 731 seeded clouds

$$\mathbf{Q = 731 * 653 = 477\,343\ kton}$$

which in acre-feet is

$$\mathbf{Q = 387\,125\ ac\text{-}f}$$

However, if we consider that the 79% increase may be extended to the whole population of seeded clouds (1031), the figure results in:

Q = 1031 * 653 = 673 243 kton

= 546 000 ac-f

This is a pretty good amount of water, but remember, it is water leaving the clouds, not reaching the ground. This figure should be considered only to estimates ranges of magnitude, keeping in mind the possible presence of intangible biases.

4. Conclusions

• Handling information of 1031 seeded clouds in 250 titan-home operational days to obtain similar results to these presented here would have been a nightmare without the TITAN evaluation software package. However, these results would give us poor insights if we do not go beyond them. The analyses shown in this paper serve to facilitate the interpretation of numbers and do not stop at these numbers. Although many of these interpretations are controversial and preliminary, they should still be considered in every attempt to improve the performance of seeding operations and the estimation of the ratio of cost to benefits. We are dealing with a very complicated problem, *a problem that has required effort and time, and* still does not have a satisfactory answer. Nevertheless, operational programs now have tools to handle the huge amount of information that is generated and to model this information to approach results very similar to those generated in randomized experiments.

• Meteorologists should improve local forecast and, together with pilots be ready for actions before the seedable clouds appear over the buffer and target areas. These actions will avoid missed opportunities and permit better timings. Additionally, meteorologists must excel in the use of radar and TITAN, studying all the features that these tools have (especially the TITAN side windows), which allow determination of precise doses to reach a dynamic mode of seeding. The latter is very important in obtaining profit from actions.

• The intensive use of TITAN permits now an approach *to operational projects that, in the style of* scientific management, may offer much more scientific credibility to the results obtained. **We believe today that a strong and active advocacy founded in these evaluations can take place against possible overselling or loss of credibility.**

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