ANNUAL EVALUATION REPORT 2016 **WTWMA (San Angelo)**

Dr. Arquímedes Ruiz-Columbié
Active Influence & Scientific Management

Cloud seeding operations 2016 began over the West Texas Weather Modification Association target area in March. This annual report serves as a summary of results.

A total of **111 clouds** were seeded and identified by TITAN in **32 operational days**.
Table 1 in page 1 summarizes the general figures:

Table 1: Generalities

First operational day: **March 7th, 2016**
Last operational day: **October 6th , 2016**

Number of operational days: 32
(Two in March, three in April, eight in May, three in June, two in July, seven in August, five in September, and two in October)

According to the daily reports, operational days were qualified as:

Twenty-seven with excellent performance

Three with very good performance

Two with good performance

Number of seeded clouds: 111 (69 small, 27 large, 15 type B)

Missed Opportunities: none with lifetime longer than 45 minutes

Small Clouds

Evaluations were done using TITAN and NEXRAD data.

Table 2 shows the results from the classic TITAN evaluation for the 69 small seeded clouds which obtained proper control clouds.

Table 2: Seeded Sample versus Control Sample (69 couples, averages)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	65 min	45 min	1.44	44 (**36**)
Area	*61.6 km²*	*41.1 km²*	*1.50*	*50 (**41**)*
Volume	*217.0 km³*	*128.4 km³*	*1.69*	*69 (**51**)*
Top Height	*10.0 km*	*8.8 km*	*1.13*	*13 (**3**)*
Max dBz	*51.2*	*49.3*	*1.04*	*4 (**1**)*
Top Height of max dBz	3.8 km	3.7 km	1.03	3 (**- 2**)
Volume Above 6 km	56.1 km^3	29.3 km^3	1.91	91 (**68**)
Prec.Flux	308.2 m^3/s	214.0 m^3/s	1.44	44 (**58**)
Prec.Mass	1735.0 kton	641.1 kton	2.71	171 (**125**)
CloudMass	143.4 kton	77.1 kton	1.86	86 (**60**)
η	12.1	8.3	1.46	46 (**41**)

Bold values in parentheses are modeled values, whereas **η** is defined as the quotient of Precipitation Mass divided by Cloud Mass, and is interpreted as efficiency. A total of 355 AgI-flares and 34 hygroscopic flares were used in this sub-sample with an excellent timing **(97 %)** for an effective AgI average dose about **45 ice-nuclei per liter**. The seeding operation for small clouds lasted about **7 minutes** in average. An excellent increase of **125 %** in precipitation mass together with an increase of 60 % in cloud mass illustrates that the seeded clouds grew at expenses of the environmental moisture (they are open systems) and used only a fraction of this moisture for their own maintenance. The increases in lifetime (36 %), area (41 %), volume (51 %), volume above 6 km (68 %), and precipitation flux (58 %) are remarkable. There was a slight increase in top height (3 %) and in maximum reflectivity (1 %).
The seeded sub-sample seemed 41 % more efficient than the control sub-sample. Results are evaluated as **excellent**.

An increase of 125 % in precipitation mass for a control value of 641.1 kton in 69 cases means:

Δ_1 = 69 x 1.25 x 641.1 kton ≈ 55 295 kton ≈ 44 844 ac-f (layer: 13.0 mm ≈ 0.51 in)

Large Clouds

The sub-sample of 27 large seeded clouds received a synergetic analysis. In average, the seeding operations on these large clouds affected 85 % of their whole volume with a perfect timing (100 % of the material went to the clouds in their first half-lifetime). A total of 531 AgI-flares and 39 hygroscopic flares were used in this sub-sample for an effective AgI average dose about **90 ice-nuclei per liter**.

Also in average, large clouds were 22 minutes old when the operations took place; the operation lasted about 45 minutes, and the large seeded clouds lived 295 minutes.

Table 3 shows the corresponding results:

Table 3: Large Seeded Sample versus Virtual Control Sample (27 couples, averages)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	295 min	225 min	1.31	31

Area	*1239 km*^{2}	*918 km*^{2}	*1.35*	*35*
Volume	*5311 km*^{3}	*3905 km*^{3}	*1.46*	*36*
Volume Above 6 km	2012 km^3	1479 km^3	1.36	36
Prec.Flux	8884 m^3/s	6784 m^3/s	1.31	31
Prec.Mass	139 819 kton	88 625 kton	1.58	58

An increase of 58 % in precipitation mass for a control value of 88 625 kton in 27 cases may mean:

Δ_2 = 27 x 0.58 x 88 625 kton = 1 387 868 kton ≈ 1 125 561 ac-f (layer: 41.5 mm ≈ 1.63 in)

Type B Clouds

The sub-sample of 15 type B seeded clouds received a synergetic analysis. In average, the seeding operations on the type B clouds affected 15 % of their whole volume with a very good timing (89 % of the material went to the clouds in their first half-lifetime). A total of 298 AgI-flares and 21 hygroscopic flares were used in this sub-sample for an effective AgI average dose of about **105 ice-nuclei per liter**.

Also in average, type B clouds were 120 minutes old when the operations took place; the operation lasted about 40 minutes, and the type B seeded clouds lived 300 minutes.

Table 4 shows the results:

Table 4: Type B Seeded Sample versus Virtual Control Sample (15 couples, averages)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	300 min	290 min	1.03	3

Area	*1747 km²*	*1685 km²*	*1.04*	*4*
Volume	*7341 km³*	*7044 km³*	*1.04*	*4*
Volume Above 6 km	2696 km³	2567 km³	1.05	5
Prec.Flux	13606 m³/s	13021 m³/s	1.04	4
Prec.Mass	127 037 kton	118 400 kton	1.07	7

An increase of 7 % in precipitation mass for a control value of 118 400 kton in 15 cases may mean:

Δ_3 = 15 x 0.07 x 118 400 kton ≈ 124 320 kton ≈ 100 824 ac-f (layer: 4.7 mm ≈ 0.19 in)

The total increase: $\Delta = \Delta_1 + \Delta_2 + \Delta_3$ = 1 271 229 ac-f

(~ 650 ac-f per small storm; ~ 41 687 ac-f per large storm; ~ 6722 per B storms)

Micro-regionalization

Increases in precipitation mass were analyzed county by county in an attempt to better describe the performance and corresponding results. **Table 5** below offers the details:

County	Initial Seeding	Extended Seeding	Acre-feet (increase)	Inches (increase)	Rain (season value)	% (increase)
Sterling	**14**	**15**	**110 500**	**1.39**	**18.13 in**	**7.7 %**
Reagan	**26**	**28**	**174 700**	**2.77**	**19.33 in**	**14.3 %**
Irion	**19**	**22**	**147 600**	**2.62**	**21.42 in**	**12.2 %**
Tom Green	**9**	**11**	**111 300**	**2.73**	**27.05 in**	**10.1 %**

Crocket	**16**	**17**	**172 700**	**1.14**	**18.41 in**	**6.2 %**
Schleicher	**16**	**18**	**165 900**	**2.34**	**25.89 in**	**9.0 %**
Sutton	**9**	**11**	**92 800**	**1.21**	**21.50 in**	**5.6 %**
Outside TA	2	7	~ 80 200	(~ 7.6 % of the total amount)		
Total	**111**	**129**	**1 055 700 ac-f**			
Average (only for the bold values)				**2.02**	**21.67 in**	**9.30 %**

(**Initial seeding** means the counties where the operations began, whereas **extended seeding** means the counties favored by seeding after the initial operations took place).

Importance of hygroscopic seeding (really dual cases)

Hygroscopic seeding operations were still used as a complement of the glaciogenic seeding**.** For the small cases, it was possible to make a comparison between pure glaciogenic seeding (43 cases) and all the small cases (69 cases, table 2). Table 6 shows the results for the former (43 small pure glaciogenic seeding cases):

Table # 6 Seeded Sample versus Control Sample (43 couples, averages)

Variable	**Seeded Sample**	**Control Sample**	**Simple Ratio**	**Increases (%)**
Lifetime	55 min	40 min	1.38	38 (**22**)

Area	*75.2 km*^{2}	*40.1 km*^{2}	*1.88*	*88 (**26**)*
Volume	*252.1 km*^{3}	*137.6 km*^{3}	*1.83*	*83 (**42**)*
Top Height	*8.1 km*	*7.7 km*	*1.05*	*5 (**2**)*
Max dBz	*51.2*	*49.3*	*1.04*	*4 (**2**)*
Top Height of max dBz	3.8 km	3.7 km	1.03	3 (**0**)
Volume Above 6 km	41.0 km^3	25.1 km^3	1.63	63 (**59**)
Prec.Flux	335.1 m^3/s	209.3 m^3/s	1.60	60 (**42**)
Prec.Mass	1426.5 kton	489.7 kton	2.91	191 (**106**)
CloudMass	120.4 kton	71.9 kton	1.67	67 (**48**)
η	11.8	6.8	1.74	74 (**39**)

A total of 192 AgI-flares were used in this sub-sample with a excellent timing (**94 %)** for an effective AgI-average dose about **40 ice-nuclei per liter**. The increases indicate a dynamic response. The vertical reflectivity gradient index for this sample was - 4.1 dBz/km, indicating a slightly maritime character. The comparison of these results with those shown on table 2 corroborates the expected synergy between the glaciogenic and the hygroscopic materials which favors the use of dual seeding when it is possible.

The increase from this sample: Δ = 43 x 1.06 x 489.7 kton ≈ 22 321 kton ≈ 18 102 ac-f
(~ 421 ac-f per storm; layer: 6.90 mm ≈ 0.27 in)

Final Comments

1) Results are evaluated as **excellent**;

2) The micro-regionalization analysis showed increases per county; 2016 seedable conditions were more frequent over the northern part of the target area; the average

increase in precipitation, referred to the seasonal value, is about **9 %.** Maximum relative increases in precipitation were located on the central stripe (Reagan-Irion-Tom Green Counties) where about 50 % of the seeding operations were made;

3) Radar estimations of precipitation should be considered as measurements of trend. Nevertheless, according to the results on this report's tables, seeding operations improved the dynamics of seeded clouds;

The results obtained for the seeded small clouds reinforce the evidence that there is a strong synergy between the hygroscopic and the glaciogenic actions. The following table illustrates how the dual seeding was applied:

Type of storm	AgI-flares used	Hygroscopic flares used
Small	355 (~ 5.1 per storm)	34 (~ 0.5 per storm)
Large	531 (~ 19.7 per storm)	39 (~ 1.4 per storm)
Type B	298 (~ 19.9 per storm)	21 (~ 1.4 per storm)

During the last season (2015), the use of hygroscopic flares was distributed as:

Small (~ 0.5 per storm), Large (~ 2.3 per storm), Type B (~ 2.4 per storm)