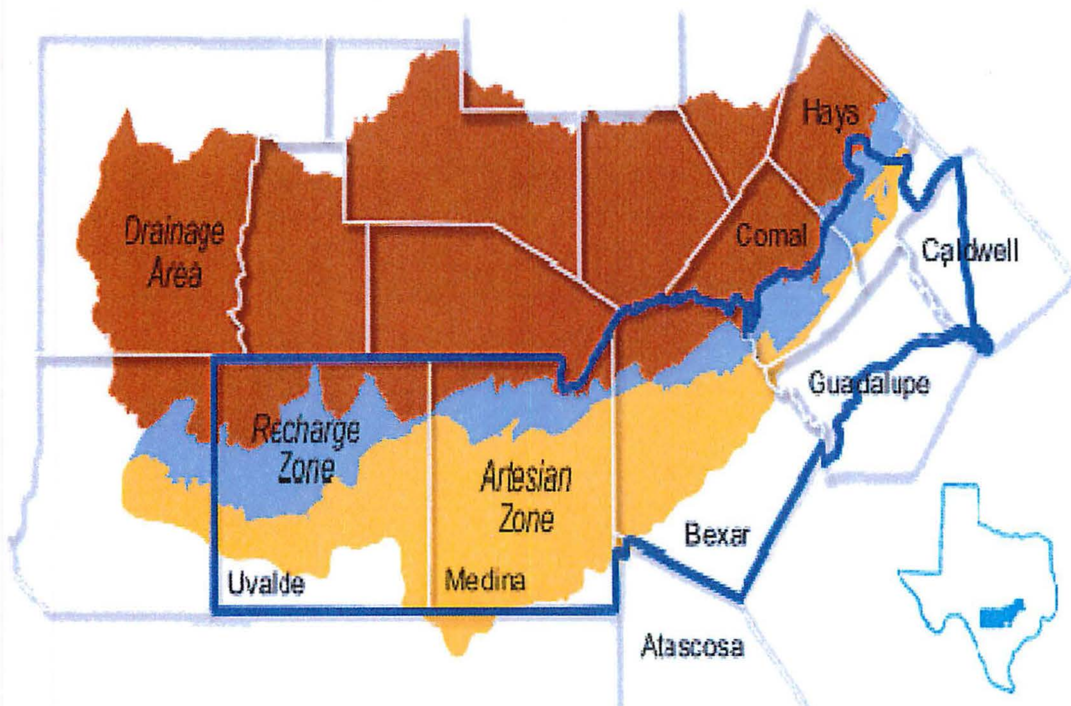
# Southwest Texas Rain Enhancement Association
# 2009 Edwards Aquifer Authority Final Report

**Prepared By:**
**Stephanie Beall**

**2009 Project Staff**

Ed Walker, Project Manager, Pilot-in-Charge (PIC)
Matthew Pope, Pilot
Stephanie Beall, Project Meteorologist
Debbie Farmer, Clerical



# Table of Contents



## Appendices

## The Year in Review

2009 marked the eighth year of operations for the Edwards Aquifer Authority (EAA) by the Southwest Texas Rain Enhancement Association (SWTREA). The project duration was the same as it has been the past couple of years, with seeding taking place in Uvalde County from May until September. Drought conditions that originated in late 2008 continued into most of 2009, which in turn had an effect on seeding operations for most of the summer. The drought was felt throughout most of south Texas and was not just limited to the Edwards Aquifer.

Seeding in the Authority target area of Uvalde County saw a total of twenty-four seeding flights for the 2009 operational season. A well, two reconnaissance flights took place during the operations season. In comparison, a total of five flights were conducted in 2008. 2008 was a dry year and very few flights occurred. As in 2008, 2009 was just as dry but the Edwards Aquifer target area saw a number of opportunities due to a number of weak cold fronts and diffuse boundaries stalling along the Balcones Escapement. In fact, the operational month of May was the busiest month that the EAA had seen since the conception of the Precipitation Enhancement Program (PEP) in 2002.

Even though drought conditions continued during most of the operational season, a number of flights took place in the Authority target area. The number of flights per month was fairly uniform throughout the season. However, the busiest month was May and the slowest month June. July, August, and September were equally busy. June, which usually can be a busy month, was very slow flight wise due to a persistently strong ridge of high pressure that was located over south Texas.

As was the case last year, in addition to normal weather modification activities in the Edwards Aquifer Authority (EAA) target area, 2009 was the third year for a randomized seeding experiment. The randomized seeding experiment was also conducted by the EAA's other weather modification contractor, the South Texas Weather Modification Association (STWMA). The objective of randomized seeding operations for the Edwards Aquifer Authority was to select clouds that met the criteria for suitable seeding candidates. This was seeding at random, and from that point, measurements and observations were taken to determine if seeding had an effect on the cloud. Due to bias that could occur the experiment was double blind so that ground operations staff would not know which clouds were seeded and which were not seeded. In other words, the staff was unaware of the seeding decision.

Even with increased flight activity in 2009 compared to 2008, randomized flights were hard to come by. No randomized seeding flights took place in Uvalde County during the 2009 season. The reason for no flights during the season was due to the fact that most of the convection in the EAA target area did not meet the randomized criteria. In particular, one criterion that must be met is that the convection is isolated and there is no other convection within a certain distance. Most convective cells that did occur in Uvalde County were not isolated and thus randomization could not be conducted on it.

Randomized procedures involved a black box with envelopes inside, each of which contained a card. The card denoted either "SEED" or "NO SEED". A box was placed in the office for each project, STWMA and SWTREA. Each of the aircraft that participated in the experiment had a box placed in the aircraft.

Once the pilot had declared a "case" based on the criteria listed, both the meteorologist and the pilot opened the first envelope in the box. The meteorologist then told the pilot the word on the card, who then determined whether to seed or not to seed based on the table below:

| Radar | Aircraft | Action |
|---|---|---|
| Seed | No Seed | No Seed |
| Seed | Seed | Seed |
| No seed | Seed | No Seed |
| No seed | No Seed | Seed |

The pilot, under no circumstances, told the meteorologist whether the decision was to seed or not seed, and the pilot and meteorologist did not communicate on issues related to the apparent effect of seeding or any noticeable effect. Any other normal conversation regarding safety of the pilot, aircraft, or any type of air traffic communication was talked about as normal.

At the September 30th conclusion of the 2008 operational season for the EAA target area, a radar evaluation was completed for the program. The findings are presented and discussed towards the end of this report. The flight logs for the 2009 seeding season are on the next page.

## 2009 Flight Log for SWTREA EAA Target Area

| Flight Number | Date | Aircraft | Total time (hours) | Materials used | Total seeding material |
|---|---|---|---|---|---|
| 1 | 5/16/2009 | 622X | 0.15 | 5(40g) BIP Flares | 200g AgI |
| 2 | 5/23/2009 | 57AA | 0.45 | 4(40g) BIP Flares | 160g AgI |
| 3 | 5/24/2009 | 622X | 1 | 26(40g) BIP Flares | 1040g AgI |
| 4 | 5/27/2009 | 622Z | 0.9 | 54(40g) BIP Flares | 2160g AgI |
| 5 | 5/27/2009 | 847P | 0.5 | 50(40g) BIP Flares | 2000g AgI |
| 6 | 5/29/2009 | 622X | 1.1 | 12(40g) BIP Flares | 480g AgI |
| 7 | 5/29/2009 | 622X | 0.5 | 26(40g) BIP Flares | 1040g AgI |
| 8 | 6/2/2009 | 622X | 0.15 | 11(40g) BIP Flares | 440g AgI |
| 9 | 6/25/2009 | 178M | 0.5 | 4(40g) BIP Flares | 160g AgI |
| 10 | 7/6/2009 | 847P | 1.1<br>0.1 | 8(40g) BIP Flares<br>4(40g) BIP Flares | 320g AgI<br>160g AgI |
| 11 | 7/17/2009 | 498P | 1 | 22(40g) BIP Flares | 880g AgI |
| 12 | 7/30/2009 | 622X | 1.5 | 21(40g) BIP Flares | 840g AgI |
| 13 | 7/31/2009 | 622X | 0.5 | 3(40g) BIP Flares | 120g AgI |
| 14 | 8/12/2009 | 622X | 1.5 | 4(40g) BIP Flares | 160g AgI |
| 15 | 8/13/2009 | 847P | 0.95 | 2(40g) BIP Flares | 80g AgI |
| 16 | 8/27/2009 | 622X | 1 | 7(40g) BIP Flares | 280g AgI |
| 17 | 8/28/2009 | 622X | 0.75 | 3(40g) BIP Flares | 120g AgI |
| 18 | 8/28/2009 | 498P | 0.9 | 6(40) BIP Flares | 240g AgI |
| 19 | 9/1/2009 | 622X | 0.9 | 3(40g) BIP Flares | 120g AgI |
| 20 | 9/9/2009 | 370P | 1.75 | 6(40g) BIP Flares | 240g AgI |
| 21 | 9/22/2009 | 622X | 1.5 | 12(40g) BIP Flares | 480g AgI |
| 22 | 9/28/2009 | 622X | 1.15 | 8(40g) BIP Flares | 320g AgI |

**Table 1: Seeding flight log for 2009**

| Flight Number | Date | Aircraft | Total time (hours) | Reason |
|---|---|---|---|---|
| 1 | 5/22/2009 | 370P | 0.4 | Equipment malfunction |
| 2 | 9/6/2009 | 847P | 1.05 | Could not find inflow |

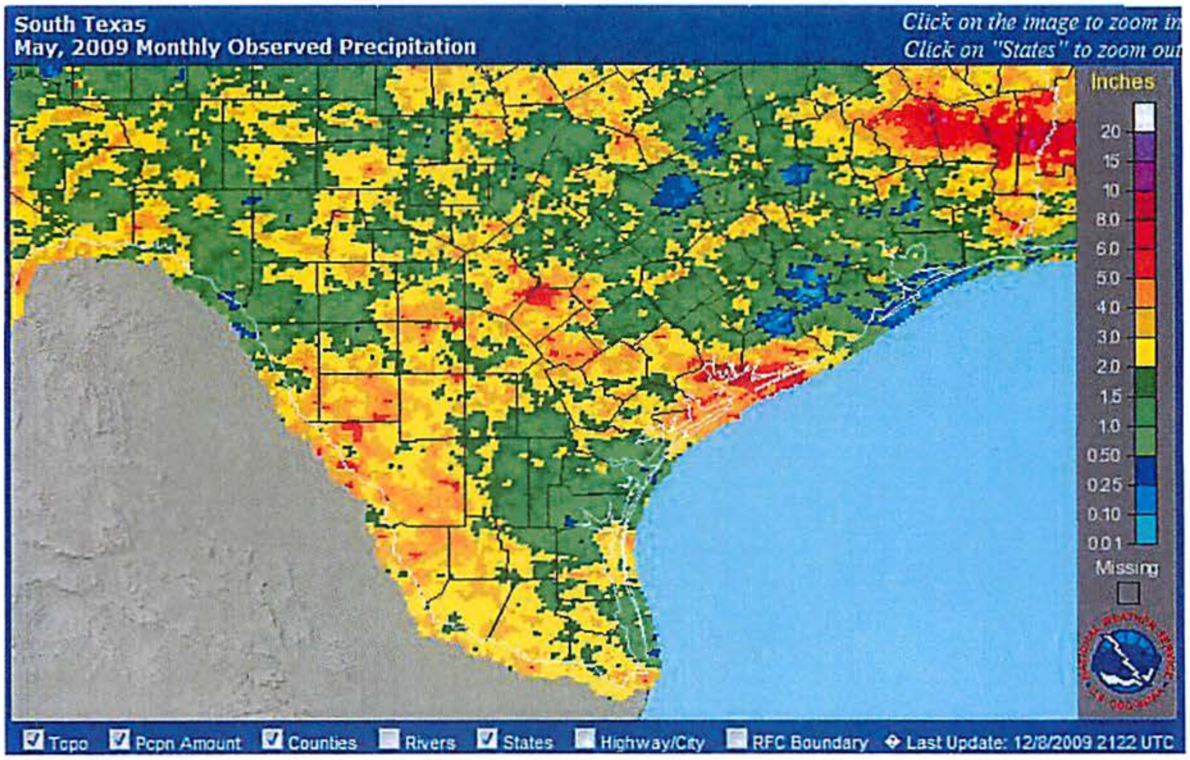
**Table 2: Reconnaissance flight log for 2009**

## Operational Summary

### May 2009

May 2009 was a definitely an unusual one. The first two weeks of the month were characterized by very dry conditions and temperatures 10-15 degrees above normal. However, mid month, the pattern shifted for the better as a series of mid to upper level troughs started to move into the southern Plains. This was the exact opposite from the beginning of the month, where a large mid to upper level high was located across the southern Plains, deflecting all troughs well to the north. Even though the area did see much needed rainfall during the month, as far as precipitation totals, the ongoing drought won with most of Uvalde County receiving between 1-5 inches, about 1-2 inches below normal. However, locations in northern and southeastern Uvalde County were above normal for the month. May was a very busy month for weather modification. The second half of the month offered a plethora of seeding opportunities. Even thought seeding operations were in full swing by mid month, no randomized flights were flown due to the randomized criteria not being met. A total of eight flights took place, with one of these being a reconnaissance flight. For the month, a total of 177 flares and 7,080g of AgI were used. As stated in the introduction, this was the busiest May that the EAA has had since the inception of the Precipitation Enhancement program (PEP) in 2002.

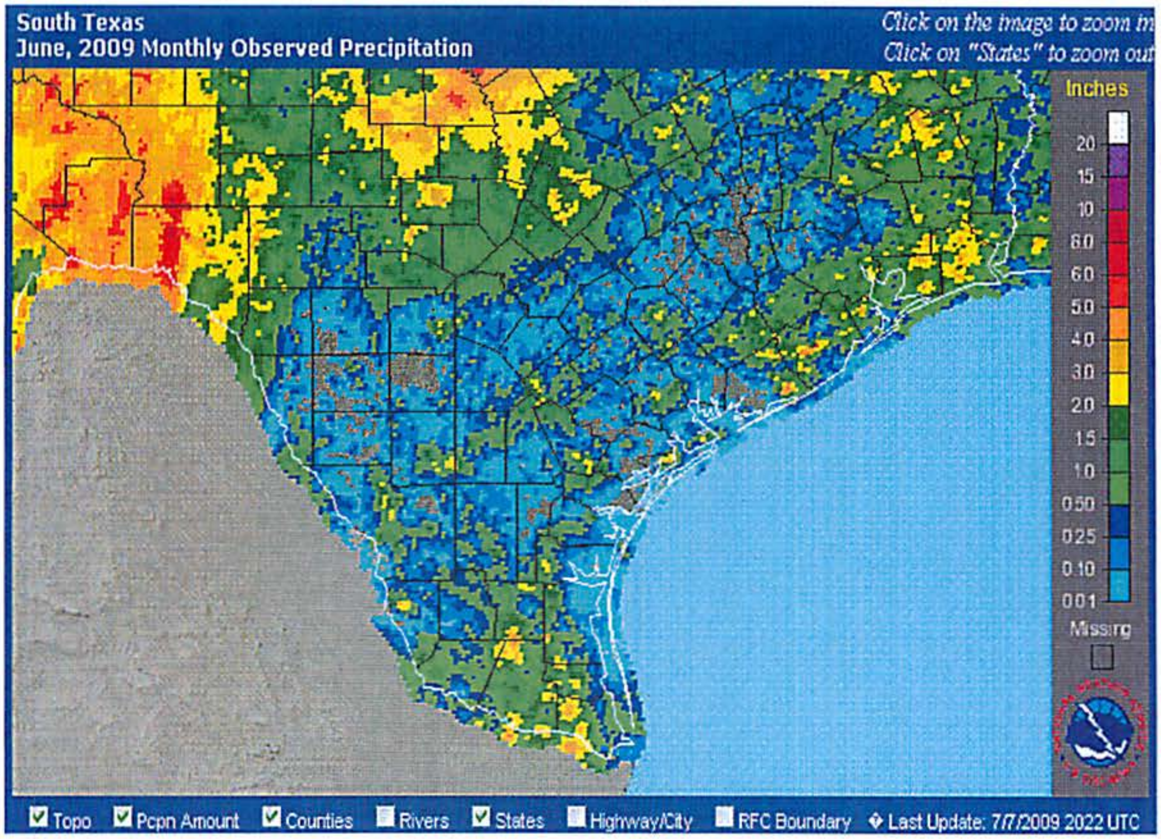
The following graphic for observed precipitation for the month of May shows some portions of the Edwards Aquifer were wet. However, there were some dry locations in Uvalde County, most notable in southern Uvalde County. May is typically one of the wettest months for South Texas and this month was about normal or a little below normal. Further to the south and southwest of Uvalde County, much more rainfall fell during the month of May.




**June 2009**

June was pretty dry for all of south Texas. An unusually strong ridge of high pressure kept the area very dry. Most areas in south Texas were about three to eight inches below normal. Locations along the southeastern Texas coast were far below normal, with locations in the Edwards Aquifer averaging about one to three inches below normal. The other story for June, besides the extreme lack of precipitation, was extreme temperatures. Temperatures for the month of June averaged about ten degree above normal, only further magnifying the drought situation over the area. A precipitation map for the month of June for south Texas is located on the next page of this report. As the precipitation pattern was dismal, so were weather modification operations for Uvalde County. Only two flights on two seeding days took place this month. A total of 15 flares and 600g of AgI was used during the month of June.

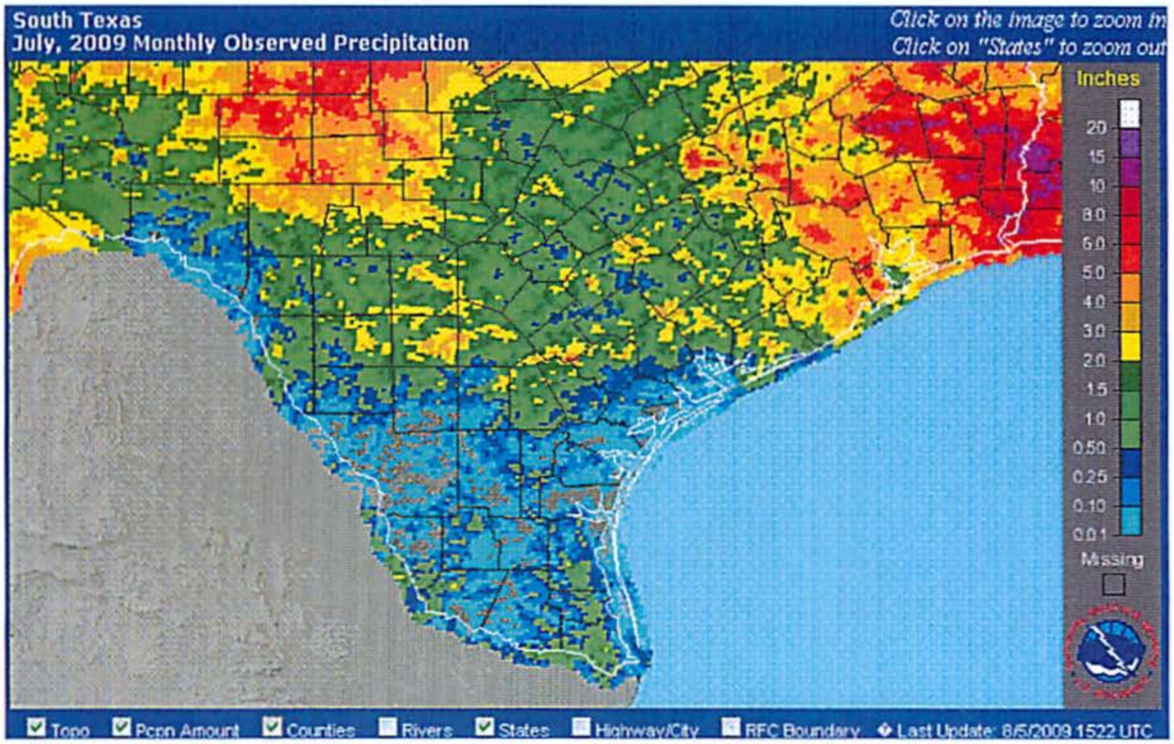
The following graphic shows a very dry month for not only Uvalde County but for most of South Texas. Most locations in Uvalde County only received between 0.01 inches and 1 inch of rainfall. Most of south Texas was very, very dry compared to normal. Locations further to the north and northwest saw better rainfall during the month of June.




**July 2009**

July proved to be yet another dry month for the area as a very strong ridge of high pressure remained over most of the southern U.S. Rainfall was sparse for all of south Texas this month, with most locations being one to two inches below normal. Surprisingly enough, there were areas that were above normal for the month, especially in the EAA target area. Some locations in southern and southeastern Uvalde County were an inch above normal for July. As well, most locations in the county were about normal for this time of year. This can be explained by the number of days that precipitation came from the north or northwest. Normally this time of year, most convection originates from the coast, not allowing for much rainfall in the Edwards Aquifer. But this year, a number of weak fronts moved close to the area, bringing more chances for seeding flights. This month was pretty busy in regards to seeding flights, even with the lack of workable convection for the most part. Only one week of the month yielded no seeding flights. A total of four seeding flights occurred on four seeding days. A total of 53 flares and 2,320g of AgI was used.

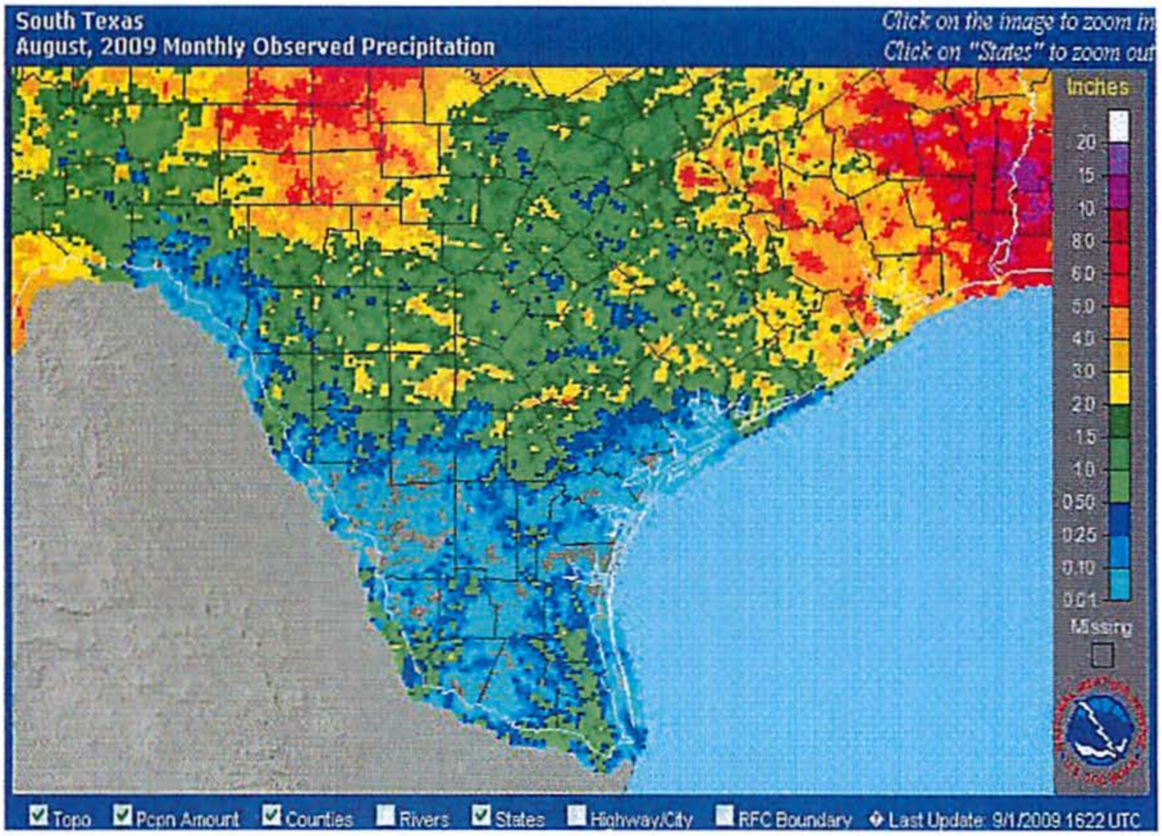
The following graphic represents rainfall for the month of July. July offered more in the way of precipitation for the area but still was well below normal for what it usually is. Most of Uvalde County saw between 1 to 2 inches of rainfall for the month of July. Locations just north of the recharge zone had much more rainfall during the month due to a number of cold fronts stalling there. Locations in the lower Rio Grande Valley were very dry with some locations not receiving any rainfall for the month.




## August 2009

August continued a very dismal summer for most of south Texas with above average temperatures and very little rainfall. However, there was one bright spot in ~~that~~ the second half of the month with the upper level pattern changing and allowing for more rainfall chances across the area. As well, this allowed for more seeding flights across the county. Most parts of the county were only about an inch below normal for the month of August. Other parts of the county were at about normal or slightly above normal as was the case for southern parts of the county. The main weather feature for the month that led to seeding flights was the prevalence of southward propagating outflow boundaries that acted as a lifting mechanism for convection across the region. The month yielded a total of five seeding flights across Uvalde County with a total of 22 flares and 880g of AgI used.

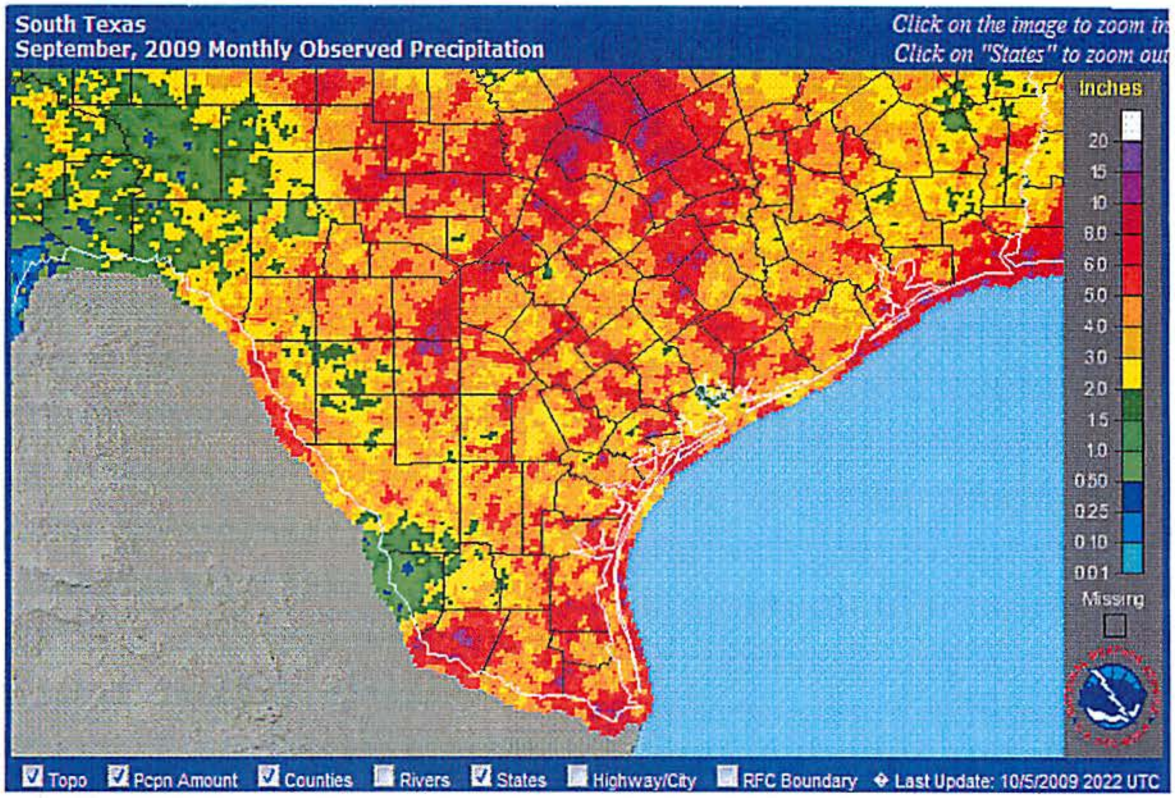
The following graphic shows the observed precipitation for the month of August for the South Texas region. As shown, yet another very dry month occurred for most of south Texas during August. Uvalde County only received between1 and 3 inches of rain for the month. Most of this precipitation came during the last half of the month. As in the previous month, locations over west Texas and southeast Texas received the most rainfall this month.




**September 2009**

September finally yielded a pattern change for most of south Texas and Uvalde County as ample rainfall occurred at the beginning and the end of the month. The monthly precipitation for September yielded just as much rainfall as had fallen all year in Uvalde County. As well, even more fell in other parts of the Edwards Aquifer. Weather modification, flight activity was about normal for this time of year. A number of flights occurred due to cold fronts moving through the area. This allowed for sufficiently deep convection, especially towards the end of the month, to develop and be seedable. Even with the increased rainfall for the year, most of Uvalde County was still 4 to 8 inches below normal by the end of September. A total of five seeding flights and one reconnaissance mission took place during the month of September. As well, a total of 29 flares and 1,160g of AgI were used.

The following graphic shows the observed precipitation for the month of September for the South Texas region. As stated, the pattern finally started to shift for the better with most locations over all of south Texas seeing at least two inches of rainfall with the maximum amounts being over ten inches. For Uvalde County, rainfall totals for the month were between two and nine inches. Southern and northwestern Uvalde County was the wet spots for the month.




## 2008/2009 EAA COMPARISON

| YEAR | 2008 | | | 2009 | | |
|---|---|---|---|---|---|---|
| MONTH | # of flights | Total Seeding Material (AgI) | # of seeding days | # of flights (recons) | Total Seeding Material (AgI) | # of seeding days |
| MAY | 0 | 0g | 0 | 8(1) | 7,080g | 5 |
| JUNE | 2 | 960g | 2 | 2 | 600g | 2 |
| JULY | 0 | 0g AgI | 0 | 4 | 2,320g | 4 |
| AUGUST | 1 | 440g | 1 | 5 | 880g | 4 |
| SEPTEMBER | 0 | 0g AgI | 0 | 5(1) | 1,160g | 4 |
| TOTAL | 3 | 1,400g | 3 | 24 (2) | 12,040g | 3 |

The preceding table gives a historical glance of a comparison of the Authority seeding activities for 2008 and 2009.

2009 was a very active year for weather modification in Uvalde County and in the rest of the PEP target area counties. Even with a very dry pattern in place, weather modification activities were able to continue.

## Meteorological Perspective of Seeding in 2009

This section is a summary of perceived efforts of cloud seeding as determined by radar trends. From the project meteorologist perspective, the 2009 seeding season saw above normal flight activity for the EAA target area. This was due to a number of stalled out cold fronts. As these fronts stalled out and dissipated, a weak boundary was left just to the north of the EAA target area. This boundary combined with the very warm temperatures we had this summer, lead to convection on more than one occasion firing in northern Uvalde County. This can explain how northern Uvalde County saw good precipitation through most of the drier months of June and July, when the rest of the county saw very little precipitation. As well, high pressure was just far enough to the south to allow this pattern to occur several times during the summer.

May was by far the busiest month of the season for Uvalde County. In fact, it was the busiest May ever for the EAA. A large number of flights were classified as rain enhancement but a couple hail suppression missions did occur as very severe thunderstorms moved into Uvalde County from the Edwards Plateau. Flights were confined to the latter part of the month, as the first two weeks of the month were characterized by above normal temperatures for most of south Texas.

June was very unlike the last couple weeks of May, with only two seeding flights taking place in Uvalde County. One flight took place during the very first part of the month with the departing system that gave rise to seeding missions during the last couple days of May. The other mission was at the end of the month as extreme surface heating interacted with a weak moisture field located over the western Hill County. This month was very slow due to the persistence of high pressure over most of south Texas.

July was almost as equally as slow as June, but offered a few more flights. The persistent ridge of high pressure that dominated south Texas for most of June remained over the area for most of July. However, due to a number of weak boundaries over the Hill County left over from dissipating cold fronts, convection occurred during the month, even under the strong high. July is usually a slow month for Uvalde County due to the origin of convection usually being from coastal areas. Due to the high over south Texas, coastal convection did not occur and gave Uvalde County a better shot at precipitation.

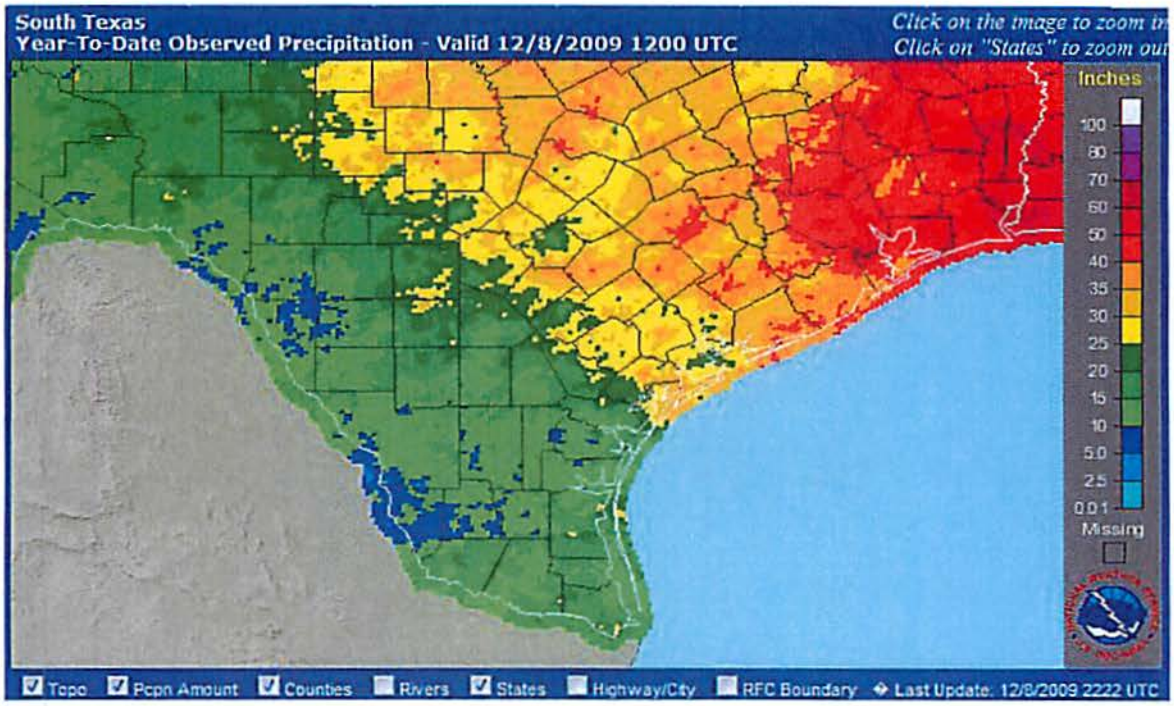
Activity began to pickup near the mid-way point of August as the pattern changed from a persistent ridge of high pressure to a more progressive one that allowed for rain chances over the area. A total of five flights occurred during the month of August and was mainly due to a series of upper level troughs that just skirted Uvalde County.

In September, a total of five seeding flights and one reconnaissance flight took place in Uvalde County. These flights were mainly due to disturbances moving across the area. One big change this month compared to the rest of the summer was the infiltration of very strong tropical moisture into the area. This is something that usually occurs in July, but did not this year due to the persistence of high pressure across south Texas. This tropical moisture made the atmosphere very buoyant, which means that it did not take much of anything in terms of a lifting mechanism to get convection started.

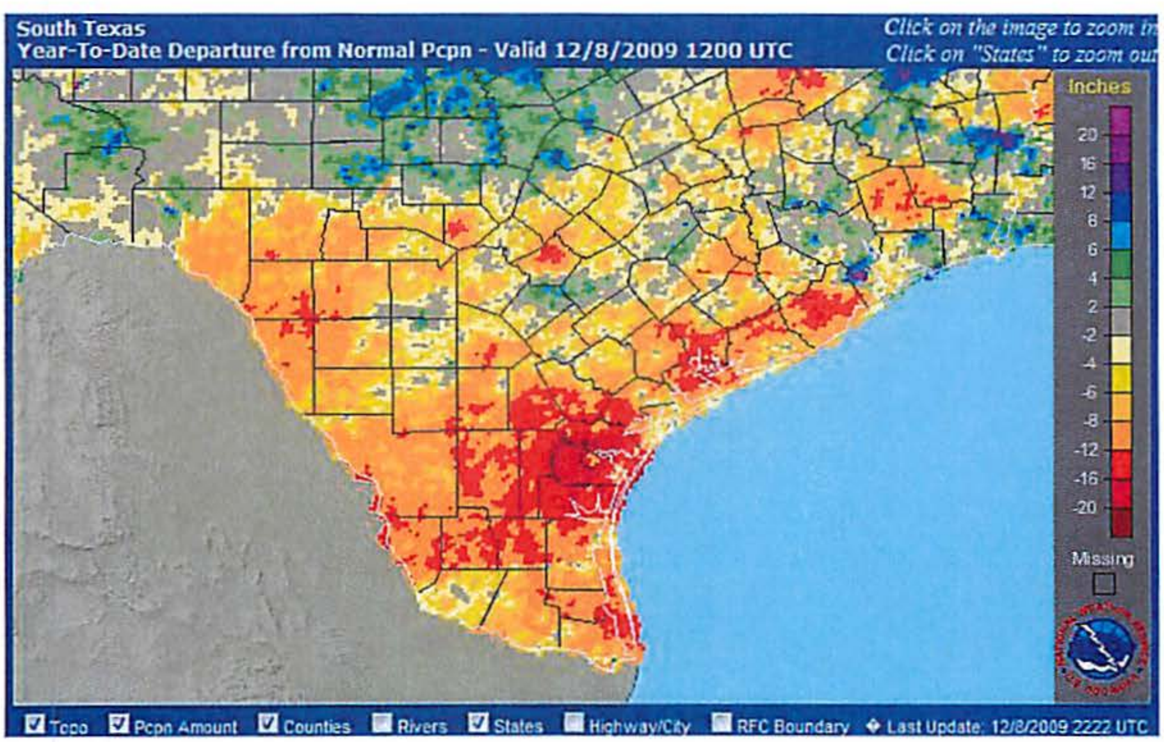
Overall, a total of twenty-four seeding flights and two reconnaissance flights took place in Uvalde County during the 2009 seeding season. Flight activity increased dramatically this year compared to last year's three flights. This was mainly due to Uvalde County being right on the dividing line of dry conditions to the south and wet conditions to the north and northwest. This allowed for several flights to take place over the area. High pressure dominated June and July but August and September continued to bring the promise of a pattern change over south Texas and with it increased convective activity leading to more weather modification activity.

The graphics on the next page show the 2009 year to date observed precipitation across south Texas and the departure from normal precipitation Just by looking at these two graphics, one can tell a lot about the weather pattern over South Texas. First of all, most of south Texas remained very dry throughout most of the winter, spring, and summer months due to a persistent ridge of high pressure over the area. The drier spots of the county included the southwest portions, with only about five inches of rain falling for almost the entire year. Precipitation amounts increase as you go to the north and northeast in the county, where locations here received 20-25 inches of precipitation. These amounts come into perspective when looking at the departure from normal precipitation, which shows how below or above normal precipitation was. In Uvalde County, the picture is quiet clear, with the west portions of the county almost 12 inches below normal. As one can see, most of the county was below normal for the year, with only a small portion of southeastern Uvalde County being at normal. This pattern was very common for most of south Texas in 2009.

## 2009 Precipitation (Year-to-date 12/8/2009)

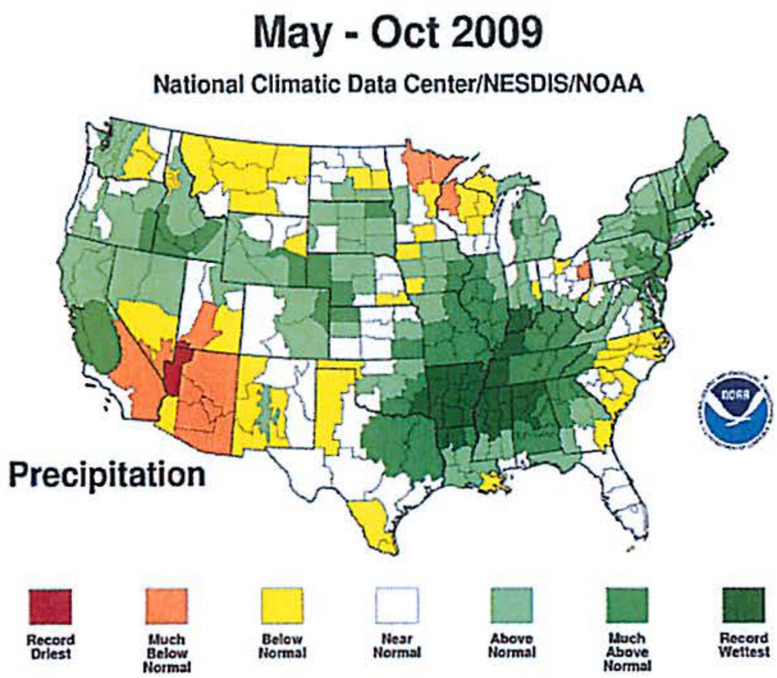



## 2009 Departure from Normal (Year-to-date 12/8/2009)



The following two figures a different look at precipitation trends across the United States and how it compared to South Texas in 2009.

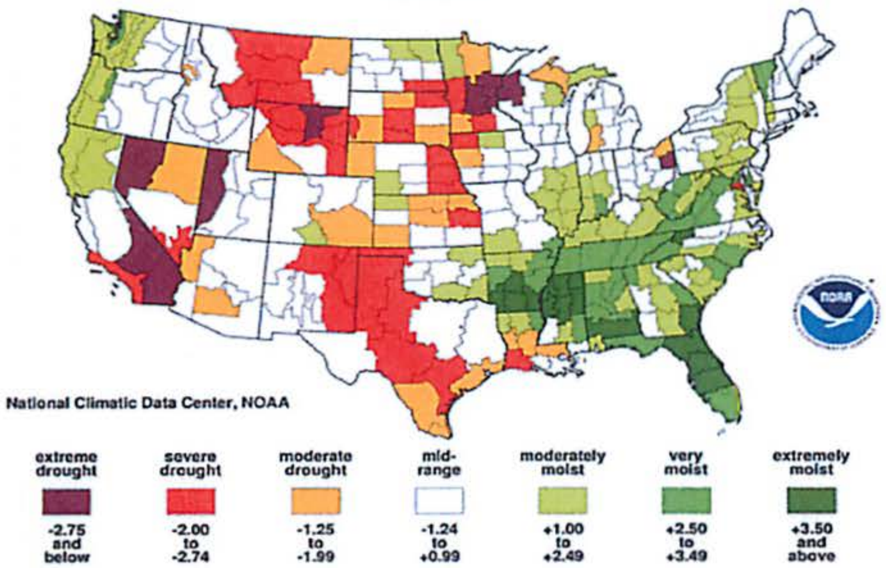
The following figure is a color coded picture of the United States. This graph represents precipitation from a period of May of 2009 to October 2009. This essentially depicts the average seeding season for the EAA, with the exception of October. Looking at the next graph, a number of things quickly jump out at the reader. First and foremost, all of south Texas is classified as below average for precipitation during this time frame. The Texas Panhandle was also below average for this period, with the rest of the state being about normal, with the exception of northeast Texas classified as being much above normal. Most of the Mississippi River valley, Tennessee River Valley, and into the central Plains were very wet for this period, while over the southwestern U.S., record dryness was recorded. From this graphic, a trough was set up over most of the southeastern U.S, while a long lived ridge of high pressure extended from southeast Texas into the rest of the southwestern U.S. For people who are unfamiliar with a trough and ridge, an explanation will follow of these common weather systems. A trough, or as it is commonly referred to, a trough of low pressure, usually induces rising air which allows cooler and warmer air to interact and create a temperature and pressure difference. These temperature and pressure differences usually create weather - most commonly in Texas, showers and thunderstorms. When a ridge or a ridge of high pressure is present, air is generally sinking, creating subsidence, or drying of the air. This eliminates most of the moisture from the air including clouds. High pressure is usually associated with fair weather and warm temperatures during the summer, whereas low pressure is usually associated with cooler temperatures and more precipitation.



The next three images will further communicate the dryness of the summer and use the Palmer Drought Severity Index (PDSI). The PDSI is a meteorological index of drought. This takes into account hydrological factors such as precipitation, evaporation, and soil moisture. This series of graphics will show the progression of the drought into the summer and finally the easing of the drought by the end of the seeding season. The first graphic shows the PDSI during the month of May. It shows the south Texas region classified as in intense drought, with locations to the south in a moderate drought. The second graphic shows the PSDI during the month of September. This shows extreme drought over some of the Edwards Aquifer with some easing along the western Hill County. Finally, the last graphic shows much improved conditions over almost all of south Texas, with moist conditions reported over much of the area.

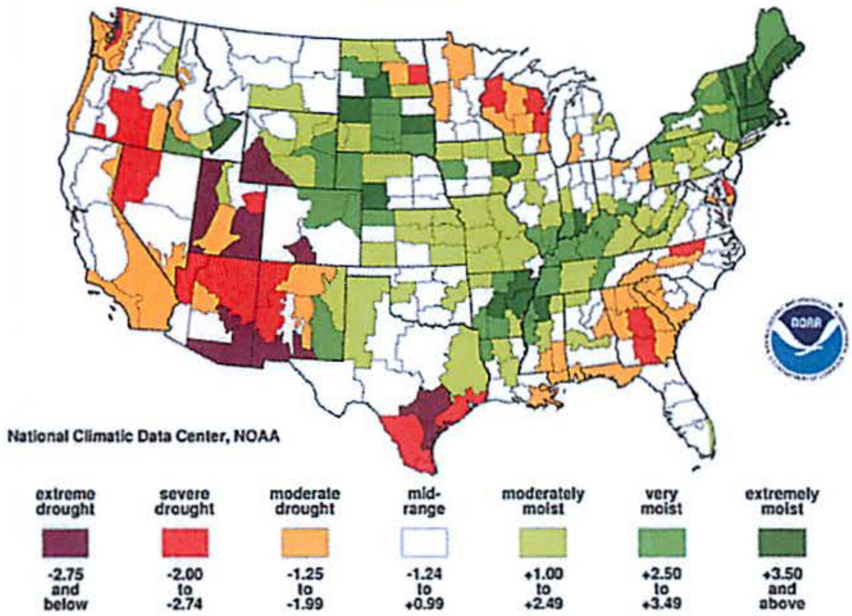
**Palmer Z Index**
**Short-Term Conditions**

**May 2009**



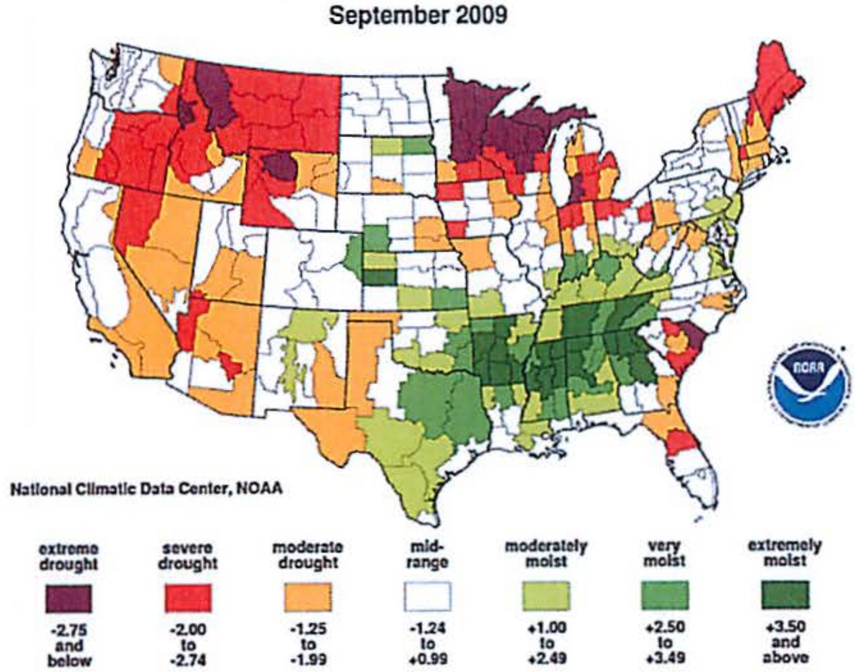
## Palmer Z Index
### Short-Term Conditions

July 2009




## Palmer Z Index
### Short-Term Conditions

September 2009



## APPENDIX A

**ANNUAL EVALUATION REPORT 2009 EAA**

**Dr. Arquímedes Ruiz-Columbié**
Active Influence & Scientific Management

Cloud seeding operations 2009 began over EAA target area in April. This annual report serves as a summary of results. A total of **57 clouds** were seeded and identified by TITAN in **26 operational days**. Table 1 in page 1 summarizes the general figures:

**Table 1: Generalities**

First operational day: **March 11th 2009 (extended seeding drifted into Uvalde County)**
Last operational day: **September 28th 2009**

**Number of operational days: 26**
(one in March, six in May, four in June, nine in July, four in August, and two in September)

According to the daily reports operational days were qualified as:

**Thirteen with excellent performance**
**Eight with very good performance**
**Five with good performance**

**Number of seeded clouds: 57**
(21 small seeded clouds, 18 large seeded clouds, 17 type B seeded clouds, 1 npf)

**Missed Opportunities: one (~ 2 %)** (with lifetime longer than 45 minutes)

September 9th: # 3012 on SWTREA TITAN screen at 23:00 over Medina County

**Small Clouds**

Evaluations were done using TITAN and NEXRAD data.

Table 2 shows the results from the classic TITAN evaluation for the 21 small seeded clouds which obtained proper control clouds.

**Table 2: Seeded Sample versus Control Sample (21 couples, averages)**

| **Variable** | **Seeded Sample** | **Control Sample** | **Simple Ratio** | **Increases (%)** |
|---|---|---|---|---|
| **Lifetime** | 55 min | 45 min | 1.22 | 22 **(10)** |
| **Area** | 79.1 $km^2$ | 48.3 $km^2$ | 1.64 | 64 **(11)** |
| **Volume** | 248.3 $km^3$ | 126.5 $km^3$ | 1.96 | 96 **(13)** |
| **Top Height** | 7.9 km | 6.8 km | 1.16 | 16 **(4)** |
| **Max dBz** | 51.8 | 48.6 | 1.07 | 7 **(3)** |
| **Top Height of max dBz** | 3.6 km | 3.4 km | 1.06 | 6 **(1)** |
| **Volume Above 6 km** | 46.3 $km^3$ | 13.7 $km^3$ | 3.37 | 237 **(39)** |
| **Prec.Flux** | 634.5 $m^3/s$ | 292.1 $m^3/s$ | 2.17 | 117 **(19)** |
| **Prec.Mass** | 2385.2 kton | 1066.8 kton | 2.24 | 124 **(93)** |
| **CloudMass** | 210.9 kton | 96.6 kton | 2.18 | 118 **(13)** |
| $\eta$ | 11.3 | 11.0 | 1.03 | 3 **(57)** |

Bold values in parentheses are modeled values, whereas $\eta$ is defined as the quotient of Precipitation Mass divided by Cloud Mass, and is interpreted as efficiency. A total of 92 flares were used in this sub-sample with an excellent timing **(78 %)** for an effective dose about **40 ice-nuclei per liter**. The seeding operations lasted in average about 9 minutes. An excellent increase of **93 %** in precipitation mass together with an increase of 13 % 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 (10 %), area (11 %), volume (13 %), volume above 6 km (39 %), and precipitation flux (19 %) are noticeable although affected by the small size of the sample, which implies a great variability. There were slight increases in maximum reflectivity (3 %) and in top height (4 %). The seeded sub-sample seemed

57 % more efficient than the control sub-sample. Results are evaluated as **excellent**.

An increase of **93 %** in precipitation mass for a control value of 1066.8 kton in 21 cases means:

$\Delta_1$ **= 21 x 0.93 x 1066.8 kton = 20 835 kton = 16 897 ac-f**

**Large Clouds**

The sub-sample of 18 large seeded clouds received a synergetic analysis. In average, the seeding operations on these large clouds affected 59 % of their whole volume; with a perfect timing (100 % of the material went to the clouds in their first half-lifetime). A total of 268 flares were used in this sub-sample for an effective dose about **75 ice-nuclei per liter**.

Also in average, large clouds were 45 minutes old when the operations took place; the operation lasted about 63 minutes, and the large seeded clouds lived 180 minutes.

Table 3 shows the corresponding results:

**Table 3: Large Seeded Sample versus Virtual Control Sample (18 couples, averages)**

| Variable | Seeded Sample | Control Sample | Simple Ratio | Increases (%) |
|---|---|---|---|---|
| **Lifetime** | 180 min | 160 min | 1.13 | 13 |
| **Area** | 662 $km^2$ | 613 $km^2$ | 1.08 | 8 |
| **Prec.Mass** | 25 962 kton | 18 190 kton | 1.43 | 43 |

An increase of 43 % in precipitation mass for a control value of 18 190 kton in 18 cases may mean:

$\Delta_2$ **= 18 x 0.43 x 18 190 kton = 140 791 kton = 114 181 ac-f**

**Type B Clouds**

Seventeen type B clouds over EAA target area were seeded during the season. In average, the seeding operations on these type B clouds affected 18 % of their whole volume; with a very timing (73 % of the material went to the clouds in their first half-lifetime). A total of 334 flares were used in this sub-sample for an effective dose about **100 ice-nuclei per liter**.

Also in average, type B clouds were 120 minutes old when the operations took place; the operation lasted about 35 minutes, and the large seeded clouds lived 265 minutes.

**Table 4: Large Seeded Sample versus Virtual Control Sample (17 couples, averages)**

| Variable | Seeded Sample | Control Sample | Simple Ratio | Increases (%) |
|---|---|---|---|---|
| **Lifetime** | 265 min | 260 min | 1.02 | 2 |
| **Area** | 2756 $km^2$ | 2707 $km^2$ | 1.02 | 2 |
| **Prec.Mass** | 157 088 kton | 144 117 kton | 1.09 | 9 |

$\Delta_3$ **= 17 x 0.09 x 144 117 kton = 220 499 kton = 178 825 ac-f**

**The total increase:** $\Delta = \Delta_1 + \Delta_2 + \Delta_3$ **= 309 903 ac-f**

**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 Seeding | Initial Seeding | Extended (increase) | Acre-feet (increase) | Inches (increase) | Rain gage (season value) | % (increase) |
|---|---|---|---|---|---|---|
| **Uvalde** | **23** | **31** | **107 300** | **1.29** | **9.94 in** | **13.0** |
| **Bandera** | **11** | **16** | **40 700** | **1.01** | **10.40 in** | **9.7** |
| **Medina** | **21** | **29** | **79 300** | **1.09** | **9.59 in** | **11.4** |
| **Bexar** | **2** | **10** | **51 000** | **0.77** | **9.02 in** | **8.5** |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Bexar** | **2** | **10** | **51 000** | **0.77** | **9.02 in** | **8.5** |
| Total | **57** | **86** | **278 300** | | | |
| **Average** | | | | **1.04 in** | **9.74 in** | **10.7 %** |

(**Initial seeding** means the number of clouds seeded when the operations began; whereas **extended seeding** means the counties favored by seeding after the initial operations took place.

**Final Comments**

1) Results are evaluated as **excellent**; no data corresponding to operations were lost.

2) The micro-regionalization analysis showed increases per county; different zones received downwind benefits; the average increase in precipitation, referred to rain gage seasonal value, is **10.7 %**.

3) Radar estimations of precipitation should be considered as measurements of trend. Nevertheless, seeding operations appeared to improve the dynamics of seeded clouds.

## Appendix B

## Glossary

**Mesoscale Convective System (MCS)** is a large complex of showers and thunderstorms at least 100 km (~60 miles) across, and may be as large as 500 km (~310 miles) across.

**Shortwave**, or shortwave trough, refers to a small-scale area of lower pressure, sometimes accompanied by showers and thunderstorms.

**Cell** refers to an updraft-downdraft couplet in a cloud. Clouds with several updraft-downdraft couplets are called **multicell** clouds. A storm with a single updraft-downdraft couplet (often rotating) that lasts for several hours is called a **supercell.**

**Pre-frontal trough** refers to an elongated area of low pressure found ahead of an advancing cold front. In south Texas, the passage of a pre-frontal trough usually signals the end of precipitation, as winds tend to turn more to the west or northwest, cutting off moisture supply.

**Precipitable Water** is the total amount of water vapor in a column of air above a given location. This value is expressed in inches. High precipitable water values (>1.5 inches) are indicative of the potential for heavy rain. Tropical airmasses usually have a precipitable water value in excess of two inches.

**Convective temperature** is the temperature required at or near the ground in order for convection (surface-based) to occur.

**TUTT**, or Tropical Upper Tropospheric Trough, refers to a upper level cold core area of low pressure found in the tropical and sub-tropical regions of the Earth. These disturbances are sometimes associated with shower and thunderstorm activity, and are associated with tropical waves.

**Theta-e**, or equivalent potential temperature, is the temperature a parcel or bubble of air would reach if it was lifted until all of the moisture condensed out, then brought back down to 1000 mb (at/near surface). A forecaster looks at theta-e to see how moisture is distributed over a region. High theta-e values are associated with moist airmasses, which storms may develop in and feed on.

**Jet streak** refers to the maximum wind speed within a river of faster-moving air (jet stream). Forecasters may look for jet streak locations at 850mb, 700mb, 500mb, and 250 mb in order to assess the possibility of strong/severe thunderstorms.

**Cap** refers to a warm layer of air aloft which acts as a lid, suppressing convection. The strength of the cap varies with time and location.

**Convective Inhibition** is the amount of energy required to overcome the cap, or the amount of energy required by a parcel of air to initiate deep convection (i.e., thunderstorms).

**Lifetime** refers to the length of time a cloud was detected on radar, with a reflectivity maximum of at least 32 dBZ.

**Area** refers to the two-dimensional space (length x width) covered by a cloud.

**Precip Flux** refers to the radar-derived volume of water falling through the bottom of the cloud per second.

**Precip Mass** refers to the total mass of water and ice for all droplets/crystals larger than 100 μm ($10^{-4}$ m) in a cloud.

**Small seeded clouds** are those clouds with a radar-derived Precip Mass less than 10,000 kilotons.

**Large seeded clouds** are those clouds with a radar-derived Precip Mass greater than 10,000 kilotons.

**Type B clouds** are those clouds, small or large, that were not seeded until they were at least one hour old, as determined by their presence on radar.

**Control clouds** are those clouds within 100 km of the radar that were NOT seeded. Control clouds are used to determine the effectiveness of seeding, as it represents "what would have happened" if seeding had not taken place.

**Effective dosage** refers to the amount of seeding material that was placed in the cloud. It is expressed as a concentration of ice nuclei per liter of air.