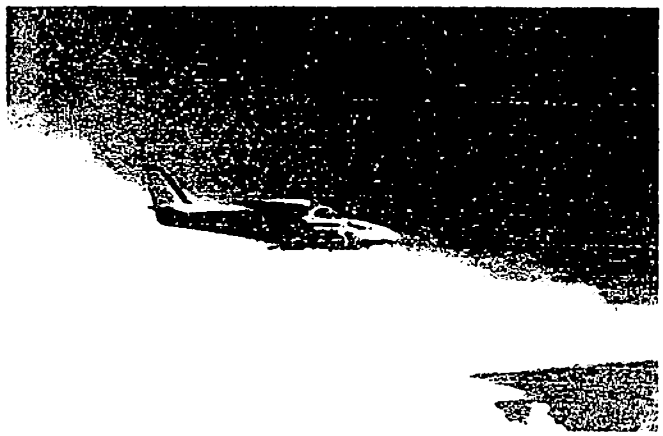
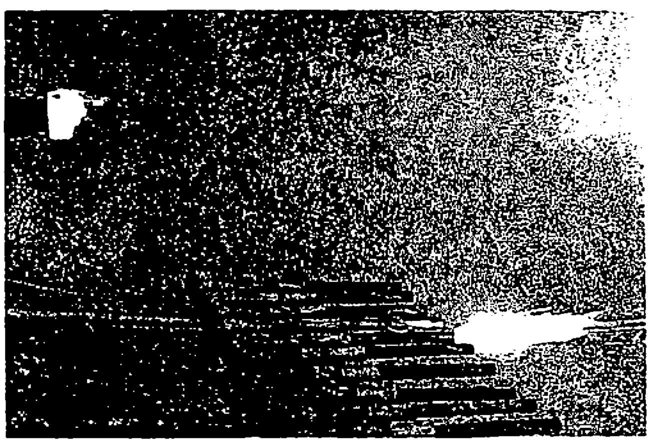
Edwards Aquifer Precipitation Enhancement Program

Final Report 1999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Edwards Aquifer Precipitation Enhancement Program

Final Report 1999

January 2000

A program designed for the Seeding of Convective Clouds with Glaciogenic Nuclei to Augment Precipitation for the Edwards Aquifer region.

By

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EXECUTIVE SUMMARY

This report summarizes the activities and data collected during the 1999 field operations of the Edwards Aquifer Precipitation Enhancement Program. This was the first year of a projected long-range program conducted by Weather Modification Inc. (WMI) of Fargo, North Dakota, for the Edwards Aquifer Authority (the Authority) of San Antonio, Texas. The program is funded partially by money from the Texas Natural Resource Conservation Commission, with the sole intent to enhance precipitation through cloud seeding. The project area was 5.44 million acres across south Texas, covering all or parts of 12 counties including Real, Uvalde, Kerr, Bandera, Medina, Kendall, Bexar, Blanco, Comal, Hays, Guadalupe, and Caldwell. A 24 hours per day, seven days per week cloud seeding service was provided from April 15th through September 15th.

The facilities and procedures for facilitating this project were as follows. One C-band weather radar, computers, and a communications system were set up in Hondo, Texas, for storm monitoring and aircraft control purposes. The radar operated continuously throughout the five-month period. Radar pictures were available and posted on the WMI Internet Home Page at 30-minute intervals, thus allowing remote viewing of operations. Two specially equipped cloud seeding aircraft were dedicated to the project. Both aircraft were stationed at the Hondo Regional Airport in Hondo, Texas, to provide adequate coverage of the target area and minimum response time to potential seeding candidates.

New and improved formulations of silver-iodide pyrotechnics and acetone solutions were used to generate high concentrations of very fast acting ice-nuclei. High performance aircraft with experienced pilots and radar meteorologists provided fast response and the direct injection of the seeding material into the developing regions of the storms.

The 1999 field program successfully achieved its objective, to seed cell with the potential to produce precipitation. During the 5-month project, the two aircraft completed 65 missions totaling 174.9 flight hours and dispersed 37.5 kg of silver iodide. The 37.5 kg of silver iodide comes from a total of 1,826 ejectable flares and 15 gallons of silver iodide - acetone solution from wing-tip generators used during the project.

The year can best be characterized as one with many low intensity thunderstorms and a few of days with very severe, long-lived, high intensity storms.

Concerns voiced during the project period were that there were clouds overhead and the planes were not. During much of the summer a strong high-pressure cell was located over the southern High Plains. Although there were numerous cumulus type clouds on most days, they were of the fair weather variety and had no potential to produce precipitation. Cloud modification cannot initiate the convective process but can aid it once convection begins. During each occasion with the potential for rainfall enhancement, seeding aircraft were dispatched to those areas within the target area.

This final report for 1999 provides a general overview of the program describing the methodology used. Pictures, tables, graphs, and references are used to summarize the operational activities. All of the project's radar data, meteorological data, and reports have been recorded onto CD-ROM and are available to the Authority.

ACKNOWLEDGEMENTS

WMI wishes to acknowledge the support of Bobby Bader, Field Office Manager, Edwards Aquifer Authority and George Bomar, Senior Technical Specialist, Water Quantity Division, Texas Natural Resource Conservation Commission. Their continued assistance and cooperation was greatly appreciated.

A number of agencies and people deserve recognition and thanks. The cooperation of Air Traffic Control (ATC) facilities at Houston is gratefully acknowledged. The excellent cooperation by the ATC played an important role in allowing the project pilots to treat developing storms in an efficient and timely manner. Special thanks to the city of Hondo and Rusty Lindeman, Airport Manager at Hondo Airport. The city of Hondo provided the property where the WMI radar trailer was located and authorized the use of the radar tower. The cooperation of these people contributed to the success of the project.

WMI wishes to acknowledge the contributions and professionalism of the staff: Jason Straub (radar meteorologist), Cory Mathiowetz, Tyler Sanders-Jones, James and Kelly Townsend, Jesse Opsal, Lilinoe Grimes, and Mike Galante (project pilots), Todd Schulz and Delrey Gjestvang (electronics technicians), and Tim Sedlock (coordinating meteorologist). The staff performed exceptionally well as a team.

Finally, the author wishes to thank Dr. Terry Krauss for his cooperation, participation, and input during the field operations as well as his editorial contributions to this final report.

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INTRODUCTION

The State of Texas has experienced a history of both prosperity and hardship due to either an abundance or shortage of water. During periods of long-term drought the state's agriculture suffers tremendously. The infamous drought of the 1930s became known as the "Dust Bowl" and was detrimental to the farming and ranching industries. Since the 1930s, droughts have reoccurred in every decade, with major droughts from 1950-52, 1953, 1955-56, the early 80s, and just recently in the summers of 1996 and 1998.

Significant benefits can be attained with increased precipitation. Agricultural benefits include increased crop yields, improved grazing conditions for livestock, reduced irrigation costs and improved water quality. Social benefits include increased rainfall runoff into reservoirs used for drinking water supplies and recreational purposes and lower evapotranspiration rates by growing vegetation.

The Edwards Aquifer region's average precipitation distribution shows an even average of 24" across the region, with slightly higher averages in the northeast (Figure 1).

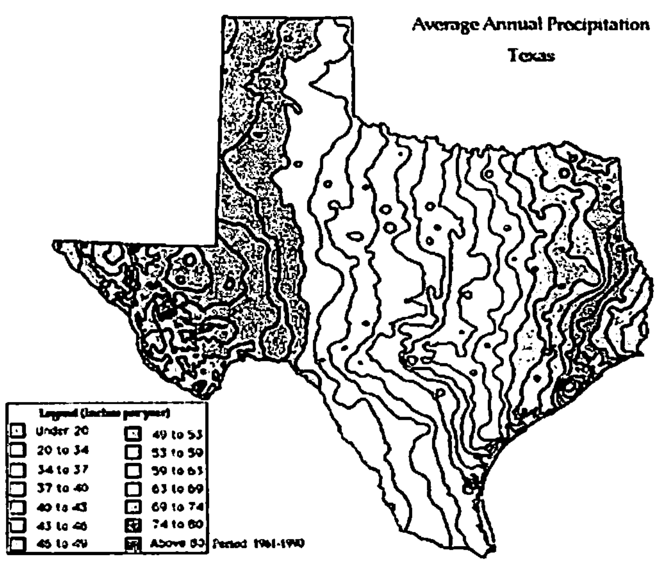

Figure 1: Annual Precipitation for south Texas.

The Edwards Aquifer Precipitation Enhancement Program (EAPEP) target area covered 5.44 million acres covering all or parts of 12 Counties in south central

Texas, including parts of the Texas Hill Country. The target area is shown in Figure 2. Two aircraft specially equipped to dispense silver iodide were stationed in Hondo. The radar was also located at the Hondo airport.

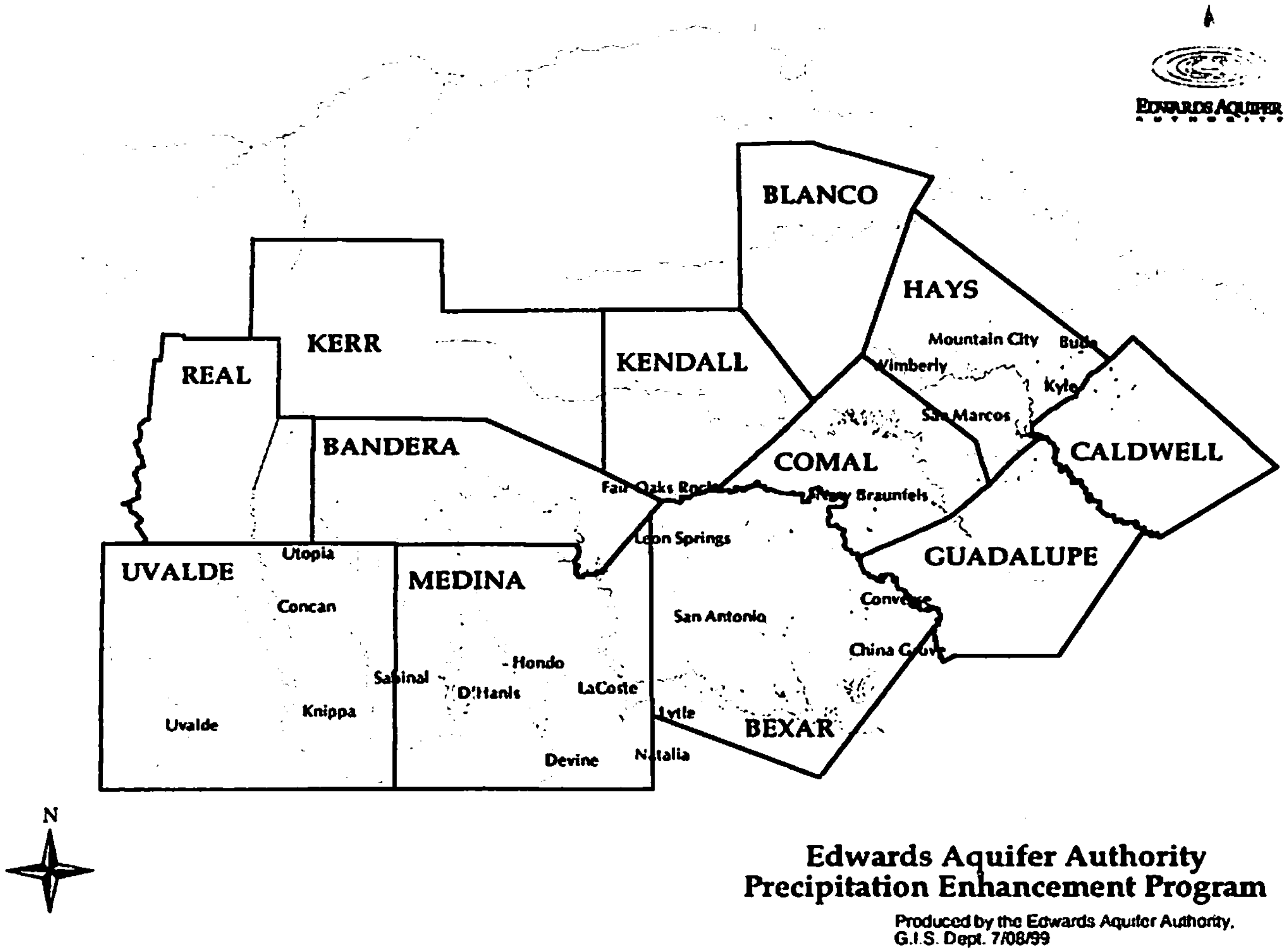

Figure 2: Edwards Aquifer Precipitation Enhancement Program Target Area

Weather Modification Inc. (WMI) has been a leader in the field of precipitation augmentation since the early 1960's. With extensive knowledge and experience in the cloud seeding industry, WMI is recognized for its successful operations in Texas, Oklahoma, the northern Great Plains, Alberta Canada, and other cloud modification services around the world. WMI was awarded the contract to conduct the Edwards Aquifer Precipitation Enhancement Program (EAPEP) in February 1999 by the Authority, for personnel and equipment to provide cloud seeding and related services for the purpose of rain enhancement across 12 counties in South Central Texas.

WMI conducted the first operational cloud-seeding field season from April 15th through September 15th, 1999. The project is based upon the techniques, methods, and results of the long-term rain and hail research projects conducted by the North Dakota Cloud Modification Project since the late 1960's through present time.

This program utilizes the latest cloud seeding technology available, incorporating several notable improvements over previous projects on various past WMI projects. Highlights include:

- An improved formulation for the silver-iodide flares which provide approximately 100 times more ice nuclei per gram of seeding material at relatively warm cloud temperatures (temperatures warmer than -10°C and the ability to nucleate ice as warm as -4°C). The majority of the improved flares used in 1999 were SAM's (Systems of Atmospheric Weather Modification), manufactured by the CHEMOD Co. of Skopje, Macedonia.
- An improved fast acting and high-yield mixture for the silver iodide and acetone solution for the wing mounted generators;
- The use of high performance, twin engine aircraft for quick response and timely seeding;
- The use of experienced meteorological and aviation staff to direct the seeding aircraft as well as to accurately identify the proper regions of storms for seeding;
- The injection of the seeding material directly into the developing cloud turrets as the most frequent seeding method; and
- The use of the latest GPS tracking and advanced TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) computer software to accurately display the aircraft locations on the radar displays to improve the controlling of aircraft and facilitate the direction of seeding operations to the most critical regions of the storms.

PROJECT OBJECTIVES

The goal of the EAPEP is to enhance rainfall in the target area by using state-of-the-art cloud seeding technology and procedures to seed suitable convective clouds.

It is the objective of Weather Modification, Incorporated (WMI) to aid the Authority in attaining the project objective by providing:

1. 24 hour a day, 7 days a week weather surveillance using one C-band weather radar.
2. Cloud seeding capability through the use of two specially equipped aircraft.
3. The capability for analysis by recording data during cloud seeding operations.

An ancillary goal is to conduct the operations safely with due regard for life and property on the ground and in the air.

OVERVIEW OF METHODS

The Authority objective is to seed clouds with silver iodide for precipitation enhancement. Seeding agent can be delivered to suitable clouds by aircraft using one of two methods:

1. Direct injection by cloud top seeding; or
2. Ingestion of ice nuclei into the updraft region by cloud base seeding.

Cloud Seeding Methodology-Seeding Techniques for Rainfall Increase

In **cloud base seeding**, silver iodide complexes are produced either by the combustion of acetone-based solutions or by the burning of silver-iodide flares attached to racks on the trailing edges of the wings. The nuclei thus produced are ingested by the target clouds, transported upward to the regions containing supercooled liquid water, and mixed through a significant portion of the cloud volume, where nucleation occurs. If treatment is timely, the seeding agent should reach the supercooled portions of the cloud at about the time the cloud top is growing through the -10°C level. Nucleation in these seeded clouds is believed to occur, on average, about 5 to 10°C warmer than most natural nucleation. Given typical cloud growth rates, this affords a "head start" in precipitation development on the order of 3 to 5 min.

In **direct-injection seeding**, ejectable silver iodide flares are used. Again, clouds growing through the -10°C level are targeted. The seeding flares are placed into the supercooled cloud where nucleation is desired, so the updrafts in these cases are relied upon only to provide a continuing source of condensate, not to transport the seeding agent upward from cloud base. This delivery technique thus requires less anticipation on the part of those directing the seeding and may have a more immediate effect.

In both cases, the intent is to glaciate portions of the cloud, initiating ice development minutes earlier than would naturally have been the case. For smaller or more isolated convective towers, glaciogenic seeding may accelerate hydrometeor growth sufficiently to allow the cloud to produce precipitation-sized hydrometeors during its short lifetime (microphysical effects), while adding buoyancy that may stimulate updrafts and prolong the cloud lifetime as well (dynamic effects). Both effects contribute to increased precipitation production.

Storm cells (defined by radar) with maximum reflectivity >35 dBZ within the cloud layer above the -5°C level, located within the project areas are seeding candidates. Radar observers and aircraft controllers are responsible for making the "seed" decision and directing the cloud seeding missions. Patrol flights are generally launched before clouds meet the radar reflectivity seeding criteria. These patrol flights provide an immediate response to developing cells. In general, a patrol is launched in the event of visual reports of vigorous towering cumulus clouds or when radar cell tops exceed 22-kft height on days when the forecast calls for precipitation.

Launches of more than one aircraft are determined by the number of storms in each area, the lead time required for a seeder aircraft to reach the proper location and altitude, and projected overlap of coverage and on-station time for multiple aircraft missions. In general, only one aircraft can work safely at cloud top and one aircraft at cloud base for a single storm.

Factors that determine cloud top or cloud base seeding are: storm structure, visibility, cloud base height, or time available for aircraft to reach seeding altitude.

Cloud base seeding is conducted by flying at cloud base within the main inflow of single cell storms, or the inflow associated with the new growth zone (shelf cloud) located on the upshear side of multicell storms.

Cloud top seeding is typically conducted between -5°C and -15°C. The 20-gram pencil flares fall approximately 1.5 km (approximately 10°C) during their 50-sec burn time. The seeding aircraft penetrate the edges of single convective cells meeting the seed criteria (Figure 3). For multicell storms, or storms with feeder clouds, the seeding aircraft penetrate the tops of the developing cumulus towers on the upshear sides of convective cells, as they grow up through the -10°C altitude.

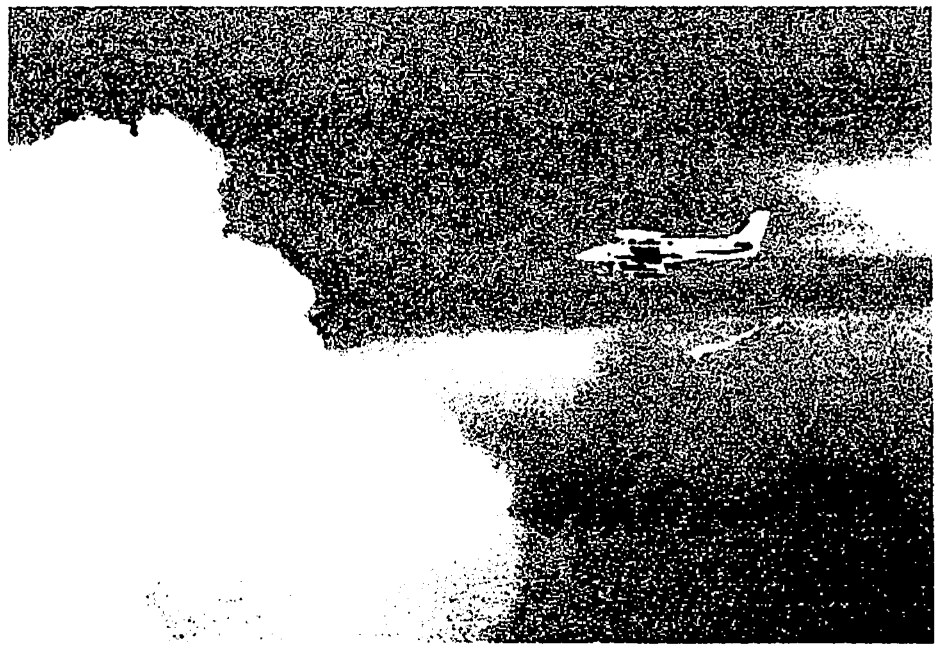

Figure 3: A photo of a cloud seeding plane dropping ejectable flares during a cloud seeding penetration (photo courtesy John Ulan).

Strictly speaking, if the radar reflectivity criteria are met, seeding of all cells is to be continued. However, seeding is effective only within cloud updrafts and in the presence of supercooled cloud water, i.e. the developing, and mature stages in the evolution of the classic thunderstorm conceptual model. The dissipative stages of a storm should be seeded only if the maximum reflectivity is particularly severe and there is evidence (visual cloud growth, or tight reflectivity gradients) indicating the possible presence of embedded updrafts.

<u>Seeding Rate</u>

A seeding rate of one 20-gram flare every 5 sec is used during cloud penetration. A slightly higher rate is used (e.g. 1 flare every 2 sec) if updrafts are very strong (e.g. > 2000 ft/min) and the storm is particularly intense. A cloud seeding pass is repeated immediately if there are visual signs of new cloud growth or radar reflectivity gradients remain tight (indicative of persistent updrafts). If not, a 5 to

10 min waiting period may be used, to allow for the seeding material to take effect, if visual signs of glaciation appear. This waiting period precludes the waste of seeding material and assures its optimum usage. Calculations show that this seeding rate will produce >1300 ice crystals per liter.

For cloud base seeding, the two wingtip generators are used. Cloud seeding runs are repeated until no further inflow is found. Base seeding is not conducted if downdrafts only are encountered at cloud base, since this would waste seeding material.

Seeding Materials

Silver iodide is dispensed using droppable flares and acetone burners. Details of the silver-iodide acetone solution recipe used in 1999 are shown below.

1999 WMI Airborne Generator Seeding Solution

Chemical Formulation: 2% AgI - 0.5 NH_4I - 0.1 $C_6H_4Cl_2$ - 1.0 $NaClO_4$

Recommended Burn Rate: ~2.5 gph

Nucleation Mechanism: Condensation Freezing

Total Solution Weight: 33.5 lbs.

Volume: ~ 5.0 gallons, scale for other amounts

Seeding Aerosol: $AgI_{0.85}AgCl_{0.15}NaCl$

Constituent	Chemical Formulation	Molecular Wt.(g/mole)	Mass (g)	Weight (lb.)	Volume (gal)
Silver Iodide	AgI	234.77	304.2	0.67	n/a
Ammonium Iodide	NH_4I	144.94	93.9	0.21	n/a
Paradichloro -benzene	$C_6H_4Cl_2$	147.00	19.0	0.042	n/a
Sodium Perchlorate, 99%	$NaClO_4$	140.48	181.8	0.40	n/a
Water	H_2O	17.99	607.7	1.34	0.202
Acetone	$(CH_3)_2CO$	58.08	13985.5	30.84	4.645

Note: Sodium Perchlorate, anhydrous can be utilized in the formula by adjusting the weight or mass to include 0.34 lb or 158.1 g respectively, although proper handling becomes more difficult. Water amounts should be increased to 1.40 lb. or 630 g (0.21 gal).

An acetone generator is shown in Figure 4. The acetone burners require considerable preventative maintenance in order to function properly and reliably. Crews kept a close watch of igniter rods, valves, and seals to ensure reliable operation.

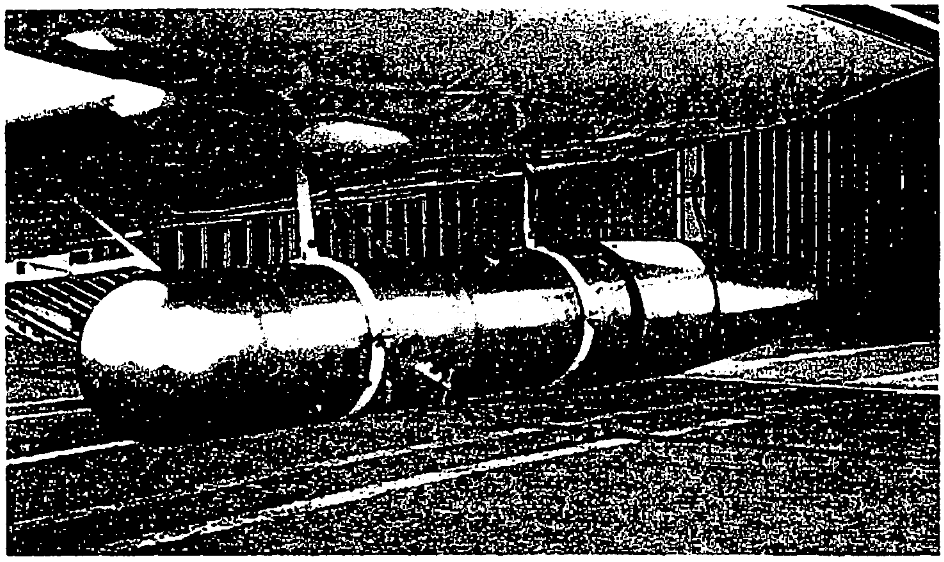

Figure 4: An acetone generator on an aircraft.

In 1999, WMI used a type of silver iodide flares manufactured by CHEMOD in Macedonia. The ejectable flares contain 20 g of seeding material and burn for approximately 50 sec, and fall approximately 4,000 ft.

Flare Tests

The ice nucleating effectiveness of the flares manufactured by CHEMOD and the Weather Modification Group, used by WMI, are well documented (Demott, 1987; 1990; 1995,1997,1998). The Cloud Simulation and Aerosol Laboratory at Colorado State University has performed routine testing of the ice nucleating ability of aerosols produced from cloud seeding flares for many years (Garvey, 1975). The primary product of the laboratory characterisation is the "effectiveness plot" for the ice nucleant that gives the number of ice crystals formed per gram nucleant as a function of a range of cloud temperatures.

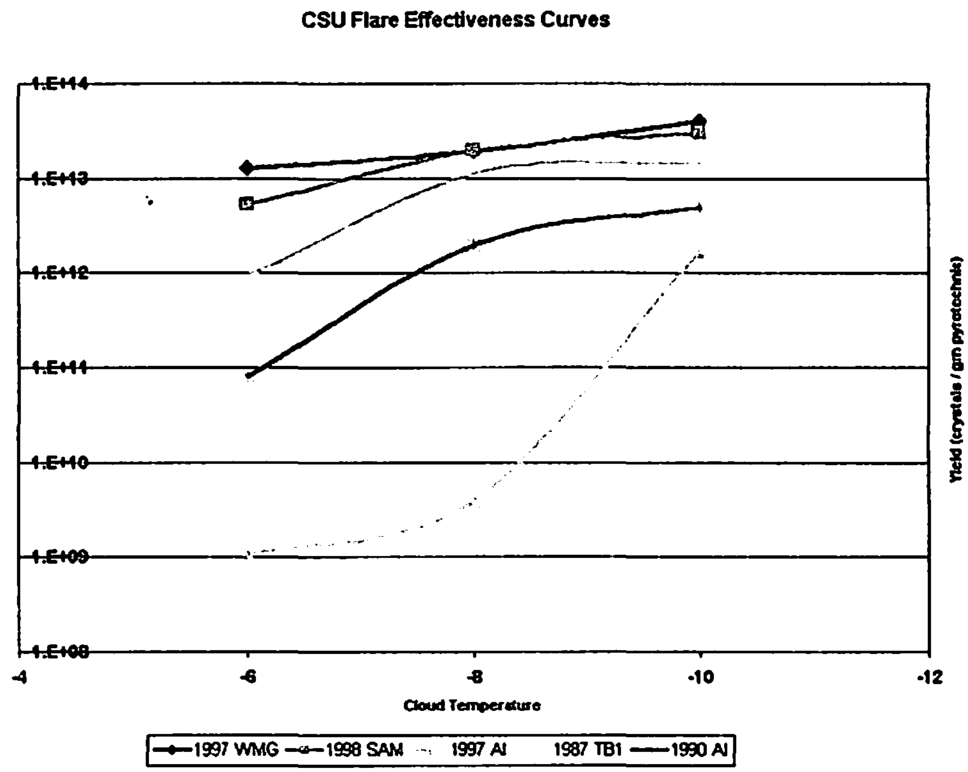

Figure 5: CSU test results for WMG (1997), SAM (1998), AI (1990 & 1997 BIP), and TB1 (1987) flares.

Specified temperatures for testing in the isothermal cloud chamber were –4°C, -6°C, -8°C, -10°C, and –12°C. Three pyrotechnics were tested at each temperature. The liquid water content of the chamber clouds was set to 0.5 g/m^3 and 1.5 g/m^3, which is quite representative for clouds in south Texas. The average effectiveness values according to cloud temperature are given in Table 1.

Temperature (°C)	SAM Effectiveness (# ice nuclei/g)	WMG Effectiveness (# ice nuclei/g)
-6°C	8.1×10^{12}	1.3×10^{13}
-8°C	1.2×10^{13}	2.2×10^{13}
-10°C	3.2×10^{13}	4.2×10^{13}

Table 1: Average Ice Nuclei Effectiveness per gm of pyrotechnic of WMG (1997), and CHEMOD "SAM" (1998) Silver Iodide Flares at 1.5 g/m^3 Liquid Water Content.

A comparison of laboratory test results for various flare types is shown in Figure 5. Significant conclusions from these recent tests for the SAM flares (Table 1) are:

1. SAM pyrotechnic aerosols possess relatively high yield per pyrotechnic. This yield is realized at a relatively warm temperature and increases by less than a factor of two between -8°C and -12°C. Significant ice formation activity was measured as warm as -4°C. Little dependence of yield on cloud liquid water content or cloud droplet distribution characteristics is expected based on the current tests.
2. Rates of ice crystal formation in the CSU isothermal cloud chamber were extremely fast and the apparent ice formation mechanism was condensation-freezing nucleation.
3. Given the fast ice formation rates and flat activity spectrum colder than -8°C, these pyrotechnics should be quite suitable for seeding summertime cumuli at warmer supercooled temperatures.

PROGRAM ELEMENTS AND INFRASTRUCTURE

A schematic figure of the operational elements for the precipitation enhancement project is shown in Figure 6 on the next page. Details of the individual elements are described in more detail in the following sections. The radiosonde (weather balloon) depicted in Figure 6 is not a part of the present WMI system in south Texas.

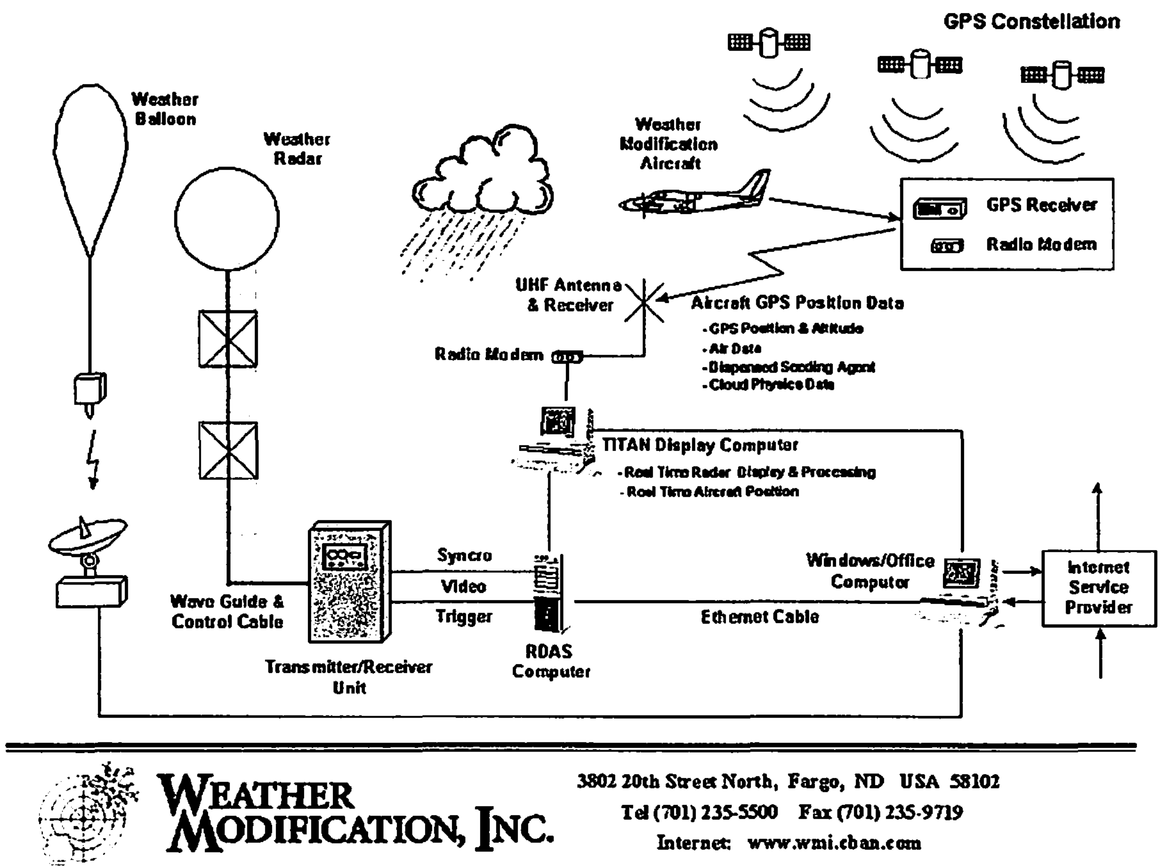

Figure 6: A schematic of the operational elements of the Edwards Aquifer Precipitation Enhancement Program.

Ground School

A ground school was conducted for all project personnel on May 7th, 1999 at the Authority boardroom in San Antonio. Operational procedures, general conduct, and reporting requirements were presented and reviewed at the ground school. The ground school presentation material was assembled and printed as an Operations Manual for all project staff.

The ground school training topics included:

i. Program overview, project area, target areas, and priorities
ii. Overview of operations and procedures
iii. Cloud seeding hypotheses for precipitation augmentation
iv. Cloud seeding theory and techniques
v. Aviation weather problems and special procedures

vi. Aircraft controlling techniques and procedures
vii. Seeding aircraft equipment and characteristics
viii. Weather radar equipment and basic principles
ix. Weather phenomena, fronts, and storms
x. Daily routines and procedures
xi. Communications procedures and teamwork
xii. Computers, documentation and reporting procedures
xiii. First aid, safety, and security precautions and procedures

Air Traffic Control

Prior to the start of field operations, ATC facilities were notified about the upcoming weather modification flight activities to be conducted in south Texas over the operational period of April 15th through September 15th, 1999. WMI of Fargo, North Dakota, maintains a license from the Texas Natural Resource Conservation Commission to conduct cloud seeding flights to increase local area rainfall during those periods in the state of Texas. Permission was granted to file pre-defined flight plans for the project aircraft, with special designations and fixed transponder codes, as Seed 1 for the Cessna 340 aircraft (N3904G) and Seed 2 for the Cessna 340 aircraft (N340AX) stationed in Hondo. Direct dial-up telephone numbers were used to notify air traffic controllers of cloud seeding launches. Aircraft were launched to a specific location identified by Very High Frequency (VHF) Omnidirectional Range (VOR) and DME (Distance Measuring Equipment) coordinates. Distinct air traffic clearance was given to project aircraft within a 10 nautical mile radius of the specified storm location. Cloud top aircraft were given 2,000-ft clearance above their altitude and 5,000 ft below their altitude. Cloud base aircraft were given a +/- 1,000-ft altitude clearance. This procedure worked very well in general. On a few occasions, seeding aircraft were asked to climb to a higher altitude or to suspend seeding a few times to allow other commercial aircraft to pass below them. The ATC clearances and codes are shown in Figure 7 on the next page.

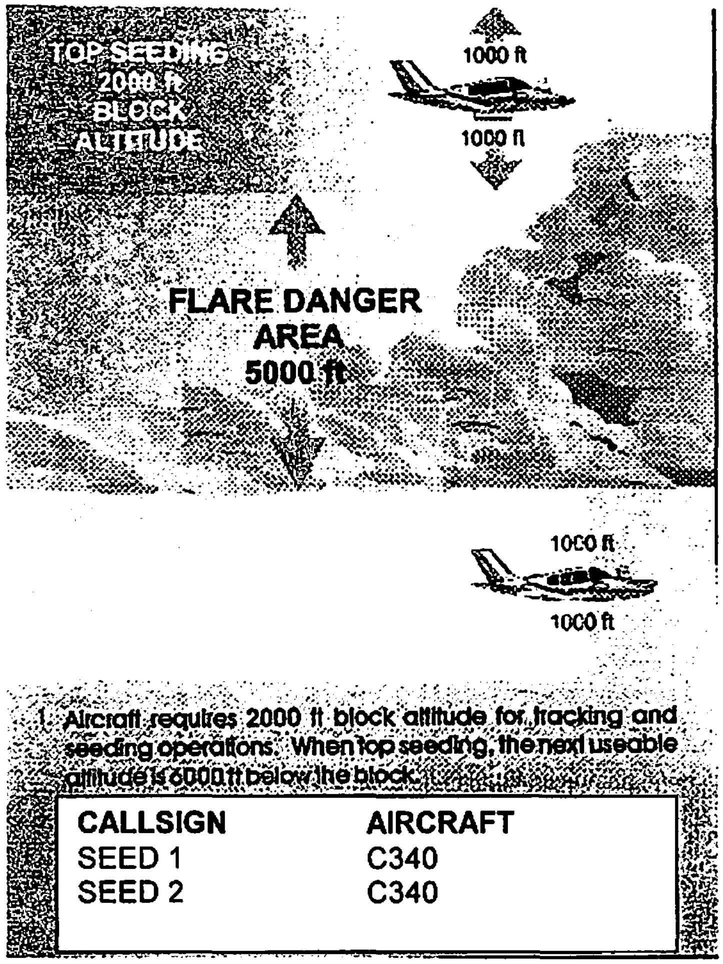

Figure 7: Schematic figure showing aircraft cloud seeding block altitudes required for Air Traffic Control (ATC).

RADAR CONTROL AND COMMUNICATIONS CENTER

The radar control room consists of the WR-100 radar console and the RDAS radar acquisition computer, the Airlink computer with radio telemetry modem for GPS tracking information, as well as the TITAN computer and display. Controllers communicate with the seeding aircraft using a VHF radio.

Weather Radar

WMI provided one 5-cm C-band weather radar located on a radar tower previously used by the National Weather Service in Hondo, Figure 8 on the next page. The project radar is an Enterprise Electronics Corporation WSR-74C, C-band radar with an 8-ft antenna. The radar operated continuously, 24 hours per day throughout the operational period April 15th to September 15th. A gas-powered generator was used to provide emergency power in the case of a power failure. Line power was very reliable at the radar during the summer. The emergency generator was not called upon during the operations, but it was tested frequently. On September 16th, the radar was shut off for the season, however the tower, radar transmitter and display equipment will remain in place until next year.

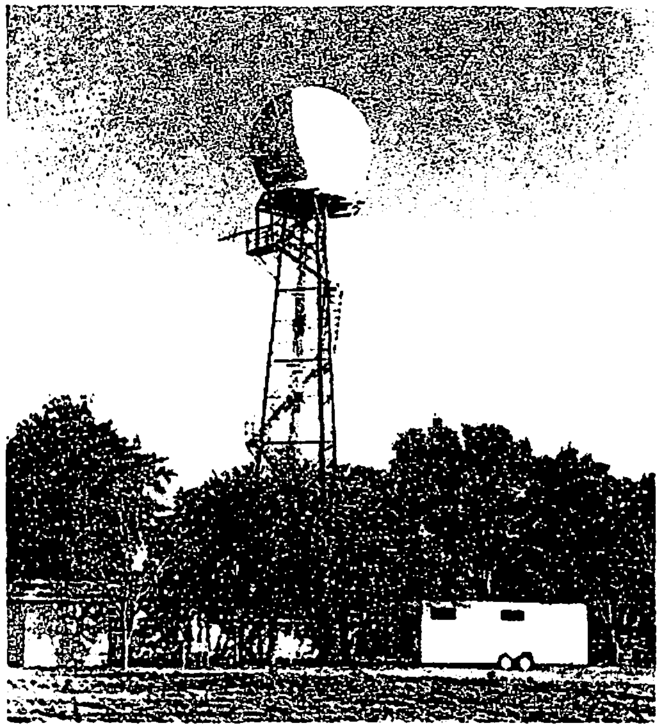

Figure 8: Hondo Radar Site

The radar signal processor is an RDAS (Radar Data Acquisition System) produced by Electronic Systems Development, South Africa. The display and analysis system is the TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting system) software package available from the National Center for Atmospheric Research (Dixon, 1993). More details and examples of the TITAN system displays and products are given in a later section. The weather radar offered by WMI is a weather sensitive instrument capable of detecting rainfall rate of 1mm/hr at 70 nautical miles (nm) displaying echoes on the PPI and RHI measuring echo reflectivity and echo top height.

Radar Calibration Checks

The quantitative use of radar requires that various parameters of the system be measured and calibrated. The WMI WSR-74C C-band radar located at the Hondo Regional Airport is used to direct seeding aircraft in the Edwards Aquifer Precipitation Enhancement Program. As such, it needs to provide accurate values of radar reflectivity along with range, azimuth and elevation.

If we assume that all the terms relating to the electrical components and propagation of the radar beam are constants and if we always assume we are looking at water (rain drops), a simplified radar equation takes the form (Rinehart, 1997):

$$z = C\, p_r\, r^2$$

Thus, calculating radar reflectivity factor z is simply a matter of getting the power from a target, p_r, of known range, r (times a constant, C, the radar constant). The new RDAS radar acquisition software performs digital signal processing to simulate a quadratic response of the receiver output (Terblanche, 1996) and uses a reference range of 100 km. The radar was found to be stable within +/- 1 dB from day to day and the radar constant varied by <1 dB over the summer.

Aircraft Flight Tracking Global Positioning System (GPS)

The WMI weather radar control and communications center was equipped to receive and record data from the aircraft GPS tracking system. The GPS system displays the exact position of the aircraft superimposed on the radar PPI display to enable the controller to accurately direct the seeding aircraft to optimum seeding locations within the storm system. The color-coded aircraft position on the PPI display enabled radar controllers to discriminate between each project aircraft. The flight track plot for both aircraft is shown in Figure 9 on the next page.

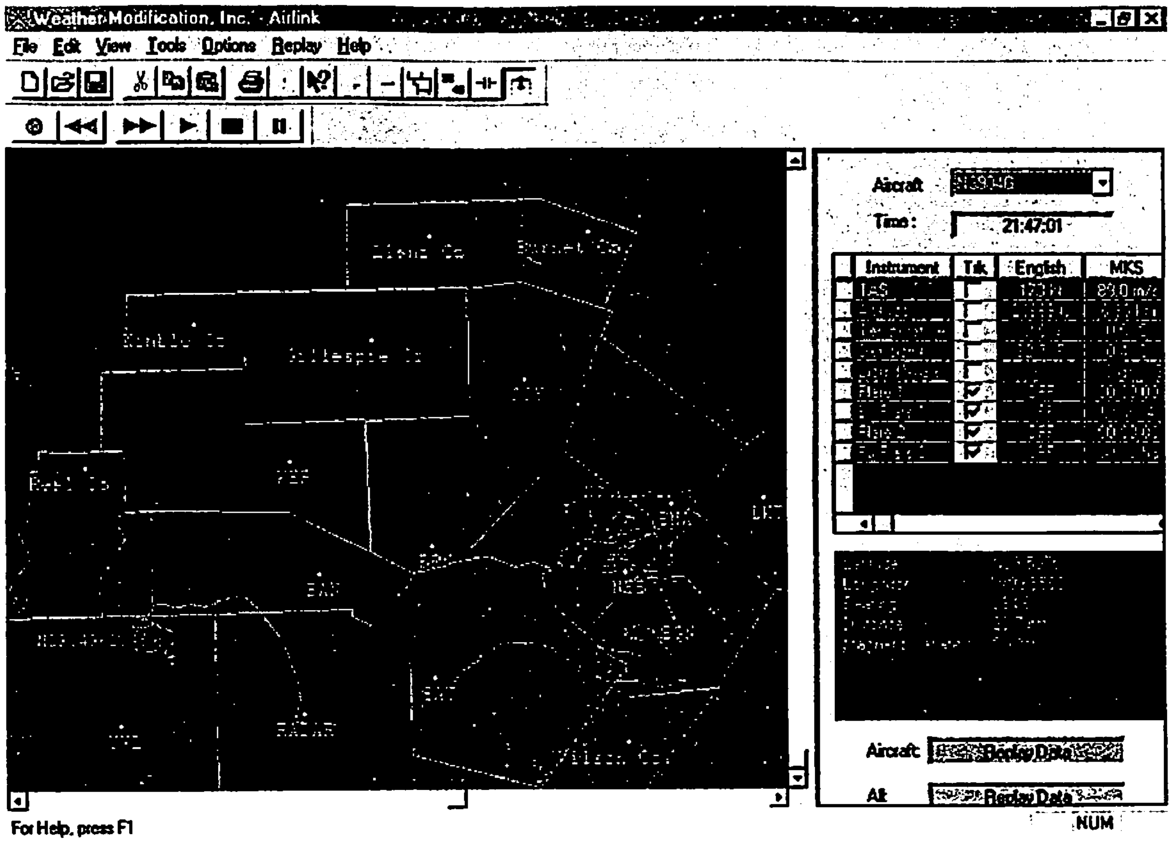

Figure 9: Aircraft Global Positioning System (GPS) flight tracks, seeding locations, and real-time meteorological information via the AIRLINK telemetry system.

The display shown in Figure 9 is of the AIRLINK program. Airlink is a windows based program that allows the controller to display the seeding events: i.e. the exact times and locations of flare drops and total time and location of the acetone generator usage.

Meteorological Data

WMI meteorologists for forecasting purposes used professional services and data from the Internet. Regular maps and data were used to determine the atmospheric conditions (temperature, humidity, pressure, and wind field) over the project area. The radar and satellite facilities were also used to support operations. The list of some of the Internet web pages utilized by the meteorologists includes:

Ohio State University Gopher	http://twister.sbs.ohio-state.edu/
Unisys Weather	http://weather.unisys.com/
UCAR	http://www.rap.ucar.edu/weather/
Storm Prediction Center	http://www.spc.noaa.gov/
Intellicast Weather	http://www.intellicast.com/
WMI Index of /radar/Hondo	http://www.wmi.cban.com/

Access to high quality, real-time weather information was readily available on the Internet. WMI made special arrangements to automatically access the necessary weather charts of objective analyses, forecasts, and bulletins to properly prepare a daily weather and operations/update briefing for the program.

Daily Briefings

All project staff participated in a "briefing session" each day at 12 noon that included a summary of the previous day's operations (if any), discussion of the weather situation, presentation of the weather forecast and operations meteorological statistics, equipment status reports, and operations plans for the day. All staff were equipped with either pagers or cellular telephones to allow constant communications day or night. The daily briefing was important in maintaining the team spirit, communications, and cooperation.

Coordinated Universal Time

Coordinated Universal Time (UTC) is used as the standard for record keeping during the project where operational days are observed. The time was formerly called Greenwich Mean Time (GMT) and is the accepted international standard of time for general aviation and meteorological observations, reporting, and communication. Although a seeding operation may occur on two separate UTC 'days', it is recorded as the same day for operational purposes. In Texas, UTC is five hours ahead of Central Daylight Time (CDT). For example, if seeding operations commenced at 5 PM CST (2200 UTC) on May 1st and continued until 9 PM CST (0200 UTC), the 'operational day' would be logged as May 1 although operations continued into May 2nd on the UTC clock. UTC can be converted to Central Daylight Time (CDT) by subtracting 5 hours. UTC can be converted to Central Standard Time (CST) by subtracting 6 hours.

The standard convention incorporated by the Texas project is to express all aircraft, radar, and meteorological times in UTC, however, for convenience, the summary tables are all organized according to the local calendar "storm" day. In other words, a storm that occurred on the evening of May 1st, 1999 at 8:00 p.m. (0100 UTC, May 2nd, 1999) is shown to occur on May 1st in all of the project summary tables and logs.

Seeding Amounts

The amount of silver iodide dispensed on each day of operations in 1999 is shown in Figure 10. A total of 37.5 kg of silver iodide was dispensed on 38 days of cloud seeding. The number of cloud-top flares used in 1999 was 1,826. Fifteen gallons of silver iodide was dispensed using the wing-tip generators. Seeding flights were performed from April 24th through September 13th of the operational period. The two busiest days during the season occurred in mid-June.

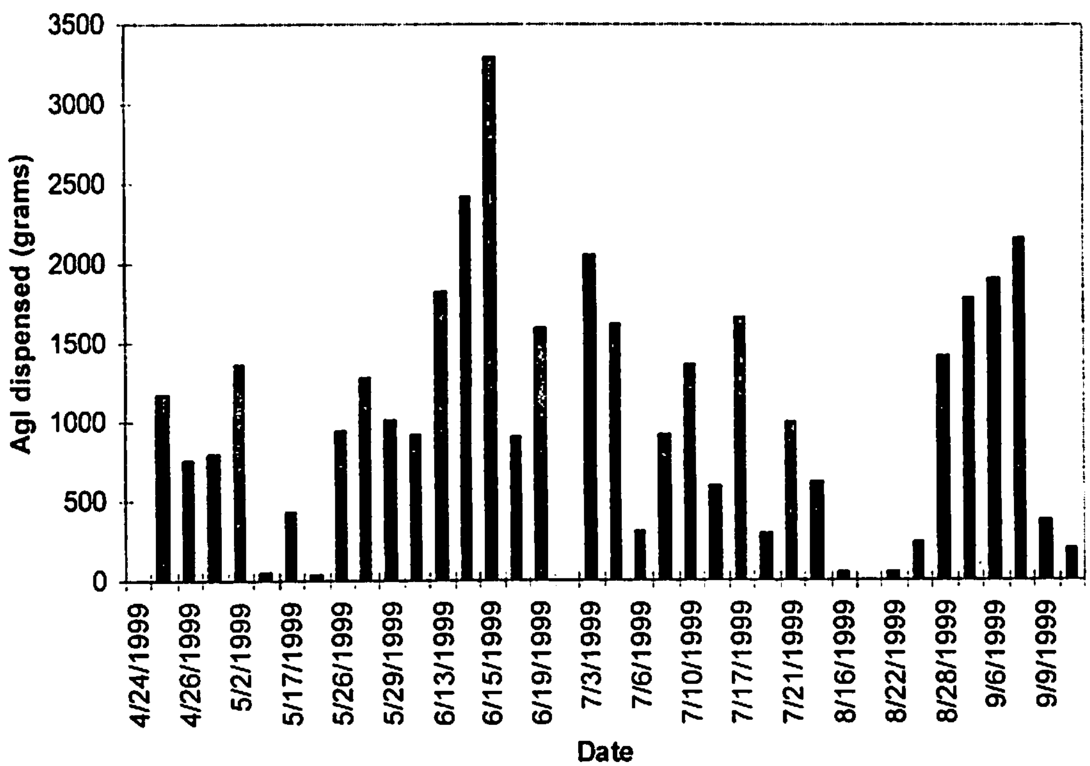

Figure 10: Amount of AgI dispensed per operational day in 1999.

Weather Forecasting

The project meteorologist provided a detailed weather forecast each day that was communicated to the project pilots. The forecast was developed using real time weather information obtained from the Internet from a wide range of weather-associated sites. A procedural flow chart of field operations was adapted from the North Dakota Cloud Modification Project (Boe et al., 1997) and represents the decision making process during the program. The flow chart is shown in Figure 11.

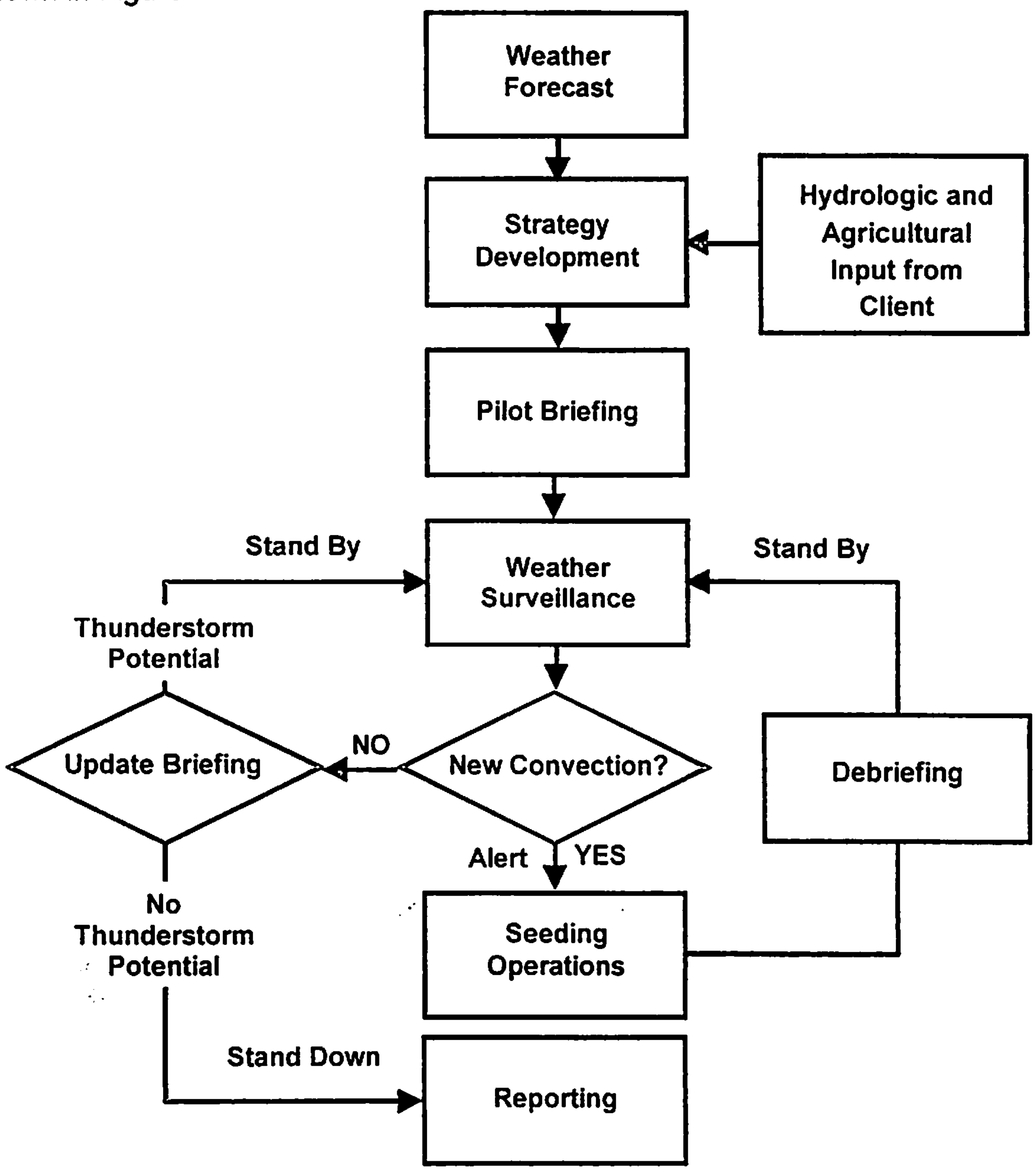

Figure 11: Decision-Making Flow Chart for the Edwards Aquifer Precipitation Enhancement Program.

Project meteorologists routinely used the following data to prepare a daily operations briefing for the EAPEP:

- Regional analyses at 850 up through 200 mb.
- A representative atmospheric sounding from Del Rio or Corpus Christi when available.
- Surface analysis of the United States.
- Current computer models (ETA, RUC, NGM, etc.).
- National Weather Service (NWS) zone forecasts
- National and regional radar summaries
- Satellite imagery
- Storm Prediction Center (SPC) Convective Outlooks (AC)

All of the meteorological data collected during the field season has been stored on CD-ROM for future reference purposes.

For simplicity, the weather forecast was once again subjectively synthesized into a single number referred to as the "convective day category" or CDC. This technique was developed for the Alberta Hail Suppression Project by Strong (1979) and gives the cloud conditions and possibility of seeding activity for the day. A description of the weather conditions for each CDC is given in the Table 2. With higher CDC values, there is a better chance of finding seedable conditions.

CDC	Description
-3	No deep convection
-2	Overcast stratus producing rain
-1	Broken to overcast conditions with some rain
0	Cumulus clouds with tops warmer than –5°C
+1	Towering Cumulus, short-lived convective targets not suitable for seeding
+2	Towering Cumulus, long-lived convective targets suitable for seeding
+3	Mesoscale Convective Systems (MCSs), storms systems, or line storms
+4	Deep convection with hail potential
+5	Deep convection containing hail & threat of severe weather

Table 2: Description of Convective Day Category (CDC) values.

The chronology of daily CDC (convective day category) values for Hondo is shown in Figure 12 and as a frequency of occurrence histogram in Figure 13.

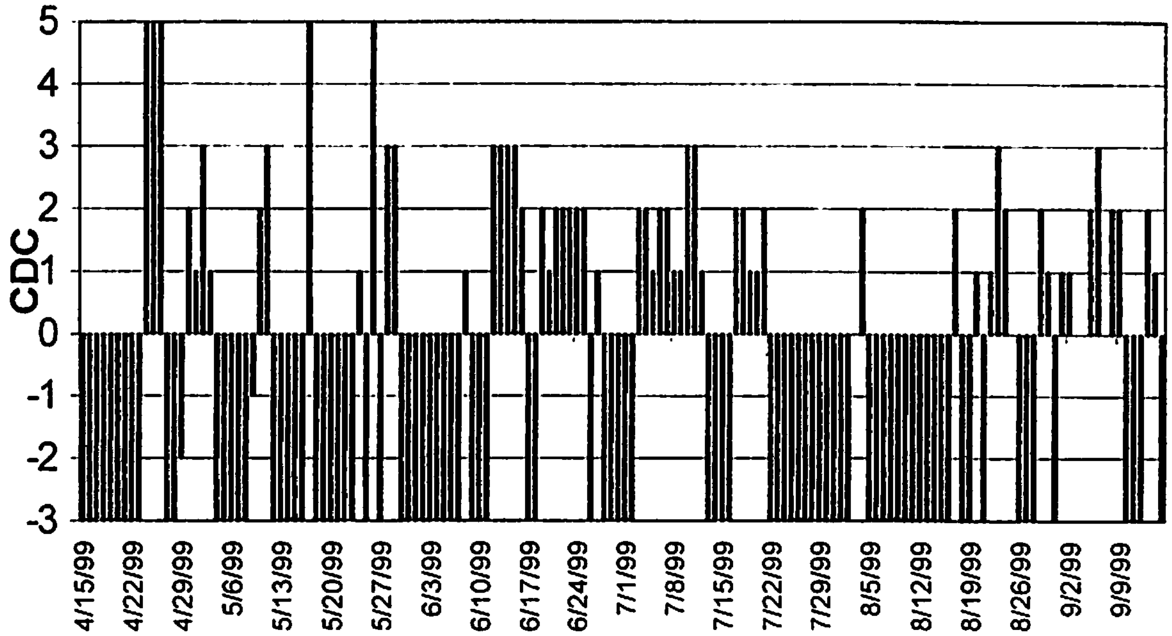

Figure 12: The chronology of daily CDC values for Hondo.

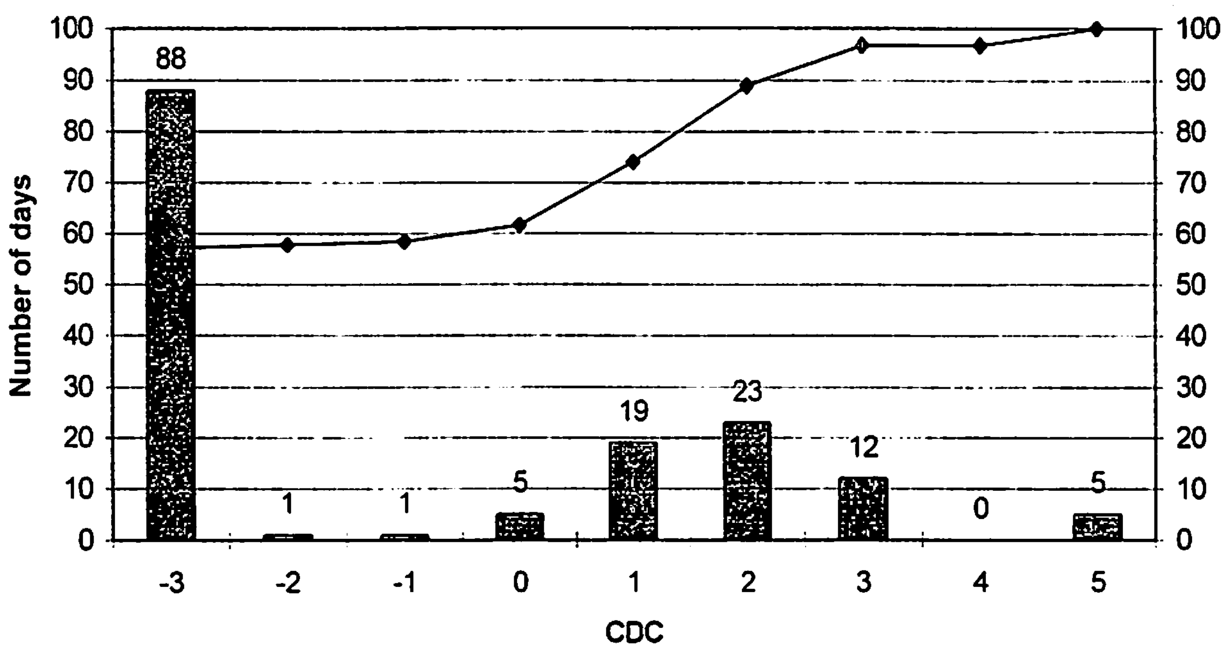

Figure 13: CDC values for Hondo as a frequency of occurrence histogram.

Forecasting Performance

The following table indicates the forecasting performance for the Edwards Aquifer Precipitation Enhancement Program (Hondo) with respect to the forecast and observed weather conditions as defined by the "Convective Day Category" or CDC. The forecasts were verified by the meteorologist's own observations, checking the weather conditions as reported by the National Weather Service, and by the reports from project personnel. Referring to Table 3, the exact forecast type of weather was observed on 98 of 153 days or 64.1% of the time. The forecast was correct to within one CDC on 115 days or 75.2% of the time. It is also important to note that there were only 3 days that seedable conditions were observed on days that were forecast as not being seedable days, and that all 3 of these precipitation events were noticed before convection started and were seeded.

Observed Convective Day Category (CDC) Weather

Forecast CDC	-3	-2	-1	0	1	2	3	4	5	
-3	60					3				63
-2										0
-1										0
0	4									4
1	18		1	3	8	1				31
2	4	1		2	8	16	2			33
3	1				2	3	10		1	17
4	1									1
5									4	4
	88	1	1	5	18	23	12	0	5	153

Percent correct exact CDC category = 98 of 153 = 64.05%
Percent correct within one CDC category = 115 of 153 = 75.16%

Table 3: Table of Forecasted versus Observed CDC Daily Values

Flight Operations

Two specially equipped cloud seeding aircraft were dedicated to the project. The aircraft and crews provided 24-hour coverage, seven days a week throughout the period. Both aircraft were stationed in Hondo, permitting close proximity to storms and fast response to launch decisions.

When development of convection was unlikely, the seeding aircraft were placed on *weather watch*. The pilots were free to do as they wished but still required to carry their pager or cell phone. When convective development was imminent or was occurring, the seeding aircraft were placed on *stand-by*. *Stand-by* occurred when clouds were not yet seedable, but the aircraft were required to launch and reach a target cloud within 30 miles of the airport 45 minutes after the request to launch had been made by the meteorologist. When seedable clouds were imminent all aircraft were placed on *alert* and aircraft were able to launch and reach the target cloud within 30 miles of the airport in 25 minutes after the request to launch had been made by the meteorologist. Aircraft were available and prepared to commence a seeding mission at any time and the seeding of a storm often continued after darkness with due regard to safety. The meteorologist provided frequent updates of the status as the day progressed.

Flight Hours

The total number of operational flight hours (airtime) was 174.9 hours. Figure 14 shows the Hondo flight hours, while Figure 15 on the next page shows the flight hour progression for 1999.

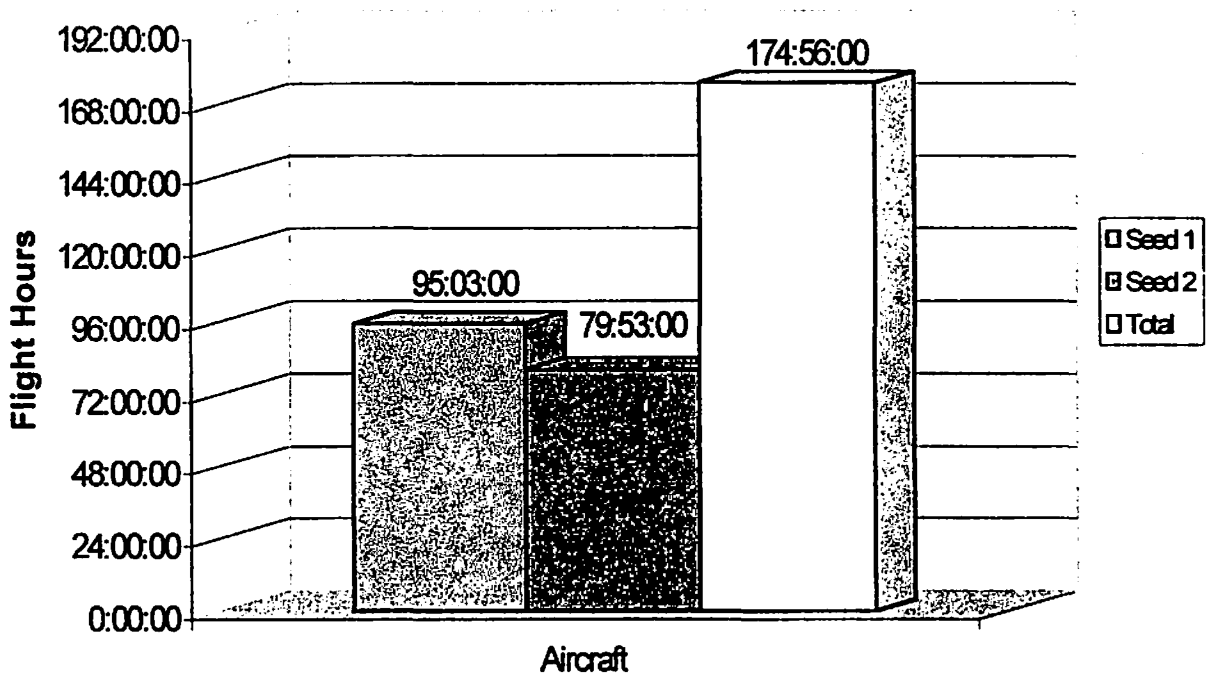

Figure 14: Hondo flight hours for 1999

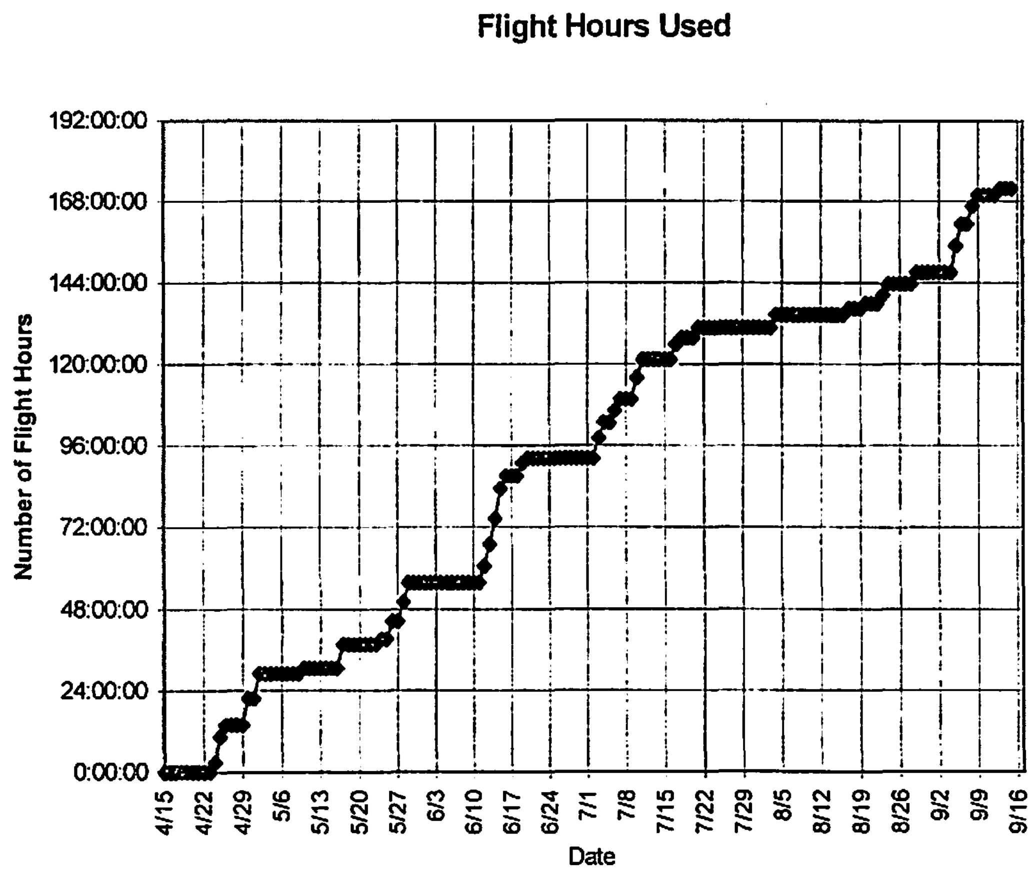

Figure 15: Flight Hour Progression during EAPEP 1999

Cloud Seeding Aircraft

Cessna 340 Aircraft

Cloud seeding was conducted using two Cessna 340 aircraft equipped with ejectable flare racks and acetone burners. The aircraft registered as N3904G, designated as Seed 1, is shown in Figure 16 on the next page. The Cessna 340 aircraft is a pressurized, twin-engine, six cylinder, turbo-charged, fuel-injected all weather aircraft. Both C340 aircraft have weather avoidance radar and a GPS navigation system. The maximum operating altitude limit is approximately 30 thousand feet with a flight endurance of 5 hours. The C340's indicated air speed for cloud penetrations is typically 155 knots. The nominal climb is 1000 ft/min from sea level to 16 thousand feet, and 700 ft/min from 16 to 20 thousand. Each C340 aircraft carried 204 20-gram ejectable silver iodide flares and two seven-gallon acetone burners. Complete specifications for the C340 are given in the Appendix.

Figure 16: Cessna 340 Cloud Seeding Aircraft.

Color Radar Recording and Display System

The color Radar Recording and Display System consists of a video processor and an angle interface that work together with computer software for the acquisition of raw radar video data. The video processor and angle interface reside in a standard IBM PC/AT compatible computer with a 16" color display that was located in the Field Office Facility. The software allows the acquisition, recording, calibration, and display of radar data. The radar data was displayed using a multi-color code that matched precisely with eight levels of contoured reflectivity values. In addition to the PPI and RHI of radar reflectivity, the system was also able to display maximum reflectivity, date, time, elevation angle and an electronic target area overlay. The GPS-derived position of each airborne aircraft is also displayed on the same screen during seeding operations, Figure 17 on the next page.

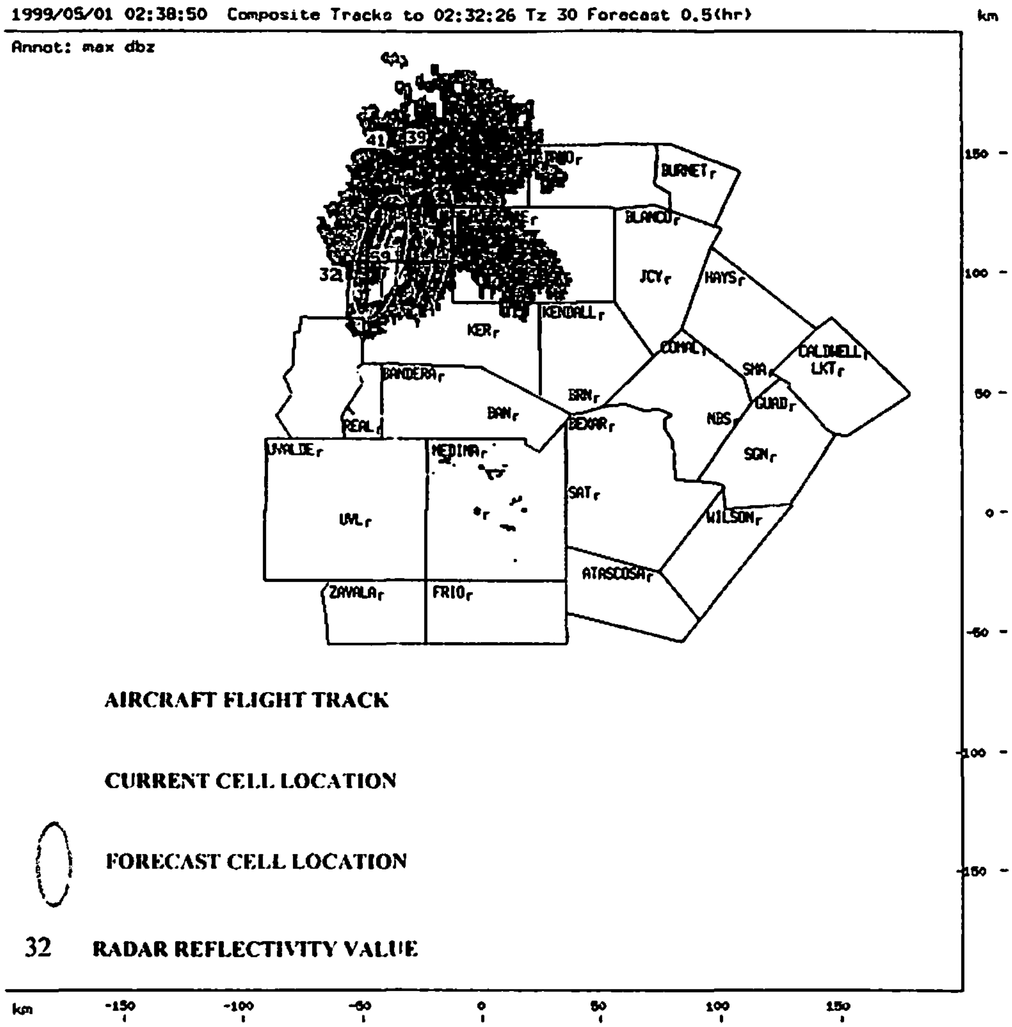

Figure 17: TITAN image of a thunderstorm from Hondo on May 1, 1999

Both the weather radar data and GPS flight track data were recorded on to CD-ROM disk for storage and playback at a later time and for possible future analysis. A Hewlett Packard color printer was located in the Field Office Facility to print color maps of the project area and radar echo and flight tracks. The printed radar maps also contain target area and county boundaries.
Radar maps and flight track data are saved automatically in user-defined increments. During normal surveillance radar maps are saved every half-hour. The frequency of which radar maps are saved increases to one every five minutes during seeding operations.

The radar maps were automatically sent to an Internet web site every half-hour to provide access to recently recorded data. This web site could be accessed using any PC with an Internet server and contained current radar maps displaying reflectivity data, as well as project GPS aircraft position.

TITAN Radar Displays

WMI was pleased to acquire the TITAN (for Thunderstorm Identification, Tracking, Analysis, and Nowcasting) radar analysis and display software from the National Center for Atmospheric Research (NCAR) in Boulder, CO, for the EAPEP. TITAN is a software system that ingests radar data, converts it into Cartesian coordinates, identifies storms, displays the storm tracks, and forecasts storm position (Dixon and Wiener, 1993). TITAN makes it possible to compute a number of relatively sophisticated storm and track parameters very easily in real-time. A detailed description of TITAN's storm and track properties can be found in Mather et al. (1996). The Texas TITAN system was set to objectively track storm cells with reflectivity >30 dBZ.

CONCLUSION AND RECOMMENDATIONS

The 1999 field operations were very successful. During the 5-month project, the aircraft completed 59 seeding and reconnaissance missions. These flights totaled 174.9 hours and took place on 38 days. On those missions, the aircraft dispersed 37.5 kg of silver iodide. The 37.5 kg came from 1,826 ejectable flares and 15 gallons of silver iodide - acetone solution used during the missions.

A detailed assessment of the seeding effectiveness is beyond the scope of the present contract of WMI. Some preliminary analyses of the TITAN radar storm tracking data support the physical hypotheses of beneficial competition and the promotion of rain within storms.

To improve operations in subsequent years, WMI recommends the following:

1. Extending the project time period for at least one month. Currently the project runs April 15 through September 15. The rainiest periods around south Texas are during the late spring and early autumn, with May and September being the rainiest months of the year. Extending the project, specifically through September into early October, would give WMI more valuable opportunities for recharging the Edwards Aquifer during peak convective rainfall periods.

2. Extension of the buffer zone around the southeastern and eastern edges of the target area. Most summertime precipitation pushed in from the southeast along the seabreeze boundary. Extending the buffer zone would provide a better opportunity to seed as convection was pushing into the target area.

3. The Authority is encouraged to involve universities and experts to analyze the radar and aircraft data that is archived from the operation.

Weather Modification, Inc. looks forward to continuing operations with the Edwards Aquifer Authority and maintaining our objective of increasing rainfall.

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Appendix

A. Organization Chart

B. List of Texas Reports

C. Aircraft Flight Summary Tables

E. Forms

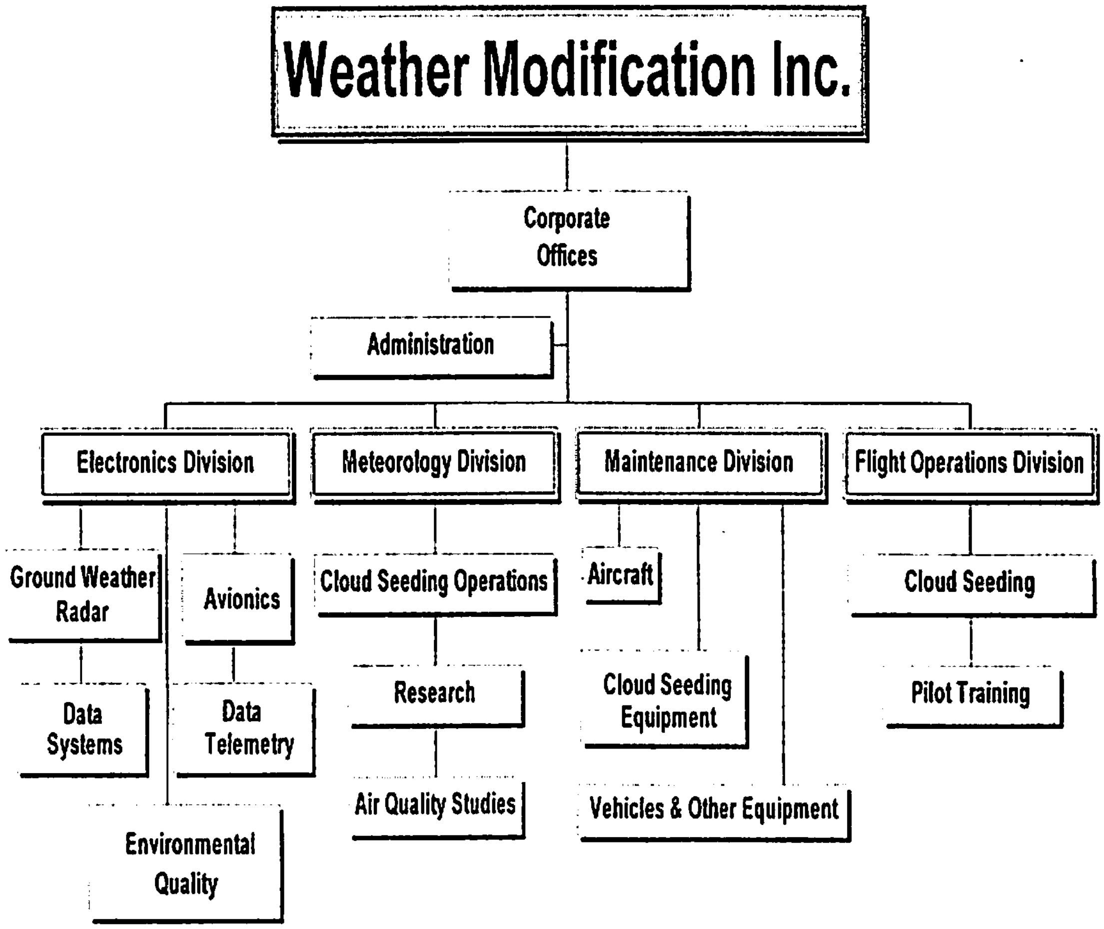
WMI Seeding Aircraft Flight Log

WMI Radar Observer Log

E. Specifications for Cessna C-340 Aircraft

F. Ground School Agenda

A. Organization Chart



B. List of Texas Reports

Report	Description	Author	Frequency
Flight Log	Description of seeding mission including amount and location of seeding material dispensed, flight crewmembers and remarks.	Pilot	Each Flight
Hobbs Sheet	Running list of takeoff and landing times and flight crew for each aircraft flight.	Pilot	Each Flight
Chemical Inventory Log	Amount of seeding material on hand after subtracting material used and adding shipments received.	Pilot	Weekly
Equipment Log	Status of project equipment including radar, computers and airplanes.	Meteorologist	Daily
Meteorological Log	List of meteorological parameters used as seeding criteria and in weather forecasting.	Meteorologist	Daily
Forecast Sheet	Graphical and textural information describing the state of the atmosphere, the day's forecast and forecast verification.	Meteorologist	Daily
Daily Operations Summary	Textural description of the day's weather and weather modification activities in a table format.	Meteorologist	Daily
Storm Summary	Description of weather modification operations for a particular event including weather conditions, aircraft activity and storm damage.	Meteorologist	Each Seeding Operation
Weekly Report	Compilation of reports describing each week's activities. Report includes daily operations summary, flight forms, equipment log and a table of flight hours and seed material used. Submitted to Client.	WMI	Weekly
NOAA Daily Log	Federal report of seeding activities including amount, location and type of nucleant material used and duration of activities. Submitted to Client.	WMI	Daily

C. Aircraft Flight Summary Tables

EDWARDS AQUIFER PRECIPITATION ENHANCEMENT PROGRAM 1999
Operations Flights

TOTALS	flights=	65		174:56	1826	6:08	
Date	Aircraft	Take-off	Landing	Duration	eject	acetone	Type
April 24, 1999	340FR	21:50	23:05	1:15	0	0	patrol
April 25, 1999	340FR	3:10	5:05	1:55	0	0	patrol
April 25, 1999	3904G	13:45	18:59	5:14	47	0	seed
April 25, 1999	340FR	18:45	21:07	2:22	12	0	seed
April 26, 1999	3904G	12:28	15:55	3:27	38	0	seed
April 30, 1999	3904G	20:25	22:47	2:22	8	00:36	seed
April 30, 1999	340FR	20:25	21:44	1:19	0	0	patrol
May 1, 1999	340FR	2:05	6:11	4:06	27	0	seed
May 2, 1999	3904G	15:18	20:18	5:00	61	0	seed
May 2, 1999	340FR	19:55	22:15	2:20	7	0	seed
May 10, 1999	3904G	5:29	7:07	1:38	3	0	seed
May 17, 1999	3904G	2:57	5:33	2:36	0	01:01	seed
May 17, 1999	340AX	20:45	0:08	3:23	14	0	seed
May 18, 1999	340AX	0:38	1:00	0:22	0	0	reposition
May 18, 1999	3904G	6:53	7:47	0:54	0	0	reposition
May 18, 1999	3904G	13:35	14:37	1:02	0	0	reposition
May 23, 1999	340AX	19:43	21:15	1:32	2	0	seed
May 26, 1999	3904G	21:28	23:01	1:33	0	0	patrol
May 26, 1999	340AX	23:55	3:41	3:46	47	0	seed
May 28, 1999	3904G	9:57	12:20	2:23	32	0	seed
May 28, 1999	340AX	16:30	19:45	3:15	32	0	seed
May 29, 1999	3904G	11:50	14:50	3:00	24	0	seed
May 29, 1999	3904G	21:30	0:10	2:40	27	0	seed
June 4, 1999	3904G	14:35	15:20	0:45	0	0	NWS visit
June 4, 1999	3904G	17:50	18:29	0:39	0	0	NWS visit
June 13, 1999	340AX	0:15	3:45	3:30	37	0	seed
June 13, 1999	3904G	4:01	5:18	1:17	9	0	seed
June 13, 1999	340AX	18:20	20:40	2:20	26	0	seed
June 13, 1999	3904G	22:33	2:28	3:55	65	0	seed
June 14, 1999	340AX	2:40	2:52	0:12	0	0	patrol
June 14, 1999	340AX	18:05	21:47	3:42	46	0	seed
June 14, 1999	3904G	21:41	1:22	3:41	75	0	seed
June 15, 1999	340AX	14:45	18:12	3:27	38	0	seed
June 15, 1999	3904G	20:45	23:31	2:46	64	0	seed
June 16, 1999	340AX	0:29	3:11	2:42	63	0	seed
June 16, 1999	3904G	20:56	0:42	3:46	45	0	seed
June 19, 1999	340AX	19:30	23:27	3:57	80	0	seed
June 20, 1999	3904G	13:00	14:21	1:21	0	0	patrol
July 3, 1999	3904G	18:33	22:06	3:33	64	0	seed
July 3, 1999	340AX	22:22	0:50	2:28	39	0	seed
July 4, 1999	3904G	17:13	21:47	4:34	81	0	seed

July 6, 1999	340AX	22:30	2:00	3:30	0	02:02	seed
July 7, 1999	340AX	22:06	1:24	3:18	46	0	seed
July 10, 1999	3904G	19:49	0:20	4:31	47	0	seed
July 11, 1999	340AX	0:25	2:20	1:55	21	0	seed
July 11, 1999	3904G	18:06	20:48	2:42	0	0	patrol
July 11, 1999	340AX	22:10	0:45	2:35	30	0	seed
July 17, 1999	3904G	14:45	19:15	4:30	83	0	seed
July 18, 1999	340AX	21:09	23:03	1:54	15	0	seed
July 21, 1999	3904G	19:52	22:55	3:03	50	0	seed
August 4, 1999	340AX	19:45	23:25	3:40	31	0	seed
August 17, 1999	3904G	23:28	1:18	1:50	3	0	seed
August 20, 1999	340AX	22:25	23:55	1:30	0	0	patrol
August 23, 1999	3904G	17:50	20:15	2:25	3	0	seed
August 24, 1999	340AX	19:32	20:20	0:48	0	0	patrol
August 24, 1999	3904G	20:20	22:45	2:25	12	0	seed
August 29, 1999	340AX	18:52	22:15	3:23	71	0	seed
September 5, 1999	3904G	20:40	1:00	4:20	63	0	seed
September 5, 1999	340AX	22:29	1:59	3:30	26	0	seed
September 6, 1999	340AX	19:45	23:14	3:29	62	0	seed
September 6, 1999	3904G	20:45	23:45	3:00	33	0	seed
September 8, 1999	340AX	17:32	20:00	2:28	51	0	seed
September 8, 1999	3904G	21:35	0:30	2:55	56	0	seed
September 9, 1999	3904G	19:50	23:06	3:16	0	02:29	seed
September 13, 1999	3904G	19:45	21:45	2:00	10	0	seed

D. Forms

WMI Seeding Aircraft Flight Log

WMI Radar Observer Log

Flight Log - WMI Seeding Aircraft

1999 Edwards Aquifer Precipitation Enhancement Program

Pilot:	Copilot:	Aircraft:	Eng. off:	Hobbs Landing:	Date:
		Seed #:	Eng. On:	Hobbs Takeoff:	Page: 1 of 1
		Flight #:	Total: 0:00	Flight Time: 0.0	Type:

Time (UTC)	Event No.	LAT	LON	Alt. (kft)	Flares Eject.	Flares Duds	Acetone (min.) Left	Acetone (min.) Right	County Worked	Remarks
	1									
	2									
	3									
	4									
	5									
	6									
	7									
	8									
	9									
	10									
	11									
	12									
	13									
	14									
	15									
	16									
	17									
	18									
	19									
	20									

Cloud Base Height	Flares Attempted	Total Burner Time	Flares Ejected by County
Cloud Base Temperature	Flares Ejectected	Left Burner Time	
Cloud Top Height	Duds	Right Burner Time	

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WMI Radar Log

1999 Edwards Aquifer Precipitation Enhancement Program

Location:

Date: ____________________

Operator: ____________________

No.	Time (UTC)	Az (deg)	Range (nm)	Max Height (kft) 20 dBZ	35 dBZ	Zmax (dBZ)	Zmax Ht (kft)	Cld Top (kft)	Remarks	Seed?

E. Specifications for Cessna C-340 Aircraft

Power Type, Turbocharged piston twin engine
6290 lbs gross weight
4400 lbs empty weight (typical)
1890 lbs useful load (typical)
310 hp per engine
280 mph max speed
263 mph rec. cruise
82 mph stall dirty
183 - 203 gals fuel capacity
29,800 feet all engine service ceiling
15,800 feet single engine service ceiling
1650 feet per minute all engine rate of climb
315 feet per minute single engine rate of climb
2175 feet for take off over 50 foot obstruction
1615 feet for take off ground roll
1850 feet land over 50 foot obstruction
770 land ground roll
34 ft. 4 in. length
12 ft. 7 in. height
38 ft. 1 in. wing span

F. Ground School Agenda

1999 WMI TEXAS GROUND SCHOOL AGENDA
SAN ANTONIO
MAY 7, 1999

08:30 INTRODUCTIONS

08:45 PROGRAM OVERVIEW – who wants this program, and why

09:00 SEEDING HYPOTHESIS/SEEDING METHODS/PREVIOUS RESULTS

10:00 *BREAK*

10:15 RADAR / TITAN – how they work and what they do

11:15 FORECASTING / DAILY ROUTINE – what goes on every day

12:00 *LUNCH BREAK*

13:00 AIRCRAFT OPERATIONS – weather / ATC / techniques / safety

14:00 OPPORTUNITY RECOGNITION – cool storm pictures

15:00 *BREAK*

15:15 SEEDING EQUIPMENT / CHEMICALS / SAFETY

16:00 PAPERWORK / COMPUTERS – no job is done until...

17:00 COMPANY POLICIES / PROJECT RESPONSIBILITIES

17:15 EXTREMELY HARD FINAL EXAM