THE SOUTHERN OGALLALA AQUIFER RAINFALL (SOAR) PROGRAM – A NEW PRECIPITATION ENHANCEMENT PROGRAM IN WEST TEXAS AND SOUTHEASTERN NEW MEXICO

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Abstract. The Sandy Land Underground Water Conservation District, South Plains Underground Water Conservation District, and the Llano Estacado Underground Water Conservation District have participated with the High Plains Underground Water Conservation District #1 for a number of years in their precipitation enhancement program. Convinced from past assessments that precipitation enhancement is a potential water management tool, the three boards decided that a program beginning in 2002, apart from the High Plains would be beneficial. The Texas Department of Licensing and Regulation (TDLR) issued a permit on January 31, 2002 authorizing a weather modification program to conduct rainfall enhancement in Yoakum, Terry and Gaines County. Additionally, with the cooperation of the State of New Mexico, an area west of Gaines and Yoakum Counties is included in the target area. This precipitation enhancement program was named Southern Ogallala Aquifer Rainfall (SOAR) program. This document presents a brief summary of the SOAR 2003 annual report detailing an effort to systematically characterize the clouds, precipitation and the seeding effectiveness of the SOAR program. Independent evaluations show average rainfall increases of 68% and 52% in favor of a seeded cloud when compared to a matching control cloud. This results in an average estimated benefit/cost ratio of 235/1.

1. INTRODUCTION

A scientific evaluation of cloud seeding for rainfall enhancement requires several efforts designed to systematically characterize clouds and precipitation in order to determine their potential response to seeding. The two fundamental questions that SOAR has searched to answer during its first year of operation in 2002 were 1) whether the frequency of clouds in the area and the associated weather patterns warrant the need for a cloud seeding program, and 2) are the clouds that occur receptive to glaciogenic and/or hygroscopic seeding?

The SOAR program has defined specific long term objectives that would systematically characterize the clouds, precipitation and the seeding effectiveness of a rainfall enhancement program, including:

1. A climatology of thunderstorm tracks and cloud characteristics as recorded by weather radar over several years to determine the suitability of clouds and their frequency of occurrence.

2. A continued assessment of seeded versus non-seeded clouds by independent qualified evaluators using scientifically accepted methodologies and statistical methods.

3. Launching carefully designed field programs, using an instrumented cloud physics aircraft and weather radar during periods when a high frequency of convective clouds is observed or anticipated. The objective of the field studies should be to document: a) background concentrations, sizes and chemical composition of aerosols that participate in rainfall processes, b) size resolved nucleation processes at variable super saturations of hygroscopic aerosol particles and their effect on the cloud droplet spectra, and c) the degree of ice nucleation achieved by glaciogenic cloud base and cloud top seeding.

4. Assessment and improvements in the data collection of rainfall, with an emphasis on the integration of conventional methods (surface rain-gauges) with more frequently used methods that demonstrate better spatial coverage and temporal resolution (radar).

This report presents a summary of the efforts employed by SOAR to characterize the clouds, precipitation and the seeding effectiveness of the SOAR program and details the recommendations made that would improve on current achievements.

2. A CLIMATOLOGY OF THE SOAR TARGET AREA

The climate of the Llano Estacado Region is classified as a dry, steppe type. The region is characterized as semi-arid, with a wide range in temperatures. In an average year, about 80 percent of the annual rainfall occurs during the warm season (May through October). Monthly rainfall quantities ordinarily decline markedly in the colder months of the year, when frequent periods of cold, dry air from North American Polar Regions surge southward and cut off the supply of moisture from the Gulf of Mexico and the Mexican Monsoon. The long-term average (1945 through 1997) precipitation received in the region is 18.4 inches. The average ranges from a high of 22 inches per year in a small area in Crosby County, to a low of about 16 inches in Cochran County. Most of this precipitation is mainly convective during the warm season and thus it is more localized and its spatial and temporal distribution as well as the intensity of rainfall is highly variable.

It is widely accepted that the primary source of low-level moisture for the United States east of the continental divide is the Gulf of Mexico. However, Texas also receives moisture from the Eastern Pacific Ocean moisture carried into Texas from the southwest by tropical continental airmasses. It is necessary to examine the synoptic conditions that initiate convection in the target area and to analyze the sources of moisture that fuels thunderstorms.

Early in the growing season, convective initiation is caused by eastward moving cyclones. The topography of the region channels warm moist air from the Gulf of Mexico northward and cold dry arctic air from Canada southward. These two very different air masses, together with westerly downslope flow off the Rockies, have important influences on the convective mechanisms in the target area. The confluence of warm dry air off the southern Rockies and warm moist air from the Gulf of Mexico produces a strong west-east gradient in moisture called the dryline. The motion of the spring and summertime southern High Plains dryline in the absence of any large-scale weather systems usually exhibits a diurnal trend. In general, this trend is described as an easterly advance of the dryline during the daytime and a westerly retreat at night. It is known that convective development often is collocated with the dryline and such development may lead to thunderstorm initiation dependent upon various airmass properties in the vicinity of the dryline. Another important feature during this period is the cold front and how it combines with the dryline to act as a focus for convective development.

The middle of the growing season is characterized by a period of transition from the cold season circulation regime to the warm season regime. This is accompanied by a decrease in mid-latitude synoptic-scale transient activity over the continental United States as the extratropical storm track weakens and migrates poleward to a position near the Canadian border. The upper air becomes rather stagnant with a persistent pattern of a high-pressure ridge over the desert southwest. A prolonged east to west flow in the lower levels of the atmosphere increases the moisture from the eastern plains to the Continental Divide. Most of the convection remains confined to the mountainous areas of southwest Texas and southeastern New Mexico due to upslope low-level winds and upslope flow. Other areas rely on diurnal heating and humid conditions with some upper air feature support from disturbances rotating in the periphery of the high pressure for convection. When an upper level low pressure develops in the northern Pacific, the ridge breaks down and a trough pushes an occasional cool front, bringing some temporary relief from the heat in the Mid West and the Great Plains. However, these fronts usually stall to the north of the region due to a strong southerly flow.

The latter part of the growing season is characterized by the onset of the Mexican Monsoon in southern and southeastern New Mexico. The main synoptic feature is a persistent broad high-pressure ridge at the upper levels meandering over the southern plains and the desert southwest. This feature increases the convective inhibition due to synoptic scale subsidence over the region. The convective energy is weak and convection is hard to forecast due to the lack of a surface feature. The sea level pressure of the southwestern United States increases significantly and leads to the development of a thermally induced trough in the desert southwest. Surges of tropical continental air with convection along this trough are very common. Tropical maritime influences from the Gulf of Mexico may also be observed even though most of this moisture remains to the southeast. During this period the ridge over the western United States weakens as the monsoon high retreats southward and Mexican Monsoon precipitation diminishes.

3. CLOUD SEEDING IN THE SOAR TARGET

The objective of the SOAR program is to increase rainfall when rain-bearing clouds are known to have poor rainfall efficiency. The SOAR project currently uses glaciogenic seeding to improve the efficiency of the cold rain process. The target of such seeding operations is the supercooled water, which is found in the cold part of the cloud above the freezing level.

3.1 The methodology of glaciogenic seeding

The agent used is silver iodide, which is released in clouds to empower the formation of ice aggregates. The maximum efficiency for aggregation occurs around -5ºC. Seedable clouds must have top heights around this temperature but warmer than -15ºC.

Typically, clouds are seeded at -5ºC level and the silver iodide is released in the early stages of development and within the first half-lifetime. Dosages should reach the dynamic mode of seeding, around 100 ice-nuclei per liter of supercooled volume. Radar volume scans are used to measure the exact dosage required to reach the dynamic mode. Clouds that are seeded are very carefully chosen in that the in-cloud coalescence of the clouds is closely monitored using the Index of Coalescence Activity.
There are two methods of glaciogenic cloud seeding utilized by the SOAR program, 1) cloud base seeding and 2) cloud top seeding.

3.1.1 Glaciogenic seeding at cloud base

Glaciogenic seeding at base is accomplished by injection of 40 gram Silver Iodide pyrotechnic flares into cloud updrafts in excess of 200 feet per minute near the bases of clouds along predetermined tracks 10 to 30 miles upwind of the target area.

3.1.2 Glaciogenic seeding at cloud top

Glaciogenic seeding at cloud top is accomplished by an aircraft flying just above the freezing level that drops up to two ejectable Silver Iodide pyrotechnic flares, each flare releasing 20 grams of Silver Iodide smoke, into the top of the growing cumulus cloud 10 to 30 miles upwind of the target area.

3.2 Pyrotechnics used

The pyrotechnics used for seeding at cloud base and on top are manufactured by Concho Cartridge. Reports from cloud chambers show that the flares are producing about 10^^13 ice-nuclei per liter at 5 ºC, and about 2 x 10^^13 at -5 ºC.

3.3 Quantifying a seedable cloud

Clouds are considered to be seedable for increasing precipitation according to the static-mode seeding concept if 1) the collision-coalescence process is inefficient, 2) the rate of formation of supercooled condensate exceeds or is comparable to the rate of depletion of supercooled water, and 3) if there is sufficient time to grow seeding-induced precipitation particles that can reach the ground (Silverman, 2001). These seedable criteria specified by the static-mode definition are difficult to apply practically because of the lack of quantification.

3.3.1 Extensive use of TITAN to quantify a seedable cloud

The TITAN software processes volume scan data from the SOAR 5cm radar recording a full volume scan in 3 minutes. The data allows analysis of different variables such as storm identification, location, area, volume, mass of precipitation, Vertically Integrated Liquid (VIL) as well as rates of variation of these parameters.

TITAN provides a tool for an appropriately trained meteorologist to quantify a seedable cloud appropriately. The meteorologist usually undergoes a series of decisions that may be best characterized as: Nowcasting, decision time, qualification, treatment, maintenance and termination.

1. Nowcasting is when the meteorologist is monitoring the atmospheric conditions desirable for deep convection and seedable clouds to form. This decision is taken after studying the meteorological model output that forecast the prevailing thermodynamic conditions. This process is usually a routine analysis of upper air conditions and surface conditions. Nowcasting of the possibility of thunderstorms follows and weather modification pilots are briefed accordingly.

2. Decision time is when the meteorologist decides to launch a seeding operation based on his/her observations of the current and forecast atmospheric conditions. This decision is usually taken after observing cloud echoes on TITAN and the echo development trend. Sometimes an operation is launched after watching clouds grow visually or by observing the surface temperature reach a threshold when convection is expected to initiate or intensify. For an operation with good timing, decision time should be preceded by qualification.

3. Qualification is when a cloud becomes seedable. This decision can be made visually by the pilot observing a cloud before it is detected by radar. Most frequently, a cloud is observed on radar before seeding occurs. In the SOAR target area, a seedable cloud echo usually reaches a VIL of 10 kg/m^2 and continues rising. The volume of the cloud echo should be in the order of $200km^3$ with cloud tops above 8 km. The development trend of other clouds outside the target area is usually observed to

determine the growth characteristics and the lifetime of the clouds. A short lifetime does not allow much opportunity for seeding. On TITAN, a seedable cloud usually shows a pocket of about 15% of the echo volume with a higher reflectivity at or slightly above 40 dBZ reflectivity at an altitude ranging from 6 to 10 km. This is characteristic of a cloud with weak coalescence and with a loading of supercooled liquid water above the freezing level early in its lifetime.

4. Treatment is the time after initial seeding. Occasionally, treatment may be preceded by qualification in isolated cases. In most cases, however, a cloud qualifies as seedable and the meteorologist instructs the pilot to start seeding. The seeding starts when the pilot encounters, locates or is directed to the updraft portion of the cloud where the agent is released. The updraft usually has to exceed 200 feet per minute.

5. Maintenance is when a constant rate of seeding is established with continued observations of growth in the echoing volume. During this period the cloud echo has not reached it's half-life time. Careful analysis of the dynamic variables of the cloud echo and their trend is necessary to define the half-life of the cloud. The pilot usually continues to experience updrafts and the meteorologist is able to locate areas of new growth within the cloud structure.

6. Termination is when seeding is stopped. A seeding operation is usually terminated either due to the absence of updrafts and/or due to the cloud echo exceeding its half-life time. When the National Weather Service issues a warning on the seeded cloud, the seeding is terminated.

3.3.2 Quantifying the collision-coalescence process

The Index of Coalescence Activity (ICA) has been developed as a predictor of in-cloud collision-coalescence activity using an atmospheric upper-air sounding. The ICA is best described as the summation of the collision and collection efficiency, which results in the coalescence efficiency. Since the inception of the SOAR program in 2002, the ICA has been used extensively as a measure of quantifying the seedability of a cloud.

3.3.2.1 The Index of Coalescence Activity (ICA)

Strautins et al. (1999) document the physics involved in the derivation of the Index of Coalescence Activity (ICA) and its relation to coalescence. The ICA is given by the equation:

$$ICA = 8.6 - T_{CCL} + 1.72(PB)$$

The temperature at the convective condensation level (T_{CCL}) is an approximation of the cloud base temperature and PB is defined as the temperature difference at 500 mb (18000 ft MSL) between the pseudoadiabat that runs through cloud base and the environmental temperature. This data is retrieved from an atmospheric upper-air sounding.

With this solution, negative ICA values are indicative of conditions when supercooled drizzle and raindrops are found in the clouds. If the ICA is strongly negative, the raindrop concentrations will be less because many of the drops will already have fallen from the clouds before reaching -10ºC. When the ICA is positive, little, if any, supercooled drizzle and raindrops are expected in the clouds (Strautins et al., 1999).

3.3.2.2 ICA for the SOAR target area

The number of positive vs. negative ICA ratio values (3:1) for the SOAR target area shows that there are good opportunities to investigate further the introduction of hygroscopic seeding in phase with glaciogenic seeding. This can also be justified after analyzing the differences in the moisture sources during the growing season as described in the SOAR climatology. Hygroscopic seeding is needed when ICA values are high and positive. This would make it possible to increase the level of success further if it were possible to use hygroscopic seeding to promote coalescence in continental clouds that have weak coalescence, increasing the efficiency of rain bearing clouds and eventually rainfall.

4. CONCLUSIONS

A careful examination of the meteorological conditions that are conducive to convective development has shown that seedable clouds navigate through the SOAR target area with a sufficient frequency to warrant a cloud seeding program. Independent evaluations by Woodley Weather Consultants (WWC) (Woodley, 2003) and Active Influence and Scientific Management (AISM) (Ruiz, 2003) have demonstrated that such clouds are receptive to glaciogenic seeding and respond positively producing additional rainfall. Advances in remote sensing technology has established radar as the tool of choice for evaluation of cloud seeding programs versus the use of more conventional methods such as rain gauges. The findings outlined in the 2003 SOAR Annual Report including the information provided by the independent evaluators has led to the following conclusions:

1. Precipitation meets about 60 percent of urban landscape water and irrigated crop demands. It provides all the water for surface reservoirs and all the water for rangeland and dryland crop production. By 2050 the region would be able to supply only 93 percent of the projected water demands unless supply development or other water management strategies are implemented (TWDB, 2002). The Llano Estacado Regional Water Planning Group identified precipitation enhancement as one of the seventeen potential strategies to conserve water. Rainfall enhancement could potentially relieve the deficit in the projected water demand.

2. Meteorological conditions, thunderstorm track climatology, Index of Coalescence climatology and the high occurrence of severe weather in the SOAR geographical region all indicate that the frequency of clouds in the area and the associated weather patterns warrant the need for a cloud seeding program. The prevailing drought conditions limits the frequency of clouds, but the number of observed cloud systems that develop in the SOAR region are big producers of rain and have responded positively to glaciogenic cloud seeding. The Woodley and Rosenfeld method of evaluation shows that projects located in the western half of Texas are much more positive than those results from projects located in the eastern half, suggesting that the seeding conditions are more favorable in the west than in the east. If true, it may be due to the more intense coalescence activity in the east that results in early cloud glaciation, leaving a smaller window of opportunity for seeding intervention (Woodley, 2003).

3. Clouds that do occur are receptive to glaciogenic seeding. Independent evaluations conducted by Active Influence and Scientific Management (AISM) (Ruiz, 2003) and Woodley Weather Consultants (WWC) (Woodley, 2003) show average rainfall increases of 68% and 52% in favor of a seeded cloud when compared to a matching control cloud respectively.

4. The scientific community seems to have reached a consensus that for continental convective storms that predominate the Texas high plains, radar should be the primary tool in detecting seeding signatures. Rain gauges should be used to quantitatively calibrate the radar data. Rain gauges used for such an application should have the capability of recording rainfall in real time. Obviously, this makes the SOAR rain gauge network immediately redundant due to its inability to record rainfall in real time.

5. Both the Active Influence and Scientific Management method and the Woodley and Rosenfeld method of evaluation of past SOAR cloud seeding events show significant increases in rainfall.

Active Influence and Scientific Management (AISM) conclude that seeding operations in 2003 appeared to improve the dynamics of seeded clouds. Seeding operations by cloud bases showed appreciable better performance and results than those made by the tops (Ruiz, 2003). Although this may indicate that seeding at cloud base may be a more effective methodology, SOAR has expressed its concerns to AISM in using the TITAN method to put forward such a suggestion. Seeding on top was conducted on 8 cases. On 4 of those cases, seeding on top took place before the cloud echo appeared on radar, which means that microphysical changes in the clouds and the reflectivity of the echo had already started to occur before TITAN had recorded or archived any data on the cloud system. This may produce significant errors in finding a match as a control, which makes it apparent that seeding on top was less effective. In addition, a sample size of 8 cases is too small to make any conclusions, especially when 4 of those cases where seeded before TITAN archived any data. Nonetheless, AISM concludes that SOAR has increased the rainfall by 86% in clouds that produce a precipitation mass less than 10000 kilotons, 76% in clouds that produce a precipitation mass more than 10000 kilotons and 42% in clouds that are seeded after a lifetime of 1 hour. This makes the average total increase in rainfall at 68% producing a total of 248491 acre-feet of water over the SOAR target area (Ruiz, 2003).

The Woodley and Rosenfeld method uses radar-defined floating targets to show increases in areas, duration, and rain volume of seeded clouds. The Woodley and Rosenfeld method provides clear proof of microphysical changes to simple cloud systems, with indications based on statistical results that precipitation has been increased in most cases. This analysis shows that the SOAR program has increased the average rainfall in seeded units by 52% in 2002. Each seeded unit shows an average increase of 5000 kilotons or about 0.1 inches over its unseeded counterpart. The apparent change in total unit rainfall due to seeding (the total change in unit rainfall is the product of the average rain increment per unit and the number of analysis units) was around 306739 acre-feet (Woodley, 2003). These results not only indicate an increase in rainfall due to seeding, but these results have achieved appreciable P-value support showing that the rainfall increases are very significant and that the probability that the results achieved where due to chance is very small (5% or less).

6. Using WWC's value for the total average increase in rainfall for the 2002 season and adding this to the AISM value for the total average increase in rainfall for the 2003 season would give the total average rainfall increase in 2002 and 2003 amounting to 555230 ac ft over an area of 5916000 acres. The cost per acre-foot of water produced by cloud seeding can be inferred by considering the cost of the SOAR program in 2002 and 2003. So far, the cost for cloud seeding in the participating counties of the SOAR program, based on average total values of rainfall increases of seeded clouds versus there matching non-seeded clouds can be assumed at an average value of 51 cents per acre foot of water produced by cloud seeding. One can go further and assume that a local farmer spends about $120 per acre-foot in pumping costs from underground water wells. This gives an average estimated benefit/cost ratio of 235/1. This means that for every dollar spent by participating counties of the SOAR program, the area benefits $235.

5. RECOMMENDATIONS

In view of the conclusions drawn above, the following recommendations are being made:

1. The results of the evaluations presented by AISM and WWC are a clear indication that the SOAR program is running a successful rainfall enhancement operation. The Woodley and Rosenfeld methodology includes statistical rerandomizations and corrections made for selection bias with the inclusion of very stringent selection criteria for suitable control clouds. However, scientists require that cloud seeding experiments be randomized, the physical hypothesis postulated be proved with sufficient P-value support and that the results be replicated. The results presented by WWC should not be viewed as substitutes for randomization and subsequent replication. It is therefore recommended that SOAR work closely with a scientific team to create an experimental randomized cloud seeding program within the SOAR target area. A large number of experimental units is required to detect a relatively small seeding effect that needs to be distinguished from chance variations and the natural variability in cloud systems. This may mean long and expensive experiments and may take several years.

2. Such a study should investigate the total seeding effect on all seeded storms' rainfall and how it compares quantitatively to an area seeding effect. So far evaluations have been relatively successful in showing a positive seeding effect of a seeded cloud when compared to an appropriately matched control, but no scientific study has been attempted to show how this seeding effect alters the area rainfall. The Woodley and Rosenfeld method has been the closest methodology in approaching such an endeavor in that all cloud systems are analyzed on a scale of roughly 2,000 km^2. The scientific community recommends that such an analysis be conducted using the latest radar technology available, with rain gauges used for ground validation.

3. It has been shown that TITAN is an indispensable tool in conducting cloud seeding operations. However, the SOAR project 5 cm radar was manufactured in 1978 and over the past few decades there have been considerable advances in the development of remote sensing technology and ground-based radar. It is recommended that SOAR upgrade its radar to match the current technology that would help the program to meet the challenges of weather modification. NEXRAD data will be available in the Spring 2004. The Midland and Lubbock NWS NEXRAD sites will cover the SOAR target area. The data will include a better-quality radar estimated rainfall product making radar estimated rainfall a much better tool in evaluating cloud seeding effectiveness.

4. The Woodley and Rosenfeld method has shown that the seeding effect is very strong after 75 to 450 minutes after the time of initial seeding. There is no question that seeding treatment early in the life cycle appears to show the greatest seeding effect. It is recommended that cloud seeding commence 15 to 30 miles upwind of the SOAR target area.

5. It has been shown that the climatology of the SOAR target area is suitable for cloud seeding. It is recommended that the SOAR meteorologist continue to define and quantify the seedable conditions within the SOAR target area and observe and document the mesoscale meteorological conditions and the microphysical changes in clouds that frequent the region.

6. So far, it has been demonstrated that the SOAR program has operated a rainfall enhancement program with a high level of success. It is being recommended that independent evaluations of cloud seeding operations continue to be funded. However, the results and hypothesis put forward by the

evaluators has failed to document the complex physical process of rainfall enhancement. Therefore, it is also recommended that SOAR investigate the possibility of working with a group of scientists capable of providing in-situ cloud physics aircraft measurements to supplement radar estimated rainfall and rain gauge data. Specifically, the data required is to:

Confirm that clouds seeded with silver iodide contain more ice than their unseeded counterparts.

Confirm that supercooled liquid water depletes faster in seeded clouds than in unseeded clouds.

Investigate the degree of liquid water depletion due to entrainment and whether on top seeding versus base seeding is a better method of exploiting the concentration of supercooled water to initiate precipitation.

Investigate the range of the size droplet spectra of convective clouds. A narrow spectrum may indicate the inefficiency of the collision-coalescence mechanism at the droplet sizes observed (ICA).

Investigate the effect of airborne pollutants below cloud base; their concentrations, sizes, chemical composition and how these alter the hygroscopic and glaciogenic seeding effect.

7. Analysis of the ICA climatology of the convective environment around the SOAR area shows signs of weak coalescence in the warm part of the cloud that leads to a very inefficient rain process. Supercooled water is retained in the cloud for long periods of time and rainfall in the cold part exhibits a delay in its initiation. When a strong forcing mechanism is present, especially in the spring, this supercooled water is pushed into the colder levels of the cloud where it freezes homogenously and usually is followed by the formation of hail. If these clouds are seeded and the supercooled water is nucleated before it moves upward in the cloud, the rain is enhanced and the hail is reduced. It has also been shown that recent experiments have renewed interest in the possibility of increasing rainfall from warm season convective clouds by cloud base release of hygroscopic particles. These particles have just the right characteristics to promote the formation of drizzle, which grows by coalescence into rain. This appears to be a fruitful area that requires further investigation. It is recommended that SOAR support or is involved in a project or experiment to investigate the opportunities of hygroscopic seeding within the SOAR target area.

To implement these recommendations, a link between the operational and research community needs to be established. The ambassadors of the Texas programs have been working hard to secure funding for such an endeavor with limited results.

6. REFERENCES

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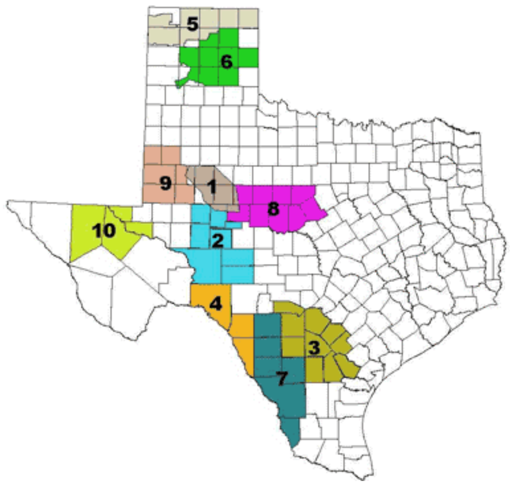

Figure 1: 2003 Cloud seeding programs in Texas (SOAR program on Texas side is number 9)

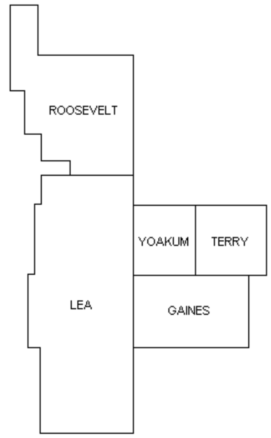

Figure 2: The SOAR 5.9 million acres target (Roosevelt and Lea Counties are in New Mexico)