"REVIEWED"

THE TEXAS WEATHER MODIFICATION PROGRAM: OBJECTIVES, APPROACH AND PROGRESS

George W. Bomar
Texas Natural Resource
Conservation Commission
Austin, Texas 78711

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado 80127

Dale L. Bates
San Angelo, Texas 76901

Abstract. Texas has a lengthy history of efforts by residents in semi-arid regions of the state to ameliorate the impact of periodic severe, even extreme, droughts by using cloud-seeding technology. Numerous rain-augmentation endeavors during the epic drought of the 1950s prompted the Texas Legislature to enact a statute governing the future use of weather-modification technology. That measure was followed by an effort, in concert with federal agencies, to assess the utility of rain-enhancement technology through a comprehensive, though often fitful, atmospheric-research program administered by Texas water agencies in the 1970s and 1980s. It was only after these multi-year research projects yielded substantial and compelling evidence that cloud seeding had efficacy with deep convective clouds in semi-arid portions of Texas that a coordinated, State-funded rain-enhancement program evolved, now covering nearly one-quarter of the state's acreage. With newer technologies being brought to bear in cloud-seeding operations and in the assessment of those activities, and with more political entities in the state now viewing cloud-seeding technology as a viable, long-term water management strategy and not a short-term, quick-fix to the drought problem, the foundation is being set for even more widespread usage of cloud seeding in the Lone Star State.

1. INTRODUCTION

The severe to extreme droughts so prevalent in Texas during the decade of the 1990s engendered among Texans a renewed appreciation for an adequate supply of fresh water. They also demonstrated just how vulnerable the state becomes when those supplies of fresh water dwindle to alarmingly low levels. With the state likely to double its population within the next 30 years, to as many as 35 million people, demands for adequate fresh water to meet the needs of so many water consumers are sure to soar, especially in times of deficit rainfall. Thus, with the dual threat of sustained population growth and inevitable drought, those planning for Texas' future are having to look for new, innovative ways to ensure that the supply of fresh water keeps up with the demand.

This growing need for adequate fresh-water supplies in arid and drought-stricken parts of Texas has focused renewed attention on alternative ways of conserving existing water resources and of procuring additional water by tapping into the abundant supply of moisture available in the Earth's atmosphere. Passage of the Texas Weather Modification Act by the Texas Legislature in 1967 was a tacit acknowledgment that the use of cloud-seeding technology had earned a measure of acceptance within the water-management community in Texas. At the same time, the law recognized many uncertainties remained with respect to the effectiveness of various forms of cloud seeding. Hence, the need to regulate the level of human intervention in cloud processes to protect the interests of the public, and to promote the development of a viable and demonstrable technology of cloud seeding, was addressed by that legislative act.

2. THE PROGRAM'S FOUNDATION: SOUND AND RELEVANT RESEARCH

To attain the objective mandated by the Texas Legislature to develop and refine cloud-seeding technologies, the State of Texas took a first step by linking up with the U. S. Bureau of Reclamation in 1973 to devise and demonstrate a viable cloud-seeding technology. Since then, an on-going, though often intermittent, research effort has ensued to corroborate and quantify the effects of timely seeding of convective clouds. Despite limited funding over the years, substantial progress has been made in pursuit of this goal. The evidence adduced from several years of intensive research has strongly suggested that researchers' efforts to explore, and appropriate, such a non-structural approach as weather modification for securing additional water supplies for a burgeoning population has been rewarded with more than a little success.

2.1 The HIPLEX Project

Texas' first step in scientifically investigating the value of cloud seeding technology for increasing water supplies was a cooperative effort with the U.S. Department of the Interior that was launched in 1973. The High Plains Cooperative Program (more popularly known as HIPLEX) was a part of "Project Skywater" that was designed to formulate an effective technology of rainfall enhancement to help supplement the Nation's fresh-water supply.

The Texas HIPLEX Program was designed as a long-term multi-phase research effort to develop a technology to augment West Texas summer rainfall. Due to Federal funding cutbacks, Texas HIPLEX was limited to its initial phase (1975 through 1980), which included the collection, processing and analysis of meteorological data in order to better understand the typical summertime cloud systems of west Texas. The data collected during the six summer field programs included surface and upper-air observations, and cloud physics, radar, satellite and rain gage data within an area of some 5000 sq. mi. in the southern High Plains of Texas (Fig. 1).

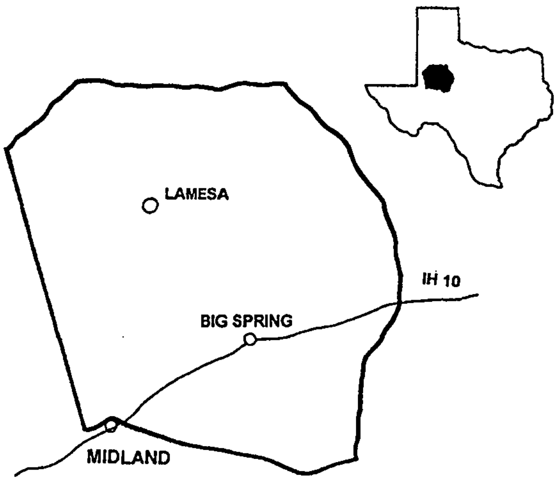


Fig. 1. Project area of the Texas HIPLEX Project, 1975-80.

Much of these data have been analyzed and insights into the physical processes responsible for convective rainfall in West Texas have been gained (see Riggio et al., 1983; and Matthews, 1983). These results indicate that most of the summer rainfall is produced by the larger, more efficient storms. More importantly, they indicate that a rain enhancement technology for West Texas ultimately must either address this type of storm or induce smaller, less efficient cloud systems to grow into their larger, more efficient counterparts. Jurica et al. (1983) were also led to the conclusion that multiple-cell convective systems offer more promise for significant rainfall enhancement than do isolated cumulus congestus.

2.2 The Southwest Cooperative Program

Randomized cloud seeding experimentation began in Texas in 1986 under the auspices of the Southwest Cooperative Program (SWCP) of Texas and Oklahoma. The SWCP was envisioned as a joint effort to develop a scientifically sound, environmentally sensitive, and socially acceptable, applied weather modification technology for increasing water supplies in the semi-arid southern High Plains. The primary initial focus was the testing of dynamic seeding concepts and procedures for the enhancement of rainfall (see Woodley et al, 1982). The sponsors of the Texas SWCP effort were the Texas Water Commission, the U.S. Bureau of Reclamation, the Colorado River Municipal Water District (Big Spring), and the City of San Angelo, Texas. Experimentation was conducted from a base in San Angelo, Texas during 1986, 1987, and 1989 and from a base in Big Spring, Texas in 1990 and 1994.

All experiments were carried out , within the same general area as that of the Texas HIPLEX Project (Fig. 1), in accordance with the SWCP Design Document (Jurica and Woodley, 1985) and SWCP Operations Plans (Jurica et al., 1987). In every case, the experimental unit was the small multiple-cell convective system within a circle having a radius of 25 km (areal coverage is 1,964 km^2) and centered at the location of the convective cell, which qualified the unit for treatment. The selection criteria are discussed extensively by Rosenfeld and Woodley (1989; 1993). The treatment decisions were randomized on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment--silver iodide (AgI) in the case of a seed (S) decision or simulated AgI in the case of a no seed (NS) decision. Rainfall is estimated using radar for the "floating target" experimental unit, which floats or drifts with the wind.

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical top heights of 5.5 to 6.5 km and top temperatures of -8°C to -12°C). The seeding devices were ejectable flares that produced 20 gm of AgI smoke during their 1.5 km free-fall through the upper portion of the cloud. Between 1 and 10 flares normally were ejected during a seeding pass, but more were ejected in a few instances in especially vigorous clouds. The flare ejection button was pressed approximately every second while the cloud liquid water reading was > 0.5 g/m^3. In the simulated seeding passes no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system.

In the SWCP design, therefore, the treatment units are the convective cells, which contain cloud towers that meet the liquid water and updraft requirements. It is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

A total of 38 experimental units (18 Seed and 20 No-Seed) have been obtained in west Texas since experimentation began. In addition, 213 convective cells (99 Seed and 114 No-Seed) have been subjected to an analysis (Woodley and Rosenfeld, 1996), which suggests the S cells produced 2.63 times more radar-estimated rainfall than the NS cells by virtue of covering more area and having greater duration and larger rain volume rates. The results for rain volume, area, duration and merger are significant at the 5% level. The apparent rain increases took place without an appreciable increase in the mean echo heights of the cells, although the disparity might have been greater for the visible cloud tops had it been possible to measure them.

The rainfall results for the 38 experimental units (18 seed and 20 no seed) obtained in the Texas experimentation to date are provided by Woodley and Rosenfeld (1996). The ratio of mean seed to no seed rainfall is 1.45 by the end of the 150-min analysis period. This result is not statistically significant. This randomized experimentation was then terminated due to a lack of funding.

2.3 The TEXARC Project

With the entry of the State of Texas into the NOAA Federal/State Cooperative Program in Atmospheric Modification Research, however, an additional (but temporary) source of funding materialized. This was earmarked for physical studies of relevance to the randomized seeding experiment. As a consequence, the State of Texas took its first steps in 1994 and 1995 in implementing a research program involving the use an instrumented cloud-physics aircraft to investigate the physical processes that are operative within vigorous supercooled convective towers before, during, and following treatment with silver iodide. The multi-year research effort was known as the **T**exas **Ex**periment in **A**ugmenting **R**ainfall through **C**loud-Seeding (**TEXARC**) Project. Research activities were focused on an area of west central Texas near and west of San Angelo (Fig. 2). It was found that cloud microphysical structure is strongly dependent on the cloud-base temperature (CBT). When the cloud base is high and the CBT cool, very few raindrops are found at temperatures ranging between -5°C and -10°C and glaciation proceeds rather slowly in these "continental" clouds. When the cloud base is low and the CBT is warm, however, the west Texas clouds are more tropical in character, having raindrops at temperatures of -5°C to -10°C. Glaciation proceeds more rapidly in these untreated clouds (Rosenfeld and Woodley, 1997).

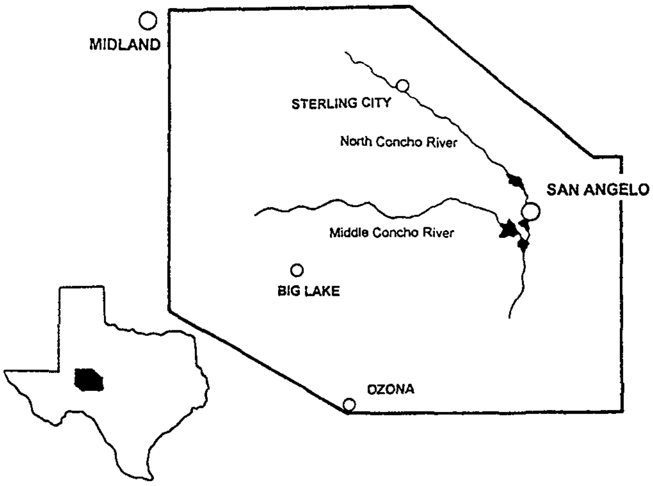


Fig. 2. Target area for the TEXARC Project, 1995-98.

It was found also that on-top seeding of supercooled cloud towers in "continental" clouds hardened them briefly in appearance but did not produce appreciable growth. As glaciation proceeded, the reflectivity of the cloud increased relative to the clouds in its environment and then it usually died. On the other hand, on-top seeding of clouds with warm cloud bases (i.e., CBT ≥ 18°C) appeared to result in rapid glaciation and vigorous cloud growth. This is consistent in what has been observed elsewhere in such clouds.

In clouds without supercooled rain it was observed that graupel grows too slowly to convert cloud water into precipitation-size particles (several mm) during the lifetime of the updraft except for the most vigorous and vertically developed clouds. This slow glaciation also does not produce a significant dynamic response in the clouds, rather the cloud normally glaciates during its collapse, accelerating its dissipation and leaving holes in the cloud field.

In clouds with supercooled rain, seeding leads to rapid freezing of the supercooled rain and its continued growth as graupel. This graupel appears to grow faster than supercooled raindrops under the same condition in accordance with theoretical calculations (Sednev, et al., 1996). The seeding also increases cloud buoyancy and further invigorates the updraft, while the cloud is still in a position to use it to support the growth of large precipitation particles.

These results emphasize the importance of when and where the various microphysical processes take place within the cloud and when and where the seeding takes place that is intended to alter these processes. Both the Rosenfeld/Woodley (see Rosenfeld and Woodley, 1993) conceptual model and these new results suggest it is crucial to produce glaciation artificially within the vigorous supercooled updraft region of the cloud when seeding for rain enhancement. It is in this region large artificially-nucleated precipitation-sized particles can be grown most efficiently. Accomplishing this through seeding requires great care in the placement of the nucleant either in the updraft directly near cloud top or in the strong inflow region at cloud base in well-developed convective systems.

3. OPERATIONAL WEATHER MODIFICATION IN TEXAS

3.1 Projects Begun Prior to 1985

Much of the rather meager amount of cloud-seeding for rainfall enhancement prior to 1985 was concentrated in a 3600-square-mile area of semi-arid West Texas, where the Colorado River Municipal Water District began seeding deep convective towers in 1971(Fig. 3). By virtue of sustaining a perennial, warm-season seeding program in the vicinity of Big Spring, Texas, the CRMWD's weather-modification effort became one of the most enduring rain-augmentation programs in the U.S. Others carefully observed the work of the CRMWD, including the City of San Angelo, which conducted its own 5-year rain-enhancement program in the latter half of the 1980s.

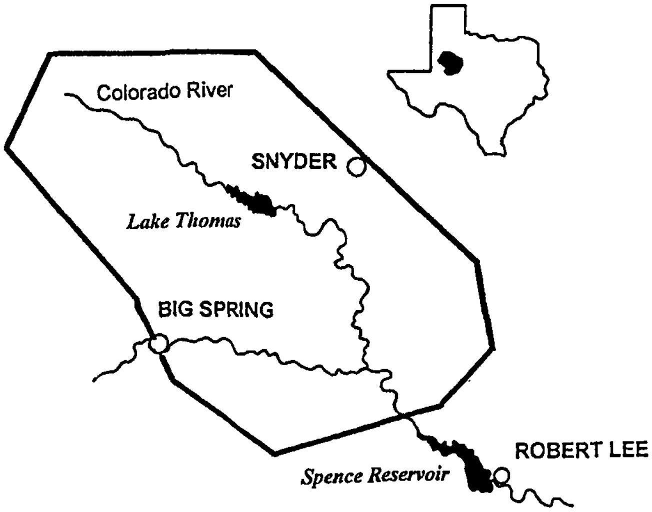


Fig. 3. Target area of the CRMWD operational rain-enhancement program, 1971-98.

3.1.1 The CRMWD Program, 1971 to Present. The CRMWD rain-enhancement program has, since its inception in 1971, had as its primary objectives the augmentation of rainwater, and hence runoff, into two reservoirs owned and operated by the District on the upper Colorado River of Texas (Fig. 3). A secondary objective of the long-running program was to increase rainfall for the agricultural interests that predominate in the gently-rolling plains of West Texas. The dispersal of seeding material (silver iodide) was achieved at or just below cloud base using a twin-engine aircraft equipped with both wing-mounted flares and, at times, acetone generators.

In assessing the apparent effect of seeding of the CRMWD program, Jones (1988 and 1997) made use of the historical rainfall record (1936-1970) to calculate percent of normal rainfall at target and control stations. He also used these data to develop target-control regressions, which were used to predict rainfall in the seeded period (1971-1988, 1990-91, 1994-95 and 1997). The predicted and observed target rainfalls were then compared. The percent-of-normal analysis indicates 34 percent above-normal rainfall in the target area, while rainfall only increased 13 percent for the unseeded areas outside the target area during the seeded years.

A second analysis by Jones (1988) of the yields of unirrigated cotton in and around the target since seeding began in 1971 indicates increases of cotton production of 48 percent in the target, and 45 percent downwind of the target, while the increase in cotton yields for the same time frame in the counties upwind of the target was only 8 percent. If one assumes that rainfall has been the major control of cotton production over the entire West Texas region (an assumption generally regarded as fair), this result may be interpreted as further evidence for seeding-induced rain increases.

3.1.2 The San Angelo Program, 1985-89. The harsh drought of 1982-84 forced the City of San Angelo to examine the potential of cloud-seeding technology for mitigating the deleterious effects of drought over the city's watershed. A cloud-seeding program was launched in the summer of 1985, using aircraft with the capability of seeding convective towers from above cloud top as well as at or below cloud base. The same seeding methodology, using either wing-mounted or droppable pyrotechnics of silver iodide, was employed for five consecutive summers in a 6-million acre area around and west of San Angelo.

A regression analysis of observed rainfall within the target area suggested an overall effect of seeding of about 17 percent for the target for the 5-year program (Woodley and Solak, 1990). The area closest to the storage reservoirs had an apparent overall effect ranging between 27 and 42 percent. It was within this region that more than half of all seeding material was dispersed.

3.2 Projects Launched Since 1985

With concern growing over the availability of ground water to meet the increased demand for fresh water, other cloud-seeding projects materialized during the 1980s. One project focused on treating deep convection over the drainage basin of the Edwards Aquifer, a vast underground 'reservoir' that furnishes much of the Texas Hill Country, including the metropolis of San Antonio, with its fresh water. The City of Corpus Christi conducted a short-lived cloud-seeding program to put more runoff into a reservoir (Choke Canyon) that serves that coastal city. However, these programs did not thrive for long, principally because of the concern for flash flooding in what is one of the three most flash flood-prone areas of the U.S. Constraints were imposed on the projects to the extent that many seeding opportunities had to be given up due to the threat of heavy rains in densely-populated areas.

4. BACKGROUND FOR THE CURRENT STATEWIDE PROGRAM

From the time prior to World War I, when C. W. Post attempted to 'shake' rainwater out of towering cumuli along and just below the Caprock region of West Texas (1911-1914), various weather-modification methodologies have been used in the Lone Star State to prompt warm-season cumulus clouds to live longer and shed much-needed rainfall. Rain-enhancement projects sprung up intermittently in parts of semi-arid West Texas in the decades between the two world wars and during the epic drought of the 1950s, usually as a measure of last resort to ameliorate the impact of a prolonged dry spell. Even after legislation was adopted in 1967 to regulate the use of cloud-seeding technology within the state, rain-enhancement programs adopted by various water interests were for the most part locally-controlled and funded, with minimal interface from the State.

The lack of state involvement in the more than a dozen independently-financed and managed weather modification projects prior to 1970 meant that the bulk of these efforts received a minimum of rigorous analysis. In fact, most of the projects were poorly documented, if at all. The impact of cloud-seeding was seldom quantified, and perceptions of the efficacy of the efforts were for the most part a function of who happened to be asked. By today's standards, methods of cloud seeding were rather primitive. For instance, many of the projects conducted between World War II and the passage of the Texas Weather Modification Act (in 1967) involved WWII-vintage aircraft and dry ice.

4.1 Role of Water Conservation Districts

What would eventually serve as a foundation for funding, designing, and implementing cloud-seeding operations on a large-scale basis in Texas began to evolve during the historic 1950s drought. Independent *water districts* began sprouting in rain-short areas of West and Southwest Texas after a precedent was established in the mid-1950s by the High Plains Underground Water Conservation District. This district, encompassing all or parts of 15 counties in northwestern Texas and covering some 6.9 million acres above the Caprock (Fig. 4), materialized in order to monitor, and eventually govern, the use of fresh water from the vast Ogallala Aquifer that underlies vast portions of the U. S. Great Plains, from Nebraska to near the Permian Basin in far West Texas. Given *ad valorem* taxing authority, the District was furnished

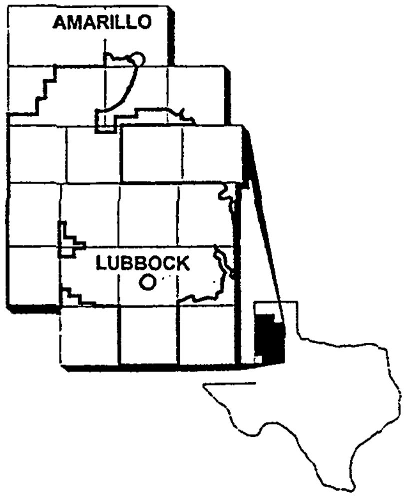


Fig. 4. Target area for the rain-enhancement program of the HPUWCD, 1997-98.

the financial wherewithal to set up a staff to quantify its ground-water resources and regulate the use of that ground water to ensure that water supplies from the aquifer would be adequate to meet the fresh-water needs of a growing populace.

Subsequent state legislation encouraged the formation of other, similarly-constructed water districts in semi-arid parts of Texas, though the 42 districts formed after 1985 (and encompassing all, or parts, of 80 Texas counties) were considerably less expansive than the original High Plains district based in Lubbock. In every instance, however, the fundamental motivation for establishing these districts (many of which are single-county districts) was to have a legal mechanism in place to control the draw-down from, and abet the recharge to, the aquifers that underlay the districts. Perhaps serendipitously, the arrangement of these districts afforded the locals a fiscal mechanism by which programs like cloud seeding for rainwater-augmentation could be equitably paid for within their respective areas of jurisdiction.

The first water district to use some of its funds to apply an innovative water-development strategy, such as precipitation enhancement through cloud seeding, was the Colorado River Municipal Water District, based in Big Spring. One of Texas' preeminent pioneers in developing new and innovative water-management strategies, Owen H. Ivie, as general manager of the CRMWD, was preeminently responsible for the program launched in 1971. After using a contractor for cloud-seeding services in the early years of his program, he saw the merits of committing the District to a long-term rain-enhancement program by securing its own aircraft, weather radar, and qualified staff to run its cloud-seeding operation during the growing season.

4.2. Origins of a Statewide Program

Despite the apparent successes of the two multi-year projects based in Big Spring and San Angelo, it was not until 1995 that interest in using cloud-seeding technology grew enough to foster serious consideration of implementing a far-reaching, region wide cloud-seeding effort. The impetus for a statewide weather-modification program was born in the region west of San Angelo, where cloud seeding had been conducted extensively in the latter half of the 1980s. During that 5-year program, numerous ranchers living west of the city in several counties whose rivers and streams supplied water to the City's reservoir system had observed what they considered to be a positive response in many of the towering cumuli seeded by the City's contractor. These counties already had in place single-county water districts, which afforded a convenient mechanism for raising funds to support the reinstatement of a regionwide cloud-seeding program.

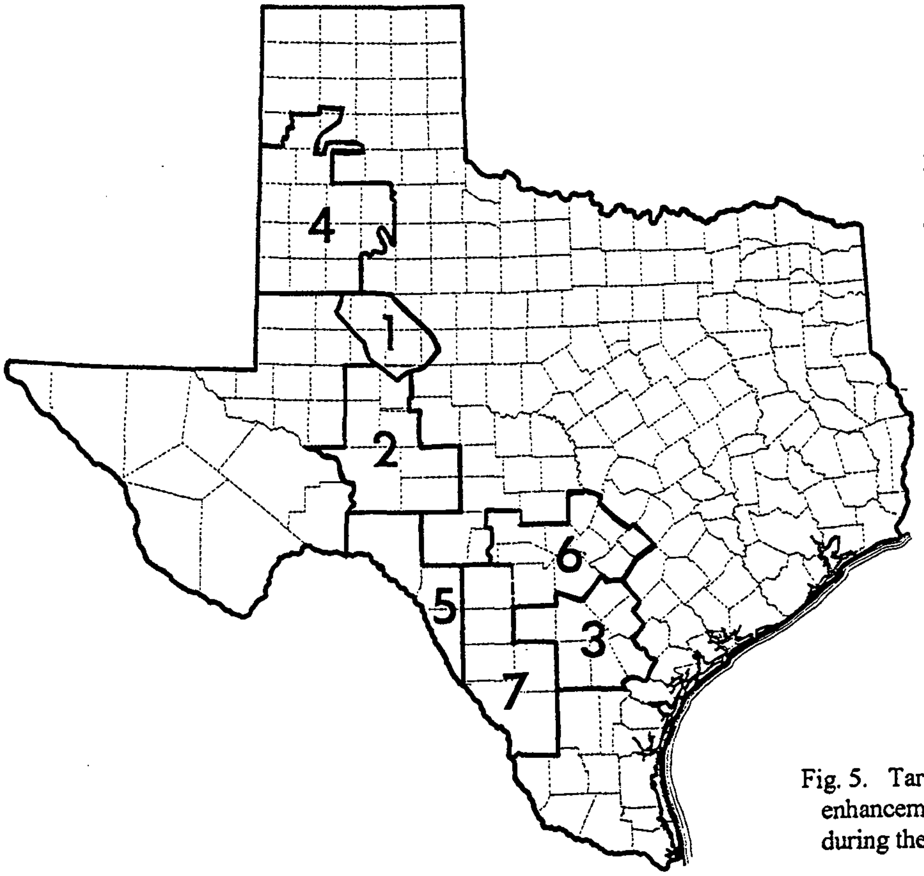
Water-district officials from these counties began holding public meetings in and near their respective county seats and invited staff from the State's water agency to attend and give formal presentations on the state of weather-modification technology for rainfall-augmentation. Soon, these counties had formed a weather-modification alliance, called the West Texas Weather Modification Association, to raise funds and implement cloud-seeding operations. The alliance was formed under the authority given the water districts to quantify and protect ground-water reserves in the aquifers beneath them. Cloud seeding was viewed by these officials as a cost-effective means of recharging the aquifers and lessening the rate of withdrawal from the aquifers.

Landowners and water-district officials in Irion and Crockett Counties of West Texas learned more about the potential of cloud seeding for augmenting rainfall in the summer of 1995, at which time the State's water agency was conducting a series of cloud-seeding experiments in the Big Spring, Texas area, known as the TEXARC Project.

As a severe drought ravaged much of West Texas in 1995, other nearby counties joined with Irion and Crockett Counties to form the West Texas Weather Modification Association (WTWMA). The establishment of this alliance of eight counties to promote the use of cloud-seeding technology would serve as a prototype for other rain-enhancement projects that would form elsewhere in West, and in South, Texas in the years to follow (Fig. 5, project number 2). With a "target" area of 7.2 million acres, a contractor was identified and both cloud-base and cloud-top seeding activities got underway in May 1996.

4.3. Local Supervision of Seeding Operations

An executive Board consisting of representation from the eight participating counties was established to facilitate decision making as the project ensued. Despite the fact that some counties making up the WTWMA target area were considerably larger than others, each county was assigned one vote. Moreover, each voting delegate had to be an elected official (e.g. water district Board member, county commissioner, city official). Such a policy ensured that control of the program resided, and was maintained, at the "grass-roots" level. Furthermore, the program was paid out of revenue raised through *ad valorem* taxes by each county. A county share's was



PROJECT ACREAGE
(millions of acres)

1	CRMWD	2.24
2	WTWMA	6.20
3	STWMA	4.41
4	HPUWCD	7.96
5	TBWMA	3.79
6	EAA	5.44
7	SWTREA	5.85
	Total	35.89

Fig. 5. Target areas of the seven rain-enhancement projects to be in operation during the summer of 1999.

determined by the total amount of acreage in that county. In one or two instances, where counties without water districts were participants, the share of funding from that county was provided by a county commissioners' court or through revenue supplied by a landowners' association.

The first year of cloud-seeding was paid solely by monies raised by the water districts constituting the WTWMA. The way these member counties linked themselves together to plan and pay for the rain-enhancement project garnered the attention of both regional and national news media. The fact that the region was in the throes of a worsening and spreading drought undoubtedly contributed to the fascination sown by both media groups and by political interests statewide. In the early weeks (June 1996) of the newly-formed cloud-seeding operation based in San Angelo, reporters from several major television news organizations (ABC, CNN, and NBC) visited the project site to interview project organizers and personnel. Several major newspapers did feature articles on the project as well.

Perhaps the most appealing aspect of the way the West Texas group organized themselves consisted of the control afforded the program at the local level. The executive Board made all decisions relative to the conduct of the program. Representation from each participating county meant the diverse needs of each major enterprise could be accommodated. For instance, a county with a heavy investment in cotton production would prefer to have a minimum of rainfall during the time of harvest in the autumn; input from that county through its representative on the Board would ensure that the county (or some large sector of that county) would be excluded from any advertent weather-modification activity during the period specified.

The West Texas group had as its preeminent objective to help as many as possible residing within their target area and not to hurt anyone. (In fact, the State water agency regulating the use of cloud seeding for rain enhancement is required to ascertain, to the extent technologically possible, that the proposed weather-modification program will not "dissipate the clouds nor prevent their natural course of developing rainfall in the area to the material detriment of people or property" within that area; such a finding must be made before the Texas Natural Resource Conservation Commission (TNRCC) can, and will, issue a permit for the project.)

Moreover, the WTWMA maintained a rain-gage network to assess soil-moisture conditions during the course of the cloud-seeding operation. These rainfall data were used to prioritize those areas within the target region most, and least, in need of rainfall. In many instances, it was possible to specify an area as small as a fraction of a county where rainwater was, or was not, needed. This policy afforded the participating counties and ranchers within them an added sense of control of the program.

4.4. The Proliferation of Projects

Using the WTWMA organizational model, a second rain-enhancement program was formed in South Central Texas, south of San Antonio and some 250 miles removed from the WTWMA site. A water district (known as the Evergreen Underground Water Conservation District) based in Jourdanton, Texas served as the nucleus for this 7-county, 4.4 million-acre project (Fig. 5, project number 3). The alliance of counties, called the South Texas Weather Modification Association (STWMA), established a governing Board, developed specifications for a warm-season rain-augmentation program, went out for bid, then secured a contracting firm to perform the actual seeding operations.

A third rain-enhancement project, covering some 6.87 million acres in the Texas High Plains, materialized in 1997. This project, based in Lubbock, was unlike its two predecessors in that it was sponsored by a lone and very large underground water-conservation district covering all or parts of 15 counties in the High Plains of Texas. That district, the HPUWCD, already had in place a governing board as well as a network of county committeemen. Those two mechanisms were used to provide the kinds of locally based input needed to structure, then supervise, the cloud-seeding program to the needs of constituents.

Still more projects, encompassing an additional 12 million acres in southwest and south Texas, were drawn up for implementation in 1998. One of them got underway just weeks before the residue from a tropical storm (Charlie) dumped flash floods in Val Verde County, the heart of the Texas Border Weather Modification Association (TBWMA) target area (Fig. 5, project number 5). (Cloud-seeding operations had been suspended a full 20 hours before the onset of those torrential, flood-producing rains inundated much of the city of Del Rio in August 1998.) The project, governed similarly by a multi-county Board, resumed cloud seeding soon after the flood water receded.

4.5. State Support of Weather Modification

A pivotal development in the statewide weather-modification program can be traced to action by the 75th Texas Legislature, which in 1997, appropriated for the first time ever a substantial amount of funds to help the various cloud-seeding projects pay for their operations. The State support was given to those water districts sponsoring cloud seeding on a 50-50 cost share basis. The amount of State funding to each project was determined strictly on a per acreage basis. This arrangement meant that, for every $0.0425 per acre raised at the local level, an equivalent amount was contributed by the State water agency (TNRCC). Funds totaling $4.197 million were also made available for operations during the warm seasons of 1998 and 1999.

To unify the various rain-enhancement projects within Texas, an 'umbrella' organization was formed in 1997 known as the Texas Weather Modification Association. A voting representative from each of the state's five operational cloud-seeding programs served on the Association's executive Board. The TWMA worked to resolve problems encountered with the use of various types of flares at the five project sites. Moreover, the association advises the TNRCC staff in the allotment of state revenue to help pay for the weather-modification programs. The group also sponsored training sessions for project personnel, including specialized training from a scientific consultant for those meteorologists running the programs.

The end result of the collaborative efforts of state and local officials to orchestrate a well-designed, coordinated weather-modification effort for the state of Texas has fostered a virtually ideal environment for continued research and development of an appropriate cloud-seeding technology for the region. This was evidenced by the successful completion of the 1998 TEXARC Project in the vicinity of San Angelo, Texas. It is also apparent in continued monetary support from the State water agency, with the bright prospect that State funding will be maintained through at least the summer of 2001 for both operational cloud seeding activities and relevant research and assessment work in support of those activities.

5. RECENT TEXAS RESEARCH FINDINGS OF RELEVANCE TO ITS OPERATIONAL PROGRAMS

The conduct of the TEXARC Project, initiated in 1994 and continued until the present day, has furnished a number of new insights on how best to carry out seeding operations, including the recognition of which convective clouds are more "seedable" as well as the optimum seeding strategies given an array of atmospheric conditions.

5.1 The L Coalescence Parameter and First-Echo Heights

Perennial questions in all rain enhancement programs are whether, when, where and how cloud seeding is to be conducted. A question being faced currently in some of the Texas programs that have decided to employ hygroscopic for rain enhancement in addition to conventional AgI methods is when either AgI or hygroscopic seeding is to be employed. Some might argue this use of hygroscopic seeding for rain enhancement in the manner of Mather et al. (1997) is premature. Others might argue the state of knowledge with respect to hygroscopic seeding is no worse than that for AgI seeding and there is no reason not to employ hygroscopic seeding in an operational context.

Because hygroscopic seeding is being employed at some places in Texas, it is appropriate to develop some guidelines for its use and evaluation. If the cloud tops are warm (i.e., > 0°C), hygroscopic seeding is the only option, if indeed any method is to be employed. If the tops are supercooled and loaded with raindrops, hygroscopic seeding is not the better choice. It makes no sense to seed to enhance coalescence and the formation of raindrops if natural conditions are already producing them in large concentrations. Further, model simulations of hygroscopic seeding show no effect from the seeding of highly maritime clouds containing raindrops. It is important, therefore, to predict when the clouds will produce raindrops naturally and to determine in real time whether the clouds are producing raindrops naturally.

One way of predicting in advance whether the supercooled (T about –10°C)) portions of clouds on a particular day will contain raindrops is to calculate the Mather L coalescence discriminator defined as

$$L = 8.6 - CCL + 1.72(PB)$$

where CCL is the temperature at the convective condensation level and PB is the potential buoyancy, defined as the temperature difference between the temperature of an air parcel rising from the CCL to 500 mb and the 500 mb temperature itself (Mather, 1986). The warmer the CCL and the smaller the PB the more likely the supercooled portions of the clouds will contain raindrops. Thus, the probability of raindrops increases as L decreases and vice versa. This was found to be the case in South Africa where the L parameter was derived.

The L parameter also performs well in Thailand as a predictor of in-cloud coalescence as shown in Figure 6. Figure 6 is a scatter-plot from Sukarnjanaset et al. (1998) in which each plotted point represents L vs. either the median maximum or the mean maximum droplet or frozen droplet size in the supercooled portions (about –8°C) in Thai clouds. The correlations for the mean and median relationships are – 0.65 and –0.66, respectively. Best fits to the mean (solid line) and median (dashed line) data are shown. The results indicate that the droplet sizes increase as L decreases.

The value of the L parameter is being investigated in Texas by relating the L parameter to first-echo heights, because first-echoes should be indicative of the presence of raindrops. So far, the L parameter has been calculated for 29 days during the 1998 season using both the San Angelo and Del Rio soundings. The first-echo top heights for the same days have been calculated using TITAN software and the San Angelo WTWMA WSR-74 5-cm radar. A scatter plot between L (the abscissa) and the first echo heights (ordinate) have been constructed for Midland and Del Rio soundings as shown in Figures 7 and 8, respectively, along with the linear correlation coefficients and best fit lines.

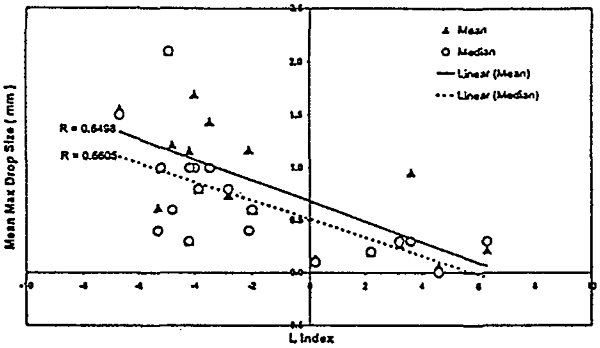


Fig. 6. Daily mean and median maximum droplet sizes in the range of -8C to -12C versus the Mather coalescence parameter (L)

Note there is a strong positive correlation between L and the first echo heights. This means as L decreases the first echo heights decrease. For large negative L values the top heights of the first echoes are < 5 km in most instances, meaning the echoing portion of the cloud containing the raindrops is warmer than 0°C. It is questionable hygroscopic seeding would enhance the rainfall from such clouds.

Because the rain in the clouds increases as L decreases, it should be possible to use the L parameter to determine which type of seeding should be employed. When L is large and negative (e.g., L < -2) silver iodide seeding should be employed instead of hygroscopic seeding if seeding is to be done. As L increases (e.g., L > 5), however, it becomes less likely the clouds will contain raindrops and hygroscopic seeding should take precedence over silver iodide seeding. Regardless of which method is chosen at the outset, the decision should be checked using the first echo heights. Whenever the first echo heights are low, hygroscopic seeding is not the better choice regardless of the L parameter. Silver iodide should be used in those circumstances.

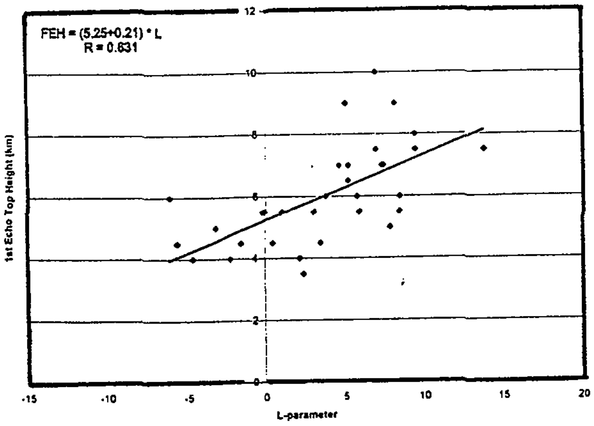


Fig. 7. Values of L-parameter versus first-echo heights using Midland sounding data, for all 1998 operational days.

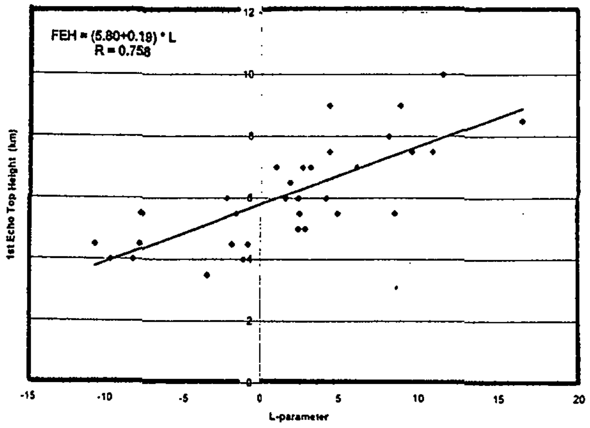


Fig. 8. Values of L-parameter versus first-echo heights using Del Rio sounding data, for all 1998 operational days.

5.2 Evaluation of Operational Seeding Activities

The Texas program has adopted the view that no operational seeding should be conducted without some provision for its evaluation. This agrees with at least one of the points made by Kessler (1998) in his critique of current operational seeding programs in Texas and Oklahoma. Evaluation can take the form of target-control historical regressions. It can also take the form of physical evaluations even though they may not address directly whether the seeding has produced more rain on the ground. Examples of both types of evaluation are provided here.

5.3 First-Echo Heights and Hygroscopic Seeding

A physical means of evaluating hygroscopic seeding is embodied in Figures 7 and 8 in which first-echo heights are plotted vs. L. If operational seeding is conducted on days when L is large and positive, the first-echo heights will be high and supercooled. By identifying a seeding area of effect on such days, one might look at the tops of the first echo heights in the presumed area of effect to determine whether they have been lowered in this area as a result of seeding. If no lowering is evident over the course of a number of seeding events, one would have reason to question the effectiveness of the hygroscopic seeding. On the other hand, if hygroscopic seeding is effective, the mean first-echo heights as a function of L should be less than for clouds that did not ingest the hygroscopic material. This analysis will be pursued in the Texas evaluation effort.

5.4 Satellite Inference of Cloud Microstructure for Evaluation of Cold-Cloud Seeding

The new method of Rosenfeld and Lensky (1998) to infer cloud microstructure using AVHRR satellite imagery shows great promise for the physical evaluation of seeding experiments. The AVHRR on NOAA-14 measures the radiance at five wavebands of 0.65, 0.9, 3.7, 10.8 and 12.0 microns with a sub-satellite resolution of 1.1 km. The visible wave band (0.65 microns) is used to select points with visibly bright clouds for the analyses. The thermal infrared (0.9 microns) is used to obtain cloud-top temperatures. Cloud-top particle size is inferred from the solar radiation component of the 3.7-micron wave band. Retrieval of particle size at cloud top is based on the fact that water absorbs part of the solar radiation at the 3.7-micron wave band. Although the back-scattered solar radiation is determined mainly by the surface area of the particles, the amount of absorption is determined by the volume of the particles. Therefore, larger particles absorb more and reflect less, so that clouds that are made of larger droplets are seen darker in the reflected 3.7-micron radiation. Knowing the energy radiated from the sun and the portion of that energy reflected back to the satellite sensor, the fraction of the solar energy absorbed can be retrieved. This provides the basis for calculating the ratio between the integral volume and integral surface area of cloud particles in the satellite measurement volume. Conventionally, this ratio has been defined as the particle effective radius, r.

5.4.1 Quantifying the Effective Radius of a Particle

The vertical evolution of reff from base to top of a growing convective cloud can be obtained by viewing the cloud in the satellite imagery during its vertical growth phase. However, the NOAA satellite is a polar orbiter, providing only a snapshot image of a specific portion of the earth only once or twice a day. Thus, a single cloud cannot be viewed continuously in the imagery provided by the polar orbiter. This difficulty is overcome by observing an area containing a convective cloud cluster composed of cloud elements at various stages of vertical growth. This allows the compositing of the reff calculations for many clouds as if they represented a singe cloud at different times, assuming the reff of a given cloud top is similar to the reff of a taller cloud when it grew through the same height.

Cloud-top temperature (T) is uniquely related to the depth of convective clouds above their bases in a given area on a given day by calculating T vs. height relationships from the nearby atmospheric sounding. In doing this, it is possible to use temperature as a measure for cloud vertical development.

Cloud top at a given T can have a range of reff values. For presentation of the dependence of r_{eff} on temperature (and therefore, height), the median and the 10th, 25th, 50th, 75th and 90th percentiles of the reff for each 1°C interval of cloud top temperature were calculated for the three areas shown in Figure 9. The image is for June 10, 1998, and the areas 1-3 are in West Texas. The number 3 in area 3 is near Big Spring, where base AgI seeding by the Colorado Municipal Water District was being conducted before, during, and after a pass of the NOAA-14 satellite. In addition, on-top seeding also had been conducted between Big Spring and San Angelo two hours earlier by the seeder aircraft of the West Texas cloud seeding program. The seeded clouds rained and then dissipated, producing a strong outflow that passed Big Spring moving to the northwest. The Big Spring convection seen in an E-W line to the north of Big Spring was initiated on this outflow boundary. Thus, it is conceivable the clouds in areas 1 and 3 ingested the silver iodide released by the two seeding programs, especially those in area 3 where seeding was taking place at the time of the image. Further analysis, using seeding track information, is needed to verify that such ingestion of seeding material did occur.

5.4.2 Depiction of Reflectance and Effective Radius

An important step in the understanding of the highly complex interactions among cloud structure, temperature, thickness, reff and the input aerosols is a clear visualization of these multi-parameter data. This is facilitated by coding various combinations of visible reflectance, T and reff as different colors, shown in Figure 9, according to the following scheme: a) The visible reflectance modulates the red (brighter is redder), b) the reflectance component at 3.7 microns, which is a surrogate for reff, modulates the green (smaller reff is greener), and c) the 10.8 microns brightness temperature modulates the blue (warmer is bluer) (For a more detailed explanation of this color scheme, the reader is urged to consult the paper by Rosenfeld and Lensky, 1998). Ice particles are typically much larger than cloud droplets at the same temperature, thus more absorbing at 3.7 microns. Therefore, ice clouds or snow on the ground appears as having very large reff, or very low green in the color images. For the same reason, small reff indicates water clouds, even at temperatures below 0°C, where the cloud is composed of supercooled water. Such clouds appear yellow in the color scheme.

The most obvious feature in Figure 9 is the large red mass on the center-right. It is the anvil top of a cumulonimbus to the N and NE of Big Spring. It is red because it is bright (high red), very cold (low blue) and has large particles (low green). The SW portion of the Cb is still active and magenta-colored clouds are noted on the periphery of this active area, to the SW in area 3 and in the center of area 1. There are no clouds with the same coloring in area 2.

Looking first at the r_{eff}plots for the three areas, the vertical colored lines on the left margin of the plots identify the growth zones within the clouds. The vertical yellow line gives the extent of the diffusional growth zone in which r_{eff} increases slowly with height. The vertical green line identifies the zone of coalescence growth in which r_{eff} increases more rapidly with height. The vertical

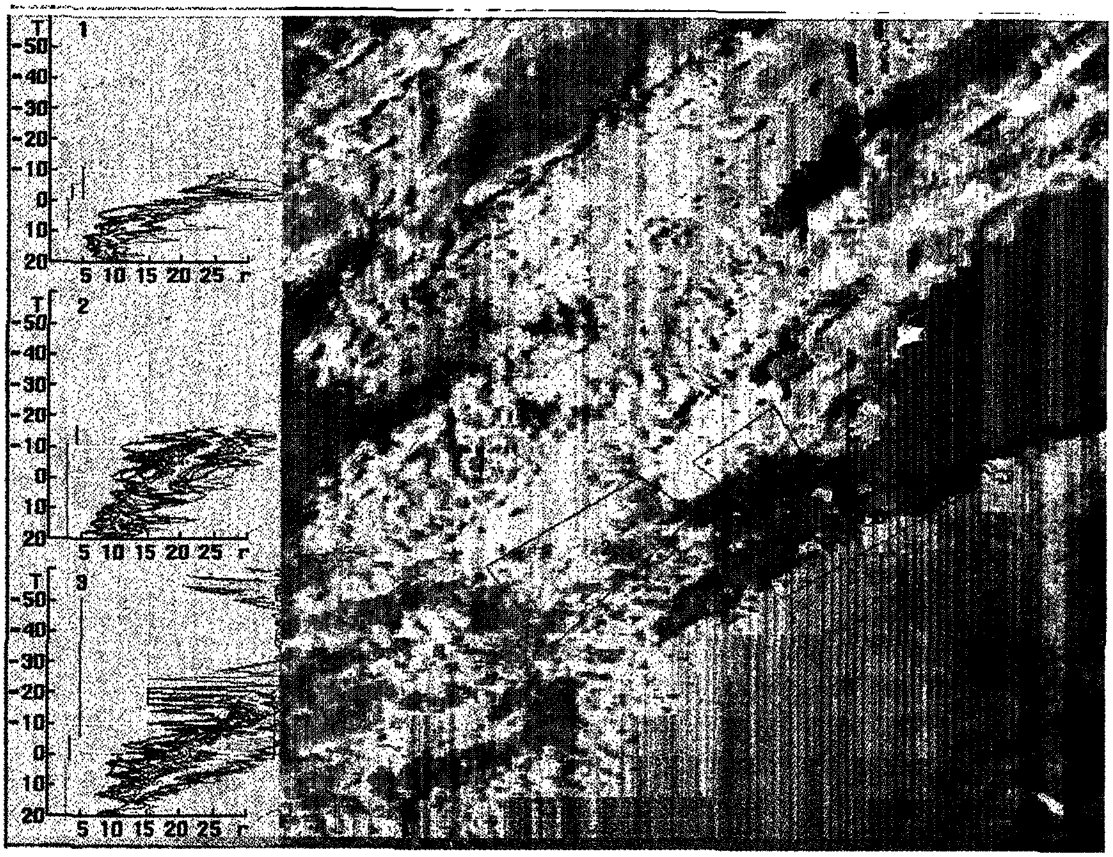


Fig. 9. A NOAA/AVHRR image from June 10, 1998, 20:54 GMT, of convective cloud development over West Central Texas, in the vicinity of Big Spring (approximate location designated by "3")

blue line, which is not shown in area 2 but exists in areas 1 and 3, is the fallout zone in which the larger drops fall out about as fast as they are replaced such that r_{eff} remains fairly constant with height. Finally, the vertical pink line identifies the zone of glaciation in which r_{eff} increases rapidly with height, reaching saturation at 30 microns where glaciation is complete. Also shown in the extreme left of the panels is a white line showing the number of pixels vs. height.

Focusing on area 2 and the median plot (the interface between the yellow and green lines), note the effective radius increases to cloud top where the temperature is about -15°C. Most of the cloud depth has coalescence growth of the cloud droplets (identified by the vertical green line). Because r_{eff} = 14 microns is usually indicative of precipitating cloud, many of the clouds in area 2 are likely precipitating, but they are not completely glaciated since r_{eff} does not reach 30 microns, which is usually indicative of complete glaciation (Gerber, 1996; Rosenfeld and Gutman, 1994). According to the plot only the cloud tops are partially glaciated.

In areas 1 and 3 the increase of the effective radius is more rapid with height. The zones of coalescence growth are shallower, there is a shallow fallout zone, and early complete glaciation is noted, achieved at temperatures between -5C and -10C. Such early glaciation may be suggestive of an effect of seeding, since the purpose of the seeding is to form ice earlier and at warmer temperatures in the cloud life cycle. This gives the seeding-induced ice particles more time to grow to precipitation size in the updraft regions.

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