The Journal of Weather Modification

Volume 33 Number 1 April 2001

WEATHER MODIFICATION ASSOCIATION

- THE JOURNAL OF WEATHER MODIFICATION -

COVER: All small photos are courtesy of Hydro Tasmania, Australia.

Upper left - Cloud Seeding Officer Graeme Vertigan with Cloud Aerosol and Precipitation Spectrometer (CAPS) and silver iodide ice nucleus generator with burner at the end (in background), mounted on cloud seeding aircraft wing. *Upper centre* - The Tasmanian Cloud Seeding Crew in front of Cloud Seeding aircraft, Kevron's Cessna Conquest (VH-LEM). *Upper right* - Large cumulus cloud over Rosebery, Tasmania. *Bottom left* - Early morning cumulo nimbus cloud, Western Victoria. *Bottom centre* - Scientific Officer Christina Nebel inside cloud seeding aircraft with M200 data acquisition and display system. *Bottom right* - Reece Dam on Spill, West Coast of Tasmania, Australia.

The satellite image of Australia (centre image) is a "Bureau of Meteorology image from the Japan Meteorological Agency geostationary satellite GMS-4". The image was taken on 9 January 1992. *Centre image* - Summary of cloud seeding operations and experiments conducted in Australia to date, experimental areas marked on satellite image.

PHOTO CREDITS IN THIS ISSUE:
Photos of WMA Annual Meeting courtesy James Miller, editor.

EDITED BY:


James R. Miller, Editor
Connie K. Crandall, Editorial Assistant

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, South Dakota 57701-3995 U.S.A.
Phone: (605) 394-2291
FAX: (605) 394-6061

PRINTED BY:

Fenske Printing
Rapid City, South Dakota USA

PUBLISHED BY:
The Weather Modification Association
P. O. Box 26926
Fresno, California 93729-6926 U.S.A.
Phone & FAX: (559) 434-3486
email: wxmod@mediaone.net

Membership information is available by contacting the WMA Association at the Fresno, California, address shown above.

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Current Membership Costs per Year:

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ISBN: 0739-1781

- THE JOURNAL OF WEATHER MODIFICATION -
WEATHER MODIFICATION ASSOCIATION

VOLUME 33 **NUMBER 1** **APRIL 2001**

TABLE OF CONTENTS: **PAGE**

- -

- REVIEWED SECTION -

- NON-REVIEWED SECTION -

- WEATHER MODIFICATION ASSOCIATION - GENERAL INFORMATION -

Review of Persistence Effects of Silver Iodide Cloud Seeding

by

Alexis B. Long

P.O. Box 41, 144 Jasper Road
Bentleigh, Victoria, Australia 3204

Abstract. This paper is concerned with persistence effects of cloud seeding for precipitation enhancement. Effects may last for hours or days. Persistence of cloud seeding effects means that this environmental technology may affect the microphysical structure of clouds and the development of precipitation for a significant amount of time after the seeding has been completed.

According to Rottner, Brown, and Foehner (1975) persistence may complicate the evaluation of a cloud seeding experiment and reduce the perceived net effect of the seeding. The sensitivity of the experiment to the actual net effect may be reduced. Their work in Colorado and New Mexico demonstrated a smaller cloud seeding effect because of persistence. When no account was taken that cloud seeding material was incorrectly present in the control period part of the time, the seed:no-seed contrast in precipitation and the effect of seeding were smaller. When the incorrectly seeded parts of the control period were reassigned to the target period, the contrast and the effect of seeding were greater.

There has been considerable post-analysis of precipitation data associated with cloud seeding experiments in Australia by Bigg and colleagues in a search for persistence effects. Unfortunately, there appears to be a flaw in some (but not all) of the analysis which exaggerates the time span (said to be up to two weeks) of the effects.

Artificial ice nuclei are generated by the cloud seeding apparatus and are injected in various ways into a cloud to increase precipitation. The surmised connection between higher nucleus concentrations and increased precipitation suggests that measuring and examining ice nucleus concentrations for a period of perhaps a few days after seeding may be worthwhile in a search for persistence.

Bigg and others have suggested that some silver iodide ice nuclei released in cloud seeding may be carried, presumably with precipitation, to the surface. There the nuclei are believed to stimulate chemical reactions, possibly on plants, that create products that are emitted into the atmosphere to function as persistent ice nuclei. An alternative scenario is that the deposited silver iodide modifies or otherwise causes bacteria on the plants to loft into the atmosphere and also act as persistent ice nuclei.

1. INTRODUCTION

Persistence effects of cloud seeding with silver iodide mean that, while seeding may have immediate effects -- occurring perhaps 0.5 - 1 hr after the seeding -- on the microphysical structure of clouds and the development of precipitation, there may also be other effects extending into the future some hours, days, weeks or months. These persistence effects complicate the evaluation of a cloud seeding operation or experiment. The evaluation normally assumes cloud seeding effects essentially are turned on and off, except for a short 0.5 -1 hr transport lag time, by executing the seeding or terminating it. The complication may be such that the net effect of cloud seeding is apparently reduced and the perceived benefit is diminished.

The U.S. National Academy of Sciences (1973) reviewed the work of several investigators of persistence effects. Although it was fairly well accepted that persistence, if present, could have important effects on the evaluation of cloud seeding effects the evidence for persistence itself as of the NAS report date was ambiguous. Since that date, there has been further research. Both the early research and the later research are examined here.

2. EARLY RESEARCH

Cloud seeding is usually characterized by the dispersal into the atmosphere near a cloud or into a cloud itself of a smoke of ice nuclei composed of the chemical silver iodide. These nuclei lead to the development of small ice crystals in clouds which, through a chain of physical events, produce precipitation at the ground. In addition to any silver iodide ice nuclei produced by cloud seeding there are natural ice nuclei occurring in relatively low concentrations throughout the atmosphere. Low measured ice nucleus concentrations suggest the nuclei are naturally induced, whereas high concentrations may indicate an artificial source such as cloud seeding. If the high concentrations occur for some time (hours, days, weeks, or months) after seeding then these elevated concentrations may reflect a persistence of the cloud seeding nuclei.

Early reports of such persistence came from Boucher (1956) and Grant (1963) who both observed elevated "freezing" ice nucleus counts for days, weeks, or months after seeding was discontinued. This evidence would be more strongly supported if good climatological information on ice nucleus concentrations existed which could establish the natural background levels, and variations from those levels, against which measured artificial cloud seeding ice nucleus concentrations can be compared.

Emerging from this work was a recommendation that an ice nucleus concentration measuring network should be incorporated into any cloud seeding experiment using silver iodide. The network should cover the target area since that is where silver iodide nuclei are to be present in greatest concentrations and where seeding effects are to be most pronounced. The network should also extend downwind of the target area since this may demonstrate where persistence is occurring and why downwind effects (treated in detail in a companion review paper (Long, 2001)) are observed. If the ice nuclei may be entrained in local circulations around and about the target area, the network should also extend laterally and upwind of the target area and control areas. This may demonstrate seeding effects in these outlying areas occurring despite confinement of any seeding to favorable wind regimes.The network should operate throughout a cloud seeding experiment, during off-seasons, and for perhaps one year after the experiment has concluded. The network should operate throughout any pre-determined quiescent, not-seeded periods inserted within the experiment to check for short-term persistent effects of the seeding.

3. BOWEN RESEARCH

Bowen (1966) showed that in a number of cloud seeding experiments the increase in precipitation calculated to be due to the seeding decreased with time. According to Bowen (1966) these experiments (Smith, 1974) included those in the Snowy Mtns, the New England region of New South Wales, the Warragamba catchment, and the South Australia areas of Australia. Effects were also observed in Israel and Arizona. Either the seeding effect actually decreased with time or else some factor was masking the seeding effect which in fact remained approximately constant with time. Bowen's (1966) mathematical analysis suggested a persistence model such that the seeding effect extended into successive subsequent periods of time

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when the clouds were not to be seeded as required by the statistical controls applied to the experiment.

Bowen's analysis implies that if some fraction *a* of a percentage seeding effect *s* (increase in precipitation) in a given seeded period extends into the subsequent no-seed period, then the net effect over the lifetime of a cloud seeding experiment is for there to be a seeding effect in the final no-seeded period that is *a* times as large as the seeding effect in the final seeded period. As a result, the perceived seeding effect overall is degraded from about *s* to about $s-a \times s$, say from 30 percent to 9 percent if *a* is 0.7 . This degradation means there is, inadvertently and misleadingly, an apparent decrease in the result of the experiment with time.

From the cumulative properties of the analysis this apparent decrease is greater for shorter, more frequent seeded and no-seeded periods of time and for longer experiment lifetimes. There is a build-up of the degrading effect with time on all seeded and not-seeded precipitation , and it becomes difficult to distinguish the actual seeding effect. The effect of persistence, devolving from the non-zero factor *a*, will decay with time if seeding is terminated and restarted after some extended gap in time. In other words it is possible to avoid the effects of persistence by careful design of an experiment.

Persistence may be less if there is photodeactivation of the silver iodide with time which would have occurred prior to the early 1970's when sodium iodide was combined with silver iodide in the seeding solution from which the smoke was made. After the early 1970's (Dennis, 1980) the solution contained ammonium iodide instead. There was then less photodeactivation and presumably more persistence.

It should be noted that the Bowen persistence model does not imply a decrease in the effectiveness of post-1970's seeding with time in an experiment (the seeding effectiveness remains as good as initially provided photodeactivation is negligible), but rather the model implies a progressive decrease in the sensitivity of the experiment to the seeding effect with time. The sensitivity is an issue because nominally not-seeded data are contaminated by seeding effects overlapping from seeded periods which cause a reduced seed/no-seed difference or ratio of precipitation amounts in the target area. An example of this reduced sensitivity appears in Bowen's analysis of the double ratio. This ratio is commonly used to measure cloud seeding effects in an experiment. It reflects the relative magnitudes of the seeded and not-seeded precipitation amounts in a target area. In Bowen's specific example the double ratio is shown to decrease from 1.2 (20 percent increase in precipitation) to a perceived 1.1 with accumulated seed and no-seed data sets even though the actual seeding effect of 20 percent remains constant.

It should be noted that use of a single area or cross-over cloud seeding experimental design instead of the target-control-design considered by Bowen (1966) will tend to exacerbate the effects of persistence. In these two cases there is either no not-seeded control area or one of the two control areas is always seeded. Both circumstances work against retaining part of the experiment in continual no-seed state and thus permit persistence effects to invade the experiment.

Bowen (1966) recommended measures be taken to negate the effects of persistence. First, good historical precipitation records should be assembled prior to the experiment to form a base against which to judge the experimental precipitation amounts before persistence effects occur. Second, the randomization should not be on the precipitation storm or day, but rather a longer period such as the week, to counter the otherwise geometric increase of persistence effects. Third, there should be a control area which should never be seeded in order that its precipitation not be influenced by persistence. Fourth, the experiment should be alternately opened and closed for long time periods such as a month or a year so that estimates can be made of the build-up and decay of persistence.

Importantly, Bowen (1968) advanced one possible explanation for the persistence of cloud seeding effects. He believed that persistence is not due to a prolonged high concentration of silver iodide ice nuclei. He believed persistence is related to the presence of elevated rain amounts in seeded areas. Bowen notes, first, that precipitation augmented by seeding leads to greater re-evaporation into the atmosphere and a moister environment for cloud development. Second, it appears (Twomey, 1960) that cloud condensation nuclei (CCN) are fewer over moist ground. Accordingly,there is a conversion of clouds from continental to maritime character with a corresponding increase in propensity to rain naturally. This conclusion is supported by the findings of Warner (1968) indicating that increased CCN produced by sugar cane fires leads to less convective showery rain and conversely reduced CCN concentrations lead to more rain. The combined effect of greater water vapor and fewer CCN then would lead to increased precipitation on a no-seed day following a seed day.

In response to Bowen (1965, 1966) Gabriel, Avichai, and Steinberg (1967) studied the precipitation data in the crossover Israeli experiment in a search for persistence effects. The analysis considers progressively shorter periods of time starting with season-to-season then turning to within-season persistence and finally treating day-to-day persistence. The statistical analyses demonstrated no persistence effect in any case. The authors believed the analyses could be adapted to other rainfall stimulation experiments to check for persistence. It should be noted that Gabriel, Avichai, and Steinberg (1967) do not comment on Bowen's (1966) Figure 4 which showed a reduced effect of seeding with time in Israel. The persistence shown by Bowen (1966) is not consistent with their findings.

4. EARLY - MIDDLE 1970'S RESEARCH

In contrast to the persistence studies based on precipitation variables of Bowen (1965, 1966, and 1968) and Gabriel , Avichai, and Steinberg (1967) was the work of Reinking (1972). It was similar to the studies of Boucher (1956) and Grant (1963) and is now summarized herein. The horizontal and vertical air motions present when silver iodide ice nuclei are released are such that a fraction of the released nuclei do not immediately reach the cloud and are not used. These residual nuclei may be transported out of the seeded area although some of them can be expected to remain. A fraction of the residual nuclei may add on to the existing population of natural nuclei and , if eventually ingested into clouds, may affect the precipitation in a way that persists beyond the initial precipitation pulse augmented by the initial seeding. This additional precipitation may occur in a nominally not-seeded period of time and reduce the seeded/not-seeded contrast in precipitation and thus any perceived seeding effect. The sensitivity of the experiment is thereby reduced. Whereas a fraction (#1) of the residual nuclei would act in approximately the above way it should be recognized that there is another fraction (#2) of the residual unused silver iodide ice nuclei which deposits from the atmosphere onto ground surfaces, vegetation, and possibly in snowpacks. These long-term nuclei (#2) may be released later into the atmosphere with effects on precipitation which can be erratic and diluted. Reinking's work did not deal with them but rather with the fraction (#1) of undeposited residual ice nuclei which would be expected to have an effect within cloud seeding seasons.

The data examined in Reinking's study were collected with the Bigg-Warner rapid expansion ice nucleus counter at two sites in the Colorado Rockies namely the High Altitude Observatory (HAO) and Rabbit Ears Pass (REP) . (Note that the Bigg attributed to the Bigg-Warner counter is the same individual whose extensive later work on persistence is reported below.) The nuclei measurements were for silver iodide seeding with 20 g per hour ground generators. A total of 10 years of HAO and 4 years of REP measurements were obtained. The measurements were assigned to a succession of time periods with S denoting the time period of the seeding itself, D denoting the remainder of that day, and D+i denoting the ith day after D. The data extended out to i=8 or 8 days after seeding, in response to the view that seeding effects may last up to about a week. Examination of the data focussed on the median count since the mean of the counts is influenced by large data outliers , and the mode of the counts is near the detection limit of the counter. The data show that for days D+1 and D+2 the ice nucleus concentrations were significantly above background but that this did not persist beyond two days. Still, many ostensibly not-seeded control storm situations were subjected to this two calendar day persistence of (#1) residual silver iodide cloud seeding nuclei. It should be noted that a residual ice nucleus concentration such as observed was about five times as high as the background concentration and is equivalent to the cloud top being about 2 C colder than normal based on the Fletcher (1962) curves. The effect of a colder cloud on precipitation was not determined.

In Hess' (1974) review of weather modification, Brier(1974) in Chapter 5 on the Design and Evaluation of Weather Modification Experiments and Simpson and Dennis (1974) in Chapter 6 on Cumulus Clouds and Their Modification concerned themselves with the subject of persistence of cloud seeding effects. The following material summarizes their findings.

Brier (1974) notes Grant's (1963) finding that freezing nuclei may 1) remain high for many days after seeding, 2) alter the no-seed character of a target area, and 3) reduce the adequacy of the controls to establish a seed/no-seed contrast for the experiment. Brier (1974) also noted that silver iodide nuclei may be trapped on vegetation in a target area and be blown into the air with nucleating effect at a later time. Finally, Brier (1974) noted that Smith (1967) made several suggestions related to detecting and investigating the persistence effect in seeding experiments of crossover design.

Simpson and Dennis (1974) included a list of tentative causes for extended temporal effects of seeding. These causes were said to be complex, widespread, and subtle. They included

a. physical transport of the seeding agent
b. physical transport of ice crystals produced by a seeding agent
c. changes in radiation and thermal balance, as for example, from cloud shadows or wetting of the ground
d. evaporation of water produced by seeding
e. changes in the air-earth boundary such as vegetation changes over land
f. advection or propagation of intensified cloud systems which subsequently interact with orography or natural circulation
g. cold thunderstorm downdrafts setting off new convection cells elsewhere.

Rottner, Brown, and Foehner (1975) summarized a study of persistence based on data from the Colorado River Basin Pilot Project (CRBPP) and the Jemez Atmospheric Water Resources Research Project (JAWRRP). Silver iodide cloud seeding material was released from ground generators in both project areas. In the CRBPP the concentration of silver iodide ice nuclei was measured with an NCAR acoustic ice nucleus counter. Concentrations were found to be factors of 100 to 1000 higher than background some hours after seeding had ceased. A similarly high concentration was assumed in the JAWRRP. This persistence of artificial seeding ice nuclei influenced the statistical results of the analysis of seeding effects on precipitation amounts. When the defined seed and no-seed periods were considered there was no seeding effect. When a 6 hr period of time was eliminated from the start of the no-seed period because it may have been contaminated with persistent ice nuclei the statistical test showed more precipitation in the seeded period. When the eliminated 6 hr periods were reassigned to the seeding period, there was an even greater seeding effect. These three sequentially different statistical analyses suggested that a seeding effect was occurring during the first 6 hr of the no-seed day because of contamination of that period with ice nuclei remaining from the previous seeded day. This work is a particularly graphic demonstration of a) how ice nuclei can remain in a seeding project area after seeding has ceased, of b) how seeding effects can be masked if seeding occurs even in parts of no-seed control periods, and of c) how seeding effects become clearer if there is a clear assignment of precipitation data to the seeded-category if warranted.

5. BIGG RESEARCH

Bigg (1985a, 1985b, 1985c, 1988, 1995), Bigg and Turton (1986, 1987, 1988) and Mather, Bigg, and Renton (1990) addressed the question of persistence seeding effects. The papers are largely concerned with rainfall and ice nuclei data from precipitation enhancement projects in Australia. The data are incorporated in several different kinds of analysis aimed at demonstrating a persistence effect if one is present.The material that follows critically examines this potentially important body of work.

a) Precipitation effects

The Tasmanian I experiment (Smith , Adderley, Veitch, and Turton, 1971) was specifically designed to reduce accumulating, persistence effects of cloud seeding by alternating entirely not-seeded (odd-numbered) years between randomly seeded (even numbered) years . Seeding was conducted one-half of the time throughout the latter years on a randomized basis. The primary controls were areas to the north and south of the target , the overall control rainfall C being the average rainfall of the two. The first year of the experiment was 1964 and the last year 1970. (Additionally, more intense seeding was conducted in 1971.) A subsidiary area to the east of the target was used for studies of downwind effects, discussed in Long (2001).

An important feature of the 1964-70 experiment was the inclusion of rainfall on days that were suitable for seeding but were not seeded. These SU days were compared with the main sequence of days (SS) that were suitable for seeding and were seeded. Altogether, there were 211 SU days and 202 SS days.

Bigg (1985a) applied a "superposition" method of analysis to the precipitation data.. To apply this method all seeded days (SS) are counted as day zero (0). Bigg states that all target-area rainfalls on those days are summed to give a total $\Sigma\ T(0)$ and the mean of north and south control rainfalls is $\Sigma\ C(0)$. Similarly, target and control rainfalls are summed for each day n to give $\Sigma\ T(n)$ and $\Sigma\ C(n)$. The ratio

$$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$$

is calculated.

The rainfall sequence subsequent to a particular seeded day was terminated at the next seeded day. This is a particularly important point since it ensures that the precipitation nominally on an n-th day is actually on the n-th day after a seeded day and not the rainfall on some smaller-n day after an intermediate seed day. This termination of the rainfall sequence prevents confusion of the day and mixing up of data from different n-value days. The purpose of emphasizing these considerations is to reflect in advance on the fact that later analyses by Bigg did not so terminate the rainfall sequence at the next seeded day and hence used confused data. In my view, this seriously compromised Bigg's later work.

Note that changes in the ratio

$$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$$

from n to n+1 and so on are an indication of systematic changes in precipitation that follow seeding. It should be noted that this ratio is not an ideal measure of persistent effects of seeding, for three reasons according to Bigg (1985a):
1) seeded days form a meteorologically biased selection, so that changes with time may be reflecting natural changes

in meteorology rather than any effect of seeding,
2) the probability of encountering another seeded day within n days diminishes in summer, so that there is the possibility of seasonal bias in changes in the ratio as n increases,
3) the level of

$(\Sigma\ T(n)/ \Sigma\ C(n))SS$

when undisturbed by cloud seeding can only be determined historically, but climatic shifts may occur that cause historical data to be an unreliable guide. The biases above may be removed by making use of the SU days mentioned above which should have a range of meteorological conditions very similar to the SS group. One then calculates

$(\Sigma\ T(n)/ \Sigma\ C(n))SU$

to go along with

$(\Sigma\ T(n)/ \Sigma\ C(n))SS$

and forms the double ratio

$(\Sigma\ T(n)/ \Sigma\ C(n))SS/(\Sigma\ T(n)/ \Sigma\ C(n))SU$

The double ratio decreases from values greater than unity for $n \leq 5$ as expected but then rises to values of perhaps 1.2 for $n > 19$. This suggests seeding effects may persist much longer than the usually accepted limit of 24 hours. But still, for large n, there are less data and they are no longer scattered throughout the experiment. Thus, the results for $n > 19$ may be questionable.

A subsequent paper by Bigg and Turton (1986) also examined the persistence effects in Tasmania. The physical layout of the target and control areas was as noted above but with a northwest control (NWC) area beyond the north area (N). The superposition method described in Bigg (1985a) and (1985b) was again employed in Bigg and Turton (1986) but the sequence of

$(\Sigma\ T(n)/ \Sigma\ NWC(n))SS$

ratios were not terminated at the next seeded day but instead carried out forward for $n = 24$ days and backward for $n = -12$ days. It was argued that by going beyond the next seeded day one uses more of the data, but it is equally clear that one is confusing the data by calling some datum the n-th datum when in fact it may be for the zeroth or first day past the next seeded day. Thus, any composite effect such as greater precipitation ratio

$(\Sigma\ T(n)/ \Sigma\ NWC(n))SS$

attributed to the n-th day may, in fact, simply exist because it is near, within a few days of, a seed day. Bigg and Turton (1986) also argue that additivity of seeding effects means that one can consider ratios at negative times, although the physical meaning of seeding effects before seeding has occurred is questionable.

Whereas Bigg and Turton (1986) start by considering single ratios

$(\Sigma\ T(n)/ \Sigma\ NWC(n))SS$

they recognize there can be biases in using them and choose to use the double ratio instead. This is consistent with the double ratio choice in Bigg (1985a) and Bigg (1985b). From Bigg and Turton (1986), the double ratio varies with number of days after a seeded day, and is high (1.41) on day zero . This was likely not due to chance. A rerandomization is used to gauge the statistical significance of the double ratios . Bigg and Turton (1986) claim from the double ratio values versus day curve a 41 percent positive seeding effect on day zero and double that for day nine. There is no discussion on how the basic procedure of calculating the ratio beyond the next seeded day affects the ratio. This is a major worry and potential flaw in this procedure.

In a later study of persistence, Bigg and Turton (1988) considered a combination of the data from seven different Australian precipitation enhancement experiments. Three of the experiments were of the target-control design, and the other four were crossover. For these latter experiments it was necessary to create new control data sets. A double ratio of seeded to not-seeded precipitation in target and control areas n days after a seed or no-seed day appeared to imply a prolonged after effect of seeding peaking at perhaps 10-15 days after seeding. The study was repeated just for the winter season and a similar effect was found. As before, the superposition function was not well-defined and represents a confusion of the number of the day for which a precipitation amount is being allocated. Also of concern is how the superposition function for no-seed days takes into account data on the farside of an intervening seed-day. Overall, Bigg and Turton (1988) consider the precipitation for all Australian precipitation enhancement experiments through 1983.

Although Bigg and Turton (1988) lay out the reasons for preferring the double ratio analysis they still resort to the single ratio analysis. Reference in this review is also made to Mather, Bigg, and Renton (1990) and Bigg (1995). The first paper compares the single ratio from Bigg and Turton (1988) with that found in South Africa where a hail suppression project apparently resulted in more rain. The ratios show what appears to be a persistence of seeding effect occurring in both South African and Australian data sets 10-15 days after a seeded day. Bigg (1995) is concerned with single ratio precipitation superposition series for the Melbourne Water target and control areas for both seeded and not-seeded days. The seeded series is found to correlate reasonably well with the single ratio series of the 7 experiments through 1983 considered in Bigg and Turton (1988). Bigg (1995) concluded there was an apparent persistence effect in the Melbourne Water experiment. That this was not coincidence was supported by a very low correlation between the MW not-seeded series and the 7-experiment seeded series. It is not clear why the Melbourne Water or the 7-experiment results of their respective series did not involve the the relatively unbiased double ratio series.Bigg (1985a) and Bigg and Turton (1986) both noted this feature of the double ratio series. Bigg (1985a, 1985c) discussed several double ratio formulations that may be used when a cross-over experiment is being evaluated.

b) Ice nucleus effects

Whereas the Bigg work presented so far has been concerned with precipitation amounts which are the bottom line of a precipitation enhancement experiment, additional understanding of the persistence effect can be gained from consideration of ice nucleus information. Bigg (1985b) presents a time-series of the ice nucleus concentration northwest of the northwest control area. The time-series shows a maximum in the concentration some ten days after seeding, suggesting some persistence of the seeding effect. Yet, these concentrations are measured upwind of the seeding area , and it is therefore difficult to understand how silver iodide reached the sampling site. These results are for up to 2 weeks after seeding. Longer term ice nucleus effects will now be considered.

In both the New England and Warragamba experiments and in an operation in a wheat-growing area of western Victoria a decrease in the ice nucleus concentration by a factor of 2 or 3 was observed after the cessation of cloud seeding activity with the decrease occurring over a period of perhaps 6-12 months. Both decreases are toward a background ice nucleus concentration thereby implying that the higher initial concentration was due to persistence of seeding effects.

Bigg (1985b) derived a cumulative seeding index which appears to have some value in predicting seeding effects from seeding material amounts . It is assumed that the concentration N of ice nuclei from seeding at time t= t(n), namely N(t(n)), is related to the initial seeding concentration N(t(0)) at time t=t(0) and to the amount of seeding material S dispensed at time t(n) by the equation

$$N(t(n)) = N(t(0)) + \sum_{t=t(0)}^{t=t(n)} S(t(n)-t(0))\exp(-\alpha(t(n)-t(0)))$$

S is an accumulating seeding material factor while the exponential is a decay term with a time constant alpha. Bigg related the target to control precipitation ratio in the Tasmania I and New England projects separately to the summation term (the cumulative seeding index) and found a reasonably linear relation in each case. The time constant alpha was 1/75 day for Tasmania and 1/36 day for New England. This finding indicates a connection between ice nucleus concentration and the precipitation seeding effect. What is particularly interesting is that if the nucleus concentration only slowly decays with time after some seeding there will be a corresponding slow decay in seeding effect - hence, a persistence effect.

c) Chemical and biological effects

Bigg and Turton (1987) are concerned with mechanisms whereby silver iodide can interact with the environment and lead to persistent cloud seeding effects. The mechanisms fall into two categories: chemical or biological. Rosinski and Parungo (1966) and Rosinski (1987) have been concerned with the chemical mechanism while Bigg (1985b, 1988) and Bigg and Turton (1986, 1987) have discussed possible biological mechanisms. Both mechanisms are treated here.

Rosinski and Parungo (1966) proposed that persistence could occur if the iodine in silver iodide reacted with terpenes in the plants on which it was deposited after release. A possible example was a seeded pine forest in which ice nuclei were found for some months subsequent to silver iodide release.

Bigg (1985b) was dubious about the above mechanism since the amounts of silver iodide (1 microgram per square meter) deposited annually were so small. In his view the silver iodide would terminate in the soil, be bound there chemically, and not be reemitted from the surface as a secondary ice nucleus. The iodine naturally present in soil would be much more abundant than that from seeding such that the iodine in silver iodide would not be relatively active to any extent. The deactivation of silver iodide in sunlight would work against it acting as a secondary ice nucleus. Bigg's point of view was also published in Bigg (1988) and eventually elicited a response from Rosinski (1987).

Rosinski (1987) argued that the iodine present naturally in the environment is not present in compounds which nucleate ice at warm (but subzero) temperatures and that it is present in any case in quantities lower than produced by plants on which silver iodide is deposited. The iodine from silver iodide takes part in a photochemically activated reaction with terpenes with the solid or liquid reaction product (ice nucleus) reaching the atmosphere by simple evaporation from the plant surface.

Bigg's (1985b) discussion of the biological origin of ice nuclei centers on the ice-nucleating abilities of two plant or soil-dwelling bacteria found in leaf litter known as pseudomonas syringae and erwinia herbicola. (Note: The former bacterium is used to nucleate water in ski snow-making. It is marketed as Snomax by Genencor, Inc.) These two bacteria possess ice-nucleating abilities which vary amongst members of the same bacteria. It has been shown that the emission of ice nuclei occurs mainly from the plant canopy. Bigg speculates that the nuclei are the bacteria themselves. The ice-nucleating ability may originate in the outer-layer of the bacterium in ice-nucleating sites mimicking those on silver iodide deposited on plant material and present in the vicinity of the bacterium. It is further speculated that ice-nucleating bacteria , compared to non-ice-nucleating bacteria, have a propensity to multiply and disperse and propagate. If this is true persistence of seeding effects may be conducive to further persistence.

Bigg and Turton (1986) conducted a

field experiment, involving the application of silver iodide to plant life on the ground, in order to discover what ice nuclei developed and whether they might be suitable for promoting the persistence of seeding effects. Two complete plastic enclosures surrounding growing grass were prepared. Silver iodide solution was added to the grass in one of the enclosures and the ice nucleus concentrations in both enclosures were measured simultaneously and daily over a succeeding 220 day period. About 2-3 times as many ice nuclei were found in the atmosphere in the seeded enclosure. This result is believed to demonstrate that application of silver iodide leads to a persistent enhanced concentration of ice nuclei. The nature of the nuclei was studied by culturing. Approximately five times as many bacterial ice nuclei were measured in the seeded enclosure as in the not-treated one. From these results it is hypothesized that a delayed effect of cloud seeding is an enhanced concentration of airborne ice-nucleating bacteria induced by silver iodide added to vegetation. Bigg (1985b) concludes that a cloud seeding experiment should be accompanied by an extensive ice-nucleus measuring network. Lengthy not-seeded periods in the experiment as in Tasmania I may aid in detection of persistent cloud seeding effects.

Bigg's (1988) second field experiment involved deposition of a silver iodide solution on a field of newly growing wheat, and subsequent measurement of the concentration of ice nuclei at various downwind or other directions from the treated field. One of the filter sites was largely upwind of the treated field and displayed a lower nucleus concentration. Overall, the directions of the high nucleus concentrations were consistent with a nucleus source in the sprayed field and travel of the nucleus with the surface winds. The highest concentrations in the sprayed area occurred within 24 hr of the treatment but peaks in the concentrations were also observed at 10, 20, and 40 days afterward as well. The observation of high concentrations was consistent with terpene-iodine reactions of Rosinski (1987) and with bacterial stimulation by silver iodide and transport, but still there is the possibility that the measured nuclei were being (re)emitted by primary silver iodide particles lodged on the ground.

6. GENETIC ENGINEERING

Levin , Yankofsky, Pardes, and Magal (1987) have explored the question of bacterial ice nucleation. They do not consider it to occur after silver iodide is dispensed into clouds. Rather, they treat ice nucleation as an inherent property of some bacteria. Their discussion begins with a recitation of bacteria which may promote condensation- followed -by - freezing. A selection of the bacteria are genetically-engineered to increase the proportion of bacteria which may promote these processes. The first process is condensation and the bacteria are highly effective in promoting it. Freezing process activity appears rarer involving perhaps 0.1 percent of all bacteria. Efforts are made to increase this percentage to 100 percent such that every particle contains a freezing nucleus.

A cloud model was used to investigate quantitative particle growth by condensation and freezing. Simulated not-seeded clouds as well as clouds seeded with silver iodide or bacteria were considered. More rain was found to fall from the bacteria-seeded cloud than from either of the other clouds. In the bacteria-seeded cloud an ice-process had developed at temperatures as warm as -5C whereas in the silver iodide seeded cloud temperatures colder than -10 C were required.

7. RELATED WORK

Ryan and Sadler (1995) argued that allowance in the past for persistence effects would have implicitly increased seeding effects though there is still a need for development of new statistical tests that explicitly take into account the possibility of persistence. Since persistence appears associated with the use of silver iodide as the particular ice nucleant efforts may be required to identify an alternative material such as bacterial nuclei. Ryan and King (1997) have also commented on the question of persistence.

Warburton (1973) described the Pyramid Pilot Cloud-Seeding Project. Radar data in the Sierra Nevada showed that in some locations radar echoes may persist while in other locations echoes are transient. If echoes persist several days after seeding then greater precipitation may occur over those days. If this persistence also occurs in a reasonable fraction of a project target area then higher amounts of precipitation may be found in the target during some time period after seeding. It should be noted that persistence of echoes may be connected with a combination of wind flow and topographic features in the target area. Hence, the kind of persistence proposed by Bigg may originate in wind flow interacting with topography and producing radar echoes in a part or parts of a target area for a lengthy period of time over which there is a persistent accumulation of precipitation.

Lund (1973) made a study of the persistence of cloudy and cloud-free lines- of -sight at a location in Missouri, U.S.A. It was found that if cloudy or cloud-free conditions of some degree prevail at some starting time then those conditions tend to continue during daylight hours. The implications are that if cloudy conditions are present when seeding is accomplished there is likely to be cloud later and, therefore, precipitation later with a persistence effect occurring. The whole sky camera, if used in numbers in a network, could be the basis of a study of cloud probability of occurrence as a function of spatial location in target and control areas. This would indicate whether cloud amount is greater during or after seeding, where seeding ought to occur, and where seeding effects would likely occur.

Lund and Grantham (1977) considered persistence, runs, and recurrence of precipitation. Although they focussed on time spans of 12 hr or less, the probabilistic methods they employed should be applicable to daily sequences of precipitation measured at a number of stations . The methods should establish the places and seasons where precipitation may persist after a seeded day. It will be important to understand the way in which a maximum of precipitation develops from the data and the kind of data that are conducive to development of the maximum. It would be important to understand what may be unique in a set of precipitation data that implies such a maximum in the precipitation when data elsewhere may not demonstrate it. There should be provision for using both Lund and Grantham's approach and methods more current with existing probabilistic and statistical methodology.

Super, McPartland, and Heimbach (1975) measured the deactivation of activity of silver iodide released from a ground generator . (The generator solution included the silver iodide as well as ammonium iodide, water, and acetone.) The plume from the generator was tracked downwind with an aircraft carrying an ice nucleus counter.Nucleus concentrations were converted to downwind fluxes in the plume, and changes in fluxes with downwind distance indicated the persistence of the nuclei. Persistences were calculated amounting to a factor of two deactivation of nuclei and possibly none at all per hour of evolution of the nuclei . (This deactivation is to be compared with that of a factor of 10-100 when generator solution includes sodium iodide instead of ammonium iodide.) The minimal deactivation of the silver iodide solution in the current tests suggests the silver iodide may be active for some time after generation and thus persist.

Persistence was treated by Vali, Koenig, and Yoksas (1988) in a study of regions of cloud seeding potential in a broad variety of clouds in the Duero Basin of Spain in three winter and three spring seasons. Such regions contained for 10 min or more, a supercooled liquid water content above 0.1 g per cubic meter over distances exceeding 10 km or above 0.3 grams per cubic meter over smaller distances. The view taken was that if such liquid water content was observed then a region of cloud seeding potential was persistently present. Whereas Bigg believes that the presence of secondary ice nuclei is necessary for large amounts of precipitation 10-15 days after a seeding day there may be other necessary conditions for this precipitation to develop. Other necessary conditions are a) the existence of updrafts to lift moist air until it has cooled sufficiently for supercooled liquid water to form, b) a minimum supercooled liquid water content, c) an upper bound on the number concentration of natural ice particles (say less than 10 particles per liter), d) microphysical colloidal stability of the clouds simultaneously with little or no precipitation, e) a liquid water content in excess of ice water content , and f) the above conditions prevailing over an economically significant target area.

Deshler and Reynolds (1990) have described a field experiment in the Sierra Nevada in which airborne generated silver iodide ice nuclei and microphysical effects on hydrometeors persisted 90 min downwind and 100 km away from the original seedline.

8. CONCLUSIONS

Persistence of cloud seeding effects means the microphysical structure of clouds and the development of precipitation may be affected for a significant amount of time (say days) after the seeding has been completed. Persistence may complicate the evaluation of a cloud seeding experiment and reduce the perceived net effect of the seeding. The sensitivity of the experiment to the actual net effect may be reduced. Studies of persistence have been ongoing by various investigators for about 40 years with mixed results as to how long it occurs in any given situation.

Ice nuclei and precipitation have been the primary focus of persistence studies. Elevated concentrations of ice nuclei introduced into the atmosphere by cloud seeding may persist and be responsible for effects on precipitation in turn. Ice nucleus concentration measurements in at least one experiment were about five times background values for two days after seeding (Reinking, 1972).

Possible persistent effects on precipitation data were found in Colorado and New Mexico. These studies demonstrated a) how ice nuclei can remain in a seeding project area after seeding has ceased, b) how seeding effects can be masked if remanent seeding occurs in parts of no-seed control periods, and c) how seeding effects become clearer if there is a clear assignment of precipitation data to the correct seed or no-seed category if warranted.

The Bigg research showed an apparent peak in the precipitation two weeks after a seeded day. A superposition method was used to extract the mean precipitation n days after a seed day. In early analyses the number n was limited by the next seed day but later analyses considered n larger than that of the next seed day. This later choice is viewed in the present paper as confusing the analysis and is not desirable.

Bigg and others have addressed chemical and biological origins of ice nuclei. The general opinion is that silver iodide being deposited on plants leads to chemical reactions or biological developments that result in the release of chemical reaction products or microorganisms into the atmosphere with ice nucleating capability. Rosinski, Levin and coworkers have made contributions to these topics.

A range of probabilistic and statistical methods may be applied to a precipitation data set or cloud cover data set (the clouds controlling the precipitation) to search for maxima in the precipitation and clouds so many days after a seeded or not-seeded day.

It should be noted that since the early 1970's photodeactivation of silver iodide no longer appears to be a factor reducing persistence given the ammonium iodide now being used in place of sodium iodide in the seeding solution. Hence, the silver iodide may now more readily persist.

Although persisting ice nucleus concentrations are viewed as being important for persistent cloud seeding effects it is known that there are other necessary conditions which must prevail if clouds with significant potential precipitation are to exist. These conditions are related to cloud formation dynamics, minimum supercooled liquid water, excess liquid water over ice water, and minimum cloud depth and area.

9. RECOMMENDATIONS

a. Incorporate design and analysis features into a cloud seeding precipitation enhancement project experiment which permit testing for and estimating persistence effects in addition to, and insofar as they influence, the traditional cloud seeding effects.

b. As part of the design develop a comprehensive long-term precipitation climatology for the experimental areas including the target, control, and surrounding areas to support a range of historical tests for experimental results.. Include in the design appropriately long, closed non-experimental periods during the experimental seasons to allow persistence to decay, to reduce persistence accumulation, and to reduce persistence influences on experimental results. Include a control area in the design but never seed it (i.e., do not use single area or cross-over designs).

c. Evaluate the persistence fraction *a* (see Bowen (1966)) and develop measures of the persistence-modified sensitivity of the main experimental tests.

d. Make a clear exposition of all data and analyses used in the persistence, main, and subsidiary experimental studies so other investigators can repeat the analyses or better understand how to make similar analyses of their own data.

e. Evaluate the precipitation superposition method of Bigg (1985a, 1985b, 1985c) and Bigg and Turton (1986, 1988) focusing on i) the double ratio versus the single ratio variable, and ii) the number of days after a seed day for which the method is valid. Develop the probabilistic-statistical method of Lund and Grantham (1977) and others for this work. Also, consider current methods for extracting delayed seeding effects due to persistence drawn from the discipline of time-series analysis.

f. In addition to ice nucleus concentration as an experimental covariate for precipitation incorporate as other experimental covariates cloud updrafts, boundary layer vapor content, supercooled cloud liquid water content, natural ice particle concentration, cloud colloidal stability, satellite cloud top temperature, cloud top area, cloud volume, and cloud form

g. Evaluate ice nucleus measurement technology (including networks) and its suitability for measuring persistence with respect to natural, silver iodide, chemical, and biological ice nuclei . Develop a network of whole sky cameras and associated data processing and analysis hardware and software for assessment of cloud persistence. Apply meteorological radar for measurement of precipitation persistence in target, control, and surrounding areas.

h. Devise further laboratory and field experiments focusing on the surface deposition of silver iodide on plants, the ground, and snowpacks and its nucleation, chemical and microbiological effects. Consider inherent bacterial ice nucleators as well. Investigate current knowledge in aerochemistry and aerobiology. Explore genetic engineering of cloud seeding bacteria and large quantity releases into the atmosphere.

ACKNOWLEDGEMENTS

Mr. Ian Searle and the Hydro-Electric Corporation supported this work.

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"REVIEWED"

Review of Downwind Extra-Area Effects of Precipitation Enhancement

by

Alexis B. Long

P.O. Box 41, 144 Jasper Road
Bentleigh, Victoria, Australia

Abstract. This paper discusses a) findings to date about downwind effects of cloud seeding and b) research methodologies that may be applied to advance our understanding of the subject. An important segment of the present report provides the intellectual foundation of any research effort aimed at understanding and assessing downwind effects of a precipitation enhancement project. The body of scientific knowledge presented here tells us by example what can be done to further understanding of downwind effects.

Downwind effects of cloud seeding demonstrate a strong signal according to the U.S. National Academy of Sciences (1973) There was evidence of effects at long distances well beyond where errors in seeding targeting might be expected and little evidence for decreases in precipitation downwind.

Two mechanisms for downwind effects have been hypothesized. They consist of a) downwind transport of ice nuclei and ice crystals from the seeding source, and b) dynamic invigoration of clouds by release of latent heat of freezing. Research and verification of these mechanisms in any precipitation enhancement project are required. This activity involves the tracking and observation of seeding effects into a downwind area. There will be microphysical observations of a) detrainment of ice nuclei and ice crystals from clouds seeded for the primary target area and their environs, b) transport and dispersion of the ice nuclei and ice crystals downwind, c) total budget of these traveling ice nuclei and crystals including destination sinks and residence times, d) entrainment of these particles into clouds downwind, and e) development of cloud and precipitation in the downwind clouds. The investigation may simultaneously be concerned with dynamic seeding effects including observations of a) the dynamics in and around the clouds being seeded for the primary target area, b) the interaction of these dynamics with other clouds , c) the dynamic development of these other clouds followed by d) the development of cloud and precipitation in the other clouds. It will be important to establish the physical context of both the microphysical and dynamical studies in terms of the cloud physical events occurring up to and including the precipitation being enhanced for the primary target area.

The research will use well-developed scientific tools. They include rawinsondes, instrumented aircraft, radar, precipitation gauges, satellite cloud imagery, microwave radiometry, and precipitation trace chemistry. Numerical models are important for incorporating relevant theory and would include terrain effects, synoptic and mesoscale meteorology, (gravity) wave motions, seeding material transport and dispersion, and cloud and precipitation microphysics.

In order to raise the entire level of knowledge of downwind cloud seeding effects the research of the form outlined here and in the main text should be undertaken.

"REVIEWED"

1. INTRODUCTION

The U.S. National Academy of Sciences (1966a, 1966b, and 1973) reviewed weather modification science when it was about 20-25 years old. By 1973 the subject of extra-area effects of weather modification was of sufficient interest for a separate treatment to be given in the last publication. The treatment handled potential lateral and upwind effects of cloud seeding apart from downwind effects. Still, the emphasis of past and current direct and related research has been on the downwind effects. The findings of downwind research and discussion of potential future studies are the subject of the present work.

For completeness we note here the character of lateral and upwind effects of cloud seeding. Lateral effects may occur when uncertainties in wind direction misguide seeding nucleants toward the side of a target area possibly into a neighboring control area. Upwind seeding material transport is more difficult to explain although strong wind shears may be important. Dynamic seeding effects, possibly in the form of cloud propagation, may also conceivably occur both laterally and upwind. Should lateral or upwind seeding effects occur then they may affect the proper statistical functioning of target-control or crossover arrangements of experimental areas. Countermeasures should be taken by rearrangement of experimental areas, close monitoring of winds at various altitudes, and radar and/or satellite observation of cloud growth and movement.

As of 1973 the range of clouds and geography connected with downwind effects covered much of the United States. There was evidence for effects along the central and north eastern seaboard, in the midwest, in the Rocky Mtns, and along the west coast. Overseas, evidence had been found in Australia, Switzerland, and Israel. Much of this information is examined here. Also appearing here are more recent results.

Downwind precipitation effects have been observed in geographic areas and time frames that are about the same magnitude as for the primary effects intended for the target area. There is little evidence of a decrease in precipitation outside a target area.

The two main physical mechanisms so far proposed for downwind effects are as follows. One mechanism involves the transport of microphysically active seeding ice nuclei or induced ice crystals from the target clouds downwind to another area. The second mechanism involves the dynamic invigoration of seeded clouds and their movement or propagation from the target to downwind.

Potential further study of downwind effects may include the following. A field program may have specific design features aimed at revealing any downwind effects . Boundary layer, cloud, and precipitation modeling may be used to focus the important design elements of a field measurement program. Measurements may include a full range of atmospheric and cloud microphysical variables over a larger area, longer time span, and greater frequency than normally associated with cloud seeding projects.

The present review includes a broader range of projects and a longer list of investigators than previously treated. Covered are projects and findings from Australia, Santa Barbara, Florida Area Cumulus Experiment, Climax, and elsewhere. Important points of the Workshop on Total-Area-Effects of Weather Modification which occurred in 1977 and other reports are examined. This is followed by sections on more recent cloud seeding experimental studies and implications for techniques for downwind studies.

2. AUSTRALIAN EXPERIENCE

Adderley (1968) analyzed precipitation downwind of cloud seeding operations in 1966 and 1967. From historical considerations he found increases in precipitation 150-300 km downwind of the operations, of about 50 percent in Victoria and about 20 percent in Western Australia. The detection of these increases was attributed to an absence of topographic discontinuities between the operations target area and the downwind area with consequent uniform (stratocumulus and cumulus) cloudiness extending downwind throughout . In Adderley's view there was a continuing microphysical effect of the seeded silver iodide (over and above any photolytic deactivation), but additionally the seeded clouds may interact dynamically with their environment to promote cloud development downwind.

Smith, Veitch, Shaw, and Miller (1979) analyzed the first Tasmanian experiment for cloud seeding effects on precipitation. The discussion suggested drift of seeded clouds beyond the target area may have been responsible for downwind effects. These effects are akin to a small error in seeding position rather than a major effect several target area dimensions downwind. Yet, this suggests aircraft positioning is important in order for downwind effects to be avoided . That positioning will depend to a large extent on wind speeds at all levels. If the speeds are strong there is a potentially greater chance for a seeding effect to be downwind of the target area.

King, Manton, Shaw, Smith, and Warner (1979) described a prospective 5 year (1979-1983) cloud seeding experiment for western Victoria aimed in part at discovering any downwind cloud seeding effect on precipitation . Although the experiment was never conducted its design for detecting downwind effects is worth describing . The experiment had a 2000 km2 target area (with 20 pluviographs) and six upwind control areas covering about 8000 km2 (45 pluviographs). Detection of downwind effects was to be with four areas 25-75 km downwind covering a fan shaped area of about 5000 km2 and containing 20 pluviographs with 0.2 mm precipitation resolution and 1 s time resolution. The precipitation in the downwind area was to be examined historically and compared to target and control amounts to ascertain whether there were seeding effects in the downwind area as near as 1 hr downwind from the target area and at most 3-4 hr downwind.

The Australian experience suggests that studies of downwind effects of cloud seeding will be enhanced by uniform topographic and cloud fields in the downwind direction, if attention is paid to the positioning of any seeding aircraft in the embedding wind field, and if appropriate target, control, and downwind areas are considered with suitable precipitation gauges.

3. SANTA BARBARA EXPERIMENTS

Elliott and Brown (1971) described studies of downwind seeding effects in the California Santa Barbara project. Convection bands were seeded as they passed from upwind of a 3500 ft mountaintop seeding site , across the site, and downwind. Precipitation at 168 recording gauges was used to measure the precipitation from each band . Precipitation was 4 times greater from seeded bands than from not-seeded bands. When the cloud top temperature was warmer than average the seeded precipitation was greater. Both of these results occurred 150-200 km downwind of the seeding site.

A cloud and precipitation model was used to explain these results. The model predicted the movement and dispersion of the ice nucleant, its entrainment into the band and its induced production of ice particles, particle growth by diffusion and accretion in the convective updrafts, and particle drift down from the tilted convection columns. The model allowed induced ice crystals in the convection band anvil to blow out ahead of the band, fall downward, and seed clouds in the forward area ahead of the band. The model did not confirm an observed increase in duration of precipitation for seeded cases.

Brown, Elliott, and Thompson (1976) also described some findings of the Santa Barbara project phases I and II. Phase I involved ground-based pyrotechnic generators seeding clouds passing across the seeding site with randomization on precipitation bands. In Phase II seeding was with an airborne system and randomization was by storms encompassing one or more bands. In downwind areas about 150-250 km from the seeding location about 50-100 percent more precipitation was found from seeded bands. These downwind effects were located in the area where effects were predicted by a cloud and precipitation model. It was concluded that the primary cause of extra-area precipitation effects of seeding is due to an invigoration of organized convective activity dynamics with some suggestion that this occurs up to about 250 km downwind of the seeding area and perhaps 30 degrees to the right of the 700 mb mean wind flow.

The Santa Barbara experiments showed that seeded convective bands with cloud top temperatures warmer than -15C may be invigorated and provide 50-100 percent additional precipitation at a distance of 150-250 km downwind of the seeding site.

4. FLORIDA AREA CUMULUS EXPERIMENT

Simpson (1980) was concerned with observational and modeling evidence on the dynamics of cumulus clouds. She found that dynamic seeding acts to increase cloud top height and breadth . (Dynamic seeding of clouds occurs through the release of latent heat of freezing of cloud liquid water.) At the same time a downdraft is developing in the cloud leading to a gust front in the atmospheric boundary layer. This gust front acts to stimulate the production of new cumulus clouds which may merge with the seeded cloud. This work bears on the downwind effects of cloud seeding since it describes at least one mechanism for dynamic communication of one cloud to extra-areas removed from it where other clouds can develop.

Cunning and DeMaria (1981) commented on the Simpson (1980) article. They argue that a seeded cumulus cloud may grow into a cumulonimbus cloud through updrafts in the cumulus leading to a pressure deficit which forces boundary layer in under the cloud with surface convergence. This converging air rises and strengthens and broadens the updrafts and invigorates the clouds with a possible change to cumulonimbus. This process is more effective if there are adjacent cumulus clouds growing together. This process of cloud growth does not require downdrafts communicating from cloud top to base as Simpson suggested.

Simpson and Cooper (1981) replied to Cunning and DeMaria(1981) and partly reiterate their downdraft hypothesis for cloud growth. More emphasis is now placed on gust fronts interacting with strong convection including the formation of tornadoes and influences on regions of convergence and divergence.

Kerr (1982) reviewed the outcome of FACE-2 which, although not confirmatory of FACE-1, demonstrated some positive extra-area effects in rainfall measured by gauges and by satellites. The FACE researchers found that seeding may have produced increased rainfall in the FACE-2 target area and downwind . Decreased rainfall upwind may have been due to subsidence drying of the atmosphere here exceeding any positive effects of seeding.Thus there may have been a varying balance of factors increasing and decreasing the precipitation outside the target area.

Meitin, Woodley, and Flueck (1984) used the satellite rain technique of Griffith, Augustine, and Woodley (1981) to estimate the precipitation in the vicinity of the FACE target area. They found a +20 percent seeding effect downwind of the area, and a -10 percent seeding effect upwind of the target. These effects occurred within 180 km of the center of the target and within 8 hr of the initial cloud seeding time. Although the results were fairly clear in the graphical presentations, statistical support through low p-values was not strong. The paper considered a conceptual model, for the effects, that they occurred by wind transport of seeding-invigorated clouds to outside of the target. The alternative model not considered, however, was that the silver iodide is transported outside of the target area and entrained into convective clouds.

The FACE work considered the dynamic effects of a seeding-invigorated cloud on downdrafts and boundary layer pressure deficits forcing surface convergence and by extension the growth of the cloud and adjacent clouds in downwind areas. There was some evidence of increased precipitation downwind and decreased precipitation upwind with a dynamic conceptual model.

5. CLIMAX

In the Colorado Climax I experiment Grant, Chappell, and Mielke (1971) considered the change in precipitation 80-240 km downwind of the Climax target area. Downwind precipitation on seeded days exceeded that on not-seeded days by a factor of 2 or more at significance levels better than 0.05 . They hypothesized that the increase in precipitation was due to ice nucleant and induced ice crystals being transported out of colder clouds in the Climax area and being ingested in warmer clouds downwind.

Brier, Grant, and Mielke (1973) noted that downwind effects of cloud seeding on precipitation are positive rather than negative and may occur 100-250 km downwind of a primary target area. They attribute these effects to the transport, of silver iodide seeding material and ice crystals induced by seeding, to clouds in a downwind area which then precipitate. Another hypothetical cause of downwind effects is the dynamical invigoration of clouds through latent heat release and movement of these clouds downwind. Finally, they refer to Bowen (1968) who suggested precipitation wetting of the ground could moisten the boundary layer and affect cloud and precipitation downwind. They referred to studies of the Climax project which showed that the precipitation was unusually high downwind of the target area.

Janssen, Meltesen, and Grant (1974) investigated downwind effects of the Climax I and II projects. They noted that their investigation was post hoc and as such was exploratory rather than confirmatory. In order to detect downwind precipitation effects drifting from the Climax target area various time lags ranging from 3 to 18 hours of precipitation data from hourly stations in downwind locales were considered. Significant ratios of seeded to not-seeded precipitation, with low probabilities of being due to chance, were found downwind east and northeast of the Climax area. These ratios were in the range 1.15 to 1.25 during the 3-12 hr time lag period.

The ratios were then stratified by 500 mb cloud top temperature which was taken to be close to Climax cloud top temperature. The ratios were found to be greatest with temperatures warmer than -20C. The natural ice nucleation process in such clouds may have then been less efficient and , correspondingly, artificial seeding may have been more effective. At temperatures colder than -24C there was little evidence of a downwind precipitation ratio maximum. Of particular interest was the finding that the ratio of seeded to not-seeded precipitation was greatest when the 700 mb temperature (near cloud top downwind) was in the -5C to -9C range. This was especially true when the subcloud relative humidity exceeded ice saturation at 70 percent. The increase in downwind precipitation on seed-days was thus greatest when the downwind clouds were suitable for artificial ice nucleation. This suggests that downwind effects of a precipitation enhancement project may be greatest when the clouds downwind are relatively warm (though still supercooled). With colder downwind clouds natural precipitation is produced more efficiently with little increment expected in the amount due to seeding of the target upwind.

Mulvey and Grant (1976) presented a conceptual model of how cloud seeding silver iodide and induced ice crystals could be transported downwind from the Climax experiment and interact with clouds over the Colorado Plains sloping up to the Rockies with beneficial effects. Although not all of the steps in the model are fully demonstrated there is sufficient plausibility to understand how the above interaction may develop. Phase A of the interaction involves lofting of Climax ground generated silver iodide ice nuclei into clouds upwind of the Climax target area. In Phase B the nuclei and induced ice crystals pass through the cloud over the target area and downwind where some sediment out of the cloud. Other particles continue downwind in Phase C through a series of cloudy waves stimulated by the mountainous terrain upwind. In Phase D the nuclei and ice crystals blow downwind over the upslope eastern Plains of Colorado. Then in Phase E the particles are entrained into convective features protruding upward from the extensive layer of orographically induced stratocumulus or stratus over the Plains.

The parts of this conceptual model nearer the Climax target area are better supported by observations. It is unclear, for example, how much transport of ice crystals occurs in Phases C and D downwind although the upward vertical motions in waves may redevelop the crystals from subliming ones in regions of downward motions.

It should be noted that the upslope Plains clouds may have cloud top temperatures of -16C to -11C or 4C to 9C warmer than the Climax cloud tops at -20C. As a result natural ice nuclei may be relatively inactive in the upslope clouds and precipitation processes may be limited. Any infusion of nuclei from the Climax project may beneficially augment the precipitation.

Mulvey, Rhea, Meltesen, and Grant (1977) formulated a non-dimensional indicator, largely based on meteorological rawinsonde data from Denver, Colorado, of the probability that upslope clouds over the Colorado Plains would be reached by ice crystals from the Climax experiment and that seeding effects may be present. Elaboration of the methods used in this paper may be valuable in quantitatively understanding downwind effects of cloud seeding in other regions.

The evidence that the Climax project had downwind effects came from three sources. First, precipitation increases of 15-25 percent and greater were found downwind of the project area in time frames consistent with atmospheric transport of ice nuclei and/or ice crystals from the project. Second, cloud top temperatures in the Climax area and over the Colorado Plains were sufficiently warm as to preclude active natural ice nucleation but not activation of artificial ice nuclei. Third, a combined ice nuclei and ice crystal conceptual transport and particle conditioning model was developed to explain the downwind seeding effect.

6. OTHER RELEVANT INVESTIGATIONS

Brown and Elliott (1968) examined the large scale dynamic effects of cloud seeding. Statistical studies were made of the ratio of seeded storm precipitation to not-seeded storm precipitation over, upwind, and downwind of four separate target areas. The Coeur d'Alene area in Idaho was studied in greatest detail. For cloud tops warmer than -6C the seed:no-seed precipitation ratio was greater. A geographic gap was present between the high ratio for the target and the high ratio next downwind. Hypotheses advanced for the latter ratio were

a. the seeding in the target area vicinity may release sufficient latent heat and affect the convective instability to induce a dynamic change in the downwind precipitation pattern.
b. the seeding in the target area vicinity may promote cirrus formation the ice crystals in which may blow downwind and fall downward and seed clusters of clouds there and promote precipitation formation.
c. seeding material (especially from ground generators) may be carried downwind through the boundary layer to the next cluster of clouds and seed them.

The analyses of the authors suggested there can be increases in precipitation about 150 km downwind of a target area at least in the United States.

MacCracken and O'Laughlin (1996) address a number of issues concerned with downwind effects of winter cloud seeding in California on Idaho precipitation. The view is that the 650 km separation of the two States exceeds that of about 300 km over which downwind effects are known. The complexities of atmospheric motion over this distance preclude definitive knowledge of seeding effects. Also, the 10-20 percent increase of precipitation in California could not be responsible for the 50-100 percent interannual variation of Idaho precipitation. Finally, the area seeded in California is much smaller than Idaho. The conclusion is that downwind cloud seeding effects from California do not impact Idaho.

Warburton (1971) described observations of silver in snow from Sierra Nevada cloud seeding projects and compared them against background values. He observed a smaller concentration of silver with airborne seeding than with ground generators. This may have been a function of seeding rates rather than different dispersion of silver iodide. He observed more silver in snow when seeding was 80 km from the snow sampling area but less silver when a distance of 250 km was involved. His major conclusion was that cloud seeding projects in mutual close proximity (less than 150 km apart) may affect each other through cross-contamination with silver iodide cloud seeding material. There would be a corresponding complication in analysis of precipitation for seeding effects.

Schickedanz (1977) describes the extra-area effects of weather modification due to urban-industrial complexes and widespread irrigation. The urban-industrial complexes studied in the United States have effects on summer rainfall, thunder, and hail-days. The irrigated areas have effects on summer rainfall. The area of the effect extended 1-2 times the cross-wind width of the irrigated region and 1-2 times downwind from it up to distances 200-400 km downwind. Hypothetical mechanisms considered for extra-area effects around irrigated areas, and related to artificial precipitation enhancement, included a land-sea breeze circulation set up downstream of the irrigated area, wetting of the ground by rainfall, and gravity wave generation by strong convection. Hypothetical urban-industrial downwind effect mechanisms are lifting of potentially unstable air by cold, dense air outflow from other clouds, enlargement of clouds by mergers, transport of silver iodide aerosols downwind, and ice crystal seeding of downwind clouds by cirrus blown overhead from upwind. Some of these mechanisms may operate in a mountainous area with reservoirs if one assumes that the mountains and their orographic lift are analogous to an urban-industrial complex and the reservoirs act as an irrigated area.

Although the Warburton (1971) work is a fair indication of how downwind effects may overlap, the other works are distinguished by an abundance of hypothetical mechanisms. It is the establishment of supported mechanisms which is one of the challenges facing the science today.

7. HIGHLIGHTS OF SELECTED OTHER REVIEWS

Grant, Brier, and Rhea (1977) briefly review evidence to 1977 on extra-area effects of cloud seeding. Increases in precipitation 150 km beyond target areas have been observed, and in some cases the increases have been observed at a distance as great as 300 km. These results were found in commercial precipitation enhancement operations in the eastern United States. These results have been supported by elevated concentrations of ice nuclei at distances of 50 km. It should be noted that the evidence for extra-area effects is primarily statistical. A program of physical research is needed to elucidate the sequence of physical steps necessary for extra-area effects from initial

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release of silver iodide from a generator, nuclei ingestion in a cloud, and transport of nuclei and induced ice particles to other clouds downwind.

Although transport of microphysical variables such as ice nuclei and ice crystals may lead to downwind effects dynamic effects on clouds related to latent heat release may invigorate clouds and also lead to additional ice production. Simplified calculations indicate that downwind production of precipitation over a succession of orographic ridges may decrease with distance and become small and inconsequential . Other evidence of extra -area effects compels one to design into a precipitation enhancement project features which will clearly reveal the existence and magnitude of extra area effects. Those features are discussed below.

Brier, Grant, and Mielke (1974) review several cloud seeding projects for evidence of extra-area effects. It is important to know the reality, magnitude, and direction of such effects since they may occur in areas where there has been no social impact planning for such effects or even no desire for them. Yet, it is recognized that in most precipitation enhancement projects there is no plan to evaluate extra-area effects either through physical measurements or statistical analyses. The projects reviewed by the authors included, for winter, several commercial projects along the east coast of the US, the Climax I and II projects and Park Range project of Colorado, the Santa Barbara II project in California, and the Israeli project. For summer there were commercial projects along the east coast of the US , Arizona I and II projects, and Grossversuch III in the Swiss Alps. Except for Arizona I and II all the projects showed positive precipitation anomalies extending out as far as 250 km downwind of the seeding area. This is an important result as it lays to rest the conjecture that seeding generally robs regions downwind of seeding of water. Still, the increases at the large distances are not explained. At smaller distances they are not surprising given the uncertainties of targeting. It should be noted that although there is a paucity of observations, upon which there can be detailed physical explanations for extra-area effects, there has been meteorological stratification of some of the results providing some understanding.

Brown, Elliott, and Edelstein (1979) have also reviewed downwind effects of cloud seeding. This review evolved from a scientific workshop sponsored by the U.S. National Science Foundation. They put these effects under the heading Total-Area-Effects i.e., extra-area effects. It was agreed that an understanding of extra-area effects is important to the beneficial application of weather modification science. Yet, most of the existing information is a posteriori, is speculative, and is based on statistical rather than physical analyses.

Still, the better quality statistical analyses (based on randomized cloud seeding programs) suggest that precipitation changes in extra areas tend to be of the same sign and magnitude as effects in a primary target area. Extra-area effects appear to be detectable as much as a few hundred kilometers from the seeding source. Beyond those distances the evidence is too weak to support any conclusions. There is little evidence that precipitation increases in a target area lead to reductions in precipitation further downwind. Two potential physical mechanisms for extra-area effects are a) transport of ice nuclei or ice crystals hundreds of kilometers downwind, and b) dynamic invigoration of convective systems with ensuing increased precipitation or, oppositely, decreased cloudiness caused by dynamic suppression.

According to the authors recommended further work would be as follows.

a. There should be a posteriori statistical reanalysis studies of past programs using more sensitive techniques in order to detect apparent changes in precipitation patterns over large areas. Valuable

information would be provided for hypothesis development and design of future weather modification field investigations incorporating study of extra-area effects.
b. To reduce the costs of weather modification field programs, in which total-area-effects are examined and which necessarily cover an area several hundred kilometers in size care should be taken in the design and proposed evaluation of the programs before inception. For example, thought should go into the temporal frequency and spatial resolution of atmospheric measurements comprising a field program.
c. Cloud physics and cloud dynamics studies should augment the present extra-area effect studies which focus more on the spatial and temporal characteristics of the seeding source and the precipitation which is apparently altered.The nominated studies should consider cloud and precipitation microphysical effects at all steps of the precipitation augmentation process. The studies should also consider the dynamics of all clouds hypothesized to be involved in the process including cloud-cloud interaction both with respect to cloud growth and cloud suppression.
d. Also of assistance to the field program - in terms of logistics, the design of the instrument measurement schedules, and interpretation of the field data - are computer modeling on the mesoscale and cloud scale of cloud and precipitation processes. This modeling can help guide and focus a cost-effective field program.

From the reviews to date it would be fair to state that extra-area effects, in fact, exist and may be found up to a few hundred kilometers downwind of a cloud seeding target area. Most of the evidence has been statistical and focused on the close-in seeding signature in a seeding project and the precipitation data. Future work should consider the cloud physics and dynamics through the region of effect with care to integrate the extra-area study into the main cloud seeding study.

In line with the previous ideas just advanced concerning the nature of extra-area, downwind studies and in the interests of efficiency of scientific investigations, it appears desirable to attach any extra-area, downwind studies to a planned or existing precipitation enhancement project aimed at a primary target area. The infrastructure and resources of that project would be utilized such as background precipitation climate studies and gauge networks (with additional gauges in the downwind area). Other resources of the main project would include meteorological analysis and forecasting. The extra-area, downwind studies would include plume dispersion tracking, physical investigations, cloud seeding models, and other topics.

Other relevant research is now discussed to provide examples of what may be done in the future in the way of extra-area, downwind studies of seeding effects.

8. PLUME DISPERSION TRACKING

Plume volumes are important as they can be used to predict the concentration of ice nuclei transported downwind and provide an understanding of the downwind seeding effect. Isaac, Schemenauer, Crozier, Chisholm, MacPherson, Bobbitt, and MacHattie (1977) provide an example of such research in cumulus clouds near Yellowknife, Northwest Territories, Canada.

Hill (1979) recommends that any cloud seeding project measure turbulent dispersion in its own clouds. He found greater dispersion in a horizontal direction and less in a vertical direction which was attributable to nonisotropic turbulence.

According to Grandia, Davis, and Renick (1979) a key factor in successful seeding is the repeat time between repeated seeding of the same part of the target in order that some overlap of successive dispersing plumes be achieved. Downwind, where plumes have dispersed and are larger, the repeat time will not be as important except insofar as maintaining a high concentration of seeding material.

Hill (1980) made field measurements of the dispersion of airborne released silver iodide in orographic clouds with limited turbulence . The horizontal dispersion of the plume was proportional to downwind distance from the initial seeding line and was about 10 times the vertical spread of the plume. Had convection been present larger dispersion of the material in both directions would have been expected.

Stith, Griffith, Rose, Flueck, Miller, and Smith (1986) describe the spatial distribution of SF6 tracer in cumulus clouds. A horizontal plume remains fairly narrow for much of its rise through a cloud until it reaches a turbulent region near cloud top. Broadening of the plume occurs here where vigorous mixing and entrainment occur. Seeding in a project desirably occurs where there is sufficient turbulence to broaden the plume.

Holroyd, McPartland, and Super (1988) described studies over the Grand Mesa of western Colorado which showed that silver iodide ground generators situated high on the windward slopes of the mesa or silver iodide airborne generators released ice nucleating material which reached horizontal positions over the mesa . Valley locations for the ground generators were inadequate because of trapping or pooling of the released material beneath an inversion. Actual lifting over, rather than flow around, the mesa will depend on the topographical aspect presented to the winds and any stability at altitude. It is important to document the mesoscale atmospheric conditions with rawinsondes near the study area.

It should be recognized that convective turbulence may carry some bubbles of ground-generated seeding material up over the orography. Plume turbulent expansion may affect whether and when plumes from multiple ground generators will merge and act to seed the clouds thoroughly downwind. Plume merger is also a consideration in back-and-forth crosswind seeding runs with an aircraft so far as run length and the repeat time go. Plume studies predict the volume that would be seeded in front of target clouds and the size of that volume downwind of the target. If seeding material is correctly released to augment precipitation in a target area material will be consumed there and there will be less material having any effect downwind.

Heimbach (1990) described field investigations of the dispersion and concentration of ice nuclei of airborne released " acetone burner" silver iodide plumes and wing-tip "flare" plumes. The burner plume was more distinct and maintained a higher concentration of ice nuclei. Photodeactivation of the burner nuclei (composed in solution partially of NH4I) was not a factor. The acetone burner material was a factor of 25 cheaper than the flare material. This was because the burner produces approximately 100 times more ice nuclei per gram of silver iodide than the flares. This work demonstrates the greater efficiency of acetone burners than wing-mounted flares and, potentially, a greater downwind effect.

Levin, Krichak, and Reisin (1997) model the transport of inert tracer material into clouds of the type encountered in the Israeli cloud seeding experiment. They find that seeding along a stipulated crosswind seeding line upwind of the target area will likely be effective only if the seeding is done directly into updrafts of clouds passing overhead. Seeding would be less efficient and more variable into clouds upwind or downwind of the seedline. This bears on downwind seeding effects.

The dispersion studies indicate a cloud seeding plume expands downwind of its release location. A decreasing concentration of seeding material is thus expected. The repeat time between seeding events determines the overlap downwind of plumes and the extent of seeding coverage. Field studies of plume dispersion can use SF6 tracer material in addition to silver iodide cloud seeding material although the concentration (and potential downwind effect) of the latter depends on the generation method. Dispersion studies in mountainous regions depend on the topography, atmospheric motions and stability, and the method for generating the seeding material.

9. PHYSICAL STUDIES

Hobbs and Radke (1973) and Hobbs (1975a, 1975b) discussed transferring snowfall eastward downwind across the north-south trending Cascade Mtns of Washington State. Drier conditions prevail on the east side. It was hypothesized that overseeding on the west side would produce ice particles smaller than natural which would fall further east downwind of the mountains. A clear cut positive seeding effect was the formation of a high concentration of smaller ice crystals downwind within a contrasting natural background of low ice particle concentrations. The ice particles prevalent in the east are unrimed while rimed ice particles are prevalent in the west. West of the Cascade Range liquid water droplets were present beneath a more tenuous volume of diffusion grown ice particles aloft while east of the range the droplets were absent with only ice particles aloft. Cloud seeding would induce additional of the downwind ice particles by ice nucleation of ice crystals and by freezing of the droplets upwind.

Calculations can be made of precipitation particle trajectories terminating on the east side depending on wind speeds and particle fall speeds at a range of altitudes. Positioning of cloud seeding and scientific aircraft in a downwind study are dictated by established ground site observation positions and calculations of "back" trajectories of the particles to infer the cloudy region where the seeding aircraft would have to be positioned for the seeding-induced particles to reach the ground sites.

In addition to ground and airborne microphysical observations supporting the snow redistribution other hypothesis verification may come from silver-in-snow concentrations and high freezing nuclei counts found in the melted snow. A practical kind of evidence is precipitation rate at the ground sites.

The work of Hobbs (1975a and 1975b) clearly demonstrated the kind of physical approach available to studies of cloud seeding effects in downwind directions from a primary target area.

Locatelli, Hobbs, and Biswas (1983) described a field investigation and analysis of an altocumulus layer (T~ -17C) producing dendrites in fallstreaks which naturally seeded and rimed in a lower stratocumulus (T ~ -5C) layer and increased in precipitation rate. Needles were produced when the stratocumulus was seeded with dry ice. The work illustrates the microphysical interaction of cloud layers and the potential effects of seeded clouds on lower, downwind clouds.

Elliott, Shaffer, Court, and Hannaford (1978) analyzed the Colorado River Basin Pilot Project. The project was designed to avoid seeding downwind areas such as Silverton, Ouray, and Telluride in Colorado as their residents did not wish more snowfall. The design eliminated certain wind directions for seeding. Ground generation of silver iodide ice nucleant was used but transport was confused in some cases with the material drifting away in some directions and back at a later time. Clearly the downwind effects depended on the actual wind velocity history. These irregular winds would have resulted in no seeding in some "seed" cases and in contamination (seeding) of some nominally not-seeded days.

Stewart and Marwitz (1982a) described observations of seeded thin, low liquid water stratiform cloud showing the evolution of ice nuclei, liquid water, and small and large ice crystals. The work illustrates how to make airborne cloud microphysics studies near an initial seedline and as it moves downwind.

Huggins and Rodi (1985) demonstrate an analysis of seeded and not-seeded clouds based on aircraft and radar for a primary target area and downwind.

Deshler and Reynolds (1990) observed physical seeding effects 100 km downwind of a seedline created on the west side of the Sierra Nevada. The seedline was repeatedly sampled as it passed to the east and showed enhanced ice nucleus concentrations and some particle growth. When the aircraft finally withdrew from the seedline about 10 per cent of the artificial ice nuclei were still available. This work clearly demonstrates the long distances (100 km) over which seeding material can be transported downwind.

Deshler, Reynolds, and Huggins (1990) describe multi-year field experiments involving CO2 and AgI cloud seeding and an instrumented aircraft, a radar, and ground instrumentation aimed at documenting the steps in the chain of physical events from cloud seeding to extra precipitation on the ground. The methods may be useful for a primary target area and downwind.

The field investigations methodology in the Sierra Cooperative Pilot Project particularly is applicable to primary target area cloud and precipitation studies and is likely useful for downwind studies as well. They have set a good example of the steps to be taken and explain the limitations of such work.

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Super, Boe, Holroyd, and Heimbach (1988) describe the experimental design and instrumentation used in focused precipitation enhancement studies in Colorado and Montana. The experimental design involves seeding upwind of an orographic cloud over a mountain and measuring changes in the cloud and its precipitation using instruments in an aircraft or on the mountain. This paper provides a useful example of how to set up a surface and aircraft based study of seeding effects in a primary target area or downwind.

Super and Heimbach (1988) describe aircraft and other observations of seeded supercooled winter clouds over a downwind Montana ridge. Seeding conditions and data were present enough times in the reported work to engender confidence that precipitation could be enhanced over the "downwind ridge" study area. The procedures of the work would be worth noting as a good example of physical studies that may be made of cloud seeding in mountainous regions and downwind.

Super and Boe (1988) described cloud seeding experiments over the Grand Mesa in Colorado which demonstrated that ground-based and airborne acetone silver iodide generators can yield a precipitation rate above natural values. The cloud seeding method and the cloud microphysics analysis verifying this kind of work are straightforward in principle but are only now feasible with the equipment and instrumentation that have become available.

Super (1990) reviews the current status of winter orographic cloud seeding in the Intermountain West of the U.S. The review includes the structure of orographic clouds, the physical chain of events when cloud seeding leads to additional snowfall, seeding material generation and activity, the spatial distribution of cloud supercooled liquid water , the transport of the silver iodide into the supercooled liquid water zone, and the relative position of successive airborne silver iodide seedlines that may merge with the aid of atmospheric turbulence. This review demonstrates the feasibility of documenting the steps in the physical chain of events leading to seeded precipitation downwind as well as near the target area.

Holroyd, Heimbach, and Super (1995) describe microphysical ice particle concentrations from a silver iodide plume release into clouds over the

Wasatch Plateau of Utah. The plume was readily transported up and over the windward slope but was so narrow as to suggest close 5 km cross-wind spacings of generators would be required for effective seeding operations assuming suitable atmospheric conditions. Seeding appeared to promote snow crystal aggregation and to increase snowfall slightly. Modeling of the event showed moderately good agreement with the data analysis.The study demonstrated how microphysical field analyses and mesoscale modeling studies can be used together to support cloud seeding investigations near and downwind from a mountain target area.

Super (1995) describes studies near the Wasatch Plateau of Utah of silver iodide cloud seeding material transport and dispersion and effects on clouds. Although comprehensive seeding coverage with more closely-spaced generators of greater activity may influence downwind seeding effects the cloud temperature there may prevent or allow seeding material activation and is thus important.

Heimbach and Hall (1996) discuss ice nucleus measurements and modeling of cloud seeding material transport and dispersion over the Wasatch Plateau of Utah. The modeling showed a gravity wave was present upwind of the Plateau and could have transported seeding material upward through an inversion into the normal orographic flow. The descending warming part of the wave could have produced sublimation over the eastern downwind part of the Plateau. From this and other evidence (Heimbach, Hall, and Super, 1997) gravity waves may play an important role in seeding material transport and dispersion near a mountain target area and downwind.

The studies in the Wasatch Plateau and elsewhere of the transport and dispersion of seeding material into clouds indicate the topographic and atmospheric conditions for varying seeding effects in a near primary target area as well as in presumed downwind locations. The investigation methodology involving instrumentation as has been applied in this work shows how to accomplish an advanced downwind study. We now consider the contribution of seeding models.

10. SEEDING MODELS

Elliott (1981) has described a seeding effect targeting model. The airflow over the Sierra Nevada as modified by the barrier and as subject to atmospheric stability is calculated. A curtain of dry ice or silver iodide falling flares is inserted in the upwind side of the model. Ice nucleation by dry ice in the curtain occurs immediately and ice nucleation by silver iodide occurs as the curtain rises up the mountains. Subsequently there is growth and fallout of the precipitation particles . Within the cloud there are updrafts and downdrafts and associated turbulence which disperse the precipitation particles until they occupy the entire cloudy mass. The particles then follow calculated trajectories to the mountain surface. A model such as this could be used to track seeding effects downwind of a target area and estimate the amount of precipitation.

Stewart and Marwitz (1981) have examined how a crosswind curtain of ice nuclei and induced ice crystals evolves in upwind-downwind width and tilt as it blows downwind in a sheared atmospheric layer. The authors consider the downwind evolution and footprint of the seeding curtain.

Stewart and Marwitz (1982b) describe theoretically the broadening of a column of ice particles growing in a sheared environment. High concentrations of small particles are present on the upwind edge of the column, and low concentrations of large particles are present on the downwind edge of the column. Atmospheric measurements confirmed these size predictions. Less obvious was an observed lower particle concentration on the downwind side . Although windshear and fallspeed can broaden a column it is recognized that turbulence and vertical motion effects will be equally important for column broadening. This work helps understand where to find seeding effects with an aircraft and the nature of the ice particles reaching the surface in a downwind environment.

King (1984) calculated the elapsed time to reach the surface of a seeding effect started at -15C in stratiform cloud . He showed that the two most important variables controlling the elapsed time are the liquid water content and the cloud depth. Greater values for both variables will accelerate the precipitation development and particle fall to the surface. The paper provided information on where to position an aircraft for correct targeting of an experimental target area and to avoid downwind seeding.

Rauber, Elliott, Rhea, Huggins, and Reynolds (1988) describe a diagnostic technique for targeting of airborne seeding experiments over the wintertime Sierra Nevada. Adequate targeting requires
a) reproducing the airflow across the mountains across the seeded cloudy region,
b) reproducing the growth and the fallout trajectories of ice particles created by seeding,
c) predicting the location of aircraft seeding to produce effects at the target
d) accounting for dispersion of a seeding curtain due to vertical wind shear and particle fall velocity variations,
e) initializing the technique with field data , and
f) running the technique in real time (~ 3 min).

The diagnostic technique was evaluated through comparison of 1) predicted wind fields with those measured by aircraft, 2) ice particle growth rates within seeded cloud regions with predicted growth rates, and 3) radar echo evolution within seeded clouds with predicted particle trajectories.

With the present diagnostic technique better weather modification targeting should become available that should significantly reduce the chance of seeding in undesired locations, for example, downwind where residents may not wish augmented rainfall.

Heimbach and Hall (1994) compare the three-dimensional "Clark" cloud model with measurements of SF6 and silver iodide ice nuclei over the Wasatch Plateau of Utah. The model and measurements show that a) seeding material can be confined to a depth of several hundred meters over terrain, b) horizontal and vertical positions of the seeding release point are critical for targeting, with the best release on the windward slopes of the barrier to take advantage of terrain-forced motions, and c) pooling of seeding material can occur in valley areas. The apparent agreement of the model with measurements suggests using it or a similar model to predict near and long distance downwind transport of seeding material.

Li, Farley, Orville, and Rife (1996) applied a three-dimensional (3D) time dependent (TD) cloud and precipitation model to ascertain silver iodide ground generator locations for seeding supercooled liquid water in Black Hills clouds and increasing precipitation. By comparing the silver iodide and modeled SF6 plumes it was possible to learn where and the extent to which the silver iodide is activated. This fundamental result illustrates the capability of a 3DTD cloud model to predict where a silver iodide seeding aircraft should be located in order to seed effectively an orographic cloud or downwind clouds.

Modeling is useful in predicting where downwind of seeding an effect on precipitation will occur. The modeling must allow for atmospheric motions over terrain, ice nucleation, the factors controlling microphysical particle growth and motion through the atmosphere, and derived trajectories. A variety of models is available.

11. TRACER AND SILVER IN PRECIPITATION

Lacaux, Warburton, Fournet-Fayard, and Waldteufel (1985) describe radar, precipitation amount, and precipitation silver measurements of hailstorms studied as part of Grossversuch IV in Switzerland. The combination of these data allows estimates of how well hailstorms were seeded (seeding quality) and of the residence times of the silver iodide in the hailstorms. The residence times usefully indicate how long silver iodide may have acted.The availability of residence times shows that silver analysis of precipitation combined with data from other instruments, and comprehensive analysis provides useful information on how long silver iodide may have acted in primary or downwind cloud.

Warburton, Young, and Stone (1995) released silver iodide and indium oxide trace chemicals into snowstorms and measured the amounts in snowfall. Less indium was measured since scavenging processes were solely operating while more silver was measured since ice nucleation was also operating with the silver iodide . The combined use of indium oxide and silver iodide demonstrates a method for evaluating ice nucleation effects of silver iodide whether in a primary target area or downwind . Recent advances in this kind of work appear in Stone and Huggins (1996)

Warburton, Stone, and Marler (1995) discuss snowfall chemistry techniques which bear on a) how well a snowfall target area or downwind area may have been treated with silver iodide , and b) the extent to which wind velocities in the seeding vicinity may have been appropriate for seeding material transport. If the silver concentration in snow is above a threshold established for a geographic area (4 ppt in the Sierra Nevada) then the silver was involved in the precipitation process either by scavenging or ice nucleation. Evidence in this paper is that 75 percent of such excess silver is due to ice nucleation processes rather than scavenging. If the silver concentration is at or below the threshold then seeding did not produce that snowfall. The authors show that a large fraction (40 percent) of the snow falling in some target areas was seeded. In other cases the silver fraction was small and nucleation would not have been much involved. Similarly, control area silver in snowfall may have been below the threshold but in other cases it could have been large. This mixture of possible results would have been due to variations in low-level and high-level winds affecting silver iodide transport and dispersion. A conventional statistical analysis of seeding effects on snowfall amount is thus likely to show a smaller seeding effect than actually occurred.

The tracer and silver in precipitation studies lead to conclusions that silver iodide seeding may not be as regular as heretofore believed with atmospheric motions and transport affecting the extent to which seeding occurs whether for a target area or downwind.

12. DEACTIVATION OF SILVER IODIDE

Fukuta (1973) notes that photolytic deactivation of silver iodide smoke due to ultraviolet light in the environment may limit how far downwind seeding effects may occur. Shortly after this paper was written silver iodide seeding solution containing ammonium iodide came into favor and has been found to have little deactivation. Downwind effects with it may be greater (Super, McPartland, and Heimbach, 1975).

Super (1974) used an NCAR acoustic ice nucleus counter to measure concentrations of silver iodide nuclei released into prevailing westerly flow over a north-south mountain ridge from two ground generators. This ridge was upwind of a parallel downwind ridge where the seeding was intended to affect the precipitation.The upwind ridge forced the released silver iodide material orographically into the atmosphere sufficiently far upwind of the downwind ridge for there to be significant turbulent diffusional broadening of the plume. This experiment used a silver iodide plus ammonium iodide solution undergoing little photolytic deactivation to promote temporal continuity of the data and downwind effects.

Super, McPartland, and Heimbach (1975) measured the flux of silver iodide ice nuclei at positions 50-100 km downwind of silver iodide plus ammonium iodide ground generators using an NCAR acoustical ice nucleus counter. The measurements suggested the silver iodide became deactivated at the rate of about a factor of two per hour or less. This indicates there may be significant downwind seeding effects with this nucleant.

13. RELATED WORK SUPPORTING DOWNWIND STUDIES

Huggins (1995) describes the use of a mobile microwave radiometer to measure the liquid water in clouds upwind and over a north-south trending mountain barrier. The liquid water increased from the west up the windward slope as condensation exceeded precipitation and decreased with evaporation and precipitation in the air descending east from the summit downwind. The supercooled liquid water was located mainly on the windward side of the mountain barrier. Ice crystals created by seeding there must follow trajectories through this windward liquid water. The mobile radiometer is excellent for delineating and measuring the amount of cloud supercooled liquid water over various terrain features and can determine whether there are seeding opportunities in a primary target area or downwind.

Huggins (1996) described a combination of radiometer , radar ,aircraft, and surface studies of orographic clouds over the Wasatch Plateau which had been seeded with silver iodide for precipitation enhancement. From the data sets an internally consistent conceptual model was developed of cloud and artificial precipitation formation over and downwind of the plateau.

Orr and Klimowski (1996) described an X-band reflectivity and circular polarization diversity radar study of the transport of chaff released from the top of Mingus Mtn in Arizona. Chaff tracking could reveal whether cloud seeding material could enter stationary gravity waves viewed as containing cloud liquid water. These case studies showed how the chaff plume location and dimensions depended on atmospheric stability and wind speed and on distance downwind.

Reinking and Martner (1996) showed how chaff observations may reveal the location and dimensions of volumes containing cloud seeding material and induced ice particles and their variations temporally and downwind.

14. CONCLUSIONS

The foregoing material has, first, shown evidence of downwind effects of precipitation enhancement by cloud seeding. Second, there has been a presentation of cloud microphysical and other studies for verifying cloud seeding effects. The techniques in these studies may be used in downwind effects studies also.

It is worthwhile quoting from National Academy of Sciences (1973, pp. 128-129) to capture the essence of the challenge still facing the weather modification scientist today. " The long-standing question of whether seeding in one target area could influence precipitation downwind has generated an additional subset of questions. The evidence suggesting some kind of propagation of effect to downwind distances distinctly greater than were assumed likely only a few years ago is now strong enough to pose very pressing questions. The evidence cannot yet be viewed as fully conclusive, but it argues urgent need for searching inquiry into the reality of, and the nature of, these apparent downwind anomalies that have appeared as temporal concomitants of a number of seeding experiments and operations. And the evidence suggestive of atmospheric responses in sectors not under influence of any simple advection action (i.e., the upwind or lateral sectors, relative to seeding sites) calls for equally careful scrutiny. The scientific payoff that could conceivably lie in these puzzling indications could be quite great."

The U.S. National Science Foundation 1977 workshop on the Total-Area-Effect of weather modification summed the situation to that date. It concluded that effects appear to be detectable as far as a few hundred kilometers from the seeding source. Further out the evidence is too weak to be conclusive. There is little evidence that precipitation increases in a target area lead to reductions in precipitation further downwind. Two physical mechanisms for effects may be a) transport of ice nuclei or ice crystals hundreds of kilometers downwind, and b) dynamic invigoration of traveling convective systems with ensuing increased precipitation or, oppositely, decreased cloudiness caused by dynamic suppression.

The American Meteorological Society (1992) in its current policy statement on planned and inadvertent weather modification has noted that "there are indications that precipitation changes, either increases or decreases, can also occur at some distance beyond intended target areas. Improved quantification of the extended (extra-area) effects is needed to satisfy public concerns and assess hydrological impacts." The American Meteorological Society (1998) reiterated this position.

From the above it is clear that study of downwind effects of precipitation enhancement is a task with scope and promise requiring scientific attention employing the full array of field investigative techniques, theory, and modelling.

From the material presented above it is possible to describe the salient features of a study of downwind effects of cloud seeding. It is assumed that the study would be more efficiently and economically conducted as part of a project aimed at precipitation enhancement in a primary target area. As such, the infrastructure and scientific resources of the primary project would be available to support the downwind study. The main features of the downwind study would be the following.

1. Understand the natural climate in and around the proposed precipitation enhancement project. Look for interrelations and correlations between the climates of different subareas of the project area including the target, control, and downwind areas under consideration. Define the terrain, its influence on climate, and the likely precipitation interactions among cloudy areas. Quantify the project terrain and surface water effects on precipitation using as analogs urban/industrial complexes and irrigation areas.

2. Devise a first-order cloud seeding methodology in terms of seeding materials, temporal frequency and spatial pattern of seeding, and choice of airborne seeding or seeding from valley or ridge terrain. Refine the desired seeding methodology with cloud and precipitation models and preliminary field investigations of seeding material transport and dispersion. Consider subsets of methodologies likely to promote or prohibit downwind effects.

3. Develop precipitation gauge, polarimetric radar, and satellite remote sensing methodologies for separately and jointly estimating short-term and long-term precipitation patterns and integral measures in the experimental primary target area, in downwind areas, and in project control areas.

4. As part of physical studies of the clouds, define and understand the populations of ice nuclei, ice particles, and liquid hydrometeors, the processes affecting their characteristics and their temporal and spatial distributions. Use in-situ, airborne, and remote sensing methodologies to define the environmental airflow. Where applicable consider the dynamical and microphysical effects of gravity waves on precipitation development. Employ the NCAR acoustic ice nucleus counter in studies of ice nucleus dispersion, and employ radar-chaff in studies of ice particle growth and transport. From this,

develop a body of knowledge of turbulent dispersion of seeding material plumes and precipitation plumes in and out of clouds. Apply the microwave radiometer to measure supercooled liquid water near the seeding target and downwind areas and serving as an environment for ice particle nucleation and growth. Correlate the supercooled liquid water with the nuclei and radar dispersion studies and use to improve calculations of particle growth in seeding plumes such as curtains. Evaluate the potential of silver-in-precipitation studies including a total silver budget study and combine silver data with winds and with cloud microphysics

5. Develop an up-to-date cloud and precipitation microphysical and dynamical model for real-time field project support in the control, target, and downwind areas. Incorporate dispersion of ice nuclei and hydrometeor plumes. Devise methods for incorporating a variety of field data in the model or for comparing the model with data to advance understanding.

6. Conduct social-economic-political-legal studies related to precipitation enhancement activities that may affect downwind areas particularly.

It should be noted that the downwind studies described above and the work in Sections 8-13 would be of an advanced kind compared to the scientific research methodologies of the 1960's, 1970's, and early 1980's which first indicated downwind effects. Hence, progress in assessing the magnitude of effects and the causes are likely with new knowledge generated with modern methodologies.

ACKNOWLEDGEMENTS
Mr. Ian Searle and the Hydro-Electric Corporation supported this work.

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Results of Monthly and Seasonal Gauge vs. Radar Rainfall Comparisons in the Texas Panhandle

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

Roni Drori and Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

Scott Orr
High Plains Underground Water Conservation District
Lubbock, Texas

George Bomar
Texas Natural Resource Conservation Commission
Austin, Texas

Abstract. Gauge and radar estimates of monthly and seasonal (April-September in 1999 and 2000) convective rainfall were compared for a large network in the Texas Panhandle. In 2000, the network, covering approximately 3.6 x 10^4 km^2 (1.4 x 10^4 mi^2), contained 505 fence-post rain gauges with individual, subterranean, collector reservoirs at a density of one gage per 72 km^2 (29 mi^2). These were read monthly to produce area-averaged rain totals, obtained by dividing the gauge sums by the number of gauges in the network. The gauges were not read in September 2000 because of negligible rainfall. Comparable radar-estimated rainfalls for the same time periods were generated using merged, base-scan, 15-min, NEXRAD radar reflectivity data supplied by the National Weather Service through WSI, Inc. and the Global Hydrology Resource Center.

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. The Z-R relationship used to relate radar reflectivity (Z) to rainfall rate (R) was $Z = 300R^{1.4}$, which is the equation used in standard NEXRAD practice. Because all of the rain gauges could not be read on a single day, the gauges do not provide an absolute basis of reference for comparison with the radar estimates, which were made in time periods that matched the average date of the gauge readings. The gauge and radar monthly rain patterns agreed in most instances, although the agreement in August 2000 was poor. The monthly correlations of gauge and radar rain amounts were 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The period of comparison affected the results. The area-average gauge vs. radar comparisons made on a monthly basis agreed to within 20% on 5 of the 11 months

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compared. Upon comparison of the gauge and radar rainfalls on a two-month basis to diminish the impact of variations in the date of the gauge readings, it was found that all but one of the five comparisons was within 5%. The exception (April/May 1999) differed by 16%. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% and 8%, respectively, which is extraordinary considering the uncertainties involved. Thus, the longer the period of comparison the better the agreement appeared to be. It is concluded that the use of radar in Texas can provide an accurate representation of rain reaching the ground on a monthly and seasonal basis.

1. DEDICATION

This paper is dedicated to the memory of Mr. A. Wayne Wyatt (Figure 1), past Manager of the High Plains Underground Water Conservation District (HPUWCD), who died suddenly on December 5, 2000. Mr. Wyatt assumed his duties as general manager of the High Plains Water District on February 1, 1978 and remained in this position until his death. Besides overseeing the Water District's many programs and activities, including the installation of the gauge network used in this study, he was serving as chairman of the Llano Estacado Regional Water Planning Group at the time of his death. The regional water-planning group is charged with developing a 50-year water plan for a 21-county area in the southern high plains of Texas. Wayne was a prime mover for the investigation of the potential of cloud seeding for enhancing the water resources for the area, and oversaw the operational cloud seeding effort under the sponsorship of the HPUWCD since its inception in 1997. In addition, he also kept a close watch on state and federal legislative issues that could affect ground water use within the region. During his 43-year career in ground water management, many peer groups and professional organizations honored him.

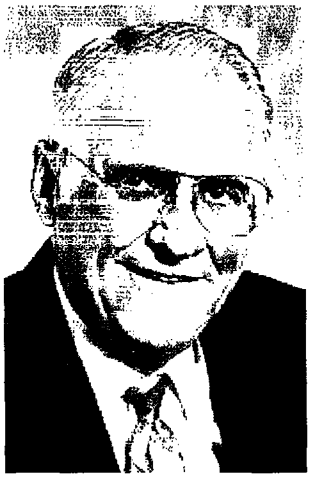


Figure 1. Photograph of A. Wayne Wyatt, manager of the High Plains Underground Water Conservation District No.1 since 1978 until his death. During the latter portion of his tenure, Wayne promoted the investigation of cloud seeding for enhancing the water resources of the Texas Panhandle. He is also responsible for the implementation of the rain gauge network used in this study.

2. INTRODUCTION

The measurement of precipitation is of concern to many interests and disciplines. Although simple conceptually, accurate measurement of precipitation is a difficult undertaking, especially if the precipitation takes the form of convective showers having high rain intensities, strong gradients and small scale. Rain gauges are the accepted standard for point rainfall measurement, although individual gauge readings are subject to errors in high winds and in turbulent flow around nearby obstacles. Rain gauges do not, however, provide accurate measurements of convective rainfall over large areas unless they are distributed in sufficient density to resolve the salient convective features. In some circumstances this might require hundreds, if not thousands, of rain gauges (Woodley et al., 1975).

Radar is an attractive alternative for the estimation of convective rainfall, because it provides the equivalent of a very dense gauge network. Radar estimation of rainfall is, however, a complex undertaking involving determination of the radar parameters, calibration of the system, anomalous propagation of the radar beam, ground clutter and "false rainfall", concerns about beam filling and attenuation, and the development of equations relating radar reflectivity (Z) to rainfall rate (R), where radar reflectivity is proportional to the sixth power of the droplet diameters in the radar beam. A good source for discussion of these matters is **Radar in Meteorology** (Atlas, 1990)

Some scientists have spent virtually their entire careers perfecting radar rainfall estimates, but even then the results are not always to their liking. Variability due to calibration uncertainties and changes of rain regimes must be accounted for by comparisons with rain gauges, especially for rainfall measurements that are based on reflectivity-only radar data.

Woodley et al. (1975) provide an extensive discussion of the trade-offs in the gauge and radar estimation of conective rainfall and disuss the combined use of both to increase the accuracy of the rain measurements. Radar provides a first estimate of the rainfall and rain gauges, distributed in small but dense arrays, are used to adjust the radar-rainfall estimates.

Accurate representation of the rainfall is crucial to the evaluation of cloud seeding programs for the enhancement of convective rainfall. Some have used rain gauges over fixed targets; others have used radar for the estimation of rainfall from floating targets (e.g., Dennis et al., 1975; Rosenfeld and Woodley, 1993; Woodley et al., 1999), while still others have made use of radar and gauges in combination (e.g., Woodley et al., 1982, 1983). The operational cloud seeding programs of Texas (Bomar et al, 1999), which numbered nine as of the summer 2000 season (Figure 2), make extensive use of TITAN-equipped C-band radars to conduct project operations and for subsequent evaluation.. For those using radar there is the nagging uncertainty about the accuracy of their radar-rainfall estimates. This is addressed in this paper.

The initial intention was to use the C-band project radars to generate rain estimates for comparison with rain gauges that provide readings on a daily basis, but this proved to be unfeasible. None of the projects operate their radars round-the-clock, meaning that some rainfalls are not measured, thereby making it impossible to make daily comparisons. Further, the project radars may suffer from other problems, including attenuation of the beam in heavy rain and ground clutter, which is sometimes interspersed with rain events, especially during their later stages. Because this "false rainfall" cannot not be removed objectively without a removal algorithm, it is a potential source of error in estimating the rainfall to be compared with the rain gauges. In addition, non-standard calibration procedure between the different radars can result in systematic differences in the Z-R relations that needed to be applied for unbiased rainfall measurements.

At this point it was obvious that a change in plan had to be made. If rainfall were to be estimated around-the-clock in Texas and spot-checked by comparison with rain gauges, it would have to be done with a different radar system. An obvious possibility was the NEXRAD radar systems that are distributed about the state. These are S-band radars, which do not attenuate appreciably in heavy rain, and they are operated continuously in a volume-scan mode unless they are down for maintenance. In addition, the NEXRAD radars have a clutter-removal algorithm that eliminates most of the false rainfall produced during periods of anomalous propagation.

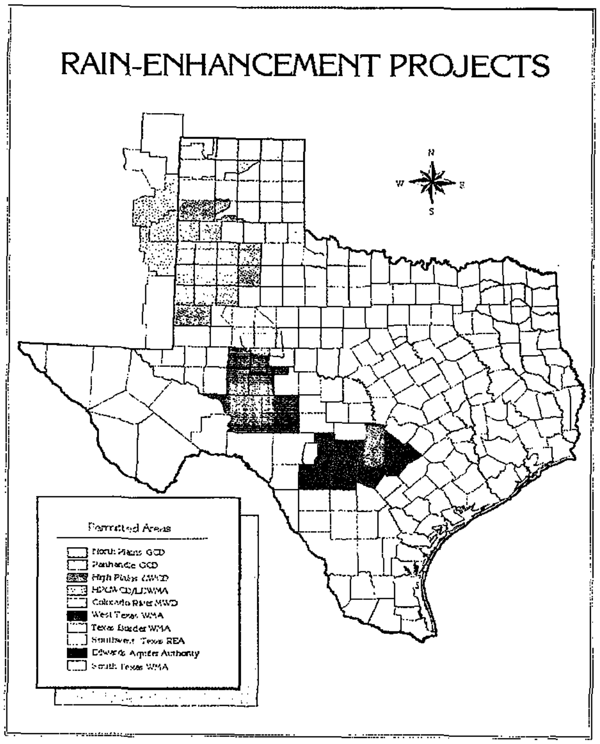


Figure 2. Map showing the nine operational cloud-seeding targets in existence in Texas as of the summer of 2000.

The availability of gauge data for this effort also posed a serious challenge. Upon looking for rain-gauge data from dense arrays big enough to resolve large convective systems on a daily basis, nothing suitable was found. It was obvious immediately, however, that it would be possible to make gauge vs. radar rainfall comparisons on a monthly and seasonal basis, using a unique network installed in the High Plains target (brown area in the Texas Panhandle shown in Figure 2). It would at least be possible, therefore, to assess the accuracy of long-term radar-rainfall estimates. These results could then be used for the benefit of the seeding projects and for others interested in the accuracy of the NEXRAD rainfall estimates.

3. GAUGE NETWORK AND DATA

Over the course of several years the High Plains Underground Water Conservation District (HPUWCD) has been instrumenting its District with fence-post rain gauges having tubing to individual, sealed, subterranean, collector reservoirs as shown in Figure 3. Evaporation is negligible under such circumstances. The network had 458 gauges in 1999 and 505 gauges in 2000 as shown in Figure 4. The gauge density in 2000 was one gauge every 72 km^2 (i.e., 1 per 29 mi^2), which would have been sufficient to resolve most individual convective systems if the gauges had had recording capability.

District personnel read and emptied the gauge reservoirs once per month, but they could not be read on one day. Typically, it took two to three days to read all of the gauges. This injected some uncertainty and noise into the gauge measurments of monthly rainfall, since the rain falling into gauges after they had been read would be ascribed to the following month whereas the same rain falling into gauges that had not yet been read would be ascribed to the current month. Thus, the gauge measurements cannot be considered an absolute basis of reference for comparison with the radar rainfall inferences.

The monthly gauge readings were made in the period April through September 1999

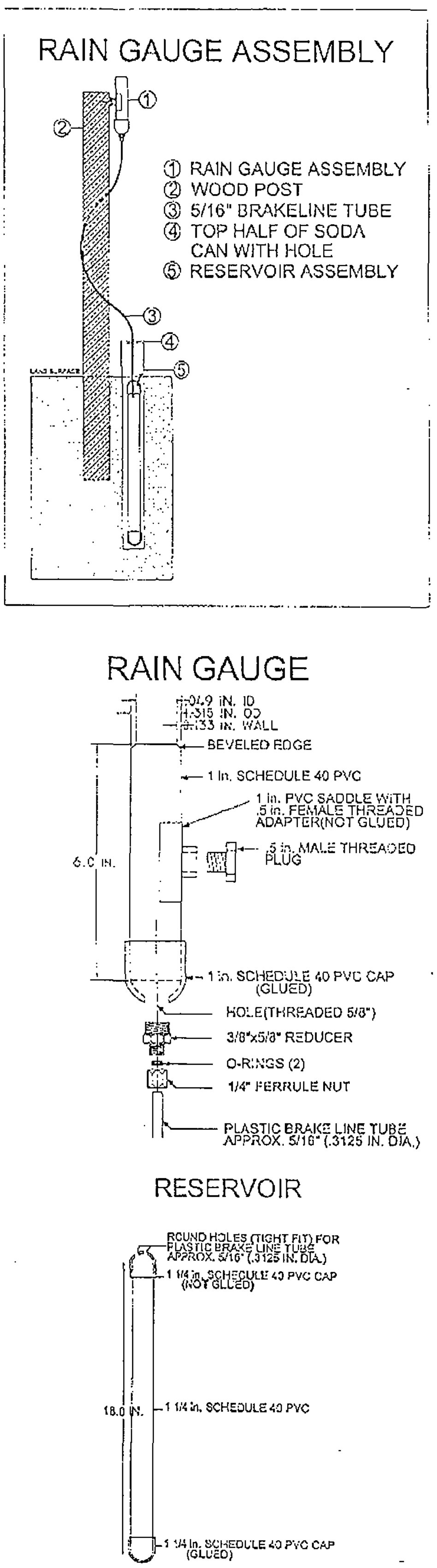


Figure 3. Design of the rain gauge system developed at the HPUWCD. a) the rain gauge assembly, b) the rain gauge, and c) the reservoir.

and April through August 2000. The gauges were not read in September 2000 because of miniscule rainfall --- 1.52 mm (0.06 in) area-average as measured by the radar --- and this month is not included in the gauge vs. radar comparisons. The gauge area means were computed by two methods. In the first method all gauge values were summed and divided by the total number of gauges in the network. The second method involved performing an isohyetal analysis, plannimetering the areas between the rain contours, the calculation of summed rain volumes, and the calculation of the area average by dividing the rain volume by the network area. Although the results for both methods are presented, the first method is preferred because of its objectivity. The gauge products and results are presented in Section 5.0, dealing with the gauge vs. radar comparisons.

4. THE NEXRAD RADAR, DATA AND PRODUCTS

Investigation of the availability of NEXRAD data revealed a source at WSI, Inc., which was made available through NASA's Global Hydrology Resource Center (GHRC). WSI Inc., receives instantaneous reflectivity data from the operational National Weather Service (NWS) radar sites located in the United States. These sites include S-band (10 cm) WSR-88D radars. The national and regional radar images are created from a mosaic of radar data from more than 130 radar sites around the United States, including new NEXRAD Doppler radar sites as they become available. A merged data set for the continental United States (CONUS) is produced by WSI, Inc., every 15 minutes, which is subsequently broadcast to the

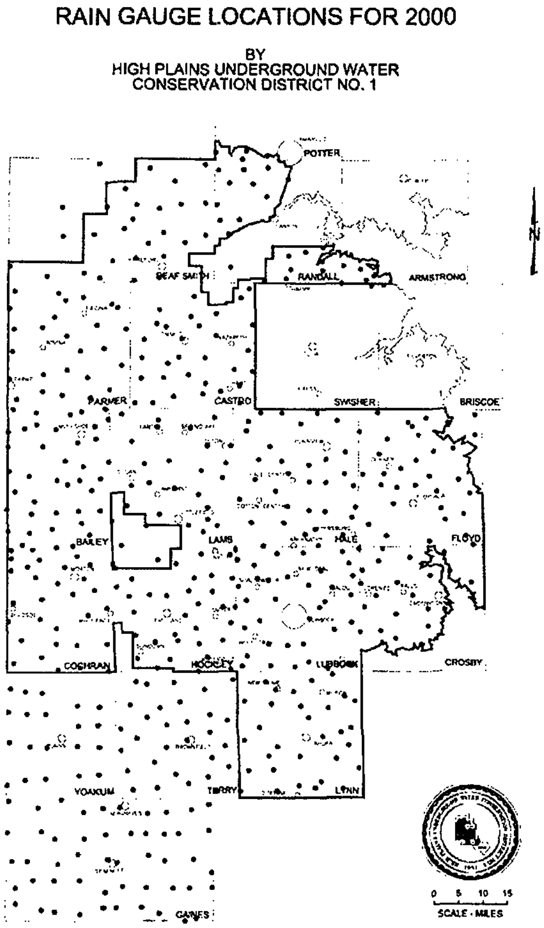


Figure 4. Map of the HPUWCD rain gauge network showing the location of its 505 gauges for the 2000 season

GHRC. The broadcast is ingested at the GHRC and stored therein at 16 reflectivity levels from 0 to 75 dBZ, every round 5 dBZ. This product has the designation of NOWrad (TM), a registered trademark of the WSI Corporation.

These base-scan 5-dBZ thresholds reflectivity data were secured for this study for the 1999 and 2000 April-September convective seasons and daily rainfall (0700 CDT on the day in question to 0659 CDT the next day) was obtained by converting the reflectivity data into rainfall rates using the Z-R relation ($Z = 300R^{1.4}$) proposed by Woodley et al. (1975) and now used as standard NEXRAD practice. Rain rates greater than 120 mm/hr were truncated to that value. The application of the Z-R relation to the threshold reflectivity values every 5 dBZ is not expected to compromise appreciably the accuracy over large space-time domains, given the fact that even a single threshold was shown to provide a remarkable agreement with the exact integration of the full dynamic range of intensities (Doneaud et al., 1984; Atlas et al., 1990; Rosenfeld et al., 1990). The rain totals were obtained for all of Texas and for various subareas, including the gauged High Plains network.

The GHRC also generates its own rainfall product for the United States For reasons unknown at this writing the GHRC rainfalls were found to be too high relative to the High Plains rain gauges by factors of 4 to 5, and with poor spatial matching, prompting us to do the integration of the 15-minute reflectivity maps, which is the basis for the analyses in this study.

5. RESULTS

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. Because of a day or two variation when the gauges were read (discussed earlier), the gauges do not provide an absolute basis of reference for comparison with the radar estimates. The gauge and radar maps for the seasonal rainfalls in 1999 and 2000 are presented in Figures 5-8. Comparable products were produced for each month, but they are not shown here because of space and cost considerations. The gauge maps are isohyetal analyses of the plotted gauge data (not shown), which were provided by the HPUWCD. The units are in inches.

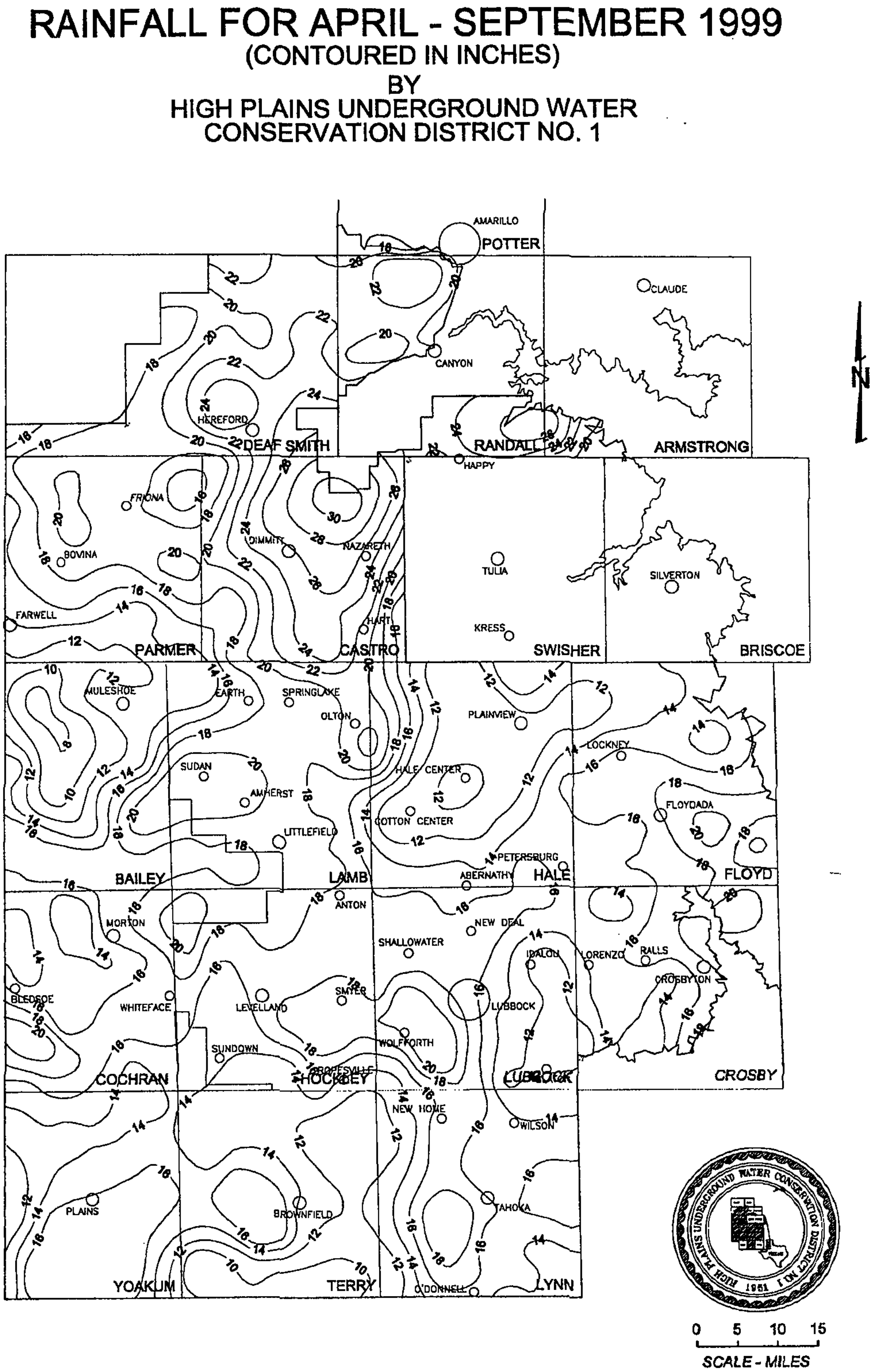


Figure 5. Isohyetal analysis (inches) in the seasonal (April through September) rainfall in 1999. The gauge maps were produced six months to a year prior to this study by personnel at the High Plains Underground Water Conservation District.

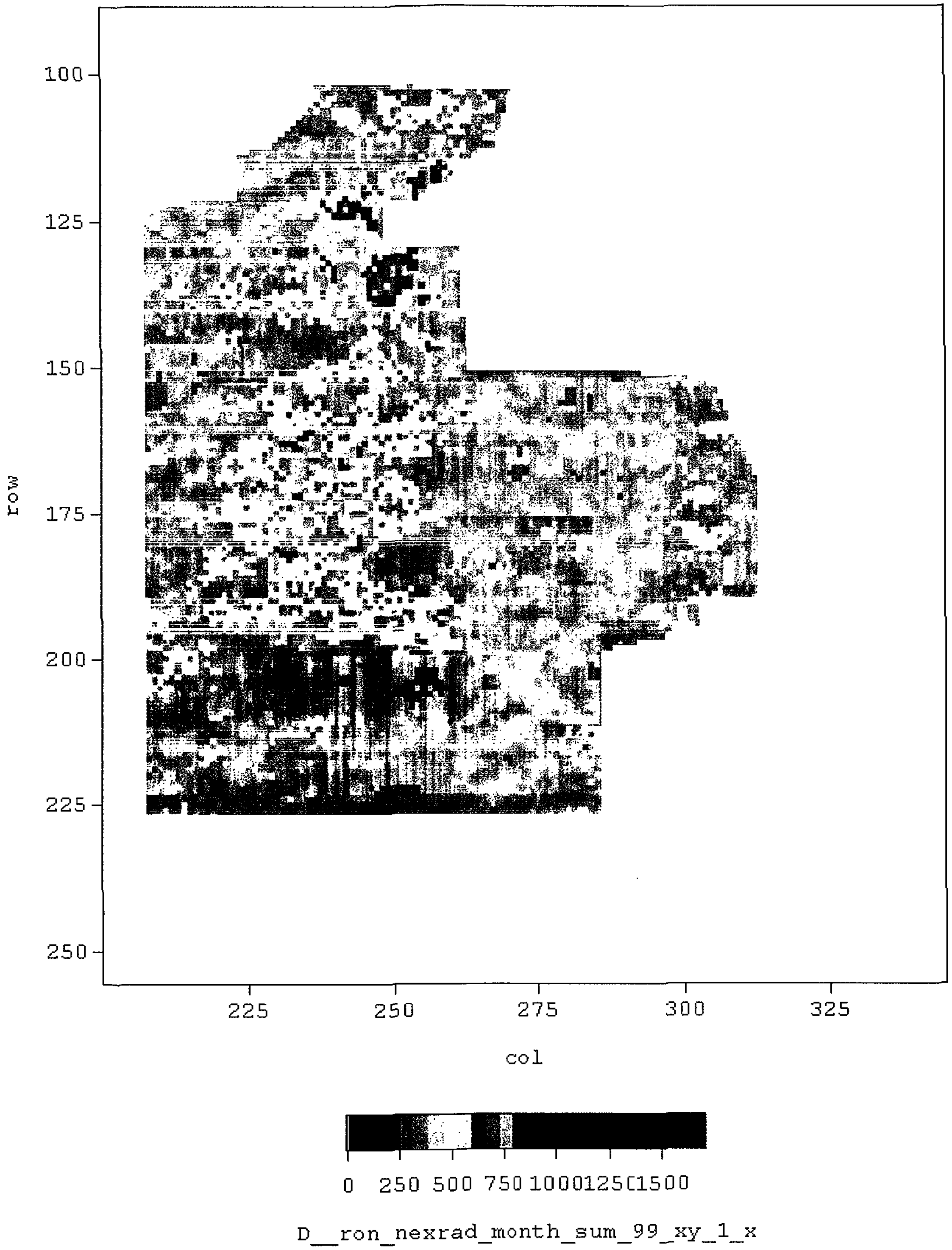
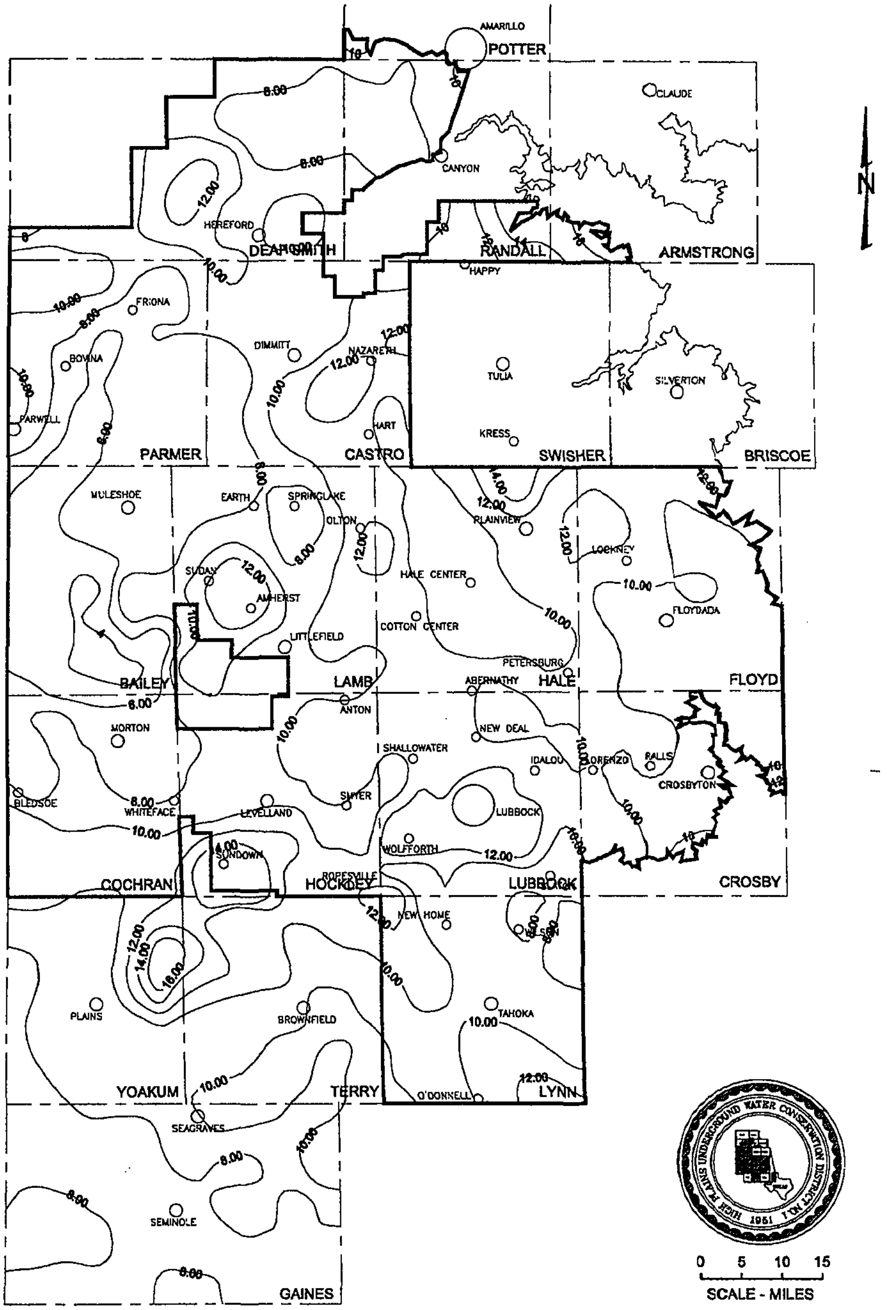


Figure 6. Map of the radar-estimated rainfalls (mm) for the 1999 season (April through September). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.



RAINFALL FOR APRIL - AUGUST 2000
(CONTOURED IN INCHES)
BY
HIGH PLAINS UNDERGROUND WATER
CONSERVATION DISTRICT NO. 1

Figures 7. Isohyetal analysis (inches) in the seasonal (April through August) rainfall in 2000. Because of negligible rainfall, the rain gauges were not read in September 2000.

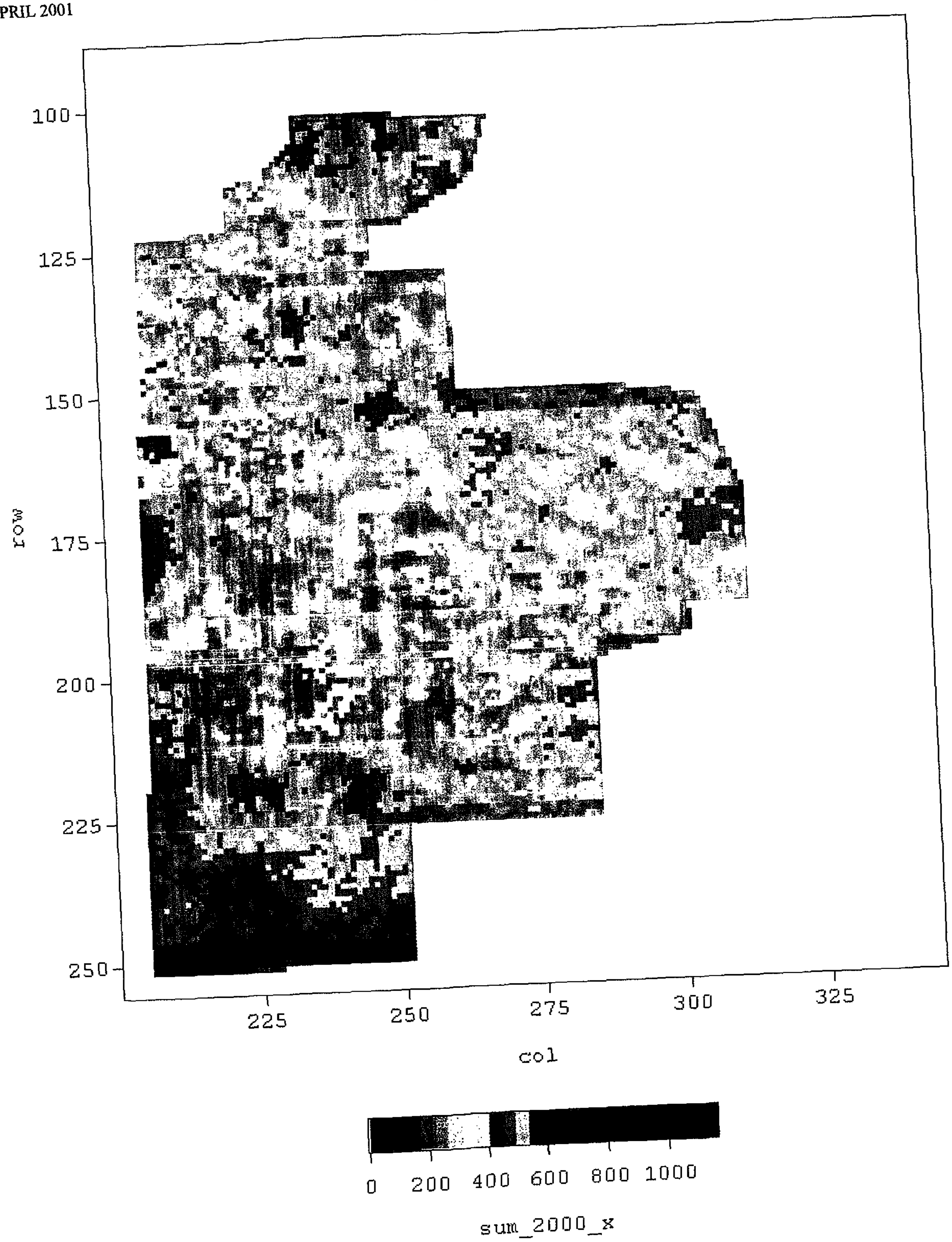


Figure 8. Map of the radar-estimated rainfalls (mm) for the 2000 season (April through August). The rainfall was negligible in September 2000). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.

The radar maps are colorized pixels, which can be related to rain depths in mm using the scale at the bottom of the figure. The first three authors generated these radar products. The independent production of the gauge and radar maps accounts for the differing rainfall units, where 1 inch is 25.4 mm.

The first step in the assessment was comparison of the rain patterning and maxima. This was a subjective process by which the agreement in each month was rated on a scale from 0 to10, where 0 means that there was no agreement and 10 indicates perfect agreement. The results are presented in Table 1. Although the results are good to excellent in most months, there were a few serious mismatches of maxima, especially in June 2000 (not shown) along the central portion of the Texas-New Mexico border. At first it was thought that this might be the result of heavy rain during the period the gauges were read, resulting in the errors discussed earlier. Only after all of the analyses had been completed was it determined that a gauge reading of 6 inches in the area of radar maximum had been thrown out as unreasonable prior to the isohyetal analysis, because it was much higher than the surrounding gauge readings. Upon adding this 6-inch maximum to the pattern, the gauge vs. radar disparity is reduced, but not eliminated entirely.

Quantification of the gauge vs. radar comparisons is presented in Table 2. Before making the comparisons the rainfall that appears in the eastern finger (covering 585 km^2) of the network on the gauge maps was subtracted from the overall gauge totals. This was necessary because the radar did not estimate rainfall for this small area.

The gauge sums divided by the number of network gauges served as the standard for the gauge vs. radar comparisons. The correlation of the monthly gauge and radar rain estimates was 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain with the crossover point at 50mm. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The area-average gauge vs. radar comparisons agreed to within 20% on 5 of the 11 months compared (Table 2). The gauges were not read in September 2000 because of negligible rainfall. Agreement was appreciably better in months with heavy rain. The longer the period of comparison the better the agreement. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% (i.e., G/R = 1.04) and 8% (i.e., G/R = 0.92), respectively.

Note that the G/R values oscillate around 1.0 from one month to the next and that the "all months" G/R values are nearly 1.0. This suggests that a portion of the monthly differences can be explained by the gauges measuring some rains not observed by the radar and vice versa. As discussed earlier, this can occur when it rains heavily during the two to three days that it takes to read all of the rain gauges. If this is true, the oscillating errors should diminish when the comparisons are done for periods of two months or longer.

This hypothesis is tested in Table 3 and the results are dramatic. Using method 1 as the standard, note that four of the five two-month comparisons agree to within 5%, and that in the lone exception the gauges and radar differ by only 16%.

Table 1

Subjective Comparison of the Gauge and Radar Rainfall Patterning
(Scale of 0 to 10 where 0 = no agreement and 10 = perfect agreement)

Month(s)	Pattern	Maxs/Mins	Comments
April 1999	8	6	Good correspondence
May 1999	7	6	Good overall agreement, few maxima do not match
June 1999	8	8	Very good agreement everywhere in a heavy rain month
July 1999	9	9	Excellent overall agreement
August 1999	8	7	Very good overall agreement except for radar maximum not on gauge map
September 1999	9	9	Excellent overall agreement
April-Sept 1999	9	9	Excellent overall agreement
April 2000	8	8	Very good agreement except for a few mismatches
May 2000	9	6	Excellent pattern match but radar maxima greater than gauge maxima
June 2000	6	5	General agreement but poor match of rain maximum, especially along New Mexico border
July 2000	6	5	General pattern match, but some serious mismatches
August 2000	5	4	Poor match of pattern and maxima
April-Sept 2000	8	8	Very good overall agreement except for poor match of maximum along central Texas-New Mexico border

Table 2
Comparison of Gauge and Radar-Estimated Rainfalls (in mm) for the High Plains Rain Gauge Network

Month	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
		1999	Season		
April	97.14	97.06	68.26	1.42	1.42
May	69.58	70.41	75.60	0.92	0.93
June	114.63	117.78	101.92	1.12	1.16
July	44.79	34.02	59.81	0.75	0.57
August	34.44	35.82	46.95	0.73	0.76
September	60.17	56.38	50.42	1.19	1.12
April-Sept	420.75	411.47	402.96	1.04	1.02
		2000	Season		
April	25.85	24.14	14.59	1.77	1.65
May	9.62	7.16	21.92	0.44	0.33
June	103.52	95.30	92.57	1.12	1.03
July	56.13	49.37	64.31	0.87	0.77
August	2.01	1.42	18.57	0.11	0.08
September	NA	NA	1.53	---	---
April-Aug	197.13	177.39	213.49	0.92	0.83
1999 & 2000	617.88	588.86	616.45	1.002	0.96

Table 3
Two-Month Comparisons of Gauge and Radar-Estimated Rainfalls (in mm) for the High Plains Rain Gauge Network in 1999 and 2000

Months	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
April/May 99	166.72	167.47	143.86	1.16	1.16
June/July 99	159.42	151.80	161.73	0.99	0.94
Aug/Sept 99	94.61	92.20	97.37	0.97	0.95
April/May 2000	35.47	31.30	36.51	0.97	0.86
June/July 2000	159.65	144.67	156.88	1.02	0.92

6. CONCLUSIONS

The results of this study suggest that NEXRAD data can be used to provide accurate measurements of monthly and seasonal convective rainfall in Texas. Contrary to our expectations, no changes in the Z-R equation appear warranted. The accuracy of the radar-rainfall inferences is certain to decrease as the period of comparison is decreased to individual days or even shorter time frames. This can be readily documented using the NEXRAD data, provided suitable rain gauges in dense arrays can be found to serve as a basis for reference.

As mentioned before, the project radars are poorly equipped for area rainfall measurements. Their best use would appear to be in the conduct of seeding operations, particularly in the real-time assessment of the properties of the convective cells and in the tracking of the aircraft, and in the post-evaluation of the properties of individual storms. Such analyses are possible now thanks to the TITAN systems that are installed on the radars. These are not readily feasible using the NEXRAD radars in their present configuration.

The radar-based evaluation of seeded storms, regardless of the radar system, is still a problem in the minds of some, because it is presumed that seeding somehow alters the cloud-base (i.e., base-scan) drop-size distribution and, therefore the radar-measured reflectivity and inferred rainfall. This would indeed be a problem compromising the use of radar for the evaluation of seeding experiments, if it were true, but the available evidence suggests that it is not for glaciogenic seeding, such as done in Texas. Cunning (1976) made measurements of raindrops from the bases of AgI-seeded and non-seeded storms in Florida and found that the intra-day and inter-day natural drop-size variability was as large as that measured in rainfall from seeded storms.

It is recommended that these studies be continued in order to evaluate the accuracy of daily radar-rainfall estimates using the NEXRAD radar products. This is possible now, provided a suitable recording rain gauge standard can be found.

7. ACKNOWLEDGMENTS

The research of the first three authors was supported by the Texas Natural Resource Conservation Commission (TNRCC) under Agency Order No. 582-0-34048 and the first author had additional support from the Texas Water Development Board under Contract No. 2000-483-343. We thank the following individuals at the High Plains Underground Water Conservation District: Gerald Crenwelge the database engineer for his technical assistance, Dewayne Hovey for gauge plotting and mapping assistance and Keith Whitworth for drafting the isohyetal analyses. Finally, the High Plains Precipitation Enhancement Program acknowledges the participation and contributions from the following entities: South Plains Underground Water Conservation District, Sandy Land Underground Water Conservation District and the Llano Estacado Underground Water Conservation District.

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"NON-REVIEWED"

CLOUD SEEDING - THE UTAH EXPERIENCE

Norman E. Stauffer, Jr.
Utah Division of Water Resources
Salt Lake City, Utah

Abstract. The first cloud seeding project in Utah began in the early 1950s in the central and southern portion of the state and lasted four years. The project was reactivated in 1973 by the original organizers and has continued to the present. The Utah Cloud Seeding Act was passed in 1973 by the Utah Legislature. This law provids for licensing cloud seeding operators and permitting cloud seeding projects by the Utah Division of Water Resources. The act states that for water right purposes all water derived from cloud seeding will be treated as though it fell naturally. The act also allows for the division to sponsor and/or cost-share in cloud seeding projects. Since 1976, the state through the division and Board of Water Resources has cost-shared with local entities for cloud seeding projects. In the 1970s, cloud seeding projects expanded to cover most of the state. The majority of projects were for wintertime snow pack augmentation, but a summertime hail suppression/rainfall augmentation project operated for six years in Northern Utah. The state participated in the NOAA Cooperative Weather Modification Research Project from 1981 to 1996. Wintertime snow pack augmentation projects continue to operate in Utah.

1. THE EARLY YEARS

Utah is the second driest state in the nation. It is not surprising, therefore, that a group of counties in Central and Southern Utah sponsored a cloud seeding project within a few years after the discovery of modern cloud seeding principles in the late 1940s, as did many other groups in the western and mid-western states.

A project began in April 1951 and operated until May 1955. The project used ground generators that burned coke impregnated with silver iodide and was operated by the Water Resources Development Corporation of Denver, Colorado. The sponsoring entity was the Southern Utah Water Resources Development Corporation.

The University of Utah Meteorology Department (Hales et al., 1955) and the American Institute of Aerological Research (1955) made evaluations of the effects of the cloud seeding. The two evaluations resulted in conflicting results, and the project ended.

The first legislation in Utah concerning weather modification was enacted in 1953. This law required the reporting of weather modification activities in Utah to the Department of Meteorology at the University of Utah.

2. THE BANNER YEARS

The years 1973 through 1981 were historic in shaping Utah's weather modification program. In 1973 some of the original organizers of the 1950s Central and Southern Utah Project reactivated the program. They lobbied the legislature, which resulted in passage of the 1973 Utah Cloud Seeding Act. They operated the Central and Southern Utah Project for wintertime snow pack augmentation in water years 1974 and 1975. They contracted, using their own funds (county taxes), with North American Weather Consultants to operate the project using ground generators that released silver iodide.

Through their lobbying and promotional efforts, state funding became available beginning in water year 1976. With the state funding and local participation, the winter program was expanded to cover more areas of the state. A summertime hail suppression and precipitation augmentation program was started in the northern portion of the state. State funding for the winter and summer programs was about 70 percent, and local funding was the remaining 30 percent.

With greatly increased interest in weather modification and the Cloud Seeding Act of 1973, the Division of Water Resources responded with a public involvement program. A Weather Modification Newsletter, published several times a year, began in 1975 and was distributed until 1980. Five annual one-day cloud seeding seminars were held, and the proceedings were published beginning in 1974. In 1975 the Division of Water Resources created a Technical Advisory Committee made up of university and government scientists, television weathermen, legislators, government agencies involved in water resources, and water users. The committee was realigned in 1977 into two separate committees. One was called the Program Advisory

Committee, comprised of water users and government agencies having stewardship over water resources. The other was the Technical Advisory Committee, composed of meteorologists, statisticians and scientists with expertise relating to program design, evaluation and research. Both committees functioned until 1983 and provided valuable input to the Division of Water Resources. Some cloud seeding research and evaluation began with state funding at Utah State University in the late 1970s. The NOAA/Utah Cooperative Research Program was in the planning stage in the late 1970s, and funding began in 1981.

The state experienced an economic downturn in the early 1980s. State funding for cloud seeding was greatly reduced and the summer project did not survive. The winter programs continued with eventually a much larger portion of the funding from the local sponsors. These nine years--1973 through 1981--were the heydays for cloud seeding in Utah.

3. 1973 CLOUD SEEDING ACT

The following is a summary of the 1973 Utah Cloud Seeding Act:

(1) Authority: The state of Utah through the Division of Water Resources shall be the only entity, private or public, that shall have authority to authorize, sponsor, and/or develop cloud seeding projects within the state of Utah.

(2) Ownership of Water: All water derived as a result of cloud seeding shall be considered as a part of Utah's basic water supply the same as all natural precipitation water supplies have been heretofore, and all statutory provisions that apply to water from natural precipitation shall also apply to water derived from cloud seeding.

(3) *Record-Keeping:* Repealed the 1953 law on record-keeping and required the Division of Water Resources to establish criteria for reporting data and record-keeping.

(4) Rules and Regulations: Any individual or organization that would like to become a cloud seeding contractor in the state of Utah shall register with the Division of Water Resources. As a part of the registration, the applicant shall meet qualifications established by the Division of Water Resources and submit proof of financial responsibility.

(5) Trespass: The mere dissemination of materials and substances into the atmosphere or causing precipitation pursuant to an authorized cloud seeding project shall not give rise to any presumption that such use of the atmosphere or lands constitutes trespass or involves and actionable or enjoyable public or private nuisance.

(6) Interstate Activities: Cloud seeding in Utah to target an area in an adjoining state is prohibited except upon full compliance of the laws of the target area state, as well as the provisions of this act.

(7) Exemptions: Cloud seeding for the suppression of fog at airports and frost prevention measures for the protection of orchards and crops are excluded from the act.

Based on the 1973 Cloud Seeding Act, the Division of Water Resources promulgated rules and regulations relating to cloud seeding in Utah. A license and permit are required for cloud seeding in Utah as well as proof of financial responsibility. Reporting of cloud seeding activities to NOAA as required by federal law is also required by the Division of Water Resources.

4. STATE FUNDING

The 1973 Cloud Seeding Act authorized the Division of Water Resources to sponsor and/or cost-share in cloud seeding projects. The legislature for water year 1976 provided funding for wintertime projects and a summertime project at about 70 percent cost sharing by the state. This level of funding continued through 1981.

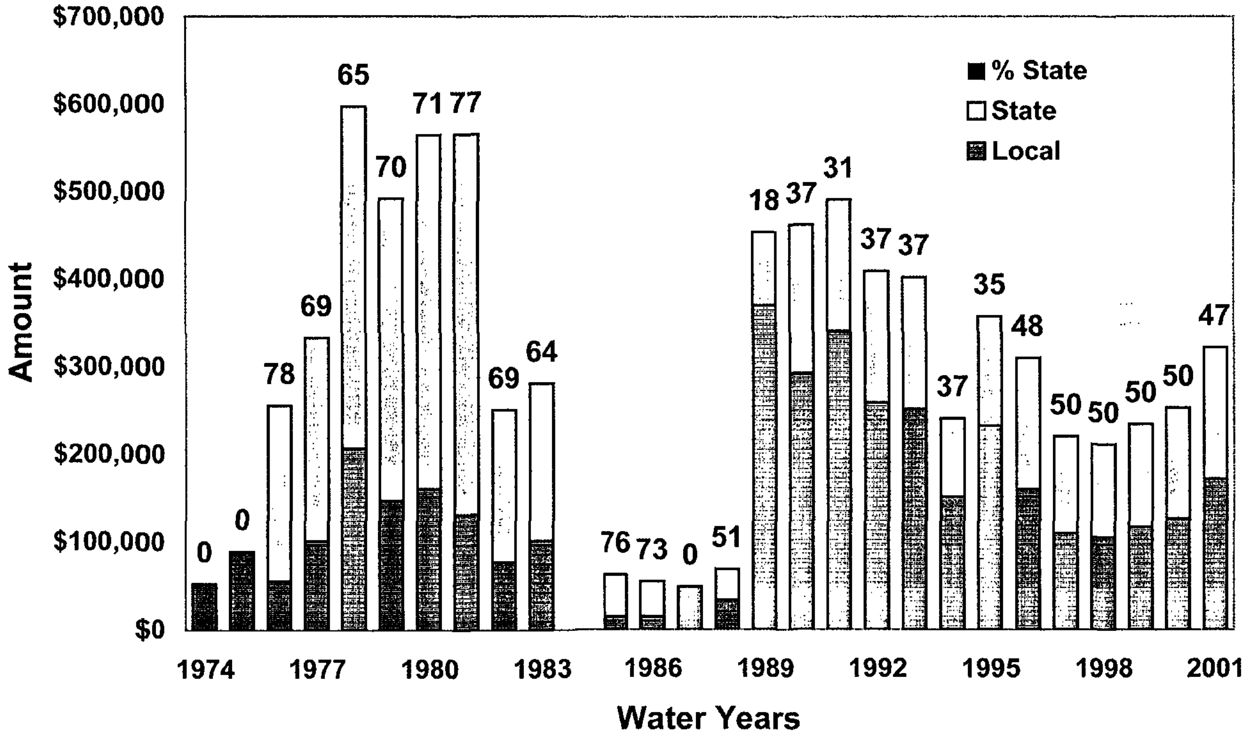
Because of the state's economic downturn in the early 1980s, the legislature only provided funding for the winter projects in 1982 and 1983. Without state funding, the summer project ended in 1981.

An extremely wet period occurred statewide in the spring of 1983 and continued into 1984. No cloud seeding activities occurred in water year 1984. The wet conditions continued over most of the state except in extreme Southern Utah (Washington County). The only cloud seeding operation for 1985 through 1987 was in Washington County. There was no state funding for cloud seeding in 1987 because the state was constructing the West Desert Pumping Project to pump water from the Great Salt Lake to reduce flood damage.

The wet period ended in 1987 and the entire state entered into its most critical 10-year dry period. By

1989 most of the state wintertime cloud seeding projects were again operational due to drought conditions. State funding for cloud seeding increased in 1989 and 1990. Beginning with water year 1991, the legislature authorized the Utah Board of Water Resources to fund (grant) cloud seeding projects up to $150,000 each year from its Revolving Construction Fund. State cost sharing with these funds has ranged from 31 to 50 percent, depending on total project costs and board policy. Figure 1 shows the state and local funding for cloud seeding since passage of the 1973 Cloud Seeding Act.

Figure 1. State and Local Funding for Cloud Seeding

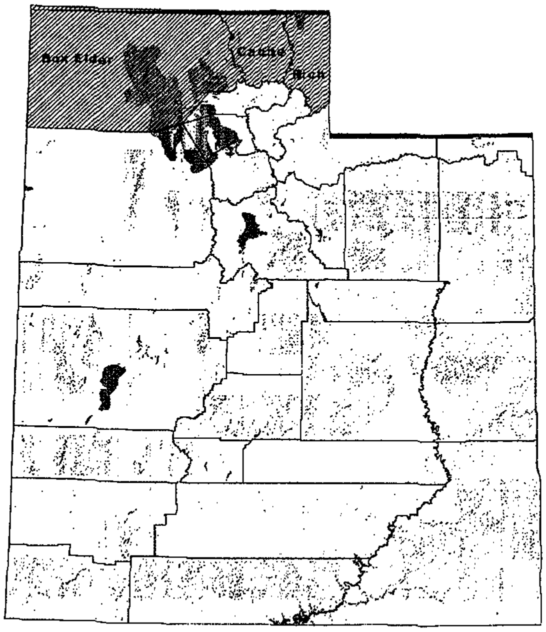


5. SUMMER PROJECT

In 1976 Atmospherics Incorporated of Fresno, California, acting as contractor for Box Elder, Cache and Rich counties in Northern Utah (Figure 2), designed and conducted a rain augmentation/hail suppression project. Equipment included a 5.5 cm weather radar system, two cloud seeding aircraft, and five silver iodide ground generators. Operational headquarters were at the Ogden Airport and the radar system was located on Little Mountain, 15 miles west of Ogden.

The program operated for six consecutive summers (1976-81). Program costs averaged near $130,000 per year. The state cost-shared with the counties, providing about 70 percent of the project cost. Due to the economic downturn in the state, the legislature did not fund the summer project in 1982 and the project ended. Beginning in water year 1989, Box Elder and Cache counties sponsored a wintertime project that continues today.

During the summer of 1977, a precipitation augmentation project was run statewide from mid-July through September. This was an emergency project funded by the state due to extreme drought conditions.



6. WINTER PROJECTS

A map of the winter projects in Utah for snow pack augmentation since passage of the 1973 Cloud Seeding Act is shown on Figure 3. The map also indicates the currently active projects (2001) as well as inactive projects. The contractor for all of the winter projects is North American Weather Consultants, Inc., of Sandy, Utah. The goal of these projects have primarily been to augment spring and summer streamflow to benefit agriculture interests, although some projects have been conducted to augment municipal water supplies.

6.1 Inactive Projects

There are six inactive project areas. The Ogden River Project Area was cloud seeded in water year 1977 and water years 1991 through 1993. The Wasatch Front Project was operated for 10 years in water year 1977 and water years 1988 through 1996. The Uinta Mountains were cloud seeded in water years 1977 and 1978 and again in 1989. The Carbon County and La Sal Mountains projects were operated in water years 1978 through 1983 and 1990, for a total of seven years. The Abajo (Blue) Mountains Project was operated for 12 years in water years 1976 through 1983 and again in water years 1990 through 1993.

6.2 Active Projects (2001)

There are six active project areas in Utah. Five large-scale project areas using ground based silver iodide generators include: (1) the Central/Southern Utah and the (2) Tooele County Project areas, sponsored by the Utah Water Resources Development Corporation; the (3) West Box Elder and (4) East Box Elder/Cache County Project areas, sponsored by the Bear River Water Conservancy District and Cache County; and the (5) West Uintas Project Area, sponsored by the Weber Basin Water Conservancy District and the Provo River Water Users Association. The total estimated cost for these projects is $321,900, of which the state will cost share 46.7 percent ($150,000). Emery Water Conservancy District is operating a small-scale project using liquid propane to seed the Wasatch Plateau above Joes Valley Reservoir. This is a continuation of part of the NOAA/Utah Research Project conducted in the 1990s.

The Central/Southern Utah Project has operated continuously since water year 1974, with the exception of the extreme wet period from 1984-87. The project has 23 seeded seasons. In some of the early years when higher state funding was available, multiple cloud seeding aircraft, weather radar, and rawinsonde operations were used to supplement the ground based silver iodide generator network. The project area currently has 65 cloud seeding generators. Using a target and control regression analysis for December through March precipitation, the Central/Southern Utah Project Area indicates a 14 percent average increase in high elevation target precipitation for this period (Griffith and Solak, 2000a).

Seeding began in the Tooele County Project Area in 1976 and continued through the 1982 water year. Seeding resumed in 1989 through 1992 and again in 1996 to the present. There are 16 seeded seasons. The project area has nine cloud seeding generators. Target and control regression analysis shows a December-March high elevation target precipitation average increase of 19 percent (Griffith and Solak, 2000a).

The East Box Elder/Cache County Project Area has operated 12 years, beginning in 1989. The project area has 22 cloud seeding generators. Target and control regression analysis shows a December-February high elevation target precipitation average increase of 20 percent (Griffith and Solak, 2000b).

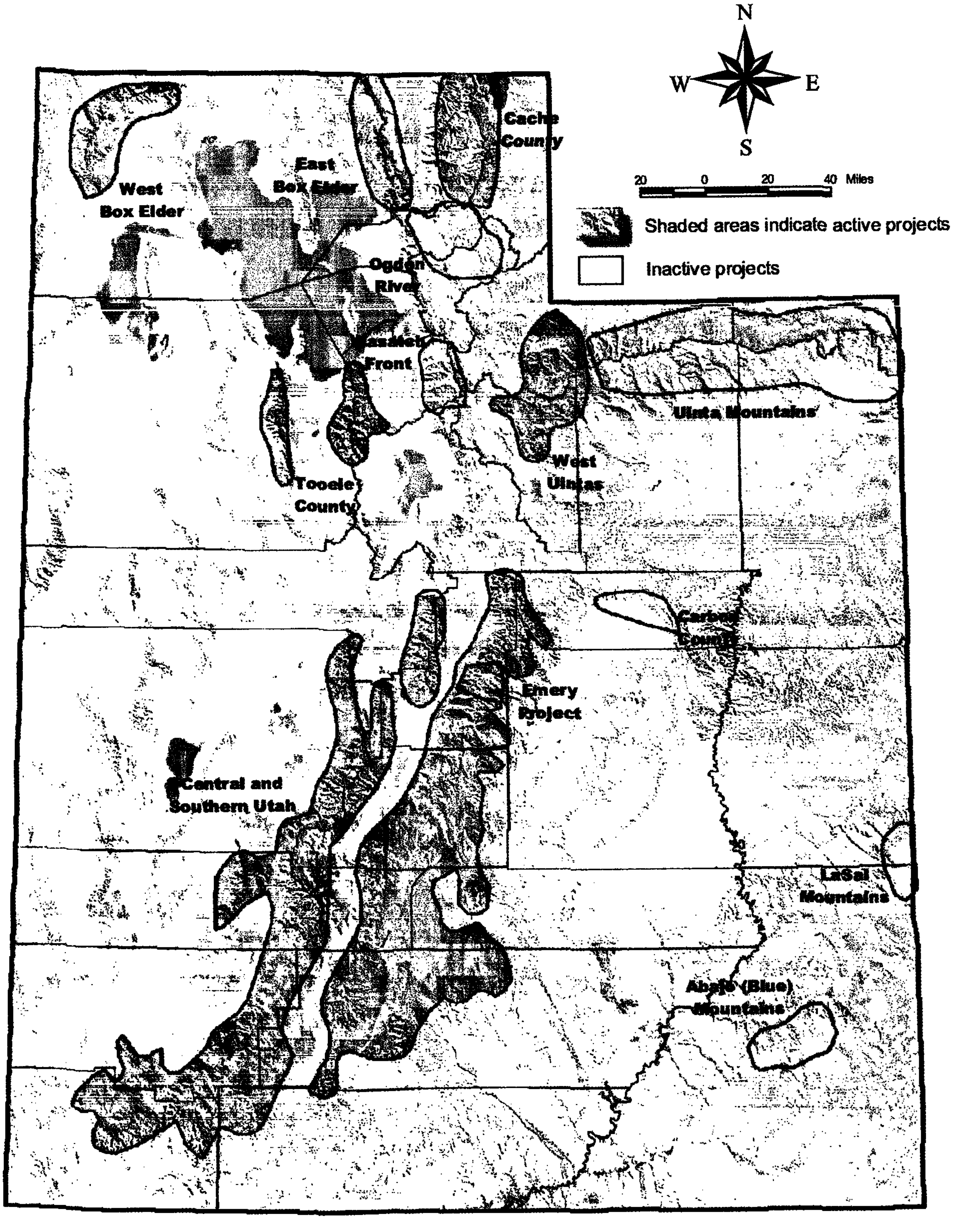


Figure 3. Winter Cloud Seeding Project Areas

The West Box Elder Project Area operated for 10 years from 1989 through 1997, 2000 and 2001. The project area has 12 cloud seeding generators. The target area has no precipitation gages; however, there are two snow courses. A target and control regression analysis shows an April 1 snow water content average increase of 18 percent (Griffith and Solak, 2000b). The target and control regression analysis for the non-seeded years of 1998 and 1999 shows no seeding effects; i.e., the regression equation accurately predicted the target April 1 snow water content even though increases of 26 percent and 13 percent continued in Cache County, which was seeded these two years.

The West Uintas Project Area operated for six years from 1989 through 1993 and during 1995. It is being operated again this year. The project area has 14 cloud seeding generators. Target and control regression analysis shows a December-March high elevation target precipitation average increase of 8 percent (Thompson, et al., 1995). Table 1 below shows a summary of the current cloud seeding project areas.

A study by the Division of Water Resources (Stauffer and Williams, 2000) estimated the average annual increase in runoff due to cloud seeding to be about 250,000 acre-feet (13.0 percent) for the project areas seeded during the 1999-2000 season. The study estimated the cost of water developed from cloud seeding in Utah to be about one dollar per acre-foot.

7. RESEARCH

In the late 1970s, the state funded research at Utah State University for expanding knowledge on winter orographic storms and ways to expand precipitation efficiency as well as evaluating winter cloud seeding projects. In the early 1980s, federal funds from the NOAA research project contributed to this research at Utah State University. The U. S. Bureau of Reclamation sponsored some ecological impact studies of snow pack augmentation in the Uinta Mountains of Utah during the years 1976 to 1980 (Harper, 1981).

In 1976 Congress passed the National Weather Modification Act (P. L. 94-490) that directed the Secretary of Commerce to conduct a comprehensive study of the state of scientific knowledge concerning weather modification. The secretary appointed a Weather Modification Advisory Board to make the study. The board suggested a local-state-federal funding program for operation/research projects. Federal funding was obtained by the continuing lobbying efforts of all the states and their congressional delegations. Project administration was carried out by NOAA. North Dakota and Utah were the first states participating in the program. Other states joining the program were Nevada, Illionis, Arizona and Texas. The program ran from 1981 through 1996, during which time approximately $30 million of federal funds was appropriated. Approximately $6.7 million was spent on the Utah program.

The objectives of the NOAA/Utah Program were to determine the following: (1) Spatial and temporal distribution of super cooled liquid water (SLW) in clouds over mountains, (2) precipitation trajectories within the clouds, and (3) transport and delivery of seeding material from ground-based generators sited upwind of the mountains to clouds passing over the mountains. Field research was conducted in 1981, 1983, 1985, 1987, 1989, 1990, 1991, 1994, 1995 and 1996. The projects prior to 1990 were conducted in the Tushar Mountains near Beaver in Southern Utah. The field projects in the 1990s were carried out on the Wasatch Plateau near Manti in Central Utah. In the latter years, experimentation with both liquid

TABLE 1
SUMMARY OF THE CURRENT CLOUD SEEDING PROJECT AREAS

Project Area	Number of Cloud Seeding Generators 2000-01 Season	Prior Seeded Seasons	Precipitation Increase During Seeding Period
Central/Southern Utah	65	23	14%
Tooele County	8	16	19%
East Box Elder/Cache County	22	12	
West Box Elder County	12	10	18%*
West Uintas	14	6	8%

*Based on April 1 snow water content.

propane and silver iodide was conducted at high altitude remote sites. Emery Water Conservancy District has continued to operate three remote high altitude liquid propane seeders as an operational project on the Wasatch Plateau.

These 16 years of research have increased the general knowledge of winter snow pack augmentation through weather modification. It has partially answered some of the questions concerning the objectives of the Utah/NOAA program. Field observations over the Tusher Mountains and Wasatch Plateau showed SLW exists during portions of winter storms near the windward slopes and tops of mountain barries. Measurements showed valley-released silver iodide is transported to mountain tops. However, further research experiments are needed to determine (1) the conditions required for the presence of abundant SLW and (2) the amount and effectiveness of the silver iodide at different temperatures of the SLW. The termination of the NOAA/state program in 1996 effectively ended federal funding for weather modification research in the United States. There continues to be a need for improving the efficiencies and the evaluation of operational programs. This can be accomplished through local, state and federal cooperative research programs. A new federal funding program is needed.

8. THE FUTURE

Predicting the future of cloud seeding in Utah is about as accurate as a long-range weather forecast. The Central and Southern Utah Project has been the mainstay of cloud seeding projects in Utah. The project has operated since 1974 and is expected to continue into the future, The Northern Utah Project has been operating continuously since 1989, and it appears it will also continue into the future. Several of the other projects in the state come and go depending on wet and dry cycles, reservoir storage and local politics. State funding appears to be stable at $150,000 per year from the Utah Board of Water Resources Revolving Construction Fund. Cloud seeding appears to be well and healthy in Utah.

9. ACKNOWLEDGMENTS

Alan Frandson of Centerfield was the leading pioneer for the water users in promoting and organizing cloud seeding in Central and Southern Utah. He was followed by Robert Nielson of Lynndyl. Reese Warburton of Grouse Creek was a leader in organizing the Northern Utah Summer Project.

Those in the commercial weather modification field having major influence in Utah were Keith Brown, Don Griffith, Thomas Henderson and John Thompson. Division of Water Resources personnel that have had significant influence on the cloud seeding program are Larry Anderson, Paul Gillette, Robert King, Dan Lawrence, Robert Murdock, Clark Ogden, Barry Saunders, Norman Stauffer, Paul Summers and Clint Warby.

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"NON-REVIEWED"

Weather Control Traditions of the Cherokee

James A. Heimbach, Jr.
Atmospheric Sciences
University of North Carolina
Asheville, NC 04083

Abstract Raven Hail, a Cherokee elder who has lectured and written on Native American culture, was interviewed during the spring and summer of 2000. The focus of the discussions was on the perceptions and methods of two cultures regarding weather control. The knowledge of another culture's perceptions and concerns about weather, and its control is intriguing. The Cherokee society is matriarchal whereas the Judeo-Christian is patriarchal, leading to significant differences in attitudes regarding weather. For example, members of a matriarchal society believe themselves to be caretakers of the Earth, and those of a patriarchal society to be dominant over the Earth and its inhabitants. Three Cherokee weather "control" incantations are discussed; the Sun Dance, Storm Deflection and the Rain Dance. Each has its conduct entwined with the structure of society, spirits and the understanding of the cosmos.

1. INTRODUCTION

Like modern western cultures immersed in technology, other cultures share a vulnerability to weather's whims. Indeed, the indigenous peoples of the Americas likely respected their vulnerability more because of their dependence on nontechnical methods. What they lacked in chemistry, computers and aircraft was compensated for by their understanding of seasons, mythology, good and evil, and magic. Who are those who rely on technology to scoff at another culture's spiritualism?

In the spring and summer of 2000, the author, a technocrat, had a rich dialogue with Raven Hail, a Cherokee woman who is an elder and historian for her people. The two learned much about the other's culture using weather modification as a focus. Ms. Hail has written several books which record many aspects of the Cherokee beliefs and culture. She is fluent in the Cherokee language and script, and translated the passages given later in this paper. As of this writing, she is residing in Asheville, NC. The figure below is her logo which is a symbol for a raven with script for her name.

Figure 1. Raven Hail's logo.

In the sections which follow, some aspects of the Cherokee culture relevant to meteorology are described. Three types of Cherokee weather control are elucidated. These are, solar radiation, tornado/severe storm deflection and rain augmentation. Exposure to the Cherokee's concerns, attitudes and deep-seated faiths can be instructive to those subscribing to the western dogma.

2. CHEROKEE CULTURE

The Cherokee culture is threatened with extinction through dispersal, as during the infamous Trail of Tears, and assimilation into the white man's culture. One of Raven Hail's purposes in life is to record her culture before it is lost entirely. Weather aspects are part of this.

Cherokee society is matriarchal, implying a partnership of genders which are separate but equal, e.g., ranking of gender such as chairman, chairwoman, chairperson is not an issue. Their culture is, however, steeped in the symbolism of gender. For example, the Moon is male, the Sun God<u>dess</u> is the supreme god or Great Spirit, all water is male, and the Earth is female. Social structure is matriolinic, meaning a white man can marry a Cherokee woman and the offspring are considered to be Cherokee, but not visa versa. The Cherokee belong to the Earth and are her caretakers. The Judeo-Christian society, on the other hand, is patriarchal which gives male (not Man-kind's which includes women's) domination over the Earth (Genesis 1:28). Patriarchal societies condemn snakes, however, in matriarchal societies, snakes are female and are displayed as female deities.

"NON-REVIEWED"

The relation to the Earth distinguishes the patriarchal and matriarchal attitudes in weather modification. Whereas the patriarchal society attempts to control the weather, the Cherokee attempt to pray to the proper spirits, soliciting rain, or diversion of storms, or other changes. For example, Grandfather Moon controls all the water on Earth and is therefore a spirit to whom water-related incantations are directed.

3. SYMBOLISM

Numbers have a symbolism for the Cherokee and are mentioned here because their use is entwined with the prayers and incantations discussed later. The number three means nothing for native Americans, though it is important in Judeo-Christian societies, e.g., "third time is a charm," and "Father, Son and Holy Ghost". Four is magic, especially for the Cherokee. Seven is a general magic number for all Native Americans. This number is so sacred that one does not use it in public or in print. Rather it is stated as another word. Note that the lunar cycle is 28 days = 4X7. The numbers 12 and 13 are magic/sacred for matriarchal societies but 13 is an anathema for patriarchal societies, as in Friday the thirteenth. Note that the Christian legacy has twelve apostles plus Christ = 13 entities. Six is the number of the Moon and the number 666 represents the triple Moon Goddess for a matriarchal society. But for patriarchal societies, 666 is associated with the devil, the archenemy.

There is no word for devil in the Cherokee language; however, there are evil spirits, such as the Raven Mocker who acts as a raven by stealing a victim's soul, causing sickness. This requires a specialist, a medicine man or woman, to ward off. A prayer must be done in Cherokee because the spirits will not pay attention to English. The tone of a prayer is not beseeching as in the Judeo-Christian tradition. For the Cherokee, an incantation is a succinct statement of how the mortal wants the situation to be (see the storm diversion incantation below).

4. THE IMPORTANCE OF WEATHER AND WATER IN CHEROKEE SOCIETY

Few details remain on the influence of weather on the Cherokee. Raven Hail remembers as a child on her mother's allotment near Bartletsville, OK, frequently grabbing a blanket and supplies, then running to the storm shelter. During tornado season, spending one night in the storm shelter per week was commonplace. She saw her home destroyed by a tornado. Her mother was so frightened by storms that she didn't consider praying for rain increases. Also, that would have required speaking in Cherokee which was discouraged during the dust bowl days.

Water was principle to the Cherokee in their lives and in their rituals (Hail, 1987), challenging the primacy of the Sun and Her alter ego, Fire. Today's weathermen frequently stress the need for water, but before catchment and conservation were developed, water shortages were even more critical. The Cherokee considered buffalo to be attractors of snow, improving moisture and hunting when the buffalo were plentiful. Likewise, the Sacred Spruce Tree attracted clouds and rain. Prayers were said to the spirits of these entities to give proper thanks and to ask permission for their taking.

The Earth came from the depths of the Ocean and the line of life is symbolized by the River or Long Man (*ibid.*). Long Man's head is the highest mountain top, and his foot, the lowest valley. He (the River) moves unstoppably and eternally. The center of a village, the town house, was near the river bank, and functions included going to the river, preferably at dawn. On the fourth or seventh day of life, infants were baptized by holding above the water while the mother touched the child with wet fingers. Polluting the Long Man was forbidden. There were no sacrifices to the River Spirit; however, freshly-killed game was washed in the river allowing the mingling of blood with the waters of life.

Below are discussed the attitudes and incantations for fair weather, severe storm deflection and rain. The facts for these came from Raven Hail's investigations and memories.

5. THE SUN DANCE

Certainly water was important to the Cherokee; however, fair weather was desirable as well. The Sun dance, to be described below, stopped before Raven Hail's time. The Spirit Red Bird, the daughter of the Sun Spirit, was killed by the Snake whose intent was to kill the Sun. The physical abode of the Sun Spirit is the Sun, and The Fire is the Sun's alter ego on Earth whose spirit is Red Bird. The Sun was so sad that SHE hid behind the clouds. The two twins, Flint and Reed, consulted a wise man who told them to have a celebration with great happy noises. Compare this to the Hebrew Psalm: "Make a joyful noise unto the Lord, all ye lands." (Psalm 100:1). There were seven nights of singing and dancing (note magic seven). The Sun saw this and SHE began to smile again, coming from behind her mournful shroud of clouds.

Contrast this to the Plains Indian sun dance. These were patriarchal, and the ritual was bloody and savage, as depicted in movies such as "Little Big Man," and "A Man Called Horse." Skin was pierced with bone and antler, and the dancers were tied to a maypole-like centroid, dancing until torn loose. This was a significant event and women were not allowed to participate in the dancing. It was necessary for both genders to observe the suffering so both could deal with it. The Plains sun dance was required to present manhood.

6. SEVERE STORMS AND TORNADOS

The Cherokee believed it was impossible to abate the fury of a storm. Instead, an attempt was made to divert the storm's course by informing the storm of their fear and revealing the storm's attractor was at some other location. Stated ineloquently using a stag as a metaphor: Storm, you scare me but I'm not the one you want. The doe you want is over there. Go to her. A translation of a Cherokee storm diversion incantation by Raven Hail is below (Copyright © 2000, Raven Hail) Translating is difficult because words can have alternate meanings in the Cherokee language, depending on the context.

To Turn Away a Storm

Yuhahi, Yuhahi, Yuhahi, Yuhahi, Yuhahi, Yu
Hear me!
Oh Great Heron of the booming cry!
You from the muggy swampland
with ruby talons under brooding shadow wings!
I greatly fear your savage jaws!
The spoor you seek is there beyond the trembling
   treetops
Let the lightning flash
the thunder roar
the wild winds blow
and the rain come down in torrents;
Grandfather Mountain will echo back your full
   majesty.
Listen!

The first line is onomatopoeic and mimics the cry of a heron. There are thirteen lines, a magic number in a matriarchal society. Here the storm is equated to an enormous heron, whose jaws the mortal fears. The heron is told that his mate is beyond the shaking trees, and he is urged to go to her, taking all his lightning, thunder, wind and precipitation. If he does, he will be revered by the mountain through the echoes of his power.

The above incantation will not work because it is not stated in Cherokee. Figure 2 displays the Cherokee script for this prayer.

A somewhat altered version of this is given by Mooney (1891) where the Storm Spirit is likened to an animal in rut, searching for his mate. Mooney describes the shaman's ritual who faces the storm with one hand toward the storm. He says the incantation several times, then blows in the direction the storm is to go, matching the direction his hand waves. A blade of corn is held while repeating the ceremony.

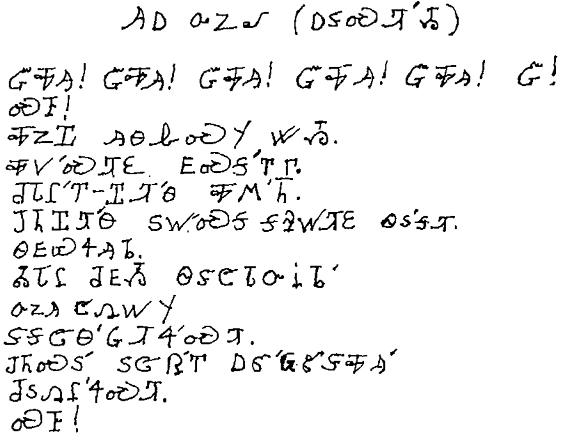

Figure 2. Script for Cherokee Storm Diversion Prayer Given in Text.

7. RAIN

The rain ritual is the most complex of the three discussed herein. Simply uttering a prayer to the Great Spirit, the same as the Sun Spirit, may not be appropriate. If something small is needed, go to a lesser spirit. Medicine women AND men, called day keepers because they kept track of the calendar, could determine which deity. Only some spirits can bring rain. The Plains Indians rain ceremony was different from the Cherokee's and is not discussed in this paper.

Dancing is part of the rain ritual. A circle of twelve stones is laid out, six round and six obelisk. In the middle should be one stone, the oolsati stone, meaning "it shines through." For the Cherokee, this is the eye of the dragon which is all that is left after its killing and burning. Quartz is the most powerful because it is the most common crystalline stone on Earth. For example, common foods are the best and caviar is the worst food because it is the rarest and most expensive. An analogous stone was on top of the Great Pyramid and is imprinted on a one-dollar bill. Stonehenge similarly has a head stone. The Cherokee circle of twelve plus one = thirteen stones is a generic setup for magic. Note that the total number of stones is magic. Men and women dance in and out of these stones, chanting and offering icantations. In so doing, a form of energy is generated, as wires moving through a magnetic field. The oolsate stone focuses this energy. The dance is around a circle, demonstrating the importance of the circle to Cherokee society.

The number of dances is unimportant. The dancers must alternate male/female to give the maximum power, and it is important for the dance to have symmetry. Some music or noise is necessary depending on the occasion. The chant/song depends on the season and the amount of rain desired. A leader or shaman beats a drum, directs by shaking shells, stopping suddenly. Everything must be done exactly as prescribed or the ceremony could be dangerous.

The rain chant below was translated by Raven Hail (Copyright © 2000, Raven Hail).

Rain Dance Chant

Redbird! Redbird! Redbird! Redbird!
Hear me, Maker of Rain!
You, up there in the Sunland!
Now, then----
Come down, O Nimbus
and touch the Earth!
It is done!

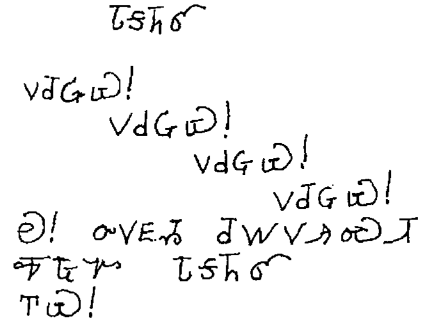

Figure 3. The Rain Incantation Written in Cherokee Script.

Don't try this version because, as with the storm diversion incantation, it will not work in English. In this case the prayer is to Redbird. Her name is said four times, a magic number. Note that in the Cherokee tradition the prayer is a simple statement of what the mortal wants. At the end of the prayer, the phrase, "It is done!" implies the American slang, "There," or "O.K., there you have it." Figure 3 shows the song/chant in Cherokee script.

8. COMMENTS

Throughout the interviews, the white man, including the author, was referred to as "White Eyes," which may or may not be derogatory depending on the tone. Like other ethnics, the Cherokee believe they are principal and a "White Eye" is anybody not Cherokee; similar to "gentile" for those of the Jewish tradition. The "white" comes from the Cherokee term, "yonig" which is a contraction of "unaka" = white, plus "yun-wi" = people. The clash of the Cherokee and White Eyes' cultures and injustices placed on the people can be summarized by her quote, "You White Eyes brought us wine which was a sacrament and destroyed us. We gave you tobacco which is a sacrament and it destroyed you."

The White Eyes may scorn the techniques described above, but attitudes can work both directions. Raven Hail, a curious intellectual, queried about the White Eye's patriarchal methods of controlling nature through weather modification. The standard glaciogenic process with anthropogenic intervention was described to her. She responded, "I never heard of such (expletive deleted)!" Then she asked for more details, satisfying her intense interest. Her response to a description of warm-cloud modification was, "Both man and nature can cause pollution."

Cherokee religion and myths were repressed by the White Eyes, and the Cherokee say few incantations anymore. For Raven Hail, the sensible thing to do would be to get elder Cherokee together with weather modification scientists to share ideas.

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THE TIME HAS COME

John Nesbett Leedom
Dallas, TX 75201

I was honored to be invited by your friend and a great leader in the weather modification effort, Mr. George Bomar, to attend the 49th Annual Meeting of the Weather Modification Association. I have long wanted to help bring about a solution for rain to fall when and where needed. This meeting was extremely beneficial for my efforts to better understand what had been going on and was going on.

The various papers presented were very professional and the obvious experience and expertise of those who presented them was very impressive. I came away from the meeting with three major reactions:

1) Many individuals have spent years learning and developing techniques. A major theme, however, was though the technology had greatly improved, the public and government attention, and awareness and funding was still minimal.

2) It seems such an important gathering should have had some active legislators and government officials present to gather around the flag, so to speak. During my five years on the Dallas City Council and then my sixteen years in the Texas Senate, I have been invited to attend and speak to several interest groups. The general purpose of such invitations was to cement my understanding of the group's efforts and mission and thereby garner my support for the appropriate government activities and funding, if needed.

3) With all due respect, I noted that average age of most in attendance was in their 50s and 60s. (I can comment on such, as I was 79 in July of 2000). The response was that the subject had not been attracting many youths. I also noted there are no prominent universities with Weather Modification Departments.

Returning from the meeting, I decided that much could and should be done, at least in Texas and so I set about many visits.

I visited with the leading weathermen in Dallas and determined that the meteorologists, who have their own association and training, are mostly only involved in predicting the weather. Very important, however, there is no effort to modify the weather. I called on a former Chancellor of the University of Texas, who is now Director of Research at the Pentagon and found that they also devote research effort to forecasting, which is a very important subject, but again, there is no effort to modify the weather.

By now I was coming to the conclusion that legislation should be introduced in Texas at the next session of the Texas Legislature to convene in January of 2001, to fund meteorology departments in some Texas' major institutions, such as the University of Texas, Texas A & M, Texas Tech University and perhaps others who would be interested.

Also, I believe that Texas should fund a Weather Modification Center that would coordinate and fund other research in weather modification for private institutions if they cared to create such research efforts.

I am a great believer that it takes three things to solve a problem. This problem is very clearly defined. It then takes people, ideas and money. Though my reputation is as a strong fiscal conservative, I do believe that government should do for the people what they cannot do for themselves and this problem certainly meets that requirement.

Before visiting with active Senators, however, I know it would require other institution's support and to determine that at least they would not be in opposition. I visited with a number of leaders. A meeting with the president of the University of Texas was very productive. In fact, he made a suggestion that I have now incorporated into the proposed legislation. He suggested that rather than a Meteorology Department, the department should be entitled Atmospheric Modification Department. The funding would be used to finance hiring professors (scientists), to buy equipment and provide facilities, as well as scholarships for a number of young people to enroll in the schools.

I also visited with the head of the Texas College Coordinating Board and again received a favorable reaction that something should be done and most likely could be done to bring about such research in some of the universities and colleges of Texas. To garner support, I visited with the president of the Texas Electric Utility Company (TXU) who recognized that without water the electric utilities could not function

Since my visits with him, three smaller electric utilities in West Texas have run out of water and are using the grid to supplement their electrical needs. I advised the TXU president I was not seeking any financial support, but did hope that he would encourage their very capable lobbyist to support and assist with the passage of the legislation and encourage the legislators to vote favorably on this proposed legislation.

Likewise I met with the vice president of a major insurance company whose losses had exceeded S100 million in the year 2000 due to the hail damage that Texas has been having. He is very supportive of efforts that might lessen the hail damage and was somewhat familiar with the efforts in Canada and other areas on hail suppression. Again, I did not request any funding support, only the assistance of their very fine lobbyist to support the passage of this new legislation for atmospheric modification. I left feeling they would.

I have since met with active Senators and at this writing believe the legislation will be filed. By the time this is printed, I am hopeful we will have made legislative progress. I believe when the legislation is submitted, it would well receive 31 co-sponsors. This would be 100% of all Texas Senators. By then I would believe there would be great public awareness and support.

The purpose of this article is to present to all weather modification practitioners a belief that now is the time to make major efforts to move forward with research and funding. The bills I am proposing will carry a financial note of millions of dollars, but it is time for Texas to step up to the plate and fund research that will release the great reservoir in the sky of its moisture. The need is great, the losses are great and human suffering is great. It is now time that we bring this to the attention of governments for funding and research and development. The public, I'm certain, will support it. Let's go forward now.

About the Author

Dallas native John Leedom has served in the Texas Senate continuously since 1980, alternating his in-session legislative duties with service on state committees and gubernatorial commissions promoting economic development, financial efficiency and intergovernmental cooperation. During the 1970s, he was twice elected to the Dallas City Council. He earlier chaired the Dallas County Republican Party and served as an elected member to the Texas State Republican Executive Committee.

Sen. Leedom is chairman of Dallas-based Wholesale Electronic Supply, Inc., which he co-founded in 1950. He has since served as a director of the Young Presidents' Organization, president of the National Electronic Distributor Association and president and chairman of the National Association of Wholesale/Distributors.

An electrical engineering graduate of Rice University, Leedom was elected treasurer of his freshman class and president of his senior class prior to enlisting in the U.S. Navy in 1943. As Navy officer during World War II, he directed classified communications projects at the Naval Research Laboratory in Washington, D.C., simultaneously chairing the Lab's Recreation for some 5,000 military and civilian personnel.

John and his wife, Betty, reside in Dallas.