PHASE II OF THE RAINFALL ENHANCEMENT ASSESSMENT PROGRAM IN THE UNITED ARAB EMIRATES

UNITED ARAB EMIRATES
JUNE 2003 ONWARDS

RANDOMIZED SEEDING PROJECT - EXPERIMENTAL DESIGN

1. BACKGROUND AND MOTIVATION

During the past ten years seeding with hygroscopic particles has received a renewed interest in response to the reported positive results from a randomized cloud seeding experiment in South Africa using hygroscopic flares (Mather et al., 1997). The seeding approach used in South Africa involved seeding mixed-phase summertime convective clouds below cloud base with pyrotechnic flares that produce small salt particles (about 0.5 μm mean diameter) in an attempt to broaden the cloud droplet spectrum and accelerate the coalescence process. Mather et al. (1997) reported the results from a randomized cloud seeding experiment that was conducted from 1991 to 1996 in summertime convective clouds in the Highveld region of South Africa. The results of this experiment indicated that precipitation amounts from seeded storms were larger than from unseeded storms (Fig. 11, Mather et al., 1997).

The development and use of the hygroscopic flares for rainfall enhancement was triggered by radar and microphysical observations of an unusual convective storm growing in the vicinity of a large paper mill. This storm and others subsequently identified as being affected by the effluent from the paper mill showed an apparent enhancement of coalescence compared to clouds not affected. (Mather, 1991). Earlier observations by Eagen et al. (1974) and Hindman et al. (1977) suggested a similar connection between the effluent of paper mills in the Pacific Northwest (USA) and enhanced precipitation.

Bigg (1997) performed an independent analysis of the South African experiments and found that the seeded storms lasted longer than the unseeded storms. Bigg (1997) suggested some dynamic responses, which also were alluded to by Mather et al. (1997). The suggestion is that the initiation of precipitation started at a lower height in the seeded clouds than in the unseeded clouds and that a more concentrated downdraft resulted closer to the updraft. The surface gust front was thereby intensified and its interaction with the storm inflow enhanced convection.

In another independent statistical reevaluation of the South African cloud seeding experiment, Silverman (2000) supported the earlier results by Mather et al. (1997). Silverman also found that 1) adjusting for differences at decision time between seeded and unseeded cases (a "potentially compromising covariate") strengthened and sharpened the suggested effects of seeding; 2) seeding existing large cloud systems had no affect on the results; and 3) cloud systems in the more continental Highveld Bethlehem region responded more favorably to seeding.

Mather et. al (1997), Bigg (1997), and Silverman (2000) all allude to apparent dynamic effects in seeded clouds that result in these systems being longer-lived. The mechanism suggested is a change or enhancement in precipitation loading and evaporation that changes the characteristics of the downdraft. This in turn affects the storm organization, evolution, and lifetime, and results in increased rainfall.

The promising results of Mather et al. (1997) led to a program in Mexico conducted from 1996 to 1998 using the South African hygroscopic flares in the same fashion as in the South African program. A randomized seeding experiment was conducted during the summers of 1997 and 1998. Although three years of randomized seeding were planned, only two years could be completed due to lack of funding for the third year. An overview of the program and some preliminary results are discussed by Bruintjes et al. (2003) and summarized in WMO (2000). The preliminary results are similar to those found from the South African experiment, which indicate increases in radar-derived precipitation from seeded storms as compared with unseeded storms.

The physical processes responsible for the apparent results found in South Africa and Mexico are not fully understood. In both the South African and Mexican experiments, the increases in rainfall from seeded storms were not due to more intense precipitation but due to precipitation over a larger area and for a longer period time. So, although promising results have been obtained with hygroscopic seeding, some fundamental questions remain that need to be answered in order to provide a sound scientific basis for this technology.

In late 2000, the government of the UAE, through the newly established Department of Water Resources Studies (DWRS) of the Office of His Highness the President, approached NCAR about developing and applying the technology of cloud seeding in the UAE. A preliminary assessment identified some key areas of study required for assessing the efficacy and potential benefits of rainfall enhancement via hygroscopic seeding, including: a) collating existing data and collecting specific data on clouds and rainfall, b) establishing the natural background and variability of aerosols in the region, c) adapting and developing numerical models for simulating UAE clouds, and d) understanding the UAE hydrology sufficiently to assess the impact of rainfall on groundwater resources. These evolved into seven specific objectives that addressed two fundamental questions for the UAE:

1. Is the frequency of cloud occurrence sufficient to warrant the investment in a cloud seeding program?
2. Are the clouds that do occur amenable to hygroscopic seeding?

A significant part of the study involved fieldwork – the intensive collection of observations (airborne and surface) during four field project periods (winter and summer of 2001 and 2002). Microphysical observations of cloud droplets and aerosols showed continental conditions in both the UAE and Oman during the summer. More varying conditions existed during the winter, mostly due to weaker cloud conditions (higher clouds and lower updraft speeds). During the 2001 and 2002 winter seasons, radar summaries showed that no hydrologically significant rainfall events occurred over the UAE. For the 2001 and 2002 summer seasons, radar studies showed that the vast majority of convective storms occurred over the Oman Mountains, southeast of Al Ain and northward, though they were relatively short-lived. The short lifetimes of the thunderstorms act to minimize the window of opportunity for cloud seeding to enhance rainfall, emphasizing the need for accurate prediction of these situations in planning seeding operations.

Summaries of the trial seeding cases suggest that conditions amenable to seeding occur on only a few days during the winter, typically late in the winter season. Conversely, suitable storms developed on more than a third of the summer days, although the number of storm tracks differed considerably between 2001 and 2002. In summary, the results have mostly answered the two fundamental questions and thus support proceeding with Phase II of the Rainfall Enhancement Assessment Program during the summer months in the UAE. This involves designing and implementing a randomized hygroscopic cloud seeding experiment during the summer season to statistically quantify the potential for cloud seeding to enhance rainfall, specifically over the UAE and Oman Mountains. The randomized seeding experiment will require at least two years to treat a sufficient number of cases, and requires close collaboration with Oman in operating the seeding experiment seamlessly across their border.

This document outlines the Experimental Design for the randomized seeding experiment. In addition, depending on the results from the randomized seeding experiment, several activities or components are required in order to quantitatively assess any increases in rainfall from cloud seeding and to initially estimate the overall economic benefit of such a program. These studies will not form part of the randomized seeding experiment but will need to be pursued at a later stage.

2. OBJECTIVES OF THE EXPERIMENT

The objectives of Phase II of the Rainfall Enhancement Assessment Program in the UAE are to:

(a) Determine whether there is a quantitative effect on radar derived storm-based rainfall from hygroscopic seeding at cloud base.

(b) If an effect is found, understand the time history of such effect and the probable cause.

(c) Test the concepts of the South African and Mexican experimental approach in the UAE.

(d) Collect concurrent and separate physical measurements to support the statistical results and provide substantiation for the physical hypothesis.

3. Seeding Hypothesis

3.1 Natural characteristics of UAE clouds

Modified-maritime situations produce convective storms with low droplet concentrations and broad droplet spectra at cloud base. Concentrations are generally less than 200 per cm^3, with sizes up to 20 μm. These storms are thought to have higher precipitation efficiency and are not expected to respond significantly to hygroscopic seeding.

This experiment is aimed at increasing rainfall from storms that are more continental in nature. Such storms have high droplet concentrations and narrow droplet spectra at cloud base. Measurements made in the UAE during the summer months indicated high concentrations of CCN and cloud droplets near cloud base typically associated with a continental and/or highly polluted environment.

Based on the numerous cloud investigations in the UAE, seeding trials, and radar data analyses, we conclude that winter clouds rarely produce conditions that are sufficiently convective with warm cloud bases and identifiable updrafts to effectively seed with hygroscopic flares. However, during the summer, suitable convective clouds develop on about a third of the days, and treating 3-4 storms on each of these days seems reasonable. It is conceivable that a randomized seeding experiment, targeting the mountains in particular, could yield results in two to three years.

3.2 Precipitation development in seeded and unseeded clouds

Precipitation formation in convective clouds may be dominated either by coalescence processes or ice-phase processes. Storms with high droplet concentrations of small sizes tend to be dominated by ice-phase processes. The result is a large number of small ice particles, many of which fail to reach the ground and either evaporate or enter the anvil cloud.

Results from the South African and Mexican experiments indicate that hygroscopic seeding at cloud base early in cloud development may significantly increase the rainfall from continental storms. The seeding material is dispersed into the inflow region at cloud base. Because these particles are larger and more hygroscopic than the natural particles, cloud droplets will nucleate preferentially on the seeding particles. This inhibits a portion of the smaller natural cloud condensation nuclei from becoming activated because the droplets already formed as a result of seeding limit the maximum supersaturation. The result is a broader-than-natural droplet spectrum near cloud base that enhances the potential for precipitation to develop earlier and more efficiently in the lifetime of the cloud. In addition, the expectation is that this seeding effect will spread to other parts of the cloud and enhance the formation of precipitation there. The ultimate effect is a more efficient precipitation process.

An overview of the experimental results, physical processes and research needs with respect to hygroscopic seeding is provided in the WMO (2000) document. In this section we will only summarize some microphysical aspects with respect to the development of precipitation in seeded clouds that could be addressed during a field effort and that could provide physical measurements to enhance the physical understanding of hygroscopic seeding and support the statistical randomized experiment.

Warm rain processes

There are two ways in which hygroscopic seeding might enhance the early formation of precipitation:

(a) Through addition of ultra-giant particles that provide embryos for rain formation
(b) Through production of larger cloud droplets that lead to an enhanced coalescence process and hence to rain.

Calculations suggest that both these processes may be important, but the framework for the calculations and our present knowledge of the aerosol size distributions in natural and seeded cases are not adequate to determine which (if either) is dominant. The next step in exploration of the physical sequence leading to precipitation (in natural and seeded cases) is to determine the relative importance of these two processes.

The first process (a) involves ultra-giant particles and is optimized by the introduction of low concentrations of very large particles (larger than 10 μm diameter). The second (b) requires higher concentrations of smaller particles (of about 1 μm diameter). The two processes also differ in how they will affect clouds: the first directly enhancing the small concentrations of precipitation embryos, while the second lowers the number concentration of cloud droplets, broadens the droplet size distribution, and hence accelerates the coalescence process that leads to rain. The two possibilities thus differ significantly in the seeding method that would be optimal and in the change produced in hydrometeor size distributions.

Any ultra-giant particles introduced into an adequate updraft will grow to precipitation embryos, so the relative importance of these two processes will largely be determined by how important (b) is. Some observable consequences that could be measured include these:

- Process (b) requires modification of the central portion of the cloud droplet size distribution at cloud base, while that is not a requirement of (a). Absence of cloud-base changes other than the introduction of ultra-giant embryos would be strong evidence for (a).
- Process (b) will lead to a broader cloud droplet size distribution at altitudes of 100-1000 m above cloud base, and so to an enhanced coalescence rate. Concentrations of drizzle at intermediate levels in the cloud that exceed the concentrations of ultra-giant particles introduced at cloud base (with appropriate correction for dilution), if linked to seeding, will be strong evidence for process (b).
- One might expect process (a) to produce an early echo dominated by a small number of very large hydrometeors while (b) might produce an early echo from a larger number of drizzle-size droplets. Calculations suggest that these two processes might be distinguished by a differential-polarization (ZDR) measurement, with a high value favoring (a) and a low value favoring (b).

It is still a question whether the tail (process (a)) or the main part (process (b)) of the particle spectra produced by the hygroscopic flares are the dominant mechanism to induce coalescence. Measurements in South Africa (Cooper et al., 1997) indicated broadening of the spectra and reduced concentrations of droplets a few hundred meters above cloud base in the seeded region of the cloud. However, measurements in Mendoza, Argentina in February 2000 did not show the reduced concentrations but an enhanced tail in the droplet concentrations. It is important to determine which of these two mechanisms are inducing the coalescence process and lead to possible drizzle formation.

In addition, diffusion of seeding material is too slow to permit spread throughout a rising turret during the typical ascent of a parcel in that turret. The spread of a seeded plume to a width of about 1 km takes about 10 min or more, or (with typical parcel ascent rates of 5-10 m s^{-1}) a rise of 3-6 km. Similar considerations of the inflow to a storm versus the inflow region that can be seeded suggest that it is difficult to affect a significant part of the inflow of a storm if the seeding effect appears in the initial ascent of the turret. This suggests, in accord with much observational evidence for natural storms, that recirculation processes may be required if seeding is to affect a significant part of the precipitation from a multi-cellular storm (unless dynamic effects from the seeding play a predominant role in propagating the seeding effect).

The number of ultra-giant particles produced by the flares seems inadequate to produce a significant seeding effect, unless enhancement of the precipitation process by break-up occurs. The flares produce an estimated concentration <1000 m^{-3} of particles larger than 10 μm (as measured behind a seeding aircraft where the plume was about 10 m in diameter). This suggests that the total number produced might be about 10 m x 10 m x 100 m s^{-1} x 17 min x 1000 m^{-3}= 10^{10} particles. If each grows to a 3 mm diameter raindrop, total rain mass is of order 10^8 g or, for a 1 km^2 area, a rain depth of 0.01 cm. The concentrations are also too low to support significant collision-induced break-up. (In contrast, drizzle concentrations up to 10^4 larger were produced in some of the calculations.) This suggests that drizzle formed from coalescence among droplets may be a significant source of embryos for rain formation. If the source is giant particles, multiplication by break-up is needed.

Continuous-coalescence calculations indicate that, for growth to a 3 mm diameter raindrop, a collecting embryo must fall over a trajectory having a path integrated liquid water content of ~ 6 g m^{-3} km (e.g., 3 g m^{-3} over 2 km). If it takes 10-20 min for this to occur, this is most of the lifetime of a typical cell.

All these factors suggest that recirculation (embryos produced in one part of a turret entering another part or another turret) may be needed to produce significant precipitation in a multi-cellular storm.

Mixed-phase and ice processes

The basic intent of hygroscopic seeding is to accelerate the coalescence process through modification of the cloud droplet size distribution. However, that modification can also affect ice phase processes in the clouds if they reach temperatures below 0°C, as could have possibly occurred in the South African and Mexico experiments. There are a number of such potential influences and the parameters involved in most are reasonably well known. Yet, the impacts of changes in the overall evolution of the seeded clouds, and in the amount of precipitation produced are not readily predicted. Just as there has been only limited success so far in modeling the formation of precipitation in convective clouds in which ice phase processes dominate, the effects of hygroscopic seeding on such clouds are also difficult to assess with any confidence.

The most important elementary ice processes that are sensitive to the cloud droplet size distributions are <u>riming rates</u> and <u>secondary ice generation</u>. Primary ice nucleation is not expected to be influenced, unless the seeding material or other products associated with it have ice-nucleating properties. This is not likely to be the case, as neither soluble particles nor combustion products are good ice nucleators. However, the earlier formation of drizzle or raindrops in seeded storms may provide the initial graupel embryos through the freezing of these large drops. Larger drops freeze preferentially at temperatures below 0^{o}C and these frozen drops provide more efficient graupel embryos than graupel formation through the primary ice nucleation process.

The accretion of cloud droplets by ice crystals is subject to alterations due to changes in cloud droplet size distributions and the associated changes in collection efficiencies. To the extent that hygroscopic seeding either increases the concentrations of the cloud droplets at the large end of the spectrum, or shifts the whole spectrum to larger sizes, it will increase the collection efficiencies of droplets on ice particles.

The breakup of ice crystals and the fragmentation of rime clusters on ice crystals are both subject to changes as a consequence of broadened droplet size distributions but not enough is known about these processes to make more precise statements about the expected changes. The most clearly established mechanism for secondary ice generation, the Hallett-Mossop (H-M) rime splintering process, is known in enough detail to consider the possible effects of altered droplet size distributions, and this effect is quite simple. The probability of splinter production (per collision between ice crystals and cloud droplets) is directly proportional to the number concentration of cloud droplets with diameters exceeding 24 μm. Thus, if the shift in droplet spectra due to hygroscopic seeding can be well predicted then the secondary ice generation rate that might arise in the cloud, provided all other conditions for this process are fulfilled, can be readily estimated.

As in the case of riming, the generation of additional ice crystals via an accelerated H-M process does not lead to a clearly predictable effect on precipitation efficiency. Model experiments comparing the precipitation produced with or without the H-M process have given somewhat divergent results, from no change in precipitation over the lifetime of the cloud to relatively modest changes. Because of the multitude of processes influencing precipitation efficiency, and limited by available moisture and instability, the impact of the H-M mechanism, or of any other specific process, on the total amount of precipitation is limited.

In summary, with a broadened cloud droplet spectra it is expected that frozen drizzle or raindrops will form the initial graupel particles, riming efficiencies are increased and that a secondary ice process might be initiated. The biggest effect of riming would be to speed graupel production somewhat. Only quantitative analysis can assess the likely importance of this. However, one should expect it to be less important than any process that increases the number of ice particles. Secondary ice generation in clouds with bases at relatively warm temperatures (+10^{o}C and higher), the impact of hygroscopic seeding on the H-M process is likely to be small. The droplet spectrum at the height of the –3 to –8^{o}C temperature level (where the H-M process is active) will already have a substantial concentration of droplets larger than the critical 24 μm size. The colder the cloud bases (<10^{o}C) the larger the potential effect of hygroscopic seeding will be.

Raindrop size distributions

Within a rain-shaft the growth processes of condensation and collision-coalescence, together with the effects of collision-breakup, lead to similarity in the drop size distributions so that an empirical relationship can be fitted to the relationship between radar reflectivity and rainfall rate. A combination of high-resolution radar measurements and in-situ measurements is needed to establish the mechanisms giving rise to this similarity and to assess the uncertainty in the reflectivity-rainfall rate relationship due to natural cloud variability and the effects of artificially-induced changes in the drop size distribution.

Characterizing the raindrop size distribution (DSD) at cloud base is important to the hygroscopic seeding question. One is as a direct measure of seeding response, where the DSD potentially changes in some unknown way due to seeding. A question exists as to whether the results from the various seeding projects are really due to DSD changes, which then confuse the radar reflectivity analysis used in the statistical evaluation. Another is as a parameter in initializing and validating numerical studies on the effect of evaporation and water loading in developing downdrafts and cold pools, which in turn may be of importance in generating new convection. Inherent in any DSD study related to seeding effects is an assessment of natural variability, encompassing the time history of DSD throughout a storm, from storm to storm, and from day to day.

3.3 Seeding conceptual model and physical hypothesis

Based on the physical chain of events in the development of precipitation in seeded and unseeded clouds the seeding conceptual model and hypothesis for a microphysical propagation of the seeding effect can be summarized as follows:

MICROPHYSICAL SEEDING CONCEPTUAL MODEL

- Hygroscopic seeding broadens the cloud droplet spectra near cloud base.
- Hygroscopic-flare seeding enhances the production of drizzle.
- Drizzle production occurs in near-adiabatic ascent of parcels (where LWC is high), resulting in drizzle near the tops of new turrets and in downdrafts (which can be stronger).
- Recirculation is important, helping drizzle enter high-LWC regions of the same turret and spread to other turrets.
- If the cloud vertically extends to temperatures colder than $0^{o}C$, large drizzle and raindrops would freeze preferentially and become the primary graupel embryos.
- Broader cloud droplet spectra below $0^{o}C$ would result in higher riming rates.
- Combination of large drop freezing and broader cloud droplet spectra may result in secondary ice generation.
- Additional loading of precipitation at lower levels in seeded clouds results in changes in updraft/downdraft structures and modify dynamic aspects of the storm.

Seeded storms will differ from unseeded:

- Modified droplet size distributions near cloud base (in narrow regions associated with the seed plumes)
- Enhanced drizzle concentrations near tops of turrets in feeder or daughter cells
- Enhanced drizzle in downdraft regions at the edges of turrets
- Enhanced large drop graupel embryos below $0^{o}C$
- Enhanced secondary ice generation below $0^{o}C$
- No differences in DSD between seeded and unseeded storms

N[illegible]l a[illegible]g experimental results in South Africa and Mexico additional dynamic effects in terms of enhanced cloud growth due to possible modification of the updraft/downdraft structures and the development of progeny clouds had to be invoked to explain the statistical results. However, as part of the UAE experiment the physical measurements will primarily focus on the microphysical aspects as described in section 4.

4. Operational procedures

4.1 Objectives of the operations

The objectives of each operation will be to select suitable candidate storms, randomly select them for seeding, and make the measurements that are required to detect and analyze any seeding effects.

Seeding will be carried out in a randomized manner, according to the procedure described in Section 4.11. This procedure is double blind, so that ground operations staff are unaware of the seeding decision. The procedure is the same as was used in the South Africa and Mexico experiments.

The randomization process is necessary to allow a rigorous statistical analysis of the seeding effects. Since the operations director (or designated radar operator) is unaware whether seeding is actually being performed or not, the pilot will fly the mission in exactly the same manner irrespective of the random seed/no-seed decision. After decision time (see 4.10 for definition) on any case, the radar operator will not provide the pilot with any information on how the storm is responding to the seeding event.

4.2 Operations director

An Operations Director will be responsible for the day-to-day management of the project. The operations director will have overall responsibility for following the Operations Plan, including:

1. Decision on daily status (color coded potential for convective development, Table 1) based on the daily forecast and the state of equipment on the minimum equipment list.

2. Decision on when to launch the aircraft.

3. Communication of seeding decisions (operations center envelopes) and possibly guidance to storms.

4. Decision on declaring off-days in advance.

5. Archiving of data and documentation as specified in the Operations Plan.

4.3 Meteorological data for forecasts

The decision for conducting operations will be based on a morning forecast provided by DWRS, using visual observations and meteorological data as available. The operations base will have a connection to the Internet. This will be used to download and view meteorological data from Web sites at to assist with the forecasts. Depending on the forecast the Operations Director will classify the day into one of the following categories:

Daily Code

CODE	% Chance of Seedable Clouds	COMMENT	Crew Readiness	Aircraft Readiness
RED	75% - 100%	There will be storms	All crew on Station	Fuelled, flares loaded
ORANGE	50% - 75%	Good chance of storms	1 hour from Station	Fueled, no flares
YELLOW	25% - 50%	Chance of storms	3 hours from Station	Fueled, no flares
GREEN	0% - 25%	Small chance of storms	12 hour check-in	Fueled, no flares
BLUE	0%	No chance of storms	24 hour check-in	Routine Maintenance if required

4.4 Launch decision

The operations director will call for the aircraft to launch when visual observations, radar echoes and/or nowcast conditions suggest a high likelihood of finding suitable cases for the randomized experiment or physical studies, provided the minimum equipment requirements are met.

On standby days (red, orange and yellow), equipment will be kept in a state of readiness for operations.

On no-go days (green and blue), maintenance and other activities that will affect the operational readiness of the equipment may be carried out.

4.5 Radar operations

The project will use the data from Al Ain 5-cm wavelength Doppler radar in automated volume-scan mode. The scan strategy will be set up to enable the high resolution data to be taken within volume scan times of 5-6 min. The radar scan parameters will be adjusted (prior to the start of the experiment) to provide adequate data for analysis of the experiment. Based on past experience, these parameters will roughly involve 15 tilts ranging in elevation angle from 0.5 degrees to 35.0 degrees (7 km MSL at 10 km distance from the radar), antenna rotation rate of 20° s^{-1}, with radar volumes in 5-6 min. Clutter will be removed using a clutter rejection algorithm based on fuzzy logic, tuned for the UAE environment.

The radar will be thoroughly checked and calibrated before and after the season. A receiver calibration check with an appropriately located feedhorn and known signal, power output check, and system checks using solar characteristics will be performed during the season at least once per week. If the calibration checks are shown to drift significantly, new calibration parameters will be determined and installed in the data-reduction software.

Time will be recorded in UTC, and synchronized regularly with a time standard.

The raw radar data will be archived at the radar site.

The TITAN (Dixon and Wiener, 1993) and CIDD software system will be installed on a workstation at the radar and the Operations Center at DWRS. The TITAN software will be used for the display of the radar and aircraft position data in real-time for the purpose of directing the operations. The TITAN system will also archive the processed data to disk, with backup at regular intervals.

4.6 Aircraft instrumentation

The seeding aircraft will be equipped with an on-board instrumentation system including a telemetry link to the operations base. The system will record time in UTC, GPS position, and state variables (static pressure, ambient temperature). Forward-looking video will record flight conditions. The cloud physics/seeding aircraft will carry an instrumentation package to conduct the physical measurements as part of the randomized experiment and during cloud conditions when no suitable clouds are available for the randomized experiment. The instrumentation package of the cloud physics/seeding aircraft will consist of the following instruments:

- Particle Measuring System [PMS] Forward Scattering Spectrometer Probe [FSSP] (able to detect cloud droplets between 2 and 47 µm diameter)
- PMS Passive Cavity Aerosol Spectrometer Probe [PCASP] (able to measure concentrations and sizes of aerosol particles between 0.1 and 3.0 µm diameter)
- PMS 2D-C Optical Array Imaging Probe (able to detect cloud and precipitation particles between 25 to 800 µm diameter)
- PMS 2D-P Optical Array Imaging Probe (able to detect cloud and precipitation particles between 0.1 to greater than 6.4 mm diameter)
- Cloud Liquid Water (CLW) sensor
- Cloud Condensation Nuclei (CCN) counter
- Condensation Nucleus (CN) counter
- Cloud seeding material (20 hygroscopic flares)
- GPS system for location and estimated winds

- Temperature, pressure and dewpoint sensors
- Forward-looking video camera
- Data recording system

The minimum operational requirement for seeding missions is the recording of GPS position and time at least once per second.

It is very desirable that all instruments are operational, as they affect variables that will be used to partition cases for exploratory analyses.

4.7 Minimum equipment list for randomized experiment

The following equipment must be operating correctly for a case to be considered valid:

1. Radar calibrated and operated in volume scan mode, recording and storing data. The radar data will be displayed and analyzed using the TITAN storm tracking software (Dixon and Wiener, 1993). If for any reason TITAN is not able to display, record, or analyze the data, the case will be discarded.

2. Aircraft for seeding.

3. Aircraft GPS system recording position and time of the seeding aircraft on the aircraft system. This is essential for identification of cases in the radar data for the randomized experiment.

4. In case of simultaneous physical measurements, the cloud physics instrumentation package on the research aircraft should be fully operational (see section 4.6 and 4.13).

The following are highly desirable:

1. Real-time display of radar data on TITAN, including telemetered aircraft position.

2. The aircraft variables: temperature, static pressure or altitude.

4.8 Flight operations

The operations director will decide when to launch the aircraft.

The data system will be turned on before takeoff, and remain on until after landing. This will allow subsequent analysis of the state of the atmosphere during the mission, as well as provide detailed information on any instrumentation runs performed either during seeding or between cases.

The pilot will after take-off from the airport follow vectoring information from the operations director or a designated radar operator. The pilot should note the cloud base altitude on climb-out, communicating that information to the radar operator.

When the aircraft is in the vicinity of storms, the pilot will begin searching for a suitable case (see 4.9).

The pilot will be responsible for logging the following information on the cards indicating the randomized decision:

1. Engine start and stop times.
2. Takeoff and landing times (and altimeter settings).
3. Cloud base altitude on climb-out.
4. Decision time.
5. Start and end times of seeding.
6. Cloud base altitude of candidate storms.
7. Number of flares burned, and times.
8. Comments on storms selected.
9. Other notes which may be helpful in later analysis (e.g., change in cloud base altitude, changes in updraft character, etc.).
10. Running summary of flight hours.

At all times, safety will be the highest priority. If the aircraft must divert from a case for safety or air traffic control reasons, that case will be discarded.

4.9 Declaration of a case

The radar operator will vector the pilot to the most promising storms. Until decision time, the radar operator and pilot may converse freely about the nature of the situation, which storm to choose and so on. Before launch of the aircraft, it would be prudent for the pilot to also monitor the radar via the internet connection at the airport up to the time the aircraft is ready for launch.

After the aircraft has taken off, radar information plays an important role in making the operation successful. In particular, the aircraft will be advised continually as to where the most active areas are, since haze and mid-level clouds often obscure the pilot's visibility. The radar can also provide an indication where new development on a storm is occurring (usually on the upwind-side of the storm).

Once an area of storm development is identified and the radar operator guides the aircraft to this area, it then becomes the pilot's responsibility to decide if a storm meets the criteria as a case for the randomized experiment. The pilot will search visually for a suitable candidate storm in the area. This storm must have a solid-looking base, lower than 15,000 ft, with a good updraft (at least 1-2 m s^{-1}) as well as the appearance of growth (cauliflower-like growing cloud-bubbles aloft). The pilot will determine whether the location of the storm relative to terrain is suitable for seeding. For the pilot to come to this conclusion, the following observations will be required:

1) During the approach to a storm, the pilot should climb the aircraft to a sufficient height so as to remain above middle cloud to to visually observe any new development (usually on the upwind side of an existing storm). During such time, the pilot should try to determine whether new development has a good rate of ascent (i.e., is actively growing).
2) The pilot must determine if a solid, well-defined cloud base exists under the actively growing cloud in order to be able to detect updrafts. This can be determined by observing cloud movement, especially around the edges of the storm in the newly developing area. The cloud base should be no higher than 15,000 ft.
3) The pilot should notice whether a ledge (pedestal cloud) has formed, which is normally caused by good updrafts from the terrain surface to the cloud base. However, if the storm is already precipitating, the effect of the rain with accompanied outflow could create a false impression as to the activity of the storm's base. Should there be any uncertainty with regard to the cloud base activity, the pilot should make an initial pass below cloud base and be able to physically feel updrafts.
4) During the approach to the storm the pilot should evaluate the potential for continuous development of the storm. For example, should the new storm develop in close proximity to a very large storm its growth may be possibly be suppressed or when a new storm develops under an anvil from a previous storm it may not be able to grow further. The storm should be located at least 20 km from storms that were previously included as cases.
5) Once the above criteria are satisfied the pilot may declare a case.

The radar operator will determine if the storm is located appropriately for good radar coverage (between 10 and 140 km range). If a case moves outside of this range, it will be discarded.

4.10Definition of decision time

When the pilot decides that a case has been found, he will declare this information to the radar operator. The time will be noted - this time is referred to as 'decision time'.

4.11Randomization procedure

This project will use the same randomization procedure as that used in the South African and Mexican experiments, with one exception. In particular, since there will be two seeding aircraft, the randomization procedure will be repeated twice. This means that there will be two sets of envelopes at the operations center, one for each aircraft. For each aircraft, two sets of decision envelopes will be utilized, one at the operations center and one in the aircraft. NCAR statisticians who will not participate in the field program will provide these sealed envelopes. This procedure is being followed to ensure that none of the project personnel have prior knowledge of the contents of the envelopes.

The random assignment of clouds to seeded and control groups will be done via a probabilistic biased coin design, as is common in sequential trials. Because the experiment has a time component, it is desirable for the sample sizes in each group to be roughly equal at any given time during the experiment. Additionally, if the weather conditions change with time, greater assignment of storms to one group at the beginning of the experiment and to the other group at the end of the experiment may bias the results. The biased coin design assigns storms preferentially to one group when the other has been selected previously. Thus, the storms in each group will be roughly equal and unbiased during the entire experimental period (Kahn, 1987).

The operations center envelopes contain either a 'seed' or a 'no-seed' decision. The aircraft envelopes contain either a 'yes' or a 'no' decision.

Once the pilot has declared a 'case', both the radar operator and the pilot open the next envelope in each sequence. The radar operator communicates the result from the operations center envelope to the pilot, who then determines whether to seed or not based upon the following decision table:

Radar	**Aircraft**	**Action**
Seed	No	**No-seed**
Seed	Yes	**Seed**
No-seed	Yes	**No-seed**
No-seed	No	**Seed**

The pilot will not tell the radar operator whether the decision is to seed or not, and the pilot and radar operator will not communicate on issues related to the effects of seeding or lack thereof. Of course safety is the primary concern; therefore, any safety-related and air traffic communications should proceed as normal.

4.12Seeding procedure

Seeding runs are normally done at low aircraft power settings and relatively low speeds which in turn assists the pilot to find good updrafts areas by observing vertical and horizontal speeds of the aircraft, as well as physically feeling the effects. Under no circumstances will the pilot deliberately do seeding runs during the time the aircraft happens to be flying through rain, as this region is usually associated with the downdraft area.

If the decision is to seed, the pilot will burn 2 flares at a time, one on each wing, while flying below cloud base and through the updraft as much as is possible. A maximum of 10 flares is to be used on any one case, leaving 10 flares for a possible second case. The flares take approximately 3 min each to burn completely and therefore the maximum seeding time will be approximately 15 min per case.

Ideally, flares should be burned continuously, starting new ones as the previous pair burnout. However, the pilot may choose to suspend seeding in order to fly away from the storm and perhaps gain altitude to get a clear picture of the position of the new development. Therefore a case may last longer than the 15 minutes of flare burn time. The pilot will record flare burn times.

If the situation deteriorates to the point at which seeding is not considered effective (i.e. when the updraft ceases or becomes poorly defined), seeding should be terminated.

If the decision is no-seed, the pilot should fly the mission in exactly the same manner as if the decision were for seeding, up to a maximum seeding time of 15 min. This includes breaking off the mission should the seeding situation become unfavorable. The reason for doing this is to maintain identical documentation on all cases, irrespective of the seed/no-seed decision. End of seeding time will be communicated and recorded.

The pilot is the final authority as to the disposition and safety of the aircraft and its occupants and under no circumstances will he ever put the aircraft in a position where safety is compromised.

4.13Ending a case

Aircraft operation on a case will always be terminated when 10 flares have been burned in a seed case, or the time for 10 pseudo flares has passed in a no-seed case.

Premature seeding termination is purely at the pilot's discretion. The pilot needs to continuously monitor the activity of the storm and the characteristics of the cloud base and updraft region. If the cloud activity (characteristics of cloud base and updraft region) deteriorates to the extent that the pilot would have not chosen it as a case for the randomized experiment, the pilot will advise the radar operator as to his decision to terminate the case. In other words, if the pilot determines that the situation has changed and the storm is no longer suitable for seeding, he/she will declare the end of the case before all 10 flares are expended. The radar operator will then assist the pilot to proceed to a suitably positioned new storm, should this be required.

4.14Finding the next case

The radar operator will vector the aircraft to the best-looking region of active storms, taking into account distance from the first case. The subsequent case should be separated from the previous case by at least 20 km (10 nm) edge-to-edge, as measured by the 30 dBz echo on radar. Given more than one alternative, the closest case should be selected to minimize flight time between cases.

If there are less than 10 flares left at the end of a case, no subsequent case will be sought before landing.

4.15 Microphysical observations during randomized experiment.

It is generally accepted that scientific understanding of the physical processes affected by seeding is needed to reinforce the statistical results before such results can be fully accepted. Because two aircraft will be available for the seeding program, with one instrumented to conduct cloud microphysical measurements, it provides a unique opportunity to validate certain parts of the conceptual model and hypothesis presented in Section 3.5. Concurrent physical measurements with the randomized experiment (conducted over the duration of the experiment) could help scientists to either confirm or discard the seeding conceptual model and strengthen the statistical results.

The following measurements will only be conducted on the first case selected on each day and when there are no opportunities for both aircraft to conduct separate seeding experiments simultaneously on different cloud systems. This could occur on some days when there are only limited cases available for the randomized experiment, or when convection is first initiated, or at the end of the day when convection is subsiding.

To validate parts of the seeding conceptual model and hypothesis presented in section 3.5, the following two measurements are suggested as part of the randomized experiment:

1) Measurement of drizzle formation, drop freezing, graupel growth, and possible secondary ice generation by conducting repeated penetrations at the –5^{o}C level (approximately 18000-20000 ft) with the research aircraft during seeding in seeded and unseeded cases (Essential instruments: PMS 2D-C and 2D-P, PMS FSSP, Liquid Water Content sensor, state parameters)
2) Measurement of the raindrop size distribution in the rain shaft immediately below cloud base during and after seeding (up until 30 minutes after seeding) by conducting repeated penetrations with the research aircraft through the rain shaft in seeded and unseeded cases (Essential instruments: PMS 2D-C and 2D-P, state parameters).

The purpose of the measurements in (1) will be to determine if drizzle and raindrops develop earlier and at lower altitudes and if graupel formation is determined and enhanced by the freezing of large drops. In addition with a broadened cloud droplet spectra it is expected that riming efficiencies will be increased and that a secondary ice process might be initiated.

The purpose of the measurements in (2) will be to determine if seeding modifies the raindrop size spectra below cloud base. It is possible that the statistical results using radar-derived precipitation estimates might be due to seeding-induced drop size changes that would affect the radar estimation of rainfall (Yin et al., 1998). The field measurements of raindrop spectra are needed to address this issue.

The two measurements described above will be conducted on an alternating basis throughout the randomized experiment.

Finally, whenever the research aircraft is conducting seeding operations as part of the randomized experiment, it is desirable to obtain cloud base droplet spectra using the FSSP. This should be done at the end of the case. The pilot should conduct an ascent in cloud from cloud base to approximately a thousand feet above the base in the updraft region, and then exit out of the cloud.

There will be situations in which it is not safe to perform these procedures because of the height of cloud base relative to the terrain or severe weather. Should this be the case the pilot should terminate the measurements.

4.16 Microphysical observations separate from the randomized experiment.

During times when there are no suitable clouds available for the randomized experiment and yet convective clouds with a vertical depth of at least 1-2 km exist or storms exist outside the Al Ain radar coverage area, airborne observations to measure the effects of seeding on droplet broadening and drizzle formation are desirable. In these situations it is suggested that after both aircraft take off for a mission, a measurement of cloud base (height, pressure, temperature and dewpoint) is obtained with the seeder aircraft flying straight and level at cloud base without penetrating any cloud. After the cloud base measurements the research aircraft will ascend to 1000ft above cloud base and conduct a penetration in an actively growing convective cloud. It is important to note that the cloud base measurements should be taken just below cloud base without penetrating cloudy regions.

When the seeder aircraft has detected an updraft region of at least 1-2 ms^{-1} a seeding experiment will be initiated. The research aircraft will subsequently conduct two or three penetrations about a 1000ft above cloud base to detect the initial affects on the droplet size distribution where after it will conduct repeated penetrations at higher altitudes (1 km vertical intervals but not higher than the $0^{o}C$ level) to detect the onset of coalescence and drizzle formation in the cloud.

Hygroscopic seeding is hypothesized to broaden the cloud droplet size distribution near cloud base resulting in earlier coalescence and the formation of many drizzle drops in addition to raindrops lower in the cloud. The measurements with the research aircraft will attempt to document these aspects of the conceptual model and hypothesis. Measurements will be conducted near cloud base to attempt to document the broadening of the cloud droplet spectra. In addition, measurements will be conducted at higher levels in the cloud to determine if drizzle- and raindrops do exist earlier and at lower altitudes in these clouds (Fig. 3). Attempts will also be made to study the mixing of the effects to other cloud turrets in the cloud system. The following measurement strategy should be followed:

- Measure the natural aerosol size distribution and Cloud Condensation Nuclei (CCN) entering cloud base by the research aircraft before a seeding experiment is called (Essential instruments: CCN, CN counter, PCASP, FSSP, state parameters).

- Measure the cloud droplet size distribution immediately above cloud base in regions affected by seeding, and compare to similar nearby regions outside the seeding plume. (Essential instruments: FSSP, PCASP, 2D-C, state parameters) Expected result: A broader size distribution and reduced droplet concentration if (b) is important.

- Measure the droplet size distribution at intermediate altitude (perhaps 1-2 km above cloud base) to determine if a coalescence process leads to drizzle faster than in the natural case. This could be done by repeated passes of a research aircraft as seeding material is introduced below, with chance encounters between the seeding material and the research aircraft. Repeated seeding passes with the seeder aircraft at cloud base might be made at intervals as short as 2-3 min in favorable circumstances. If these seeding lines spread to about 500 m vertical extent in the ascent to 2 km and are rising at 5 m/s at 2 km above cloud base, there is a good chance that the upper-level aircraft flying perpendicular to the seeding plume direction will encounter the rising plumes (Essential instruments: FSSP, 2D-C, 2D-P, state parameters).

5. EVALUATION

5.1 Framework for statistical analyses

Weather modification research has a long history. However, it is still in need of “proof” that it works. Researchers rely, in part, on statistics for their evidence. However, even if weather modification experiments had been able to produce unequivocal statistical “proof” of an effect, replication of that effect is required before weather modification efforts can be declared a success. A wide variety of tests and analyses have been completed on weather modification experiments.

The problem lies with the use of statistical hypothesis testing as a “rubber stamp of approval.” Statisticians argue that a single test variable is necessary to guard against multiplicity and to provide an unambiguous proof of concept. Data from cloud seeding experiments are highly variable, and this reduces the power of a single test to detect differences. Dividing the allowable error among multiple tests makes detecting differences practically impossible. However, multiple statistical tests of different covariates can be helpful in guiding physical understanding. Statistical tests will continue to play an important role in enhancing physical understanding; statistics can be used not only as tool to test proof-of-concept, but also as a tool for discovery (a mathematical ‘magnifying glass’). Randomized experiments will continue to play an important role in weather modification studies, but the acceptance of results from these experiments will only come when we are able to physically explain the statistical results and vice versa. The recommended solution is to complete a single hypothesis test in the confirmatory phase of the experiment to retain maximum power to detect an effect from seeding. In addition, other exploratory statistical analyses will be undertaken as a tool for discovery, a mathematical magnifying glass.

5.2 The experimental unit

The experimental unit is defined as the storm as measured by the radar and tracked by TITAN, using a 30 dBz threshold, for the time period 20 min prior to decision time to 60 min after decision time. If the storm does not exist 20 min before decision time (<30 dBz and zero rainfall values), the case starts at the first detection by TITAN. Similarly if the storm dies before 60 min after decision time the case ends (<30 dBz and zero rainfall values) when TITAN no longer detects it. If after a case is selected and the storm within 60 minutes moves within 10 km of the radar or more than 140 km away from the radar the case will be excluded from the randomized experiment.

Any mergers and splits that occur during the specified time period will be included in the analysis, but any mergers and splits that occur outside of that time period will be ignored.

The TITAN tracking and analysis is fully automated. Therefore there is no possibility of bias based on the knowledge of the seed/no-seed decision. TITAN will produce time series of storm properties for use in the analysis. TITAN also will produce the value of the response variable for the confirmatory analysis.

5.3 Range limits

To qualify as a valid experimental case, storm range from the radar (up to 60 min from decision time) must remain between 10 km and 140 km.

5.4 Response variable for confirmatory analysis

Conducting a single hypothesis test in the confirmatory phase of the experiment limits the questions that can be answered to (at most) one. Thus, it is important to choose the most important question. Clearly, the main goal of rainfall enhancement experiments is to determine if rainfall has been enhanced. Thus, the confirmatory analysis will test if the radar-estimated rainfall amounts are greater from seeded storms than control storms.

The response variable for the confirmatory analysis is defined as follows:

Radar-estimated total precipitation mass. Precipitation will be estimated using the Marshall-Palmer Z-R relationship ($Z=200\ R^{1.6}$) applied to a composite of maximum reflectivity (>30 dBz volume) at any height at or below 6 km MSL. The composite technique will be used to minimize range bias. The total precipitation mass from decision time to 60 minutes post decision time will be calculated by integrating the radar estimated precipitation flux over time with units in kilotons.

5.5 Statistical hypothesis for confirmatory analysis

The seeded cases will demonstrate an increase in total precipitation mass from the unseeded cases over the lifetime of the storm (up to 60 minutes from decision time).

The null hypothesis is of differences less than or equal to zero in precipitation amounts between the seeded and unseeded cases.

5.6 Confirmatory evaluation

The Wilcoxon-Mann-Whitney (WMW) statistic will be used to conduct the hypothesis test. This test compares the sums of the ranks from two continuous samples to detect differences in location (i.e. mean or median). The test also applies when, under the alternative hypothesis, the cumulative distribution functions of the two samples of rain-mass measurements (denoted *x*) have the following relationship: $F(x) \leq G(x)$ with strict inequality for at least some *x*. If cloud seeding has no effect, then $F(x) = G(x)$, so if seeding has a positive effect on at least some of the clouds, then $F(x) \leq G(x)$ should hold. It is important to note that the WMW test is non-parametric, i.e. it does not require that the samples come from a specified distribution, such as the normal. It requires only that the samples be from a continuous distribution rather than a discrete. Significance levels and confidence intervals for the WMW test can be obtained from the permutation distribution of rank sums under the null hypothesis (Sprent, 1993).

The WMW test was chosen over the Student's *t*-test because cloud seeding measurements tend not to be normally distributed. The Student's *t*-test is the optimal hypothesis test for normally distributed samples. Unfortunately, for non-normal distributions, the *t*-test can be inefficient and lack power. The WMW test is only slightly less efficient and powerful than the *t*-test for detecting differences in location (e.g. shift) in normal data, it is highly efficient and powerful in detecting them in non-normally distributed samples (Dixon, 1954). Hodges and Lehman (1956) determined that use of the WMW test instead of the *t*-test never entails a serious loss of efficiency for testing against shift. However, the WMW test may be much more efficient than the *t*-test. Further, the power of the WMW is only slightly less than that of the *t*-test for normal samples. The limiting ratio of sample sizes required for the WMW and *t*-test to achieve the same power is $3/\pi$, about 0.955. This means that for normally distributed data, if the WMW test requires a sample of 100 cases to detect a real difference, that the *t*-test will only require a sample size of 95.5 cases to detect that difference. In summary, WMW appears to be a better choice for non-normally distributed data and even if the sample distribution is normal, the utility of the WMW is only slightly less than that of the optimal Student's *t*-test.

5.7 Sample size estimates

For the WMW test, there is no documented method for determining the sample sizes necessary to detect differences. However, when the data are normally distributed, the *t*-test and WMW test are very closely related, as mentioned in the previous section. Thus, in the case of normal data, the sample size necessary to detect a difference using a *t*-test can be multiplied by $\pi/3$ to estimate the sample size required for the WMW test to detect the same difference. Fortunately, the logarithm of the rain mass measurements is nearly normal, thus this method can be used to estimate sample sizes.

Sample sizes have been estimated by this method utilizing data collected during the 2001 and 2002 UAE field studies. The sample size required for 5% error and 80% power to detect a 25% increase in rain mass due to seeding is 266 cases, evenly divided between the seeded and control groups. It is important to note that this is just an estimate. There are several factors that may change the required sample size. For example, radar measurements collected by the Abu Dhabi radar during the summer seasons of 2001 and 2002 are used to derive the sample size estimate. These measurements may not accurately represent the conditions during different years when the cloud seeding experiment is being conducted because the radar was located more that 100 km away from the randomized study area and range effects may play an important role. During the planned randomized experiment the newly installed and more optimally located Al Ain radar will be utilized. Further, the distribution of the storms may differ due to the storm size, time and distance between storms, and other constraints placed upon storm selection during the experiment; constraints that were not imposed during the past field studies.

5.8 Exploratory analyses

"An important element of the exploratory approach is flexibility, both in tailoring the analysis to the structure of the data and in responding to patterns that successive steps of analysis may uncover." (Hoaglin *et al*., 1983). In order to maintain flexibility, exploratory analyses must be undertaken as appropriate rather than planned in advance. Thus, this section will give some examples of analyses that will be utilized in the exploratory phase of the experiment. Most likely, other types of analyses will also be completed. More examples of exploratory analyses of cloud seeding samples may be found in Fowler *et al*., (2001).

Measurements of various storm properties from the radar and cloud microphysics instruments will be compared for the seeded and control cases. Some of the quantities that will be examined in the exploratory phase of the analysis are:

1. Cloud droplet size distributions, near cloud base and aloft.
2. Rain drop size distribution near cloud base.
3. Concentrations of drizzle-size drops.

4. Graupel embryos.
5. Ice formation process (ice crystal concentrations, riming rates, etc.)
6. Duration of storm after decision to seed.
7. Area Time Integral.
8. Time-history of the number (percent) of active storms.
9. Precipitation flux measurements every 5 minutes over the lifetime of the storm.
10. Storm mass measurements every 5 minutes over the lifetime of the storm.
11. Storm area measurements every 5 minutes over the lifetime of the storm.
12. Storm mass measurements above 6 km every 5 minutes over the lifetime of the storm.

Some of the radar estimated fields that will be examined are cumulative totals from the storm while others are time series measurements. The distributions of the overall measurements from the seeded and control storms will be compared using boxplots and qqplots. The time series measurements will be examined as in the Coahuila, Mexico (NCAR, 1997) and South Africa experiments (Mather *et al*, 1997), with time series plots of the quartiles. Distributions of the time series measurements conditioned on the existence of rainfall at that time may also be analyzed. Further, other stratifications, such as capped convection cases, may be studied separately.

Each of the listed measurements will be studied individually. Additionally, many combinations of them may be studied jointly to determine the existence and nature of the relationships among them. As these measurements are also unlikely to be normally distributed, non-traditional methods will have to be employed in any multivariate analyses. Some candidate methods for multivariate analysis include spatial models and permutation procedures.

REFERENCES

Bigg, E. K., 1997: An independent evaluation of a South African hygroscopic cloud seeding experiment, 1991 - 1995. *Atmos. Res.*, **43**, 111-127.

Bruintjes R.T., D. Breed, G.B. Foote, V.Salazar, T. Fowler, B. Brown, M. Dixon, 2003: Program for the augmentation of rainfall in Coahuila: Overview and results. *Proc. Eighth WMO Conf. On Weather Modification*, 7-12 April 2003, Casablanca, Morocco, 103-107.

Cooper, W. A., R. T. Bruintjes and G. K. Mather, 1997: Some calculations pertaining to hygroscopic seeding with flares. *J. Appl. Meteor*., **36**, 1449-1469.

Dixon, M. J. and G. Wiener, 1993: TITAN - Thunderstorm Identification, Tracking, Analysis and Nowcasting - a Radar-based Methodology. *J Atmos Oceanic Tech*, **10**, 785-797.

Dixon, W. J., 1954: Power under normality of several non-parametric tests. *Ann. Math. Stat*., **25,** 610-614.

Eagen, R.C., P.V. Hobbs, and L.F. Radke, 1974: Particle emissions for a large Kraft paper mill and their effects on the microstructure of warm clouds. *J. Appl. Meteor*., **13**, 535-552.

Fowler, T.L., B. G. Brown, and R.T. Bruintjes: 2001. Statistical evaluation of a cloud seeding experiment in Coahuila, Mexico. Preprints, *15th Conference on Planned and Inadvertent Weather Modification*, AMS, Albuquerque, NM, 14-19 January.

Hindman, E.E., II, P.V. Hobbs, and L.F. Radke, 1977: Cloud condensation nuclei from a Paper Mill. Part I: Measured effects on clouds. *J. Appl. Meteor*., **16**, 745-752.

Hoaglin, D. C., R. Mosteller, and J. W. Tukey, editors, 1983: *Understanding Robust and Exploratory Data Analysis*. John Wiley and Sons, New York, 447 pp.

Hodges, J. L., Jr., and E. L. Lehmann, 1956: The efficiency of some non-parametric competitors of the *t*-test. *Ann. Math. Stat*., **27,** 324-335.

Kahn, A., 1987: Statistical Aspects of a weather modification experiment. Special Report, Center for Applied Statistics, University of South Africa, Pretoria, South Africa, 208pp.

Mather, G.K., 1991: Coalescence enhancement in large multicell storms caused by the emissions from a Kraft paper mill. *J. Climate Appl. Meteor*., **25**, 1780-1784.

Mather, G. K., D. E. Terblanche, F. E. Steffens and L. Fletcher 1997: Results of the South African cloud seeding experiments using hygroscopic flares. *J. Appl. Meteor*., **36**, 1433-1447.

Silverman, B.A., 2000: An Independent Statistical Reevaluation of the South African Hygroscopic Flare Seeding Experiment. *J. Appl. Meteo.*, **39**, 1373–1378.

Sprent, P., 1993: *Applied Nonparametric Statistical Methods*. Chapman and Hall, London, UK, 342pp.

WMO, 2000: Report of the WMO International Workshop on Hygroscopic Seeding: Experimental results, physical processes, and research needs. WMP Report No. 35, World Meteorological Organization, Geneva, Switzerland, 68 pp.

Yin, Y., Z. Levin, T. G. Reisin and S. Tzivion. 1998. Model simulation of the effect of cloud seeding on the evolution of radar-derived properties. Preprints, *14th Conf. on Planned and Inadvertent Weather Modification*. AMS, Everett, Washington. 630-631.