NCAR FEASIBILITY STUDIES FOR WEATHER MODIFICATION PROGRAMS OVER THE PAST 10 YEARS

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1. INTRODUCTION

Over the past ten years or so, a small weather modification group within the Hydrometeorology Program of the Research Applications Laboratory (RAL) has participated in a number of programs aimed at assessing the feasibility of cloud seeding for rainfall or snowfall enhancement. (See the following website for examples: www.rap.ucar.edu/hap/.) A renewed interest in much of this work was stimulated by participation in the 1995 Arizona Program (Klimowski et al., 1998). This program investigated the interaction of topographically-induced gravity waves with ambient upslope flow over the Verde Valley and the Mogollon Rim during the winter, using many observational components (e.g., dual-polarized radars, instrumented aircraft, radiometers, acoustic sounder, etc.) to compare with predictions using the Clark-NCAR 3-D numerical model. The impetus for the program was to investigate, through observations and modeling, some of the detailed dynamics and cloud physical responses for potential snowpack enhancement through cloud seeding in this important watershed region of Arizona.

Funding for the Arizona program included allocations from the last major weather modification effort supported by U.S. federal funds – the NOAA Atmospheric Modification Program. Therefore, most of the programs described here were initiated and funded through foreign governments and/or foreign businesses. The observational tools for the field projects were quite limited, especially in comparison to the Arizona study, but usually involved a project radar and an instrumented aircraft, both of varying capabilities. Five different programs are described briefly to highlight the interest in weather modification across a spectrum of geographical regions and a range of weather conditions. The various programs had multiple objectives and resulting data analyses, but we will focus on only a few aspects to emphasize the uniqueness of each program or incremental advancements from program to program. Our only domestic program, a snowpack enhancement assessment in the state of Wyoming, is currently underway and represents an attempt to address concerns about evaluating weather modification efforts raised in a report by the National Academy of Sciences (NRC, 2003).

2. Mexico - PARC (1996-1998)

One of our first major projects to assess cloud seeding potential took place in the border state of Coahuila in northern Mexico (Fig. 1). In 1996, concern by representatives of the state of Coahuila and a local steel company (Altos Hornos de México) regarding regional pressures on water resources led to the development of the Program for the Augmentation of Rainfall in Coahuila (PARC), which was proposed as a four-year program consisting of a randomized seeding experiment, physical studies, and collaboration with and training of Mexican scientists and students.

Figure 1. State of Coahuila highlighted in purple. The operational area is denoted as a circle (~90 km radius) centered at the radar site in Monclova

The overall objective of PARC was to develop, test, implement, and transfer the technology of cloud seeding, with an emphasis on hygroscopic cloud seeding, in Coahuila. The first step in achieving this broad objective was to characterize the development of convection and precipitation in central Coahuila, and compare them to storm characteristics in other regions where cloud seeding had been successfully evaluated. In particular, the measurements taken during the first-year field project (PARC-96) were compared with those taken in South Africa, where seeding with newly developed hygroscopic flares had met with some success (Mather et al., 1997). While there were general differences in storm structure and lifetime, microphysical characteristics, cloud initiation,

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*Corresponding author's address: Daniel Breed, NCAR/RAL, P.O. Box 3000, Boulder, CO 80307-3000, USA; Email: breed@ucar.edu and storm size were similar enough to warrant tests of hygroscopic seeding in Coahuila as practiced in the South African experiments.

As done in South Africa and specified in the PARC Experimental Design document, cases were selected by the pilot, who looked for clouds with suitable characteristics (*e.g.,* solid-looking base with a strong updraft). When more than one case was selected on the same day, a minimum separation distance of 20 km was maintained between cases. To qualify as a valid experimental case, storm range from the radar had to be between 10 km and 90 km in order to minimize range biases. Clouds that were selected for seeding were seeded at cloud base, using up to a maximum of 12 flares, with the plane staying with the cloud for at most 24 minutes. Two flares were burned at a time and the flares burned for about 4 minutes after which another two were ignited. Seeding was terminated if the cloud deteriorated so that it appeared that further seeding would be ineffective. Non-seeded storms were treated the same way, with the airplane remaining with the cloud up to a maximum of 24 minutes, or until cloud conditions seemed unfavorable for seeding.

The experimental unit was defined as the storm measured by the radar and tracked by TITAN (Dixon and Weiner, 1993), using a 30 dBZ threshold, for the time period 20 min prior to decision time to 60 min after decision time. It was important for the experimental unit to be defined objectively, to avoid possible biases between seeded and unseeded cases. If the storm did not exist 20 min before decision time, the case started at the first detection by TITAN. Similarly if the storms died before 60 min after decision time, the case ended when TITAN no longer detected it. Any mergers and splits that occur during the specified time period were included in the analysis, but any mergers and splits that occur outside the time period were 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 subsequently produced time series of storm properties that were used in the analysis.

Variables to be evaluated for differences between the sets of seeded and non-seeded storms were the same as those identified in the South African experiments as being related to the effect of seeding. Time series (every 5 minutes from decision time until 60 minutes after decision time) of the following radar measured and derived quantities were selected as response variables:

1. Radar-estimated precipitation flux (m^{-3} s^{-1}), estimated using the Marshall-Palmer Z-R relationship applied to a composite of the maximum reflectivities at any height in the storm
2. Total storm mass, where storm mass (in kilotons) is computed using the relationship m = 20300 $Z^{1.67}$, where m is in g m^{-3} and Z is the radar reflectivity factor in mm^6 m^{-3}.
3. Storm mass above 6 km MSL.
4. Storm area (km^{-2}).
5. (Height of maximum reflectivity) - (Z-weighted vertical centroid).

The time series response variables were evaluated using the 0.25th, 0.50th, and 0.75th quartiles (i.e., first three quartiles) of the distributions of the values of the variables for seeded and unseeded cases. The 0.25th quartile (1st quartile) is the value of the response variable for which 25% of the storms had smaller values. Similarly, 50% of the storms have larger and 50% have smaller values than the 0.50th quartile (2nd quartile), and 75% have smaller values than the 0.75th quartile (3rd quartile). These statistics represent the overall distributions of the response variable, and thus provide an indication of overall differences between the sets of seeded and unseeded storms.

A statistical technique called "re-randomization" was used to test the statistical significance of the differences in the 0.25th, 0.50th and 0.75th quartiles of the time series response variables for the seeded and unseeded cases at the specified times. These tests were one-tailed tests at the 0.05 level, testing the alternative hypotheses of increases in the response variables for the seeded storms. The re-randomization procedure is the same as the procedure used to evaluate results of the South African experiment (Mather et al., 1997). The re-randomization procedure computes the so-called P-factor, which is the probability (in percent) that the difference between the seed and no-seed values is a result of chance

During the summer of 1997 (PARC-97), the field project focused on beginning the randomized seeding experiment as well as continuing to collect meteorological data for further evaluation of the randomized experiment and other physical studies. Forty-six cases were selected and treated during the 3-month field project, although two cases did not meet the criteria for inclusion as an experimental unit (as specified in the Experimental Design). In 1998, the randomized experiment was continued, with the secondary objective to conduct additional cloud microphysical studies with the same basic purpose as in PARC-97. Fifty-three cases were selected in the randomized experiment during the 2-month period of operations with the radar. Three cases did not meet the experimental unit criteria, leaving a total of 94 valid cases over the two-year period: 43 seeded cases and 51 non-seeded cases.

One of the objectives of PARC was to determine if the South African results could be replicated in another area of the world. Figure 2 displays a comparison of the rain mass in seeded (solid lines) and non-seeded (dashed lines) cases for the three different quartiles as a function of time after “decision time” for the South African (dark lines) and PARC (gray lines) experiments. The rain mass is computed by integrating the precipitation flux for every minute for the period of the analyses. The differences in both the South African and PARC experiments were statistically significant after about 20 minutes and remained significant for the remainder of the period. It is clear that the results from both experiments are in good agreement. The only difference is that the storms in South Africa tended to live longer than the storms in Coahuila. The likely reason for this difference is that the atmospheric environmental winds in South Africa are stronger than in Coahuila providing for better organization of the storms. However, the differences between the seeded and unseeded storms are remarkably similar. This is a major achievement, because it is one of the few (perhaps only) instances where positive results from one program were replicated in another location. It also provides additional confidence that the results were not obtained by chance but that seeding produced a real difference in the development of precipitation in the clouds.

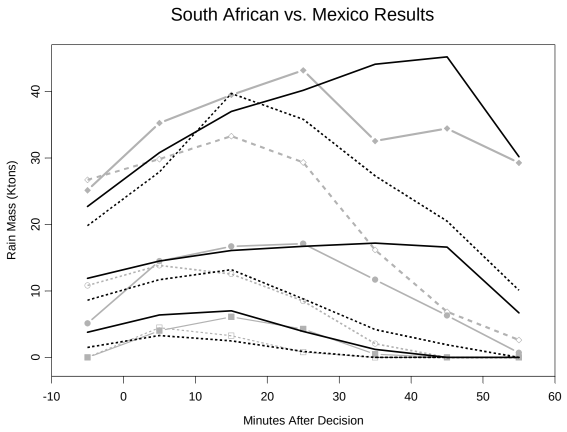


Figure 2. Quartile values of Rain Mass (Precipitation Flux integrated per minute) versus time after “decision time” for seeded and non-seeded cases for the South African (dark lines) and PARC (gray lines) experiments. 1st quartile is the value of Rain Mass that is larger than the value for 25% of the storms; 2nd quartile value exceeds the value for 50% of the other storms; and 3rd quartile value exceeds the value for 75% of the storms.

Re-randomization tests indicate that most of the observed differences between seeded and non-seeded cases for the different response variables were statistically significant at the 95% level. However, in some instances statistical significance was not reached. Thus, a small possibility exists that the apparent seeding effects may be the result of chance. Nevertheless, the results are very encouraging. It is important to note that the number of cases (94 cases) is still marginal for any statistical analysis. The South African experiment consisted of approximately 130 cases. The PARC program was planned for four years, and the fourth year would probably have provided a sufficient number of cases. However, due to funding problems, the fourth year of the experiment could not be completed.

3. United Arab Emirates (2001-2004)

Encouraged by recent results from hygroscopic cloud seeding in other parts of the world and by improved measurement systems, the government of the United Arab Emirates (UAE), through the Department of Water Resources Studies of the Office of His Highness the President, undertook a study (Phase I of the Rainfall Enhancement Assessment Program) to assess the potential benefits of rainfall enhancement via hygroscopic seeding as a means to support freshwater resources.

Past climatological studies had identified the winter season (December-March) as accounting for the bulk of rain in the UAE. Based on these studies, the UAE had conducted operational cloud seeding during the early 1990’s but without an evaluation component. Our initial field studies also took place in the winter. However, no major strong synoptic events occurred during the 2001 winter project, and studies were extended into 2002 to supplement the 2001 data. No strong systems occurred in the winter of 2002 either, emphasizing the fact that the annual rainfall in the UAE is highly variable – the standard deviation being larger than the mean.

Summer convective rainfall did not show up in the climatological studies as being very significant, but convective rainfall over the Oman Mountains in eastern UAE and northern Oman (see Fig. 3) during the summer season is a phenomenon that is widely known to local meteorologists. Although rainfall records in Al Ain (eastern UAE) show a slight indication of a summer convective component, the frequency and importance of mountain rainfall was not well documented. The UAE project therefore was extended into the summer months to document the importance and potential suitability of summer convection for rainfall enhancement.

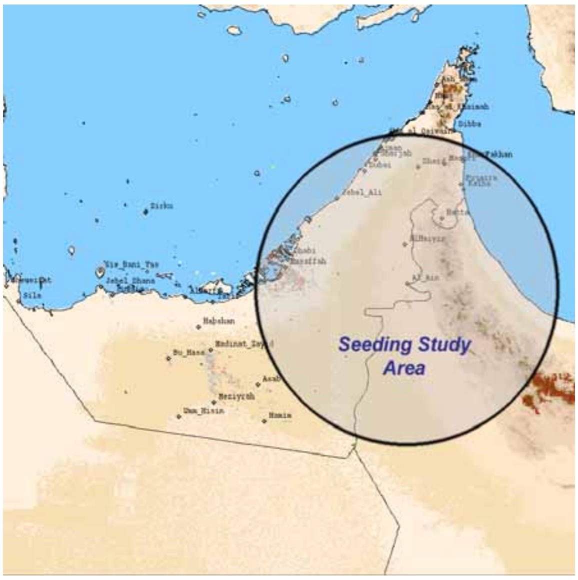


Figure 3. Map of the UAE and northern Oman with coarse topography – note the Oman mountains paralleling the eastern coast. The summer seeding

study area is highlighted, centered at the radar based at the Al Ain airport.

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. A number of convective storms also formed in the south-central sections of the UAE, and some storms extended westward from the mountains into the coastal areas of the Gulf.

Based on results from the 2001-2002 field projects, Phase II of the Rainfall Enhancement Assessment Program, consisting primarily of a randomized cloud seeding experiment, was proposed. The objectives were 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 in a subset of the randomized cases to support the statistical results and provide substantiation for the physical hypothesis.

Using radar storm characteristics from 2001-2002 over the Oman Mountains, a statistical estimate of sample size suggested that a randomized seeding experiment in the UAE would require at least two years to treat a sufficient number of cases (~250 cases), which would also require close collaboration with Oman in operating the seeding experiment seamlessly across their border.

A total of 134 cases were treated over the summer seasons of 2003 and 2004, of which 96 met the analysis criteria established in the Experimental Design. Of the 59 randomized seeding cases. Of the 75 randomized seeding cases in 2004, fifty-five met the analysis criteria. Of the 96 qualified cases, 45 were seeded and 51 were unseeded. Box and whisker plots of rain mass for the seeded and unseeded storms are plotted in Figure 4. The middle of the box is the median and the notches represent the approximate 95% confidence intervals of the median. The whiskers show the minimum and maximum extremes, and the lines show two low outliers for the seed cases. The fact that the notches overlap for the seeded and unseeded cases indicate that there is no significant difference between the two sets of cases. The same is true for all the variables that were investigated.

Figure 4. Box plots of rain mass for the 2003-2004 unseeded and seeded storms. Rain mass is in kilotons on a natural log scale.

Sounding analyses, radar studies, aerosol measurements, and case studies of microphysical development (particularly the existence of drizzle drops) have identified several possible reasons why hygroscopic seeding did not appear to be effective in the UAE clouds. For example, storm conditions over the Oman Mountains in the summer typically show that a ubiquitous subsidence inversion often suppresses convection. A weakening of the inversion, coupled with other factors such as low-level moisture or circulations creating convergence zones, leads to cycling of convective clouds and storms and often to the formation of precipitation. The radar data for several cases show that earlier convection likely pre-conditioned the region of convective development with mid-level moisture and ice particles. Subsequent cells and storms developed significant precipitation as they grew above 6 km (around -5° C). This is consistent with the concept that recycling particles into the same and adjacent turrets is an important process in precipitation development. Since no seeding occurred in these examples, the question remains whether a seeding technique designed to increase drizzle formation would have helped the precipitation process in the ‘second shift’ storms, or helped to increase particles in the initial storms, or had no effect since the process might have already been efficient. This process and others are discussed in more detail in conference papers (Breed et al., 2005; Bruintjes et al., 2005; Breed et al., 2006).

In summary, the results of the seeding experiments and cases in 2001-2002 and the randomized seeding experiment in 2003-2004 support the following conclusions:

- Surface humidity and atmospheric thermodynamic (stability) structure governs cloud dynamical and microphysical processes, affecting among other things the height of radar first echoes.

- There is no significance difference in total rain mass (the primary response variable) between seeded and unseeded storms.
- The duration of seeded storms were less than unseeded storms (~50 min compared to ~65 min).
- While the storms were treated consistently (judging from similar distributions of time differences between start of the TITAN track and decision time) between seeded and unseeded cases, the typical difference of +20-30 min is considerably late in the lifetime of an ideal case. For example, about 25% of the cases were treated more than 40 minutes after the start time of the track. This indicates that storms were treated quite late in their lifetime and non-optimally for hygroscopic seeding.
- There were no clear biases between seeded and unseeded cases at the time of treatment, but storm volumes were already substantial and relatively near their maximum at decision time. This reflects the lateness of treatment in the storm cycle mentioned above.

4. Italy (2004-2005)

Unlike the Mexico and UAE multi-year programs, the Italy program was a one season effort embedded within an operational project. We were tasked with conducting a preliminary feasibility study on the design and execution of a rainfall enhancement experiment via cloud seeding in the Puglia region of Italy (far southeastern area of Italy – see Fig. 5). The cloud seeding program was funded by the Puglia regional government through Aerotech SA of Lugano, Switzerland. Our emphasis during the 2004-2005 winter season (1 November 2004 to 31 March 2005) was on studying natural clouds – their frequency and precipitation characteristics – and on assessing their suitability for seeding based on observations and numerical modeling.

The Puglia project involved two locations: the Operations Center (with a weather radar) located at the Bari-Palese Air Base and aircraft operations based out of the Brindisi Airport (Fig. 5). An operations plan was developed to guide the collection of relevant observations in order to do the assessment. The program also involved training local meteorologists on the various aspects of a field project (e.g., forecasting, radar operations, communications, data archiving, etc.)

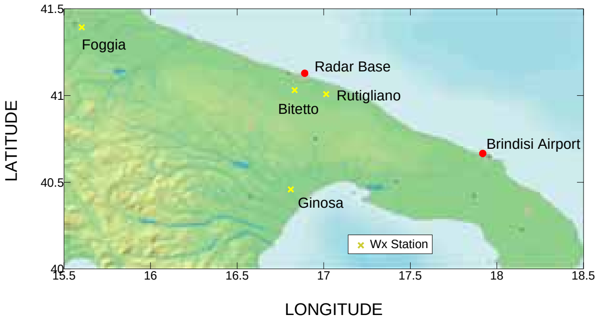


Figure 5. Map of SE Puglia showing the locations of the radar operations center in Bari and the aircraft operations center in Brindisi. (Also depicted are four meteorological surface stations that contributed to a regional analysis of precipitation distribution.)

The Puglia project was originally based on the design of an earlier project in the early 1990's. The targets were winter storms (mostly stratiform with some embedded convection) often associated with mid-latitude depressions and cold-frontal systems. Seeding was with silver iodide (AgI) in lines paralleling the coast – to the northeast. However, most of the systems did not have a substantial onshore component, which is probably one reason why the earlier project had inconclusive results. Also, the transport and dispersion of AgI into clouds at an effective temperature was not ensured with the line seeding technique.

The temperature plots of soundings indicate that seeding during the beginning and end of the 2004-2005 Puglia project period would have had to be conducted at altitudes above 3500 m MSL, while during the middle part of the project period it should have been conducted between 2000 and 3500 m MSL. The measurements of relative humidity indicate that although on a few occasions deep frontal systems traversed the region, the clouds were mostly organized in layers with most of the high-moisture levels (>80% RH) occurring below 2000 m MSL. Thus, the sounding data suggest that large parts of the cloud systems occur at warmer temperatures (>-5^{o}C) and may not have substantial regions of super-cooled liquid water (SLW) at colder temperatures for glaciogenic seeding to be effective.

Radar-derived precipitation maps were produced for each month (over two winter seasons) and show many different features. The highest monthly precipitation amounts appear to be due to more widespread or frequent organized low-pressure systems that traversed the region. There is also a shift in maximum precipitation amounts from the land in December 2004 towards the Adriatic Sea in January 2005. In fact, except for December 2004, all the months had a maximum in precipitation over the Adriatic Sea (although sometimes extending on shore). This feature could be due to gravity wave activity initiated by the mountains upwind of the area or, more likely, to local land-sea breeze circulations. Although previous cloud seeding operations in the Puglia region have attributed the increase in precipitation over the Adriatic Sea to seeding, it is clear that this is a common natural phenomenon.

The seeding operations with the aircraft were severely limited, because the project aircraft were not certified for flight into IFR and known-icing conditions. Because of these limitations, seeding was always conducted at or below cloud base. This likely minimized the effects of seeding, because in frontal cloud bands, the seeding material rarely reached the regions of SLW due to the stably stratified flows in these winter frontal systems. However, in the convective cloud situations, seeding may have been effective because of stronger updrafts lifting seeding material to higher altitudes. Successful seeding depends almost entirely on the accuracy of dispersing the seeding material only in updrafts and SLW regions. The lack of aircraft measurements and cases of in-cloud seeding required a different approach to assessing seeding potential.

Numerical simulations with explicit and detailed microphysical parameterizations were designed and conducted to investigate the effects of seeding. The Weather Research and Forecasting (WRF) model was used for this purpose and included a separate module to simulate the dispersion of tracer (seeding) material from a pre-determined location, either as a point source or a moving source. This flexibility allows for representation of both ground-based generators (point source) and aircraft-based generators (moving source). One of the cases that were simulated occurred on 9 December 2004.

The initial simulation was designed to mimic cloud base seeding, but the results indicated that the seeding tracer material was never transported to temperatures colder than -5°C, remaining below 800 hPa for the entire period. Although the seeding material dispersed within the lower cloud water regions, these regions were at temperatures warmer than 0°C where seeding with AgI would have no effect. It suggests that cloud-base seeding in winter frontal stratiform cloud systems would be largely ineffective. While the use of moderate seeding rates resulted in some isolated regions of high concentrations of cloud ice, the increases in ice were marginal and insufficient to result in additional growth to snow unless AgI is activated in a region of SLW.

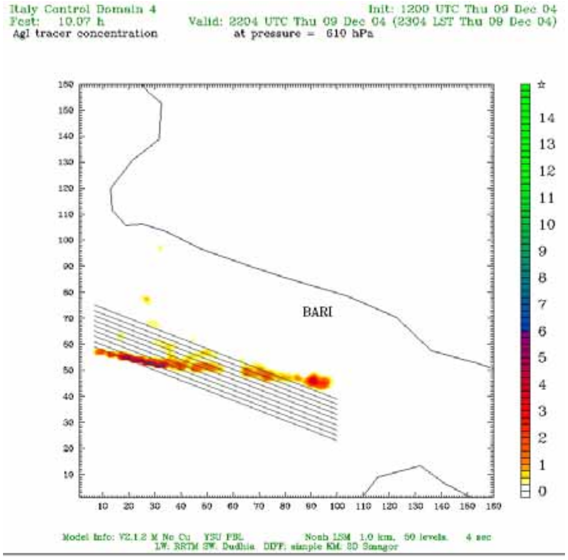
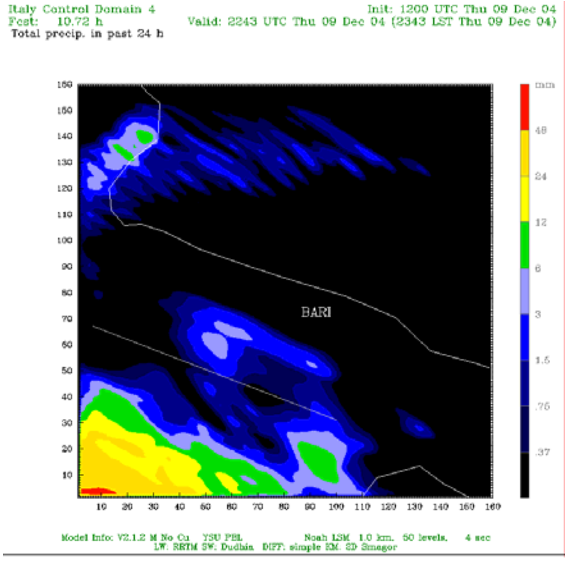


Figure 6. Horizontal cross-section at 610 hPa of the seeding plume at 2204 UTC on 9 December 2004.

Using results from the first simulation to optimize the seeding strategy, the subsequent simulation showed more definitive changes in cloud ice, snow, and reflectivity. Figure 6 shows one track of the simulated seeding plume at a level closer to the maximum in SLW. A comparison of between the control and seeded model runs shows that seeding at this level eventually led to 50-100% increases in accumulated precipitation over a significant area SW of Bari some 45 min after seeding (Figure 7).

a.



b.

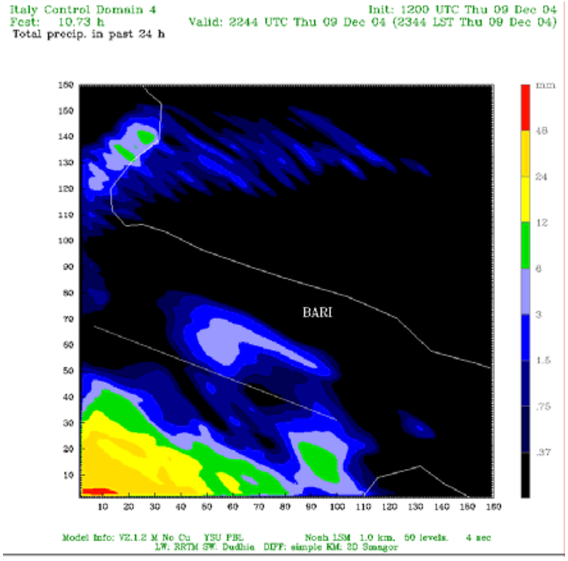


Figure 7. Model-generated accumulated precipitation at 2245 UTC on 9 December 2004 for the control run (a.) and seeding run (b.). Color scale is logarithmic (base 2) – doubles in value (mm) at each level.

These model results indicate that seeding material needs to be directly injected into regions of substantial amounts of SLW at temperatures between -5° and -15°C. Otherwise, seeding will not have a significant effect on precipitation in winter frontal stratiform-type cloud systems. The results also indicate that mixing of the seeding material in these cloud systems is very limited and that neither cloud-base nor cloud-top seeding is likely to be effective. Nonetheless, the modeling work verifies that AgI can produce significant amounts of cloud ice and precipitation. These results emphasize the point that seeding should be done according to the design of the Puglia seeding mission as put forth in the Operations Plan, requiring the capability of flying into or above regions of significant SLW.

5. Indonesia (2005)

The feasibility study for the augmentation of rain in Sulawesi, Indonesia was, like the Italy program, embedded within an operational seeding project but consisted of an even shorter term field campaign. The program was funded by a local nickel plant, PT INCO Indonesia, through the Indonesian government Agency for the Assessment and Application of Technology (BPPT) and contracted to Weather Modification Inc. (WMI). The field program occurred during a 35-day period when convective clouds frequently develop over the Soroako region in Sulawesi. The objective of the study was to document the microphysics and dynamics of natural clouds including some seeding trials using an instrumented cloud physics aircraft. The cloud physics aircraft collected data in both natural and treated clouds, prior to and, in some cases, following seeding.

Figure 8. Map of central Sulawesi showing the target area (watershed) covered by the project radar at the Soroako airport.

The stated objectives and actions of the April-May 2005 program were to:

a) Develop a basic understanding of the natural cloud characteristics and precipitation processes occurring within the clouds near Soroako. Specifically, the natural microphysical characteristics of the warm and cold clouds were documented between cloud base and the -10^{o}C level. Natural and anthropogenic aerosols were sampled to determine their effect on precipitation processes.

b) Test the concepts of the South African and Mexican methods of hygroscopic seeding in Soroako by conducting hygroscopic seeding experiments using hygroscopic flares of the latest design.

c) Test the most recent concepts of glaciogenic seeding using modern formulations of silver iodide (AgI) flares in Soroako by conducting AgI seeding experiments.

d) Document the time history and evolution of hygroscopic and glaciogenic seeding experiments using both in-situ microphysical measurements and radar.

e) Determine whether there is an effect on radar-derived storm-based rainfall from hygroscopic and glaciogenic seeding.

f) Implement the MM5 high-resolution atmospheric model in order to support the physical measurements.

g) Gather information in order to propose a multi-year research program that will determine whether investment in cloud seeding is a viable water management technology for PT INCO and the Government of Indonesia.

The Sulawesi conditions were unique in that large contrasts were evident that appeared to have large impacts on the clouds and precipitation. For example, the INCO smelter plant had a distinctive plume that could be traced directly to some clouds. One example of the aerosol size distribution of the INCO plume (with distance) is shown in Figure 9. The red line represents the size distribution of clean air while the INCO plume is easily identified with highest concentrations nearest the plant.

The effects of the INCO plume are also quite evident in the droplet distributions of clouds ingesting the aerosols. Figure 10 shows time series data for four penetrations with the resulting droplet size distributions. An interesting result is that all the penetrations, even though they represent passage through “dirty” air, have broad size distributions. This suggests that the clouds would develop rain through the coalescence process rather quickly.

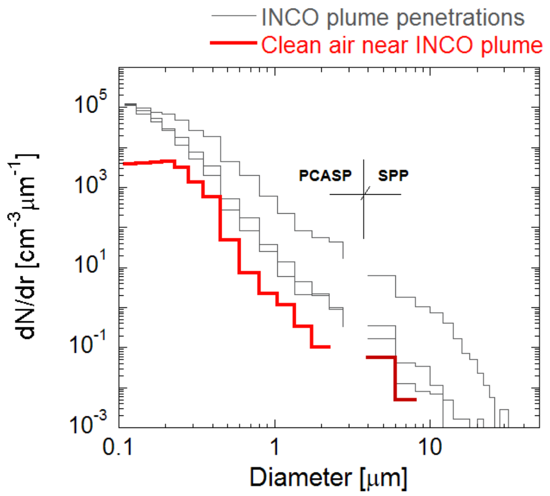
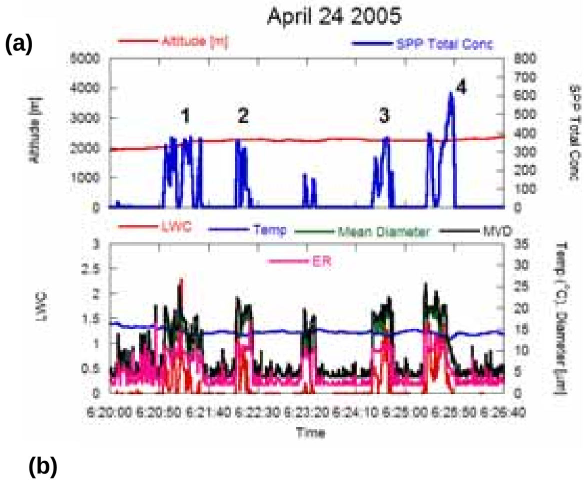


Figure 9. Size distributions of aerosol particles for different time segments and for the clean background samples (red line). Measurements are from PCASP and FSSP probes.

The results from the radar observations confirm some of the microphysical observations. The first echo analysis in Figure 11 shows all the storms had an active warm rain process, indicating that especially during May, clouds in the Soroako region developed precipitation efficiently. In these situations, seeding should have had no effect. These results are not totally unexpected, because with rain occurring on nearly all days in an especially wet season such as the 2005 season, the atmosphere would be very clean due to the continuous washout of aerosol particles.



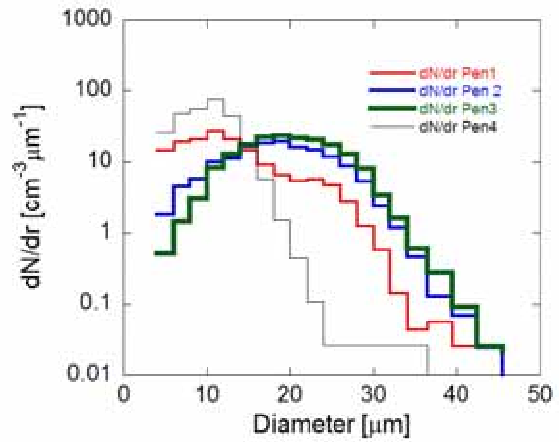


Figure 10. (a) Time-series of altitude (m), cloud droplet concentration (cm^{-3}), temperature (^{o}C), liquid water content (LWC, g m^{-3}), mean droplet diameter (MD, µm), mean volume diameter (MVD, µm), and effective radius (ER, µm); and (b) droplet size distributions for the four penetrations marked in (a) – near cloud base.

Although limited in scope and timeframe, these detailed cloud physics measurements provide a framework in which to evaluate cloud seeding efforts. General characteristics, conclusions, and relevant comments from these observations are summarized:

1. Low background aerosol and CCN concentrations (<300 cm^{-3}) are prevalent, except in areas affected by the INCO smelter plume where aerosol concentrations are enhanced by one to two orders of magnitude. The INCO smelter plume aerosols are concentrated in the accumulation mode (<0.1-0.5 µm diameter), although larger particles are present in close proximity to the smelter.

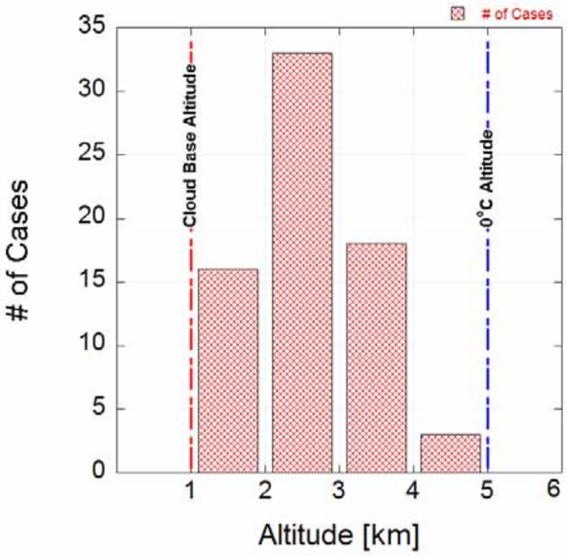


Figure 11. First-echo analysis from 1 May to 15 May 2005 for isolated TITAN storms developing in the

vicinity of the Soroako radar (30-80 km). Seventy cases are represented in this plot. (The first echo in all cases was <25 dBZ.) The dashed red line represents the average altitude of cloud base and the dashed blue line shows the approximate altitude of the 0°C level, both obtained from sounding data.

2. Background cloud droplet concentrations are consistent with the CCN measurements and generally less than 300 cm^{-3}, but again are elevated (up to 800 cm^{-3}) in clouds affected by the INCO plume.
3. Cloud droplet sizes increase rapidly in clouds with height in the Soroako area, and coalescence generally becomes effective within 1000 m above cloud base, indicating a very efficient "warm rain" process. In clouds affected by the INCO plume, this process is delayed because of the higher droplet concentrations and somewhat smaller droplet sizes, but coalescence becomes active approximately 2000 m above cloud base.
4. In all clouds (natural and those affected by the INCO plume), drizzle and rain drops are present at the 0° to -5°C level as convective cloud tops rise through these levels.
5. Drizzle and rain drops generally freeze around the -5°C level and activate a natural ice seeding (ice multiplication) process in all Soroako clouds (both natural and those affected by the INCO plume). However, the INCO-plume affected clouds generally have more cloud liquid water available at the colder temperatures.
6. The radar first-echo analyses indicate that the first echoes are all initially produced by the "warm rain" process.
7. The freezing of drizzle and rain drops at -5°C in combination with the natural seeding process provides for the freezing of a large amount of supercooled liquid water content between the -5° and -10°C levels.
8. The freezing of the water produces latent heat that enhances buoyancy in the cloud and results in increased updrafts which in turn results in a more active and larger cloud with more rain over a longer period.
9. This is consistent with the dynamic seeding hypothesis as discussed in the next section, but in the case of the Soroako clouds, it also occurs due to the natural seeding process. This effect may be enhanced in clouds affected by the INCO plume as discussed in the Section 7.
10. The radar echo analyses indicate that storms and rainfall occur on most days during the period March to early May in the Soroako region.
11. The storms generally develop during the early afternoon, but new development continues throughout the early evening hours and often extends well into the night.
12. Precipitation during the night period results mostly from light to moderate continuous stratiform-type rainfall, probably from the remains of afternoon and early evening thunderstorms.
13. The lake-land circulation seems to enhance rainfall during the night along the shores of Lake Matano in particular. Whether the INCO plume also plays a role in these nighttime rainfall events is not clear, because no aircraft measurements were obtained during the late night periods when this type of rainfall generally occurred. In addition, these periods of rainfall seem to be more dominant in late April and early May, just before the onset of the dry season.
14. The plume from the INCO plant generally only affects clouds growing along the shores of Lake Matano and does not seem to affect clouds growing in the Lake Towuti catchment area.
15. The mean lifetime of the storms is between 30 and 60 minutes, but a significant number of the radar-tracked storms lived longer than 2 hours with a few cases during stratiform rain events lasting for more than 4 hours.
16. Storm tops showed a tendency to decrease from March to May. This indicates that the rainfall during March was from storms with greater vertical depth than during May. This is consistent with subjective (visual) observations, which indicated that more thunderstorms during March had cloud tops colder than 0°C than storms during May.
17. One explanation for the higher cloud tops during early March could be that the air contained larger concentrations of background or natural aerosols and thus clouds had to grow to higher altitudes before developing precipitation. There are no *in situ* cloud physics measurements to verify this however. Another explanation could be that the thermodynamic structure and the vertical profile of winds were different during March than in April-May.

Based on the observations, it is clear that the Soroako clouds observed from 15 April to 15 May 2005 do not satisfy the primary criteria for seedability with hygroscopic flares. These criteria are the requirements of a narrow cloud base droplet spectra and a high concentration of droplets. The measurements taken during April and May 2005 in the Soroako region indicate that the cloud droplet size distributions are typical of maritime environments and that only the clouds affected by the smoke from the INCO plume may potentially satisfy these criteria. However, even in some of these affected clouds, large cloud droplets were already present although in lower concentrations compared to the natural background clouds not affected by the INCO plume. In the clouds affected by the INCO plume, coalescence was somewhat delayed initially.

Concentrations of precipitation-size particles increase rapidly at temperatures colder than 0°C, although a large fraction of the penetrations at warmer temperatures apparently already encountered drizzle and rain. Perhaps more interesting is the large concentrations (>100 L^{-1}) at the coldest temperatures (-5° to -10°C) with only a small fraction of the penetrations at temperatures colder than 0°C having no 2DC counts. Precipitation development through the ice phase with high concentrations of particles may be indicative of an active natural ice-multiplication process (H-M process; Hallet and Mossop, 1974), which would be consistent with the cloud droplet spectra and large drop measurements.

Exploring the characteristics of the precipitation-size particles in more detail indicate that the concentrations increase rapidly at temperatures colder than 0°C with an associated increase in ice water content. The particle image data collected in numerous penetrations support the earlier findings, showing drizzle and raindrops already present at the 0°C level indicating an active coalescence process. The large drops appear to freeze around -5° to -8°C and activate the H-M secondary ice process, with mostly needle and small irregular ice particles present around the -6° to -7°C level. Due to the large concentrations of ice particles, the clouds glaciate rapidly with mostly ice present around the -10°C level as the smaller ice particles from lower levels grow in the updrafts to larger sizes.

The development of ice and precipitation described above has important implications for cloud seeding experiments. First, because an efficient collision/coalescence process is already active and very efficient in the Soroako clouds, hygroscopic seeding should have a minimal impact, because the goal of seeding with hygroscopic flares is to enhance the onset of the coalescence process. Secondly, because ice is already observed in large concentrations between -5° and -10°C, glaciogenic seeding with AgI may result in the cloud glaciating more rapidly and could potentially provide for a less efficient ice and precipitation formation process. This is due to faster depletion of liquid water and hence decreased growth of ice crystals via the riming process (ice crystals collecting droplets), resulting in only small ice crystals that are not able to precipitate out of the cloud. However, it is uncertain if this is a common feature in Soroako clouds and needs to be further explored.

Based on these results, it can be concluded that glaciogenic seeding with AgI flares will not have the same effect on Soroako clouds as in other parts of the world where such experiments have been conducted. Although glaciogenic seeding might have some effect, the effect would be much reduced in Soroako clouds and precipitation increases due to seeding will probably be less. However, this picture may change substantially if the AgI flares were able to freeze cloud water at temperatures between 0° and -5°C. An effort should be made to develop a flare or devise a technique that is able to freeze water at these warmer temperatures.

6. Wyoming (2005-2010)

The Wyoming Weather Modification Pilot Project is a multi-year program funded by the state of Wyoming to develop operational infrastructure and techniques but with an evaluation component for assessing the results of any seeding. The operational contract is being fulfilled by WMI, while the evaluation is being contracted NCAR/RAL. The overall goal of the pilot project is to seed winter orographic storms in three Wyoming mountain ranges (Medicine Bow, Sierra Madre, and Wind River) with silver iodide (AgI) and then evaluate the impacts of the seeding, if any, on the snowpack. Based on past studies, the expected impact of seeding is to increase snowfall and hence the snowpack, but hard evidence of increased snowfall and particularly the amount of increase is scanty. Therefore, a further goal of the pilot project is to quantify the impacts, if possible, and understand the steps leading to the impacts. Other potential impacts from seeding that are to be examined include environmental impacts due to the use of AgI and effects on precipitation downwind of the target areas.

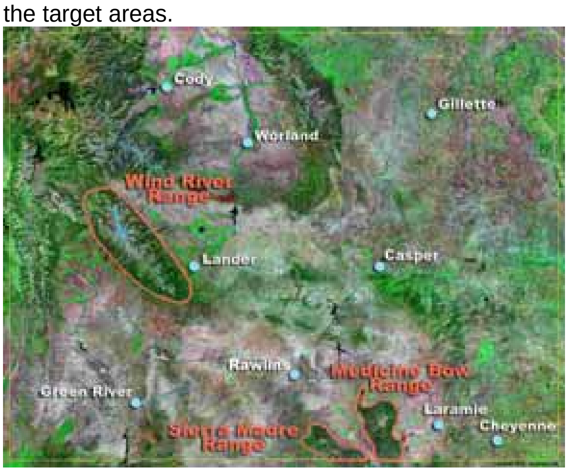


Figure 12. Map of Wyoming roughly depicting vegetation areas (such as forests, scrub brush, etc.). The target mountain ranges are outlined in red.

The three ranges of interest – Medicine Bow, Sierra Madre, and Wind River – are individually large areas (see Figure 12), and together are very challenging for designing and implementing a seeding program. Some of the challenges include their wide separation (although wind flows and storms affecting the Medicine Bow and Sierra Madre may cause some interactions between those ranges), the different modes of seeding to be investigated (ground-based and airborne, AgI generators and AgI flares, etc.), the sparse data networks compared to the size of the areas, and the myriad of agencies involved in permissions and restrictions for siting equipment, making measurements, and generally operating a cloud seeding program.

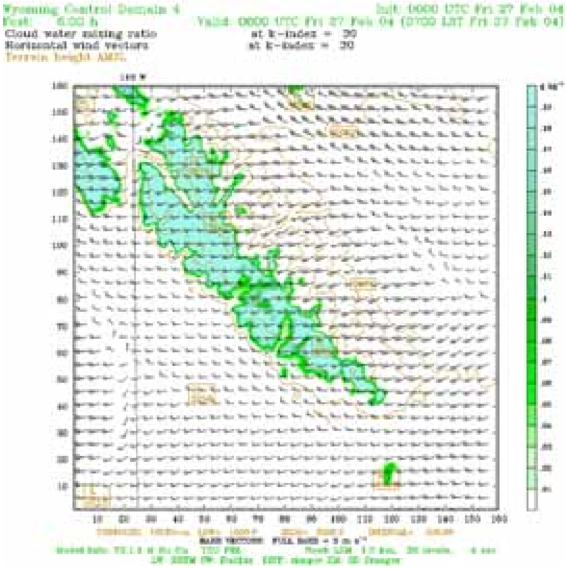


Figure 13. WRF model 6-hr forecast of cloud water mixing ratio (scale on right) and horizontal wind vectors for 27 February 2004 case over the Wind River Range.

The evaluation entails two general approaches; a randomized experiment that builds distributions of seeded cases and control (unseeded) cases, and physical studies to document the steps or chain of precipitation formation events hypothesized to be important to snowfall production in orographic storms. One of the main tools in the evaluation effort is the WRF model, using nested grids (to 0.5-1-km resolution) with detailed microphysics. Figure 13 shows an example of the cloud water field output by the WRF model during a strong west wind case in the Wind River Range. The model is used both as a forecast tool for identifying seedable conditions and as an evaluation tool for evaluating plume transport, snow development, potential downwind effects, etc. So, along with adequate measurements to statistically evaluate snowfall in the ranges, auxiliary data will be collected to validate all details of the model. This line of study continues to evolve rapidly, which consequently requires some flexibility in the collection and use of measurements in model validation and evaluation.

Other monitoring and evaluation methods that will be used, locations where they will be implemented, who will implement the methods, and when they will be implemented, are as follows:

- weather prediction and seeding agent targeting (WRF numerical model);
- measurement of cloud characteristics and response to seeding (microphysical instrumentation) including cloud droplet size and number, ice crystal size, shape, and number, atmospheric aerosols, liquid water content, temperature, pressure, and dew point;
- upper air measurements (instrumented weather balloons);
- statistical analysis of precipitation (high resolution precipitation gauges, SNOTEL, WRF);
- evaluation through the detailed analysis of physical measurements (super-cooled liquid water and ice particle development) of the clouds and their response to seeding using airborne (*in situ*) instrumentation;
- evaluation of clouds and their response to seeding through the detailed analysis of physical measurements (super-cooled liquid water and ice particle development) using ground-based instrumentation (passive microwave radiometer);
- precipitation development over generator sites for seeded and non-seeded storms using weather radar (1-2 winters 30-40 days at a time) and satellites to analyze the seeding effect;
- trace chemistry analysis for background silver content in surface water, soils, and vegetation;
- snowpack samples for naturally-occurring (non-seeded) storms to determine silver content in snowpack (prior to seeding operations);
- snowpack samples for selected seeded storms to determine silver content and effectiveness of targeting;
- snowpack monitoring with high resolution precipitation gauges, SNOTEL sites and auxiliary measurements of snowfall characteristics and snow-water equivalent (i.e., hotplate, disdrometer) every season beginning 2005-2006;
- measurements of natural cloud characteristics and cloud responses to seeding using additional *in situ* instruments and remote sensors that may deployed as part of other research projects located in or near southeastern Wyoming and the Wind River range.

Completion of the Experimental Design, deployment of the ground-based generators, adding air motion and ice nuclei instruments to the aircraft, development of operational procedures, and gaining permissions for deployment of auxiliary instruments are still in progress or just being completed. Further details of the Wyoming program may be presented at the symposium.

7. SUMMARY

Five programs in which NCAR/RAL scientists have participated over the past ten years involving feasibility studies for assessing cloud seeding have been described. In Mexico, the hygroscopic seeding technique, developed and tested in South Africa, was successfully replicated. However, the program first required the development of infrastructure and a season of detailed microphysical studies to ensure that conditions were sufficiently similar between the two regions. In the UAE, initial studies were also needed to identify the summer season and convective clouds as the most promising weather conditions to investigate hygroscopic seeding, contrary to earlier climatological studies. However, the randomized seeding experiment using hygroscopic flares did not provide positive results. The concurrent physical studies were important in explaining the ineffectiveness of hygroscopic seeding and emphasized the importance of accounting for cloud dynamics in conceptual models. The UAE program also involved an expanded effort to characterize aerosols and their effects on clouds. Contrary to the multi-year field programs of Mexico and the UAE, the programs in Italy and Indonesia were short-term efforts embedded within operational programs. The Italy program demonstrated the usefulness of numerical modeling on potential seeding strategies, and highlighted the importance of characterizing storms (frequency and type) to identify opportunities for potential cloud seeding. It was also different from the previous programs in that it was a winter program using AgI seeding methods. The Indonesia program showed the importance of aerosols on clouds, and again emphasized the importance of detailed microphysical and radar measurements in characterizing storms. The results from that very limited study were rather negative with regards to rain enhancement from cloud seeding. Wyoming is another multi-year effort with a randomized seeding component but differs in its goals of snowpack enhancement and evaluation of two seeding methods – airborne and ground-based. Major difficulties in that program will be securing observational resources to adequately cover large data poor regions.

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