6.2

USE OF ACOUSTIC ICE NUCLEUS COUNTERS TO MAP SURFACE-BASED SEEDING PLUMES IN WYOMING

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1. INTRODUCTION

A critical factor in the success of any cloud seeding program is the ability to consistently deliver seeding agent in quantities sufficient to alter the intended clouds. This is generally referred to as “targeting”.

Many winter orographic programs have failed for lack of effective targeting, or have failed and not confirmed that targeting was routinely effective, leaving the question unanswered.

The Wyoming Weather Modification Pilot Project (WWMPP) randomized statistical experiment uses sixteen remote-controlled ground-based ice nucleus generators to produce glaciogenic aerosol intended to target very limited portions of two mountain ranges in south-central Wyoming (NCAR 2007). Eight generators are sited on the western flanks of each range (Figure 1).

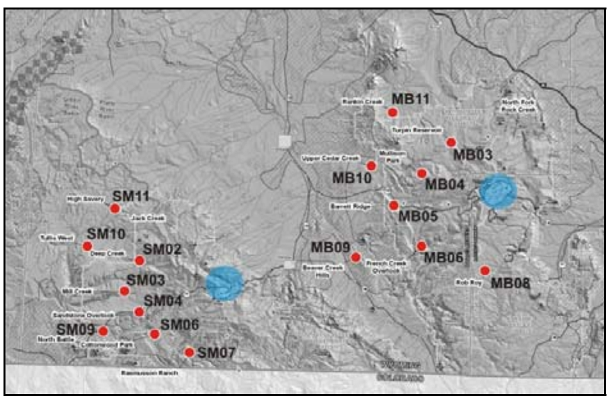

Figure 1. The locations of the ground-based ice nucleus generators for the Sierra Madre (left) and Medicine Bow (right) ranges, used in the 2007-2008 season. The generators are shown by the red dots, and the approximate target locations as delineated by the NCAR statistical design by the blue circles.

Detailed descriptions of the randomized statistical experiment design are provided by Pocernich (2008) and Breed (2008) in companion papers within this conference.

Given the importance of the targeting question, efforts have begun to acquire physical evidence of targeting efficacy.

2. THE GLACIOGENIC AEROSOL

The ground-based ice nucleus generators deployed in the WWMPP burn a 2% AgI solution at a rate of approximately 1.5L (0.40 gallons) per hour. The solution is comprised of silver iodide, ammonium iodide, sodium perchlorate (monohydrate), para-dichlorobenzene and acetone, as described by DeMott (1997). The resulting aerosol functions by the condensation-freezing mechanism (Figure 2).

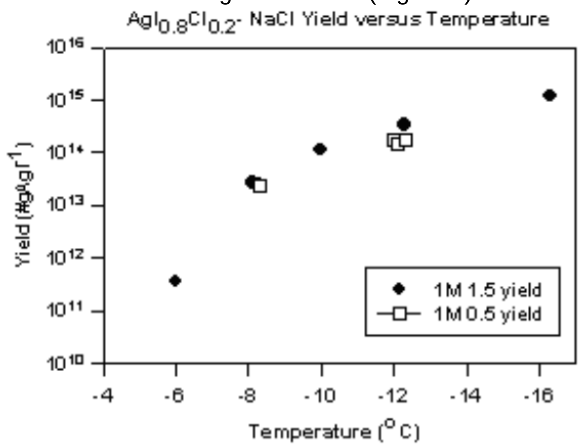

Figure 2. Ice nuclei yield is plotted as a function of cloud temperature (from DeMott 1997). While limited activity is found at -6°C, activity increases substantially at temperatures colder than -8°C. The black diamonds (⊄) denote cloud liquid water content of 1.5 g m^{-3}, while the boxes (9) denote a cloud liquid water content of 0.5 g m^{-3}.

3. THE ACOUSTIC ICE NUCLEUS COUNTERS

Two acoustic ice nucleus counters (AINC) were employed during the 2007-2008 season. Both units are described in detail by Heimbach *et al.* (2008). The ice nuclei produced by the ground generators are readily detected by these AINCs.

The AINC owned by WMI was first flown during the 2006-2007 WWMPP season. This served as a shake-down for the instrument, but nonetheless, an initial late-season plume-mapping effort was successful.

The WMI unit was returned to the field for the 2007-2008 season, and operated as opportunities and staffing allowed. The author notes that to his knowledge no AINC is truly a “turn-key” instrument; as each of the five systems (cooling, humidifying, atomizing, deicing, and flow) requires careful monitoring and adjustment.

The second AINC, obtained from A.B. Super, was operated at high elevation on the eastern slope of the Medicine Bow Range, within 2 km of the target area precipitation gauges, during the month of February 2008.

3.1 Airborne Plume Detection Requirements

The initial plan was straightforward: fly the aircraft when visual flight rules (VFR) applied over the Medicine Bow and/or Sierra Madre ranges, while operating one or

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more of the ground-based ice nucleus generators. The VFR flight (during daylight only) would allow the aircraft to descend low enough to encounter the plume(s), the horizontal and vertical extent of which could then be mapped by repeated reciprocal passes perpendicular to the mean wind direction, at varying altitudes and distances downwind. Ideally, such flights would be conducted beneath mid-level or high overcast, and insolation (and convection) would be limited.

For such missions to replicate seeding conditions as closely as possible the wind speed and direction should be comparable to those required for seeding. Temperature was less important to the extent that the AINCs have their own supercooled clouds. However, warmer atmospheres tend to be more convective, so ultimately temperature proved to be a factor as well.

The WMI AINC was securely anchored to the seat rails of the aircraft aft of the data system and seating, in the only possible location with the aircraft configuration. While functional, this location was not ideal, as the requisite monitoring of its many systems required the operator (the author) to frequently leave his seat. Flight at low levels over mountains in significant cross-barrier flow is seldom smooth. Though a tool box (also anchored) provided a makeshift seat (Figure 3), the operator's presence aft was limited by necessity.

Figure 3. The author is shown aft in N234K, noting the condition of various AINC systems. A forepump attached to the sampling inlet was used to ensure adequate sampling of air external to the pressurized cabin.

3.2 Surface Plume Detection Requirements

There were far fewer operational constraints upon the ground-based AINC. The unit was situated in a small cabin located at the Snowy Mountain Lodge at 3.03 km (9,950 feet) AGL. The unit could be (and was) operated any time, day and night, beneath clear skies and in snowfall. In all, there were four different modes of operations for the ground-based AINC:

1. In concert with the airborne plume-tracing missions.
2. Independent of plume-tracing missions when randomized seeding was not being conducted but when flow and weather was thought to be similar to that required for seeding.
3. Whenever flow was thought to be sufficient to transport IN from a generator to the surface AINC.
4. When the University of Wyoming cloud radar missions were being flown (Geerts 2008).

Collectively these provided many opportunities during the one-month deployment.

Though sited close to the Medicine Bow Range WWMPP target gauges and at a similar elevation, the location was not ideal. The cabin housing the unit was located in a well-timbered area slightly lower than the target (Figure 4). Winds would accordingly be reduced, and flow frequently swirled.

Figure 4. The cabin housing the ground-based AINC was located in old-growth forest. The simple copper sampling inlet is seen on the left, and was run through the window seen behind and slightly left of AINC operator Jack McPartland.

4. PLUME DETECTION EFFORTS

The 2008 season plume detection and mapping efforts are summarized in Table 1. Airborne and ground-based detection was attempted twice. The University of Wyoming flew their cloud radar on two days and the ground-based AINC was operated during both missions.

Actual “cases” for inclusion in the randomized statistical experiment were called twice during February, and the ground-based AINC was operated both times. In addition, the ground-based AINC was operated “solo” on four other occasions, for a total of 12 events. Each of these is summarized in the following sections.

4.1 Airborne Tracing – 26 January

Conditions were favorable for a plume tracing flight on 26 January 2008, and the aircraft took at 2053 UTC, bound for the Medicine Bow Range.

However, shortly after takeoff a leak in the glycol (anti-frost) pump for the cloud chamber forced the mission to be aborted. No data were obtained.

TABLE 1. PLUME DETECTION SUMMARY						
Case ID	Date	Start/Stop (UTC)	Mission Type Airborne	Ground	Max Conc (/L)	Mode
A1	26-Jan	2053-2101	A		*	airborne
G1	7-Feb	0000-0400		G	1	case
G2	11-Feb	2130-2330		G	2	UWyo flight
G3	16-Feb	1725-1930		G	1	air/ground
A2		1745-2012	A		3	
G4	18-Feb	1921-2324		G	11	ground
G5	22-Feb	2100-0000		G	8	air/ground
A3		2113-0012	A		242	
G6	23-Feb	2000-2200		G	<1	ground
G7	24-Feb	2129-2229		G	56	ground
G8	25-Feb	2200-0000		G	44	UWyo flight
G9	26-Feb	0215-0615		G	24	case
G10	28-Feb	1800-2000		G	1	ground
A4	28-Mar	1800-1910	A		**	airborne
*glycol pump failure after takeoff forced mission to be aborted						
**cloud chamber only cooled to -8C, so counts are radical underestimates						

4.2 RSE Case – 7 February

A randomized seeding case was declared beginning at 00Z on 7 February 2008, and the ground-based AINC was activated accordingly.

The maximum IN concentration observed during the period was no more than 1 L^{-1}. Light snow was observed during much of the period.

4.3 Cloud Radar Flight – 11 February

The University of Wyoming King Air flew a cloud radar mission on 11 February, and two ground-based generators were operated for a period of two hours. The SML AINC was operated throughout the period, which included some periods of moderate snowfall.

The maximum observed IN concentration never exceeded 2 L^{-1}. However, it should be noted that only two of the three ground generators originally requested for the test were operational. Though MB03 and MB05 functioned without difficulty, MB04, the optimum generator for targeting the SML, was unavailable. This was known to be the case before the flight, but because the aircraft would cover a significant fraction of the range the flight proceeded as originally planned.

4.4 Combined Air & Ground Tracing – 16 February

The afternoon of 16 February 2008 was cloudy over the Medicine Bow and Sierra Madre ranges, with brisk westerly winds prevailing at all flight levels. The aircraft (N234K) took off from Rock Springs at 1725 UTC.

Though the RT-FDDA winds forecast for the Medicine Bow Range were not ideal for targeting the SML AINC, MB04, MB05, and MB10 were activated at 1730 UTC. The SML AINC began data collection at 1745 UTC.

Upon arrival at the Medicine Bow Range it was quickly determined that the orographic clouds would preclude sampling immediately downwind of the generators, as they were all in cloudiness. A broad racetrack pattern was flown over the North Platte River Valley in the hopes that the clouds would retreat enough to allow some low level sampling, but they did not.

The decision was made to sample with the aircraft downwind of the range. The air was very rough even several km downwind, and several passes failed to detect any real semblance of an IN plume.

Results at the SML were very similar, though for brief periods IN concentrations near 3 L^{-1} were observed.

It had been recognized in advance that conditions were not ideal for this kind of work, and the crews were not shown otherwise.

4.5 Ground Detection – 18 February

Two generators, MB04 and MB03, were activated at 1922 and 1924 UTC, respectively. The SML AINC began data collection at 1945 UTC. Weather at the SML was characterized by most clear skies, but with occasional cirriform cloudiness.

By 2100 UTC IN concentrations exceeded 3 L^{-1} and continued to increase, maximizing at 12 L^{-1} by 2245 UTC. After 2300 UTC the observed IN concentrations decreased markedly, even though the generators continued to run until 2320 UTC. It is surmised that a gradual wind shift changed the targeting. With just two generators operating this would not be unexpected.

Though it was encouraging to observe IN concentrations greater than a few per liter, greater numbers would be desired.

4.6 Combined Air & Ground Tracing – 22 February

A second combined airborne and ground-based tracing and detection effort was attempted on 22 February 2008. On this day the winds over the Medicine Bow Range were forecast to be southwesterly, so MB04, MB05, MB06 and MB09 were all selected and activated just prior to 2100 UTC. The SML AINC began data collection at 2030 UTC and the aircraft took off at 2113 UTC. The Medicine Bow Range and nearby Elk Mountain both had orographic cloudiness (Figure 5), which heightened the plume tracing degree-of-difficulty.

Figure 5. Showers were present over the Medicine Bow Range at 2246 UTC. Cloud coverage shifted throughout the mission, complicating efforts to sample in a methodical fashion.

Initial passes were flown several miles downwind of the active generators, with no pronounced "hits". Winds within ~300 m (1,000 ft) of the surface over the Medicine Bow Range varied from 4 to 8 m s^{-1}, typically from 210-220 degrees. Significant shear was present, however, as winds at altitudes > 3.3 km (~11,000 ft) were seldom less than 10 m s^{-1}, and more westerly, from 240-250 degrees. The aircraft encounters of IN are plotted with respect to aircraft position in Figure 6.

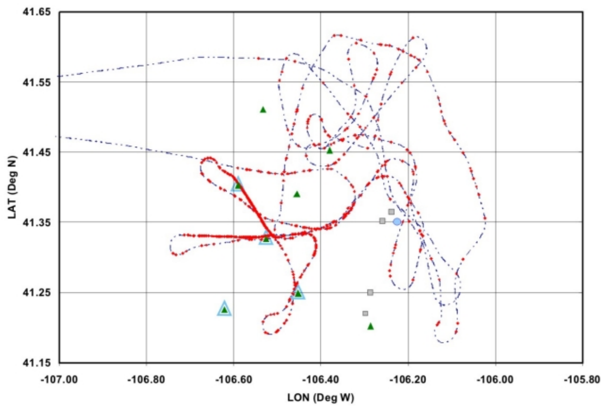

Figure 6. Triangles mark the positions of seeding generators. Grey squares show the locations of project high-resolution precipitation gauges. The small blue dot at about -106.00 longitude and 41.35 latitude shows the location of the SML. The four generators operated for the 22 February 2008 study are denoted by the larger, light blue triangles. Airborne encounters with IN are shown by the red symbols plotted along the aircraft track.

The SML AINC reached operating temperature at 2035, when data collection began. Clouds motion was initially reported to be westerly, with a "breezy WSW wind". Except for a hint of a plume between 2200 and 2215, no significant IN concentrations were measured. By 2230, "a few flakes" were observed, and by 2300, broken skies with less wind.

At ~0000 UTC all four generators were shut down. At that time winds at the SML were recorded as, "very light, almost dead calm." However, over 45 minutes after generator shutdown, IN began to be recorded at the SML. This continued for 30 min, at which time an "absolute" clean air filter was placed on the AINC intake to verify the authenticity of the apparent IN. The recorded IN immediately dropped to zero, but returned upon removed of the filter. At 0200 UTC, two hours after generator shutdown, the IN observations approached background levels, and the AINC was finally shut down.

Though numerous encounters with IN plumes were recorded, the relatively light winds and variable direction made mapping of plume extents difficult. Matters were further complicated by the presence of clouds and precipitation over the range.

This case is deserving of more in-depth analysis, as clues to plume behavior in light winds may be discerned. The good news from this case is that it is possible to conduct at least quasi-successful airborne tracing flights even with limited clouds and precipitation.

4.7 Ground Detection – 23 February

Another "solo" ground detection effort was made on 23 February 2008. Ground generators MB04 and MB05 were both operated for a two-hour period beginning at 2000 UTC. Data collection with the SML AINC commenced at 1952 UTC.

Conditions at the SML varied from scattered orographic cloud to overcast with very light snow. Winds were light throughout.

No discernible IN plume was detected, and data collection was terminated at 2305 UTC, over an hour after generator operations ceased.

4.8 Ground Detection – 24 February

Data collection begin at 2134 UTC on 24 February 2008, in a ground detection effort with a single ground generator, MB06, operating, beginning at 2119 UTC.

Winds were strong as observed at the SML, but the RT-FDDA model suggested effective targeting would be possible. A definite plume was detected beginning shortly after 2200, with IN concentrations >15 L^{-1}. Skies at the SML were overcast, with light to moderate snowfall.

MB06 was shut off at 2219 UTC, but the plume continued to be observed until about 2315. The maximum observed 15 min average IN concentration was 56 L^{-1}.

The IN plume decreased rapidly thereafter, and data collection was terminated at 0015 UTC.

4.9 Cloud Radar Flight – 25 February

A second University of Wyoming cloud radar flight was conducted on 25 February 2008. Generators MB04 and MB05 were operated from ~2155 to ~2355 UTC. Data collection at the SML began at 2145 UTC.

Initial suggestions of an IN plume were observed at the SML as early as ~2230 UTC (1-2 L^{-1}) and persisted until 0000 UTC, when the generators were turned off. Interestingly, the observed concentrations increased from 0000-0030 UTC, peaking at 44 L^{-1}. The plume weakened after that, reaching background levels by 0115 UTC.

Light to moderate snowfall was observed at the SML throughout, with westerly winds characterized initially as "moderate", but becoming "light" after 0000 UTC.

4.10 RSE Case – 26 February

The second case for the randomized statistical experiment was called on 26 February 2008, and the ground-based AINC was activated accordingly.

The maximum IN concentration observed during the period was 24 L^{-1}, in light snow.

4.11 Ground Detection – 28 February

The final attempt to detect a plume at the surface during the 2008 season was made on 28 February

2008. A single generator, MB04, was operated from 1900-2100 UTC, under clear skies and westerly winds characterized at the SML as "strong".

Though the AINC did detect some IN, the 15 min average concentration never exceeded 1 L^{-1}, and data collection was terminated at 2300 UTC.

4.12 Airborne Tracing – 28 March

A final airborne tracing mission was flown on 28 March 2008. The mission was conceived as a Sierra Madre ground release, with the intent of tracking the plume as far eastward (toward the Medicine Bow Range) as possible.

Generators SM04, SM06, and SM07 were activated at ~1730 UTC, and N234K was airborne at 1800 UTC, from Rock Springs.

As the aircraft approached the Sierra Madre Range it was noted that the AINC cloud chamber was warming, failing to maintain the desired -18^{o}C temperature. The chamber's temperature had risen from the -18.5^{o}C observed on the ground prior to takeoff, to ~ -10^{o}C. As the initial passes just downwind (NE) of the active generators were flown the temperature continued to warm to -8^{o}C. While the aerosol being produced by the generators has been shown to be rather active at -8^{o}C, the short residence time within the comparatively small AINC chamber (at such warm temperatures) is not sufficient to grow ice crystals large enough to be detected, and the mission was aborted.

The addition of a small amount of refrigerant to the cooling system solved the problem, but not in time to allow a second flight to be undertaken that day.

5. SUMMARY

The 2007-2008 efforts to quantify plume density, spatial variability, and persistence, while somewhat successful, are just a start. Lessons learned during these initial efforts include:

1. The requisite conditions for airborne AINC application to plume tracing are more narrow than initially thought. If the cross-barrier winds are too strong the turbulence at low levels precludes safe flight at low altitudes, where the plume(s) reside(s). If the winds are too light, the plume meander becomes excessive. (One wouldn't seed with light winds anyway.)
2. The best conditions for airborne plume tracing are transitory. By late season it was realized that pre-storm conditions may routinely provide an opportunity for such flights. Often the wind speed and direction are sufficient, but moisture advection has not been sufficient for cloud formation. Temperatures may also be too warm for seeding, but with the AINC providing the cold environs for IN nucleation and growth, this doesn't matter.
3. The RT-FDDA model in most cases provides very good guidance with respect to the transport and dispersion of IN from specific generators to the target. This was usually verified by the successful detection of IN plumes when the model indicated successful targeting should be possible, and conversely, unsuccessful targeting when the model suggested targeting would be "iffy".
4. While IN concentrations ~50 L^{-1} were observed at the SML on two occasions, it would have been nice to see greater numbers, perhaps 100 L^{-1}. This would have provided some assurance that sufficient IN to alter the cloud processes were reaching the target. Still, the difference is only a factor of two, not an order of magnitude, so these numbers are encouraging. Interestingly, in both of these cases snowfall was occurring at the SML. It is not known if the relatively sheltered location of the SML is in any way a factor.
5. Measurements of plume widths and mixing depths as a function of varying wind speed are desired. However, the lessons in (1) suggest that doing so may be rather challenging. Such physical measurements of plume dimensions would provide information critical for the improvement of predictive models, and also for targeting confidence.
6. Airborne AINC measurements of IN released from generators in the Sierra Madre should be helpful in quantifying the potential impacts of "contamination" of the often downwind Medicine Bow Range. If the Sierra Madre is targeted, then the Medicine Bow Range is the control area established in the statistical design. Such measurements have not yet been attempted.

More in-depth analyses of the IN data collected during the 2007-2008 season are planned for the months to come.

6. PLANS FOR 2008-2009 SEASON

It would be desirable to again operate both AINCs during the 2008-2009 season, if only for a portion of the 4.5 month season. Simultaneous deployment would be ideal, as much useful work remains to be done (see Section 5).

Increased emphasis will be placed on plume tracing and detection, to obtain the needed targeting information.

Plume dimensions, as determined by the reciprocal-pass method with an airborne AINC (Super and Boe 1988) could refine models and better establish generator siting requirements.

7. ACKNOWLEDGEMENTS

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