3.1 RECENT RESULTS FROM A RANDOMIZED WINTERTIME CLOUD SEEDING EXPERIMENT IN THE SNOWY MOUNTAINS OF AUSTRALIA

A. W. Huggins*[1], S. L. Kenyon[2], L. Warren[2], A. D. Peace[2], S. P. Bilish[2], J. Denholm[2] and S.K. Chai[1]
[1] Desert Research Institute, Reno, Nevada, USA, [2] Snowy Hydro Ltd., Cooma, New South Wales, Australia

1. INTRODUCTION AND BACKGROUND

The Snowy Mountains are one of the few places in Australia with regular yearly snow accumulation, enough to support a viable ski industry. The spring snow melt is collected in reservoirs that are used to provide water for hydro-electricity and irrigation in southeastern Australia. The snow cover and duration at some sites in the Snowy Mountains has decreased significantly over the past century (Hughes, 2003 and references therein) resulting in a reduction of available water and motivating Snowy Hydro Ltd. (SHL) to pursue a wintertime cloud seeding trial – the Snowy Precipitation Enhancement Research Project (SPERP).

The SPERP is one of only a few cloud seeding experiments in the last two decades to employ a randomized design, and the first such randomized experiment to incorporate dual-trace chemistry analysis of snowfall as part of the project evaluation.

The SPERP was initiated following the submission of an independent expert panel report (Environ, 2003) to the New South Wales (NSW) government in 2003. The objectives of the project are to determine the technical, economic and environmental feasibility of precipitation enhancement over the main range of the Snowy Mountains. The 1000 km^2 target area for the project is located entirely within the Kosciuszko National Park (KNP; see Figure 1).

The six-year project commenced in June 2004 (Heggli et al., 2005) with meteorological data collection, verification of cloud seeding equipment, and the development of an experimental design and operational procedures. The formal randomized experiment started in winter 2005. This paper describes the design and operational aspects of SPERP and presents some preliminary results from physical and snow chemistry studies conducted during the 2006 field campaign.

* *Corresponding author address:* Arlen W. Huggins, Desert Research Institute, Reno, NV 89512-1095; email: huggins@dri.edu

2. PROJECT DESIGN

Winter precipitation over the Snowy Mountains is largely from moist westerly weather systems. As these systems approach the mountain ranges the air mass is lifted and condenses to form orographic clouds, often characterized by an excess of supercooled liquid water (SLW). This excess SLW indicates that either there are not enough ice nuclei in the clouds to promote crystal formation, or the crystal formation occurs too slowly or late for precipitation-sized crystals to grow before passing across the mountain range and sublimating, or melting and evaporating on the lee side.

The premise or conceptual model of the SPERP is to redress both these issues by promoting the excess SLW to form ice crystals earlier than expected naturally. This is achieved by introducing additional ice nuclei into suitable clouds over the entire target to enhance the ice crystal concentration, while allowing sufficient time for the crystals to grow and fall out, resulting in an enhancement of snowfall on the ground.

2.1 *Background Studies and the Randomization Scheme*

The project design was initially based on an Expert Panel Assessment (Environ, 2003) that drew from a climatological feasibility study (Shaw and King, 1986), an Environmental Impact Statement written in 1993, and the results of the Snowy Mountains Atmospheric Research Program (SMARP) conducted in 1988–1989 (Warburton and Wetzel, 1992). The results of SMARP also showed that the background concentrations of silver (Ag) and indium (In) were both ≤ 3 PPT in the Snowy Mountain snowpack. Based on these results, a snow chemistry evaluation similar to that of Chai et al. (1993) and Warburton et al. (1995, 1996) was incorporated into the project design.

The Snowy Mountains Cloud Seeding Trial Act (2004) prescribes a number of restrictions on the SPERP to satisfy the concerns of various stakeholders. These include limiting SPERP operations to snow (rather than rain) enhancement, and prescribing silver iodide (AgI) as the ice-nucleating and indium sesquioxide (In_2O_3) as the tracer agents and only

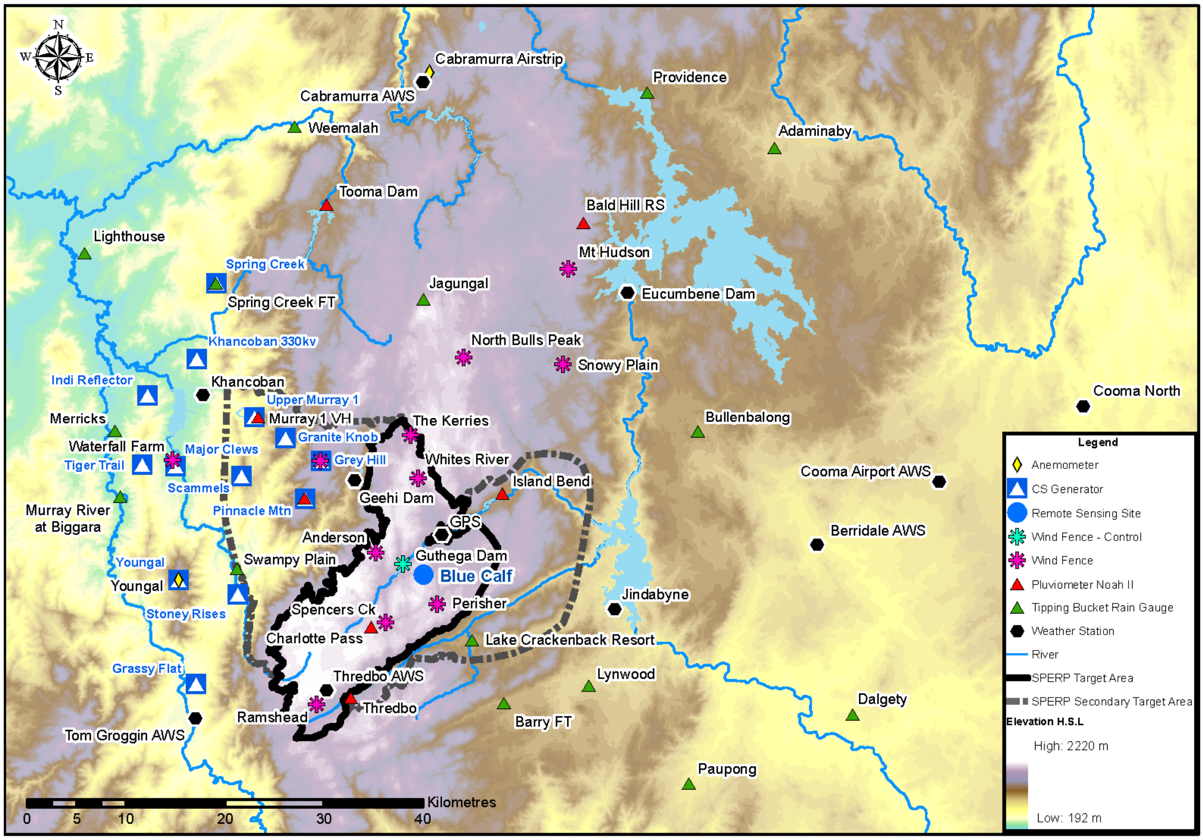


Figure 1. Map of the Snowy Mountain region. Legend at the lower right identifies the various SPERP instrument sites. Project soundings are launched from the Khancoban weather station site. The primary SPERP target area is outlined in black and the blue circle represents the Blue Calf remote field observing site with radiometer, laser imaging probe, icing sensor and standard meteorological instruments. Icing sensors were also located near Thredbo AWS and Cabramurra AWS. Post-storm snow profile samples in 2006 were also collected at all sites with wind fences, except Snowy Plain, Mt. Hudson and Waterfall Farm. Pluviometer sites Cabramurra, Weemalah, Lighthouse, Merricks, Waterfall, Murray River and Tom Groggin are part of the set of control sites for the statistical evaluation.

allowing these agents to be released from the ground. (The seeding aerosol is specifically $AgCl_{0.22}I_{0.78}\cdot 0.5NaCl$, reported on by Feng and Finnegan (1989), with an activity of 1.2×10^{14} nuclei gm^{-1} at -10^{o} C and approximately 10^{12} nuclei gm^{-1} at -6^{o} C.) In addition, the SPERP had to prepare and implement an Environmental Management Plan, must have a comprehensive monitoring system to evaluate the effects of cloud seeding operations, and is required to report environmental sampling results annually.

The details of the project were refined in 2004 by way of a climatological analysis combined with "opportunity recognition" studies using atmospheric soundings, microwave radiometer measurements and plume dispersion modelling. Using the results, an Experimental Unit (EU) duration of five hours was selected as practical for evaluation of the impact of seeding. Plume dispersion modelling and atmospheric soundings were also used to decide the optimum placement of the ground-based generators.

SPERP is a single target area experiment with a randomization scheme based on a 2:1 seed to no seed ratio within every group of six sequential EUs. For "seeded" EUs, silver iodide (*seeder*) and indium sesquioxide (*tracer*) aerosols are released simultaneously from collocated generators; in a "no seed" EU only the tracer aerosol is released. The randomization scheme was developed by an independent statistician from Charles Sturt University and is a blind draw known only by the personnel operating the generators and the maintenance personnel, who are independent of the SPERP scientific staff. The seed draw will be made available to the scientific personnel at the conclusion of the trial period. There is a purge time of at least one hour between EUs to ensure that the target area is clear of the seeding and tracer agents

2.2 EU Operating Criteria

The SPERP is subject to a number of criteria that must be met in order for an EU and cloud seeding operations to begin and continue:

- The high reservoir storage of the Scheme's largest dam, the snow water content and the snowpack accumulation must be below set threshold levels.
- There must be no severe weather threats that precipitation enhancement could exacerbate.
- The height of the freezing level in the atmosphere must be lower than 1600 m (MSL)
- The temperature of the cloud top must be ≤ -7°C and there must be at least 400 m of cloud above the height of the -5°C level (the temperature at which silver iodide activates as a nucleating agent).
- The output from a plume dispersion and cloud physics diagnostic scheme called GUIDE (Rauber et al., 1988) must show one or more generator plumes passing over the target area, and these generators must be available for operation.
- Finally, the controller in charge of the event must be confident that the event will last at least three hours.

2.3 Evaluation Plan

The SPERP has a comprehensive measurement network comprised of a variety of instruments collecting physical and chemical data across the study area. The evaluation plan for the project includes a primary analysis of these data using statistical techniques to compare precipitation in the target and control area (which comprises sites generally upwind of the target area – see Fig. 1), and ultra-trace chemistry analysis (for example, see Chai et al., 1992; Warburton et al., 1996 and McGurty, 1999) of snowfall to ensure that any impact is consistent with the seeding hypothesis. This primary analysis aims to identify and quantify the impacts of seeding in the target area. A secondary analysis encompasses physical evaluation of the cloud seeding processes and further statistical tests to confirm the primary analysis and investigate the physical processes involved. The evaluation plan was developed from the experimental design by an independent and impartial research group from Monash University; this group will also conduct the statistical analysis at the conclusion of the 5-year research period.

3. SPERP INFRASTRUCTURE

The SPERP is centrally managed from the Cloud Seeding Control Center (CSCC) based in Cooma, NSW. Throughout the winter season CSCC personnel continually monitor meteorological conditions and forecast for potential cloud seeding opportunities. Six hours prior to an expected event, atmospheric soundings commence and data from instruments located in the target area are monitored. Data from all the critical instrument systems are telemetered to the CSCC in real time and displayed on monitors in the CSCC control room. Cloud seeding operations begin once the operating criteria (see section 2.2) are met. The Cooma facilities also include a clean room for the preparation of snow sampling equipment and the management of snow chemistry samples.

The infrastructure of the SPERP project includes a radiosonde launch site near Khancoban, a remote observing facility located on Mount Blue Calf, 13 ground generator sites, 11 snow profiling sites and 50 surface meteorological stations. Figure 1 shows the locations of these sites. Since a large portion of the project infrastructure is located within the KNP there were limitations on the selection of sites for generators and weather monitoring associated with environmental and visual impact, and access.

3.1 Project Soundings and the Remote Observing Facility

Radiosondes are released from Khancoban, NSW, about 20 km west and upwind of the target area. The first sonde is released six hours prior to the expected start of an EU and then every three hours during operations. The data received from the sonde are used to address various operating criteria and are input to the GUIDE model.

The remote facility on Mount Blue Calf (located close to the center of the primary target area) hosts a number of key instruments including a microwave radiometer, an icing rate detector, a 2D laser imaging probe, a heated wind vane and anemometer, and temperature and humidity sensors. Real-time snow sampling also takes place at the site during operations using a unique swivelling snow collector to allow sample collection in high winds.

The dual-channel radiometer measures the liquid water and water vapour in the atmosphere integrated along the zenith. For SPERP operations, a 30-min running average of liquid water is calculated in real-time and used as part of the operating criteria. The SPERP also uses three icing rate detectors that are located at Blue Calf and two other locations on the main ridge of the target area (Eagles Nest near the Thredbo AWS and Cabramurra in Fig. 1). For three field campaigns a two-dimensional (2D) laser imaging probe has also been operated at Blue Calf. In 2005 the probe was a Droplet Measurement Technologies cloud imaging probe (CIP), and in 2006 and 2007 a precipitation imaging probe (PIP) was used.

3.2 *The Ground Seeding Generator Network*

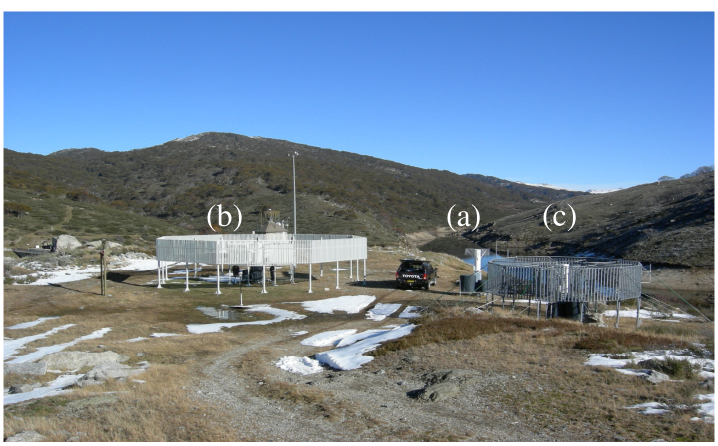
The SPERP uses thirteen pairs of seeding generators, located along the western perimeter of the target area at altitudes ranging from 439 to 1662 m (five above 1000 m), to dispense the seeding and tracer aerosols into the atmosphere. The generators are remotely operated from the SHL Snowy Mountains Control Center, thus ensuring that all CSCC personnel are blind to whether the EU is a “seed” or “no seed”. Many controls (including environmental controls) have been implemented for the operation of the generators.

For interpretation of the ultra-trace chemical results, the seeder and tracer particle sizes and releases rates must be known (see for example Warburton et al., 1995). In SPERP the solution release rates are automatically regulated (at 1250 mL per hour) during operations via computer-managed control valves to ensure an expected mass ratio of Ag/In in snowfall of one, if both are removed from the atmosphere *only* by scavenging processes.

3.3 *Meteorological Stations*

Fifty meteorological stations are used to monitor parameters such as precipitation, temperature, relative humidity, wind speed and direction, and atmospheric pressure in the upwind, target and downwind areas. Sixty-one pluviometers are positioned at 47 of the stations to monitor snow and rainfall; twenty-four are 0.01 in (0.25 mm) resolution total precipitation gauges, used to measure precipitation at sites above the height of the typical snowline. Tipping bucket gauges are used at sites below the snowline and are outfitted with low-power heaters at sites that occasionally experience snowfall events. The majority of the tipping buckets have a resolution of 0.2 mm and the remainder are resolved to 0.5 mm.

Many of the precipitation gauge sites on the Snowy Mountains are exposed to high wind speeds with limited or no shelter from topographic features or vegetation.



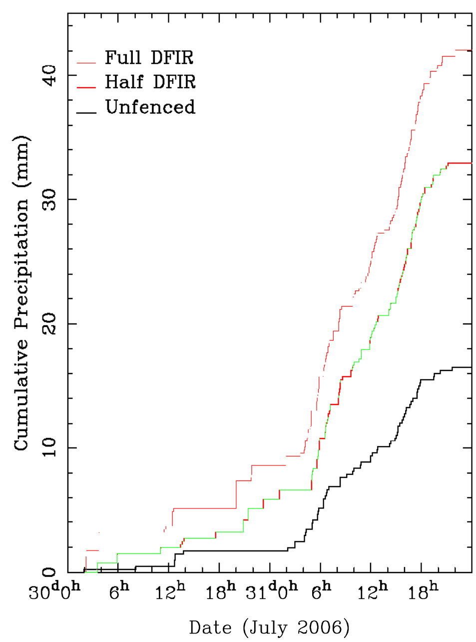


Figure 2. Left: The pluviometer comparison site at Guthega Dam, consisting of an unfenced gauge (a) and identical gauges fenced with a full DFIR (b) and a half DFIR (c). Right: The cumulative precipitation measured by the gauges over a two day period in July 2006.

The World Meteorological Organization (WMO) standard for collecting snow under these conditions is to use Double Fence Inter-comparison Reference (DFIR) structures around the gauges (Goodison et al., 1998). The SPERP was not able to install these full-sized structures at all the gauge sites because of the limitations associated with placing infrastructure in the KNP. As a solution, SHL developed half-sized structures (½ DFIR), which were collocated with unfenced gauges at four key sites prior to the 2006 cloud seeding season. A full-size and half-size DFIR were collocated with an unfenced pluviometer gauge at Guthega Dam to provide a comparison site. Figure 2 shows a photo of the site and a graph of the cumulative precipitation recorded by the three gauges over a two-day period. An additional seven ½ DFIRs were installed at exposed sites prior to the 2007 season. To account for differences in gauge shielding among years unshielded gauge data will be adjusted based on regression analysis between shielded and unshielded gauges prior to the formal statistical evaluation.

3.4 *Snow Sampling Sites*

Vertical snow profiles are collected as soon as possible following each field campaign with sufficient snowfall. Each profile is divided into 2-cm segments that are each analyzed for the presence of the seeder (Ag) and tracer (In) elements. Snow samples are collected from eleven sites, selected to represent the primary target and control areas, to have reliable access, and to be collocated with ETI pluviometers.

The snow samples are collected in ultra-clean polycarbonate vials, each identified with a unique barcode. The samples are maintained in a frozen state from collection to delivery to Melbourne University (Australia) for ultra-trace analysis using an Inductively Coupled Plasma Mass Spectrometer (ICPMS). Results from snow chemistry analysis for each season are used to confirm that the primary target and upwind mountain ranges are being effectively targeted by seeding material during EUs. The chemical results are also used in combination with high resolution precipitation measurements in a new technique to estimate the quantitative effect of cloud seeding.

4. BRIEF SUMMARY OF THE FIRST FOUR SEASONS OF SPERP

The SPERP began operations on 18 June 2004. During the start-up year (2004), the generators were operated whenever the conditions were suitable and were not subject to the randomized five-hour EUs. Table 1 documents the number of campaigns (single storm events), EUs, hours of operation, and the seeding operational periods for each year. Preliminary results from the last four years are encouraging and annual assessment of snow chemistry has shown strong seeding signatures and effective targeting of the study area.

Table 1. Summary of 2004 – 2007 SPERP winter field programs.

Year	Campaigns	Max Snow Depth (m)[a]	Total EUs[b]	Hours of Operation	Operational Period
2004	12	2.25	N/A[c]	187	18 Jun - 13 Sept
2005	13	1.45	31 (3)	164	15 Jun – 29 Sept
2006	8	0.82	10 (2)	55	7 May – 24 Sept
2007	10	1.62	22 (1)	112	21 May - 29 Sept

[a]At Spencers Creek: Average since 1954 = 2 m [b]Number of suspended EUs in brackets [c]No randomized experiments in 2004

4.1 *Snowfall in the SPERP Target Area*

Snow accumulation in the Snowy Mountains is naturally variable from year to year. Table 1 lists the highest snow depth measured at Spencers Creek, a long-term measurement site located within the primary target area, for each SPERP season. Only one of the first four seasons had snow accumulation above Spencers Creek long-term average maximum of 2 m. More typical of the long-term trend was the seasonal peak snow depth for 2004 to 2007 which generally occurred in August.

4.2 Targeting Effectiveness Using Ag/In Ratios

Warburton et al. (1995) demonstrated the use of the Ag/In mass ratio to evaluate cloud seeding targeting effectiveness and showed that Ag arrived in the snowpack by the ice nucleation process rather than by cloud and precipitation scavenging processes. The hypothesis indicated that both aerosols would be removed by scavenging at the same rate and, with known particle sizes and release rates, the expected mass ratio in snowfall due to scavenging could be computed. SPERP uses a similar dual-tracer technique, with the main difference in approach being that the AgI nucleant is expected to operate by a fast-acting condensation-freezing mechanism, rather than by contact nucleation as in Warburton et al. (1995). If ice nucleation occurs more rapidly over or upwind of the SPERP target, then the peak Ag/In ratio could be displaced further upwind, but evidence of ice nucleation (versus scavenging) should still be demonstrated by an Ag/In ratio greater than one as predicted by the release rates noted in Sec. 3.2.

The snow samples analyzed from the 2004 and 2005 SPERP seasons indicated that relatively effective targeting was occurring, and also that some improvement in targeting occurred after generators were repositioned or added following the 2004 testing season. At nine target sites in 2005 the percentages of samples with Ag/In ratio greater than one ranged from about 10 – 55%, with eight of nine having >30%. This was considerably better than in 2004 where only three of the same sites had >20% of samples with Ag/In greater than one. Also, the mean Ag concentrations were 2-10 PPT higher in 2005, and the coverage of the target by higher ratios and concentrations was generally better than in 2004. This improvement in targeting was noted even though all storms in 2004 were seeded, while, as a consequence of the randomization, only about two thirds of the qualifying storm periods in 2005 were treated with AgI.

5. RESULTS FROM AN EXTENDED OPERATIONAL PERIOD

An extended experimental campaign, consisting of two storms occurring between 30 July 2006 and the early hours of 1 August 2006, is examined in detail in this section. Five experimental units (EUs 38–42) were conducted during these events; however, EU 39 was suspended after three hours because the freezing level rose above 1600 m. The first storm (EU 38) started with the arrival of a cool moist westerly airstream over the Snowy Mountains. This was followed by a short period of warmer dry air ahead of a cold front. A return to cool moist conditions with the passage of the front allowed recommencement of seeding operations (EUs 39-42). An extensive snow sampling campaign followed the entire operational period. In this section we discuss the atmospheric conditions as measured by soundings, the GUIDE plumes generated from the sounding data and the data collected from Blue Calf and the surrounding area.

5.1 Soundings

Thirteen radiosondes were launched during this operational period and Fig. 3 summarizes some of the data pertinent to seeding operations. Figure 3(a) shows the wind speed and direction at the height of the -5° C level. At the start of the first storm and continuing through EU 40 the winds were predominately from the west, providing potentially good coverage of the target area from several generator sites. The winds backed to the southwest halfway through EU 41 indicating fewer generators were likely to provide effective coverage of the target. The heights of the freezing levels and cloud layers are shown in Fig. 3(b). The hatched areas indicate the cloud regions suitable for seeding (i.e., with temperature less than -5° C). Note that the lower part of these cloud layers was often near or below the height of the highest point in the target (Mount Kosciuszko, 2228 m).

5.2 GUIDE Plume Plots and Blue Calf Targeting

GUIDE is used to predict the trajectory and spread of the aerosol plume from each generator and the locations where ice nucleation and fallout first occur. It is the method that SPERP uses to select cases in which seeding plumes should reach at least the -5^{o} C level, and far enough upwind to permit crystal nucleation, growth and fallout in the target. GUIDE uses data, such as temperature, and wind speed and direction, from the three-hourly atmospheric soundings for these predictions. Two plan view plots are produced from the model; one shows the predicted centerline and the other the boundaries of the plume from each generator. Figures 4a and 4b show these plots for the model run preceding EU 38. An EU can only be declared if GUIDE predicts the crystal fallout from at least one generator in the vicinity of the target area, and a generator can only

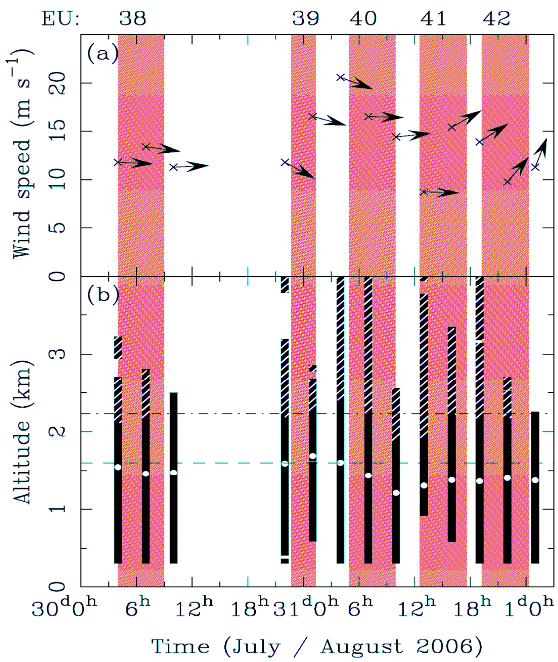


Figure 3. A time series showing data from the thirteen radiosondes that were launched during the operational period (in local Eastern Standard Time). The shading shows the durations of EUs which are numbered at the top. (a) The wind speed and direction at the -5 °C level. (b) The heights of the freezing levels (white dots) and cloud layers (black and hatched bars), where the hatching shows the regions of the cloud layers with temperature less than -5° C. The dashed line shows the 1600 m level and the dash-dot line shows the height of Mt Kosciuszko (the highest peak in the range).

be turned on if the predicted centerline crosses the target area. The GUIDE plots preceding EUs 39 to 42 showed that winds shifted from northwesterly to southwesterly as the storm progressed.

GUIDE also predicts the vertical trajectory of the aerosol plumes, where an ice crystal is expected to form and the expected ice crystal habit (plate, column, dendrite, needle or small crystal). Once an ice crystal is formed GUIDE then estimates its growth and fallout trajectory. The parameterizations for ice crystal nucleation, growth and fall speed can be found in Rauber et al. (1988). Figures 4c and 4d show examples of the vertical trajectory plots from two sites for EU 38.

Figure 5 indicates which generators produced GUIDE plumes over the Blue Calf observing facility during each EU. Ice crystal fallout was also predicted in the vicinity of Blue Calf from a number of generators during EUs 38, 39 and 41. For EU 40 the fallout was predicted downwind of Blue Calf and for EU 42 nucleation was not predicted for the plumes passing over Blue Calf. Given these predictions that the observing facility was potentially being targeted during almost every EU, the data from Blue Calf are examined for evidence of seeding effects.

5.3 Description of Data from Blue Calf and the Surrounding Area

In this section a detailed description of chemical and physical data recorded at Blue Calf and the nearby sites of Perisher and Guthega Dam (see Fig. 1) is given. The wind, temperature, radiometer, icing sensor and precipitation data were collected continuously throughout the winter. Real time snow sample collection and operation of the laser imaging probe at Blue Calf only occurred when observers were at the site, generally from a few hours prior to the start of an EU until the end of the purge period following the last EU of a campaign. The pertinent wind data were shown in Fig. 3.

The depth of the liquid water (*LW*) in the atmosphere above Blue Calf is shown in Fig. 6b as a 30-minute running average. Also shown is the threshold depth of liquid water required as part of the SPERP starting criteria for an EU. It is obvious that EUs 39, 40 and 41 easily satisfied the radiometer LW criterion, but that LW during EU 38 and 42 was marginal, after the EU began. It is also interesting to note that radiometer LW and the icing rate are not particularly well correlated. There was steady icing during EU 38 (Fig. 6c), but the radiometer LW was barely above background, suggesting the liquid cloud was surface-based and quite shallow. In contrast, radiometer LW between EU 38 and EU 39 and during EU 40 and EU 41 was substantial while the icing rate was quite slow. This lack of correspondence indicates a relatively deep LW cloud existed over the site during these periods, but that the cloud base was likely above the surface much of the time.

Cloud liquid and precipitation also showed two interesting relationships. In the period between EU 38 and EU 39 there was very little precipitation (Fig. 6d), but a considerable amount of LW and icing, indicating that the precipitation process was inefficient; the “classic” definition of good cloud seeding potential (the period did not qualify for EU consideration due to insufficient cloud depth and increasing temperatures). However, during EU 40 there was a large amount of

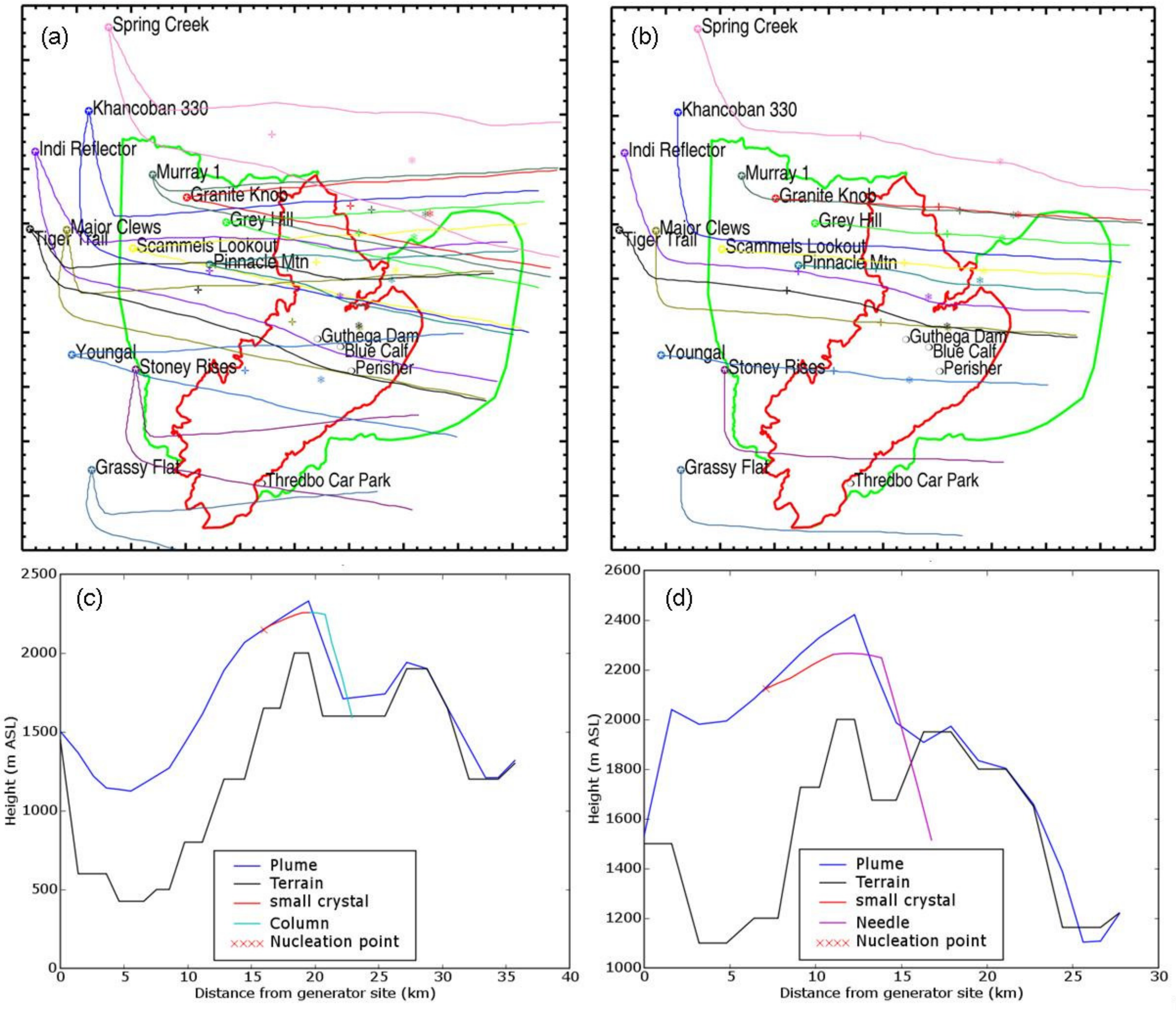


Figure 4. GUIDE model output based on the sounding released before EU 38. Top: Plan view plots of the expected plume boundaries (a) and centerline (b) from each generator. The predicted point of nucleation (cross) and fallout (star) for each plume, and the locations of Guthega Dam, Mt. Blue Calf, Perisher and Thredbo are also shown. Bottom: the vertical trajectory of the aerosol plume and ice crystals from the Youngal (c) and Pinnacle Mountain (d) generators.

liquid water available in the clouds, and at the same time the highest precipitation rate of the 2-day period was observed at Perisher (Fig. 6d) a short distance away. High ice crystal concentrations were also measured with the PIP (see Sec. 5.5). This suggests a significant seeding potential can exist even in the presence of moderate precipitation or high crystal concentrations. Finally, the liquid water dropped to the background level and the icing (Fig. 6c) decreased at Blue Calf soon after the start of the last EU, corresponding temporally to the drop in temperature seen at all sites (Fig. 6e) and likely to an advection of drier air into the region after the passage of the upper level trough.

Snow samples were collected at Blue Calf whenever an adequate amount of snow for trace chemical analysis was present in the snow collector, so the temporal extent of each sample varied considerably. Figure 6a shows the collection period for each of the 15 separate snow samples from the 2-day period. The concentrations of Ag and In detected in the real time snow samples are also shown. (Note that background levels of 3 PPT and 1 PPT have been subtracted from the Ag and In concentrations, respectively.)

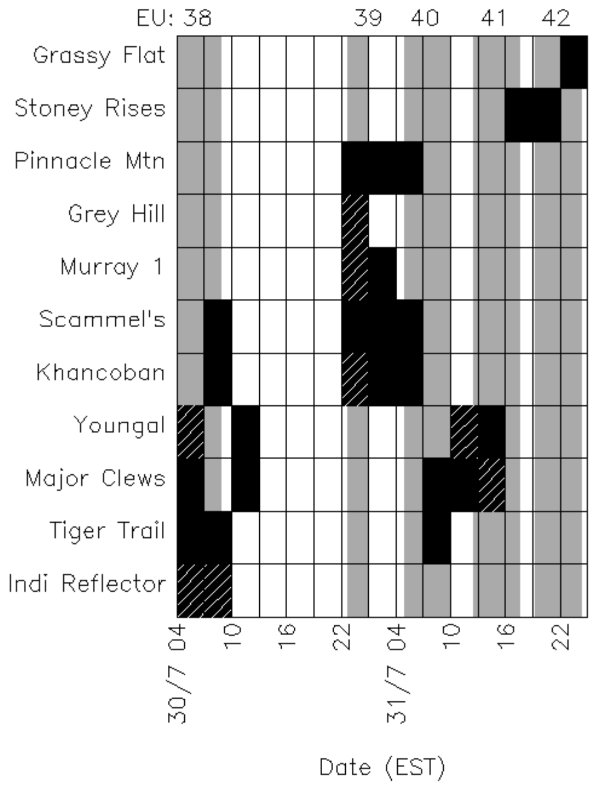


Figure 5. Plot showing which GUIDE generator plumes existed over Blue Calf for each atmospheric sounding in the two-day storm period. The grey shading shows the duration of each EU, the black shading shows the generators that were targeting Blue Calf and the hatching shows the generators that had crystal fallout predicted upwind of Blue Calf. Sounding dates and times are noted on the bottom axis (local Eastern Standard Time).

Based on the GUIDE predictions of successful plume and ice crystal targeting of Blue Calf the following trace chemical results might be expected. If an EU was seeded, then enhanced levels of both Ag and In would be expected. If ice nucleation by AgI contributed to the Ag concentration, then the ratio of Ag/In would be expected to exceed 1.0. If an EU was unseeded, then the Ag concentration would be near the background level and the In concentration would be enhanced. The Ag/In ratio would also be less than 1.0, or would not be able to be calculated if Ag minus the background was zero. Examining the chemistry data in Fig. 6a it is obvious that Ag sample concentrations were enhanced during EUs 38 and 40, and that the Ag/In ratio was also greater than one, ranging from about three to five. This indicates that EUs 38 and 40 were likely seeded and that ice nucleation contributed to the enhanced Ag at Blue Calf.

In the suspended EU 39 there was only enough snow for the collection of one sample in which no In and approximately background Ag were detected. The result from this one sample is not very conclusive, but suggests Blue Calf was not targeted during the brief seeding period. During EU 41 no Ag above background was detected, but In was detected at concentrations similar to EUs 38 and 40, indicating EU 41 was likely a “no seed” decision. In the one sample collected after the start of EU 42 both Ag and In were slightly enhanced and the Ag/In ratio was 0.6. As with EU 39 it is difficult to draw conclusions from one sample, but the indication is that the EU was seeded, but that ice nucleation did not contribute to the presence of Ag in the snow. Overall, from the three EUs that were sampled reasonably well at Blue Calf, the snow chemistry data are consistent in suggesting what the seeding decision was and that the GUIDE results were at least qualitatively verified in their predictions of plume and ice crystal targeting.

5.4 *Spatial Results from Snow Chemistry Profiles*

On 1 August, following the two-day storm event, snow profiles were collected at nine sites within and to the north of the SPERP target. The condition of the snow at the bases of the profiles indicated that the profiles only contained snow from the period of interest. Although the 2-cm resolution of the profile segments did not permit as clear a delineation of EUs as the real time snow data from Blue Calf, there was still an indication of the EU seeding decision based on the Ag and In concentrations within the profiles. Two profiles collected north of the target (Tooma and Bulls Peak) showed no evidence of enhanced Ag or In. All seven of the other profiles showed evidence of enhanced Ag or In in one or more segments.

Recalling the precipitation data from Fig. 6, the Guthega trace indicates that 53% of the precipitation came between the start of EU 38 and the end of EU 40. At Guthega the snow water in the profile matched the total gauge precipitation quite well, so with Guthega just upwind of Blue Calf the seeding effects from EU 38 and EU 40, as noted at Blue Calf, should have been present in the lower 50% of the Guthega profile samples. Likewise the “no-seed” indium signature from EU 41 should have been present in the upper 50% of the profile segments (assuming temporal targeting as at Blue Calf). Figure 7 shows the Guthega snow water profile together with Ag and In concentrations at each level. Based on the timing of the EUs using the precipitation data in Fig. 6d (and adjusted for transport time to Guthega), the EU periods on the Guthega profile

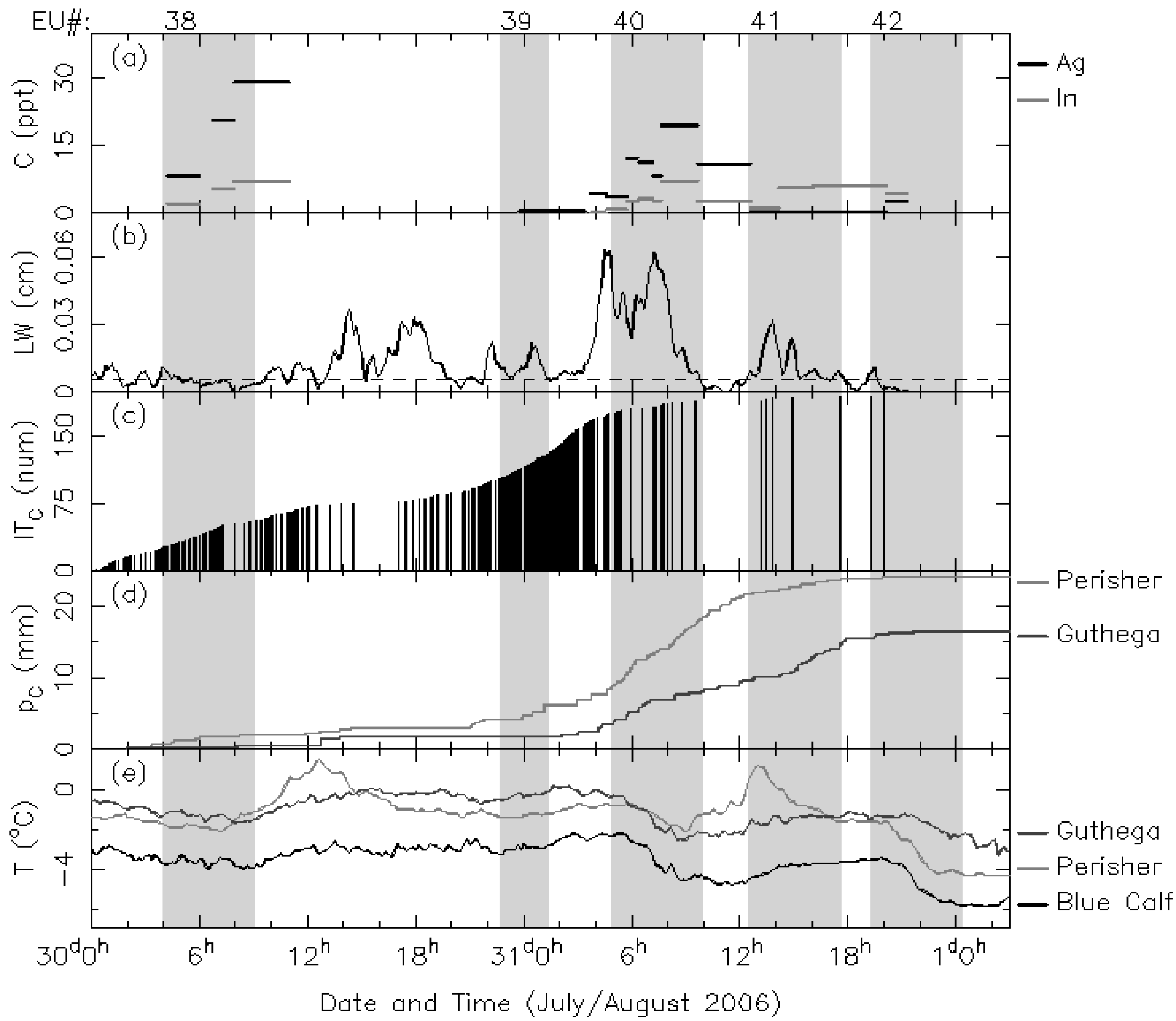


Figure 6. A time series of physical and chemical data collected from Mount Blue Calf, Perisher and Guthega Dam (see Figs. 1, 8 and 9 for locations). (a) The concentration (C) of Ag and In detected in the Blue Calf real time snow samples (the length of the lines shows the collection period for the sample). Note, a snow sample bag was lost in high wind conditions between the first and second sample, accounting for the gap in the data. (b) The 30-minute running average liquid water depth (LW) and (c) the cumulative number of icing trips (IT_C) recorded at Blue Calf. (d) The cumulative precipitation (p_C) from the unfenced gauges at Guthega Dam and Perisher. Figure 3 shows the precipitation measured by the fenced gauges at Guthega over the same time period. (e) The temperature (T) measured at each site.

have been marked. The bottom two layers contained snow from EU 38 and EU 39 and suggest both events were seeded (above background Ag and In). The snow from EU 40 was present mostly in the 5th and 6th layers below the surface (8-12 cm), and the Ag and In concentrations also suggest a seeded EU. The 4th layer with near background values of both Ag and In likely came from snow deposited between EU 40 and EU 41. Snow from EU 41 was mostly in the top three layers, where the 2nd and 3rd layers indicate EU 41 was a no-seed event. The top layer had snow from EU 41 and EU 42, and the reappearance of Ag above background suggests EU 42 was a seeded event. The Guthega profile results match the Blue Calf temporal samples quite well, and provide additional evidence that both EU 39 and EU 42 were likely seeded.

Five of seven other target profiles showed evidence of a seeding effect in the lower 75% of their profiles and three of seven showed evidence of a no-seed event in

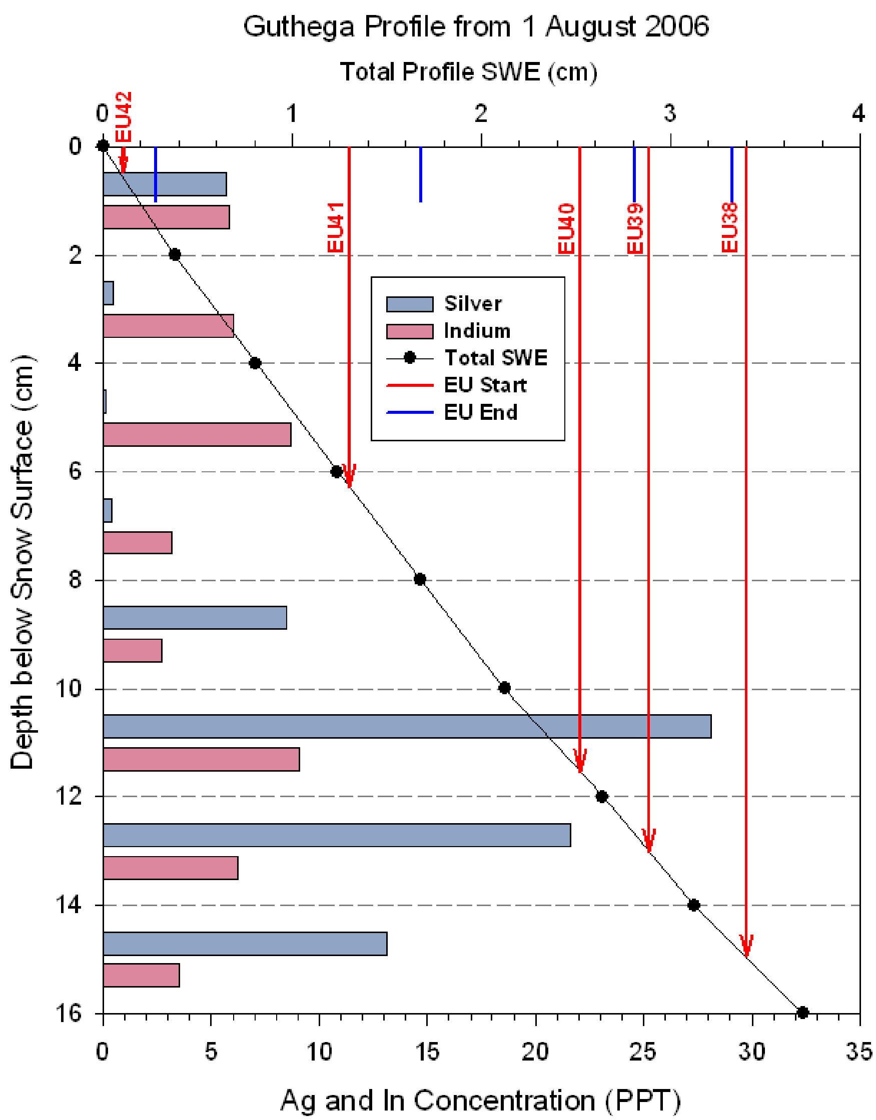


Figure 7. Data from Guthega snow profile taken 1 August 2006 showing snow water equivalent (SWE) and Ag and In concentrations in each 2-cm layer. Red arrows show the estimated start times of EUs based on the Guthega precipitation trace and EU timing in Fig. 6. Blue line segments indicate the end times of EUs.

the top 25%. This partitioning was more closely matched to the precipitation trace from Perisher in Fig. 6, which showed about 75% of the total precipitation came during EUs 38, 39 and 40. For all profile segments and temporal samples the percentages of Ag/In ratio > 1 ranged from about 29% to 80% and the spatial pattern is shown in Fig. 8. The highest percentages were actually from sites in the Grey Mare range upwind of the primary target, but within the secondary target and a short distance downwind of two seeding sites. Individual site statistics are also shown in Fig. 8. The Ag/In percentages for this 2006 event were 30-50 points higher than the seasonal values from the same sites in 2004, and 20-40 points higher than 2005 sites. Additional trace chemical statistics in Fig. 8 show that all sites except Bulls Peak north of the target had average values of Ag and In above background, and average Ag/In ratios that exceeded the expected value by more than a factor of three in the majority of profiles.

5.5 Ice Particle Characteristics Measured with the PIP at Blue Calf

The SPERP target has no convenient high altitude roadways to enable use of mobile ground instrumentation, and to date instrumented aircraft have

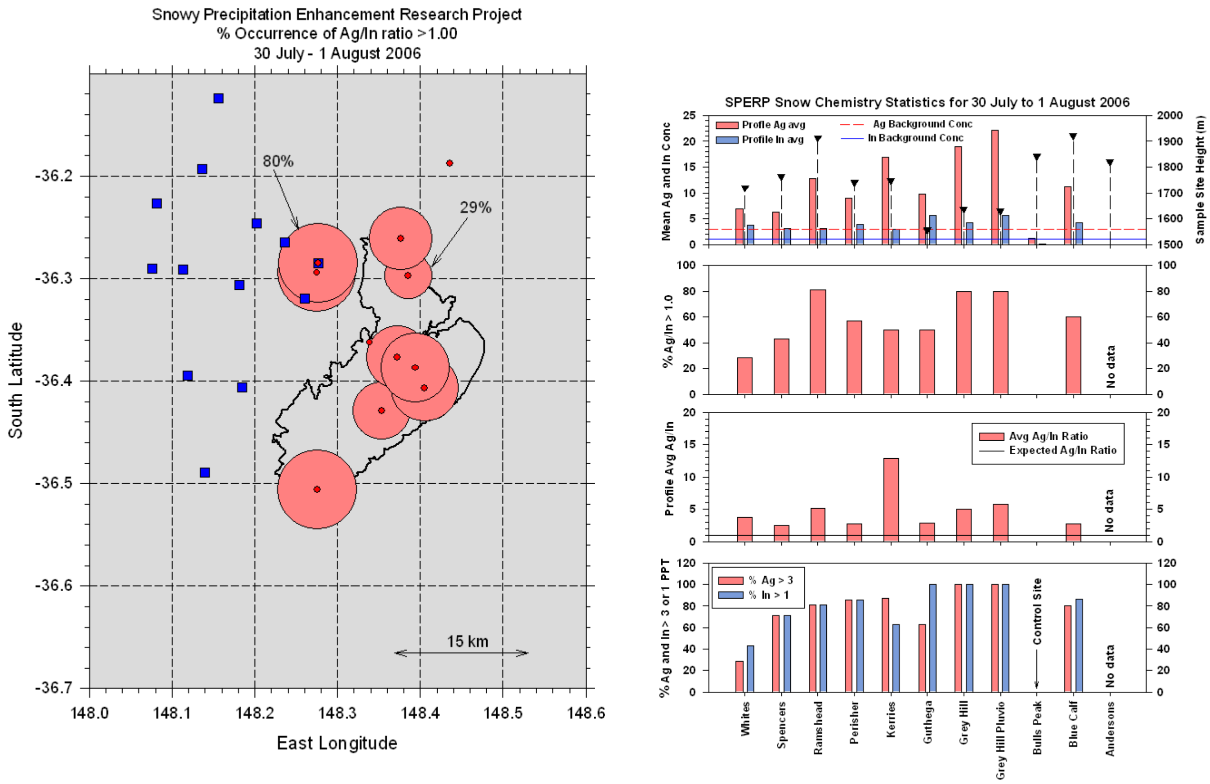


Figure 8.Left: Map showing the percentage occurrence of Ag/In ratio > 1 for sites sampled after the 30 July – 1 August 2006 storm period. Circle area is proportional to percentage. Small red circles show site locations. One site (Andersons) near the west edge of the target was not sampled. The site north of the target (Bulls Peak) near -36.2 south latitude had 0% occurrence. Right: For the sites shown on the map, bar charts showing the profile average Ag and In concentration (top panel), percentage of samples in each profile with Ag/In ratio > 1 (2^{nd} panel), profile average Ag/In ratio (3^{rd} panel), and percentage of samples in each profile with Ag and In concentrations above the background concentrations.

not attempted relatively low altitude flights over the main range of the Snowy Mountains. Detailed physical observations to document the effects of seeding have been limited to the remote field site at Blue Calf, where high temporal resolution real-time sample collection began in 2006. The snow chemistry measurements are the only datasets that permit any type of seed-no seed comparisons in SPERP, without knowledge of the seeding decision. This section presents some preliminary analyses of the microphysical data in three of the five EUs.

5.5.1 Microphysics Data from EU 38

The PIP at Blue Calf collected data continuously from 0000 EST through 1600 EST on 30 July and therefore sampled the period before, during and after EU 38. The data were processed to obtain 30-s averages of ice particle concentration, 5-min averages of particle size, size distributions at 10-min intervals, and a variety of variables including ice water content (IWC), ice mass concentration and radar reflectivity that were derived from empirical size-mass relationships. A complete set of the two-dimensional images from the PIP was also archived. In addition, a particle habit recognition scheme similar to that of Korolev and Sussman (2000) was employed to obtain the fractional contribution of habits to concentration and mass. These preliminary results focus on only a limited set of the measured and derived variables.

Figure 9 shows the temporal history of several PIP variables together with the snow sampling periods and trace chemical concentrations measured at Blue Calf for the period surrounding EU 38. Also indicated on the time axis are the earliest and latest times (36–75 min transit times) of seeding plume arrival at, and departure from Blue Calf based on GUIDE estimates from four ground generators (see Fig. 5). From GUIDE vertical plume trajectory estimates and sounding temperatures the seeding plumes potentially interacted with cloud in the -5° to -11° C temperature range (suitable for

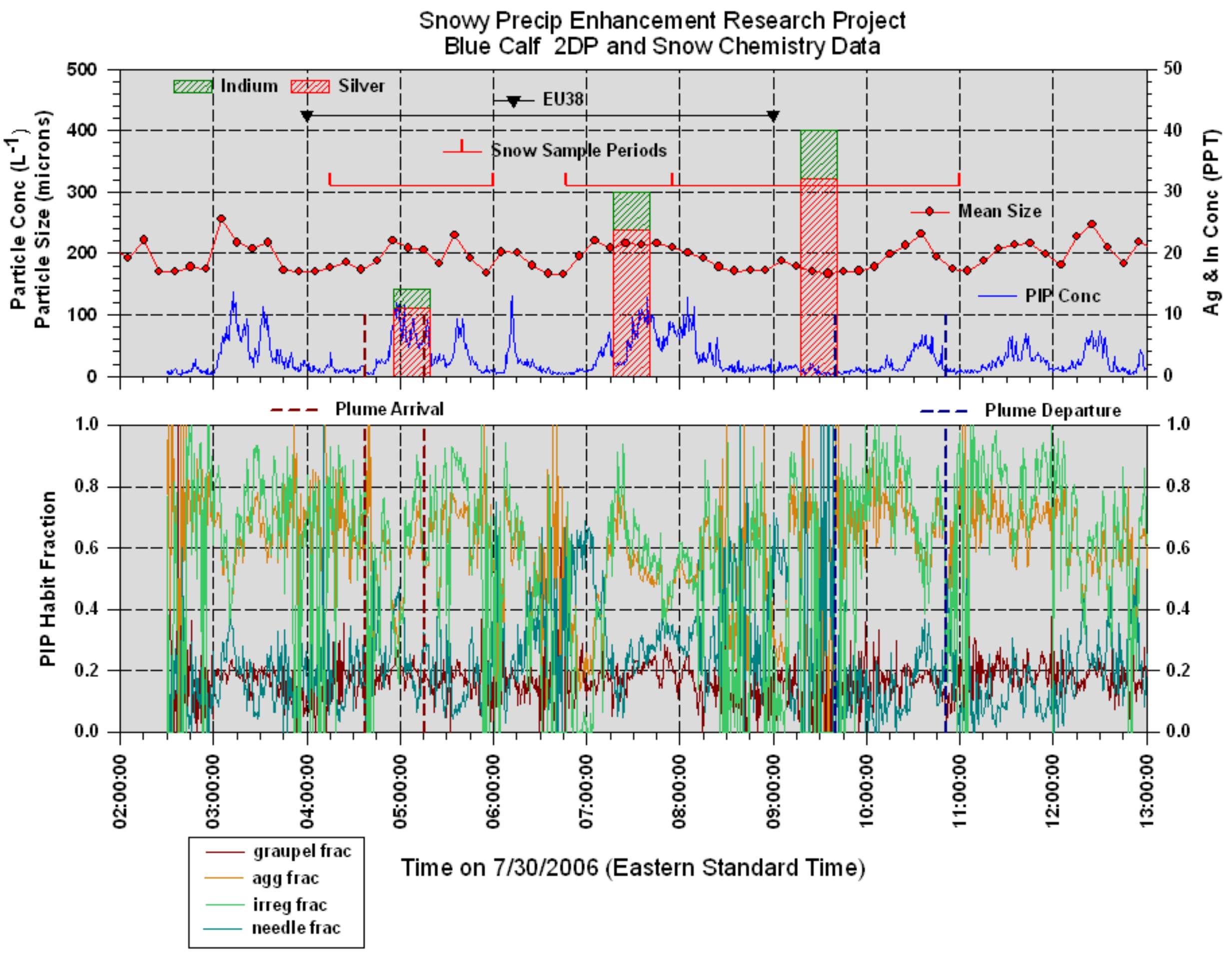


Figure 9. Time series plot of Blue Calf PIP data and real time snow chemistry data for the period encompassing EU38 on 30 July 2006. Actual indium concentration is the difference between the total bar concentration and the silver concentration. Plume arrival and departure times predicted by GUIDE for two different generators are indicated. PIP mean sizes are 5-min averages and particle concentrations are 30-sec averages. In the bottom panel the regions above the highest trace represents the unclassified particle habit fraction.

nucleation by AgI), but the higher concentrations of aerosols were likely below the -8°C level. The range of transit times and nucleation temperatures could have produced a variety of particle sizes and habits at Blue Calf, but "warmer" habits like needles and columns would be the most likely in the -5° to -8° C temperature range. In the low-level SLW layer above the mountain these crystals could also potentially rime quickly into small graupel.

The plume arrival times in Fig. 9 bracket a sharp increase in particle concentration to >100 L^{-1} (0455 EST) following a one hour period where concentrations were generally < 15 L^{-1}. Snow from this initial peak and a second peak at about 0540 EST would have been collected in the first snow sample in EU 38 that showed enhanced Ag and In concentrations. A broad concentration maximum which exceeded 100 L^{-1} (0720-0815) was contained in the second and third snow samples where Ag concentration was about 24 and 32 PPT, respectively, and the Ag/In ratio was >4 in both samples. The third snow sample covered about three hours of snowfall, but the enhanced Ag was likely contributed by the ice particles collected at 0755-0820 EST. Particle concentrations in the two to three hours following the last plume had peaks about 40 L^{-1} less than the peaks between plume arrival and departure, where trace chemistry verified that ice crystals contained the seeding and tracer elements.

Figure 10 shows the average concentration in the seeded period was 31.2 L^{-1}, compared to 27.7 L^{-1} in the

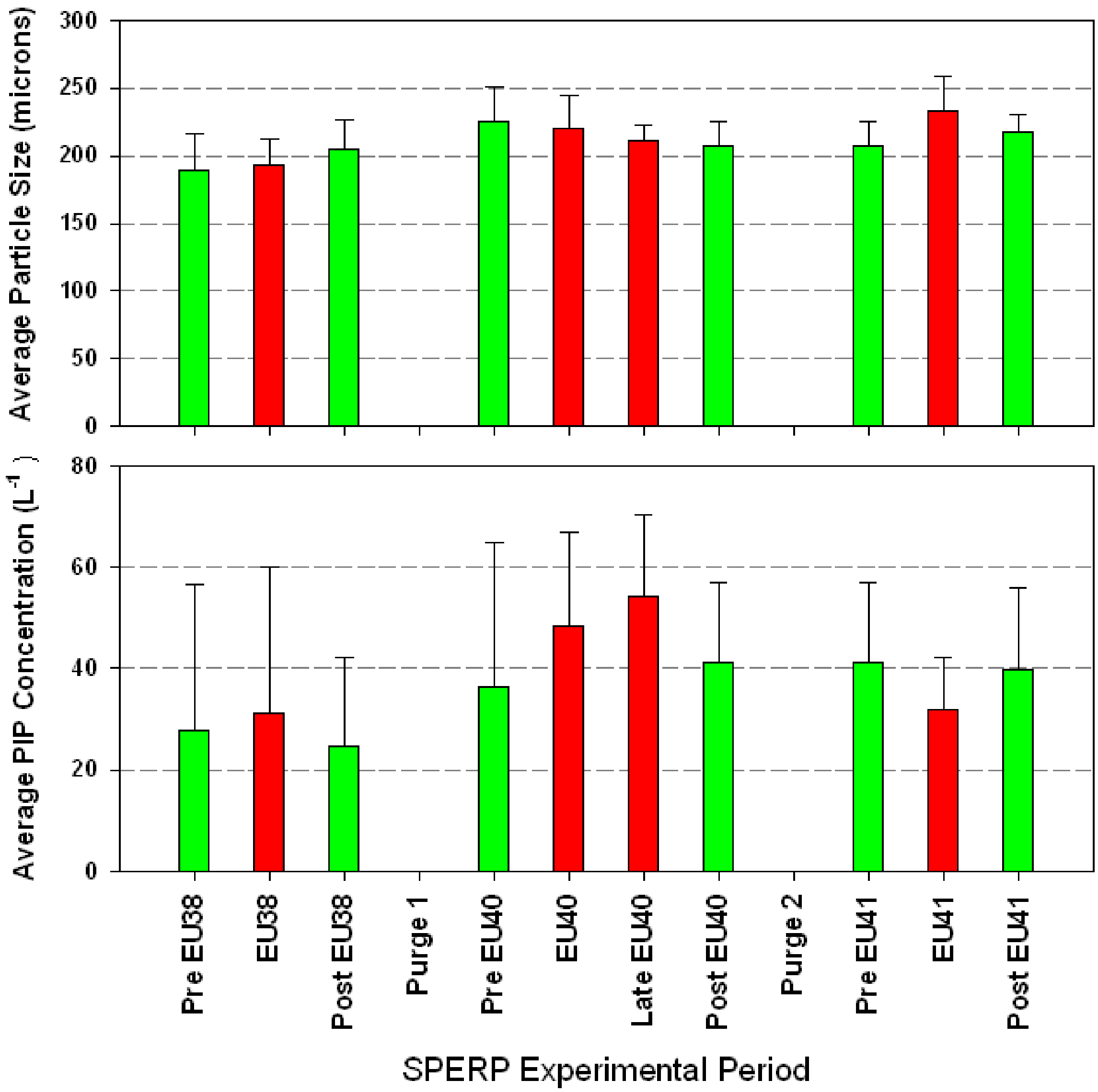


Figure 10. Bar charts showing the average particle size (top) and average particle concentration (bottom) recorded by the PIP at Blue Calf before, during and after EU 38, EU 40 and EU 41. The bars labeled EU 40 denote the entire EU period, while the bars labeled Late EU 40 represent averages over only the last three hours of the period of effect at Blue Calf.

two-hour period prior to seeding, and 24.6 L^{-1} in the two-hour period following plume departure. The standard deviations were similar to the means in all periods, so the differences noted are not significant. Similarly, Fig. 10 shows the average particle size in the seeding plume was only 10-15 μm different from the periods before and after the seeded period.

Ice crystals in the period between plume arrival and departure were dominated by single crystals with habits fluctuating among needles and columns, and small rimed columns or graupel. At times, uniformly-sized particles of similar habit that could have initiated from a seeding point source were noted, but this was not observed in all the concentration maxima. Overall there was some evidence of microphysical changes that could have been induced by cloud seeding during passage of seeding plumes over Blue Calf, but none that could be definitively termed seeding signatures. The variability noted could have resulted from a mixture of natural and

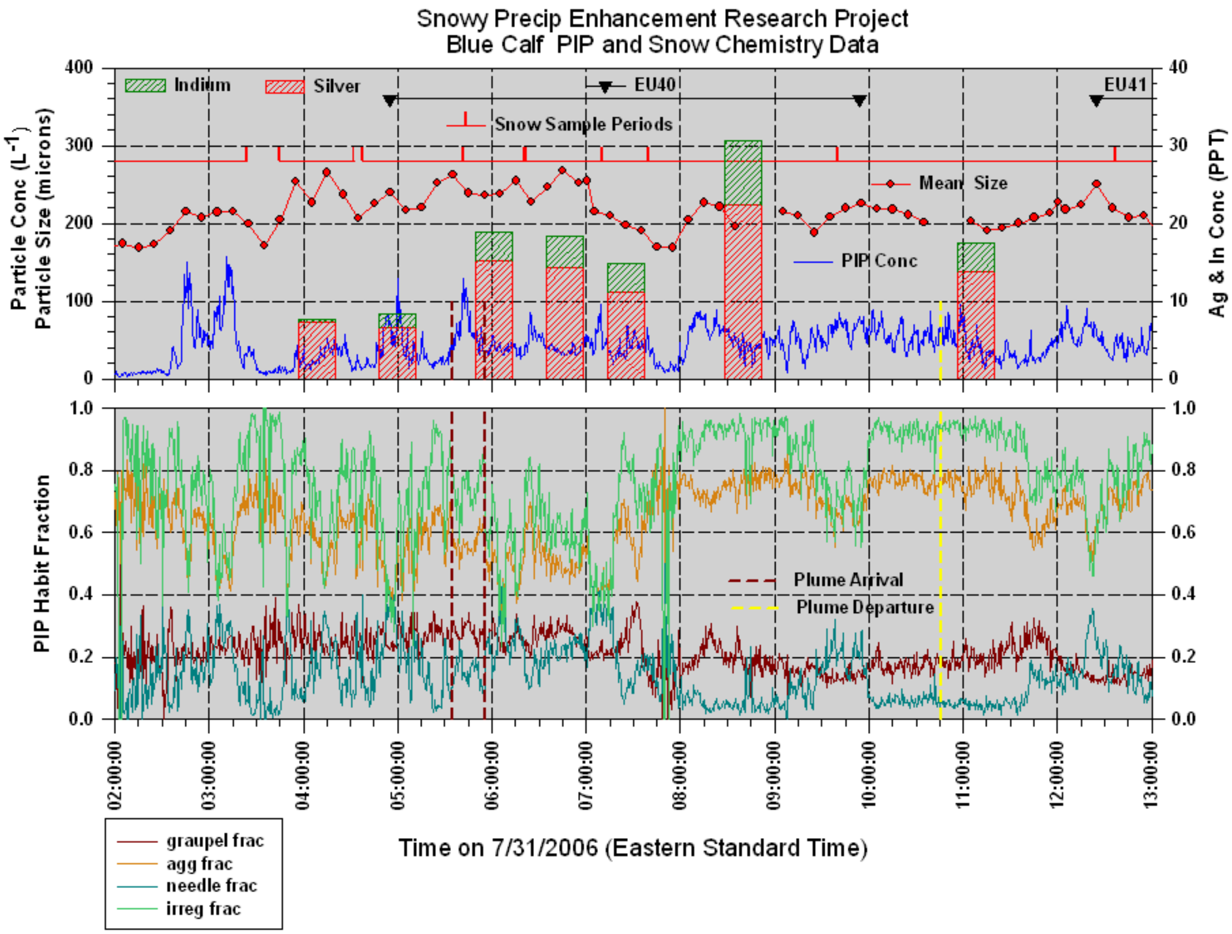


Figure 11. As in Fig. 9, except for a time period encompassing EU40 on 31 July 2006. Two GUIDE plume arrival times are indicated, but only one plume departure.

seeding-induced ice and also from ice in seeding plumes originating at various times and temperatures.

5.5.2 Microphysics Data from EU 40

The time series of PIP data and snow chemistry for EU 40 is shown in Fig. 11. For this case the range of plume arrival times (0535-0556) at Blue Calf was based on GUIDE predictions for three generators, with transit times to Blue Calf between 39 and 60 min. Wind direction shifted somewhat during the EU so the plume departure time (1046) was based on the GUIDE prediction from just a single generator. The estimated plume arrival corresponded quite well to a marked increase in Ag and In concentrations (from ~6 to >15 PPT for Ag). The enhanced trace chemistry concentrations continued throughout the period of effect at Blue Calf with Ag/In ratios ranging from 2.8 to 4.2. In the sample taken after 1300 (Fig. 12) Ag and In concentrations had dropped to values of about 0.3 and 2 PPT, respectively.

The plume arrival corresponded to an increase in PIP particle concentration from ~20 L^{-1} to >100 L^{-1}, and Fig. 10 shows the average particle concentration over the plume period at Blue Calf was about 26% greater than the combined averages over the 2.5 hours before and 2.25 hours after the plume period. Although the standard deviations of the three periods overlap, the difference between seeded and unseeded periods is markedly greater than for EU 38. Strong evidence of ice particle enhancement in seeding plumes has been previously documented (e.g., Holroyd et al., 1994 and Huggins, 2007), but in these case studies the background concentrations in natural precipitation were quite low, often less than 5 L^{-1}, so the seeding signal stood out well above the background. In the current case with a relatively high natural ice particle

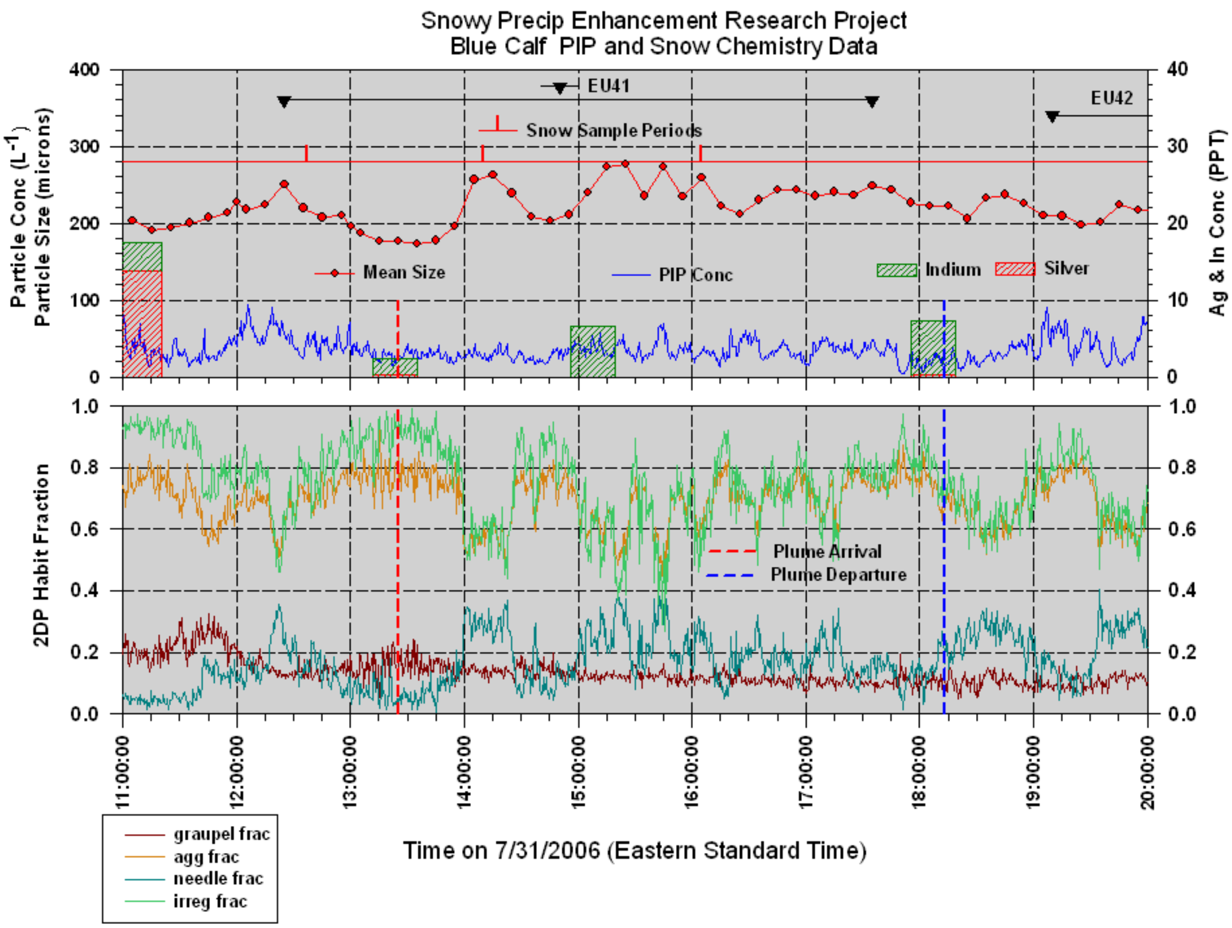


Figure 12. As in Fig. 9, except for a time period encompassing EU 41 on 31 July 2006. Only one GUIDE plume arrival and departure time is indicated.

background (~ 36 – 40 L^{-1} before and after EU 40) a statistical method will be required to test for differences between seeded and unseeded periods. Such a comparison is part of the SPERP evaluation plan.

Changes in ice crystal habits during EU 40 can be seen in the bottom panel of Fig. 11. Prior to EU 40 the fraction of needle habits shows at least three prominent peaks (0305, 0415 and 0455) of about 0.4. During these needle peaks the fraction of aggregates or irregular particles generally decreased from 0.8 to 0.4 or less. Within the plume period at Blue Calf there were several interesting habit transitions. The first habit fluctuation came between 0700 and 0800 when needles first peaked to about 0.4, then declined to a relative minimum of <0.1, while graupel and then aggregate fractions increased markedly to 0.6-0.8. Another needle maximum (fraction >0.2) occurred from 0930-1000 with a corresponding drop in aggregates.

The final three hours within the plume period had very steady fractions of the four habit types with the bulk, about 0.6 of the total, being classified as aggregates. The period from just after 0800 to 1100 had characteristics that were most consistent with a seeding effect; an abrupt particle concentration increase that stayed between 60-80 L^{-1}, the highest Ag concentration of the EU (~23 PPT), and PIP images that indicated a predominance of small graupel and rimed particles ≤ 2 mm in size. Note also from Fig. 6 that this period was the coldest of the storm, except for the last few hours of EU 42. Figure 10 shows the average concentration for this “Late EU 40” period was about 41% greater than the unseeded periods, and particle size was also slightly smaller than during the entire EU 40 period.

5.5.3 Microphysics Data from EU 41

Microphysical data bracketing EU 41 are shown in Fig. 12. The period between estimated plume arrival and departure was characterized by slightly enhanced In concentrations and background Ag concentrations in two Blue Calf snow samples, indicative of a no-seed event. The snow sample periods were long due to the low snowfall rate. Particle concentration was relatively steady in the 20-40 L^{-1} range, with no abrupt changes as noted in earlier EUs. The bottom panel of Fig. 12 shows that the fraction of graupel particles gradually declined during the seeding period, likely a result of the decrease in LW shown in Fig. 6. Figure 10 indicates the average PIP concentration during EU 41 was about 20 L^{-1} less than during EU 40, but particle size was slightly larger. Also, in contrast to EU 38 and EU 40 the average concentration was actually less during EU 41, compared to the periods immediately before and after. Although this is not confirmatory, it does support the evidence of seeding effects in two cases and a lack of in the third.

6. SUMMARY

The SPERP design is based on several climatological, physical and environmental studies in the Snowy Mountains of Australia. The conceptual model and plan for the randomized portion of the experiment are similar to orographic ground-based cloud seeding experiments of the past, but there are also characteristics that are unique to the SPERP. The experimental unit has a relatively short duration of five hours, which was chosen in order to collect enough samples to detect a statistically significant difference in both treated and untreated EUs, and between the target and control areas, over the planned 5-year duration of the experiment. Legislative restrictions have limited the seeding methodology to a specific seeding agent (AgI compound) and release method (ground-based), and introduced some environmental seeding criteria; the overall effect of which could be a reduction in the seasonal number of EUs.

The SPERP infrastructure and data collection plan provide for the measurement of precipitation in the target and surrounding region, and at several control sites that are required for the statistical analysis that will be conducted at the end of the project. A much improved precipitation network, comprised of gauges in the primary target that are shielded by half-size DFIRs, has been installed for this purpose. Other SPERP measurements provide continuous monitoring, with real time data access, of meteorological variables (winds, temperature, and SLW) needed to assess project seeding criteria. A simple plume dispersion and ice crystal trajectory prediction scheme (GUIDE) has been adapted to the Snowy Mountains to aid in the objective selection of EUs.

Sixty nine EUs have been completed to date within the first three formal randomized experimental seasons of SPERP, which puts the project essentially on track to reach the estimated required target of 110 EUs in five seasons. This has occurred even with the large variability in storm frequency and snowfall during the three seasons, particularly during the 2006 El-Nino season, which experienced very low snowfall and resulted in only 12 EUs, with two of these suspended.

The randomized seeding project also incorporates additional physical and trace chemical measurements to verify certain aspects of the conceptual model. The simultaneous release of an ice nucleating aerosol and an inert tracer from all ground-based generator sites, and the subsequent ultra trace chemical analysis of snow samples collected at sites spread across the target permit an assessment of targeting frequency. Enhanced ratios of seeding element (Ag) mass to tracer (In) mass also indicates whether the seeding agent was deposited in the snow as a result of ice nucleation, and not just removed by scavenging. Results from the first two seasons revealed enhanced Ag concentrations over most of the target and enhanced Ag/In ratios were found in up to 50% of individual profile samples. Profiles from an extended storm period in the third season (2006) showed even better coverage of the target through enhanced Ag concentrations, and enhanced Ag/In ratios in up to 80% of samples in some profiles, with a range of 29-80%. Profiles are typically collected after every storm event, so this technique permits a targeting assessment on a storm-by-storm basis.

Analysis of atmospheric soundings, SLW measurements, real time snow samples and laser imaging probe data from a 2006 extended storm period produced some insights into probable seeding processes within a storm. A time series of chemical results from the center of the target showed a pattern that was consistent with the apparent seeding decision for several EUs conducted during the storm, even though the seeding decision has not yet been revealed. The results also showed that seeding or tracer material was reaching the center of the target throughout each EU, that the GUIDE prediction of plume and ice crystal trajectories for the target were verified (not specific generator origin), and that ice nucleation contributed to the Ag in the snowfall at the observing site. As noted above, the snow profiles for this storm period showed similar results for the bulk of the target, and also verified that sites north of the target area were not affected by seeding operations.

The trace chemical data delineated periods when the aerosol and ice crystal plumes were present at the Blue Calf observing site. One period with a markedly higher Ag concentration near the end of EU 40 also showed a coincident particle concentration increase and crystal habits and sizes that were consistent with the time required for nucleation, growth and fallout from a seeding site. In general the PIP microphysical data did not show consistent and obvious ice particle enhancement when compared to periods before and after the seeding period of effect. There were times when ice particle increases were found to be coincident with plume arrival times, and average particle concentrations were slightly higher than average concentrations from surrounding periods, but the plume average was generally within the background variability. Likewise ice particle habits that were consistent with the cloud temperature range where nucleation and growth likely occurred in the seeding plume were observed, but similar habit occurrences were also noted outside seeding plume periods.

In one case the PIP data showed periodic occurrences of relative high ice particle concentrations (peaks to 100 L^{-1}), with a low background ($\leq$ 10 L^{-1}) between peaks. In the second case during the 2-day storm period, the ice concentration background was 20-30 L^{-1}, with occasional peaks > 80 L^{-1}. Both situations tended to mask any obvious ice particle enhancement signatures. Compared to results from experiments where obvious seeding effects were noted, such as Huggins (2007) in Utah, the SPERP cloud temperatures were markedly higher, -5^{o} C to about -10^{o} C, versus temperatures in the Huggins case study where the seeding plume interacted with cloud at -12^{o} C to -17^{o} C. The nucleation activity of AgI is about two orders of magnitude greater in the latter case. The ice concentration background in the Utah case was often 5 L^{-1} or less (so seeding enhancement of 30+ L^{-1} was obvious), while the SPERP case had natural averages of 10-30 L^{-1} and peaks of 80-100 L^{-1}.

7. DISCUSSION AND CONCLUSIONS

A number of conclusions can be drawn regarding the design and operation of SPERP and the preliminary results that have been presented. Based on the seeding hypothesis that ground-based seeding with an AgI-type seeding agent can increase precipitation in the mountainous target area, the design of the generator network appears sufficient to transport seeding plumes across the target in the typical wind directions that accompany snow-producing storms. The snow chemistry data have verified that seeding and tracer material reach the target area a relatively high percentage of the time during experimental seeding periods. However, for the case study analyzed, the current instrumentation did not fully assess real time seeding plume aerosol concentrations over the target, and siting an ice nucleus counter at the Blue Calf site would be a good addition to the physical measurements. This would also allow other measurements such as SLW, precipitation and ice particle measurements to be analyzed and stratified with respect to seeding plume presence, and increase the likelihood of identifying seeding effects in the target.

Additional physical measurements, including aircraft measurements, and cloud modelling studies are being considered by the SPERP and these could contribute significantly to the understanding of the natural cloud processes and to changes induced by seeding. In particular microphysical measurements made in the upwind portions of the orographic cloud over the main range of the Snowy Mountains combined with Blue Calf radiometer and microphysics data could provide a much clearer picture of both natural and seeding-induced precipitation development.

The real time meteorological measurements collected and monitored by the SPERP have been shown to be well suited for the declaration of EUs. The GUIDE scheme, although simple by current model standards, was found to correctly predict plume presence and arrival time over the Blue Calf site within the time resolution of the real time snow samples which verified when Ag and In were present in snowfall at the site. The addition of ice nuclei measurements would provide another means of verifying plume transport to Blue Calf. Also, another way of verifying the source generator would be the addition of a third tracer element to one or more generators in the network. The SLW measurements are critical to the success of SPERP and, although there is considerable variability, the case study suggests excess SLW is relatively common, and at times present coincident with moderate precipitation and relatively high ice particle concentrations.

Although the main range of the Snowy Mountains provides good orographic lift, with the terrain ascending approximately 1800 m over a horizontal distance of about 15 km, the overall height of the ranges may occasionally be a detriment to ground-based seeding in that the typical layer where the seeding plumes are expected to be found (~300-600m above the terrain) represents temperatures where AgI is less effective as an ice nucleant. This situation might be improved by aircraft delivery of AgI, or with the use of materials such as liquid propane which can create ice at temperatures lower than about -2° C. However, because of aircraft terrain avoidance restrictions, it may not be feasible to fly where seeding would be most beneficial, and additional equipment for ground-release of propane would likely require new and time consuming environmental studies and approvals.

The SPERP precipitation gauge network, particularly in the primary target, has been significantly improved and the spatial coverage and data quality from this network should permit an assessment of seeding impact using the proposed statistical evaluation. At least two factors could impact the success of detecting a positive seeding impact; a lower than expected number of EUs in the five-year experimental period and a seeding effect that is less than that used to project the number of EUs required to attain a significant result. On the positive side several of the current data sets, including SLW, temperature, microphysics observations, and the trace chemical data can be used as either secondary response variables or as a means of stratifying EUs to statistically evaluate those cases that have the best potential to show an enhancement in precipitation.

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