

THE SNOWY PRECIPITATION ENHANCEMENT RESEARCH PROJECT: A DESCRIPTION AND PRELIMINARY RESULTS

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Abstract. A gradual reduction in water from snow-melt over the past century has motivated Snowy Hydro Ltd. to pursue a wintertime cloud seeding project in the Snowy Mountains of southeastern Australia. The Snowy Precipitation Enhancement Research Project 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 project design, seeding criteria, ground-seeding network, and measurement infrastructure are described, as are the general components of the statistical evaluation plan. Some initial results from analysis of physical and trace chemical measurements are presented for an extended storm period in 2006 that included five randomized experimental units. The trace chemistry results were found to validate several of the components of the seeding conceptual model, and a unique time series of tracer element concentrations appears to indicate when seeding and tracer materials were released. Progress during the first four seasons of the project is described, as are various findings that could affect the outcome of the project.

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.

Cloud seeding is viewed as one means of increasing snowfall in the Snowy Mountains region. Australia has a long history of cloud seeding research and operations, with initial investigations occurring about 60 years ago. Between 1955 and 1959, the Snowy Mountains were the focus of an aircraft-based cloud seeding experiment run jointly by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Snowy Mountains Hydro-Electricity Authority (SMHEA). From this experiment, Smith et al. (1963) reported a 19% precipitation increase in seeded events; however, despite these encouraging results cloud seeding over the Snowy Mountains was not pursued.

Recurring drought conditions in the early 1980s rekindled interest in cloud seeding in the area. A feasibility study by Shaw and King (1986) assessed the potential for cloud seeding over the Snowy Mountains as positive. This study considered meteorological and cloud physics data over the region as well as the ecological, community and wider-area effects of cloud seeding. Further evaluation of the physical and chemical characteristics of the clouds and snowfall over the region during the winters of 1988–1989 (Warburton and Wetzel, 1992) supported the findings of Shaw and King (1986).

In 1993 SMHEA drafted an Environmental Impact Statement (EIS) proposing a six-year cloud seeding experiment over a 2000 km² area of the Snowy Mountains. This experiment did not proceed because of objections from key stakeholders. An independent expert panel report, addressing the principal objections that had been raised in 1993, was submitted to the New South Wales (NSW) government in 2003. The Snowy Mountains Cloud Seeding Trial Act (NSW) was passed in 2004 allowing Snowy Hydro Limited (SHL) to undertake a six year winter cloud seeding trial — the Snowy Precipitation Enhancement Research Project (SPERP). The objectives of SPERP are to determine the technical, economic and environmental feasibility of precipitation enhancement over the main range of the Snowy Mountains.

The SPERP commenced in June 2004 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. Physical and chemical data collected over the duration of the experiment are used to document the conditions in which seeding has occurred and to verify the seeding conceptual model employed by SPERP. 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.

2. PROJECT DESIGN

Winter precipitation over the Snowy Mountains is largely from moist westerly weather systems. As these systems approach the mountain ranges (orientated along ~30–210 degrees), 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 promote the excess SLW to form ice crystals earlier than expected naturally by introducing additional ice nuclei into suitable clouds over the entire target, producing a significant enhancement in the ice crystal concentration, and allowing sufficient time for the crystals to grow and fall out, resulting in an enhancement of snowfall on the ground. The target area for the project covers approximately 1000 km² of the main range of the Snowy Mountains; this area is located entirely within the Kosciuszko National Park (KNP). A map of the area is shown in Figure 1.

2.1. Legislative Restrictions

The Snowy Mountains Cloud Seeding Trial Act (2004) prescribes a number of restrictions on the SPERP to satisfy the concerns of various stakeholders; briefly:

- SPERP operations can only occur when precipitation is likely to fall as snow over the primary target area;

- Silver iodide (AgI) must be used as the ice-nucleating agent, and indium sesquioxide (In₂O₃) as the tracing agent; these agents must be dispersed from ground-based generators, which cannot be placed within the Jagungal Wilderness Area (north of the target area);

- SPERP must have a comprehensive monitoring system to evaluate the effects of cloud seeding operations.

In addition, SHL had to prepare and implement an Environmental Management Plan prior to commencing operations and is required to report environmental sampling results annually.

2.2. Background Studies and the Randomization Scheme

The project design was initially based on an Expert Panel Assessment (Environ, 2003) that drew from the climatological feasibility study (Shaw and King, 1986), the 1993 Environmental Impact Statement and the results of the Snowy Mountains Atmospheric Research Program (SMARP) conducted in 1988–1989. SMARP focused on the cloud seeding potential over the Snowy Mountains using observations of wind, cloud liquid water and temperature structure (Warburton and Wetzell, 1992). The results of SMARP also showed that the background concentrations of silver (Ag) and indium (In) were ≤ 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.

An additional climatological analysis of surface precipitation and temperature records at a site immediately to the north of the target area was conducted in 2004 to refine the details of the design. Using the results, an Experimental Unit (EU) duration of five hours was selected as practical for evaluation of the impact of seeding. The climatological analysis, combined with “opportunity recognition” studies using atmospheric soundings, microwave radiometer measurements and plume dispersion modelling, was used to predict the number of suitable storm periods and EUs expected over the five year experiment, and to assess the number required for statistically significant results, taking into consideration the impact of operational constraints and cessation criteria. The outcome of this was similar to the number of suitable

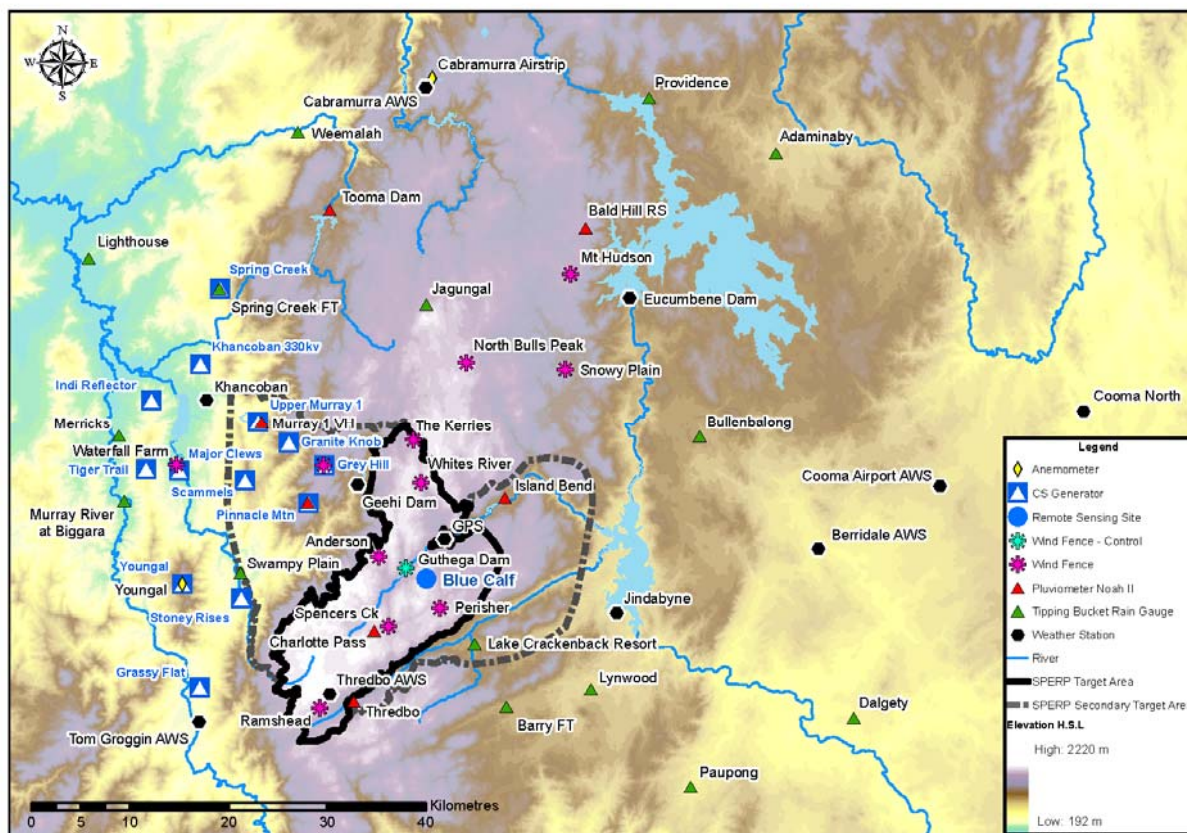


Figure 1. Map of the Snowy Mountain region. Legend at the lower right identifies the various SPERP instrument sites. Project soundings are launched from the Khancoban weather station site. The primary SPERP target area is outlined in black and the blue circle represents the Blue Calf remote field observing 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. Pluviometers at Cabramurra, Weemalah, Lighthouse, Merricks, Waterfall Farm, Murray River and Tom Groggin are part of the set of control sites for the statistical evaluation.

seeding days estimated by Shaw and King (1986) for a 5-6 year experiment. 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 that, when various seeding criteria are satisfied, randomizes the decision to seed. The randomization scheme is 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 personnel. 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. The purge time may be increased as determined by a simple model that uses wind data collected from atmospheric soundings to predict the transport of aerosol plumes over the target area. Time series of trace chemical data indicate the purge time is adequate.

2.3. 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 first set of criteria is associated with environmental concerns:

- The high reservoir storage of the Scheme's largest dam, the snow water content and the snowpack accumulation must be below set threshold levels. These levels were described in the SPERP Environmental Management Plan and are measured weekly.

- There must be no severe weather threats that precipitation enhancement could exacerbate (for example, flooding).

- The height of the freezing level in the atmosphere must be lower than 1600 m (MSL) to ensure that precipitation falls as snow, rather than rain, over the higher elevations. If the freezing level is between 1550 and 1600 m then remote cameras and external observers are consulted to ensure that precipitation is not falling as rain.

A number of criteria rely on the meteorological conditions. The temperature of the cloud top must be $\leq -7^{\circ}\text{C}$ 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). These parameters and the freezing level are measured, or estimated, using upper air soundings. In addition, a radiometer located on Mount Blue Calf in the primary target area (Figure 1) must show SLW in the cloud. The threshold value is 0.005 cm, slightly above the radiometer's detection limit for liquid water.

A plume dispersion and cloud physics diagnostic scheme called GUIDE (Rauber et al., 1988) was adapted to the terrain and wind characteristics of the Snowy Mountains and is used to predict the transport and dispersion of the plumes from the generators to the target area. Tests using an atmospheric dispersion model with MM5 wind fields were used to adapt GUIDE's highly parameterized wind fields to the Snowy Mountain region. Data, such as wind speed and direction and temperature, from atmospheric soundings are used to initialize the GUIDE model. For seeding to take place, the

GUIDE output 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 (the time between routine sonde releases).

2.4. 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), and ultra-trace chemistry analysis 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.

The primary analysis uses regression methods to estimate the precipitation in the target area based on observations in the control area during unseeded EUs. These estimates are then applied to estimate the 'natural' precipitation in the target area during seeded EUs. Statistical tests are used to compare the estimated 'natural' precipitation with the observed precipitation in the target area during EUs. While area-averaged values of precipitation can be used to quantify the impact of seeding, more sensitive tests involving principal components and canonical correlations can be applied to the data in order to detect an effect of seeding against the noisy background of natural variability. This approach provides a robust and sensitive method for detecting the presence of a seeding effect. Further, based on the successful use of ultra-trace chemistry techniques in evaluating winter cloud seeding projects in the western United States (e.g., Chai et al., 1992; Warburton et al., 1996 and McGurty, 1999), a

snow chemistry analysis will be used in parallel with the statistical methods to identify the presence of a seeding effect in the target area. One specific, and new, method for quantifying the effect of seeding using trace chemical analysis of snow profiles collocated with recording precipitation gauges, and comparisons between sites with and without chemical seeding signatures, is in progress, but will not be addressed in this paper.

The secondary analysis considers additional statistical tests, such as the classic double ratio of the average precipitation in the target to the control area, and a single area analysis, comparing the total precipitation in the target area in seeded versus unseeded EUs. In addition, the probability distribution of precipitation in seeded and unseeded EUs will be compared using the Kolmogorov-Smirnov test (Press et al., 1986). A set of sensitivity analyses will also be performed and these will include a repetition of the primary statistical analysis with more predictor variables, which should help ascertain the sources of the seeding impact, or identify how it was masked or suppressed.

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 2.3) 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, such as the height of the freezing level, cloud top temperature and cloud depth. The SPERP uses Vaisala Digital Radiosondes (Model RS92-SGP), the DigiCORA III Sounding Software package and the GC25 Ground Check Set (used for pre-testing the sonde and setting the radio frequency of the transmitter). Data from the lower levels of the sounding are telemetered to the CSCC and input to GUIDE, which is then typically run about 15 - 30 min after a sounding launch.

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 (NRG IceFree3 2450) and anemometer (NRG IceFree3 2448), and temperature (Vaisala HMT337) and humidity (Vaisala Humicap 180) 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. Additional equipment may be added to the facility in the future to further strengthen the physical measurements.

The dual-channel radiometer (Radiometrics, Inc, Model WVR-1100) 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. A heavy-duty heated blower system is directed towards the radiometer to keep the window clear of water and icing. This system is used in lieu of the Radiometrics blower which was found to be inadequate in keeping the window clear in the very harsh environment on Blue Calf. The SPERP also uses three icing rate detectors (Goodrich Model 0871LH1) 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). These detectors have a probe that resonates at about 40 kHz. When icing on the probe damps the resonance by an amount equivalent to 0.020 ± 0.005 inches of ice accumulation, a pulse is registered as a de-icing cycle begins. 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. The CIP measures particles over a range of 25–1600+ microns at 25-micron resolution and the PIP has a range of 100–6400+ microns at 100-micron resolution. The sampling rate of the instrument is controlled by a heated wind speed sensor mounted near the probe tips.

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 disperse the seeder and tracer aerosols into the atmosphere. (The seeding aerosol is specifically $\text{AgCl}_{0.22}\text{I}_{0.78} \cdot 0.5\text{NaCl}$, reported on by Feng and Finnegan (1989), with an activity of 1.2×10^{14} nuclei gm^{-1} at -10°C and approximately 10^{12}

nuclei gm^{-1} at -6°C .) The generators were all placed on sites that had already been disturbed to minimize the environmental impact of installing the structures. Three of the sites have burners elevated on towers 15–26 m above the ground to ensure the aerosol plume is released above the forest canopy. At the remaining sites the burners are located on trailers and are 5 m above the ground (Fig. 2). 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 release rates must be known (see for example Warburton et al., 1995). In SPERP the solution flow rate of all generators is set at 1250 mL h^{-1} , and is automatically regulated during operations via computer-managed control valves. The particle size distributions of both aerosols have been measured and found to have average diameters of about $0.07 \mu\text{m}$. The mass release rates of silver iodide and indium sesquioxide are 20.4 g h^{-1} and 11.4 g h^{-1} , respectively. The elemental mass release rates of Ag and In are both 9.4 g h^{-1} , which leads to an expected mass ratio of Ag/In in snowfall of one, if both are removed only by scavenging processes.



Figure 2. The two types of ground-based generator mountings used by the SPERP. Three generator pairs are elevated on towers (right) and the remainder are mounted on trailers (top).

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 supplied by ETI Instrument Systems (Model NOAH II). These are used to measure precipitation at sites above the height of the typical snowline. Australian Hydrological Services tipping bucket gauges (Model TB3) are used at sites below the snowline. The gauges are outfitted with low-power heaters (Model TB323LP) 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. In these conditions precipitation gauges are known to “under-catch” snow because it is blown across the gauge orifice. 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. These structures consist of two concentric-circle (4 and 12 m diameters) lath-fences around the gauge (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 ($\frac{1}{2}$ DFIR), which were collocated with unfenced gauges at four key sites (Perisher, Guthega Dam, the Kerries and Grey Hill) prior to the 2006 cloud seeding season. A full-size DFIR was also constructed at Guthega Dam to provide a comparison with a gauge shielded with a $\frac{1}{2}$ DFIR and an unfenced gauge. Figure 3 shows a photo of the Guthega Dam site and a graph of the cumulative precipitation recorded by the three gauges over a two-day period; the precipitation under-catch by the $\frac{1}{2}$ DFIR and unfenced gauge is clearly shown. An additional seven $\frac{1}{2}$ 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.

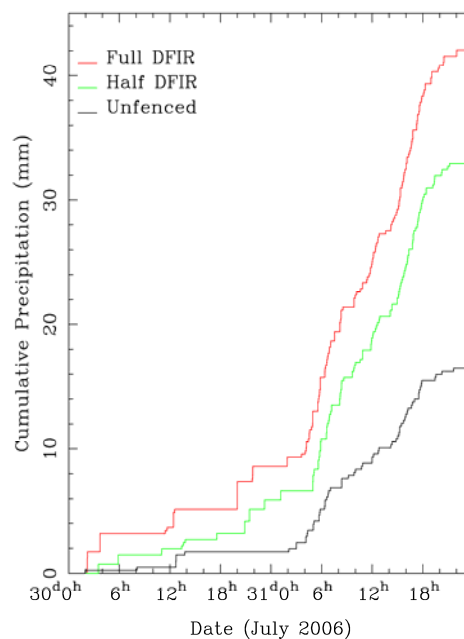
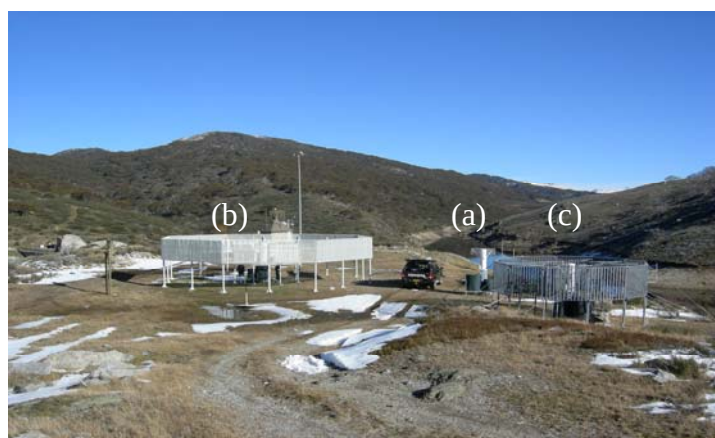


Figure 3. Left: The pluviometer comparison site at Guthega Dam, consisting of an unfenced gauge (a) and identical gauges fenced with a full DFIR (b) and a half DFIR (c). Right: The cumulative precipitation measured by the gauges over a two day period in July 2006.

3.4. Snow Sampling Sites

Vertical snow profiles are collected as soon as possible following each field campaign of 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. In the 2004 season samples were collected from 26 sites, which were usually accessed by over-snow vehicles. Often the sampling would extend over three days following the end of a field campaign because weather conditions prevented access. The number of sampling sites was reduced to eleven for the remaining years of the project. These sites were selected to represent the primary target and control areas, to have reliable access, and to be collocated with ETI pluviometers.

After some campaigns there was not enough snow to warrant sampling because rain or wind had depleted the snow, or the storm event had not produced much precipitation. In particular, during the 2006 season the storm events were very short and produced only limited snowfall.

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. Since 2004 was the start-up year, 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 operation dates for each year. The winter of 2006 was a particularly dry season and did not offer many cloud seeding opportunities. In addition, two of 12 EUs were suspended in 2006 because changing weather conditions during the EU period led to a rise in the freezing level above the restricted height of 1600 m. 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.

4.1. Snowfall in the SPERP Target Area

Snow accumulation in the Snowy Mountains is naturally variable from year to year. Figure 4a shows the highest snow depth measured at Spencers Creek (located within the primary target area) each year since 1954. As shown in this figure, only one of the first four SPERP seasons had snow accumulation above the long-term average. The 2006 season stands out as having the least snowfall during the entire 54 year period. Despite the below average snowfall during the three randomized seeding years, only 2006 produced fewer EUs than the average number estimated to be needed annually for the statistical evaluation after five years. Figure 4b shows the seasonal snow depth for 2004 to 2007 where the peak snow levels generally occurred in August

Table 1. Summary of 2004-2007 SPERP cloud seeding seasons.

Year	Campaigns	Experimental Units ^a	Hours of operation	Operation dates
2004	12	N/A ^b	187	18 Jun-13 Sept
2005	13	31 (3)	164	15 Jun-29 Sept
2006	8	10 (2)	55	7 May-24 Sept
2007	10	22 (1)	112	21 May-29 Sept

^a The number of suspended EUs is shown in brackets.

^b 2004 was the start-up year and no randomized experiments occurred.

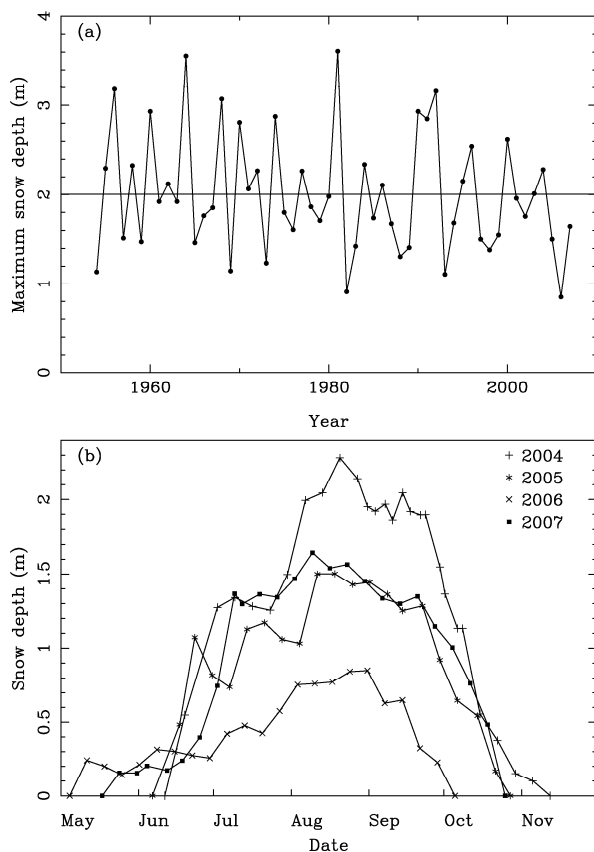


Figure 4. The snow depth measured at Spencers Creek in the Snowy Mountains. (a) The maximum snow depth each year from 1954 to 2007 and the long term average (horizontal line). (b) The temporal trend in snowfall accumulation for SPERP winters 2004–2007. Data courtesy of Water Resources (SHL).

4.2. Targeting Effectiveness Using Ag/In Ratios

The use of the Ag/In mass ratio to evaluate cloud seeding targeting effectiveness and to demonstrate that Ag arrived in the snowpack by the ice nucleation process rather than by cloud and precipitation scavenging processes was documented by Warburton et al. (1995). 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. Figure 5 (left) displays the percent of snow samples at each sampling site in 2004 that were found to have an Ag/In ratio greater than the expected 1.0 (from scavenging alone), and Figure 5 (right) displays the same data for the 2005 season. The percentages in 2005 were higher at all sites but one, with less variability over the target. The 2004 data tend to show a deficiency in targeting across the center and some eastern portions of the target. Figure 6 compares 2004 and 2005 snow chemistry data for sampling sites that were the same for both years. The mean Ag concentrations were 2–10 PPT higher in 2005 and the percentages of samples with Ag/In ratios greater than 1.0 were at least 10 percentage points higher in 2005 for all but one site. This apparent improvement in targeting is noted even though all storms in 2004 were seeded, while, as a consequence of the randomization, only about 2/3 of the qualifying storm periods in 2005 were treated with AgI.

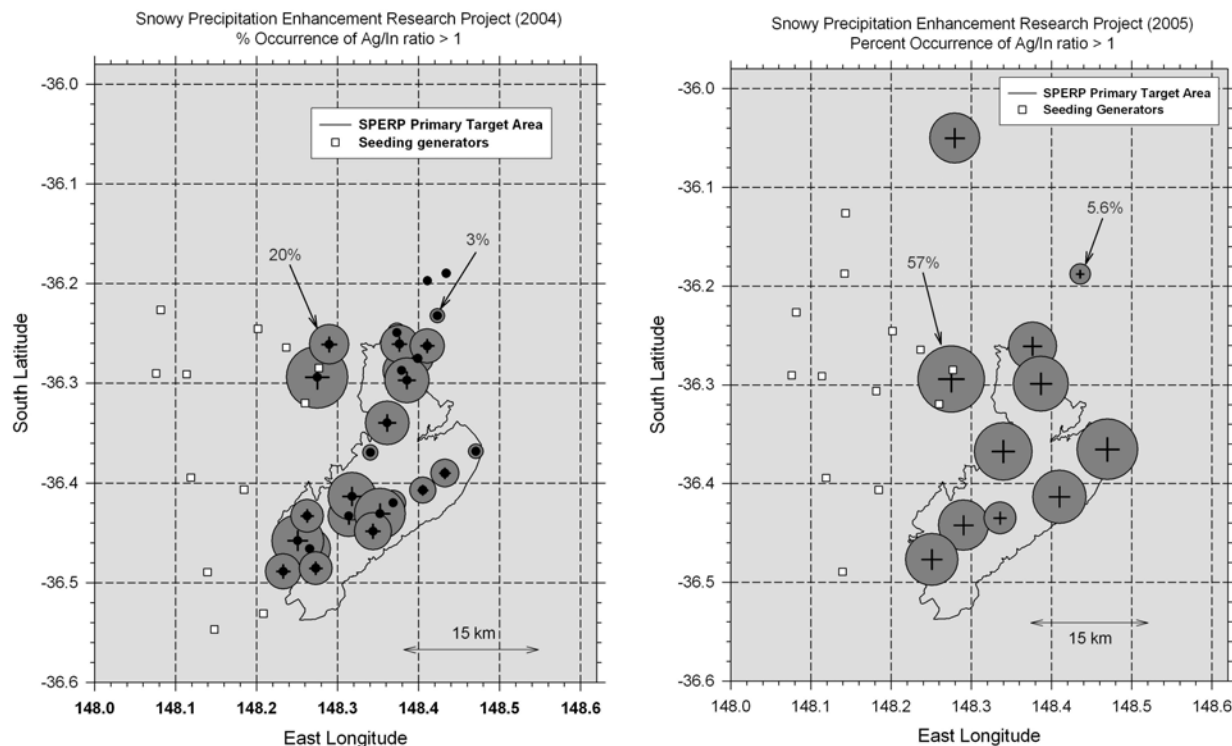


Figure 5. Plots showing the percent occurrence of Ag/In ratios greater than 1.0 (circles) for snow samples collected at the SPERP sites shown in 2004 (left) and 2005 (right). Circle size is proportional to percentage as indicated by examples in each plot. Note the two small dots above the 3% circle in the left plot represent 0%. White squares represent seeding generator sites for each season.

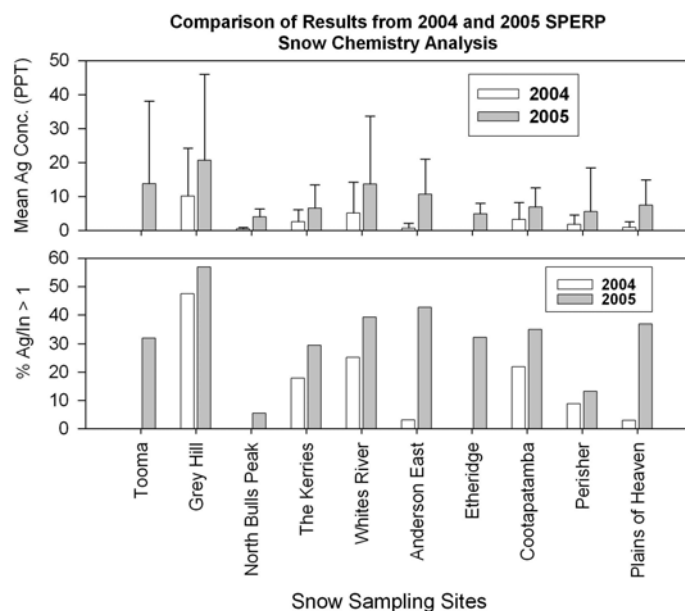


Figure 6. Comparison of snow chemistry results at similar sampling locations for 2004 and 2005 SPERP seasons. Top: Mean Ag concentration from all samples collected at each site with bar indicating the standard deviation. Bottom: Percentage of Ag/In ratios that exceeded 1.0 at each site. Note that North Bulls Peak was intended to be a control site.

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. 7 summarizes some of the data pertinent to seeding operations. Figure 7(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. 7(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).

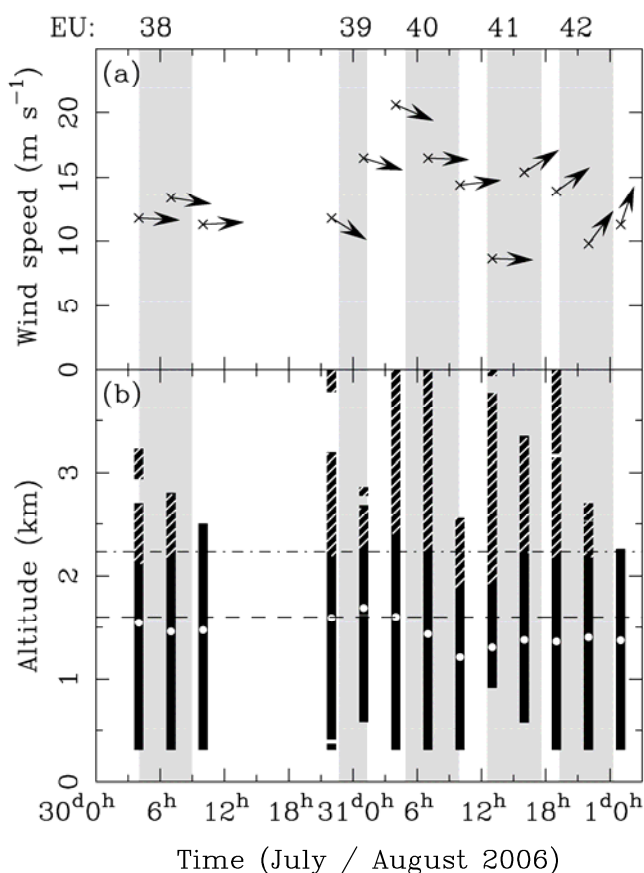


Figure 7. A time series showing data from the thirteen radiosondes that were launched during the operational period. The grey shading shows the durations of EUs which are numbered at the top. (a) The wind speed and direction at the -5°C level. (b) The heights of the freezing levels (white dots) and cloud 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). Time is local Eastern Standard Time.

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°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 8a and 8b 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 be turned on if the predicted centerline crosses the target area. As indicated in Fig. 8, all generators except Spring Creek and Grassy Flat were predicted to produce plumes over the target, so these two generators were not turned on at the

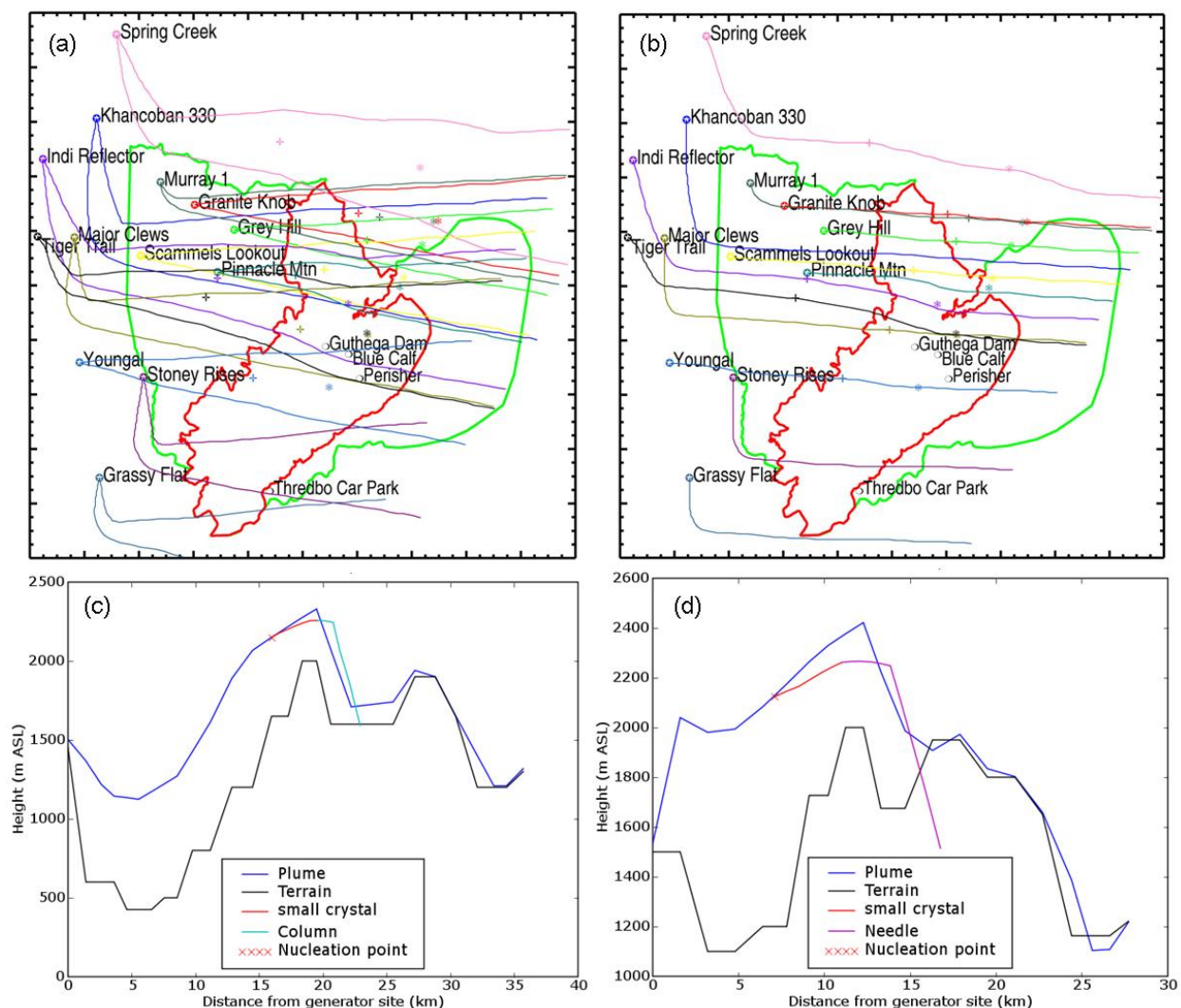


Figure 8: GUIDE model output based on the sounding released before EU 38. Top: Plan view plots of the expected plume boundaries (a) and centerline (b) from each generator. The predicted point of nucleation (cross) and fallout (star) for each plume, and the locations of Guthega Dam, Mt. Blue Calf, Perisher 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.

beginning of EU 38. Spring Creek was turned on part way through the EU following a later balloon release. Figure 9 shows the centerline plots for the GUIDE runs preceding EUs 39 to 42. The winds clearly 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 8c and 8d show examples of the vertical trajectory plots.

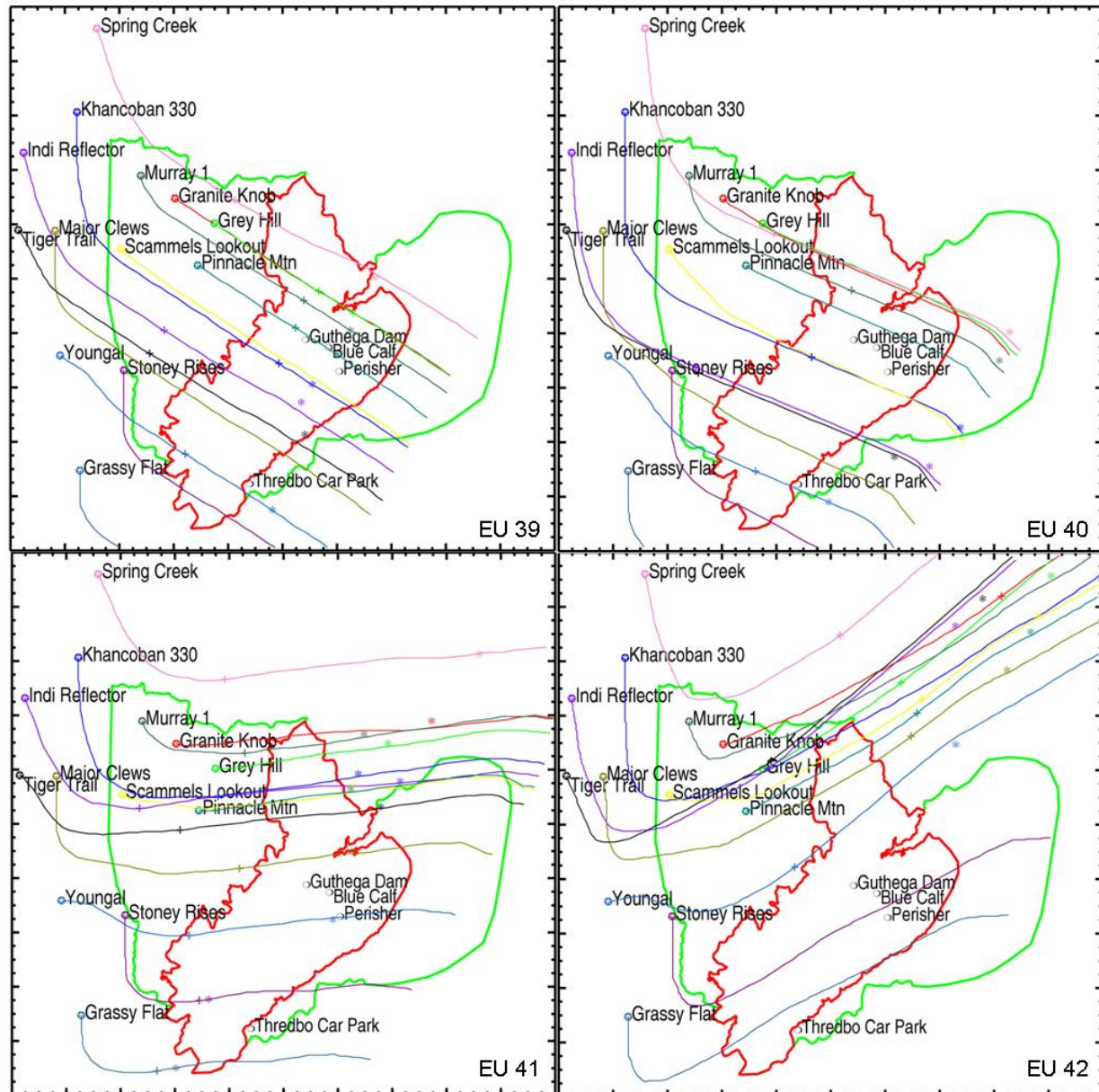


Figure 9. GUIDE centerline plots of the aerosol plume from each generator based on the sonde released before each EU. See Figure 8 for further details.

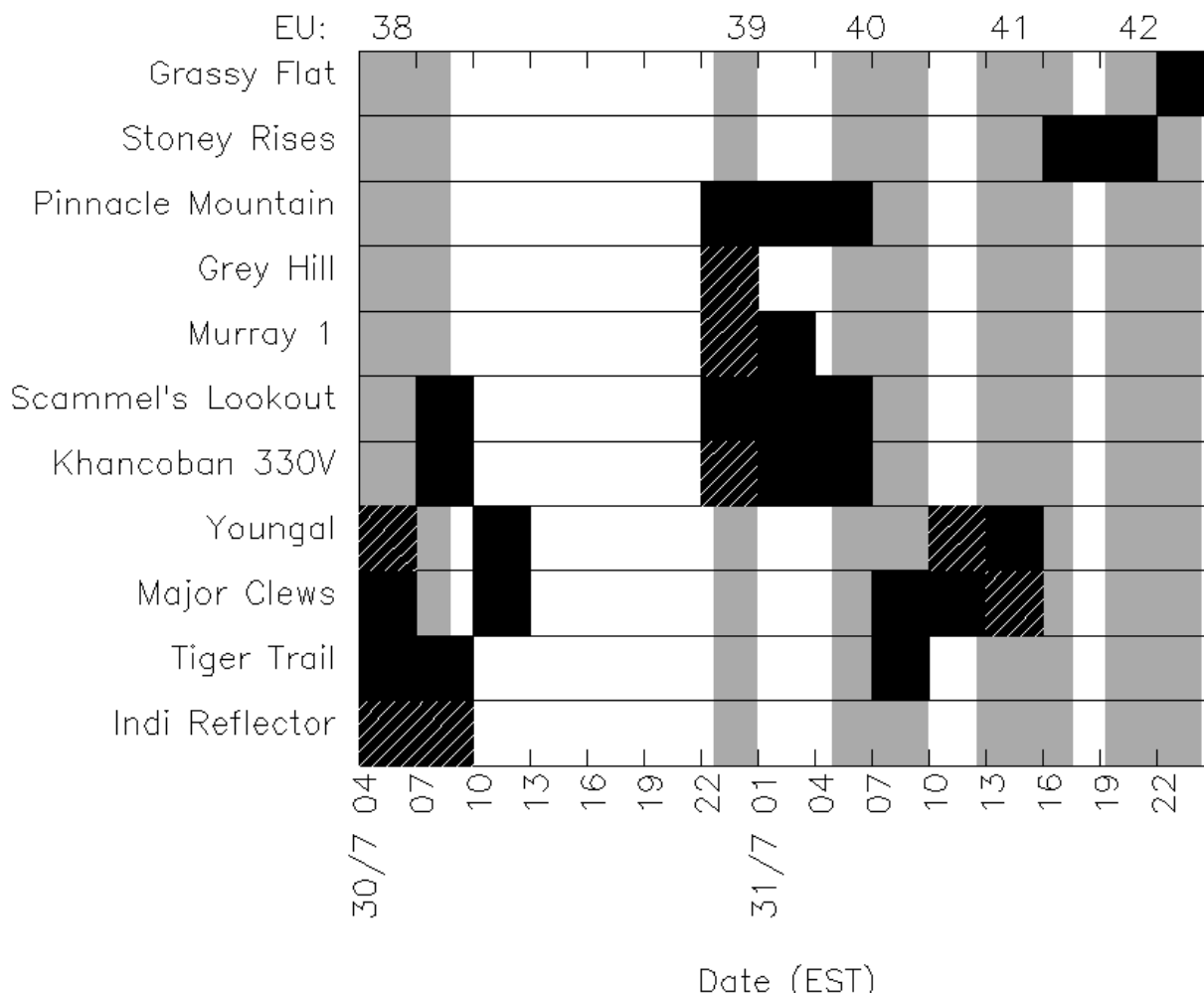


Figure 10. Plot showing which GUIDE generator plumes existed over Blue Calf for each atmospheric sounding in the two-day storm period. The grey shading shows the duration of each EU, the black shading shows the generators that were targeting Blue Calf and the hatching shows the generators that had crystal fallout predicted upwind of Blue Calf. Sounding dates and times are noted on the bottom axis (local Eastern Standard Time).

Figure 10 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 from the last EU of a campaign. The pertinent wind data were shown in Fig. 7.

The depth of the liquid water (LW) in the atmosphere above Blue Calf is shown in Fig. 11b 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. 11c), 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. 11d), 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 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. 11d) a short distance away. High ice crystal concentrations were also

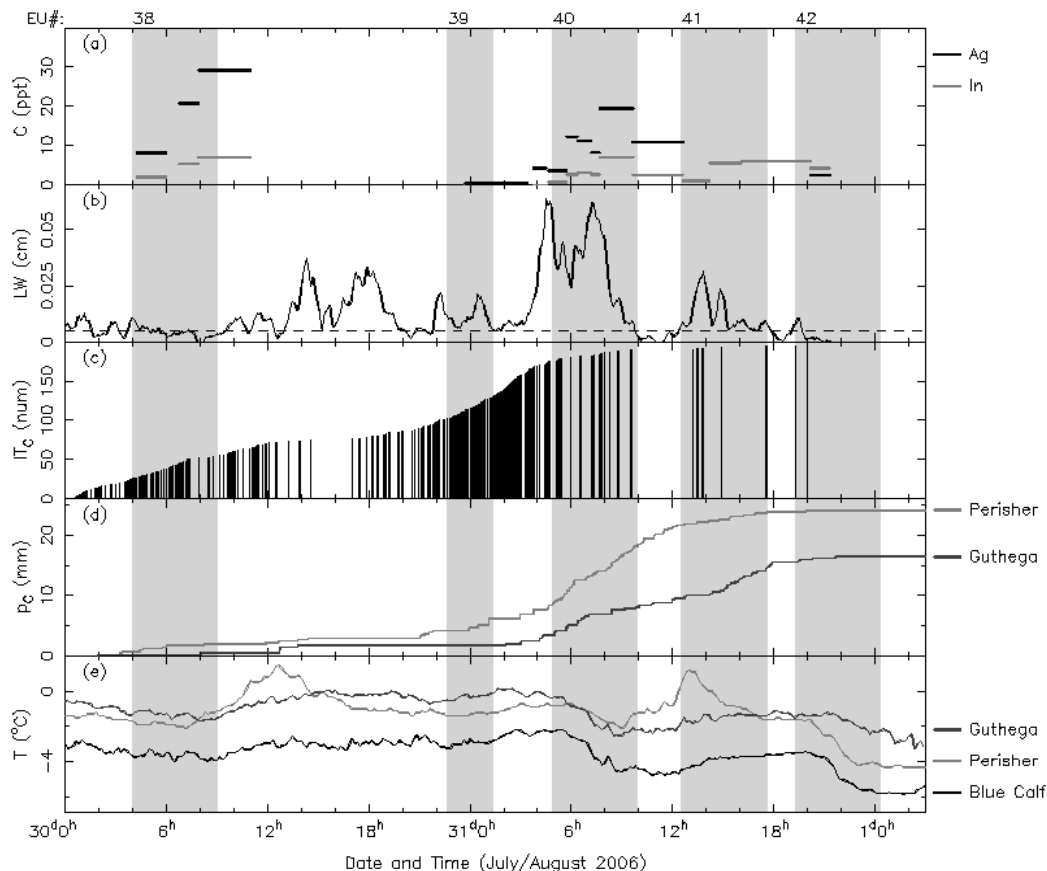


Figure 11. A time series of physical and chemical data collected from Mount Blue Calf, Perisher and Guthega Dam (see Figs. 1, 8 and 9 for locations). (a) The concentration (C) of Ag and In detected in the Blue Calf real time snow samples (the length of the lines shows the collection period for the sample). (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.

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. 11c) decreased at Blue Calf soon after the start of the last EU, corresponding temporally to the drop in temperature seen at all sites (Fig. 11e) 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 11a 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 these 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.) A snow sample bag was lost in high wind conditions between the first and second sample, accounting for the gap in the data.

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. 11a 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. 11, the Perisher trace indicates that 80-90% of the precipitation came between the start of EU 38 and the end of EU 40. If snow in the profiles was deposited proportionally, then the seeding effects from EU 38 and EU 40, noted at Blue Calf, should have been present in the lower 75% of the target profiles. Likewise the “no-seed” indium signature from EU 41 should have been present in the upper 25% of the profile segments (assuming temporal targeting as at Blue Calf). Five of the seven profiles showed evidence of a seeding effect in the lower 75% of the profile and three of seven showed evidence of a no-seed event in the top 25%. Three other profiles showed evidence of enhanced Ag and Ag/In ratio in the top segments, possibly from the last EU which was not well observed at Blue Calf.

The spatial pattern of enhanced Ag/In ratio from all profiles is shown in Fig. 12 (as in Fig. 5). The percentage of samples with enhanced Ag/In ratio from Blue Calf is also plotted. For all profile segments and temporal samples the percentages ranged from about 29% to 80%. The highest percentages were actually from sites in the Grey Mare range upwind of the primary target, but within the secondary target and in close proximity to two seeding sites. The 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 shown in Fig. 6. In all cases the intended control site at Bulls Peak showed no chemical evidence of being targeted. Additional trace chemical statistics from the 2006 case

study profiles are shown in Fig. 12. All sites except the Bulls Peak control had average values of Ag, In and Ag/In ratio that exceeded the natural background, or values to be expected if the target was not being affected by the SPERP cloud seeding operations.

5.5. Ice Particle Characteristics Measured with the PIP at Blue Calf

Several past research experiments related to ground-based cloud seeding have documented ice crystal enhancement within seeding plumes. Super (1999) summarizes orographic seeding experiments in the mountains of Utah, and notes ice crystal enhancement and particle habit changes induced by ground seeding with

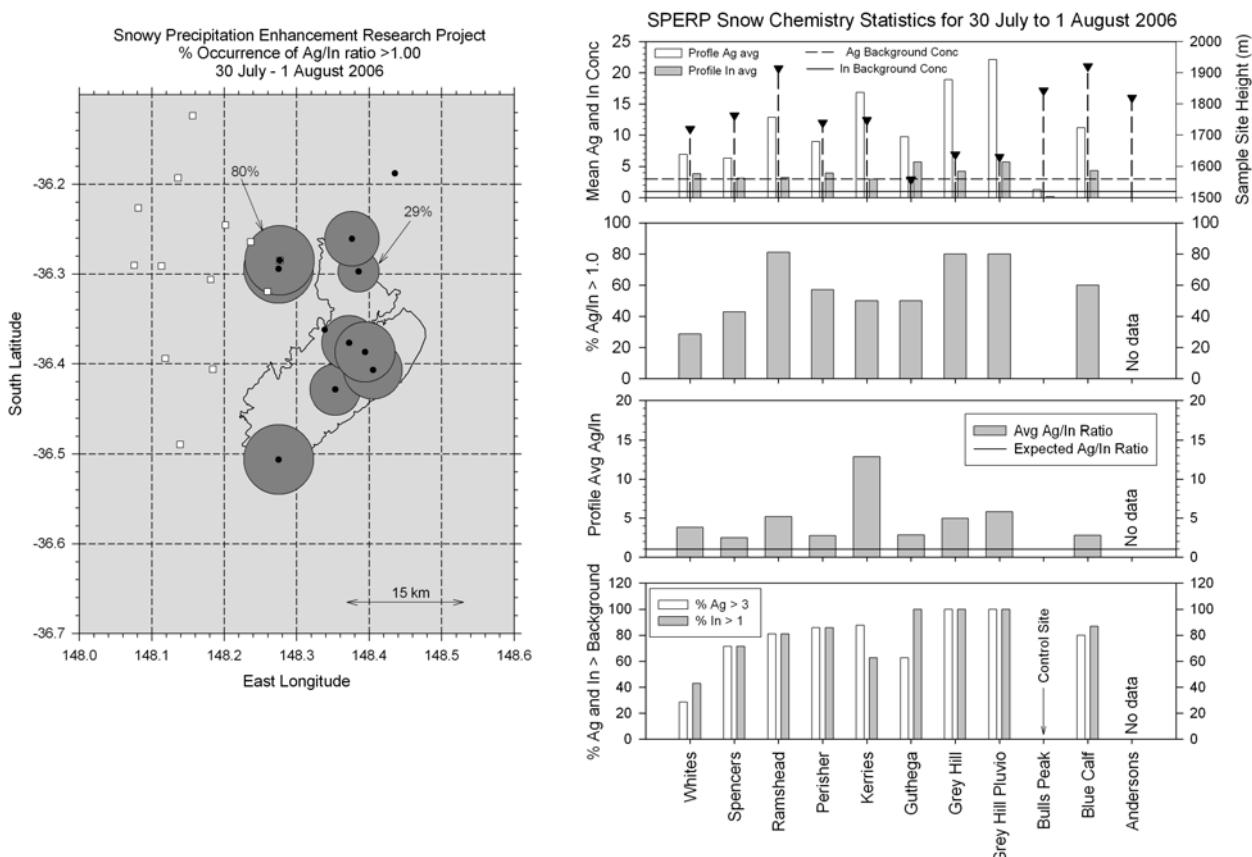


Figure 12. Left: Plot showing percentage occurrence of Ag/In ratios > 1.0 in snow profile samples collected at the sites indicated on 1 August 2006. Circle size is proportional to percentage. One site in the target near the west edge with no circle was not sampled. White squares are seeding sites. Right: Graphs showing trace chemical statistics from each sampling site on the map to the left. Top panel: Average Ag and In concentrations from all profile samples. Triangles indicate the heights of the sites. Second panel: Percent of samples with Ag/In ratio > 1.0. Third panel: Average Ag/In ratio computed from all samples in a profile. Bottom panel: Percent of samples in each profile with Ag and In concentrations greater than the background concentrations in unseeded snowfall.

AgI and liquid propane. In other case studies Holroyd et al. (1995) and Huggins (2007) documented microphysical responses to seeding in the data from ground-based and aircraft particle imaging probes (CIP model). These experiments were aided by terrain which allowed (by special waiver) aircraft flights within 300 m of the surface and roads through the target region that permitted penetration of seeding plumes by instrumented vehicles. Also, in a specific experiment there was typically only one source of seeding material and therefore no ambiguity in estimating times and distances to plume intersection points. Several experiments documented seeding-induced ice particles that were quite uniform in size and habit, and easily differentiated from natural ice crystals.

The SPERP target has no convenient high altitude roadways to enable use of mobile ground instrumentation, and to date instrumented aircraft have 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 Utah studies made use of mobile and stationary NCAR ice nucleus counters (Langer, 1973) and other tracer gas releases and detection equipment to document seeding plume locations in space and time. This permitted detailed comparisons of seeded and unseeded cloud regions. The snow chemistry measurements are the only datasets that permit any type of seed-no seed comparisons in SPERP. This section presents some preliminary analyses of the microphysical data in two of the apparently seeded 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 13 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. 8). 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 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. 13 bracket a sharp increase in particle concentration to $>100\text{ L}^{-1}$ (0455 EST) following a one hour period where concentrations were generally $<15\text{ L}^{-1}$. 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. The average concentration in the seeded period was 31.1 L^{-1} , compared to 28.9 L^{-1} in the two-hour period prior to seeding, and 25.7 L^{-1} in the 2.5 hour period following the plume period. The standard deviations were similar to the means in all

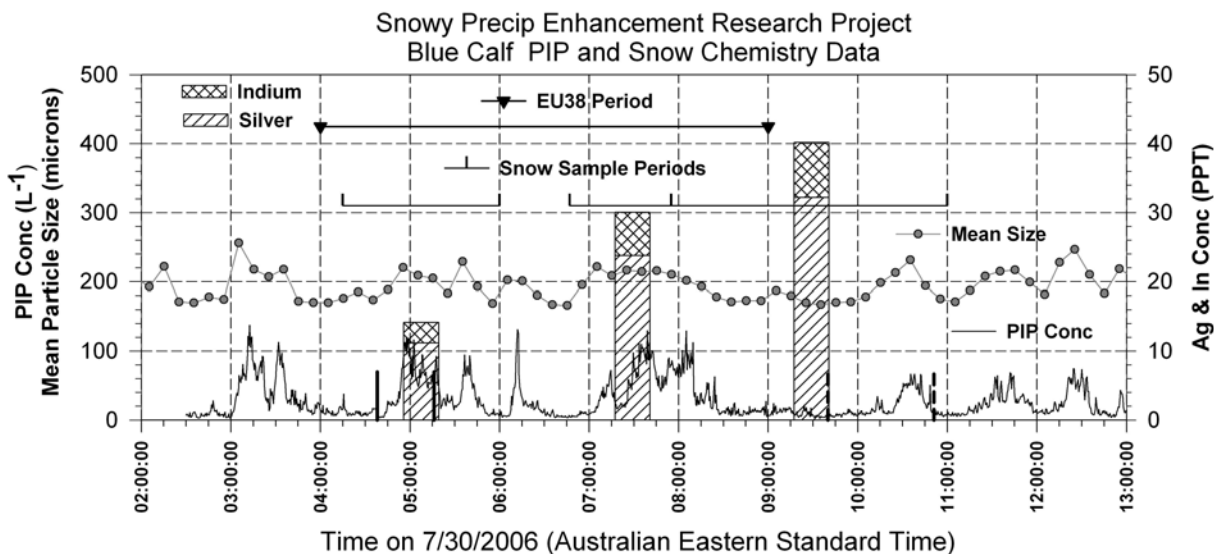


Figure 13. Time series plot of Blue Calf precipitation imaging probe (PIP) data and real time snow chemistry data for the period encompassing EU 38 on 30 July 2006. Actual indium concentration is the difference between the total bar concentration and the silver concentration. Solid black lines on the time axis represent the initial aerosol plume arrival times at the start of an EU predicted by GUIDE for one or more generators. Dashed black lines are similar departure times for the back edge of plumes to reach Blue Calf once generators are turned off.

periods, so the differences noted were not very meaningful.

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, as in Fig. 14 from 0527-0537, 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 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. 15. 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 (not shown) Ag and In concentrations had dropped to values of about 0.3 and 2 PPT, respectively. Although the plume arrival corresponded to an increase in PIP particle concentration from ~20 L⁻¹ to >100 L⁻¹, the average particle concentration over the plume period at Blue Calf was only 8-10% greater than the averages over the 2-3 hours before and after the plume period, with the averages being well within the standard deviations of all three periods. 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 background

($\sim 20\text{--}30\text{ L}^{-1}$ 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. 15. 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

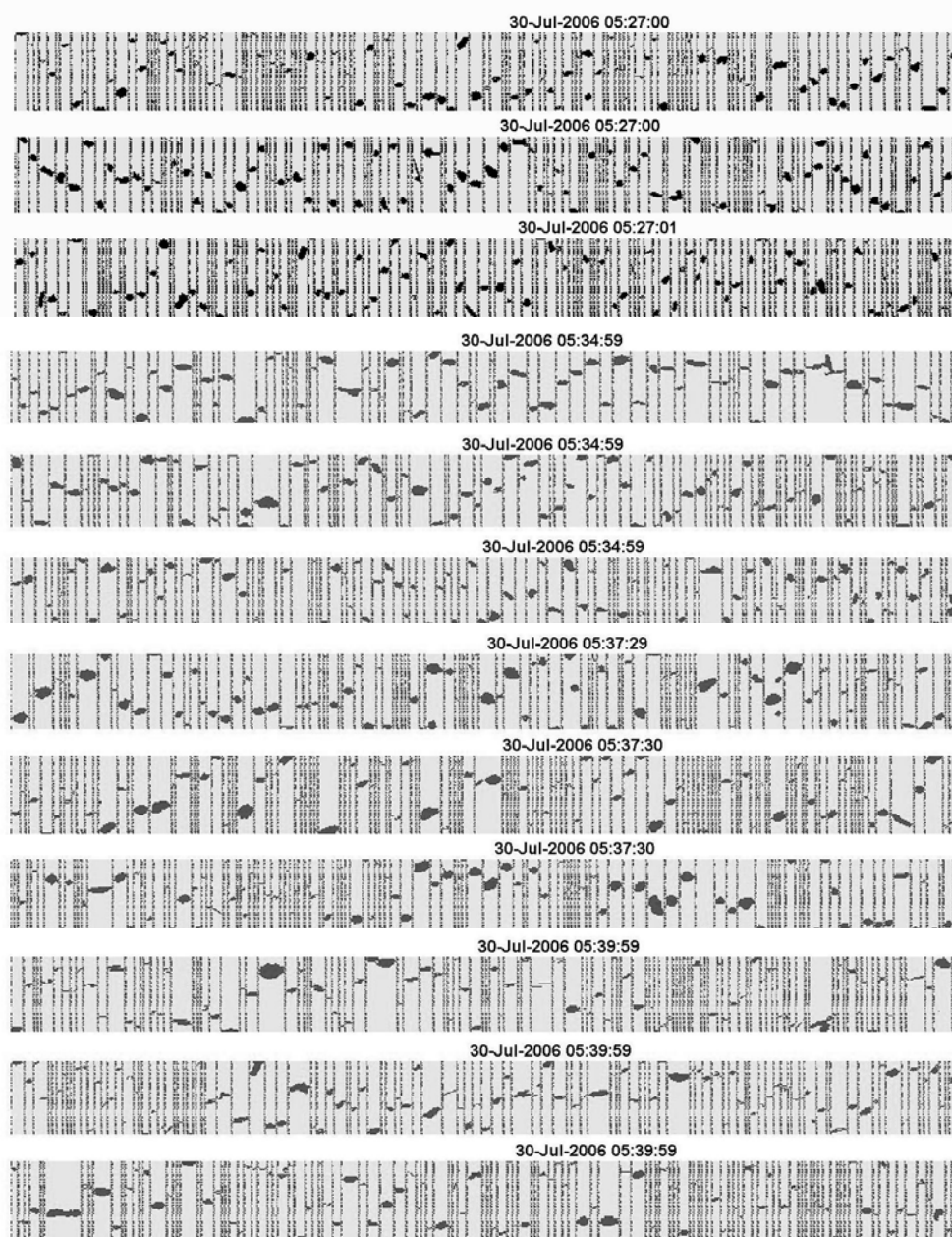


Figure 14. Ice particle images recorded by the PIP at Blue Calf between 0527 and 0540 EST during EU 38, and corresponding to the second concentration maximum in Fig. 13 following the initial seeding plume arrival. The images appeared to be rimed columns, plates, or small graupel. The height of the vertical bars is 6.4 mm.

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 hour within the plume period, and most of the subsequent hour, had very steady fractions of the four habit types with the bulk, about 0.6 of the total, being 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. Images from this period and from a later period outside the plume, which was dominated by large crystals and aggregates, are shown in Fig. 16.

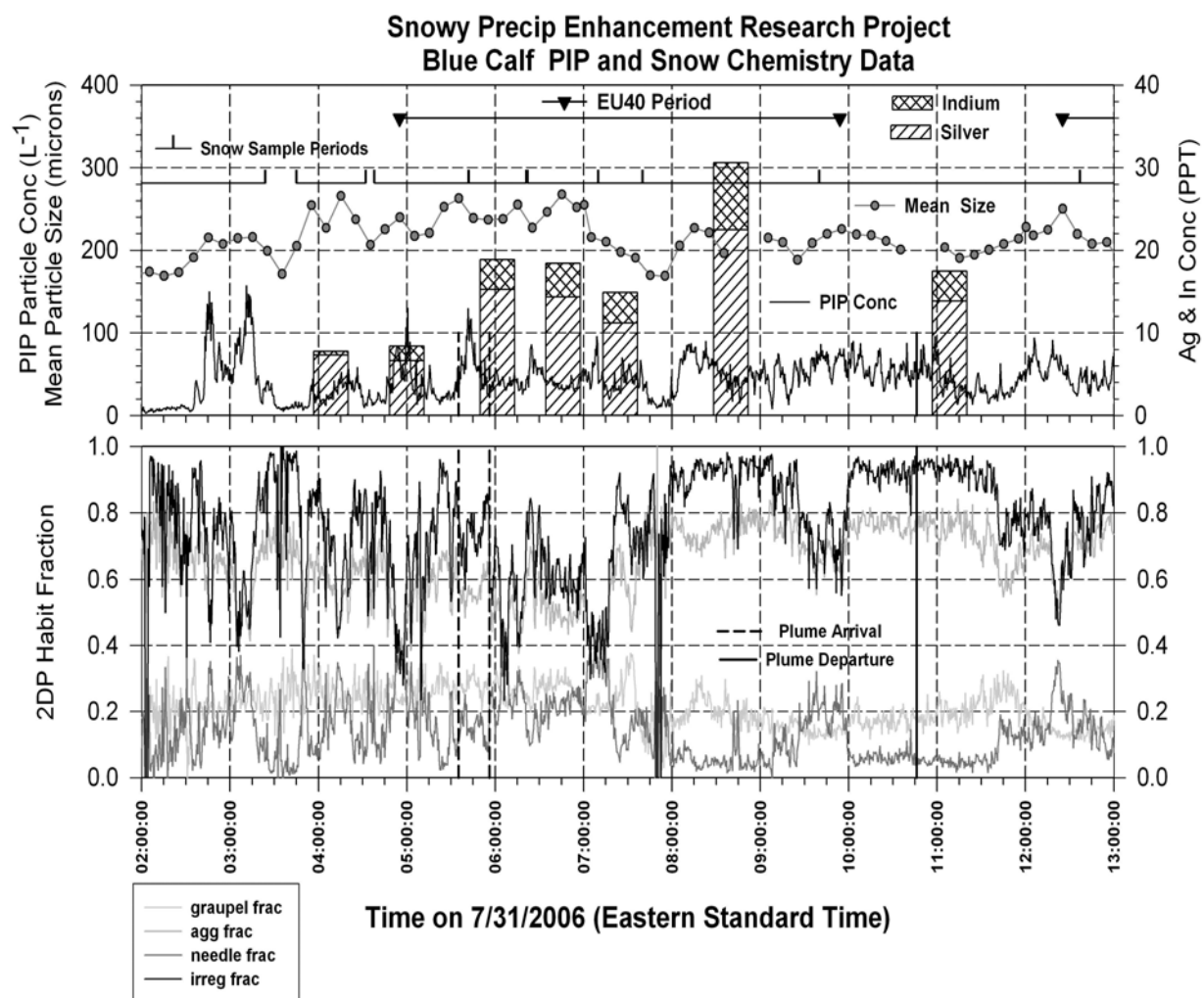


Figure 15. Top: As in Fig. 13 for a time period encompassing EU 40. Bottom: The fractional partitioning of particle habits classified by the PIP processing program. The partition above the irregular trace represents the unclassified particle fraction. For reference, between 08:00 and 09:00, the traces from bottom to top are needle, graupel, aggregate and irregular.

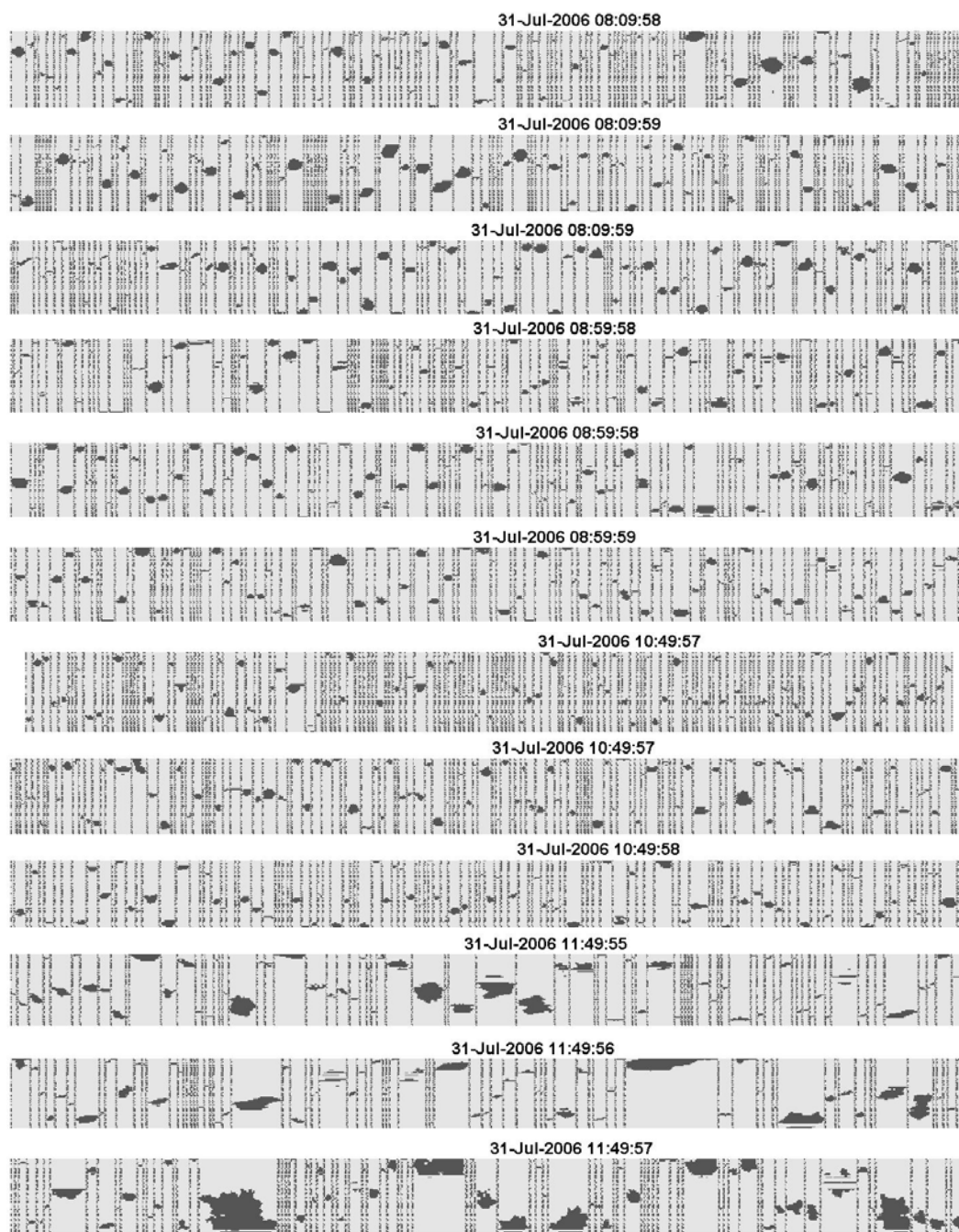


Figure 16. Images as in Fig. 14, except recorded during and after EU 40. Images in top three strips were recorded at about 0810, the next three strips at 0900, and the next three strips at 1050, during the late plume period of EU 40. Images in bottom three strips were recorded at 1150, about one hour after the plume period ended.

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 well 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 ($\leq 10 \text{ L}^{-1}$) between peaks. In the second case during the 2-day storm period, the ice concentration background was $20\text{--}30 \text{ L}^{-1}$, with occasional peaks $> 80 \text{ L}^{-1}$. 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° to about -10°C , versus temperatures in the Huggins case study where the seeding plume interacted with cloud at -12° to -17°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 $30+ \text{ L}^{-1}$ was obvious), while the SPERP case had natural averages of $10\text{--}30 \text{ L}^{-1}$ and peaks of $80\text{--}100 \text{ L}^{-1}$.

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 ($\sim 300\text{--}600\text{m}$ 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.

Acknowledgments

The SPERP is strongly supported by an AusIndustry Renewable Energy Development Initiative (REDI) grant. The authors wish to thank John Denholm, Phil Boreham, Mike Mathews, Amanda Johnson, Barry Dunn (all with Snowy Hydro Ltd.) and Mark Heggli (Innovative Hydrology) for the initial development and ongoing support of the SPERP. We are grateful to all the SHL personnel who are involved in the project, in particular with instrument maintenance, balloon launching, snow sampling activities, and operation of the Blue Calf facility.

We also thank Stephen Siems, Jingru Dai and Thomas Chubb from Monash University, School of Mathematical Sciences for their contributions to the project.

In addition, thanks are given for all the further support provided to the SPERP, in particular, Stephen Chai, Ross Edwards (Desert

Research Institute), Brian Williams, Alan Greig (Melbourne University), Kevin Wilkins (Charles Sturt University) and Doug Shaw (CSIRO Mathematical and Information Sciences).

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