

EVALUATION PLAN FOR A SNOW ENHANCEMENT EXPERIMENT IN AUSTRALIA

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Abstract. A comprehensive suite of tests is developed to evaluate the Snowy Precipitation Enhancement Research Project, a cloud seeding project in south eastern Australia aimed at increasing snow fall. The project will use both physical and chemical observations for its primary evaluation. An analysis of historical data shows that there is an 80% chance that more than 100 five-hour experimental units will occur over the five-year duration of the project. Moreover, although there is a significant amount of natural variability in the properties of experimental units, it is appropriate to treat all experimental units as members of the one class of event. A bootstrap analysis of the historical data shows that there is about a 75% chance that a 20% increase in precipitation will be detected at the 10% significance level. On the basis of bootstrap analysis, the primary analysis for the project is taken to be the identification of a positive seeding impact at the 10% significance level in the primary target area, together with snow chemistry results showing at the 5% significance level that ice nuclei have been activated in the primary target area. A number of secondary analyses are identified to support the results of the primary analysis.

1. INTRODUCTION

Huggins *et al.* (2008) describe the overall design of the Snowy Precipitation Enhancement Research Project (SPERP), which commenced in 2004 with the aim of increasing snow fall over an area of about 1,000 km² in the Snowy Mountains of south eastern Australia. Ground-based generators are used to disperse silver iodide into suitable cloud systems. Following a year of experimentation, the formal operation commenced in 2005 using a 2:1 seeded:unseeded randomised sequence of experimental units (EUs). The randomised sequence is known only to the technical operators of the seeding-material generators, and it will be revealed only at the end of the five-year operational phase of SPERP. Huggins *et al.* provide a description of the instrumentation deployed in SPERP and a summary of some initial results of the snow chemistry observations taken during the Project. The plan for evaluating SPERP is described only briefly in their paper.

The purpose of the present paper is to describe the development of a systematic plan for evaluating the experiment based on analysis of historical data. The approach follows the well-established practice of carrying out numerical simulations of the impact of seeding (for example, Twomey and Robertson, 1973). However, the evaluation plan recognises the potential role of snow chemistry in providing information on the targeting of seeding

material, while using statistical analysis of precipitation gauge data to determine quantitative information on the impact of seeding on snow amount.

The specific nature of the statistical evaluation is designed on the basis of analysis of historical data across the region. In order to maximise the number of seeding opportunities and to localise the period in which seeding may be effective, EUs of 5 hours (with an operational purge period of at least 1 hour between EUs) have been selected for SPERP (Huggins *et al.*, 2008). An initial analysis is therefore an examination of the spatial and temporal variation of precipitation across the region from historical data. This analysis suggests that the precipitation in the target area can be reasonably well represented by a simple arithmetic mean of individual observations, and so bootstrap simulations of the mean precipitation are used to estimate the probability of detection of a seeding impact over the five-year duration of SPERP.

In order to mitigate the effects of multiplicity (that is, false positive results from the application of many tests), the evaluation of SPERP is split into primary and secondary analyses. The primary analysis is designed to determine whether there has been an impact of seeding on the amount of precipitation in the target area, while the secondary analyses should provide supporting evidence and physical understanding of the results of the primary analysis.

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2. SELECTION OF TARGET AND CONTROL AREAS

The key areas for consideration in SPERP are shown in Figure 1, where the locations of precipitation measurements are shown as black dots. The primary target area (red outline) is the region where snow is consistently the predominant form of precipitation in winter, and it lies on the highest ridge of the region with site elevations extending from 1560 m to 1950 m. From use of the GUIDE model (Rauber *et al.*, 1988), it is expected that solid precipitation induced by seeding will fall in the primary target area. To allow for uncertainty in the targeting of seeding material, a secondary target (blue outline) area is specified to the east and west of the primary target with site elevations from 1000 m to 1630 m. Together the primary and secondary target areas form the overall target area, which is expected to have increased precipitation due to seeding.

The control area (green outline) includes all the sites outside the secondary target area and westward of 148.41°E. The control area is selected to

provide precipitation measurements in a region unaffected by seeding material but with a similar climatology to that of the target (see Section 3). If sites in the control area are occasionally affected by seeding then the outcome is to reduce (rather than increase) the estimated impact of seeding. It is noted that there is an absence of sites to the south of the target area.

An extended area is specified to include sites outside the target and control areas at which potential impacts of seeding will be investigated. Sites in the extended area lie mainly downwind of the target area.

Figure 1 shows that there are 9 sites in the primary target area and an additional 8 sites in the secondary target area so that there are 17 sites in the overall target area. The control area has 13 sites, and the extended area has 24 sites generally to the east of the target. Hourly data from the sites in the target and control areas are used for the primary analysis of the impact of cloud seeding on precipitation.

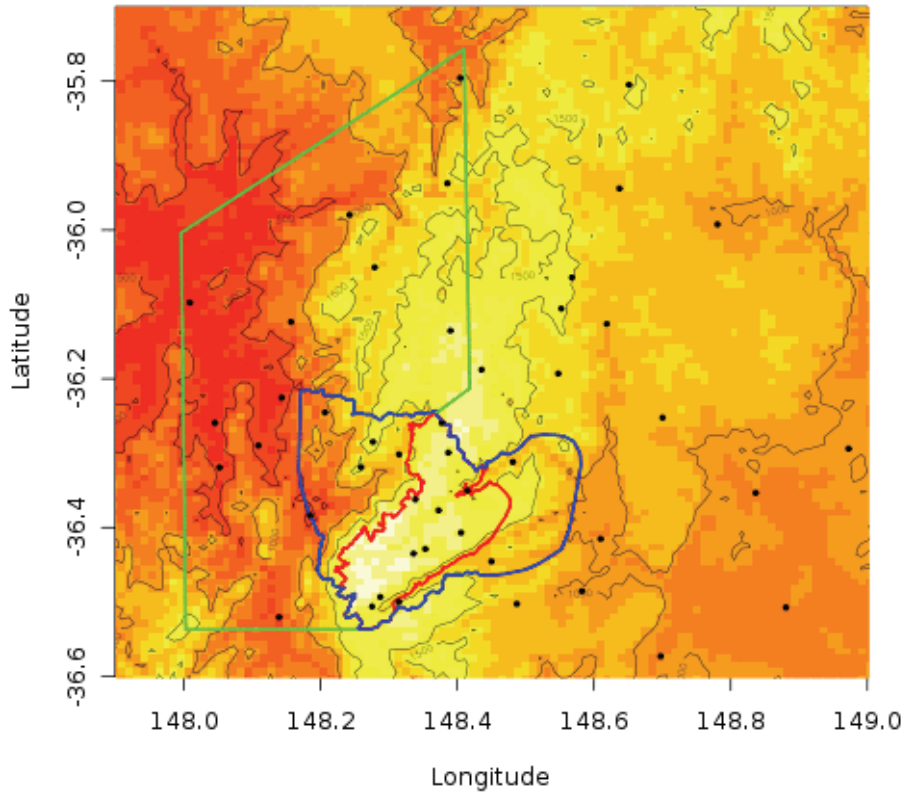


Fig. 1. Sites (black dots) at which precipitation measurements are taken in the primary target (red), overall target (blue), control (green) and extended areas; orography contours shown at 500, 1000 and 1500 m; the overall target area is about 40 km wide.

3. CLIMATOLOGICAL STUDIES

In designing a cloud seeding project, it is usual to conduct detailed analyses of historical precipitation records across the region in order to determine the spatial and temporal variability of precipitation and to ensure that the project aims can be achieved in a reasonable time. An initial study of the probability of detection of a seeding impact was carried out by Shaw and King (1986). That study used daily data at sites that were largely outside the selected target and control areas, and it suggested that about 100 EUs (days) should yield sufficient data to detect a seeding effect within five or six years. Further analysis of historical data by Snowy Hydro Ltd (2004) showed that about 100 EUs of 5 hours duration should be obtained in a period of five years.

3.1 Historical data set

The present study aims to determine more accurately the probability of detection of a statistically significant result over the specified five-year duration of the project. In order to refine the analysis of Shaw and King (1986) which used daily data, it is necessary to develop a precipitation time series that has at least 1-hour resolution to identify 5-hour EUs. As most of the sites used in SPERP have been established at the start of the project, it is found that only 13 of the 30 sites in the target and control areas have at least a decade of historical hourly data, as shown in Figure 2. It is seen that there are 3 sites in the primary target area, 3 in the secondary area, 5 in the control area, and 2 in the extended area. A consis-

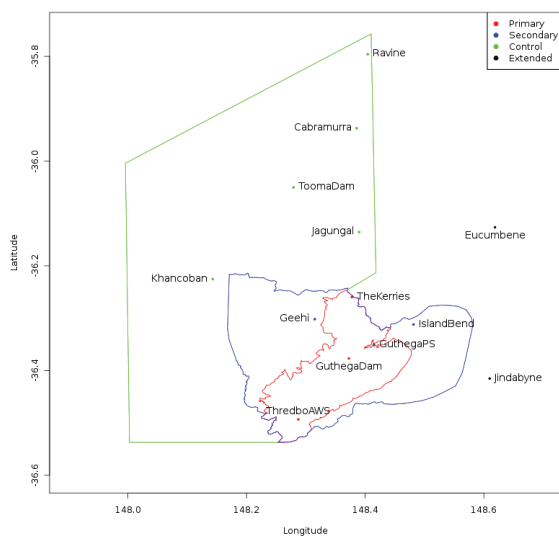


Fig. 2. Sites at which there are historical hourly precipitation data

tent historical record is obtained from all sites over the period from May 1995 through to September 2003, bearing in mind that snow falls consistently only in the winter period (May to September) and that SPERP operations began in May 2004.

In order to develop a climatology of precipitation during EUs, an historical time series of EU occurrence is generated by analysis precipitation data from Guthega Dam, temperature data from Cabramurra and upper-air data from Wagga Wagga (147.47 E, 35.17 S) over the period from May 1995 through to September 2003. The criteria for the start of an historical EU are specified to closely match the formal criteria used for an EU during the experimental phase of SPERP. The criteria for an historical EU can be summarised as:

- Measurable precipitation for 5 consecutive hours
- Freezing level less than or equal to 1600 m
- Surface temperature less than or equal to 1°C
- Wind (average of 850 and 700 hPa) has a westerly component (i.e. between 180° and 360°).

An historical EU data set is generated containing the start data and time of each EU, wind direction, wind speed, and the total (5-hr) precipitation at each site. A total of 214 EUs are found over the period from May 1995 through to September 2003. The validity of the selection process is checked by extending the analysis to 2004 during the start-up period of SPERP. It is found that the method is valid because the estimated EUs coincide well with the operational times (even though a small portion can be missed). We can therefore be confident in using the historical data set to estimate the climatology of EUs.

3.2 Statistical properties of EUs

To examine the basic climatology of EUs we use the precipitation data from Guthega Dam alone. Figure 3 shows histograms for each of the EU variables over that 9-year period. It is seen that the total precipitation during an EU varies from 1 to 26 mm, with a mean value of 5.4 mm. Fifty percent of the values lie between 2.6 and 6.9 mm.

The freezing level varies from 480 to 1600 m, with a mean value of 1260 m. Figure 3 shows that the distribution of the freezing level appears

to be truncated at 1600 m, and so it would seem that the criterion of a freezing level lower than 1600 m is eliminating a number of possible EUs. However, the mode of the distribution is around 1300 m, suggesting that the rain-producing events are in the tail of the overall distribution of 5-hr precipitation events with a westerly component. Further analysis is needed to determine the actual impact of the criterion that removes rain-producing events.

It is apparent that the wind tends to be from the south west during the historical EUs, with 50% of the values lying between 240 and 270 degrees. The wind speed varies from 10 to 100 km/hr, with a mean value of 57 km/hr. Although there are no significant correlations between the EU variables, there is a suggestion that higher precipitation occurs when the freezing level is lower and the wind speed is higher, both of which suggest more intense storms. An analysis of the synoptic conditions during EUs would clarify the overall meteorological environment during EUs.

3.3 Inter-annual variability of EUs

There is clearly a considerable amount of variability in the precipitation associated with each EU, and we find that this variability (as with total precipitation in eastern Australia) occurs on annual as well as shorter time scales. To quantify this variability, we first consider the year-to-year variations of each of the key EU variables. It is found that the number of EUs each year varies from 10 to 36 with a mean of 24, while the annual average intensity of EUs varies from 4.5 to 6.6 mm with a mean of 5.4 mm. There is a weak positive correlation (0.51) between the annual intensity and the annual-average wind speed, suggesting that large events are associated with high winds.

The climate of the Snowy Mountains region is complex and there are a number of large-scale factors that affect the precipitation (Murphy and Timbal, 2007). However, it is useful to consider whether any major external factors have a domi-

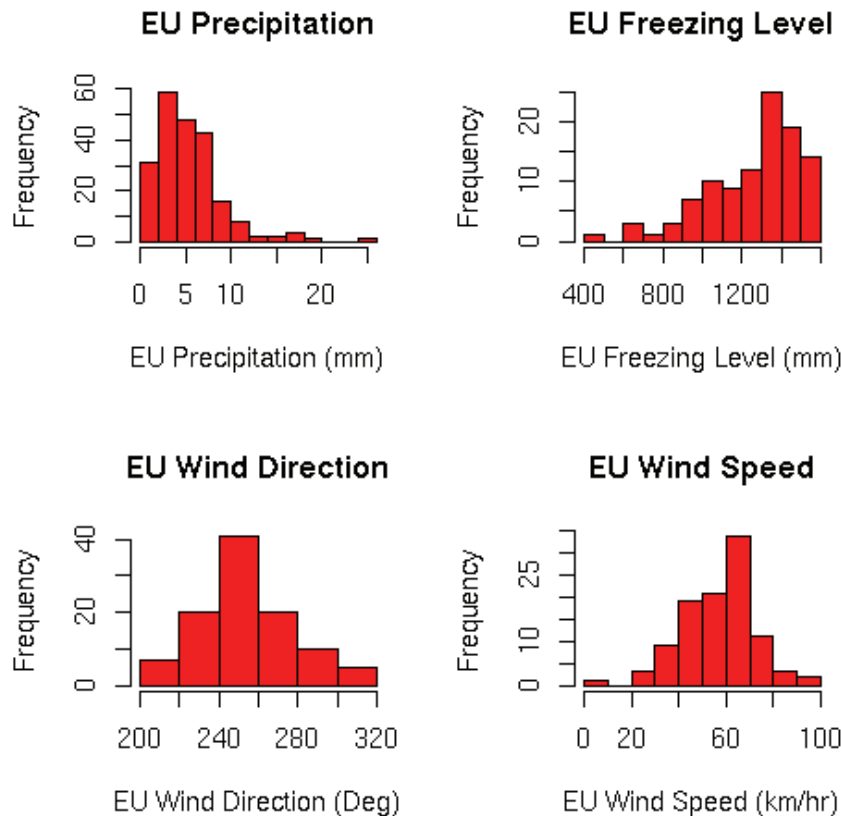


Fig. 3. Histograms of historical EU variables; the ordinate shows the number of counts in each bin of the histogram

nant impact on the inter-annual variability of EUs, as they may provide a predictor of EUs a season ahead. The Snowy Mountains lie in the south eastern sector of the Murray Darling Basin. Three factors known to influence climate in the Murray Darling Basin are the Southern Oscillation Index (SOI), which represents the El Niño influence of the Pacific Ocean, the Dipole Mode Index (DMI), representing a sea-surface temperature index in the Indian Ocean, and the Southern Annular Mode (SAM), which represents the large-scale pressure pattern around the south pole. We should note that these three factors are not entirely independent (for example, Allan *et al.*, 2001), and there is a significant correlation of -0.61 between the SOI and the DMI over the nine-year period of the historical EUs. The data source for the SOI is Bureau of Meteorology (2008), for the SAM is British Antarctic Survey (2008), and for the DMI is Frontier Research Centre for Global Change (2008). It is found that there are no significant correlations with the SOI. On the other hand, there is a positive correlation at the 5% level between the DMI and the mean wind direction during EUs. This result suggests that the wind has a more northerly aspect when the DMI is positive, which may correspond to weaker synoptic systems. Indeed Verdon and Franks (2005) find that eastern Australia tends to have higher rainfall in years with a negative DMI. On the other hand, the winter-mean EU precipitation is found to have a weak positive correlation with DMI. The influence of the DMI is therefore not altogether clear. There is a significant (p -value of 0.006) negative correlation between the SAM and the winter-mean freezing level. This result does not appear to be consistent with the finding of Hendon *et al.* (2007) that positive SAM values are associated with higher rainfall in the summer in south eastern Australia, but with lower rainfall in winter.

From this very preliminary analysis, it would seem that the large-scale factors affecting the properties of EUs are not revealed by a linear regression analysis over a 9-year period. More detailed studies and longer time series may provide a greater insight into the large-scale controls on EUs.

3.4 Seasonal variability of EUs

While we have found that there is large variability in the number of EU events each year, the properties of each EU do not show the same degree of variation from year-to-year. This result gives us some confidence that all EUs can be treated

as coming from the same class. However, confirmation of this hypothesis requires us at least to consider whether there are seasonal variations in the properties of EUs.

It is found that there is a strong seasonal cycle in the occurrence of EUs, with a peak in July and reduced numbers in the early and late months of the five-month winter season. However, this expected seasonal variability in the frequency of EUs does not mean that individual EUs vary significantly with the seasons. Indeed the month-to-month variations in EU properties are less than the variability within each month. As may be expected, the mean amount of precipitation in an EU tends to be less in May and September than in mid-winter, but even here the differences in the monthly means are well within the standard deviation for each month.

From the climatological analysis, it is appropriate to treat all EUs as coming from the same class of event, and so the analysis of the impacts of cloud seeding should not have to take into account either large-scale climatological factors or seasonal variations.

3.5 Variability of total number of EUs

We have found that there is substantial inter-annual variability in the number and intensity of EU events. This variability may tend to reduce the total number of cloud seeding opportunities, and so it is useful to examine the total number of events that are expected over the five-year duration of SPERP. We first note that annual precipitation in south eastern Australia has substantial decadal variability (Nicholls and Wong, 1990), and so the 9-year historical record is really too short to provide precise estimates of probabilities. Nonetheless we use the historical EU record to provide an estimate of the total number of events in a 5-year period.

There are only weak correlations between the EU variables and the large-scale climate factors, and so a basic estimate of the total number of events is found by sampling five-year ensembles from the historical EU data set. The 9-year data set means that there are only five real (but overlapping) 5-year runs to be considered. It is readily found that these runs imply there is a 50% chance that the total number of EUs over a 5-year period will lie between 100 and 122, with a mean of 112. In order to get a more robust estimate of the distribution of 5-year runs, we use a

simple bootstrap technique to randomly select (with replacement) 5 years from the overall data set. It is found that the resulting distribution of total number of EUs implies that there is an 80% chance that the total number will be greater than 100. The range of the total number is from 50 to 180, which correspond to repetitions of the lowest (10) and highest (36) annual number of events. The 5% confidence limits are from 83 to 154 events.

Given the short length of the historical data set, the present analysis implies that there is a good chance that there will be around 100 EU events over the five-year period of SPERP.

3.6 Spatial variability of EU precipitation

A key feature of a cloud seeding experiment is a comparison of precipitation in the target area with that in a neighbouring control area. It is therefore appropriate to consider the spatial variability of precipitation during EUs in order to determine how best to represent the precipitation in the target and control areas. For example, if there is substantial spatial variability across the region then it may be necessary to compare detailed spatial patterns of precipitation, rather than simply the area-mean value.

To analyse the spatial variability of precipitation during EUs, we first select only EUs for which there are valid precipitation observations at all of the 13 historical data sites. This condition reduces the number of available EUs from 214 to 138.

Figure 4 shows the spatial patterns of the mean and standard deviation of EU precipitation. There is a considerable degree of consistency in both mean and variance across the target and control areas. There is a suggestion of reduced precipitation in the south of the target area, but this result may be a reflection of the under-catch of precipitation gauges in the high-wind regions of the mountains. On the other hand, there is a clear rain-shadow to the east of the high mountains in the extended area of SPERP.

A test of spatial variability is a principal component analysis (Becker *et al.*, 1988), in which we identify the dominant spatial patterns of variability. The first principal component represents the most consistent spatial pattern. It is found that the first principal component (PC) explains nearly 80% of the variance of precipitation across the region and the pattern of that PC is very similar to pattern of the mean precipitation in Figure 4.

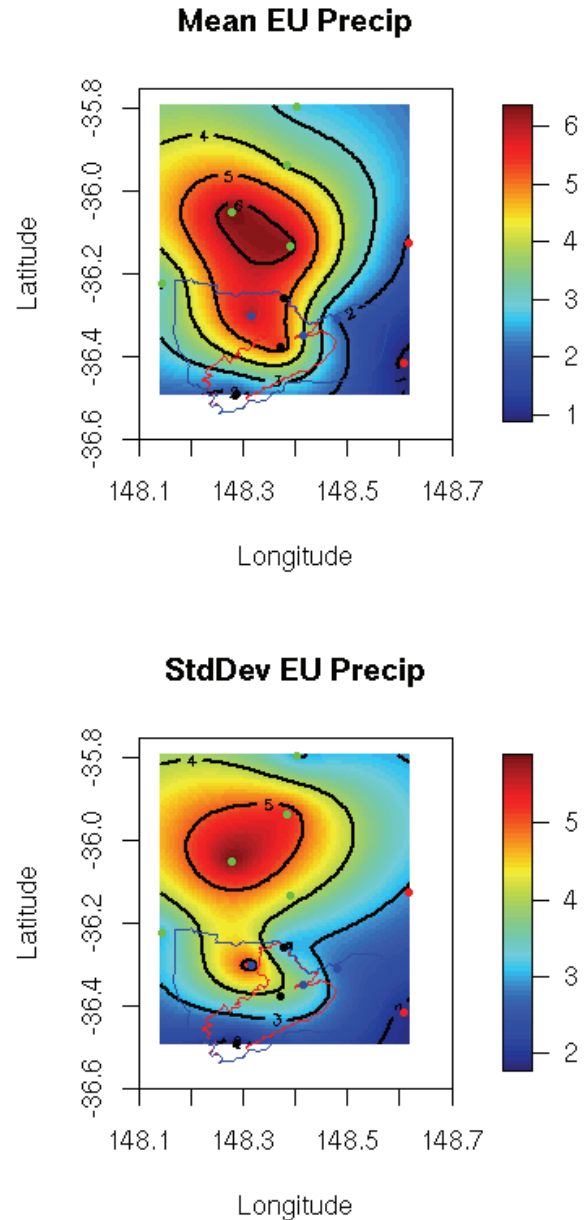


Fig. 4. Spatial variation of mean and standard deviation of precipitation during historical EUs; dots show location of precipitation sites; the overall target area is about 40 km wide.

If we extend the analysis to sites in the target and control areas separately, then it is found that the first PC in each of these areas also explains about 80% of the variance. All these results suggest that, at least to a first approximation, the primary analysis of a seeding impact may be carried out using area-mean values of precipitation, rather than more complex variables that reflect the spatial variability of precipitation across the region.

4. PROBABILITY OF DETECTION OF SEEDING IMPACT

It is shown in Section 3 that, while there is a significant amount of natural variability in the properties of EUs from month-to-month and from year-to-year, it is appropriate to treat all EUs as members of one class of event. We therefore can use the historical EU data set to estimate the probability that a seeding impact can be detected over the 5-year lifetime of SPERP.

Before considering the detailed analysis of the probability of detection, we first establish that there are significant correlations between the precipitation in the target and control areas during EUs. The analysis of spatial variability in Section 3.6 suggests that such correlations exist. However, this test must be carried out to ensure that the basic assumption of a detection analysis (that is, that the control area can be used to estimate the natural precipitation in the target area) is valid.

Based on the analysis of Section 3.6, we use the most basic measure of precipitation over an area: the arithmetic mean of the available observations in the area. The EU precipitation time series are calculated from hourly data at each site using the timing of events from the historical EU data set. All the correlations between the areas of interest are found to be significantly different from zero. However, because of the variability in precipitation across the region, the correlations are not particularly high. The correlation between the primary target and control areas is found to be 0.71, but the correlation increases to 0.79 when the control is compared with the overall target area. Because the spatial correlations are not especially high, the detection of an impact of seeding in the target area is not expected to be straightforward. On the other hand, it is expected that the increased number of observing sites in the target and control areas (from 11 to 30) during the operational phase of SPERP will provide greater statistical robustness to the analysis.

4.1 Detection of seeding impact

Having established that all EUs can be treated as being from the one class and that the correlations between the target and control areas are significantly different from zero, it is appropriate to carry out simulations of a cloud seeding experiment, in which the precipitation in some EUs is artificially increased (for example, Twomey and Robertson, 1973). The simulations use the three data sets of historical EU precipitation in the pri-

mary target, the overall target and the control areas. Each record has 214 EUs over the period from 1995 to 2003. A bootstrap method (Davison and Hinkley, 1997) is used to estimate the probability that the impact of cloud seeding will be detected. The impacts of specified increases of 5, 10, 20 and 40% are investigated.

From the analysis of Section 3.5, it is apparent that the expected number of EUs over the 5-year duration of the operational phase of SPERP is between about 100 and 130. The seeding strategy of SPERP is to seed twice as many EUs as are left unseeded; that is, the seeding ratio is 2:1. In order to make a conservative estimate of the outcome of SPERP and to have a convenient number of events for the specified seeding strategy, we assume that there are 99 EUs in the simulations.

For each simulation, 33 EUs are randomly selected (with replacement) from the total of 214 EUs as unseeded events, and 66 are selected as seeded events. The precipitation in the target is $T(t)$ and in the control is $C(t)$, where t is the EU number. For the unseeded EUs, we have the target precipitation $TU(t)$ and the control precipitation $CU(t)$ given by

$$TU(t) = T(t) \text{ and } CU(t) = C(t).$$

For the seeded EUs, we increase the natural precipitation by the seeding impact (s), and so the target $TS(t)$ and control $CS(t)$ precipitation are given by

$$TS(t) = (1 + s) * T(t) \text{ and } CS(t) = C(t)$$

where $s = 0.05, 0.10, 0.20$ or 0.40 .

We consider two alternative approaches to measure the calculated impact of seeding. The first is the well-known double ratio (Smith *et al.*, 1963) and the second is based on a regression analysis. The double ratio approach compares the ratio of the target to control precipitation in seeded and unseeded periods; in particular, we calculate the double ratio

$$D = \frac{[\text{sum}(TS(t))\text{sum}(CS(t))]}{[\text{sum}(TU(t))\text{sum}(CU(t))]} \quad (1)$$

The ratio on the denominator of DR is assumed to normalise the numerator by accounting for the natural relationship between precipitation in the target and control areas. It is clear that if there is a seeding impact then DR should be greater than one, and $DR-1$ is an estimate of the seeding impacts.

For the regression approach, we use linear regression to estimate the “natural” precipitation in the target area; in particular, we calculate

$$TU \sim a + b * CU$$

where the coefficients a and b are estimated by a linear regression of the target and control precipitation in the unseeded EUs. Then the impact of seeding is estimated by the “error” variable

$$ES(t) = TS(t) - a - b * CS(t), \quad (2)$$

which is the difference between the actual and natural precipitation in the target area for the seeded EUs. It should be found that the distribution of ES has a positive bias when compared with the unseeded EUs, for which the error variable is

$$EU(t) = TU(t) - a - b * CU(t). \quad (3)$$

The overall precipitation increase is given by

$$PI = \text{sum}(ES(t)), \quad (4)$$

while the fractional increase in natural precipitation is estimated by

$$FI = PI / [\text{sum}(TS(t)) - PI].$$

The variable PI is useful in providing a quantitative estimate of the actual increase in precipitation across the target area, while FI is a normalised variable that provides an estimate of the seeding impacts.

The regression analysis outlined here is slightly different from the approach taken by Smith *et al.* (1979) and Mielke *et al.* (1982). The earlier analyses essentially used all the data to estimate the basic regression between the target and control precipitation. The current approach is based on the physical argument that the unseeded EUs provide the only unbiased data for estimating the ‘natural’ relationship between precipitation in the target and control areas. Having established that relationship, it can be applied to estimate the natural precipitation in the target area during seeded EUs. Thus the statistical analysis is based on a simple physical argument.

It is found that stable results are obtained using 600 simulations for each value of the seeding impact. The simulations yield statistical distributions for DR , PI and FI , and so it is straightforward to estimate the probability that $DR > 1$, $PI > 0$ and $FI > 0$. The precipitation increase (PI) is included in the analysis as it provides an estimate

of the explicit impact of seeding, independently of whether the impact is multiplicative or additive. However, as PI and FI are almost linearly related, the results for PI are similar to those for FI . Moreover, most evidence suggests that the impact of seeding is multiplicative, and so we will focus attention on FI rather than PI .

The simulations discussed at this stage consider only the question of the likelihood that the estimated impact of SPERP will be positive. Another important question is whether analysis of one realisation of the experiment can yield a robust estimate of the seeding impact; that is, can we get accurate estimates of the uncertainty associated with the observed value of the fractional increase (or double ratio). For this question, we carry out an additional bootstrap analysis within each simulation. This analysis corresponds to the statistical analysis to be carried out on the actual observed data during the operational phase of SPERP (when there is clearly only one experimental result).

From any given simulation, we have one estimate of the fractional increase (FI) and the double ratio (DR). These estimates are based on the 99 “measurements” of precipitation in the target and in the control area for each event. To test the significance of the estimates of FI and DR , we randomly select (with replacement) 66 events as “seeded” events and 33 as “unseeded” events. The “unseeded” events are used to estimate the natural precipitation in the target area by regression. From the “seeded” and “unseeded” events, values for FI and DR can be computed. The random selection is repeated to build up the statistical distributions of FI and DR . Analysis of the distributions of FI and DR yield estimates of the significance of the observed value of FI and of DR ; for example, the one-sided significance of FI is estimated by the fraction of the distribution having values greater than the observed value of FI (Smith *et al.*, 1979). It is found that stable estimates of the significance levels are obtained with 400 replications.

The results of the simulations are summarised in Table 1. As expected, the chance of finding a significant seeding effect increases as the actual seeding impact increases. However, the chances are not greatly increased by using the overall rather than the primary target area. This result is reflected in the relatively small increase in the correlation of precipitation in the control area with the target when the target is enlarged from the primary to the overall area. Table 1 does not include the results for the PI , as the probabilities for PI are essentially the same as for FI owing to

the almost linear relationship between them.

The results for the double ratio (DR) and fractional increase (FI) are found to be similar. However, the probability of $DR > 1$ is found to be a little less than the probability of $FI > 0$. Moreover, the chance of obtaining a significant result is found to be generally larger for the FI than for the DR. This result suggests that the fractional increase method may be a little more sensitive than the double ratio for this problem, and so it is appropriate to use the fractional increase for the primary analysis.

A feature of Table 1 is that the probability of detecting a seeding impact at the 5% level is not large unless the seeding impact is greater than about 0.2. For example, there is only about a 65% chance of finding a significant result at the 5% level when the actual impact is 0.2; on the other hand there is an 85% chance that a positive result will be found. The chance of having a significant result at the 10% is substantially greater than at the 5% level. This observation suggests that, recognising the limited number of EUs expected in the 5-year duration of SPERP, it is appropriate to seek an impact of seeding at only the 10% level. This level of significance may be questioned by statisticians. On the other hand, if there is other evidence (arising from secondary analyses) supporting a positive impact then the relatively low statistical significance can be acceptable (for example, Nicholls, 2001).

5. PRIMARY ANALYSIS OF SEEDING EFFECTS

Many variables are measured in a cloud seeding experiment in order to ensure the scientific integrity of the results. All these data can be used to conduct many different tests of the results of the experiment. However, Mielke *et al.* (1982) points out that, as there is a substantial random component in a cloud seeding experiment, the application of many different statistical tests leads to the problem of multiplicity; that is, the application of many tests can lead to false positive results.

In order to minimise the risk of multiplicity, the analysis for SPERP is separated into primary and secondary tests. The primary analysis is seen as the key test of whether there has been an impact of seeding on the amount of precipitation in the target area. If a positive result is obtained from the primary analysis then the secondary analyses are used to confirm the scientific integrity of the primary result. If the primary analysis yields a negative or uncertain result then the secondary analyses are used to clarify where and how the seeding hypothesis broke down. An important purpose of the secondary analyses is to support scientific advice to assist policy decisions on potential future cloud seeding activity.

The primary analysis for SPERP has two components. The first is the detection of a seeding im-

Table 1. Results of simulations of specified impacts (SI) of cloud seeding using 99 EUs; DR is the double ratio and FI is the fractional increase of precipitation

Target	SI	Prob DR>1	Prob DR	Prob DR	Prob FI>0	Prob FI	Prob FI Sig
Primary	0.05	0.68	0.13	0.22	0.72	0.16	0.27
Primary	0.10	0.79	0.22	0.36	0.85	0.28	0.42
Primary	0.20	0.95	0.53	0.67	0.97	0.63	0.77
Primary	0.40	1.00	0.96	0.98	1.00	0.98	0.99
Overall	0.05	0.69	0.13	0.26	0.73	0.14	0.25
Overall	0.10	0.85	0.27	0.46	0.87	0.32	0.46
Overall	0.20	0.98	0.63	0.76	0.99	0.68	0.81
Overall	0.40	1.00	0.98	0.99	1.00	0.98	1.00

impact on precipitation based on the regression analysis to determine the fractional increase in precipitation (FI) in the primary target area, used in Section 4.1 in simulation experiments of historical data. A bootstrap analysis for Section 4.1 will also yield confidence limits on the observed value of FI. The second component of the primary analysis is the confirmation that activated seeding material has reached the target area, based on the measurements of the silver (Ag) and indium (In) at the ground during each EU (Huggins *et al.*, 2008).

5.1 Targeting of seeding material

Analysis of the precipitation data provides an estimate of the physical impact of seeding. To ensure that any impact is consistent with the seeding hypothesis, snow chemistry data are also analysed as part of the primary evaluation. The basic technique is described by Chai *et al.* (1993). Snow chemistry measurements of the concentration of Ag and In in 2-cm slices of snow are taken at eight sites in the primary target area. At least two important factors need to be clarified in order to obtain quantitative estimates from the snow chemistry data. The first factor is the estimation of the time associated with each snow slice, and the second is the selection of the most appropriate variable associated with Ag and In. The timing of the period associated with each snow slice can be estimated from alignment of each snow slice within the total snow depth of a profile against the timing tips of a collocated precipitation gauge. The number of slices that fall within an EU depends upon the rate of precipitation, but the number is likely to be small in any 5-hour period. Indeed it is possible that no well-defined snow slices can be obtained during an EU, and so chemistry data may not be available for all EUs.

Chai *et al.* (1993) suggest that the Ag:In ratio is a suitable indicator of the microphysical impact of seeding in the target area. However, this ratio can vary greatly in both seeded and unseeded cases. Such variability is partly caused by substantial variations in the background level of Ag. On the other hand, observations in the Snowy Mountains region in 2004 (Snowy Hydro Ltd, 2004) suggest that the presence of In at concentrations above 1 ppt is indicative of the presence of tracer material from a seeding generator.

Given the uncertainties associated with the chemistry measurements, it is appropriate to take a simple indicator as the variable for use in the primary analysis. For data from a specific site in

the target area to be used in the chemistry analysis for a specific EU, we first require that the chemistry sample can be identified unambiguously with the specific EU. Secondly we require that the In concentration is greater than 1 ppt to indicate that material from a generator has impinged on the site. The concentration of Ag is then taken as the variable indicating whether Ag has been active in nucleating ice particles that fell in the target area. It is anticipated that this variable will be significantly larger in seeded EUs than in unseeded EUs. The peak value of Ag across all valid measurements is chosen as a sensitive indicator of activated seeding material reaching the target area. In principle, the mean value may be more statistically robust. On the other hand, the technical difficulties associated with the snow chemistry suggest that it may not be possible to obtain consistently valid estimates of Ag over the target area. The use of peak values is a pragmatic decision to identify whether activated seeding material has fallen somewhere in the target area.

In summary, the second component of the primary analysis is required to demonstrate that the peak value of Ag is on average larger during seeded EUs than in unseeded EUs. There will be two distributions of the peak value of Ag: one from seeded EUs and one from unseeded EUs. Bearing in mind that the samples of Ag may be limited in number and that the observed values of Ag can vary widely, a Wilcoxon rank-sum test (Bauer, 1972) will be used to demonstrate the differences between the means of the two distributions. The primary analysis will require the difference to be significant at the 5% level.

5.2 Interpretation of primary analysis

A fully successful outcome of SPERP will be achieved if both components of the primary analysis are achieved; that is, the precipitation analysis shows a positive seeding impact at the 10% significance level and the snow chemistry analysis that ice nuclei have been activated in the primary target area at the 5% significance level. These two tests are physically independent in that the first test seeks evidence of a macro-scale impact of seeding across the primary target area, while the second seeks evidence of microscopic impacts of seeding. Thus the second test aims to confirm the physical hypothesis (that the seeding material reaches the target area and that it activates additional ice particles) underpinning any observed increase in precipitation in the primary target area.

In Section 4.1 it is noted that the limited duration of SPERP implies that, while it is likely that a positive seeding impact will be detected, the statistical significance of the result may not be high. For example, analysis of the historical data suggests that there is a less than 30% chance that a 10% increase in precipitation will be detected with a significance level of 5%. The inclusion of the second (and independent) component of the primary analysis aims to consolidate the detection of a seeding impact at only the 10% significance level.

6. SECONDARY ANALYSES OF SEEDING EFFECTS

The purpose of the secondary analyses is to support the results of the primary analysis if it yields positive results or to help explain the sources of uncertainty if the primary results are negative or uncertain. The natural variability of precipitation and the inherent uncertainties associated with cloud seeding processes mean that there is no guarantee of a positive result from the primary analysis, and so the secondary analyses are vital elements in the overall assessment of a cloud seeding experiment such as SPERP. The secondary analyses assist our understanding of the physical basis of the impact of seeding. The secondary analyses should also provide a basis for refinement of the operational procedures used in future cloud seeding experiments in the region. It is expected that additional secondary analyses to those enumerated in this section will be carried out as part of SPERP as new data and insights are gained during the execution and analysis phases of the experiment.

The primary analysis is very specific, and there are a number of variations that would be worthwhile secondary analyses; for example:

- Repetition of primary analysis using the overall target area (rather than the primary target)
- Comparison of the distributions ES and EU, given by Eq. (2) and Eq. (3), to demonstrate the differences in the deviations from the estimated natural precipitation in the target
- Analysis of the double ratio (DR) given by Eq. (1)
- Analysis of the precipitation increase (PI) given by Eq. (4).

As SPERP extends over five years and as we know that precipitation in the Snowy Mountains region has high inter-annual variability, a useful

secondary analysis is to investigate the inter-annual variations in the estimates of the parameters FI, PI and DR. The small numbers of samples means that the year-to-year estimates are not individually robust. However, the time series can identify outliers and so determine whether a result (positive or negative) is affected by a small number of “anomalous” events. Indeed, Mielke *et al.* (1981) points out that the magnitude of the double ratio can be dominated by a few extreme values, and a similar criticism could be applied to FI. This sensitivity to extreme values can be reduced either by taking the logarithm of the single ratios of target to control precipitation (Gabriel, 1999) or by using the median (rather than mean) precipitation for the area averages (Super and Heimbach, 1988). Adderley (1961) describes a number of statistical tests that can be applied to the double ratio data to estimate the significance of the result.

In theory the most direct method of assessing the impact of seeding is to simply compare the ratio of the total precipitation in the target area during seeded EUs to that during unseeded EUs. This approach would be valid provided that the precipitation in each EU is represented by a stationary random variable, with no serial correlation and with no trends or long-term variability. In practice, it is found that serial correlations, trends and long-term variability ensure that such an analysis is not statistically robust. Nonetheless, it will be instructive to compute this statistic at the conclusion of the field phase of SPERP, and Gabriel (1999) provides an analysis of the statistical properties of the “single ratio”.

All the analyses described at this stage are aimed at identifying differences between the area-average precipitation in the target area during seeded and unseeded events. The following analyses use more detailed information from SPERP to resolve spatial and temporal differences between seeded and unseeded events.

6.1 Sensitivity studies of primary analysis

The primary analysis described in Section 5 is aimed at determining that seeding material is found in the target area during seeded EUs and that the impact of seeding is an increase in precipitation in the target area. If a positive impact of seeding is established from the primary analysis then the following secondary analyses should provide results that enhance our understanding of the scientific basis of the positive impact. If, on the other hand, the primary analysis is inconclusive then the secondary analyses can provide

supplementary evidence of the impact of seeding as well as clarifying the science of the processes associated with seeding.

One set of secondary analyses should involve repetitions of the primary analysis with additional predictor variables to help identify the sources of the seeding impact. Moreover, such analyses can sometimes demonstrate why the primary seeding impact is masked by other factors. Although these regressions are listed individually, it would be appropriate to use a stepwise regression to identify possible compounding effects of subsets of the predictor variables. Thus the primary analysis can be repeated, with additional independent variables set to:

- wind direction
- wind speed
- height of the freezing level
- temperature of cloud top
- temperature of cloud base
- ice particle size and concentration
- amount of supercooled liquid water (SLW)
- flux of SLW
- number of seeding generators used.

The ice particle size and concentration and SLW are taken from the 2D probe and radiometer at a site (Blue Calf near Guthega Dam in Figure 2) in the primary target area (Huggins *et al.*, 2008), and upper-air variables are taken from the soundings at Khancoban to the west of the target area (Figure 2).

6.2 Time history of key variables

An important aspect of the secondary analyses of SPERP is the clarification of the physical processes occurring during seeding. Variables that characterise the physical processes are SLW and ice particle size and class. The source of any precipitation enhancement is the SLW, and it is measured at Blue Calf well within the target area. It may therefore be found that the level of SLW decreases during an EU, and so the ratio of SLW at the start to that at the end of an EU may be an indicator of seeding effect, if the ratio is significantly different in seeded and unseeded EUs. If an interesting result is apparent from this analysis, then a more detailed time-history of SLW over an EU should be investigated using the basic key data set (with at least half-hour time resolution).

It is not clear *a priori* how the nature of precipitation should vary during an EU, except that seeding should lead to an increase in precipitation over an EU. On the other hand, seeding is assumed to act at the microphysical level, and so it is appropriate to investigate any changes in microphysical properties over an EU. Thus, the ratio of ice particle size and concentration between the start and end of an EU should be analysed for seeded and unseeded EUs. A contingency table analysis (Press *et al.*, 1986) can be carried out on changes in the particle class between the start and end of an EU, and between seeded and unseeded EUs. Results from other cloud seeding experiments (for example, Super, 1999) suggest that microphysical changes should be observed during seeded EUs.

In addition to the calculation of indicator variables, such as the ratio of SLW at the start and end of an EU, it is also important to consider the detailed time variation of key variables over the lifetime of an EU. Composite time histories, with at least half-hour resolution, should be prepared for seeded and unseeded EUs covering such variables as precipitation, SLW, particle size and particle class. It is expected that differences between the seeded and unseeded composites should be apparent.

6.3 Spatial variability of precipitation

Having considered the temporal variations in total precipitation and related variables in the target and control areas, it follows that the detailed spatial variability of the precipitation in seeded and unseeded EUs should also be examined. This comparison should involve a study of the variations of the principal components, in order to reduce the number of variables to be considered.

The technique of principal component analysis (Johnson and Wichern, 1988) is often used in meteorology and other fields to identify the main modes of variability among a set of variables. Mielke *et al.* (1971) and Smith *et al.* (1979) employ principal components to represent rainfall across the control areas of cloud seeding experiments. It is commonly found that the number of modes (or principal components) needed to describe most of the observed variability is much fewer than the number of variables. Using the data from the unseeded EUs, the principal components for the primary target, control and overall target areas can be calculated. Only the components needed to describe the bulk of the observed variability will be retained in the subsequent analysis to evaluate the impact of seeding.

Inspection of the weightings of the principal components should provide some insight on the main sources of spatial variability across the target and control areas.

If significant differences are found between the seeded and unseeded weightings, then it would be appropriate to extend the analysis to examine the temporal variability of the dominant precipitation patterns in the target and control areas in seeded and unseeded EUs. For example, Hart *et al.* (2006) use a cluster analysis to determine the dominant combinations of principal components for the spatial variability of surface ozone. This technique could be applied to identify changes in the dominant precipitation patterns in seeded and unseeded periods. In order to investigate the possible contamination of the control area by seeding, the analysis could be carried out using the overall target plus the control area as a single region.

6.4 Spatial variability of snow chemistry data

Aircraft observations of the dispersion of silver iodide (Stewart and Marwitz, 1982) and passive tracers (Bruitjies *et al.*, 1995) show that well-defined plumes of seeding material are expected to evolve downwind of the ground-based generators. We therefore expect to be able to observe spatial signatures of the impacts of seeding across the target area.

The primary analysis (Section 5.1) should indicate whether the activated seeding material has been effective in the target area. Secondary analyses are proposed to investigate further the spatial and temporal variations in targeting. These analyses will involve the measurement of Ag and In at various sites across the areas where snow is expected in each EU. Snow chemistry data are collected at 9 sites in the target area, 1 site in the control area, and 1 site in the extended area.

The first analysis should extend the primary analysis to investigate the spatial variability of the targeting over all sites at which snow chemistry is obtained. For EU number t and site x , we can generally observe the peak value of the Ag, $S(t,x)$. The primary analysis is an examination of the temporal distribution of the maximum value of S across all sites in the target area at each EU. The simplest secondary analysis is to examine the spatial pattern of $S(t,x)$ for seeded and unseeded EUs. It is expected that the patterns will be quite different. The value of S should be uniformly close to zero at all sites in the unseeded

EUs, while S should be high in the target area during the seeded EUs. The values of S should be close to zero at all times in the control and extended areas.

If it is found that the patterns of S are inconclusive or inconsistent with the basic seeding hypothesis, then a principal component analysis should be carried out. By considering the variance explained by each principal component, we can decide how many components are needed to adequately describe the spatial variation of the snow chemistry; this number is expected to be very much less than the total number of sites. For each of these key components, the weighting given to sites in the target, control and extended areas can be inspected, and so we can consider the apparent connections between variations across the target, control and extended areas.

6.5 Hydrological impacts

Since SPERP is aimed at increasing snow-pack, hydrological impacts of seeding cannot be analysed over the EUs of 5-hour duration. Therefore, hydrological impacts of seeding will be investigated through studies of differences in annual streamflow in catchments in the target area with that in potential 'control' catchments outside the target area. Three catchments in the target area and three control catchments have been identified, and a 'double-ratio' analysis will be carried out on data from these sites using historical records before 2004 as the unseeded years. However, such analyses are fraught with problems, especially because the historical record is far from being statistically stationary; major external forces such as bushfires have imposed significant spatial and temporal variations across the catchments of the region.

6.6 Persistence effects

Since cloud seeding commenced in Australia, the possibility of a persistent effect of seeding has been recognised (Bigg and Turton, 1988; Bigg, 1995), but not fully documented or explained (Long, 2001). If such effects are significant, then a controlled experiment, like SPERP and most other experiments around the world, would be unable to identify the effect of seeding. It is therefore important to conduct some investigations on the possibility of persistent effects in SPERP.

Persistent effects are defined to be physical and biological processes that cause the effects of seeding to persist well beyond the period of seeding. Thus the target area could be contami-

nated during unseeded periods, and even the control and extended areas could be contaminated as random winds move ice nuclei from one place to another. In this section, we concentrate on indicators of persistence in the target area. Extra-area effects are considered in Section 6.6.

The highest level of persistent effects may be seen at annual scales. In order to enhance the robustness of the results the primary analysis in Section 5 is carried out on all the available EUs. It may be interesting to carry out this analysis on each individual year, without concern for the lack of significance of each result. Indeed each result can be treated as a random variable, which would be analysed for a trend using a regression against year. This analysis is recommended earlier in Section 6 in order to identify outliers rather than trends.

The impact of any persistent effect is seen to decay with a time scale of days to months (Bigg and Turton, 1988), and so another analysis could be focused on trends within each year. For example, annual time series of the ratio of target to control precipitation for seeded and for unseeded EUs could be generated. The first test of each ensemble would be to identify any consistent trend over the five months of operations each year. The second test would be to identify differences (or lack of differences) between the ratios in the seeded and unseeded EUs.

Any persistent effects are assumed to be associated with the generation of secondary ice nuclei (Bigg, 1995). It would therefore be appropriate to investigate the time series of the microphysical measurements in each EU over the annual cycle. If persistence leads to secondary ice nuclei, then the ice nucleus concentration level should essentially become saturated as more and more secondary particles are generated. This effect should lead to a decrease in SLW as the annual cycle moves on, and indeed the frequency of seedable EUs should decrease with time. Studies of the particle size, concentration and class should also show convergence of these variables between seeded and unseeded EUs as time goes on.

6.7 Downwind effects

Section 6.4 describes how the snow chemistry data can be used to investigate some possible downwind effects of seeding. Similar analyses of the precipitation data can be carried out to determine whether there are discernible effects of

seeding on the amount of precipitation downwind of the target area. The aim is to look for coherent patterns in the rainfall downwind of the target.

We first consider all the precipitation data $PS(t,x)$ obtained during seeded EUs and the data $PU(t,x)$ from the unseeded EUs. The time-means of these variables are $PSM(x)$ and $PUM(x)$. These data will display a lot of spatial variation due to the inherent variability of natural rainfall. However, the data will be more coherent spatially if they are normalised with respect to the local climatological mean value, $PCM(x)$. (In some circumstances, it may be necessary to approximate PCM by PUM .) If the impact of seeding is primarily a multiplicative effect then the ratio

$$M(x) = PSM(x) / PCM(x)$$

provides a map of the apparent impact of seeding across all areas. The ratio

$$A(x) = PSM(x) - PCM(x)$$

provides a map of the impact if seeding leads primarily to an additive effect.

As discussed earlier, it is not expected that the maps M and A will be statistically robust because of the high natural variability of precipitation in space and time. However, it will be of interest to note if there are any consistent patterns in M and A that extend from the target area into the control or downwind areas.

Similar maps to $M(x)$ and $A(x)$ can be produced for the unseeded EUs during SPERP. Comparison of all these maps should help estimate the robustness of any apparent patterns in M and A . That is, the maps from the unseeded EUs should yield some estimate of the natural variability of M and A .

As for the snow chemistry in Section 6.4, it may be appropriate to use a principal component analysis to investigate changes in the patterns of the leading modes of spatial variability in the precipitation.

Having carried out these analyses for data collected in the 5-hour EUs, it would be instructive to repeat the analysis for a period following each EU to account for the transport time of any effects from the target area. From these calculations, it should be apparent whether (i) the patterns of variability in and after the EUs are simi-

lar, and (ii) there is an apparent seeding impact after an EU in the downwind area. We note that it is possible for the period after one EU to overlap with the following EU, and so care will need to be taken to restrict this analysis to distinct EUs.

7. CONCLUSIONS

This paper outlines a comprehensive suite of tests to identify and quantify the effects of seeding in the target area of SPERP in a rigorous manner. Secondary analyses use data from all the instruments in the SPERP to help understand the physical processes associated with seeding. The analyses should also help identify whether there are discernible downwind effects from the seeding, and whether there are signs of persistent seeding effects. As the analysis proceeds, it is expected that the range of secondary analyses will increase in order to explore unexpected results.

Acknowledgements. The evaluation plan for SPERP was enhanced by thoughtful comments of Doug Shaw and Warren King, who reviewed the draft plan.

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