Further analysis of a snowfall enhancement project in the Snowy Mountains of Australia

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\textbf{A B S T R A C T}

The first phase of the Snowy Precipitation Enhancement Research Project (SPERP-1) was a confirmatory experiment on winter orographic cloud seeding (Manton et al., 2011). Analysis of the data (Manton and Warren, 2011) found that a statistically significant impact of seeding could be obtained by removing any 5-hour experimental units (EUs) for which the amount of released seeding material was below a specified minimum. Analysis of the SPERP-1 data is extended in the present work by first considering the uncertainties in the measurement of precipitation and in the methodology. It is found that the estimation of the natural precipitation in the target area, based solely on the precipitation in the designated control area, is a significant source of uncertainty. A systematic search for optimal predictors shows that both the Froude number of the low-level flow across the mountains and the control precipitation should be used to estimate the natural precipitation. Applying the optimal predictors for the natural precipitation, statistically significant impacts are found using all EUs. This approach also supports a novel analysis of the sensitivity of seeding impacts to environmental variables, such as wind speed and cloud top temperature. The spatial distribution of seeding impact across the target is investigated. Building on the results of SPERP-1, phase 2 of the experiment (SPERP-2) ran from 2010 to 2013 with the target area extended to the north along the mountain ridges. Using the revised methodology, the seeding impacts in SPERP-2 are found to be consistent with those in SPERP-1, provided that the natural precipitation is estimated accurately.

1. Introduction

Aircraft-based cloud seeding was first carried out in the Snowy Mountains of south eastern Australia in the 1950s (Smith et al., 1963). While a statistical analysis of the seeding impact showed a significant increase in precipitation during seeded periods compared with unseeded periods, other analyses (such as a search for differences in precipitation within the first few hours of seeding) were inconclusive, and so the overall impact was deemed to be inconclusive. Similar experiments on wintertime precipitation were carried out in the western highlands of Tasmania in the 1960s (Smith et al., 1979) and the late 1970s (Ryan and King, 1997). The second experiment in Tasmania confirmed the statistically significant results of the first, as well as demonstrating that tightening the start criteria for seeding led to more effective seeding impacts. Ryan and King also report that inconclusive results were found from an experiment in the late 1980s in the Thompson Reservoir catchment, south of the Snowy Mountains. Despite some tantalising results, the totality of these early experiments in the mountains of south eastern Australia is essentially consistent with the conclusions of the National Research Council (2003) that ‘there is still no convincing scientific proof of the efficacy of intentional weather modification efforts’.

The absence of convincing scientific evidence of the efficacy of cloud seeding in south eastern Australia did not arise from a lack of evidence of suitable conditions for seeding. Warburton and Wetzel (1992) used a ground-based microwave radiometer to show the presence of supercooled liquid water (SLW) in wintertime storms passing over the Snowy Mountains, and they used the GUIDE aerosol-trajectory model (Rauber et al., 1988) to suggest the practicality of cloud seeding in the region through ground-based generators. Long and Huggins (1992) and Long (1993) used similar measurements of SLW over the catchment of the Thompson Reservoir to demonstrate that there are large fluxes of SLW across the region, especially during post-frontal conditions. Aircraft measurements over Tasmania have also

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confirmed the presence of SLW at levels suitable for seeding (Ryan and King, 1997; Morrison et al., 2010). Using five years of MODIS data from the Terra and Aqua satellites (Platnick et al., 2003), Morrison et al. (2013) find that SLW occurs about 40% of the wintertime over the mountains of south eastern Australia, while the frequency is much lower over higher mountains in USA where cloud seeding has been conducted for the Sierra Cooperative Pilot Project (Desher et al., 1990), Climax I and II (Mielke et al., 1981), and the Bridger Range experiment (Super and Heimbach, 1983).

Building on the decades of earlier research, Manton et al. (2011) describe the first phase of the Snowy Precipitation Enhancement Research Project (SPERP-1), which used ground-based generators to seed the mountain ridges of the Snowy Mountains during the winters from May 2005 to June 2009. Analysing all 107 5-hour experimental units (EUs) in SPERP-1, Manton and Warren (2011) find that the fractional increase in precipitation in the overall target area for seeded EUs is 0.09 greater than for equivalent unseeded EUs. However, the statistical significance of the increase is only 13%. On the other hand, an increase of 0.14 at 3% significance is found when EUs with low amounts of released seeding material are omitted from the analysis. Analysis of snow chemistry provides physical evidence both of successful targeting of seeding material and of microphysical changes in the precipitation.

The initial results from SPERP-1 are similar to those found more recently in the Wyoming Weather Modification Pilot Program (WWMPP) (Breed et al., 2014). The draft executive summary of the WWMPP (Wyoming Water Development Commission, 2014) notes that the seeding signal is greatly enhanced when events with a low number of generator hours (and hence low amount of seeding material) are removed from the analysis. The statistical analysis of WWMPP is supported by very strong observational (Boe et al., 2014; Geerts et al., 2010) and modelling (Xue et al., 2014) studies.

While the results from the SPERP-1 and WWMPP are encouraging as they imply that a seeding signal can be drawn out from the background noise when the most impacted events are selected, it is worthwhile to consider whether the background noise can be reduced without such selection. One purpose of the present paper is to consider the sensitivity of the statistical impact of seeding to sources of noise. In particular, there is an investigation of the estimation of the natural precipitation in the target area which is usually assumed to be well estimated by the precipitation in an upwind control area (for example, Smith et al., 1979). With an improved method for estimating the natural precipitation in the target, it is possible to consider the spatial coherence of seeding impact across the region of interest.

The knowledge gained from the detailed analysis of SPERP-1 can be applied to data from phase 2 of the Snowy Precipitation Enhancement Research Project (SPERP-2). For SPERP-2, refined criteria are adopted for starting a 5-hour experimental unit and the target area is enlarged. Following the completion of SPERP-1, the remainder of the 2009 cool season was used as a transition period during which additional generators and precipitation sites were installed. The SPERP-2 experiment then ran for the four winters from May 2010 to September 2013. Because SPERP-1 was a confirmatory experiment, the new experiment aimed to demonstrate that the impacts could be extended to a larger area and to refine the design and analysis to optimise the actual and estimated impacts of seeding.

### 2. Design and initial results of SPERP-1

The detailed design of SPERP-1 is described in Manton et al. (2011) and the initial results are presented in Manton and Warren (2011). A 5-hour experimental unit (EU) was commenced when specific environmental criteria were satisfied to provide conditions suitable for seeding and to ensure certain environmental constraints were satisfied (Table 1). The criteria make use of the GUIDE model (Rauber et al., 1988) to ensure that ice particles, nucleated from seeding material, are likely to fall within the target area. A radiometer further ensures that there is supercooled liquid water (SLW) available for the growth of such nucleated particles. The conditions suitable for seeding tend to be associated with the passage of winter cold fronts from the west (Manton et al., 2011).

Fig. 1 shows the orography and mean precipitation per seeded EUs around the target area for SPERP-1. There were 13 generator sites to the west of the mountain ridges, which rise to over 2000 m. Based on a randomised sequence with a seeding ratio of 2:1 (twice as many seeded as unseeded EUs), silver iodide was dispersed from the generators during 71 of the 107 total number of EUs; 36 EUs were unseeded. A passive tracer, indium (III) oxide, was dispersed from collocated generators for all EUs. During seeded EUs, the ratio of silver to indium could be used to identify ice nucleation due to seeding, as described by Chai et al. (1993). During all EUs, the presence of indium could be used to monitor the targeting of seeding material.

Precipitation was measured by 62 instruments at 44 sites: 16 in the overall target area, 12 in a control area to the west of the ranges, and 16 in an extended area to the east of the target and control areas. It is seen from Fig. 1 that the peak precipitation during seedable EUs was over 3.5 mm along the mountain ridges, with a distinct rain shadow to the east, especially in the south east. Linear interpolation is used throughout the present analysis to avoid the smoothing of any spatial incoherence in plotted data.

Soundings were taken every 3 h from Khancoban (KH in Fig. 1) near the north west tip of the target area, and data from the soundings were

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Year</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezing level ≤ 1600 m with snow below 1400 m</td>
<td>2005</td>
<td>Government legislation</td>
</tr>
<tr>
<td>At least 0.05 mm SLW</td>
<td>2005</td>
<td>Sufficient SLW for seeding (Manton et al., 2011)</td>
</tr>
<tr>
<td>Cloud depth &gt; 400 m above −5 °C level</td>
<td>2005</td>
<td>Sufficient cloud depth above activation temperature of silver iodide for ice crystal growth (Manton et al., 2011)</td>
</tr>
<tr>
<td>Cloud top temperature ≤ −7 °C</td>
<td>2005</td>
<td>Silver iodide is several orders of magnitude more active below −7 °C than −5 °C (Manton et al., 2011)</td>
</tr>
<tr>
<td>At least one generator plume indicates fallout within target area</td>
<td>2005</td>
<td>Ensure nucleation is possible and seeded precipitation falls in target area (Manton et al., 2011)</td>
</tr>
<tr>
<td>Puff time from GUIDE model has elapsed from the end of the previous EU</td>
<td>2005</td>
<td>Ensure target is purged of seeding material before next EU commences</td>
</tr>
<tr>
<td>Suitable conditions are forecast to continue for at least 5 h</td>
<td>2010</td>
<td>Reduce likelihood of suspended EUs; before 2010 the forecast period was 3 h</td>
</tr>
<tr>
<td>At least 0.2 mm of precipitation in 30 min before start of EU</td>
<td>2010</td>
<td>Ensure there is precipitation to be enhanced</td>
</tr>
<tr>
<td>At least 15 generator plumes over target area</td>
<td>2010</td>
<td>Ensure adequate seeding material over target (Manton and Warren, 2011)</td>
</tr>
<tr>
<td>Seeding material must exit target area within 160 min</td>
<td>2010</td>
<td>Remove very low wind speed EUs when vertical mixing is likely to be poor (Manton and Warren, 2011)</td>
</tr>
<tr>
<td>Cloud top temperature ≥ −35 °C</td>
<td>2013</td>
<td>Reduce likelihood of natural ice particles that reduce cloud seeding efficiency</td>
</tr>
</tbody>
</table>
used in the GUIDE dispersion model (Rauber et al., 1988) to estimate the dispersion of seeding material from each generator. Path integrated liquid water and water vapour were measured by a dual-channel radiometer (Huggins, 1995) at Blue Cow (BC) near the middle of the target area. Snow chemistry data were collected at 17 sites (Huggins et al., 2008).

Initial analysis of the snow chemistry data from SPERP-1 showed that there was minimal seeding material outside the target area, that the material was well dispersed within the target area, and that there was evidence of additional nucleation of ice particles in seeded EUs (Manton and Warren, 2011). However, using the precipitation in the control area to predict the natural precipitation in the target area, the fractional increase in precipitation per seeded EU was found to be 0.09 with a statistical significance of only 13%, which was less significant than the a priori specification of 10% based on an analysis of historical data (Manton et al., 2011). The statistical significance was found by randomly selecting (with replacement) 71 ‘seeded’ and 36 ‘unseeded’ EUs from all 107 EUs 100,000 times, and computing the fraction of those samples with a precipitation increase greater than the observed value.

2.1. Measurement of snow

The measurement of snow is subject to under-catch in high-wind conditions, and so it is a source of uncertainty (Rasmussen et al., 2012). Eleven sites in SPERP-1 were equipped with 6-m double wind fences (Manton et al., 2011), and twelve sites had at least two instruments with higher-quality instruments collocated with long-term precipitation gauges. Guthega Dam (GD in Fig. 1) is a reference site with four different gauges near to each other to provide detailed inter-comparison data; it is located at an elevation of 1560 m near the centre of the target area.

For the initial analysis, a priority-gauge strategy was used to determine the instrument to be selected for the analysis of each EU at sites with more than one gauge. The priority was based on the a priori quality of each instrument; for example, highest priority was given a NOAH II gauge in a Double Fence Inter-comparison Reference (DFIR) and lowest to an unheated and unfenced tipping bucket. Inspection of the observations at Guthega Dam (Fig. 2) shows that the highest-priority gauge does not always have the maximum reading. Such behaviour is confirmed by Chubb et al. (2015) in a detailed inter-comparison of gauges measuring winter-time precipitation in the Snowy Mountains. Because all analysed data are quality controlled and because under-catch can have very local effects, it is reasonable to assume that a valid alternative to the priority-gauge selection strategy is to select the gauge with the highest reading for each seedable EU. This maximum-gauge strategy leads to some differences in mean EU precipitation at some sites; for example, the mean precipitation at Guthega Dam is 3.71 mm with the priority-gauge strategy and 3.83 mm with the maximum-gauge strategy. However, these differences are found to have a negligible effect on the estimation of seeding impact over the whole target area.

Chubb et al. (2015) demonstrate that there is systematic under-catch of snow at unfenced gauges in the Snowy Mountains, and that the readings at unfenced gauges can be adjusted to account for the under-catch. However, while the adjustment of 6-hour readings at individual sites can be as much as 50%, spatially-averaged seasonal under-catch tends to be less than 15%. Moreover, most sites above the snowline can be as much as 50%, spatially-averaged seasonal under-catch tends to be less than 15%. Moreover, most sites above the snowline have a gauge with a double fence. We note that under-catch is very unlikely to impact the analysis, because the data are quality-controlled to remove the effects of ice falling into a gauge and of late melting. Bearing in mind that gauge adjustment introduces additional uncertainties, no adjustment is carried out in the present paper to account for under-catch at unfenced gauges. We also note that, provided observed values of precipitation increase monotonically with actual precipitation, comparison of seeded and unseeded EUs will yield differences of the correct sign, independently of the detailed accuracy of the observations.

It would appear that, while the measurement of snow is a real source of uncertainty, it is not a major issue for the analysis of the overall seeding impact from SPERP-1 data. However, based on the observation that under-catch can affect any gauge and on the fact that all valid observations have been quality controlled, it is appropriate to select site values of precipitation based on the maximum reading from all valid gauges, rather than on a priority gauge. Higher estimates of precipitation would be obtained by adjusting unfenced gauges above about 1500 m for under-catch of snow.

2.2. Spatial variability of precipitation

Inspection of Fig. 1 shows that the terrain across the target area is complex and that there are substantial gradients in the mean precipitation across the target area. This observation suggests that the results of
the seeding impact analysis may be sensitive to the treatment of spatial variability in precipitation. For the initial analysis of SPERP-1, the estimate of areal precipitation was taken simply to be the arithmetic mean of all valid site values in the area for each EU (Manton and Warren, 2011).

It may be argued that the arithmetic mean biases values towards the maximum, and so a basic test of this bias is to use the median values of all valid site values in the target area. As expected the median values of target precipitation for each EU are somewhat lower than the mean values; for example, the median EU precipitation is 2.0 mm when the mean value is used, but it is 1.7 mm when median values are used. On the other hand, the seeding impact is essentially unchanged with a fractional increase of 0.10 at 16% significance.

A more sophisticated test of sensitivity to spatial variability is to use an interpolation analysis to compute gridded values of precipitation across the target. When we apply linear interpolation (without extrapolation) on a 0.025-degree grid to all site values, the EU precipitation is lower than in the initial analysis; for example, the median EU precipitation is 1.7 mm rather than 2.0 mm for the arithmetic mean. The reason for the drop in estimated precipitation is seen from Fig. 1: owing to the sparsity of gauges across much of the high ranges, gridded values for the target area are greatly influenced by sites in the control and extended areas. This influence is especially large for the western sector of the target, because the site at Swampy Plain, which is very near the western border of the target (Fig. 1), was nominated as a control site for SPERP-1 (because of its low elevation of 445 m). Contamination of the estimates of the target precipitation by the precipitation in the control and extended areas leads to a slightly reduced estimate of seeding impact: 0.08 at 15% significance.

If the interpolation is restricted to sites within the target area, then the median target precipitation is 2.0 mm; that is, unchanged from the arithmetic mean of the site values. Consequently, the seeding impact is very close to the original result of 0.09 fractional increase at 14% significance.

In summary, the estimates of seeding impact are not greatly sensitive to the method used to estimate the precipitation in the target area, provided that the estimate is not contaminated by precipitation at sites in the control or extended areas (which are in principle unaffected by seeding).

2.3. Dispersion of seeding material

With 13 generators and 5-hour EUs, each EU in SPERP-1 could have up to 65 generator hours of seeding material dispersed across the target area. Manton and Warren (2011) find that about 20% of seedable EUs have less than 45 generator hours. On the assumption that the impact of seeding should be related in some manner to the total amount of seeding material dispersed during an EU, they find that the seeding impact is increased to 0.14 at 3% significance when EUs with less than 45 generator hours are removed from the analysis. A similar result has been found for the WWMPP (Wyoming Water Development Commission, 2014), where seeding increases of up to 0.17 were obtained when EUs with low generator hours were ignored.

Results from two independent cloud seeding experiments have now found a sensitivity of the seeding impact to the amount of seeding material dispersed across the target area. This result could be used to infer that seeding is acting in an expected manner, but it also emphasises the need to ensure that sufficient seeding material is dispersed across the target area during each seedable EU.
2.4. Estimation of natural precipitation

A key element in the estimation of the impact of cloud seeding on precipitation in a target area is the estimation of the natural precipitation in the target in the absence of seeding. Indeed the inherent variability of natural precipitation is the reason that long-term statistical analyses have been the main method for assessing the impacts of cloud seeding over catchment-scale areas and over seasonal time scales. Numerical modelling (for example, Xue et al., 2013) provides the potential to provide statistically and physically robust estimation of natural precipitation, but at this time a numerical model has not been used to accurately simulate a long-term cloud seeding experiment (Tessendorf et al., 2015).

The precipitation in an up-wind control area in unseeded EUs is commonly used to estimate the natural precipitation in the target area, either through a ‘double-ratio’ or through a regression equation (Smith et al., 1979). Manton and Warren (2011) used a linear regression to estimate the natural precipitation for SPERP-1, and inspection of the goodness of fit of the regression shows a RMS error of 1.0 mm and a skewness of 1.1; that is, the variations around the regression line are quite large and are quite skewed. This observation suggests that the uncertainty in the estimation of the natural precipitation may be a significant source of uncertainty in the estimation of seeding impact.

3. Natural precipitation in target area of SPERP-1

In Section 2.4 above we found that the use of only the precipitation in the control area (Pc) to estimate the natural precipitation in the target (Pt) does not provide an especially close fit to the observations. It is therefore reasonable to ask whether other environmental variables could be used with Pt to provide a better estimate of the natural precipitation.

The application of multi-variate regression can lead to a major problem of over-fitting, where the model equation tends to fit the random noise rather than the underlying physical relationships. However, the problem of model selection is well understood (for example, Burnham and Anderson, 2002), and a systematic approach can be used to obtain a mathematically sound balance between goodness of fit and complexity. Two indicators are generally used to optimise model selection, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). (The Mallows Cp statistic is also used, but it produces the same ranking as AIC.) The main difference between AIC and BIC is that BIC tends to give less weight to more complex models. Erring on the conservative side, we use the BIC as the criterion for the present analysis.

The detailed flow across a mountain range is largely controlled by the wind speed and stability of the atmosphere, as well as the geometry of the mountain (Smith, 1989). These factors also influence the character of precipitation forced by the orography (Watson and Lane, 2012; Geert et al., 2015).

The characteristic wind speed for SPERP-1 was taken as the value at the −5 °C level (U5), which generally lies near the top of the ranges, around 2000 m (Manton et al., 2011). While this value can be readily used in the calculation of EU start criteria (Table 1), an average value of the wind below the range top may be more appropriate for representing the impact on the target precipitation (Pt). Noting that soundings are taken at Khancoban at an elevation of 308 m, we consider the mean wind speed between 400 and 2000 m (Uav) as an alternative indicator of the characteristic wind. An exhaustive search (Miller, 2002) of the possible linear combinations of U5 and Uav finds that Uav is the better predictor of Pt for SPERP-1. A further refinement is to consider the westerly components of these winds (U5w and Uavw) as predictors, but the average wind speed Uav remains optimal for SPERP-1.

For cloud conditions, it is usual to represent the atmospheric stability by the Brunt-Vaisala frequency (Nbav), where

\[
N_{bav}^2 = \frac{g \partial \theta_a}{\partial z}
\]

\(g\) is gravitational acceleration, \(z\) is height and \(\theta_a\) is the saturation equivalent potential temperature; the gradient is computed between 400 and 2000 m. However, because Khancoban lies on the slopes of the ranges, the soundings can indicate unstable conditions with \(N_{bav}^2 < 0\), and so the Brunt-Vaisala frequency cannot always be calculated. Even the \(N_{bav}^2\) based on the equivalent potential temperature \(\theta_e\) can be negative at Khancoban. Only \(N_{bav}^2\) based on the potential temperature \(\theta_a\) is consistently positive. For each \(N_{bav}^2\), we can define an effective Richardson number; for example,

\[
R_{i,av} = N_{bav}^2 H / U_{av}^2
\]

where \(H\) is the effective mountain height (1600 m). Based on the potential temperature, we can also define a Froude number by

\[
F_{av} = U_{av} / (H N_{bav})
\]

A priori it is not clear which of all the dimensional and dimensionlessness variables is the best predictor of \(P_t\). However, an exhaustive search of all possible combinations using the BIC selection criterion shows that the Froude number \(F_{av}\), together with \(P_c\) gives the optimal predictors of \(P_t\) for SPERP-1, even when \(U_{av}\) is included as a potential predictor.

It is well established that the Froude number is an important factor in characterising the nature of precipitation over a mountain (for example, Watson and Lane, 2012). For SPERP-1, \(F_{av}\) ranges from 0.17 to 1.64 with a median value of 0.59. The low values of \(F_{av}\) may suggest that the flow over the ranges is blocked. On the other hand, the Froude number represents the dry stability conditions and so low values of \(F_{av}\) are to be expected.

Knowing the optimal predictors of the target precipitation, we can now compute the natural precipitation in the target area from the unseeded EUs by the regression equation

\[
P_{av, nat} = a + bP_c + cF_{av}
\]

where \(a\), \(b\) and \(c\) are constants. Then the precipitation residual (\(R\)) for all EUs is given by

\[
R = P_t - (a + bP_c + cF_{av})
\]

where \(P_t\) is the observed precipitation in the target area.

When the natural precipitation is calculated using the optimal predictors, the RMS error for unseeded EUs is 0.87 mm and the skewness is 0.43; that is, the fit to the unseeded data is much better than when \(P_t\) alone is used in the regression. The improved estimate of the natural precipitation leads to a fractional increase in precipitation due to cloud seeding of 0.11 at 6% statistical significance. Thus the estimated fractional increase is somewhat larger and much more statistically significant than when \(P_t\) alone is used in the regression. Moreover, the significance is close to that obtained (Section 2.3) by ignoring EUs with low amounts of seeding material; that is, improving the estimate of natural precipitation, the cloud seeding signal can be better identified against the reduced background noise.

The exhaustive search shows that \(U_{av}\) is almost as important as \(F_{av}\) in the prediction of natural precipitation in the target area, and if \(F_{av}\) is replaced by \(U_{av}\) in Eq. (2) then the fractional increase is 0.13 at 3% significance, with an RMS error of 0.89 mm and a skewness of 0.29 in fitting the natural target precipitation. The reason for the similar results using either \(F_{av}\) or \(U_{av}\) for the estimation of natural precipitation is that there is a high correlation (0.82) between \(F_{av}\) and \(U_{av}\), because the range of \(N_{bav}\) is relatively small so that \(U_{av}\) is the dominant variable in Eq. (1).

It is worth noting that, while \(F_{av}\) is selected over \(U_{av}\) in the exhaustive search because the RMS error is smaller, the skewness of the regression fit for the natural target precipitation is smaller for \(U_{av}\). This suggests that \(U_{av}\) could be used to estimate the natural precipita-
tion for SPERP-1, rather than \( F_{\text{cr}} \). Moreover, the seeding impact is larger and more significant when \( U_{\text{aw}} \) is used as the predictor. Nonetheless, to maintain a consistent approach of regression selection based on the well-established BIC, we will take \( F_{\text{cr}} \) with \( P_c \) as the optimal predictors.

4. Subsets of SPERP-1

We found in Section 3 that, using all 107 EUs from SPERP-1 and optimal predictors of natural precipitation (\( P_i \) and \( F_{\text{cr}} \)), the fractional increase in precipitation due to cloud seeding is estimated to be 0.11 with 6\% significance. The observation that \( P_i \) alone is not the optimal predictor of the natural target precipitation implies that the impact is not simply multiplicative, and so it is useful to consider the mean increase in precipitation per seeded EU as an alternative indicator of impact. From the analysis in Section 3, the mean increase in precipitation per seeded EU in SPERP-1 using all EUs is 0.30 mm.

During SPERP-1, eight EUs were suspended when the seeding criteria were not satisfied, generally owing to the freezing level rising above 1600 m. The optimal predictors of natural precipitation remain \( P_i \) and \( F_{\text{cr}} \) when these EUs are removed from the analysis, and the fractional increase in precipitation is 0.13 at 5\% significance; the mean increase per seeded EU is 0.37 mm. As expected, removal of suspended EUs slightly increases the seeding impact. The following analyses in the present paper are carried out using this subset of SPERP-1, because suspended EUs are by definition not completely suitable for seeding.

It is noted in Manton and Warren (2011) that many EUs in SPERP-1 have low precipitation. Indeed Fig. 3 shows a bimodal distribution for \( P_i \) with the main mode near zero. The sensitivity of seeding impact to \( P_i \) is investigated by inspection of the cumulative sum of seeded and unseeded precipitation residuals (Eq. (3)) with EUs ordered by \( P_i \). By definition, the cumulative sum of unseeded residuals is zero at the maximum value of \( P_i \), as shown in Fig. 4. On the other hand, the cumulative sum of seeded residuals at the maximum value of \( P_i \) is equal to the overall impact of seeding (24.1 mm). We see from Fig. 4 that the seeded accumulated residual increases steadily for \( P_i \) greater than about 1.5 mm. On the other hand, the seeded accumulated residual curve essentially follows the unseeded accumulated residual curve for \( P_i \) less than 1.5 mm, suggesting that there is little impact of seeding on EUs with low values of \( P_i \).

The lack of seeding impact for low \( P_i \) is emphasised in Table 2, where the analysis is carried out by splitting the EUs at the median value of \( P_i \) (1.7 mm). Analysis of the Low group (\( P_i < 1.7 \) mm) shows no impact of seeding, while analysis of the High group shows a fractional increase of 0.16 and a mean increase of 0.63 mm at 7\% significance. The implication of this analysis is that the overall impact of seeding for EUs with \( P_i \) greater than 1.5 mm is diluted by inclusion of EUs with low values of \( P_i \).

Fig. 4 and Table 2 clearly show that, perhaps counter-intuitively, there is little or no seeding impact in SPERP-1 at low values of \( P_i \). The reasons for this result could be investigated through detailed numerical modelling, but one potential cause may be the observed correlation between \( P_i \) and wind speed (Manton and Warren, 2011). That is, Manton and Warren found that low \( P_i \) events tended to occur in low wind conditions. Moreover, they also found that EUs with low wind speed appeared to have little impact from seeding. This observation is confirmed by inspection of Fig. 5, where the cumulative sum of the seeded residuals is essentially zero for EUs with \( U_{\text{aw}} \) less than about 7.5 m/s. The result may reflect the dependence of seeding impact on vertical mixing (associated with wind speed) that raises the seeding material from the ground to the nucleation level.

A key finding from SPERP-1 is that there is little impact of seeding from EUs with low values of generator hours (Section 2.3). This result is highlighted in Fig. 5, where it is clear that the seeding impact is evident only for generator hours greater than about 49.

In the initial analysis of SPERP-1, Manton and Warren (2011) find that there is little seeding impact for EUs with cloud top temperature \( (T_t) \) less than about \(-20 \) °C which is consistent with earlier observations by Super (1986) and Ryan and King (1997). However, inspection of Fig. 5 indicates that there may be some impact for EUs warmer than \(-35 \) °C, although the physical basis of impacts at such cold temperatures is not clear. Moreover, the seeded residual curve is systematically greater than the unseeded curve only for \( T_t \) greater than about \(-25 \) °C.

In summary, inspection of the ordered cumulative sum of precipitation residuals provides a means to identify ‘windows’ of seeding impact for each environmental variable. From this technique, it is found that there is little impact of seeding for EUs with low \( P_i \) or \( U_{\text{aw}} \). We note that all the present calculations are carried out using site precipitation data applying the priority-gauge selection approach (Manton and Warren, 2011). If the maximum-gauge selection approach (Section 2.1) is used, then similar conclusions are reached.

5. Spatial variability of seeding impact in SPERP-1

By improving the accuracy of the estimation of the natural
precipitation in the target area, we have found that robust and consistent estimates of seeding impact can be obtained using all (especially all valid) EUs. It is therefore appropriate to consider whether the seeding impacts found by averaging over the whole target area are associated with a coherent spatial pattern of impact, or whether they are due to isolated or random anomalies.

Using Eqs. (2) and (3), the mean increase in precipitation per seeded EU ($MnInc$) and the overall fractional increase ($FrInc$) are computed at each precipitation site for all SPERP-1 EUs that were not suspended. Fig. 6 shows the variation of $MnInc$ and $FrInc$ across the target area using linear interpolation. The spatial variation is generally consistent with a positive impact across the target area, with values of $MnInc$ larger than 0.3 mm around the main ridge and a peak value of 0.8 mm. There are five sites with $MnInc$ at significance levels better than 10%, which is notable given that the analysis is carried out at individual sites rather than across the average of the site values. Similarly, the values of $FrInc$ are over 0.1 for much of the target area, with four of the target sites having better than 10% significance. It is apparent that the peak values in $FrInc$ tend to be on the lee side of the ranges where the natural precipitation is lowest. On the other hand, the distribution of $MnInc$ is more consistent across the target, especially along the mountain ridges. This observation suggests that the impact of seeding may be better represented as a mean increase per seeded EU, rather than by a fractional increase.

There is a large negative anomaly at Pinnacle Mountain, where $MnInc$ is $-0.7$ mm, and there is a smaller negative value at The Kerries to the north east of Pinnacle Mountain. Unlike other gauge sites, Pinnacle Mountain is at the southern extreme of a sharp mountain range (Fig. 1), and so at times it may be affected by complex wind patterns channelling air around the ranges. Because there were many EUs in SPERP-1 with low wind speeds, it is quite possible that seeding material did not consistently affect the site. There are no snow
chemistry observations from this site to test this assumption. The effects of variations in wind are explored by calculating the seeding impact with EUs split by wind direction. The median value of the direction of Uav is $299^\circ$, indicating that the low-level wind tends to be channelled along the valleys of the ranges around Khancoban as shown in Fig. 1. In contrast, the median value of the wind direction at $-5^\circ$C-level is $277^\circ$; that is, the wind near the range tops tends to be reasonably distributed around the westerly sector. We therefore split EUs at the median value of the direction of the wind at $-5^\circ$C($\phi_5$), resulting in 16 unseeded and 32 seeded EUs for Northerly conditions and 18 unseeded and 33 seeded EUs for Southerly conditions.

Splitting the EUs by wind direction means that the number of events for each analysis is halved, and so it may be quite surprising to find any consistent results across the individual sites. Nonetheless it is apparent from Fig. 7 that there is a significant positive seeding impact in Northerly wind conditions ($\phi_5 \geq 277^\circ$), along the central ranges, with nine target sites along the mountain ridges having significance at the 10% level. On the other hand, the negative anomaly at Pinnacle Mountain arises mainly in these Northerly wind conditions. All these results suggest that the dispersion of seeding material is systematically dependent on wind direction. In Southerly wind conditions ($\phi_5 < 277^\circ$), the dispersion of seeding material appears to be limited to the central west of the target area. There is a large negative anomaly in Southerly conditions at The Kerries in the north of the target, leading to the small negative anomaly identified in Fig. 6.

Detailed modelling would be required to explain the spatial variations of seeding impact, but the present analysis aims simply to demonstrate that the spatial variations seen in Fig. 6 may be associated with spatial variations in the dispersion of seeding material under different wind conditions.

6. Design of SPERP-2

The design of the second phase of the Snowy Precipitation Enhancement Research Project (SPERP-2), which ran from May 2010 to September 2013, builds on the results of SPERP-1. To increase the overall impact of seeding, the target area is extended to the north (Fig. 8), with the south target corresponding to the SPERP-1 target and the north target having an area of 1309 km$^2$. The split target allows for...
orographic differences, as the peak ridges are around 2000 m in the south and around 1700 m in the north. The split also allows some comparison with SPERP-1, although the control sites for SPERP-2 do not exactly correspond to those of SPERP-1.

There are 61 sites with precipitation gauges: 16 sites in the control area, 16 in the south target, 13 in the north target, and 16 in the extended area. Only 8 of the original SPERP-1 control sites are continued in the SPERP-2 control area. Three of the SPERP-1 control sites are now in the north target and one control site (Swampy Plain in Fig. 1) is moved to the south target, based on the positive seeding impact found in SPERP-1 (Fig. 6).

The 13 seeding generators of SPERP-1 are supplemented with an additional 10 generators targeted on the north area (Fig. 8). Because the snow chemistry analysis of SPERP-1 demonstrated that the seeding material is well targeted and that the silver has an impact on the cloud microphysics (Manton and Warren, 2011), dispersion of the tracer material ceased after 2011, and snow chemistry is not considered in the present analysis. For the first three years of SPERP-2 (2010–2012), seeding material was dispersed from generators in a randomised sequence with a 1:1 seeding ratio; as with SPERP-1, the seeding sequence was not known by any personnel associated with scientific aspects of the experiment. From 2013, in anticipation of operational seeding, the seeding ratio was raised to 7:1 and the sequence became visible to scientific personnel. The GUIDE (Rauber et al., 1988) model (modified to account for the north and south targets) is used to determine which generators have plumes that would pass over the target area.

The conditions for starting an EU suitable for seeding are summarised in Table 1. Most of the criteria were established for SPERP-1, but specific changes to the start criteria are

- A total of at least 15 generators must be targeting the overall (north and south) target area
- Seeding material must leave the target area within 160 min of being emitted from a generator
- At least 0.2 mm of precipitation must have fallen in the previous 30 min at any site in the target or control areas
- Conditions suitable for seeding are predicted to exist for the 5-h duration of an EU.

The first change recognises the need to have an adequate amount of seeding material dispersed across the target (Section 2.3). The second takes into account the low impact of low-wind EUs (Section 4), and reduces the need for long purge periods between EUs. The third change arises from the negligible impact of low-precipitation EUs (Section 4), and the fourth from the desirability of reducing the number of suspended EUs. In 2013, an additional criterion for the cloud top temperature ($T_t$) to be warmer than $-35$ °C was imposed, based on the mounting evidence (Section 4) that seeding is ineffective when $T_t$ is very low.

After the completion of SPERP-1 in June 2009, the seeding experiment was continued while new infrastructure was installed and the revised start criteria were tested. SPERP-2 commenced in May 2010 and was completed in September 2013. A total of 97 EUs were recorded during SPERP-2, with 54 seeded and 43 unseeded EUs. The inter-annual variability of EUs was reasonable, with the number of EUs equal to 24, 18, 24 and 31 in years 2010 to 2013. Only one (seeded) EU was suspended when the freezing level rose above 1600 m (Table 1). The reduction in the number of suspended EUs from 8 out of 107 EUs in SPERP-1 to 1 in 97 is a clear measure of the improvement in experimental design and implementation.

### 7. Observed variables for SPERP-2

As with SPERP-1 (Manton et al., 2011), several datasets have been compiled to support a range of analyses. The core dataset, used in the present analysis, consists of the values of all the key variables during each seedable EU. Based on the discussion in Section 2.1, the precipitation at sites with more than one gauge is taken to be the maximum reading of valid records for each EU. As found for SPERP-1 (Section 4), this approach does not lead to substantial differences in the results, but it does recognise that under-catch can occur in any gauge arrangement. A site value is the accumulated precipitation from the selected gauge over the 5 h of each EU. The precipitation in each area is set equal to the arithmetic mean of the individual site values across each area. The control precipitation is $P_n$ and the precipitation in the north and south target areas is given by $P_n$ and $P_s$.

The statistical properties of relevant variables over the 96 valid EUs are summarised in Table 3. Comparing the statistics for SPERP-2 with those from SPERP-1 (Manton et al., 2011), we see quite good agreement for the independent variables. The median of $P_n$ is 1.6 mm which is similar to the SPERP-1 value of 1.7 mm. The start criterion on wind speed leads to the median $U_{\text{avg}}$ being 1.5 m/s higher than for SPERP-1, but the first quartile is about 2 m/s higher. The wind direction is a little more northerly, with the median $\phi_w$ being 284°, compared with 277° for SPERP-1. The median $T_t$ is 0.8 °C colder than for SPERP-1. These differences result in the median Froude number $F_{\text{fr}}$ being about 0.1 higher than for SPERP-1, mainly due to the higher wind speeds.

The representative height of the ranges ($H$ in Eq. (1) for the Froude number) is taken to be 1600 m for both target areas. Although the ridges are higher in the south than the north, the foothills to the west are also higher. The main difference in character between the north and south targets is that the peaks are narrower in the south with the eastern foothills up to 500 m lower than in the north; that is, the effective ratio of width to height is smaller in the south.

A major difference in variables between SPERP-1 and SPERP-2 is in the target precipitation. The stricter start criterion on precipitation leads to the median value of $P_n$ being 3.4 mm, much larger than the 2.0 mm of SPERP-1. This observation suggests that the similarity in the median values of $P_n$ arises mainly from the change in sites for control gauges. The quartiles for $P_n$ are generally a little lower than for $P_{\text{fr}}$.

### 8. Seeding impact of SPERP-2

The analysis of seeding impact is carried out with the one suspended EU removed. It was shown in Section 3 that $P_n$ and $F_{\text{fr}}$ are the optimal predictors of the natural precipitation in the south target for SPERP-1. When the same exhaustive search process is applied to the unseeded variables for SPERP-2, we find that the optimal predictors are $P_n$ and $U_{\text{avg}}$, the westerly wind component at the $-5$ °C level; that is, the natural precipitation in the south target is given by

$$P_{n,\text{fr}} = a + bP_n + cU_{\text{avg}}$$

where the coefficients $a$, $b$ and $c$ are found by linear regression using the unseeded EUs.

It was found in Section 3 that for SPERP-1 the wind speed was
essentially as significant as the Froude number in optimising the estimation of the natural target precipitation, and so it is not unexpected for the wind speed to be more important than the Froude number in SPERP-2. Moreover, the important wind speed for SPERP-2 is the value around the range tops rather than the mean low-level wind, and this result reflects the higher wind speeds and larger Froude numbers; that is, the environment tends to be more unstable for SPERP-2. A further difference from SPERP-1 is that the westerly component of the wind is more relevant than the absolute wind speed, and this is likely to reflect the observation from Table 3 that the wind direction ($\phi_w$) tends to be more northerly in SPERP-2; that is, the generation of precipitation through the lifting of air over the ranges is represented by the westerly wind component around the range tops. For SPERP-1, precipitation generation was related more to the low-level winds channelling their way through the ranges.

The use of two targets allows for differences in the character of the natural precipitation along the mountain ranges. However, an exhaustive search for the optimal predictors of the natural precipitation in the north target finds the same variables as for the south target, that is $P_t$ and $U_{5w}$. On the other hand, the orographic differences between the north and south targets leads to differences in the regression coefficients, as in Eq. (4). Table 4 shows that, while the regression coefficient for $P_t$ is essentially the same in each target, the effect of wind speed on precipitation is much larger in the north than in the south target.

Using the regression coefficients found from unseeded EUs, the precipitation residual for each target can be computed from the equivalent of Eq. (3). From the seeded residuals, the mean increase and fractional increase per seeded EU are calculated and are shown in Table 4. It is apparent that the fractional increase in precipitation for the south target is similar to that found in SPERP-1, but the mean increase at 0.47 mm is much larger reflecting the higher precipitation in SPERP-2. The seeding impact in the north target is seen to be larger than that in the south: the mean increase per seeded EU is 0.55 mm.

We note that if the optimal predictors are not used to estimate the natural precipitation in the targets, then with only $P_t$ as the predictor the estimated increases in precipitation are very low: a fractional increase of 0.04 in the south and 0.01 in the north with negligible statistical significance. The poor fit to the regression equation is especially apparent in the north, where the RMS error is 1.3 mm. The larger errors in SPERP-2 when $P_t$ is the only predictor are most likely due to the much larger values of precipitation, to the greater difference between target and control precipitation, and to the greater dependence of target precipitation on wind speed (Table 4).

In Section 4, we found that information on the sensitivity of seeding impact to environmental variables in SPERP-1 could be deduced from the cumulative sum of the seeded precipitation residuals ordered by each variable. Fig. 9 shows that the revised start criterion on precipitation (Table 1) ensures that there is a positive impact for all values of $P_t$ in SPERP-2. However, the impact in the south is less consistent than in the north. There is also an indication in both targets that there is less net gain from seeding EUs with $P_t$ greater than about 6 mm. This limitation is not apparent from SPERP-1 (Fig. 4), but the number of EUs with $P_t$ greater than 6 mm is quite limited in both experiments.

The cumulative sum of residuals ordered by west wind speed ($U_{5w}$) is somewhat different in the north and south, perhaps reflecting the difference in aspect ratio of the ranges (Section 7). The impact in the south is somewhat erratic. There is some uncertainty in the north at higher wind speeds which may be due to the larger regression coefficient for $U_{5w}$ than in the south (Table 4). The additional start criterion on wind speed (Table 1) ensures that there is a positive impact at low wind speeds in both targets.

It is clear for both targets that the seeding impact is erratic for cloud top temperature $T_t$ less than about $-20^\circ$C, which aligns with earlier findings (Super, 1986; Ryan and King, 1997; Manton and Warren, 2011). Indeed, if EUs with $T_t < -35^\circ$C are removed from the analysis (Table 1), then the mean increase per seeded EU is 0.53 mm for the south and 0.61 mm for the north target, while the fractional increase is 0.14 for the south and 0.18 for the north.

As for SPERP-1 in Section 5, we can estimate the spatial variability of the seeding impact by carrying out the impact analysis at each precipitation site across the region. Fig. 10 shows the spatial distribution of mean and fractional increase for SPERP-2. Comparing Figs. 6 and 10, we see that the anomaly around Pinnacle Mountain is not apparent for SPERP-2. On the other hand, the seeding impact across much of the south is low compared with the northern part of the south target. Indeed if the analysis is carried out with EUs split at the median value (284°) of $\phi_w$ (as in Fig. 7) then there is a region of low impact across the south for EUs with a Northerly ($\phi_w > 284^\circ$) wind component. This widespread feature would seem to limit the overall seeding impact in the south target. Nonetheless there are six sites in Fig. 10 (mainly in

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**Table 4**

Summary of seeding analysis for SPERP-2; first five rows refer to analysis of unseeded EUs; last four rows refer to seeding impact; coefficients $b$ and $c$ are regression coefficients for natural target precipitation, as in Eq. (4).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>South</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. unseeded</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>Coefficient $b$</td>
<td>1.44</td>
<td>1.47</td>
</tr>
<tr>
<td>Coefficient $c$</td>
<td>0.10 mm/(m/s)</td>
<td>0.17 mm/(m/s)</td>
</tr>
<tr>
<td>RMS error</td>
<td>0.91 mm</td>
<td>1.05 mm</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.37</td>
<td>0.47</td>
</tr>
<tr>
<td>No. seeded</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Mean increase</td>
<td>0.47 mm</td>
<td>0.55 mm</td>
</tr>
<tr>
<td>Fractional increase</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Significance</td>
<td>6%</td>
<td>3%</td>
</tr>
</tbody>
</table>
At sites with multiple gauges in SPERP-1, Manton et al. (2011) selected the gauge with the highest inherent quality to be taken to represent the site record for each EU. Due to the vagaries of under-catch of snow, it is observed that the highest-quality gauge does not always have the highest reading at such sites. The strategy of selecting the gauge with the highest (quality-controlled) reading at sites with multiple gauges is therefore seen to be an appropriate alternative.

The estimation of the natural precipitation in the target area is found to be a significant source of uncertainty. The use of only the control precipitation to estimate the natural target precipitation in the absence of seeding leads to substantial RMS error and skewness in the fit to the associated regression equation. The introduction of additional environmental variables can reduce both the RMS error and especially the skewness in the regression fit. When the Bayesian Information Criterion (BIC) is used to optimise the balance of model complexity and goodness of fit, it is found that the Froude number of the low-level flow over the ranges is the most important additional predictor of natural precipitation. The improved estimation of natural precipitation leads to a fractional increase in precipitation for SPERP-1 of 0.11 at 6% statistical significance when all EUs are considered. The mean increase in precipitation per seeded EU is 0.30 mm. If the eight EUs that were suspended during SPERP-1 are removed from the analysis then the fractional increase is slightly better at 0.13 at 5% significance, but the mean increase rises to 0.37 mm.

By inspecting the cumulative sum of the seeded residuals (differences between observed and natural precipitation for each EU) when they are sorted by the value of a specific environmental variable, we can determine the sensitivity of seeding impact to the value of that variable. For example, it is demonstrated that there is negligible impact from EUs with very low precipitation, as suggested by Manton and Warren (2011). Events with low wind speed, very cold cloud top temperature or low generator hours are also found to have limited impact from seeding.

With a robust method to estimate seeding impact, the analysis can be repeated at each site across the region to examine the spatial distribution of seeding impact. The mean precipitation increase per seeded EU is found to be larger than 0.3 mm around the main ridge with a peak value of 0.8 mm. The fraction increase is also consistently above 0.1 but it peaks where the mean precipitation is lowest (that is where the denominator is smallest), and so the mean increase is perhaps a more appropriate indicator of impact. However, it is apparent that the impact of seeding is neither simply additive nor multiplicative to the mean precipitation.

There is one site in the western part of the target for SPERP-1 with a large anomalously negative impact. Investigation of the spatial impact with EUs split at the median wind direction shows that the anomaly occurs mainly when the wind has a northerly component. It is suggested that such anomalies are a result of the channelling of seeding material around the ranges, but detailed numerical modelling would be needed to identify the likely distribution of seeding material.

Building on the results of SPERP-1, the second phase of the project (SPERP-2) was carried out from May 2010 to September 2013. A north target area was added to the original (south) target, and additional seeding generators and precipitation gauges were installed. The start criteria for seedable EUs were made more strict, especially to reduce the number of EUs with very low precipitation or wind speed. The stricter start conditions lead to EUs with higher precipitation and so higher increases per seeded EU in the south target (mean increase of 0.47 mm). The north target generally has a greater and more consistent impact from seeding, with a mean increase per seeded EU of 0.55 mm.

Investigation of the spatial distribution of seeding impact for SPERP-2 shows consistent increases over the target areas. The large anomaly found in SPERP-1 in the south target is not apparent, but the impact is quite low over the southern part of the south target. The region of low impact occurs when the wind has a northerly component. Apart from a small anomaly at one site in the north west of the north target, the
impacts in the north are consistently large. As with the south target, the anomaly occurs when the wind has a northerly component. When the wind is from the west or has a southerly component, the impact of seeding is quite consistent across both targets.

The overall conclusion is that, on the basis of two experiments over the last decade, there is strong evidence of a positive seeding impact across the overall target area of the Snowy Mountains. The statistical evidence of an overall impact is supported by physically reasonable relationships between seeding impact and a number of environmental variables, and by a spatially consistent impact of seeding across the target area.

References


