USING DYNAMICALLY DEFINED CONTROLS TO EVALUATE THE IMPACT OF AN IONIZATION TECHNOLOGY

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ABSTRACT. An additional field trial of an ionisation technology, called Atlant, was conducted in late 2010. Previous analysis of the data collected in field trials of the technology conducted in 2008 and 2009 used spatio-temporal statistical models to account for the impact of meteorological and topographic conditions not controllable by the randomised experimental design. In addition, a novel application of a random effect block bootstrap was developed for inference. These techniques are applied to the analysis of the 2010 Atlant field trial. In response to peer-review of previous trials, a new modelling approach is developed for this 2010 analysis, that uses dynamically defined upwind control areas to generate values of an instrumental variable that integrates the effects of meteorology and topography induced variation in rainfall. This allows a much simpler model specification and a clearer delineation between naturally occurring rainfall and any additional rainfall attributable to the operation of Atlant. Results using both the statistical methodology of previous trials and also by fitting this so-called "instrumental" model are consistent with those obtained in previous analyses, which had suggested a positive increases in rainfall of around nine percent relative to the predicted rainfall that would have occurred in the absence of Atlant operation.

1. INTRODUCTION

Ground-based ionisation as a means of weather modification was first investigated experimentally by Bernard Vonnegut (Vonnegut and Moore, 1959). Vonnegut carried out numerous experiments into the electrification of clouds, including the widespread releases of ions into the sub-cloud air using a high-voltage power supply that generates corona discharges from an extensive array of small diameter wires elevated above the ground and exposed to local winds and updrafts (Vonnegut et al. 1961, 1962a, 1962b).

Over the years a number of field experiments have been run using technologies derived from this technique (Moore et al. 1986; Kaufman and Ruiz-Columbié, 2005, 2009). Most recently a series of field trials of ground-based ionisation rainfall enhancement technology known as Atlant have been conducted in Australia (Beare et al. 2010; 2011). Further detailed information on the Atlant technology can be downloaded from the Australian Rain Technologies' website (ART, 2012).

Several mechanisms exist by which ions might influence the microphysical processes of precipitation formation at multiple stages through the process (e.g. Harrison and Carslaw, 2003 for an overview; Harrison 2000, Khain et al. 2004, Tinsley et al. 2000). In particular, there is evidence consistent with ions enhancing the coalescence efficiency of charged cloud droplets compared to the neutral case, which provides the basis for a possible hypothesis for how the Atlant system may function to affect rainfall. Initially, negative ions generated from a high-voltage corona discharge wire array become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN). The ions are conveyed to the higher atmosphere by wind with the electric charges on these particles being transferred to cloud droplets. Finally the electrostatic forces on droplet interaction aids the coalescence of the cloud droplets, resulting in enhanced raindrop growth rate and ultimately increasing rainfall downwind from the Atlant ion emitter. However while previous studies provide this at least semi-plausible “chain of events” mechanisms by which ions generated by the Atlant may influence precipitation, they are yet to be verified observationally and at present there is no physical evidence to indicate that Atlant affects the microphysical properties of clouds. While a scientific program to investigate these mechanisms is highly desirable, this may prove to be a long-term and expensive operation, as the required airborne measurement technologies, remote sensing and modelling capabilities are not as yet sufficiently advanced to readily conduct such investigation. In part, the Atlant field trials have been conducted to establish whether such a major scientific undertaking would be warranted.

Previous analysis of the data collected in these field trials used spatio-temporal statistical models to account for the impact of meteorological and topographic conditions not controllable by the randomised experimental design. In addition, a novel application of a random effect block bootstrap was developed for inference (Chambers and Chandra, 2011). We applied these techniques to the 2010 Atlant field trial using methods similar to those used for the 2008 and 2009 Atlant field trials, see Beare et al. (2010; 2011). In addition, we develop a new modelling approach for the 2010 analysis. This approach uses dynamically defined upwind control areas to generate values of an instrumental variable that integrates the effects of meteorology and topography induced variation in rainfall. This allows a much simpler model specification and a clearer delineation between naturally occurring rainfall and additional rainfall induced by operation of Atlant. Results from fitting this so-called "instrumental" model are consistent with those obtained in previous analyses.

2. APPROACH TO EVALUATION OF THE 2010 TRIAL

The fundamental aspect of the methodology used in the evaluation of the 2008 and 2009 trials is the use of a statistical model to estimate the unobserved (or natural) rainfall that would have occurred in the target area had the Atlant system not been operating. The weather modification effect is then the difference between observed rainfall and the estimated natural rainfall. The target area, as in the 2009 trial, was defined to be the region defined by the union of two 60º downwind arcs extending out from the two Atlant sites used in the trial. The statistical model adopted for this purpose was itself rather complex, being a mixture of fixed effects, based on meteorological and orographic covariates, plus random spatial andtemporal affects to account for correlations in the data due to systematic but unmeasured influences that might be inadvertently attributed to the operating status of the system.

Peer review of the 2009 trial identified three issues that needed to be considered in the design and analysis of the 2010 trial. First, the ex-post development of the statistical model made statistical inference less reliable than indicated by the model fit diagnostics. Second, the complexity of the modelling approach, while not seen as undue, made it difficult to follow and interpret the results. Third, the absence of blocking in the randomised design used to determine day-to-day operation of the Atlant mechanisms was a potential source of inefficiency that should be considered in further trials. The last of these issues was the driving force in the design that was adopted for the 2010 trial.

3. DESIGN OF THE 2010 MOUNT LOFTY RANGES TRIAL

A primary aim of the 2010 Mount Lofty Ranges trial was to again test the hypothesis that operation of the Atlant systems in the assessment region lead to increased rainfall in the trial target area. The sites C2 and C3 used in the 2009 Mount Lofty Ranges Trial were again selected for the 2010 trial (Figure 1).

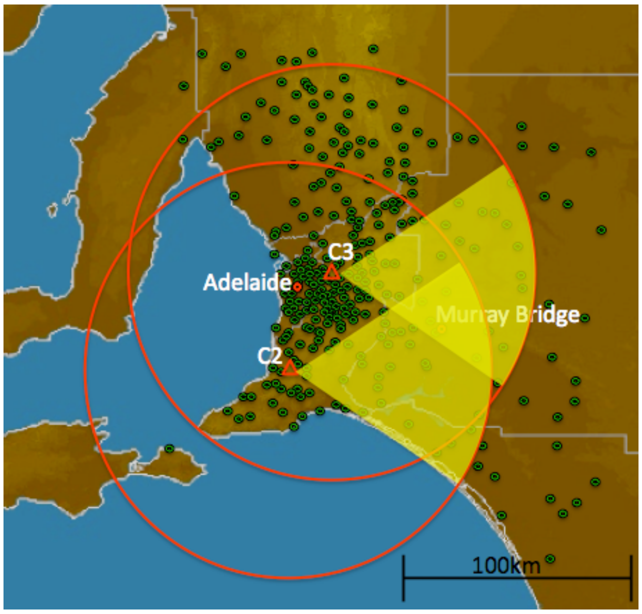

Figure 1. The location of the Atlant sites (∆) at C2 and C3. The rain gauges used in the trial are indicated by green dots. The circles centred on the Atlant sites have a radius of approx 90 km. Downwind target sectors (yellow) are shown for a westerly wind. The orientation of the sectors and degree of overlap is dependent on the direction of the wind.

Note that the C2 site was the only one used in the 2008 Mount Lofty Ranges Trial. The trial ran for 128 days subject to the operating protocol described below, commencing at 9 am 11 July 2010 and finishing at 9 am 14 December 2010, local time. During the trial, the Atlant ion generation sites were switched on and off at 9 am in accor dance with the specified switching regime. This was to coincide with the Bureau of Meteorology (BoM) reporting time for the rain gauges, and to reduce the chance that overlap of rainfall measurements diluted the results. An additional advantage was one of operational convenience, in that 9 am is approximately the start of a working day.

A 30-minute 'temporal buffer' was also added to the switch time, in recognition that there may be a delay, albeit of unknown length, between when the device is switched off or on and any effect on rainfall downwind of the device. Thus, with a nominal switch time at 9 am, the operating Atlant was turned off at 8.30 am and the ongoing Atlant was then turned on at 9 am.

The Atlant systems were operated according to a standard randomised block design. This plan was "blocked" by calendar time and propensity to rain, with rainfall propensity on a day determined by the BoM Poor Man's Ensemble (PME) rainfall model forecast in the assessment region on the day. A random number generator in Matlab was used to randomly allocate the one-day units leading to a random sequence of 64 days when each Atlant (either C2 or C3 depending on the site) is on, and 64 days when it is off. On each day, if the PME model 'chance of rainfall' showed that there was at least a 10 per cent chance of average rainfall greater than 1 mm within the assessment region (34°S-36°S, 138°E-140°E) for the morning of the day in question, then this day was deemed a 'suitable day' and operation commenced. If a day was deemed not suitable, then no operation took place until the next suitable day when the next consecutive randomised day schedule was followed. The PME model combines several Numerical Weather Prediction (NWP) models to produce rainfall forecasts using a technique known as "probability matched ensemble mean". Such a combination has been shown to provide a more accurate forecast than using a single model, and is considered to be BoM's most accurate small area rainfall model (Ebert, 2001). The PME model is updated at approximately 5 am each day. Of the 128 days of the trial, 117 were considered suitable according to this procedure. There were equipment malfunctions on 5 of these suitable days leading to a loss of operating hours. As a consequence, only data from the 112 suitable days when the Atlant mechanisms operated continuously for at least 12 hours each day (57 days when C2 was operated and 55 days when C3 was operated) were used in the trial analysis.

4. COMPARISON WITH 2009 MODELLING APPROACH

The same statistical methodology used in the 2009 trial was used with the 2010 trial data. This was done in order to ensure comparability with the model used to assess the 2009 trial and also to address the issue of ex-post model development that had been raised with respect to the analysis of the data collected for that trial. The model is for rainfall at individual gauges (hereafter termed gauge-level rainfall) in the target area each day, and controls for the influence of meteorological and orographic conditions on observed rainfall. Daily variation in atmospheric moisture is controlled using the proportion of upwind gauges (i.e. those gauges at least 90º away from directly downwind at either Atlant site) that reported rainfall on the day. There were substantial differences in meteorological conditions over the 2009 and 2010 trials. In particular, there was an increase in prevailing winds from the southwest. Average rainfall for the trial area was also much higher in 2010, with two days where average rainfall across the trial area exceeded 20 mm, with over 90 per cent of gauges reporting rainfall. There were a further 10 days when widespread heavy rain was recorded, defined as an average rainfall of 10 mm or more across the trial area, with over 85 per cent of gauges recording rain. Overall, the statistical model was able to explain 68 per cent of the gauge-by-day variation in observed rainfall for the gauges in the target area, which was similar to its performance in the 2009 trial.

A total of 4711 rain measurements were made over the 112 days of the trial when the Atlants were operational, and an average of 4.7 mm of rain was recorded at each downwind gauge that reported rainfall. The model estimated that 4.2 mm of this rain could be attributed to natural causes, leaving 0.5 mm of rainfall attributable to the operation of Atlant. This corresponded to an estimated rainfall enhancement effect of 11.5 per cent, with a bootstrap p-value of 0.04. This is of the same order of magnitude as the effect estimated for the 2009 trial. Figure 2 shows the random effect block bootstrap distribution of the estimated enhancement effect for 2010, based on 10,000 bootstrap replicates. This shows that a one-sided 95 per cent bootstrap confidence interval for the true enhancement effect excludes zero.

As with the model fitted to the data collected in the 2009 trial, there was asymmetry in the contribution of the two Atlant sites to this estimated enhancement effect. In 2009, the estimated effect was strongly associated with the operation of C3 rather than C2. However, in 2010 this asymmetry was reversed, with the estimated effect strongly associated with the operation of C2 rather than C3. No single clear reason could be identified for this switch. However, there is some evidence that it is partly the result of the change in meteorological conditions between 2009 and 2010.

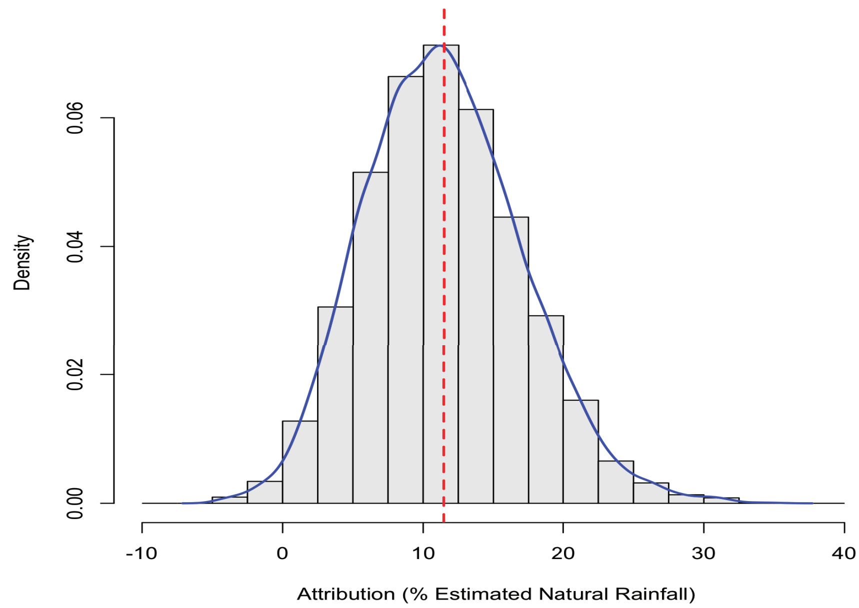

Figure 2. Random effect block bootstrap distribution of the estimated Atlant enhancement effect (Attribution) relative to estimated natural rainfall over the 112 operating days of the 2010 trial period. Vertical dashed line indicates the value of the estimated enhancement effect.

5. A SIMPLIFIED APPROACH TO MODELLING THE 2010 TRIAL DATA

The complexity of the model used to fit gauge-level rainfall in the presence of potential effects due to the operation of Atlant was raised in the peer review of the 2009 trial. In particular there was some concern about the fact that the model simultaneously accounted for both the day-to-day variation in natural rainfall at a gauge, as well as the potential Atlant effect.To address this issue of model complexity, a simpler instrumental variable model was developed for the 2010 trial data.

This model bases prediction of natural rainfall downwind purely on the relationship between upwind rainfall and the meteorological and orographic covariates. This predicted value is then used as a fixed effect in a much simpler second model for downwind rainfall that accounts for the operating status of the system and the spatial and temporal random effects.

5.1 Upwind model development

A key aspect of the instrumental modelling approach is the development of the instrumental variable, i.e. the variable that is used to indicate the expected amount of 'natural' rain at a gauge. This variable was defined by modelling the relationship between observed rainfall and meteorological and orographic covariates for upwind gauges. As noted earlier, these are gauges that are at least 90º away from directly downwind at either Atlant site on the day. Effectively, rainfall data from these gauges over the trial period were used to generate a 'modelled' control value for every downwind rainfall observation. Like the downwind target area, the upwind control area is dynamically defined, since a gauge can be downwind one day (when its rainfall is subject to Atlant influence, and so constitutes a potential target value) and be upwind the next day (when its rainfall is not subject to Atlant influence and hence serves as a control).

In order to develop the upwind model, two changes were made to improve the explanatory power of the meteorological and orographic covariates used in this model. The first involved modifying the wind direction variable used in the 2009 modelling exercise to further reduce its non-monotone behaviour.As measured, the difference between any two wind directions has two values with a singularity at 0 or 360 degrees. An initial attempt to transform wind directions was made for the 2009 trial analysis in order to address the first problem. However, the transformation was not monotone as can be seen in the left hand panels of Figure 3. Note that directions shown here are 'East Zeroed', i.e. due East is set to 0/360 degrees. An iterated logarithmic transformation was used to define the smooth monotone transformations shown in the right hand panel. Wind direction values defined by this modified transformation, denoted LSWD, were then used in the modelling process. A second issue related to the use of an indicator variable for days with heavy widespread rainfall. This indicator was necessary in order to stop rainfall values from such days dominating the modelling process. However, peer review of the 2009 trial analysis suggested that it should be possible to remove much of the need for this ad-hoc model adjustment by including the daily values of the three BOM stability indices into the model. There were three such indices: the Total Totals index (TT); the Lifted Index (LI); and the Precipitable Water index (PW). Values of these indices were available at 12 hourly intervals. An examination of the relationship between the values of these indices and daily gauge level rainfall indicated a strong relationship between Precipitable Water and gauge-level rainfall, but much weaker relationships between the other two indices and gauge level rainfall. In particular, values of Precipitable Water were generally good indicators for widespread rain events in 2010. However, none of these indices were able to identify two extreme rain events: 3 September, when average rainfall across the trial area was 32.9 mm with 287 out of 294 gauges reporting rain; and 7 December, when average rainfall across the trial area was 51.1 mm with 286 out of 294 gauges reporting rain. Consequently these two days were the only days allocated a separate mean effect (Heavy Rain Day) in a model that included three extra effects defined by these indices - the average of the two Precipitable Water readings (Precipitable Water) and the first and second principal components of the remaining four index values, denoted 1st PrinComp (TT&LI) and 2nd PrinComp (TT&LI) respectively.

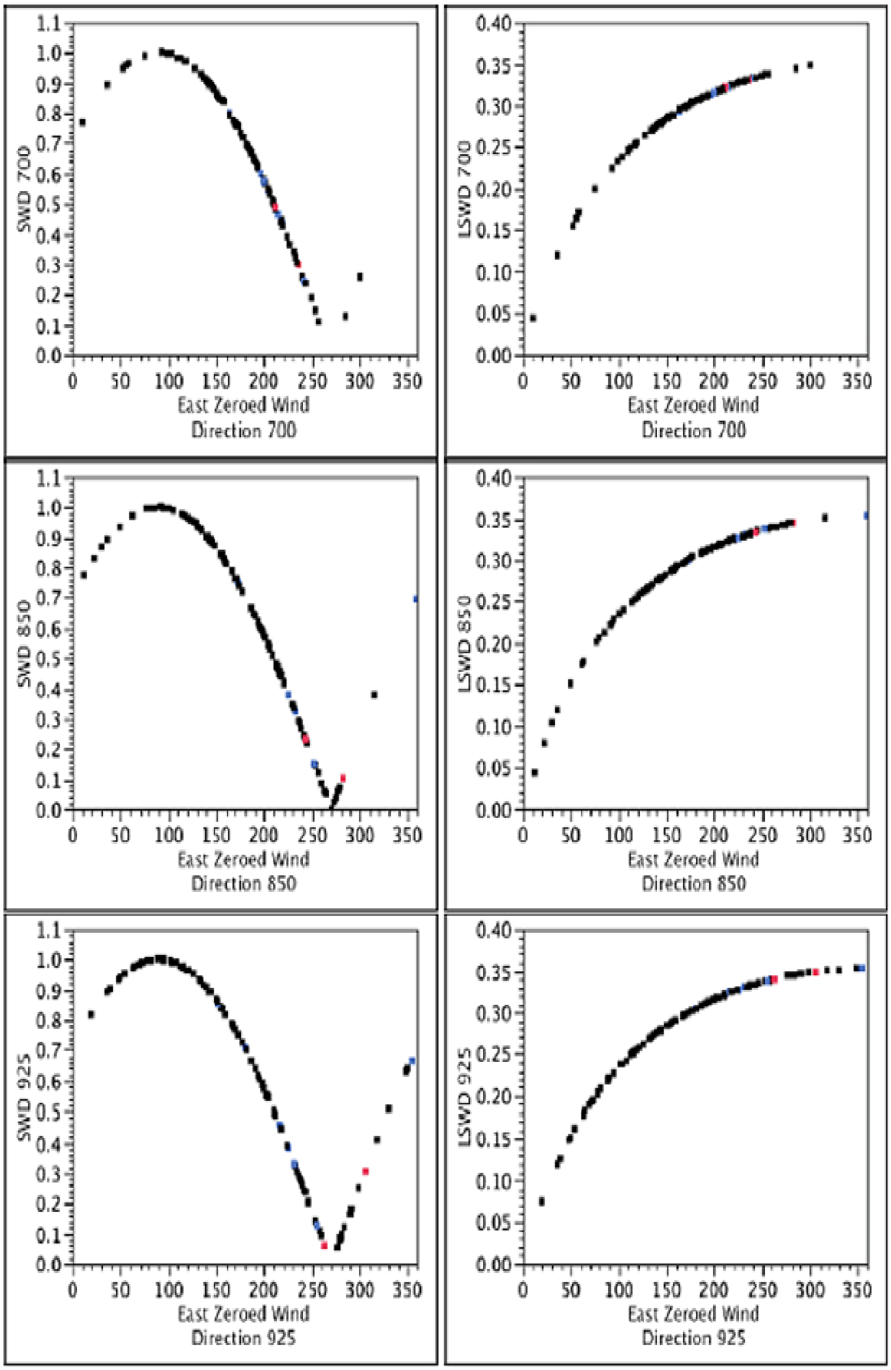

Figure 3. Transformation of wind direction data. Left panel is transformation used in 2009 trial analysis (denoted by SWD). Right panel is new transformation (denoted by LSWD). Rows correspond to different values of hPa.

Table 1 shows the fit of the regression model to the logarithm of upwind gauge level rainfall from 2010, based on the 4388 upwind rainfall readings over the trial period. The variable definitions are the same as in 2009, with the exception of the introduction of revised wind direction effects (denoted by LSWD - see Figure 3); the inclusion of daily range effects for Average Daily Temperature, Dew Point Temperature and Sea Level Pressure; and the use of average daily values of Precipitable Water and the first two principal components of daily values of the Total Totals and Lifted Index indices. The use of Precipitable Water in particular allowed the dropping of the Widespread Rain Day effect used in 2009. However, as we have already noted, there were still two days (3 September and 7 December) in 2010 when the rainfall was extreme. These days are allowed for via the inclusion of the zero-one effect Heavy Rain Day. Note that significant day-to-day and gauge-to-gauge differences in the rainfall data unexplained by the meteorological and orographic variables in the model were allowed for in model fitting by the inclusion of random gauge and day effects. Together, these effects account for approximately 55 per cent of the unexplained variability in the logarithms of the gauge level upwind rainfall data that was recorded.

Table 1. Upwind model parameter estimates for logarithm of rainfall in the 2010 trial. Statistically significant covariates are bolded.

Parameter	Estimate	SE	Significance
Intercept	0.4994	25.3697	0.9843
AugSept	0.1934	0.2768	0.4866
Heavy Rain Day	1.3670	0.7988	0.0910
Precipitable Water	0.1191	0.0290	**<.0001**
1st PrinComp (TT&LI)	-0.0165	0.0883	0.8518
2nd PrinComp (TT&LI)	0.1136	0.1095	0.3025
Wind Speed 700	-0.0212	0.0086	**0.0158**
Wind Speed 700 L1	-0.0036	0.0075	0.6341
Wind Speed 850	0.0156	0.0157	0.3230
Wind Speed 850 L1	0.0061	0.0141	0.6650
Wind Speed 925	0.0105	0.0142	0.4645
Wind Speed 925 L1	0.0041	0.0115	0.7203
LSWD 700	1.3414	3.5852	0.7092
LSWD 700 L1	2.3376	3.0528	0.4459
LSWD 850	2.5695	3.4882	0.4632
LSWD 850 L1	3.4868	2.4322	0.1550
LSWD 925	-4.4023	3.0688	0.1549
LSWD 925 L1	-4.3302	2.9794	0.1495
Average Daily Temp	-0.0478	0.0608	0.4340
Temp Range	0.0027	0.0423	0.9495
Dew Point Difference	-0.0220	0.0580	0.7054
Dew Point Range	0.0339	0.0492	0.4935
Sea Level Pressure	-0.0025	0.0243	0.9184
Pressure Range	0.0612	0.0333	**0.0693**
Elevation (100 m)	0.0618	0.0138	**<.0001**

Ideally, one would like to measure rainfall on the same day at matched control and target gauges, i.e. gauges that differ only in their exposure to the Atlant process. In this context, upwind gauges on any particular day satisfy the requirement that they are not exposed.

Unfortunately, an individual gauge cannot serve as a control for the entire period of the trial as it can be upwind of the Atlant sites on one day and downwind on another. However, given that the level of rainfall recorded when a gauge is upwind is determined independently of anything occurring downwind, it is possible to use the rainfall data measured when the gauge is upwind to construct an instrumental control variable that is independent of a gauge's location relative to the prevailing wind direction. This instrumental control variable is defined by the model fit shown in Table 1, since the predicted value of upwind rainfall generated by this model as a function of meteorological and fixed orographic effects is independent of any downwind influence. The fitted values generated by applying the model parameters in Table 1 to the meteorological and orographic conditions when a gauge is downwind can then used to calculate a prediction of natural rainfall at this gauge at that time. This instrumental prediction is by construction independent of any downwind conditions associated with the gauge's relative location to the Atlant devices and their operating statuses. As an aside, we also note that no attempt has been made to simplify the model in Table 1 using statistical methods of variable selection, since its main use is calculation of unbiased rainfall predictions independent of the operation of the Atlant mechanisms.

5.2 <u>The instrumental variable downwind model</u>

By construction, the instrumental control variable developed in the previous section provides a prediction of rainfall at a downwind location under similar meteorological and orographic conditions and therefore serves to replace the large number of meteorological and orographic covariates used in the 2010 version of the downwind model underpinning the results discussed in section 4. However, there is still the need to include effects in the instrumental variable-based downwind model associated with location of a gauge relative to steering wind direction and the location of the ion generation sites, since these are relevant to assessing the impact of Atlant operation on downwind rainfall. In this context we note that operating effects in the 2009 model specification included a distance interaction but not a crosswind interaction. However, the extent to which a gauge is crosswind as opposed to downwind when the systems are operating seems a relevant consideration, and so these interactions were included in the 2010 downwind model. In particular, the relative downwind locations (both for the day of measurement as well as the previous day) of a gauge were specified in terms of its distances from the two Atlant sites and its angles of orientation relative to the direction of the steering wind at these sites. The spatio-temporal random effects in the 2009 downwind model were also retained.

The fit of the downwind instrumental model for the 2010 gauge level data is shown in Table 2. Note that the instrumental variable Predicted LogRain in Table 2 is calculated as the fitted value generated by the upwind model fit defined by Table 1. Note that the model fit shown in Table 2 only includes the instrument and significant effects defined by operating status and gauge location relative to the Atlant locations C2 and C3. There are significant effects identified with respect to the operating status of the Atlants at C2 and C3 as well as interaction effects at C3 with respect to relative wind direction.The spatio-temporal random effects account for just under 50 percent of the unexplained variability in the model fit.

Based on this fitted model, the overall Atlant enhancement effect for 2010 is estimated at 10.0 percent with a standard error of 6.4 percent. The confidence bounds are shown in Table 3 and the bootstrap distribution of this estimated enhancement effect is shown in Figure 4. The estimated level of enhancement is significant at the 95 percent level.

Table 2. Parameter estimates for the instrumental model for logarithm of downwind rainfall in the 2010 trial. Statistically significant covariates are bolded.

Parameter	Estimate	SE	Significance
Intercept	-0.5132	0.1028	**<.0001**
Predicted LogRain	1.1482	0.0533	**<.0001**
C2 Distance	-0.1797	0.1091	0.0997
C2 Theta	0.0023	0.0004	**<.0001**
C3 Distance	-0.1208	0.1441	0.4017
C3 Theta	0.0002	0.0004	0.6772
C3 Theta L1	-0.0005	0.0003	0.1384
C3 Distance*C3 Theta	0.0053	0.0011	**<.0001**
C3 Distance*C3 Theta L1	0.0015	0.0005	**0.0063**
C2 Target	0.2651	0.1085	**0.0150**
C3 Target	0.5811	0.1448	**<.0001**
C3 Theta* C3 Target	-0.0100	0.0023	**<.0001**
C3 Theta L1* C3 Target	-0.0015	0.0007	**0.0350**

Table 3. The lower confidence bounds for the size of the Atlant enhancement effect (in %) from the instrumental model-based gauge-level analysis of the 2010 trial.

Confidence Level	Estimate
99 percent	**-2.4**
95 percent	**0.7**
90 percent	**2.4**
80 percent	**4.7**
70 percent	**6.4**
60 percent	**8**
50 percent	**9.6**

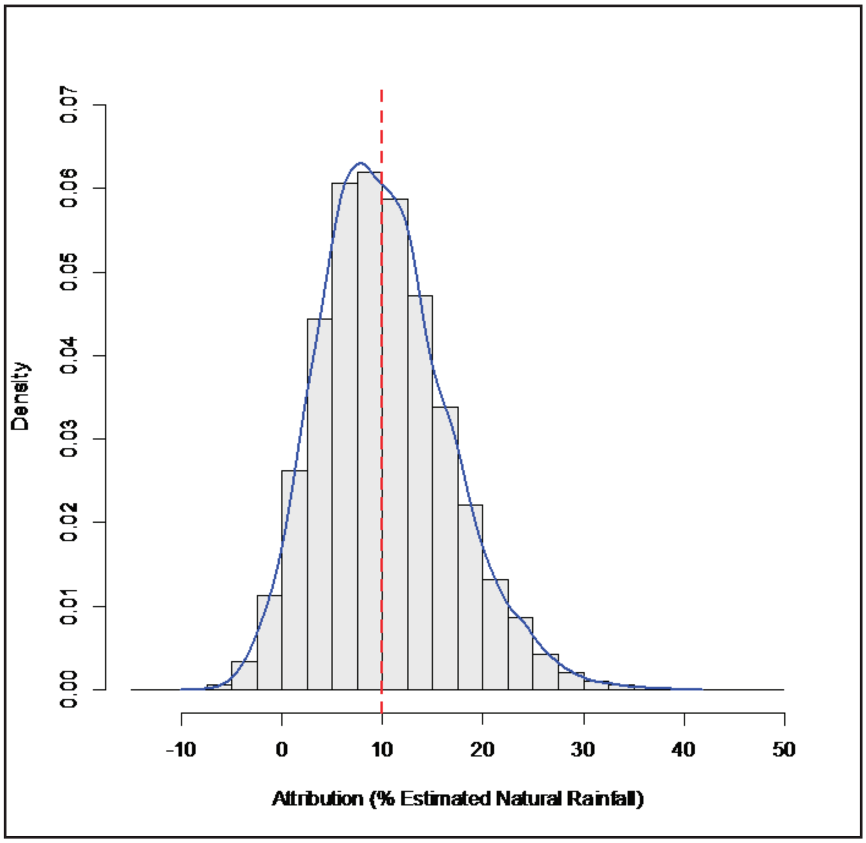

Figure 4. Random effect block bootstrap distribution of the estimated Atlant enhancement effect (Attribution) relative to estimated natural rainfall over the 112 operating days of the 2010 trial. Estimates are based on the instrumental model. The vertical dashed line shows the value of the estimated 2010 enhancement effect under this model

Overall, the instrumental model-based analysis of the 2010 trial led to very similar results in terms of the level of increased rainfall attributed to the operation of the ion generation system. The significance levels of the enhancement estimates are also quite similar. When compared to the approach developed for the 2009 trial, the instrumental model was able to isolate significant effects at both C2 and C3 in 2010, whereas the approach used in the 2009 trial (which only modelling the downwind rainfall data) was only able to identify a significant effect at C3 in 2009 and at C2 in 2010. However, the estimated enhancement levels under both approaches were of the same order of magnitude.

6. CONCLUSION

Australian Rain Technologies (ART) conducted a field trial of the Atlant ionisation technology in the Mount Lofty Ranges trial from July to December 2010, utilising the same installation sites as those used in the 2009 trial. The trial was conducted using a randomised cross-over design and the data collected in it were analysed using the same spatio-temporal statistical methodology that was developed for analysis of the 2009 trial.

Even though meteorological and rainfall conditions in 2010 varied considerably from 2009, and experimental conditions also varied, similar models and estimation methods to those used in the analysis of the 2009 Mount Lofty Ranges trial were used when analysing the 2010 trial. The analysis of the 2010 trial showed enhancement estimates consistent with those obtained in the analysis of the 2009 trial, of the order of 9 percent. It should be noted however that this analysis is purely statistical, and so interpretation of its results with respect to the efficacy of ionization as a means of planned weather modification are indicative. However, the repeated demonstration of a positive enhancement effect of the order of 9 percent, the plausible, though not well understood mechanisms of this effect, and the significant cost and environmental advantages of the technology if proven, warrant further research in this area.

Refinements to the analysis methodology used in 2009 were also investigated. These included redefining the variable used to measure wind direction in order to make it more monotone, inclusion of daily range data for temperature and pressure and the use of BOM stability indices to replace subjective assessment of widespread rain events. The main development however was the introduction of an instrumental model specification for the logarithm of gauge-level rainfall. The instrument itself was developed by modelling daily rainfall data from the trial gauges when they were upwind of the two ion generators. The values of the instrument were then used to replace the meteorological and orographic variables in the 'standard' model, leading to a more transparent model specification that focused solely on variables measuring daily variation in gauge characteristics (e.g. target/control status, distance, orientation etc.) downwind of the generators. Although this refined model did not lead to any significant change in the estimated level of enhancement, it did allow effects associated with the two sites to be compared with less noise due to between site differences in meteorological and orographic effects. Although not shown here, when applied to the 2009 data, the instrumental model indicated that effects at C2 compared with C3 were similar to those observed in 2010.

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