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Atlant 2010

Mount Lofty Ranges Trial

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Executive Summary

Atlant is a ground-based ion generator that is deployed to increase rainfall downwind of the system. The physical process by which it operates has not been established. However, it has been hypothesized that the operation of the Atlant promotes the introduction of charged aerosols into the cloud layer, thereby increasing the coalescence of water droplets and hence promoting the formation of raindrops. Atlant is claimed to be a rain-enhancement technology rather than a rain-making technology. The enhancing effect of electric forces on the collision/coalescence and formation of raindrops has been investigated experimentally since the 1950s. However no substantive progress has been made in either identifying the underlying physical process or in the statistical measurement of the effect of such ionisation on rainfall.

In previous Australian trials, there has been a suggestion of a positive correlation between increased rainfall and the operation of the Atlant system. However, due to the inherent high variability in weather data and the difficulties in conducting statistical analysis on such data, no firm conclusions could be drawn with respect to the effect of Atlant on rainfall. However these trials have led to the development of new statistical techniques for the estimation and evaluation of the effect of the Atlant system on rainfall.

A new statistical modeling approach was designed to overcome the problem of measuring an effect that is small relative to the degree of natural background variability. A steering wind direction was determined on a daily basis and used to identify whether a gauge in the target area was downwind of Atlant and hence likely to be exposed to its effect. Any positive Atlant enhancement was therefore restricted to a dynamic target area oriented according to daily wind direction and described by a 60˚ sector of a circle of radius approximately 90 km centred on the Atlant.

Using this methodology, a trial of the Atlant system was held in the Mount Lofty Ranges from August to early December 2009. A mixed crossover design based on two Atlant sites was employed, with a randomised operating schedule. Steering wind direction was calculated from readings at Adelaide airport. Daily meteorological data on wind speed and direction as well as temperature and pressure, together with the spatial location and elevation of the gauges in this target area on each day of the trial, were then combined with the rainfall values recorded by these gauges to define the data set.

An initial double-ratio analysis of the trial data was equivocal in terms of identifying whether an Atlant effect existed. A subsequent double-ratio analysis of historical rainfall patterns in the trial area (i.e. when Atlant was not operational) displayed high variability, implying very large negative 'effects' in some years and very large positive 'effects' in others. Given the order of magnitude of the expected Atlant signal, it was therefore deemed impossible to measure it against such an erratic baseline. This led to the conclusion that while a double-ratio analysis may be appropriate for an experiment run over a period of many years with a randomised crossover design based on static areas that are identical except for application of the treatment, it does not provide the level of control necessary to detect a relatively small enhancement signal or determine whether there was no signal, against the background variation in natural rainfall. The new statistical modeling approach for detection of any Atlant effect was therefore adopted.

Statistical modeling of the 2009 Atlant trial data showed significant downwind effects associated with operation of Atlant for daily average rainfall as well as for gauge by day rainfall. In particular, the model for daily average rainfall implied an estimated downwind enhancement of 6.4 per cent. A nonparametric bootstrap analysis, using random re-sampling of the data, was used to derive standard errors and confidence intervals for rainfall enhancement estimates based on this model, and indicated that there was 80 per cent confidence that the true enhancement was positive. Under the preferred gauge by day rainfall model, which included spatio-temporal random effects, the estimated enhancement was 7.5 per cent, and a similar nonparametric bootstrap analysis indicated that there was a higher level of confidence (90 per cent) that the true downwind enhancement was positive.

A further trial was run in 2010 using the same trial area in the Mount Lofty Ranges. The trial ran for 156 days from 11 July to 14 December 2010. The same Atlant locations (C2 and C3), dynamic target area definition and Bureau of Meteorology (BOM) data, as well as similar models and estimation methods to those used in the analysis of the 2009 Mount Lofty Ranges trial were employed when analysing the 2010 trial. However there were some key differences in the experimental design of the 2010 trial, which included:

- The two Atlant antennas were operated in a standard randomised blocks design; that is the experimental units were randomly arranged in groups (blocks). In particular, the operating plan was “blocked” by calendar time and propensity to rain, with the time unit being one day, for those days that the BOM's small area rainfall model forecast greater than 10% chance of rainfall greater than 1 mm in the trial area. The resulting operational schedule yielded 112 suitable days.
- Additional data describing the stability and moisture content of the atmosphere were included in the analysis.

The weather patterns in the trial area differed substantially between 2009 and 2010, most notably in terms of the level of rainfall and the composition of prevailing winds. Overall there was a substantial increase in the number of rainfall gauges in the sector downwind of C2 with the change in wind direction, however the number of rainfall gauges downwind of C3 remained constant even with changes in wind direction. There was also a substantial increase in both the amount and the variability of rainfall. In the context of the trial, the greater number of days on which there was precipitation in the trial area would have increased the extent to which ion generators operated under more favourable conditions, given the proposed physical model through which the system operates. At the same time, there was a higher level of background variation in rainfall. Both of the above observations suggest an increase in the difficulty of detecting a relatively small enhancement signal in 2010.

Within the limits of the changes to the experimental design and the consideration of days on which there were heavy and widespread rainfall, the 2010 data was analysed in the same manner as 2009, including analysis of: means; average daily rainfall; and rainfall at individual gauges. Where possible the approach, model covariates and random effects were as specified in the 2009 statistical model. As with the 2009 trial it was not possible to make any firm inferences from a simple comparison of means. Average daily rainfall in the target area was higher at C2 and lower at C3 when compared to the control. However the overlap in the confidence intervals was large regardless of how the target area was defined.

The level of variance in the daily average rainfall data that was explained by the statistical model (model fit) was less in 2010, due to the increased variability of rainfall recorded at individual gauges relative to 2009. Meteorological covariates were included the model without pre or post selection to limit the possibility of model selection bias. Covariates such as wind speed and direction at different elevations as well as dew point temperature difference and barometric pressure were strongly correlated and so individual effects could not be estimated with high degree of precision. This was evident in the lack of significance of some of these effects and the fact the significant effects switched between years. At the same time orographic effects and measures of available moisture were significant and consistent between years. As the identification of metrological effects was secondary issue when compared to the introduction of bias, variable were not eliminated on basis of statistical significance.

As in 2009, a statistically significant effect was detected at only one of the two sites in 2010 on the basis of modelling daily average rainfall data. However, this significant effect was at C2 and not at C3, which was a reversal compared to the 2009 analysis, which indicated a significant effect at C3 and no significant effect at C2.

The effects of meteorological covariates in the model were not stable between the two years. Only the proportion of upwind rainfall, elevation effects, and the degree to which gauges were crosswind of C2 and the distances from C3 were consistent between years.

In the analysis of rainfall from individual gauges (gauge-level analysis) there was a significant effect associated with the status of C2 and not C3. In the 2009 gauge-level analysis similar significant effects were reported for the status of C3 and not C2. The estimated attribution associated with the operation of the two systems was calculated in the same way as in the analysis of the 2009 trial and the same bootstrapping procedure was used to calculate the standard error of the estimated attribution and the lower confidence bounds for positive attribution. The bootstrap mean attribution was 8.6 per cent with a bootstrap standard error of 6.8 per cent. The estimated level of enhancement was significant at the 90 per cent level. The significance of the estimated mean effect was below 90 per cent due to the asymmetry of the bootstrap distribution. Overall, the 2009 and 2010 trial results yielded similar results despite the differences in weather conditions and the experimental design.

Several improvements were considered for the gauge-level modelling approach. The overriding concerns were to: improve the consistency of the covariates; to make better use of the upwind gauge observations; and to simplify the model structure. With respect to the covariates three changes were made:

- An iterated logarithmic transformation was used to obtain smooth monotone transformations of wind directions;
- A crosswind interaction term was added to the model; and
- Daily values of the three BOM stability indices were integrated into the model to replace subjective assessment of widespread rain events.

A major change in the model specification process was also made, addressing the way upwind gauge data were utilised. As gauge location can be considered relative to wind direction at the ion generation sites, any given gauge may serve as:

- A downwind target; and
- An upwind control, where upwind is defined as being in the overlap of the two 180 degree upwind arcs defined at each site.

An individual gauge cannot serve as a control as it can be upwind of a site on one day and downwind on another. However, given that the level of rainfall recorded when a gauge is upwind should be determined independently of anything occurring downwind, it is possible to use upwind gauge data to construct an instrumental control that is independent of a gauge's location relative to the prevailing wind direction.

This instrumental control variable is created by modelling upwind gauge-level rainfall in terms of meteorological and orographic covariates. The resulting rainfall predictions produced by this model as a function of meteorological and fixed orographic effects should then be independent of any downwind influence. Given meteorological and orographic conditions when the same gauge is downwind, the same model can then be used to predict downwind rainfall. This instrumental prediction is by construction independent of any downwind conditions relating to operation of the Atlant ion generators.

The values of the instrument were used to replace the meteorological and orographic variables in the 'standard' model, leading to a more transparent model specification that then focused on variables measuring daily variation in gauge characteristics relative to the location and operational status of the Atlant ion generators. The spatio-temporal random effects in the model were retained.

There were significant effects identified with respect to the operating status of C2 and C3 as well as interaction effects at C3 with respect to relative wind direction. The additional rainfall across all gauges in the trial area during the period attributed to the operation of the Atlant ion generators was 10.0 per cent with a standard error of 6.4 per cent. The estimated level of enhancement was significant at the 95 per cent level.

The instrumental model specification was also applied to the 2009 trial data, adjusted for differences in the experimental design. Again there were significant effects associated with operating status at C2 and C3. The bootstrap mean level attribution was 10.5 per cent with a bootstrap standard error of 5.3 per cent. The estimated level of enhancement was significant at the 95 per cent level.

Overall, the instrumental analysis of the 2009 and 2010 trials led to very similar results in terms of the level of increased rainfall attributed to the operation of the ion generation systems. The significance levels of the attribution estimates were also quite similar.

1 Introduction

Over the past 10 to 15 years, temperate Australia has experienced significantly lower-than average rainfall, with severe financial impacts on agriculture, forestry, rural and urban water supplies, hydroelectricity and mines. All have been and are expected to continue to be adversely affected by extended periods of low water availability. Australian Rain Technologies (ART) has been trialing a technology known as Atlant, which employs ground-based ionization as a catalyst to enhance rainfall. Results from initial field trials in both Queensland and South Australia suggested a positive correlation between increased rainfall and the operation of the Atlant system. However, there are a number of issues relating to the design of the first three trials that impact on the validity and robustness of their findings. In particular, operation of the Atlant system was not randomised in any of these trials.

More recently, multi-system randomised trials ran in 2009 and 2010 in the Mount Lofty Ranges near Adelaide in South Australia. The statistical analysis and results from the 2010 Mount Lofty Ranges trial of the Atlant system are presented in this report. The results are compared with results from the 2009 trial. Additional analysis of the 2009 data was done where it facilitates the comparison of the two trials. Detailed information pertaining to the 2009 trial can be found at (Beare et al. 2010a; 2011). The background and the basic operational aspects of the 2010 trial were unchanged from 2009, however, differences in the 2010 experimental design are set out in this report.

1.1 STRUCTURE OF REPORT

This report first introduces the challenges and approaches of evaluation of weather modification technologies in Chapter 1, followed by a description of the theoretical basis and operation of the Atlant system in Chapter 2. The design and results of the 2009 trial are discussed in Chapter 3. Chapter 4 describes the differences in experimental design in the 2010 trial. A comparison of the trial period meteorological conditions in 2009 and 2010 is presented in Chapter 5. An analysis of the 2010 data using the 2009 modelling methodology is conducted in Chapter 6. This approach controls for meteorological conditions and orographic effects with a view to reducing background noise. The results presented are for modeling daily average rainfall initially, followed by more sophisticated modeling of individual gauge rainfall records. Chapter 7 presents a simplified modelling approach to both the 2009 and 2010 trials, briefly discussing the merits of this different approach. The report concludes with a summary of its main findings in Chapter 8.

1.2 APPROACHES TO EVALUATING WEATHER MODIFICATION TRIALS

A prerequisite of rainfall enhancement detection is an estimate of the amount of rain which would have fallen had the treatment not been applied. In weather modification experiments, an estimate of this value is usually derived from mean rainfall measurements over the course of a trial within an untreated, control area. This estimate is compared with mean rainfall over a target area in an attempt to identify the degree of rainfall enhancement.

A premise of this type of analysis is that a randomised treatment protocol, along with a sufficiently large sample size, will balance out the effects of variation between the target and control. However, very high levels of variability in rainfall make this assumption problematic. This variability is both temporal, across days, months and even years, as well as spatial, with some areas receiving a lot of rain while neighbouring areas concurrently receive little. Temporal variation in rainfall reflects the variation in meteorological conditions over time, while orographic factors such as elevation and proximity to a coastline will interact with meteorological conditions to produce spatially varied precipitation across adjacent areas.

This high level of variability produces a large spread of rainfall measurements, or large variance in the data. As a consequence, the calculated estimates of mean target and control rainfall are associated with large errors and it is therefore necessary to reduce the errors of measurements of mean control and target rainfall in order to obtain a significant result if one exists. This either requires a huge rainfall enhancement effect so that the consequent shift in mean rainfall is the main contributor to the observed variability in rainfall measurements, or a large enough sample size so that the control and target mean values are estimated precisely irrespective of the high variation in the actual rainfall measurements. The reality, however is that any rainfall enhancement signal is likely to be modest and the sample size limited, with the high variability of rainfall then creating a lot of background 'noise' against which it is often not possible to detect a rainfall enhancement signal.

Various experimental design techniques can be employed to counter this variability, and thereby decrease the error in estimated means. By choosing a control area that is as similar as possible to the target area, one can minimise variation due to differences in the spatial distribution of rainfall measurements. This is the basic principle underpinning a typical crossover design, where two areas with similar rainfall patterns are selected and treatment is applied to either one or the other area using a randomised schedule. The untreated area acts as a control for the area being treated, and allows for a traditional double-ratio analysis. This approach goes some way to balancing random spatial variation (NRCNAS 2003).

Increasing the sample size by running trials for long periods, often many years, has been necessary to reduce the margin of error towards levels where analysis can potentially yield significant results. One can identify certain combinations of temporal conditions as providing a different level of rainfall enhancement from other combinations (known as 'blocking'). Then by restricting randomised treatment allocation to blocks consisting of 'similar' temporal conditions, it may be possible to reduce the variance of outcome measures thus reducing variability caused by day-to-day changes in these conditions.

However, despite extensive efforts over the past fifty years to reduce the effect of natural variability in rainfall by employing these design techniques in randomised trials of rainfall enhancement, it seems clear this approach has not produced a reliable methodology for detecting rain enhancement (Cotton and Pielke 2007). Most cloud seeding experiments still do not provide evidence sufficient to reject the null hypothesis of no enhancement, and usually produce data 'not sufficient to reach statistical conclusions' (NRCNAS 2003).

The problem with this 'pure' randomisation-based analysis of rainfall is that it treats all rainfall measurements as being randomly drawn from the same distribution of potential values (in the sense that treatment application for these measurements was at random). However, we know that this is not true. We know that variation in rainfall from gauge to gauge within a day is driven by variation in orographic conditions and dynamic conditions, and that day-to-day variation for a particular gauge is driven by variation in meteorological conditions.

This constantly changing background of spatial and orographic variation typically has a much greater influence on rainfall than any potential enhancement effect. We can measure many of the important factors that potentially contribute to this background variation. However, this knowledge is ignored when we simply average target and control rainfall in the hope these external effects then cancel out. Insofar as they do not, the resulting variability in our estimation of an enhancement effect can (and typically does) far outweigh the actual level of this enhancement. This leads to significant limitations when a randomisation-based approach to evaluation of an enhancement effect is applied to this problem. More efficient means of analysis are required if we hope to gain significant results in realistic time frames.

Statistical techniques have seen tremendous improvements in recent decades. However, within the field of weather modification, methodology is largely based on treatment randomisation and mean rainfall comparisons, and the use of alternative methods of statistical analysis have not, as yet, been widely adopted. Given the complexity of the problem at hand and the importance of any consequent improvements in water management, these significant developments in statistical sciences ought to be explored by weather modification scientists.

A review of statistical analysis in weather modification by the US National Research Council of the National Academies (NRCNAS 2003) makes the following assessment: "To fully consider and evaluate the myriad of variables in weather modification experiments, multivariate statistical process models that exhibit spatial and temporal dependence are much better suited [to this analysis than the single test]".

Statistical methodologies for the analysis of spatiotemporal data were not available in the early days of weather modification. It was not until the 1990s that they could be realistically implemented in the analysis of field trials (NRCNAS 2003). Consequently randomisation has continued to serve to mitigate both spatial and temporal correlation effects in many evaluation studies. "However, just as blocking designs can improve efficiency over randomisation, one can get more efficient estimates by modeling the spatial (and spatiotemporal) effects" (NRCNAS 2003).

The basis for these spatiotemporal methods is that evaluation is carried out in the context of statistical models that explicitly account for the different sources of variation in the rainfall measurements through covariates. Covariates are measurements of variables that influence rainfall (either directly or as proxies for unmeasured influences) that are themselves, not influenced by rainfall. Covariates are intended to control for variation in natural rainfall making is easier to detect an enhancement signal if it exists. In contrast to a pure randomisation analysis this type of analysis estimates the conditional contribution to rainfall of meteorological, orographic and enhancement covariates. The estimated enhancement effect is then calculated from these estimates. While potentially a much more powerful statistical technique than pure randomization, it is sensitive to choice of the statistical model. A poorly specified model can lead to false inference.

Meteorological covariates that have some correlation with rainfall over both time and/or space include, but not limited to, wind direction and speed as well as barometric pressure, air temperature and moisture content in the air. Important orographic covariates include the spatial location of a rain gauge relative to the source of the treatment and the elevation of the gauge. Gauge-specific orographic effects that are uncorrelated between gauges can be removed via the introduction of a random effect for each gauge in the model.

These models can be estimated using maximum likelihood methods and the available daily rainfall data from each gauge (gauge-level data) within the target and control areas, rather than just the average rainfall measurements over all target and control gauges for a particular day. Overall, our experience is that gauge-level models that include the meteorological and orographic covariates described in the previous paragraph can account for around half the observed variation in gauge level daily rainfall (Beare et al. 2010). Consequently, if data for a large number of gauges are available (as is usually the case), then this approach has the potential to increase the power to detect an enhancement effect over a shorter time frame.

It should be noted, however, that this extra power is dependent on our ability to adequately control for the between-gauge variability in rainfall on a day using appropriate spatial covariates in the analysis model. This information, which is averaged over when performing classical randomised, means-based, analyses, is effectively utilised in a model-based approach to derive a more accurate prediction of the natural rain in the target area, i.e. the rain that would have fallen in the absence of treatment. As a consequence, this yields a method to determine if there exists an Atlant effect and a means to estimate the level of any effect. This is done by the taking the difference between the actual rainfall in the target gauges and the modeled estimate of the corresponding natural rain.

Accurate assessment of the precision of the estimated enhancement effect must also be considered. Given the complex nature of the statistical models for rainfall that underpins this estimate, standard approximation-based approaches to determining this precision, typically based on the use of t-statistics, become problematic as they often involve assumptions about rainfall measurements from different gauges being uncorrelated. In this context adoption of a bootstrap approach to determining the distribution of the enhancement estimate, allowing direct calculation of confidence intervals for its expected value, is recommended. Bootstrapping involves creating an appropriate sampling design and then repeatedly re-sampling the trial data in a way that allows for the underlying correlation structure in the model errors, recognizing that to not do so would typically overstate the precision of the estimate. The choice of sampling design is important and should reflect the likely sources of correlation such as spatial or temporal proximity. This is the approach taken for the model-based analysis described in this report. In particular, we assess precision of the estimated enhancement via nonparametric bootstrap simulation based on model errors derived from the same models that are employed to obtain this estimate.

2 Background

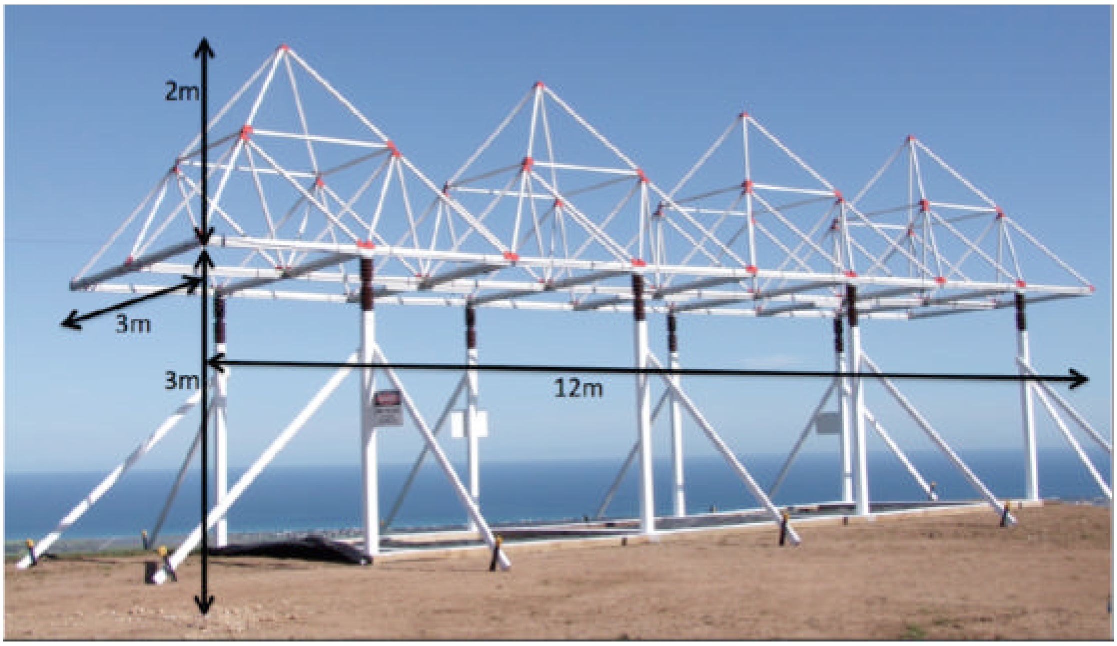
The hypothesis that the presence of electric forces enhances collision-coalescence and formation of larger raindrops has been investigated experimentally (Sartor, 1954; Goyer et al. 1960, Abbott, 1975; Dayan and Gallily, 1975; Smith, 1972; Ochs and Czys, 1987; Czys and Ochs, 1988) and theoretically (Sartor, 1960; Lindblad and Semonin, 1963; Plumlee and Semonin, 1965; Paluch, 1970; Schlamp et al. 1976). The current literature in the field of cloud and aerosol microphysics suggests that ions can influence the formation of clouds and raindrops at multiple stages throughout the process (e.g. Harrison and Carslaw, 2003 for an overview; Harrison 2000, Carslaw et al. 2002, Khain et al. 2004). In particular, there is evidence consistent with ions enhancing the coalescence efficiency of charged cloud droplets compared to the neutral case. Though electrical effects on cloud microphysics are not fully understood (see Chapter 10 of McGorman and Rust, 1998 and Chapter 18 of Pruppacher and Klett, 1997 for an overview), enhancement of the coalescence process may play an important role in explaining any effect on raindrop formation and consequent rainfall enhancement attributable to the Atlant technology, described below.

Research attempting to link the micro-level effects of ions on the formation of raindrops and the macro-level application of ion generation to enhance rain in the atmosphere has been limited. Bernhard Vonnegut speculated that electrical charges in clouds could aid in the initiation of rainfall (Moore and Vonnegut, 1960). Vonnegut carried out numerous experiments into the electrification of clouds, including the widespread releases of ions into the air to test the effect of priming clouds with negative space charges (Vonnegut and Moore, 1959). In subsequent work, Vonnegut et al. (1961, 1962a, 1962b) showed that the electrical conditions in clouds could be modified with the release of ions of either polarity. These ions are released 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. These discoveries confirmed that anomalous polarity clouds developed over sources of negative charge, and suggested the operation of an influencing electrification mechanism. It has also been reported (Moore et al., 1962; Vonnegut and Moore, 1959; Vonnegut et al., 1961) that the space charge released from an electrified fine wire produces large perturbations in the fair-weather potential gradient for distances of 10km, or more, downwind. Kaufman and Ruiz-Columbié (2005, 2009) conducted field experiments using a DC-corona antennae for the purpose of precipitation enhancement and also as a means of aerosol deposition. Mostly recently, Beare et al., (2010) conducted field trials of a ground-based ionization technology called Atlant in Australia.

2.1 DESCRIPTION OF ATLANT

Although previous investigations of ion-based rainfall enhancement were not conclusive, they do provide the basis of a possible hypothesis for how the Atlant system functions to affect rainfall. This hypothesis was used to design key elements of the statistical analysis. Each Atlant ion-emitting device consists of a high-voltage generator connected to a large network of thin metal wires supported on a frame with a series of pyramids on top. The approximate dimensions of the device are 12 m x 3 m x 5 m (***Figure 1***). It consumes about 500 W of power and generates voltages of 70 kV.

Figure 1 The Atlant at C2 Site (Willunga, SA)



2.2 A PHYSICAL MODEL FOR ATLANT

The experiments detailed above have shown the coalescence efficiency between colliding drops of opposite charge is enhanced by the presence of the charge, as is that between charged drops and uncharged drops, and is significantly higher than the pure gravity and hydrodynamic-induced values. At collision, the thin film of air between the drops and the surface tension of the drop surfaces prevent coalescence. At small separation distances, the size of the electrostatic forces between the drops increases markedly. In the case of drops of opposite charge, or a charged drop and neutral drop, the electrostatic forces can overcome the viscous forces provided by surface tension and thin film of separating air, so that a higher portion of collisions result in coalescence rather than bounce (Ochs and Czys, 1988).

Counter-intuitively this may also occur for drops of the same polarity. As two drops with same polarity of net charge get very close together, the drop with the larger charge can induce the opposite charge on the near surface of the other (Sartor and Abbot, 1972). However this requires very large charges on one of the drops, and must overcome the initial repulsive electrostatic force.

There is no physical evidence to indicate that Atlant delivers charged droplets into the cloud layer. The direct physical measurements required to establish such causal mechanisms represents a major scientific undertaking. In part, the Atlant field trials have been conducted to establish whether this would be warranted. As a consequence, questions remain to be answered about the underlying physical processes. However a working hypothesis is outlined below.

1. Initially, negative ions are generated from a high-voltage corona discharge wire array;
2. The ions become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN);
3. The ions are conveyed to the higher atmosphere by wind;
4. The electric charges on these particles are transferred to cloud droplets; and
5. The electrostatic forces on droplet interaction aid the coalescence of the cloud droplets, resulting in enhanced raindrop growth rate and ultimately increasing rainfall downwind from the Atlant ion emitter.

Two key points relevant to using this model in a field evaluation of the Atlant system are therefore that the area of influence is:

- Unique to orographic conditions at the site; and
- Dynamically defined, depending primarily on wind speed and direction.

3 The 2009 Mount Lofty Ranges trial

3.1 EXPERIMENTAL DESIGN

A primary aim of the 2009 Mount Lofty Ranges trial was to test the hypothesis that operation of the Atlant system in the assessment region led to increased rainfall in the expected area of influence of Atlant.

In order to test this hypothesis, it was decided to use a modified form of a crossover design, which would then also allow evaluation by the traditional double-ratio analysis method. In a crossover experiment, two distinct areas are chosen such that they are sufficiently near each other for there to be a good correlation between natural rainfall in each area, but sufficiently far apart that there is little chance of the treatment in a target area influencing rainfall in a control area. When a randomised operating schedule is used with a crossover design it allows for a double-ratio analysis of the data.

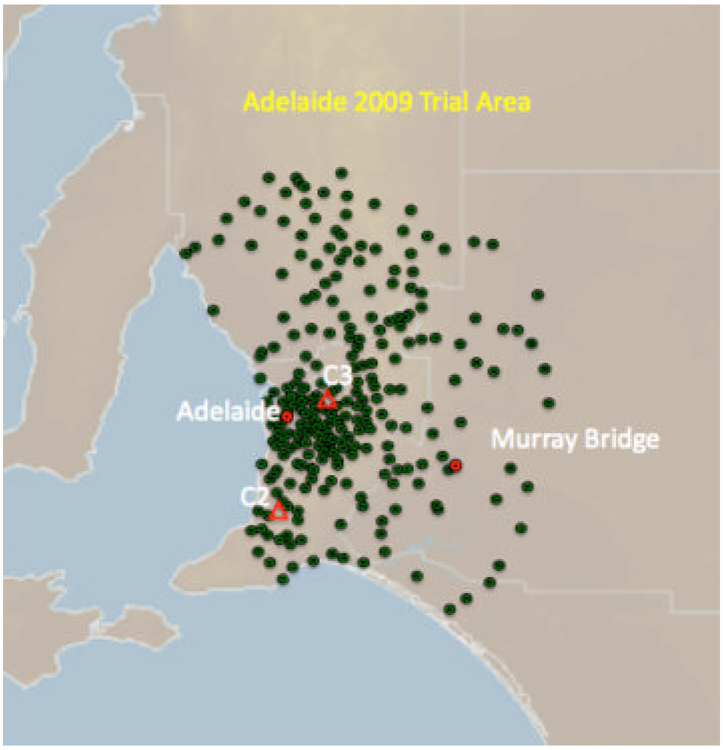
3.2 THE ATLANT LOCATIONS AND TRIAL AREA

The Atlant site used in the 2008 Mount Lofty Ranges Trial at Willunga (C2) was again selected for the 2009 trial. In addition to this site, a second Atlant was introduced at Tea Tree Gully (C3) around 58 km north east of C2 (***Figure 2***). The C2 Atlant site (35°18’ 41.34’S, 138° 31’ 22.02’E) is located 44 km south-southwest of the Adelaide CBD and approximately seven km from the coast on the Gulf of St Vincent. The C3 Atlant site (34°49’ 28.10’S, 138° 44’ 48.70’E) is located 18 km northeast of the Adelaide CBD and approximately 25 km from the coast on the Gulf of St Vincent.

Variations in rainfall were assessed through an analysis of rainfall data from the Bureau of Meteorology rain gauges shown in ***Figure 2***. Although the true extent of Atlant influence is unknown, if any, this trial area was selected on the basis of being likely to capture the bulk of gauges whose measured rainfall might be influenced by the operation of the Atlant. A gauge was included in the analysis if it was within one degree of 'Euclidean distance' from one of the two Atlant ion generators. 'Euclidean distance' is the square root of the sum of the squared difference between the latitude of the gauge and the latitude of the site and the squared difference between the longitude of the gauge and the longitude of the site. This distance approximates 90 km.

The extensive rain gauge and weather station network provided by the Bureau of Meteorology (BOM) includes 282 rain gauges within this trial area. Of these, 262 gauges recorded rainfall data over the period of the trial. Only 85 of these gauges provided data for every day of the trial. The C2 and C3 sites are sufficiently near each other for there to be a reasonably strong correlation between the natural rainfall in each area. Note that both target areas are dynamic, in the sense that the gauges that they cover vary from day to day depending on the direction of the steering wind, which was taken to be the speed-weighted average of the wind directions at 850 hPa and 925 hPa at Adelaide Airport.

Figure 2 The location of the Atlant sites (∆) at C2 (Willunga) and C3 (Tea Tree Gully). The rain gauges used in the trial are indicated by green circles. The circles which delineate the trial area are centred on the Atlant sites and have a radius of approx 90 km. All gauges within these circles were used in the analysis with the exception of those producing data of insufficient quality.



3.3 METEOROLOGICAL AND OROGRAPHIC FEATURES OF THE ATLANT LOCATIONS

The Atlant sites in the 2009 trial are both in the Mount Lofty Ranges, which are orientated northeast to southwest. Both sites are along the first significant ridgeline closest to the coast, and are exposed to the prevailing weather—from the south west to the north west.

South Australia is classified as having a Mediterranean climate and is influenced by offshore trade winds in the summer and on-shore westerlies in the winter. As a consequence, the trial location experiences a dry and warmer period from November to April with prevailing winds from the southeast to east and a moderately wet and colder period from May to October with prevailing winds from the northwest to southwest (BOM, 2008). The climate of the Mount Lofty Ranges is significantly affected by an elevation ranging from 350 m to 700 m and winds sweeping across the Gulf of St Vincent.

The C2 and C3 sites are located at an elevation of 348 m and 373 m above sea level respectively, and have significant upslope valleys located to the west and northwest. At C2, the landform elevation rises from the coast travelling from west to east for 4300 m at a 1.1 per cent rise (i.e. 1.1 m vertical for every 100 m horizontal), then continuing east for 2100 m the rise increases to 12.3 per cent with the last 200 m corresponding to a very steep 21.7 per cent rise. Similarly, C3 has an elevation rise from the coast travelling from west to east for 23,000 m at 3.3 per cent followed by a steeper rise of 11.2 per cent over the final 2,000 m (see ***Figure 3*** and ***Figure 4***).

Typically, a moist marine onshore airflow from the west rises as it approaches these sites—i.e. there is orographic lifting. The resultant turbulence and vertical movement of air would be expected to result in upward dispersal of the any charged aerosols generated by Atlant, however the exact rate and dispersion of such particles has not been measured. It is clear from ***Figure 2*** that locating an external control area that matches the trial area is difficult. The meteorological and topographic characteristics of neighbouring areas were quite different from the trial area. The land area to the north and east of the trial area is relatively flat and dry when compared to the trial area, and the influence of offshore fronts on precipitation in these areas is not nearly as strong.

Figure 3 Southern Mount Lofty Ranges elevation rise from west to east

Figure 4 Northern Mount Lofty Ranges elevation rise from west to east

3.4 OPERATING SCHEDULE

The trial ran for 128 days subject to the operating protocol described below, commencing at 9am 1 August 2009 and finishing at 9am 7 December 2009. All times were measured in local time. During the trial the Atlant ion generation sites were switched on and off at 9am in accordance with the specified switching regime. This was to coincide with the BOM reporting time for the rain gauges, and to reduce the chance that overlap of rainfall measurements diluted the results. An additional advantage is one of operational convenience, in that 9am is approximately the start of a working day. A 30-minute 'temporal buffer' was also added to the switch time, in recognition that the 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. Based on long-term average wind speeds, 30 minutes is the approximate time it would take an aerosol plume (that Atlant ions are proposed to affect) to clear the majority of trial area. Thus, with a nominal switch time at 9am, the operating Atlant was turned off at 8.30am and the ongoing Atlant was then turned on at 9am.

The two sites were operated according to a randomised, asynchronous, alternating daily schedule. C2 was operated on a randomised on-off sequence. C3 was operated on a randomised on/on-off/off sequence. Rather than randomly generating the schedules for C2 and C3 and then combining them, a schedule was constructed from the eight two-day groups and then this schedule was randomly sequenced. An advantage of this approach was that it ensured that each of the four C2-C3 operating combinations (on-on, on-off, off-on, off-off) was scheduled for an equal number of days. The two-day sequence was repeated eight times so that each combination had an equal probability of 1/8 of occurring. The 64 two-day groups were then randomly sequenced to give the operating schedule commencing 1 August 2009 and completing 6 December 2009. Note that use of the above design was motivated by the need to compromise between maximising the cross-over frequency, which would have had C2 and C3 both operating on an asynchronous on-off basis, and the desire to allow testing for carryover Atlant operating effects from previous days, which required at least one site to operate continuously for two or more days. These carry-over effects had been noted in analysis of previous Atlant trials and while there was no physical reason to hypothesis that such effects should occur, it was still important to test whether it represented something more than an artifact of the way the Atlant had been operated in those trials.

The groups were randomly sequenced using the *rand* function in the statistical package Matlab, which generates pseudo-random values drawn from a uniform distribution on the unit interval. The function uses the Mersenne-Twister algorithm (Nishimura and Matsumoto, 1998). The full random sequence yielded 32 days when both sites were on, 32 days when both sites were off, 32 days when C2 was on and C3 off; and 32 days when C2 was off and C3 on.

In some instances an Atlant system was scheduled to operate but did not operate due to technical faults. Similarly, for two days the systems were shut down despite being scheduled to operate due to fire dangers, in accordance with risk management plan. The Atlant operating data used in the preliminary analysis of the 2009 Mount Lofty Ranges trial reflected the actual duration of Atlant operation on a day. However, because there are a number of cases where either C2 or C3 ran or did not run for a very short time during the day, a site was treated as operational on a day if it ran for 12 or more hours that day. Otherwise it was treated as non-operational.

3.5 ADDITIONAL METEOROLOGICAL DATA

In addition to BOM rainfall data, other data were collected for use in the analysis. These data sets included daily meteorological observations from Adelaide airport and the location and elevation of BOM rainfall gauges.

Observations from Adelaide airport were computed as daily averages and included:

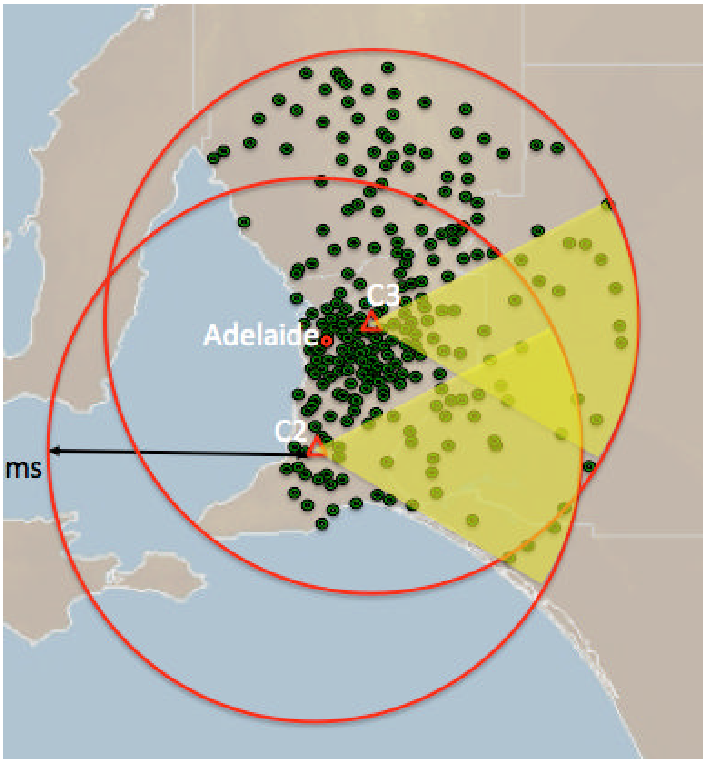
- Wind speed (km/h) and wind direction (degrees from due north, clockwise). Each day the BOM generated wind and temperature vertical profile data at six-hourly intervals commencing around 3am local time. The readings at pressure levels 925 hPa, 850 hPa, and 700 hPa (approximately 660 m, 1500 m and 3300 m respectively) were vector averaged (speed weighted) across each day.
- Air temperature; dew point temperature; and mean sea level pressure, were all measured at the surface. These readings were provided by the BOM at 30-minute intervals commencing midnight local time.

Steering winds are associated with the general direction and speed of cloud movement and vary with the height of the cloud layer(s). Steering wind direction and speed for the trial were approximated by a vector average of the 850 and 925 hPa values of wind direction and speed.

3.6 TARGET AREA DEFINITION

The determination of whether a gauge is exposed to the ion plume generated by the Atlant technology cannot be ascertained with any degree of precision because our current understanding of the physics underlying the spread of the ion plume is incomplete. However, the plume will be directed by surface and upper level winds. The direction of these winds will change through the course of a day, but the typical range of wind directions over a 24-hour period is not great, with the analysis carried out at C2 indicating an average range of between 60˚ and 80˚. It was therefore presumed that the path of a plume could spread across a similar sector originating at the Atlant device. This angle was set before the trial commenced to reduce potential bias in the analysis. The orientation of this 60˚ sector is dynamically defined on a daily basis, being centred on the radial vector describing the downwind direction from the Atlant. Rather than including all gauges across a target area, this dynamic daily partitioning of the target area in relation to steering wind direction serves to focus the signal generated by the Atlant system, if it is effective. The target areas for a westerly wind are shown in ***Figure 5***. The determination of primary steering wind flows was obtained using radiosonde data (vertical wind profile), produced by the BOM. Radiosonde data was recorded at Adelaide Airport at six-hourly intervals to provide four readings per day. To obtain a steering wind direction, the vectors of wind speed and direction were averaged between the surface and upper winds (925 hPa and 850 hPa respectively) at each of the four time points throughout the day, and the vector average of these four averages was taken to obtain the daily wind direction. Vector averages were taken rather than geometric averages as the speed of the wind will impact on the overall transport of the plume.

Figure 5 Downwind sectors (yellow) in a westerly wind, showing gauges and C2 and C3 Atlant location. The degree of overlap is dependent on the direction of the wind. The red circles indicate 90 km distance from each site respectively.



3.7 SUMMARY OF TRIAL DESIGN AND DATA

Aspect	Description
Period of trial	1 August 2009 to 6 December 2009
Operating schedule	Atlant was operated on a randomised daily schedule for all days of the trial, starting and ending at 9:00am
BOM Data	Meteorological data consisted of daily averages of four wind speed and direction readings at a single point, Adelaide Airport, taken at approximately equally spaced intervals, together with daily average air temperature, dew point temperature and air pressure, all at Adelaide Airport Gauge-specific data included the location (latitude and longitude) and the elevation of each gauge The unit of observation was daily gauge level rainfall starting and ending at 9:00am
Target/control areas	Two overlapping sectors defined by 60˚ sectors extending 90 km downwind of each Atlant, where downwind was determined by the steering wind direction on a day. This was calculated as a speed-weighted average of measured wind directions at 850 hPa and at 925 hPa at Adelaide Airport

3.8 RESULTS FOR THE 2009 MOUNT LOFTY RANGES TRIAL

An initial double-ratio analysis of the trial data was equivocal in terms of identifying whether an Atlant effect existed, indicating a large positive effect when the double-ratio statistic was based on total rainfall in downwind gauges and a negative effect when it was based on summing daily average rainfalls for these gauges. A subsequent double-ratio analysis of historical rainfall patterns in the two trial areas (i.e. when Atlant was not operational) displayed high variability, implying very large negative 'effects' in some years and very large positive 'effects' in others. Given the order of magnitude of the expected Atlant signal, it was therefore deemed impossible to measure it against such an erratic baseline. This led to the conclusion that while a double-ratio analysis may be appropriate for an experiment run over a period of many years with a randomised crossover design based on static areas that are identical except for application of the treatment, it does not provide the level of control necessary to detect a relatively small enhancement signal or determine whether there was no signal, against the background variation in natural rainfall. A statistical modeling approach to detection of an Atlant effect was therefore adopted.

Exploratory analysis of the trial data revealed a predominance of heavier rainfall events in association with winds from a north-westerly direction. This had the effect of greatly reducing the number of downwind rain gauges relative to the south-western Atlant location (C2) on days of heavier rainfall. It also showed that these gauges tended to vary much more in their distance from C2. In contrast, the number of downwind rain gauges relative to the north-eastern Atlant location, C3, was much more balanced across days of heavier rainfall, and also tended to vary much less in terms of their distance from this site. These considerations indicated adoption of statistical models that differentiated between the effects due to operation of the two sites, and also included interactions determined by the distance of a gauge from a site.

Initial statistical regression modeling was carried out using daily average rainfall data and a limited range of meteorological and orographic covariates, reflecting the fact that there were limited daily data on average rainfall downwind of each site. The modeling approach allowed for:

- The time varying selection of target and control gauges;
- The treatment of zero rainfall days;
- The weighting of the daily average data according to the number of contributing gauges.

The analysis revealed that operation of the Atlant system does not appear to influence the probability of rainfall occurring downwind of the Atlant site. However, it found that for days when rainfall did occur there was a significant enhancement effect downwind of the C3 site, but no significant enhancement downwind of the C2 site. Taking an average across all downwind gauges, this model indicated an overall enhancement of 6.4 per cent . A bootstrap simulation analysis of this model showed a 80 per cent confidence that the true enhancement was greater than zero.

The use of individual gauge-day rainfall records as the unit of modeling allows more sophisticated models for identifying Atlant effects. In particular, the large sample size implicit in this type of modeling permits the use of a much wider variety of meteorological and orographic controls as well as a more detailed decomposition of the Atlant effects into lagged and contemporaneous components and the introduction of interactions with individual gauge distances from the Atlant sites. However, it also requires consideration of potential correlation between rainfall readings from the same gauge on different days and from different gauges that are exposed to a similar extent on the same day. As a consequence, a random effects model was fitted to the gauge level data. Random effects were allocated to groups of gauges that were judged to be similarly exposed to meteorological conditions.

Overall, the 'spatio-temporal' random effects structure produced the better model fit to the gauge-day rainfall data, with the model again indicating a difference in the Atlant effect at C2 and C3, with significant, but oppositely signed, lagged effects at both sites and with significant distance interactions. Lagged effects are covariates measured at previous time periods. For the analysis, lagged covariates correspond to measurements on the day previous to Atlant operation. The corresponding overall enhancement under a spatio-temporal random effects model was 7.5 per cent with a confidence level of over 90 per cent.

Use of the gauge-day data also allowed direct modeling of the probability of a gauge recording rain on a day. This showed that operation of Atlant was associated with a statistically significant but small (2.4 per cent) reduction in this probability. However, many rainfall 'events' correspond to very small amounts of rain being recorded by a gauge (< 1 mm). When the model was refitted to rainfall events defined by at least 1 mm of rain being recorded by a gauge, the reduction referred to above virtually disappears. This provides some indication that operation of Atlant may serve to depress very light to negligible rainfall, but has little effect on whether more substantial rainfall events occur.

4 Changes in the experimental design in the 2010 Trial

4.1 EXPERIMENTAL DESIGN

Similar to the 2009 trial, the primary aim of the 2010 Mount Lofty Ranges trial was to test the hypothesis that operation of the Atlant system in the assessment region leads to increased rainfall in the expected area of influence of Atlant. That is, there is a null hypothesis that corresponds to no effect on rainfall, with this being rejected in favour of evidence of rainfall enhancement if parameters (defining conditions) associated with operation of Atlant are significant in the statistical model for rainfall defined under this hypothesis, and this model also implies a statistically significant relative increase in observed rainfall that can be attributed to operation of Atlant. In taking this approach, it is recognised that the level of significance used to test the hypothesis depends on the risk associated with falsely rejecting the null or alternative hypotheses.

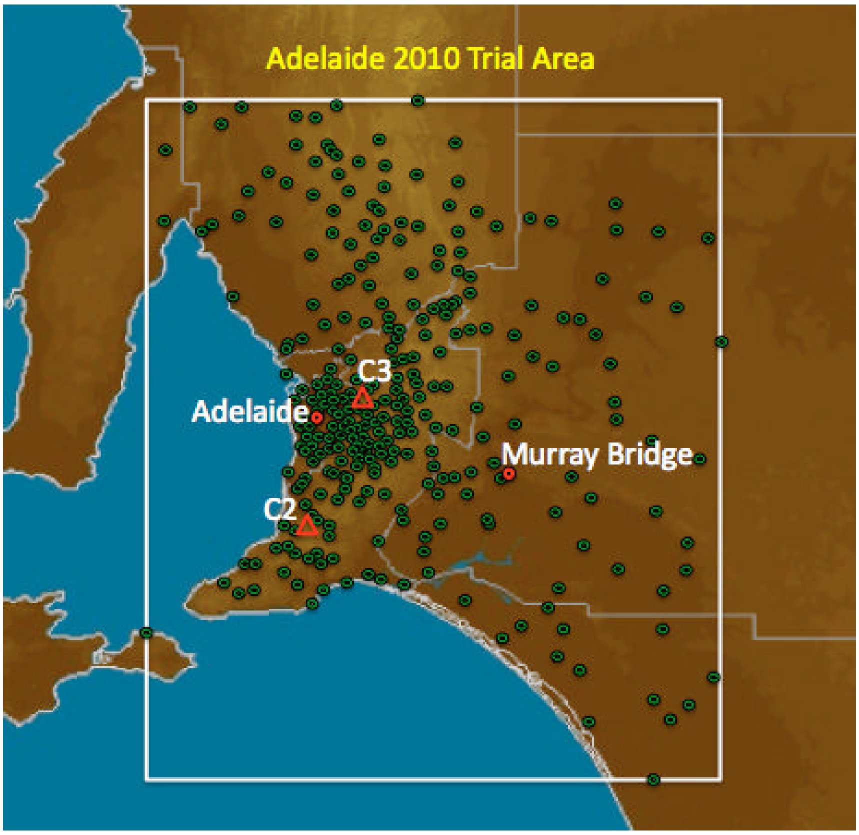
There were some differences in the experimental design of the 2010 trial. The aspects that differ from the 2009 trial are explained in detail in the following section. For further detailed explanation of the 2009 trial design the reader is direction to Beare et al. (2010a; 2011).

4.2 ATLANT LOCATIONS AND TRIAL AREA

The Atlant sites were the same used in the 2009 Mount Lofty Ranges trial - at Willunga (C2) and at Tea Tree Gully (C3) around 58 km north east of C2 (***Figure 6***). The C2 site (35°18’ 41.34’S, 138° 31’ 22.02’E) is located 44 km south-southwest of the Adelaide CBD and approximately seven km from the coast on the Gulf of St Vincent. The C3 site (34°49’ 28.10’S, 138° 44’ 48.70’E) is located 18 km northeast of the Adelaide CBD and approximately 25 km from the coast on the Gulf of St Vincent. Variations in rainfall were assessed through an analysis of rainfall data from the Bureau of Meteorology rain gauges shown in ***Figure 6***. Following the analysis used in the 2009 Atlant trial, the area of influence of Atlant was confined to two 60-degree sectors extending downwind from C2 and C3.

The extensive rain gauge and weather station network provided by the Bureau of Meteorology (BOM) included 294 rain gauges within this trial area in 2010.

Figure 6 The location of the Atlant sites (Δ) at C2 (Willunga) and C3 (Tea Tree Gully). Green circles indicate the rain gauges used in the trial.



4.3 OPERATING SCHEDULE

The trial ran for 156 days subject to the operating protocol described below, commencing at 9am 11 July 2010 and finishing at 9am 14 December 2010. All times were measured in local time. During the trial the operating Atlant was turned off at 8.30am and the ongoing Atlant was then turned on at 9am in accordance with the specified switching regime.

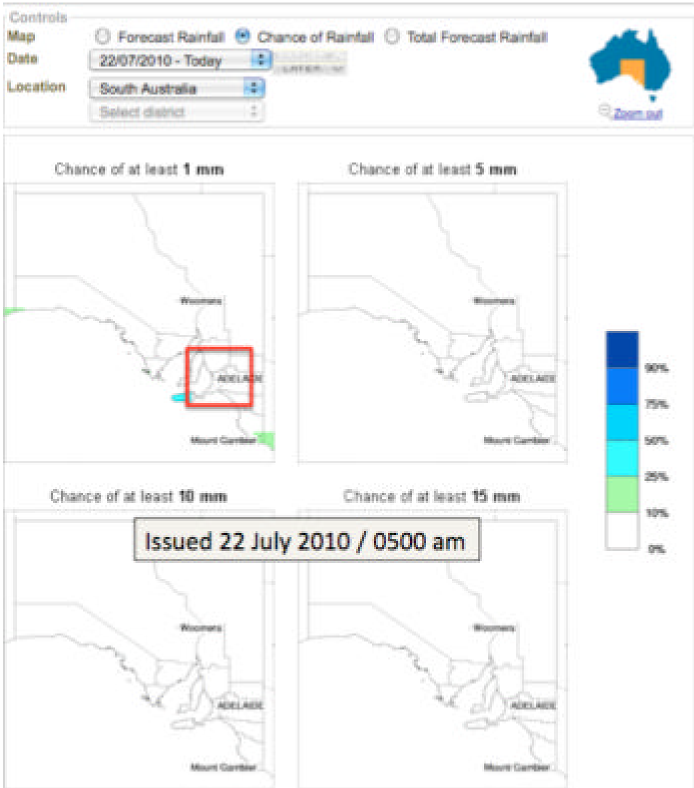
The two Atlants were operated in a standard randomised blocks design; that is the experimental units were randomly arranged in groups (blocks) corresponding to calendar time and propensity to rain, with units defined by those days when BOM's small area rainfall model forecast greater than 10% chance of rainfall greater than 1 mm in the trial area (explained further below). The reason such a low probability was chosen, was to ensure the maximum amount of days where rainfall was possible was included in the trial, while removing days when Atlant would have a low probability of having any affect, based on the proposed physical model.

A random number generator in the Statistical package Matlab, which generates pseudo-random values drawn from a uniform distribution on the unit interval, was used to randomly allocate the one-day units. The operating schedule is laid out in Appendix A. The full random sequence, if Atlant was operated every day, would have yielded 78 days when each of C2 and C3 is on, and then off.

On each day, the operation schedule was followed if the precondition of model rainfall was indicated on the Poor Man's Ensemble (PME) rainfall forecast charts provided by the Bureau of Meteorology. PME 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).

If the PME graphic output for 'chance of rainfall' showed any colour (10% chance of greater than 1 mm) within the bounds (34S-36°S, 138E-140°E) for the proposed operating day (Day 1), on the morning of the day in question, this 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. On the next suitable day, the next consecutive randomised day schedule was followed (e.g. Day 2). The PME model is updated at approximately 6 am each morning. An example PME output is shown in ***Figure** 7*. The resulting operational schedule yielded 112 operational days, i.e. the 112 days when meteorological conditions were suitable and both C2 and C3 were available for operation on a C2 On (Off) / C3 Off (On) basis. Note that on 8 of these days the scheduled Atlant was operated for less than 12 hours, typically because of mechanical failure, and so was not considered to have operated on the day. Note also that of the 294 gauges in the trial area in 2010, two did not provide rainfall readings on any of the operational days, while 190 provided rainfall readings on every one of these days.

Figure 7 PME model output showing target area in red.



4.4 ADDITIONAL METEOROLOGICAL DATA

In addition to BOM rainfall data, other data was collected for use in the analysis. These were the same as used in the 2009 trial, and were obtained from the BOM. These data sets included daily meteorological observations from Adelaide airport and the location and elevation of BOM rainfall gauges.

Observations from Adelaide airport were computed as daily averages and included:

- Wind speed (km/h) and wind direction (degrees from due north, clockwise). Each day the BOM generated wind and temperature vertical profile data at six-hourly intervals commencing around 3am local time. The readings at pressure levels 925 hPa, 850 hPa, and

700 hPa (approximately 660 m, 1500 m and 3300 m respectively) were vector averaged (speed weighted) across each day.

- Air temperature; dew point temperature; and mean sea level pressure, were all measured at the surface. These readings were provided by the BOM at 30-minute intervals commencing midnight local time.

Steering winds are associated with the general direction and speed of air (and hence cloud) movement and vary with the height of the cloud layer(s). Steering wind direction and speed for the trial were approximated by a vector average of the 850 and 925 hPa values of wind direction and speed. This is a standard method for estimating average transport direction of a plume in basic atmospheric pollution modelling studies.

4.5 STABILITY INDICES

Peer-review of the 2009 trial suggested that additional data describing the stability and moisture content of the atmosphere should be added to the analysis. This included several well-known indices described below. Consequently the following data were added:

- Within day temporal ranges of BOM readings for air temperature, dew point temperature and mean sea level pressure.
- Commonly used stability and moisture indices derived from BOM vertical profile data at 12-hourly intervals. These were Precipitable Water, Total Totals, and Lifted Index.

Total Totals Index (TT)

The Total Totals Index (TT) (attributed to Miller 1972) is equal to the temperature at 850 hPa plus the dew point at 850 hPa, minus twice the temperature at 500 hPa. In general, values of less than 50 or greater than 55 are considered weak and strong indicators, respectively, of potential severe storm development.

Lifted Index (LI)

Lifted Index (LI) (attributed to Galway 1956) is found by lifting a surface parcel adiabatically to 500 hPa. The difference between the 500 hPa temperature and the lifted parcel's temperature is the LI. The LI has proved useful for indicating the likelihood of severe thunderstorms. The chances of a severe thunderstorm are best when the lifted index is less than or equal to -6. This is because air rising in these situations is much warmer than its surroundings and can accelerate rapidly and create tall, violent thunderstorms. Values less than -9 reflect extreme instability. An LI of between 0 and -2 indicates that there is a small chance of having a severe thunderstorm. Air mass thunderstorms can occur when the LI is slightly positive.

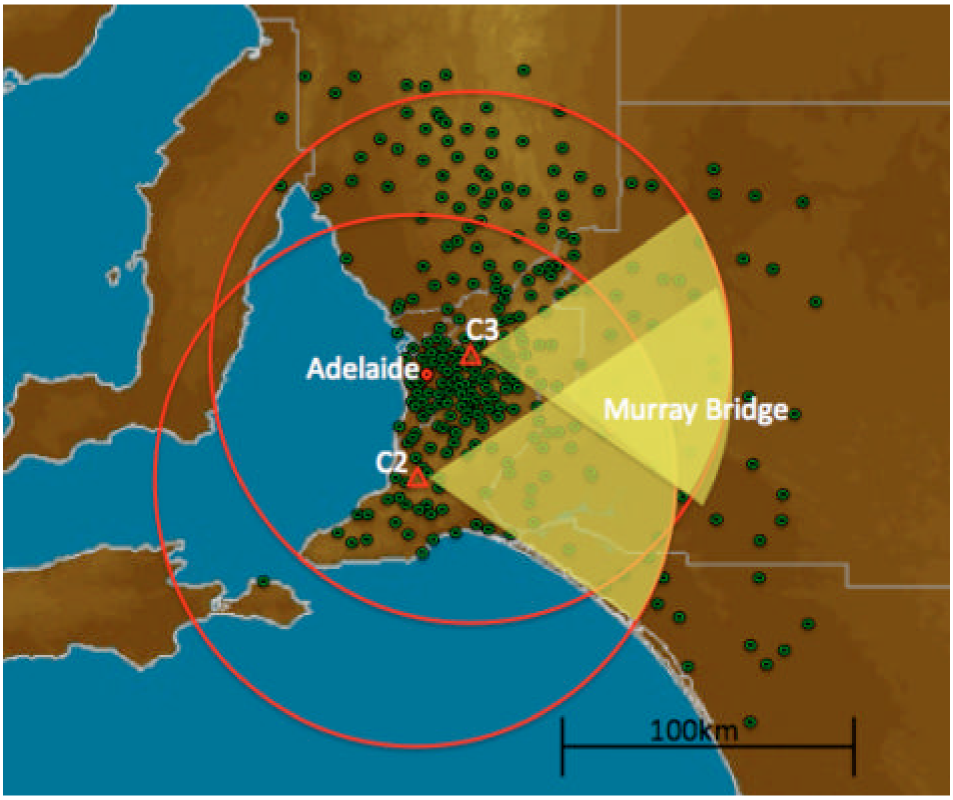
Precipitable Water (PW)

Precipitable Water (PW) is the depth of the amount of water in a column of the atmosphere if all the water in that column were precipitated as rain. Precipitable Water is the sum of average mixing ratios across pressure layers up to and including 500 hPa.

4.6 TARGET AREA DEFINITION

The dynamic definition (position re-defined every day) of the target in the 2009 trial was retained in the 2010 trial. The orientation of this 60-degree sector is dynamically defined on a daily basis, being centred on the radial vector describing the steering wind direction, downwind from the Atlant. Rather than including all gauges across a target area, this dynamic daily partitioning of the target area in relation to steering wind direction serves to focus the signal generated by the Atlant system, if it is effective. The target areas for a westerly wind are shown in ***Figure 8***. Note that both target areas are dynamic, in the sense that the gauges that they cover vary from day to day depending on the direction of the steering wind, which was taken to be the speed-weighted average of the wind directions at 850 hPa and 925 hPa at Adelaide Airport.

Figure 8 The location of the Atlant sites (∆) at C2 (Willunga, 35°18' 41.34'S, 138° 31' 22.02'E) and C3 (Tea Tree Gully, 34°49' 28.10'S, 138° 44' 48.70'E). The rain gauges used in the trial are indicated by green dots. The circles centred on the Atlant ion generator sites have a radius of 90 km. Downwind sectors (yellow) are shown for a westerly wind. The degree of overlap is dependent on the direction of the wind.



5 Comparison of rainfall and meteorological conditions during the 2009 and 2010 trials

The weather patterns in the trial area differed substantially between 2009 and 2010, most notably in terms of the amount of rainfall and the direction of prevailing winds.

5.1 2010 RAINFALL AND WIND DIRECTION

The combination of a La Niña event and the negative Indian Ocean Dipole through 2010 provided extremely favourable conditions for increased rainfall over South Australia (BOM, 2011). As a result of these tropical influences, South Australia recorded its third wettest year on record, with a State average of 362 mm following 1974 (484 mm) and 1973 (385 mm), and its wettest spring on record (133 mm) exceeding spring 1975 by 3 mm.

Across the whole of South Australia, rainfall in 2010 was 161% of the average. In the trial area, Adelaide (Kent Town) annual rainfall was 592.6 mm recorded over 128 rain days, which exceeds the annual average of 549.1 mm (average is calculated over all years of record from 1978 to 2009). The last time Adelaide received more than its average annual rainfall was in 2005. The record highest annual rainfall for the complete Adelaide record (measurements made at both Kent Town and West Terrace, back to 1839) was recorded in 1992, with 883.2 mm in the gauge. The station recording the highest rainfall across South Australia was Uraidla with 1195.6 mm, followed by 1180.8 mm at Crafers (Mount Lofty), both in the Mount Lofty Ranges.

In contrast, 2009 began with weak La Niña conditions in the Pacific Ocean, and by trial commencement was under influence from the southern ocean through winter, and warmer than average waters off north-western Australia through spring, despite the development of an El Nino in the Pacific mid-year. Rainfall was slightly above average through autumn and into winter and spring, apart from drier periods in August and October, which saw trial period rainfall slightly below the long-term average. Across the whole of South Australia, rainfall in 2009 was 88% of the average. Adelaide's annual rainfall was 517.2 mm in 118 days, slightly below the average of 550.2 mm.

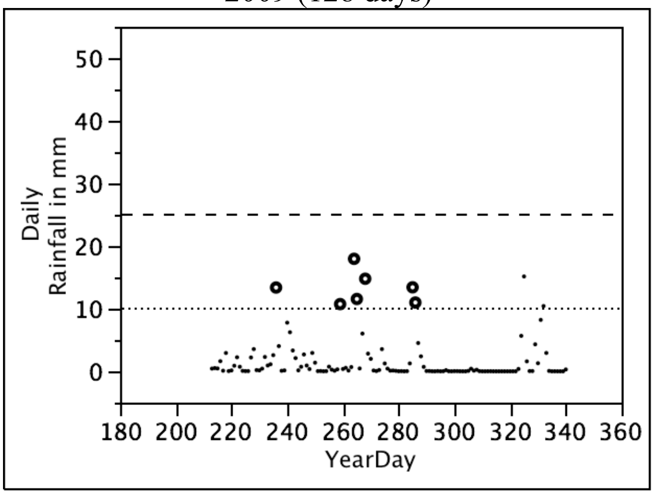
Daily rainfall for all days and for all rainfall gauges in the trial area during the 2009 and 2010 trial period is shown in ***Figure 9***. It is clear that there was greater number of days on which rain fell in 2010. Average rainfall on days when rain fell was also high. There was a larger number of widespread rainfall events, defined as days when an average of 10 mm or more rain fell across the entire trial area and when a high number of gauges reported rain (250 or more in 2009, 245 or more in 2010, with the smaller 2010 number reflecting the smaller number of gauges in the trial area, 294 vs. 301, in 2010 compared with 2009). These days are denoted by bold circles in ***Figure 9***. Overall average rainfall increased from 1.8 mm per day to 2.6 mm per day. The standard deviation in daily rainfall increased from 3.6 mm in 2009 to 5.8 mm. in 2010. The relative standard deviation increased from 200 per cent to 223 per cent.

The distributions of daily rainfall are shown in ***Figure 10*** in average levels, the logarithm of average rainfall and the average of the logarithm of rainfall for gauges that recorded positive rainfall. The smaller proportion of zero and low rainfall observations as well a few extreme rainfall events can be seen in the level data. The reduction of low or isolated rainfall days in 2010 can be seen more clearly in the logarithm of the daily average rainfall. The general increase in the intensity of rainfall that occurred in 2010 is apparent in the average of the logarithm of rainfall data. The increase in the variability of rainfall when an average of more than 1 mm of rainfall was recorded can also be seen.

In the context of the trial, the greater number of days on which there was precipitation in the trial area would have increased the extent to which ion generators operated under more favourable conditions, given the proposed model (described in Chapter 2) through which the system operates. At the same time, there was a considerably higher level of background variation in rainfall. ***Figure 11*** displays the distributions of wind directions for 2009 and 2010, allowing a comparison between the two years.

Figure 9 Average daily rainfall over the 2009 and 2010 trials; simple averages of all gauges in the trial area. Bold open and closed circles denote widespread rain events.

2009 (128 days)



2010 (159 days)

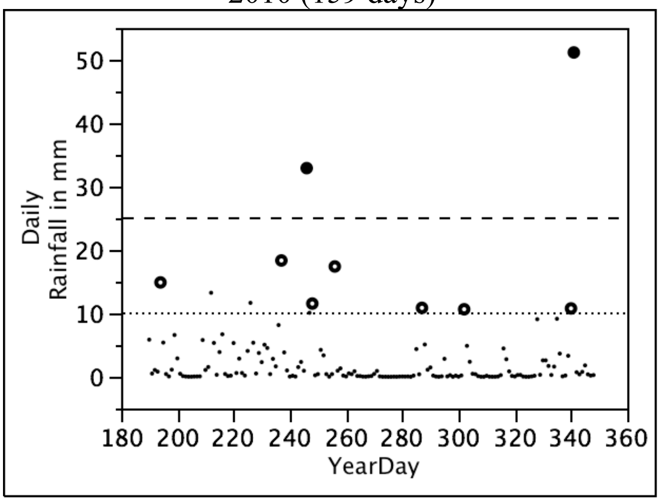
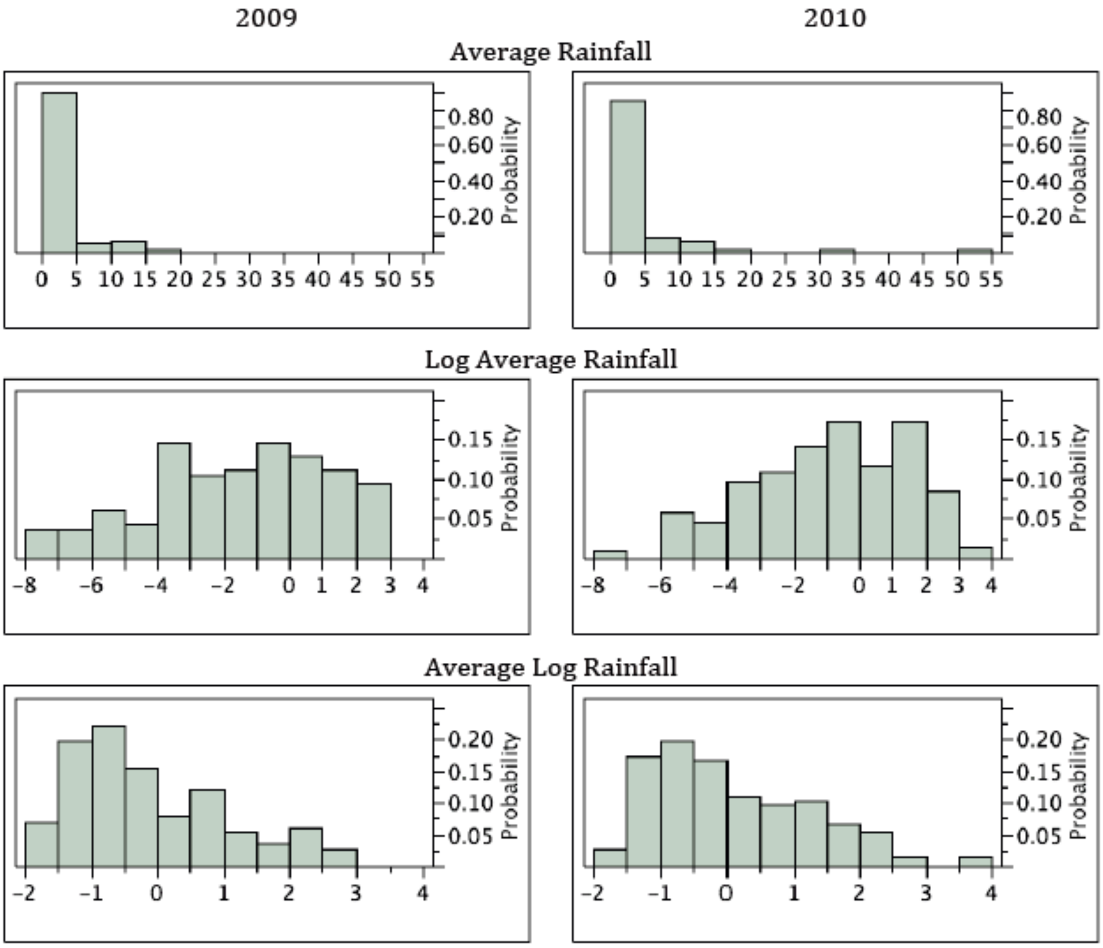
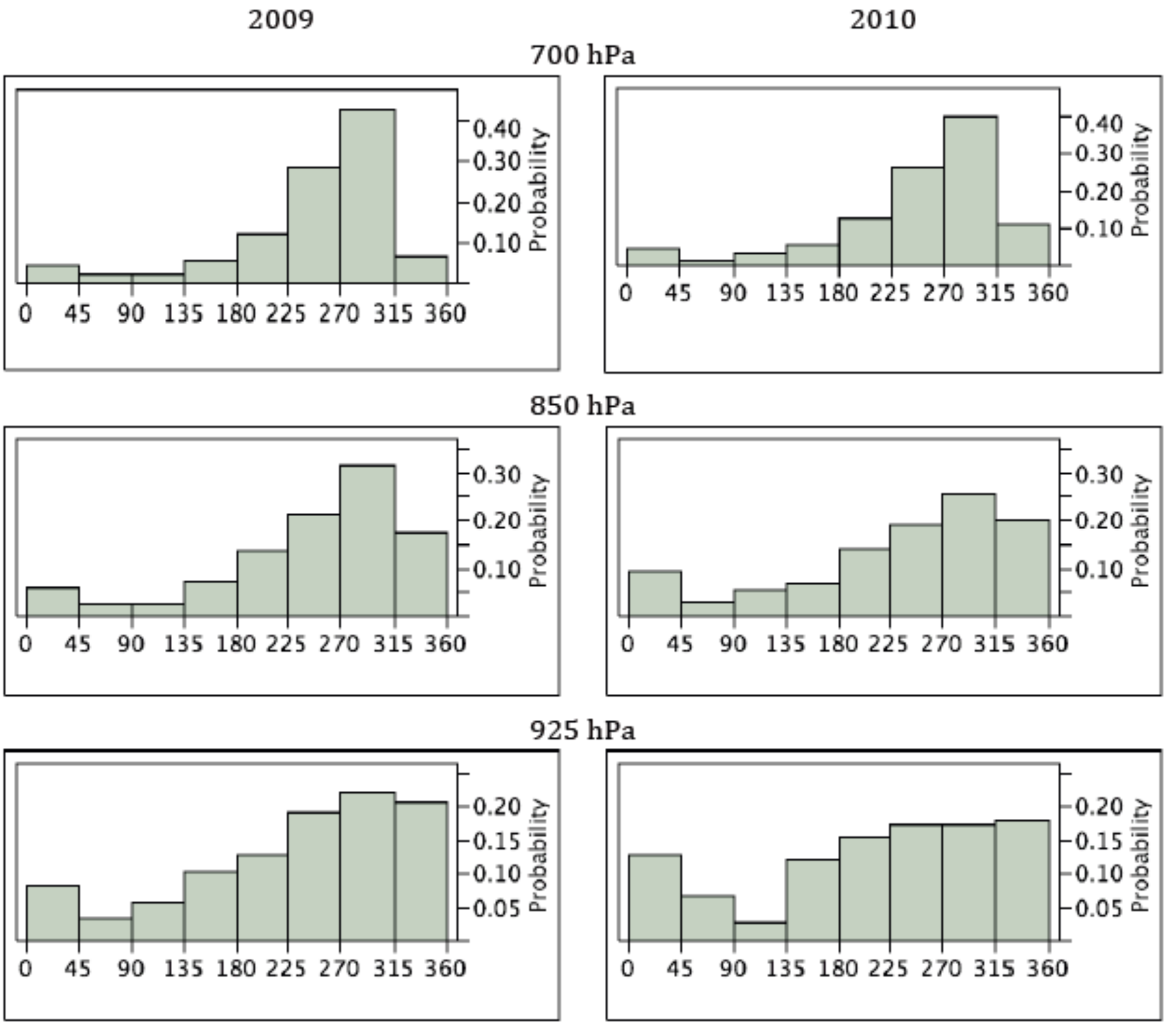


Figure 10 The distributions of average daily rainfall, the logarithm of average daily rainfall greater than zero and the daily average of the logarithm of positive rainfall observations over the 2009 and 2010 trials.



	Average Rainfall		Log Average Rainfall		Average Log Rainfall	
Year	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Mean	1.8	2.6	-1.50	-0.92	-0.14	0.08
Std Dev	3.6	5.8	2.64	2.34	1.16	1.17

Figure 11 The distributions of daily averages of 6 hourly wind directions, over the 2009 and 2010 trials.



Pressure	700 hPa		850 hPa		925 hPa	
Year	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Mean	248	251	245	234	229	210
Std Dev	70	69	82	96	95	104

5.2 A COMPARISON OF DOWNWIND GAUGE NUMBNERS - 2009 AND 2010 TRIALS

The shift in prevailing wind directions between 2009 and 2010 affected the number of gauges that fell inside the target and control areas over the course of the trial. The distributions of the daily average number of downwind gauges in the 2009 and 2010 trials are summarised in ***Table 1***. The counts of gauges that reported rainfall at least once in a downwind area are also shown.

There is an overall reduction in the number of reporting downwind gauges in 2010 as opposed to 2009. The reduction is in the order of 20 per cent. However, there is a significant increase in the average number of gauges contributing downwind of C2 in 2010. The difference is more pronounced on days when rainfall was recorded downwind of the site. The implications being that a smaller number of gauges were more consistently found downwind of C2. The standard deviation relative to the mean is about the same in both years for all gauges. The relative standard error (which is simply the standard error divided by the mean and expressed as a percentage) is small on days when rain was recorded in 2010. There is a similar pattern for the average number of gauges downwind of C3. However, the differences are not significant. There was an increase in average number of overlap gauges in 2010, the difference was significant when rainfall was recorded in the overlap sector.

Table 1 Summary statistics for the daily average number of contributing downwind gauges in the 2009 and 2010 trials.

Year	2009			2010		
Selection Criteria	All	Rain > 0 mm	Rain > 1 mm	All	Rain > 0 mm	Rain > 1 mm
Downwind C2 only						
Mean	32.6	13	8.2	42.8	23.4	12.7
Standard Deviation	35.3	22.7	16.4	41.1	28.2	20.5
Standard Error Mean	1.6	0.8	0.5	2.0	1.2	0.9
Count	115	115	115	88	88	88
Downwind C3 only						
Mean	29	11	7.7	30.4	16.4	11.8
Standard Deviation	11.4	12.2	11.3	15.4	15.3	14.8
Standard Error Mean	1.1	1.2	1.1	1.7	1.6	1.6
Count	105	105	105	87	87	87
Downwind overlap C2 and C3						
Mean	15.9	4.4	2.3	20.1	8.2	4.6
Standard Deviation	17.9	9.4	6.1	20.1	11.8	9.0
Standard Error Mean	0.1	0.1	1.6	2.0	1.2	0.9
Count	122	122	122	98	98	98

5.3 SUMMARY

Overall there was a substantial increase in the number of gauges in the sector downwind of C2 with the change in wind direction, however the number of gauges downwind of C3 remained constant even with changes in wind direction. There was also an increase in rainfall both in amount and variability.

Both of the above observations suggest an increase in the difficulty in detecting an enhancement signal in 2010 if it is small.

6 An analysis of the 2010 data using the 2009 methodology

The analysis of the data from the 2009 trial included a mean level comparison of gauges in the target and control areas as well as a regression analysis that used covariates to control for meteorological conditions and the average elevation of gauges contributing to the average on a given day. It was clear that the aggregation of gauge-level data into daily averages would not allow the detection of an enhancement signal against the natural variation in rainfall. An analysis of gauge-level data was then conducted using regression models with covariates to control for:

- Meteorological conditions;
- Gauge elevation; and
- Gauge orientation with respect to wind direction and distance relative to the location of the ion generators.

An enhancement effect was found in the gauge level of analysis. However the significance of that effect was potentially exaggerated due to the correlation in the unexplained variation in gauge level rainfall in terms of :

- Absolute gauge location (spatial correlation); and
- Relative downwind and crosswind gauge location (spatiotemporal correlation).

In accounting for these effects the significance of the enhancement effect was reduced from a figure in excess of a 99 per cent confidence level to around 90 per cent.

Within the limits of the changes to the experimental design and the consideration of days on which there was heavy and widespread rainfall, the 2010 data was analysed in the same manner.

6.1 ANALYSIS OF VARIANCE: DAILY AVERAGES

The daily averages of the logarithm of gauge-level rainfall in the target and control areas were compared for all 112 operational days of the 2010 trial. The target and control areas are defined as being within a 60-degree downwind arc of the ion generator that is either on or off, respectively. A gauge reading can therefore be allocated to one of four Operating Status values: C2 Target, denoting a reading from a gauge downwind of C2 when it is operational; C2 Control, denoting a reading from a gauge downwind of C2 when it is not operational; C3 Target, denoting a reading from a gauge downwind of C3 when it is operational; and C3 Control, denoting a reading from a gauge downwind of C3 when it is not operational. Note that the target area (i.e. the 60 degree arc downwind of an operating generator) can either:

- Include any area of overlap; or

- Exclude any area of overlap.

An analysis of variance that ignored within day correlation of average rainfall values (and hence would tend to overstate significance) was conducted using both definitions and is summarised in ***Table 2***.

Table 2 Analysis of variance of the daily averages of logarithm of rainfall for the 2010 trial.

Gauges in the overlap area included						
Source	**DF**	**SSQ**	**MSE**	**F-Ratio**	**Significance**	
Operating Status	3	7.07	2.34	1.57	0.19	
Error	179	268.08	1.50			
Total	182	275.88				
Operating Status Value	**Average Daily Rainfall in mm**			**Average Daily Log Rainfall**		
	Days	**Mean**	**SE**	**Days**	**Mean**	**SE**
C2 Control	46	2.57	0.70	42	0.19	0.19
C2 Target	50	2.77	0.59	45	0.49	0.19
C3 Control	50	3.75	1.10	45	0.35	0.20
C3 Target	53	1.86	0.42	51	-0.03	0.15
Gauges in the overlap area excluded						
Source	**DF**	**SSQ**	**MSE**	**F-Ratio**	**Significance**	
Operating Status	3	3.83	1.27	0.79	0.49	
Error	155	248.22	1.60			
Total	158	252.05				
Operating Status Value	**Average Daily Rainfall in mm**			**Average Daily Log Rainfall**		
	Days	**Mean**	**SE**	**Days**	**Mean**	**SE**
C2 Control	46	2.57	0.70	42	0.19	0.19
C2 Target	42	3.04	0.65	38	0.58	0.19
C3 Control	50	3.75	1.10	45	0.35	0.20
C3 Target	37	2.53	0.61	34	0.19	0.22

As with the 2009 trial it is not possible to make any firm inferences from a simple comparison of means. Average daily rainfall in the target area was higher at C2 and lower at C3 when compared to the control. However the overlap in the confidence intervals is large regardless of how the target area is defined.

6.2 MODELLING DAILY AVERAGE DATA

The regression analysis of the daily data was done in two stages. The first stage was to determine if the operation of the ion generation sites had an observable impact on the proportion of rain gauges that recorded rain on a given day. That is, was there a significant increase or decline in the occurrence of rainfall events in the target as opposed to the control areas? In the second stage, the effect of the operation of the ion generation sites on the average of the logarithm of observed rainfall was examined. This second stage only models averages across gauges that recorded rainfall. Taken together, the two stages allow the effect on overall rainfall in the target versus the control areas to be derived. The definition of the target area excluded the overlap area.

The two models make use of meteorological covariates and average gauge elevation and a variable taking on the value of one when there is widespread rainfall and zero otherwise. There were two covariates that took on the value of one if a site was operating on the day and zero otherwise.

There were two models that could have been used to test the hypothesis that operation of Atlant leads to increased rainfall events. The first is a generalised linear model that assumes that the daily proportions of rainfall events follow a binomial distribution, i.e. rainfall events on the day are independently distributed. Because of the strong spatial correlation in the gauge level rainfall readings on a day, this model may not be inappropriate. Consequently, a simple ordinary least squares regression model was used to model the proportions directly without any constraints on the range of the predicted proportions. The results for this model are summarised in ***Table 3***. Note that two sets of estimates are provided - the first uses all the daily proportions, the second excludes proportions that are either zero or one.

Table 3 First stage regression results for the daily average data: the proportion of gauges recording rainfall

Parameter	Estimate	SE	Significance
Ordinary Least Squares Using All 175 Daily Proportions			
Intercept	13.007	4.363	0.0033
Average Gauge Elevation	0.075	0.022	0.0007
Steering Wind Direction	-0.371	0.378	0.3274
Steering Wind Speed	0.007	0.002	<.0001
Average Daily Temperature	-0.043	0.011	<.0001
Dew Point Difference	-0.010	0.010	0.3111
Sea Level Pressure	-0.012	0.004	0.0037
Precipitable Water	0.028	0.006	<.0001
Widespread Rain Day	0.187	0.082	0.0245
C2 Target	0.030	0.047	0.5199
C3 Target	-0.000	0.049	0.9975
Summary			
RSQ = 0.54			
Obs = 175			
Ordinary Least Squares Using Proportions Strictly Between Zero And One			
Intercept	10.250	4.320	0.0190
Average Gauge Elevation	0.078	0.022	0.0006
Steering Wind Direction	-0.514	0.374	0.1721
Steering Wind Speed	0.007	0.001	<.0001
Average Daily Temperature	-0.037	0.010	0.0005
Dew Point Difference	-0.006	0.010	0.5516
Sea Level Pressure	-0.010	0.004	0.0216
Precipitable Water	0.028	0.005	<.0001
Widespread Rain Day	0.115	0.086	0.1797
C2 Target	0.037	0.047	0.4329
C3 Target	-0.006	0.049	0.9036
Summary			
RSQ = 0.50			
Obs = 154			

The two sets of model estimates are similar. There is clearly no detectable effect of the ion generators on the proportion of downwind gauges reporting rainfall in the target as opposed to the control area. This is the same conclusion that was reached in the analysis of the 2009 trial. The second stage regression results for the daily average of the logarithm of rainfall are set out in ***Table 4.*** The results are presented for all operating days and with one possible outlier day removed. The outlier is identified in bold in ***Figure 12***. There is a significant increase in rainfall estimated for the target as opposed to the control area downwind of C2. The level of significance is over 90 per cent with all observations and increases to over 95 per cent with the outlier removed. There is an estimated reduction in rainfall at C3. However, this estimate is not significant at the 70 per cent confidence level with the complete data set or with the outlier removed. The standard errors of the estimates at C2 and C3 are of the same order of magnitude. The lack of significance of the effect at C3 is due to the small size of the corresponding estimate.

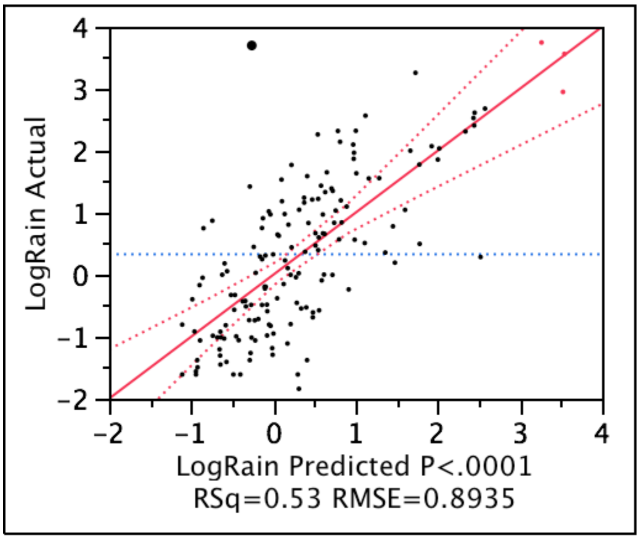
The results of the modelling of the daily rainfall data in 2009 and 2010 are similar in that an effect was suggested at only one of the two sites. However, there was a reversal in the location of this site with the 2009 analysis indicating that the effect was moderately significant at C3 and insignificant at

C2. This difference may have been caused by changes in the spatial distribution of the selected gauges downwind of C2 and C3 in 2009 versus 2010. However, the possible influences of such changes are better explored using gauge-level analysis.

Table 4 Second stage regression results for the daily average data: the average of logarithm of rainfall

Parameter	Estimate	SE	Significance
Ordinary Least Squares			
Intercept	36.404	16.518	0.0291
Average Gauge Elevation	0.090	0.084	0.2856
Steering Wind Direction	1.308	1.446	0.3672
Steering Wind Speed	0.017	0.006	0.0038
Average Daily Temperature	-0.133	0.039	0.0009
Dew Point Difference	0.031	0.037	0.3998
Sea Level Pressure	-0.037	0.016	0.0224
Precipitable Water	0.098	0.021	<.0001
Widespread Rain Day	1.592	0.304	<.0001
C2 Target	0.301	0.179	0.0944
C3 Target	-0.085	0.186	0.6503
Summary			
RSQ = 0.53			
Obs = 158			
Ordinary Least Squares with Outlier Excluded			
Intercept	34.336	15.396	0.0272
Average Gauge Elevation	0.133	0.079	0.0923
Steering Wind Direction	0.858	1.351	0.5262
Steering Wind Speed	0.017	0.005	0.0018
Average Daily Temperature	-0.135	0.037	0.0003
Dew Point Difference	0.027	0.034	0.4339
Sea Level Pressure	-0.035	0.015	0.0204
Precipitable Water	0.106	0.020	<.0001
Widespread Rain Day	1.605	0.284	<.0001
C2 Target	0.370	0.167	0.0287
C3 Target	-0.044	0.174	0.8007
Summary			
RSQ = 0.58			
Obs = 157			

Figure 12 Actual versus predicted rainfall for the daily average model using all operating days. The potential outlier is identified in bold.



6.3 MODELLING INDIVIDUAL GAUGE DATA

The main problem with comparing model fits and consequent attribution estimates between 2009 and 2010 at the gauge level is the change in the operating protocol and hence the definition of what constitutes an Atlant effect between the two years. This is clear when considering that 25 per cent of the time both C2 and C3 were in operation in 2009. This led to the use of an indicator variable in the definition of the Atlant effect in 2009 to represent the operational status of a system when it had been on two days in a row. This in turn led to the inclusion of rain data from gauges outside the area downwind of C2 when C2 is on and vice versa.

In 2010, this 'Two days in a row' indicator variable takes the value of zero throughout the trial. This allows the use of a more precise testing of the Atlant effect. In particular, we now replace C2 On by C2 Target (takes the value one only when the gauge is downwind of C2 and C2 is on) and C3 On by C3 Target (takes the value one only when the gauge is downwind of C3 and C3 is on). However, it should be noted that this Target definition includes 'target' gauges in the C2/C3 downwind overlap area. These gauges are typically located much more to the east of the trial area and so tend to be widely dispersed and in low rainfall areas. An argument might be made for eliminating these overlapping gauges. However, to maintain as much consistency as possible with the 2009 analysis they are retained. The remaining model covariates and random effects were as specified in the 2009 model. The model estimates are summarised in ***Table 5***.

The level of variance in the observations that was explained by the statistical model (model fit), was less in 2010, due to the increased variability of gauge level rainfall relative to 2009. The meteorological covariates were included the model without pre or post selection to limit the possibility of model selection bias. This type of bias can arise with the omission of a relevant covariate or eliminating variables that have an influence of the parameters of interest. Inclusion of an irrelevant effect may reduce estimation efficiency but is not a source of bias.

Covariates such as wind speed and direction at different elevations or dew point difference (average ambient temperature minus average dew point temperature) and barometric pressure are strongly correlated and so individual effects could not be estimated with high degree of precision. This was evident in the lack of significance of these effects or the fact that significant effects switched between years. At the same time orographic effects and measures of available moistures were significant and consistent between years. As the identification of meteorological effects was a secondary issue when compared to the introduction of bias, variable were not eliminated on basis of statistical significance.

As with the daily analysis there is a significant effect associated with the status of C2 and not C3. In the 2009 gauge-level analysis similar significant effects were reported for the status of C3 and not C2. The estimated attribution associated with the operation of the two systems was calculated in the same way as in the analysis of the 2009 trial and the same bootstrapping procedure was used to calculate the standard error of the estimated attribution and the lower confidence bounds for positive attribution. The bootstrap mean attribution was 8.6 per cent with a bootstrap standard error of 6.8 per cent. The confidence bounds are shown in ***Table 6*** and ***Figure 13.*** The estimated level of enhancement is significant at the 90 per cent level. The significance of the estimated mean effect is below 90 per cent due to the asymmetry of the bootstrap distribution. Overall, the 2009 and 2010 trial results yielded similar results in terms of the estimated level of attribution despite the differences in weather conditions and the experimental design.

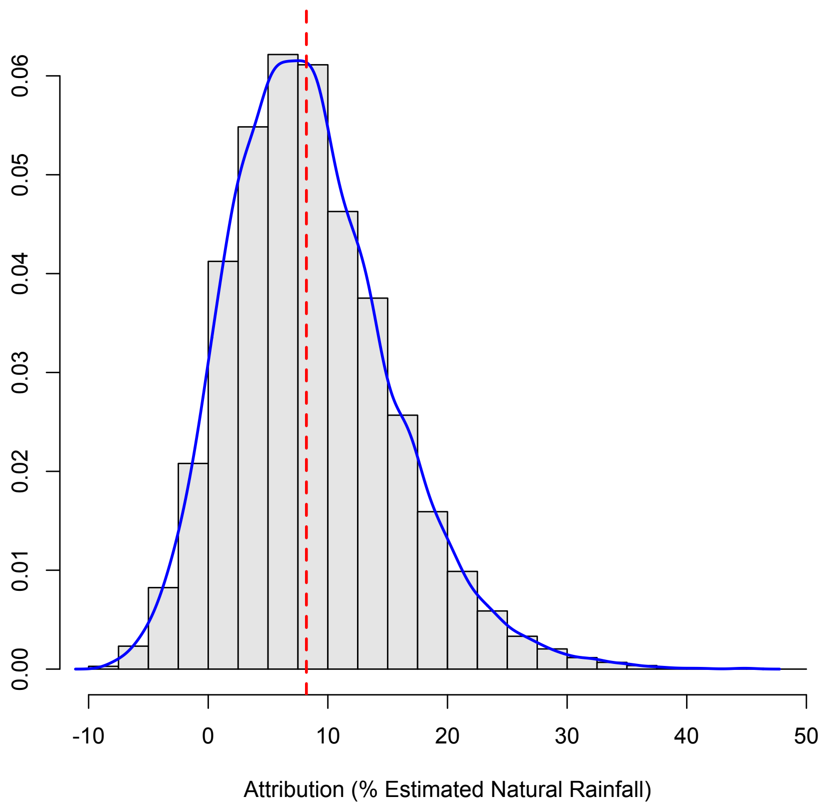
Table 5 Gauge-level regression results for logarithm of rainfall in the 2010 trial using the same model specification as in the analysis of the 2009 data. Variable names and definitions are the same as in 2009.

Parameter	Estimate	SE	Significance
Intercept	11.1637	10.1558	0.2724
AugSept	-0.1217	0.1382	0.3790
Widespread Rain Day	1.5456	0.1795	<.0001
Upwind Rain Proportion	1.6009	0.1623	<.0001
Wind Speed 700	-0.0072	0.0033	0.0287
Wind Speed 700 L1	0.0018	0.0035	0.6027
Wind Speed 850	0.0014	0.0063	0.8256
Wind Speed 850 L1	-0.0089	0.0062	0.1564
Wind Speed 925	0.0201	0.0057	0.0005
Wind Speed 925 L1	0.0139	0.0050	0.0057
SWD 700	-1.0284	0.3998	0.0105
SWD 700 L1	0.1645	0.3185	0.6059
SWD 850	0.4987	0.3933	0.2055
SWD 850 L1	-0.4424	0.3924	0.2602
SWD 925	0.1659	0.3659	0.6504
SWD 925 L1	0.5854	0.3544	0.0993
Average Daily Temp	0.0289	0.0207	0.1629
Dew Point Difference	-0.0793	0.0218	0.0003
Sea Level Pressure	-0.0125	0.0100	0.2100
Elevation (100m)	0.1530	0.0099	<.0001
C2 Distance	-1.2012	0.3766	0.0014
C2 Theta	0.0022	0.0007	0.0010
C2 Theta L1	-0.0005	0.0005	0.2674
C2 Distance*C2 Theta	0.0023	0.0016	0.1518
C2 Distance*C2 Theta L1	0.0018	0.0016	0.2762
C3 Distance	1.0920	0.3769	0.0038
C3 Theta	-0.0005	0.0004	0.2555
C3 Theta L1	-0.0005	0.0003	0.1787
C3 Distance*C3 Theta	0.0016	0.0016	0.3202
C3 Distance*C3 Theta L1	-0.0004	0.0016	0.8228
C2 Target	0.3254	0.1174	0.0057
C2 Distance*C2 Target	-0.0440	0.1019	0.6660
C3 Target	0.0226	0.1130	0.8419
C3 Distance*C3 Target	-0.0408	0.1082	0.7065
Random Effects			
Group	**Variance Component**	**Per Cent of Total**	
Spatio-Temporal	0.480857	40.6	
Residual	0.704413	59.4	
Total	1.185270	100	
Summary			
RSQ = 0.67			
Obs = 4711			

Table 6 The lower confidence bounds for the attribution of additional rainfall from the gauge-level analysis of the 2010 trial

Confidence Level	Estimate
99 per cent	-4.3
95 per cent	-1.2
90 per cent	0.6
80 per cent	2.6
70 per cent	4.7
60 per cent	6.3
50 per cent	7.9

Figure 13 Bootstrap distribution of estimated attribution from the gauge level analysis of the 2010 trial. The vertical dashed line shows the actual estimated attribution from the 2010 trial data.



7 A simplified approach to modelling the 2009 and 2010 trial data

Several improvements were considered for the gauge-level modelling approach. The overriding concerns were to:

- Improve the consistency of the covariates;
- Make better use of the upwind gauge observations; and
- Simplify the model structure.

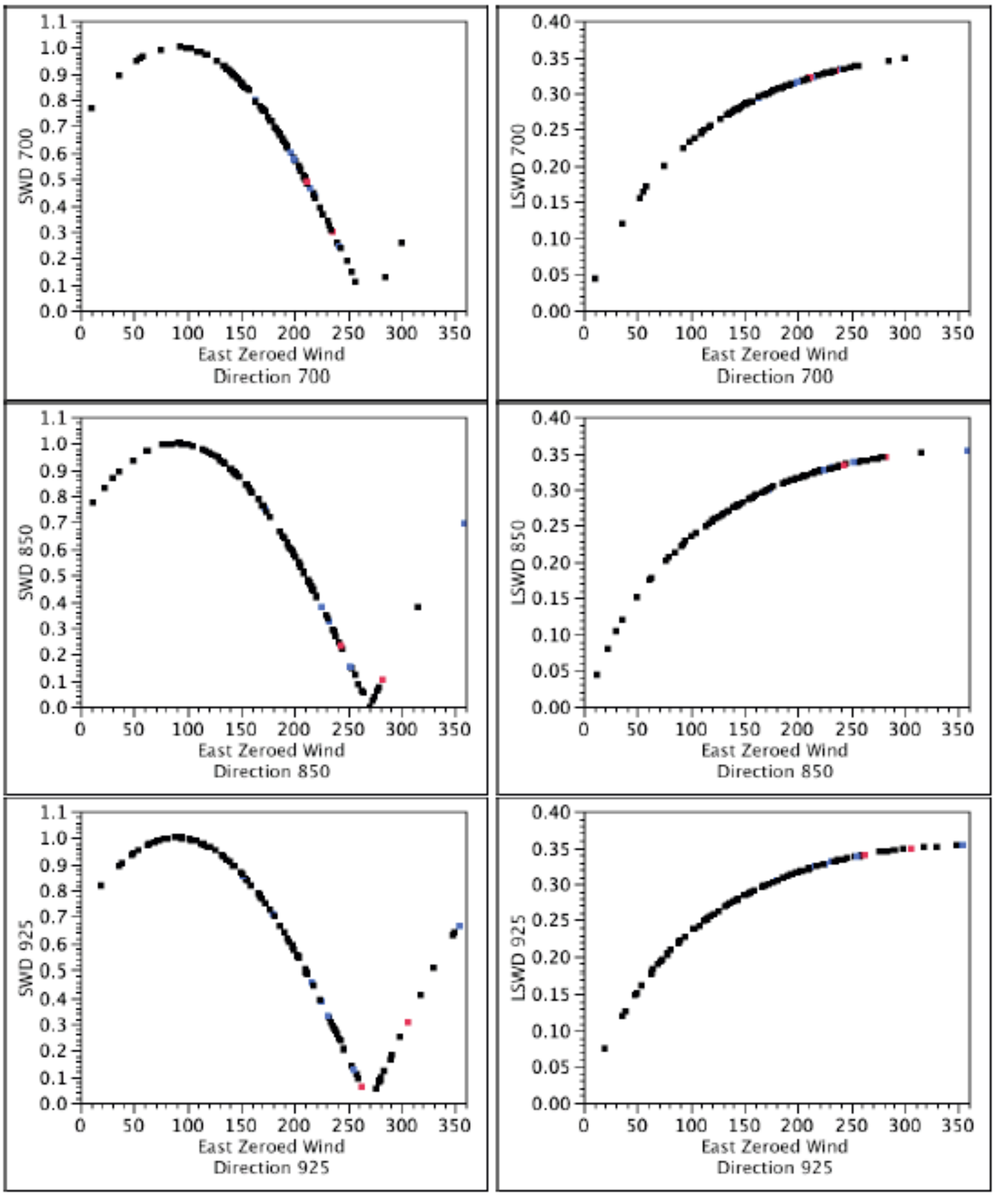
With respect to the covariates three changes were made.

The most problematic covariate is wind direction. 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 14***. 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 obtain the smooth monotone transformations shown in the right hand panel. These modified transformations were applied to the data.

A second issue was that the operating effects in the 2009 specification included a distance interaction but not a crosswind interaction. The extent to which a gauge is crosswind as opposed to downwind when the systems is operating seems a relevant consideration.

Lastly, the daily values of the three BOM stability indices needed to be integrated into the model to reduce as much as possible the reliance on effects in the model associated with defined widespread rain events. There were three such indices: the Total Totals index; the Lifted Index; and the Precipitable Water index. 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: September 3, when average rainfall across the trial area was 32.9 mm with 287 out of 294 gauges reporting rain; and December 7, when average rainfall across the trial area was 51.1 mm with 286 out of 294 gauges reporting rain.

Figure 14 Transformation of wind data (Left Panel) transformation of 2009 wind data (denoted by SWD) (Right Panel) New transformation (denoted by LSWD). Rows correspond to different values of hPa.



Consequently these two days were the only days allocated a separate mean effect in a model that included three effects defined by these indices - the average of the two Precipitable Water readings and the first and second principal components of the remaining four index values.

The major change in the model specification process, however, was with the way upwind gauge data was utilised. As gauge location can be considered relative to wind direction at the ion generation sites, any given gauge may serve as:

- A downwind target; and
- An upwind control, where upwind is defined as being in the overlap of the two 180 degree upwind arcs defined at each site.

An individual gauge cannot serve as a control as it can be upwind of a site 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 construct an instrumental control that is independent of a gauge's location relative to the prevailing wind direction.

The instrumental control variable is created by fitting meteorological and orographic covariates to gauge rainfall when it is strictly upwind of the sites. The predicted value of upwind rainfall generated by this model as a function of meteorological and fixed orographic effects is then independent of any downwind influence. Meteorological and orographic conditions when a gauge is downwind are then used to calculate a prediction of rainfall. 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 status.

Ideally, the instrumental control variable provides a prediction of rainfall at a downwind location under similar meteorological and orographic conditions and can therefore serve to replace the large number of meteorological and orographic covariates in the downwind model. Obviously, there is still the need to include effects in the model associated with location of a gauge relative to wind direction and the location of the ion generation sites. Wind directions will clearly differ when a gauge is classified as upwind or downwind and the extent to which orographic effects vary with wind direction still need to be accounted for. The relative downwind location of a gauge can again be specified in terms of distance and angular direction to the prevailing wind. The spatio-temporal random effects in the model are also retained.

7.1 2010 INSTRUMENTAL CONTROL MODEL

The 2010 instrumental control model fit based on the upwind data is provided in Appendix B. The downwind regression model for the 2010 gauge level data that uses the instrument (Predicted LogRain) defined by this model is shown in ***Table 7.*** Note that the model only includes the instrument and significant effects defined by operating status and gauge location relative to C2 and C3.

Table 7 Instrumental control model gauge-level regression results for logarithm rainfall in the 2010 trial

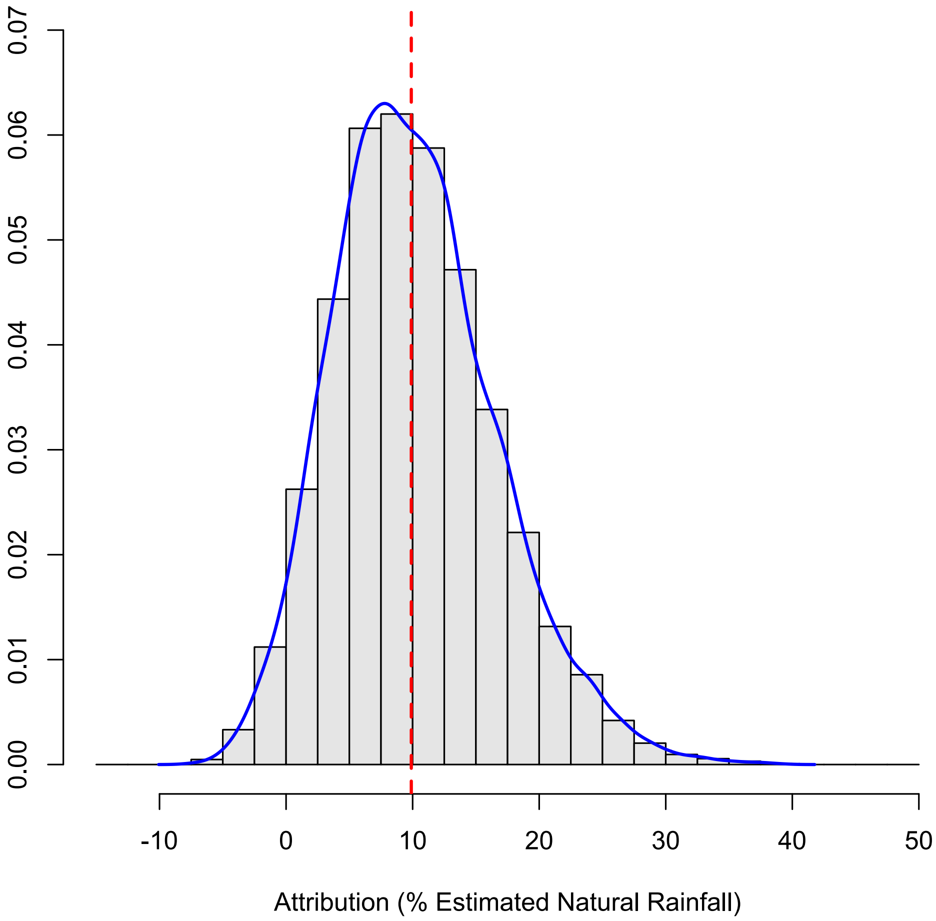
Parameter	Estimate	SE	Significance
Intercept	-0.5132	0.1028	<.0001
Predicted LogRain	1.1482	0.0533	<.0001
C2 Distance	-0.1797	0.1091	0.0997
C2 Theta	0.0023	0.0004	<.0001
C3 Distance	-0.1208	0.1441	0.4017
C3 Theta	0.0002	0.0004	0.6772
C3 Theta L1	-0.0005	0.0003	0.1384
C3 Distance*C3 Theta	0.0053	0.0011	<.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
Random Effects			
Group	Variance Component	Per Cent of Total	
Spatio-Temporal	0.671707	48.5	
Residual	0.711991	51.5	
Total	1.383698	100	
Summary			
RSQ = 0.68			
Obs = 4711			

There are significant effects identified with respect to the operating status of C2 and C3 as well as interaction effects at C3 with respect to relative wind direction. The overall attribution is 10.0 per cent with a standard error of 6.4 per cent. The confidence bounds are shown in ***Table 8*** and ***Figure 15***. The estimated level of enhancement is significant at the 95 per cent level.

Table 8 The lower confidence bounds for the attribution of additional rainfall from the instrumental control model gauge-level analysis of the 2010 trial

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

Figure 15 Bootstrap distribution of estimated attribution from the instrumental control model-based gauge-level analysis of the 2010 trial. The vertical dashed line shows the actual estimated attribution from the 2010 trial data



7.2 2009 INSTRUMENTAL CONTROL MODEL

It is of interest to see how the instrumental control specification, adjusted for differences in the experimental design, performs with the 2009 trial data. The instrumental control regression fit to the upwind data in 2009 is shown in Appendix B. The corresponding downwind regression model for the 2009 gauge-level data is shown in ***Figure 9.*** The model includes modified effects related to operating status and the location of the gauge relative to C2 and C3 during the 2009 trial. In particular, separate effects for being strictly downwind of C2 (C2 Target) or C3 (C3 Target) and being in the overlap area (C23 Target) are identified to allow for days when both generators are operational.

Again there are significant effects associated with operating status at C2 and C3. The bootstrap mean level attribution is 10.5 per cent with a bootstrap standard error of 5.3 per cent. The confidence bounds are shown in ***Table 10*** and ***Figure 16***. The estimated level of enhancement is significant at the 95 per cent level.

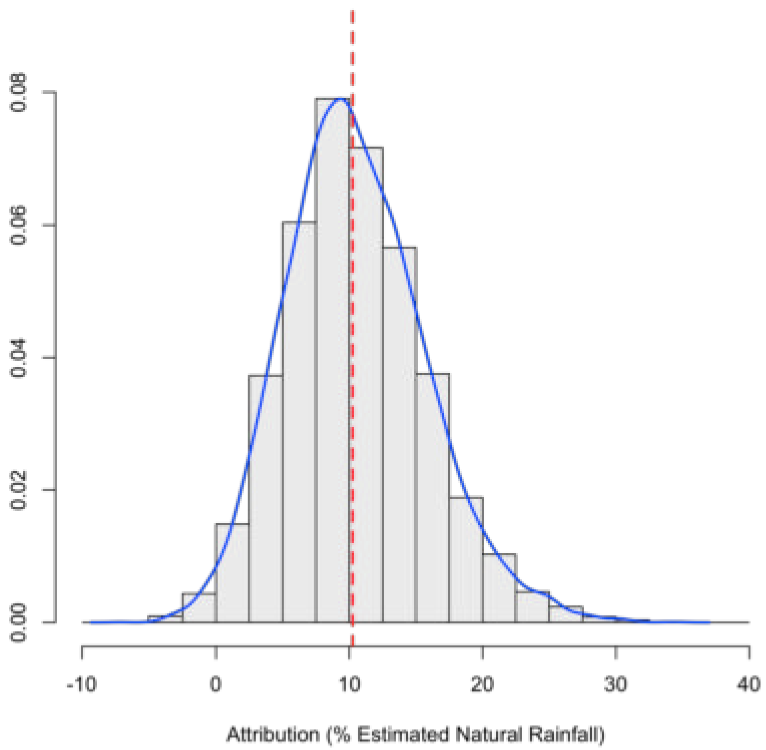
Table 9 Instrumental control model gauge-level regression results for the logarithm of rainfall in the 2009 trial

Parameter	Estimate	SE	Significance
Intercept	-0.0100	0.1547	0.9485
Predicted LogRain	1.3321	0.0568	<.0001
C2 Distance	-0.4896	0.2658	0.0658
C2 Theta	0.0033	0.0011	0.0028
C2 Theta L1	-0.0023	0.0008	0.0037
C2 Distance*C2 Theta	-0.0011	0.0021	0.6043
C2 Distance*C2 Theta L1	0.0012	0.0014	0.3865
C3 Distance	-0.4382	0.2582	0.0900
C3 Theta	-0.0010	0.0005	0.0595
C3 Theta L1	-0.0015	0.0005	0.0008
C3 Distance*C3 Theta	0.0047	0.0016	0.0041
C3 Distance*C3 Theta L1	0.0057	0.0013	<.0001
C2 Target	0.2161	0.1548	0.1633
C3 Target	0.4243	0.1484	0.0044
C23 Target	0.1497	0.2267	0.5093
C2 Distance*C2 Target	-0.2839	0.1657	0.0868
C3 Distance*C3 Target	-0.5173	0.1963	0.0085
C2 Distance*C23 Target	-0.8999	0.3930	0.0223
C3 Distance*C23 Target	0.9654	0.3960	0.0150
Random Effects			
Group	Variance Component	Per Cent of Total	
Spatio-Temporal	0.61447	48.2	
Residual	0.66074	51.8	
Total	1.27521	100	
Summary			
RSQ = 0.71			
Obs = 3177			

Table 10 The lower confidence bounds for the attribution of additional rainfall from the instrumental control model gauge-level analysis of the 2009 trial

Confidence Level	Estimate
99 per cent	-0.4
95 per cent	2.5
90 per cent	4
80 per cent	6.1
70 per cent	7.6
60 per cent	8.8
50 per cent	10.1

Figure 16 Bootstrap distribution of estimated attribution from the instrumental control model-based gauge-level analysis of the 2009 trial. The vertical dashed line shows the actual estimated attribution from the 2009 trial data



7.3 SUMMARY

Overall, the instrumental control analysis of the 2009 and 2010 trials lead 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 attribution estimates are also quite similar.

When compared to the approach developed for the 2009 trial, the instrumental control model was able to isolate significant effects at C2 and C3. The previous approach was only able to identify a significant effect at C3 in 2009 and at C2 in 2010. However, the attribution levels in both approaches were of the same order of magnitude.

8 Summary and conclusions

Meteorological and rainfall conditions in South Australia in 2009 and 2010 were very different, with much more rain recorded in 2010 and a shift in wind direction over the trial period towards the south-west. This led to quite different configurations of downwind gauges for C2 and C3 in 2010 compared with 2009. The impact of these changes on analysis of the rainfall data collected was further complicated by changes in the experimental design used in 2010. This shifted from a mix of an 'On/Off' configuration at C2 and a 'On,On/Off,Off configuration at C3 on all days of the 2009 trial to rotating 'On/Off' configurations at C2 and C3 on days judged as suitable for Atlant operation during the 2010 trial. The end result was that in 2009 there were data for 128 trial days (suitable as well as unsuitable), while in 2010 there were data for 112 suitable trial days.

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 results of this analysis show a comparable level of enhancement in 2010 compared with 2009, of the order of 9 per cent.

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 use of BOM stability indices to replace subjective assessment of widespread rain events. The main development however was the introduction of an instrumental control 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 attribution, 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. In particular, when applied to the 2009 data, the instrumental model indicated that effects at C2 compared with C3 were similar to those observed in 2010.

Appendix A – Operating protocol

Table A.1 Operating sequence for the trial period, showing both the scheduled sequence of suitable days and actual operating sequence for each site. Where the two differ is indicated in red. All of these differences were attributable to technical faults in the Atlant system.

Date	Operating Day (CNM = Criteria Not Met)	Atlant Operation C2 (red = technology fault less than 12 hours operation u/s = unserviceable)	Atlant Operation C3 (red = technology fault less than 12 hours operation u/s = unserviceable)
11-Jul-10	1	X	
12-Jul-10	2		X
13-Jul-10	CNM		
14-Jul-10	3		X
15-Jul-10	4	X	
16-Jul-10	5	X	
17-Jul-10	6	X	
18-Jul-10	CNM		
19-Jul-10	7		X
20-Jul-10	8		X
21-Jul-10	CNM		
22-Jul-10	CNM		
23-Jul-10	CNM		
24-Jul-10	9		X
25-Jul-10		X	
26-Jul-10		u/s	u/s
27-Jul-10		u/s	u/s
28-Jul-10	10	X	
29-Jul-10	11		X
30-Jul-10		X	
31-Jul-10	12	X	
1-Aug-10	13	X	
2-Aug-10	14		X
3-Aug-10	15	X	
4-Aug-10	16		X
5-Aug-10	17		X
6-Aug-10	18		X
7-Aug-10	19	X	
8-Aug-10	20		X
9-Aug-10	21	X	
10-Aug-10	22	X	
11-Aug-10	23	X	

12-Aug-10	24		X
13-Aug-10	25	X	
14-Aug-10	26	X	
15-Aug-10	27	X	
16-Aug-10	28		X
17-Aug-10	29		X
18-Aug-10	30	X	
19-Aug-10	31		X
20-Aug-10	32		X
21-Aug-10	33		X
22-Aug-10	34	X	
23-Aug-10	35	X	
24-Aug-10	CNM		
25-Aug-10	CNM		
26-Aug-10	CNM		
27-Aug-10	CNM		
28-Aug-10	36		X
29-Aug-10	CNM		
30-Aug-10	CNM		
31-Aug-10	37	X	
1-Sep-10	38	X	
2-Sep-10	39		X
3-Sep-10	40	X	
4-Sep-10	41		X
5-Sep-10			X
6-Sep-10		u/s	u/s
7-Sep-10	42		X
8-Sep-10	43	X	
9-Sep-10	44		X
10-Sep-10	45	X	
11-Sep-10	46	X	
12-Sep-10	47		X
13-Sep-10	48		X
14-Sep-10	49		X
15-Sep-10	50	X	
16-Sep-10	51		X
17-Sep-10	52		X
18-Sep-10	CNM		
19-Sep-10	CNM		
20-Sep-10	CNM		
21-Sep-10	53	X	
22-Sep-10	54	X	
23-Sep-10	55	X	
24-Sep-10	CNM		
25-Sep-10	CNM		
26-Sep-10	CNM		
27-Sep-10	56		X
28-Sep-10	57		X
29-Sep-10	58		X
30-Sep-10	CNM		
1-Oct-10	CNM		
2-Oct-10	CNM		
3-Oct-10	CNM		
4-Oct-10	59		X
5-Oct-10	60	X	
6-Oct-10	CNM		
7-Oct-10	61		X

8-Oct-10	CNM		
9-Oct-10	CNM		
10-Oct-10	CNM		
11-Oct-10	CNM		
12-Oct-10	62	X	
13-Oct-10	63	X	
14-Oct-10	64	X	
15-Oct-10	65	X	
16-Oct-10	66	X	
17-Oct-10	67	X	
18-Oct-10	CNM		
19-Oct-10	CNM		
20-Oct-10	CNM		
21-Oct-10	CNM		
22-Oct-10	68	X	
23-Oct-10	69		X
24-Oct-10	70	X	
25-Oct-10	71		X
26-Oct-10	CNM		
27-Oct-10	CNM		
28-Oct-10	CNM		
29-Oct-10	72		X
30-Oct-10	73		X
31-Oct-10	74		X
1-Nov-10	75		X
2-Nov-10	76		X
3-Nov-10	77	X	
4-Nov-10	CNM		
5-Nov-10	CNM		
6-Nov-10		X	
7-Nov-10		u/s	u/s
8-Nov-10		X	
9-Nov-10	u/s	u/s	u/s
10-Nov-10	78	X	
11-Nov-10	79	X	
12-Nov-10	80		X
13-Nov-10	81		X
14-Nov-10	82		X
15-Nov-10	83		X
16-Nov-10	CNM		
17-Nov-10	CNM		
18-Nov-10			X
19-Nov-10	84	X	
20-Nov-10	CNM		
21-Nov-10	CNM		
22-Nov-10	85		X
23-Nov-10	86		X
24-Nov-10	87	X	
25-Nov-10		X	
26-Nov-10	88	X	
27-Nov-10	89		X
28-Nov-10	90	X	
29-Nov-10	91	X	
30-Nov-10	92	X	
1-Dec-10	93	X	
2-Dec-10	94	X	
3-Dec-10	95		X

4-Dec-10	96		X
5-Dec-10	97		X
6-Dec-10	98		X
7-Dec-10	99	X	
8-Dec-10	100	X	
9-Dec-10	101		X
10-Dec-10	102		X
11-Dec-10	103		X
12-Dec-10		X	
13-Dec-10	104	X	

Appendix B Estimation of rainfall enhancement

All models for positive rainfall used in this report are linear in the logarithm scale. In what follows, we describe the method for estimating the rainfall enhancement component of these positive rainfall values using the gauge-level model with spatio-temporal random effects. It is straightforward to extend this description to the two other models that are considered in this report, the gauge-level model with random gauge effects and the day-level model.

Under the gauge-level model with spatio-temporal random effects, *LogRain* can be written in the form

$$LogRain_{itkj} = \alpha^T x_{itkj} + \beta^T z_{itkj} + \gamma_{itk} + \varepsilon_{itkj} \,. \qquad \text{(B1)}$$

Here the indices *i, t, k*, and *j* correspond to gauge, day, spatio-temporal group and individual gauge-day observation respectively; x_{itkj} denotes the vector of fixed effects in the model that are not Atlant effects (i.e. the rows corresponding to the first 28 parameters in (***Table 5***); x_{itkj} denotes the vector of fixed effects in the model that are Atlant effects (the rows corresponding to the last four parameters in (***Table 5***) γ_{itk} is a random spatio-temporal effect and ε_{itkj} is the model error.

The aim is to decompose the observed rainfall for observation *itkj* as:

$$LogRain_{itkj} = NaturalLogRain_{itkj} + LogAtlantEffect_{itkj} \qquad \text{(B2)}$$

where $Natural\ Rainfall_{itkj}$ is the natural rainfall that would have been observed if Atlant had not been operating. Since we cannot observe natural rainfall while the Atlant system is operating, we derive estimates of the logarithm scale values of the components of the decomposition (B2) using the assumed linear model (B1) for $LogRain$. In order to do so we note that (B2) implies an additive relationship on the logarithm scale:

$$LogRain_{itkj} = NaturalLogRain_{itkj} + LogAtlantEffect_{itkj} \,. \qquad \text{(B3)}$$

Here $NaturalLogRain_{itkj}$ is the logarithm of $Natural\ Rainfall_{itkj}$ and $LogAtlantEffect_{itkj}$ is the logarithm of $1 + Enhancement\ Effect_{itkj}$. Comparing (B1) and (B3), we define

$$LogAtlantEffect_{itkj} = \beta^T z_{itkj} \,. \qquad \text{(B4)}$$

We can estimate $LogAtlantEffect_{itkj}$ by substituting the coefficient values displayed in ***Table 5*** into (B4). Estimated values of $1 + Enhancement\ Effect_{itkj}$ are then obtained by exponentiation. That is, our estimate of the Atlant enhancement for a particular gauge-day observation is:

$$Enhancement\ Effect_{itkj} = K\exp\left(LogAtlantEffect_{itkj}\right) - 1 \,. \tag{B5}$$

The corresponding estimate of *Natural Rainfall* is obtained from (B2) as:

$$Natural\ Rainfall_{itkj} = K^{-1}\exp\left(-LogAtlantEffect_{itkj}\right) \times Observed\ Rainfall_{itkj}$$

Finally, the estimated contribution from Atlant (which can be positive or negative) for a gauge-day observation of rain is:

$$Atlant\ Attribution_{itkj} = Observed\ Rainfall_{itkj} - Latent\ Rainfall_{itkj} \,.$$

The constant K in (B5) above is typically greater than one and corrects for the bias that is inherent in using exponentiation to move from logarithm scale rainfall to raw scale rainfall. This bias arises because an effect that changes the mean on the log scale has an asymmetric effect on the variance at the raw scale, understating positive residuals and overstating negative residuals.

In order to motivate how K is calculated, we merge the indices *itjk* into a single index *i* that identifies individual day-gauge observations. We then note that (B1) implies

$$R_i = AE_i \times OE_i \times \delta_i = \exp(ALE_i + OLE_i)\delta_i$$

where R_i denote the observed rainfall at a gauge on a given day, AE_i and OE_i are positive-valued random variables that represent the contributions from Atlant and non-Atlant sources respectively to observed rainfall, with $ALE_i = \beta^T z_i$ and $OLE_i = \alpha^T x_i + \gamma_i$ denoting the corresponding logarithm scale contributions, and δ_i is a positive-valued random variable with expectation equal to one whose values are mutually uncorrelated with one another.

Let $\widehat{ALE_i}$ and $\widehat{OLE_i}$ denote the predicted values for ALE_i and OLE_i defined by the fit described in ***Table 5***. Since $E\left(\log(\delta_i)\right) \neq 0$, the naive predictor of raw scale rainfall obtained by 'back-transformation' of the logarithm scale predictor (B1) is

$$\hat{R}_i^{naive} = \exp(\widehat{ALE_i} + \widehat{OLE_i}) = \widehat{AE_i}^{naive} \times \widehat{OE_i}^{naive} \,.$$

This predictor is biased low. Its bias can be corrected using a smearing adjustment (Duan, 1983),

$$\hat{R}_i^{adj} = \lambda \hat{R}_i^{naive}$$

where

$$\lambda = n^{-1}\sum\left(R_i / \hat{R}_i^{naive}\right).$$

This adjusted estimated value of R_i can then be decomposed into corresponding adjusted Atlant and non-Atlant contributions by writing

$$\hat{R}_i^{adj} = \lambda \hat{R}_i^{naive} = \lambda_{AE}\widehat{AE_i}^{naive} \times \lambda_{OE}\widehat{OE_i}^{naive} = \widehat{AE_i}^{adj} \times \widehat{OE_i}^{adj}$$

where $\lambda_{AE} > 1$, $\lambda_{OE} > 1$ and $\lambda_{AE}\lambda_{OE} = \lambda$. Since there is no obvious way of defining these component adjustments, we adopt a pragmatic approach, setting $\lambda_{AE} = 1 + a$, $\lambda_{OE} = 1 + ma$, where m is a suitably chosen positive constant. Noting that $\lambda = 1 + r$, where $r > 0$ is known, it follows that we must have $a + ma + ma^2 = r$, and solving for a we then obtain

$$a = \frac{\sqrt{(1+m)^2 + 4rm} - (1+m)}{2m}$$

or equivalently

$$k_{AE} = 1 + \frac{\sqrt{(1+m)^2 + 4rm} - (1+m)}{2m}.$$

How to choose m? One choice is $m = 1$, in which case

$$\lambda_{AE} = \sqrt{1+r} = \sqrt{\lambda}.$$

Other choices are $m = 0$, in which case $\lambda_{AE} = \lambda$, and $m = \infty$, in which case $\lambda_{AE} = 1$. Given that the relative sizes of λ_{AE} and λ_{OE} should reflect the relative difference in the variances of ALE_i and OLE_i, we use

$$m = \frac{Var(\widehat{OLE_i})}{Var(\widehat{ALE_i})}.$$

With this definition, we see that if $Var(\widehat{OLE_i}) >> Var(\widehat{ALE_i})$ then $\lambda_{AE} \approx 1$, i.e. there is virtually no transformation bias adjustment for the estimated Atlant contributions, while if the reverse holds then virtually all the transformation bias adjustment λ for fitted values of *Observed Rainfall* is concentrated in the estimated Atlant attributions. Finally, we set $K = \lambda_{AE}$.

Appendix C – Instrumental model regression

The following tables show the fit of the instrumental variable model to upwind gauge level data from 2010 and 2009. 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 14***); 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, there were still two days (3/9 and 7/12) in 2010 when the rainfall was extreme. These days are allowed for via the inclusion of the zero-one effect Heavy Rain Day in the 2010 model. 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. The instrumental variable Predicted LogRain in ***Table 7*** and ***Table 9*** is then calculated using the fitted value formula generated by the appropriate instrumental model fit.

Table B1 Gauge level regression results for upwind logarithm of rainfall in the 2010 trial.

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 (100m)	0.0618	0.0138	<.0001
Random Effects			
Group	**Variance Component**	**Per Cent of Total**	
Gauge	0.068010	4.769	
Day	0.717713	50.329	
Residual	0.640307	44.901	
Total	1.426031	100.000	
Summary			
RSQ = 0.72			
Obs = 4388			

Table B2 Gauge level regression results for upwind logarithm of rainfall in the 2009 trial.

Parameter	Estimate	SE	Significance
Intercept	37.0118	22.3420	0.1019
AugSept	-0.5926	0.2645	0.0279
Precipitable Water	0.0847	0.0267	0.0022
First PC (TT&LI)	-0.0663	0.0812	0.4169
Second PC (TT&LI)	0.0558	0.1030	0.5893
Wind Speed 700	-0.0103	0.0075	0.1728
Wind Speed 700 L1	0.0079	0.0072	0.2802
Wind Speed 850	0.0276	0.0141	0.0539
Wind Speed 850 L1	-0.0066	0.0145	0.6530
Wind Speed 925	-0.0034	0.0132	0.8003
Wind Speed 925 L1	0.0041	0.0125	0.7415
LSWD 700	4.4326	2.9691	0.1383
LSWD 700 L1	1.5523	4.3178	0.7201
LSWD 850	-1.1294	2.8941	0.6971
LSWD 850 L1	-3.4136	3.1373	0.2795
LSWD 925	0.0615	2.1266	0.9770
LSWD 925 L1	2.1888	1.8304	0.2353
Average Daily Temp	-0.1124	0.0617	0.0724
Temp Range	-0.0477	0.0284	0.0971
Dew Point Difference	0.0025	0.0540	0.9627
Dew Point Range	0.0277	0.0397	0.4874
Sea Level Pressure	-0.0375	0.0215	0.0856
Pressure Range	0.0172	0.0248	0.4915
Elevation (100m)	0.0609	0.0155	0.0001
Random Effects			
Group	**Variance Component**	**Per Cent of Total**	
Gauge	0.060601	4.482	
Day	0.631826	46.729	
Residual	0.659685	48.789	
Total	1.352112	100.000	
Summary			
RSQ = 0.69			
Obs = 3274			

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