STATISTICAL MODELING OF RAINFALL ENHANCEMENT

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ABSTRACT. Non-stationary spatial variation makes it difficult to establish real-time areas of control and effect in weather modification. Non-stationary temporal variation makes the comparison of long-term averages from limited climatic records open to question. Here we describe a statistical methodology which addresses both problems explicitly, in a trial of a ground-based ionization technology known as Atlant, and which could be applied to other weather modification technologies more generally. The approach adopted here is based on a statistical model for daily rainfall that achieves a high level of real-time control by the inclusion of both spatial and temporal components. In particular, it makes use of daily gauge level rainfall data, orographic and daily meteorological covariates, as well as dynamically defined downwind areas, to model the impact of Atlant operation on rainfall. Subject to the caveat that the trial was not randomized in any way, this type of dynamic control demonstrates a clear rainfall enhancement effect at both a simple observational level and when a spatial random effects model is used to control for covariates. Rainfall downwind of the Atlant test site was 15% higher than rainfall in the control (crosswind or upwind) areas. Based on these results, randomized trials with multiple sites are currently being conducted in the same area.

1. INTRODUCTION

With predicted climate change anticipated to have major impacts on the world's fresh water supply in the coming decades, it is imperative that new statistical models and techniques be developed to accurately quantify and evaluate a range of rainfall enhancement technologies in cost effective time frames. However, conclusive empirical evidence of weather modification – that is, persistent or recurring changes in local or regional weather patterns due to human intervention – is difficult to obtain because of the non-stationarity of meteorological conditions over space and time. The former, in particular, makes it difficult to establish real-time control and effect areas, while the latter makes comparison with long-term averages obtained from limited climatic records open to question. For decades major cloud seeding experiments have reported statistically significant increases in rainfall at high levels of confidence (e.g. CLIMAX I and II, Mielke *et al.* 1971; ISRAEL I and II, Grant and Neumann 1974, 1981). However, conclusive evidence that establishes various types of cloud seeding as an effective and viable means of rainfall enhancement remains elusive (WMO 2007; NRC 2003). Recent reviews of cloud seeding experiments to enhance precipitation detail a history of reported positive statistical results that have come under scrutiny and have been questioned, weakening their scientific credibility (Ryan and King 1997, Bruinjtes 1999). Most recently a comprehensive review of 45 years of cloud seeding in Tasmania, Australia, found consistent and credible statistical results but concluded that further field measurements of the cloud microphysics were needed to provide a physical basis for these statistical results (Morrison *et al.* 2009).

The problem is exacerbated where a causal link between the operation of a rainfall enhancement technology and increased rainfall has not been demonstrated. Establishing a physical link between ground-based ionization and rainfall would require an extensive multi-disciplinary research effort. Since the 1950's, various forms of ionization devices have been the focus of experiments involving the release of ions into the air from electrified wires (e.g. Vonnegut and Moore 1959, Vonnegut *et al.* 1961, Kauffman 2009). However, the general consensus of the scientific community is one of high skepticism (WMO 2007) despite current literature in the fields of cloud and aerosol microphysics suggesting that ions can influence the formation of clouds and raindrops at multiple stages throughout the process. Within the domain of physical experimentation, the need for statistical evidence is still inevitable (Haman 1976), and field trials appear to be the most effective means of initially establishing

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whether there is a statistical link between rainfall enhancement technologies and rainfall.

An experimental design and statistical method that explicitly addresses the problem of non-stationarity in space and time of meteorological conditions, in the context of a trial of a ground-based ionization technology, known as Atlant, in South Australia is presented in this paper. This effort focuses on the use of spatial statistics to exploit correlations in observed rainfall between individual gauges, on a daily or higher frequency basis, and the application of dynamic control areas defined on the basis of prevailing meteorological conditions. Specifically, the approach is based on a statistical model for daily rainfall during the trial that achieves a high level of real-time control by the inclusion of both spatial and temporal components. In particular, it makes use of daily gauge level rainfall data, orographic and daily meteorological covariates, as well as dynamically defined downwind areas, to model the impact of Atlant operation on rainfall in the trial area. More generally the method is intended for the purpose of measuring the effects, if any, of ion generation and other enhancement technologies on rainfall.

2. ATLANT

2.1 Background

Lord Rayleigh (1879) was the first to suggest that electrical effects in the atmosphere and rainfall are related. It has been hypothesized that the presence of electric forces enhances collision-coalescence and formation of larger raindrops. This aspect of rain formation has been intensely investigated, both 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 or with modeling studies (Sartor 1960, Lindblad and Semonin 1963, Plumlee and Semonin 1965, Paluch 1970, Schlamp *et al.* 1976). The current literature in the fields 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 Ch. 10 of McGorman and Rust [1998] and Ch. 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/enhancement attributable to the Atlant technology.

However, 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 has been limited. Bernard 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 release of ions into the air to test the effect of priming clouds with negative space charges (Vonnegut and Moore 1959). 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 which 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 space charge released from an electrified fine wire produces large perturbations in the fair-weather potential gradient for distances of 10km or more downwind. Most recently Kauffman and Ruiz-Columbié (2005,2009) conducted field experiments on a DC corona antennae for the purpose of precipitation enhancement and also as a means of aerosol deposition.

2.2 Description of Atlant

Although these previous investigations were not conclusive, they do provide the basis for a plausible hypothesis for how the Atlant system may function 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 framework with a series of pyramids on top. The device's approximate dimensions are 12m x 3m x 5m (Figure 1). It consumes about 500W of power and generates voltages of 70kV.

2.3 Atlant Model

Assumptions about the operation of the Atlant relate to condensation nuclei and drop coalescence. As experiments detailed in section 2.1 have shown, the coalescence efficiency between colliding drops of opposite charge is enhanced, as it also is 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

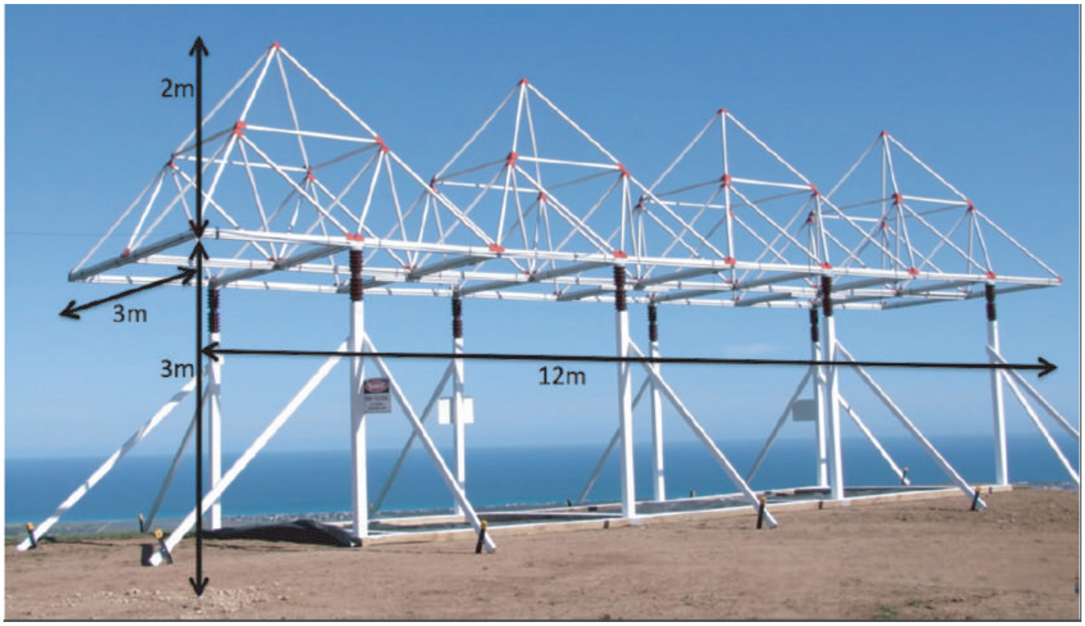

Figure 1. The Atlant Site in South Australia.

drop surfaces prevents coalescence. At small separation distances, the significance of electrostatic forces between the drops increase markedly. In the case of drops of opposite charge, or a charged and neutral drop, the electrostatic forces cause the viscous forces provided by surface tension and thin film of separating air to be overcome more readily, resulting in a higher portion of collisions resulting in coalescence and less bounce (Ochs and Czys 1988). Counterintuitively, 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 largest 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 initial repulsive electrostatic force.

Many questions remain to be answered about the underlying processes; however, based on current understanding, the working hypothesis is outlined below:

1. Initially, negative ions are generated from a high-voltage corona discharge wire array.
2. The ions will be conveyed to the higher atmosphere by wind, atmospheric convection and turbulence.
3. The ions become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN).
4. The electric charges on these particles will be transferred to cloud droplets.
5. The increase in cloud droplet charge enhances coalescence, resulting in enhanced rain drop growth rate and ultimately increasing rainfall downwind from the Atlant.

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

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

2.4 Summary of Previous Trials

2.4.1 Wivenhoe Dam

In May-June 2007, Australian Rain Technologies Pty. Ltd. funded a pilot study trial of the technology in southeast Queensland, closely monitored and evaluated by a team from the University of Queensland (UQ), led by Professor Jurg Keller, Head of the university's Advanced Water Management Centre. The area of influence was defined as the combined catchment area of the Wivenhoe, Somerset and North Pine dams. The control area was defined as that part of the wider study area outside the area of influence. The study used direct measurements of rainfall through official Bureau of Meteorology (BOM) stations and an additional 50 University of Queensland measurement stations installed in the area of hypothesized influence. Comparison of monthly rainfall amounts over the trial period inside and outside the area of influence were made and compared to historic values for the same month over the past 50 years. The results were positive and showed that average rainfall in the catchment area was increased by 28% (Keller *et al*. 2008). Also noted was unusual intensification of radar returns downwind of Atlant that appeared to be correlated with increases in rainfall.

2.4.2 Paradise Dam

From January 2008 until May 2008, the Atlant was trialed over the Wide Bay and Burnett district in Queensland, targeting a 70km circle centered on Paradise Dam, southwest of Bundaberg, again monitored by an evaluation team from the University of Queensland (UQ). Two external control areas, one to the north near Gladstone and the other to the south near Gympie, were selected as they were well outside any potential influence of the Atlant system but had similar historical rainfall patterns. Rainfall gauges were located uniformly in the target and control areas. In the target area 26% more rainfall was recorded than in control areas in 2008, whereas the long-term average rainfall difference only represents 3% of the value recorded in the control areas (Keller *et al*. 2008).

2.4.3 Initial Spatial Analysis

Beare and Chambers (2009) used data from the Paradise Dam trial to conduct an exploratory spatial analysis using daily rainfall data from individual rain gauges within the control and target areas. Random effects models were fitted to daily gauge data. Separate control and effects models were estimated to identify a potential effect of the Atlant (from here on, any potential effect of the Atlant will be referred to as the Atlant effect). The analysis also made use of dynamically specified partitions within the target area, determined by gauge location in relation to distance from the Atlant site and relative to wind direction (derived from daily vertical wind profiles). For example, a gauge 20km from the Atlant site may be directly downwind one day and at a crosswind angle the next. The directional analysis reflects the postulated downwind effect of the ion plume generated by the Atlant system.

The key findings from spatial analysis of the Paradise Dam trial data were that:

- the operation of Atlant was not associated with a significant increase or decrease in the probability of observing a rainfall event in the target area;
- given there was a rainfall event in the area of influence the operation of the Atlant system was associated with a significant and directional impact on rainfall. Within a 30° arc extending 70km downwind of the Atlant site, rainfall was estimated to be 17.6% higher. The effect was significant at the 99% confidence level. The effect was calculated as the predicted difference in rainfall between the control and effects model within and outside the downwind arc;
- the estimated Atlant effects in the areas upwind and crosswind of the site were not significant at the 90%-confidence level.

There were a number of issues raised with regard to the exploratory analysis. They included:

- the need to include an expanded set of meteorological and geographic covariates into the model, such as temperature, humidity and gauge elevation;
- eliminating the use of subjective criteria for determining when and for how long the system was operated; and
- explicitly accounting for spatial correlation between rain gauges when calculating standard errors of the estimated rainfall attributed to the Atlant system.

These issues were addressed in the 2008 Mount Lofty ranges trial.

3. DESIGN OF THE 2008 MOUNT LOFTY RANGES TRIAL

3.1 Site Location and Trial Area

The Atlant emitter was situated 44km south-southwest of Adelaide, South Australia, approximately 7km inland, on the first significant ridgeline of the southeast Mount Lofty Ranges (Figure 2). A successful trial had the potential to significantly augment supplies in this region, which had experienced an extended period of well below average rainfall, creating water shortages for commercial, urban users and the environment. The region has a Mediterranean climate, and generally experiences a dry and warmer period from November to April with prevailing trade wind from the southeast to east and a moderately wet and colder period from May to October with prevailing wind from the northwest to southwest with regular cold fronts (BOM 2008). The ranges are oriented northeast to southwest, and expose the Atlant to the prevailing weather during the trial period, typically from the west. The site was located at an elevation of 348m above sea level and has significant upslope valleys located to the west and northwest. The landform elevation rises from the coast travelling from west to east at a 1.1%

rise while the final 4.3km distance travelling east is a steeper 12.3% rise for 2.1km and the last 200m a very steep 21.7%. Typically, a moist marine onshore airflow from the west rises as it approaches the Atlant site due to orographic lifting.

In a previous trial, the University of Queensland estimated the probable area of influence of a single Atlant emitter to be within a range of 50-100km from the Atlant site, depending on the meteorological situation (Keller *et al.* 2007). However, prior to this trial the potential downwind extent of the Atlant footprint had not been statistically evaluated. Given the topography of the region, identifying an external control area would be difficult because the meteorological and topographic characteristics of neighboring areas are quite different from the trial area. When compared with the trial area, the land area to the north and east is relatively flat and dry, and the influence of offshore cold fronts on precipitation is not nearly as strong.

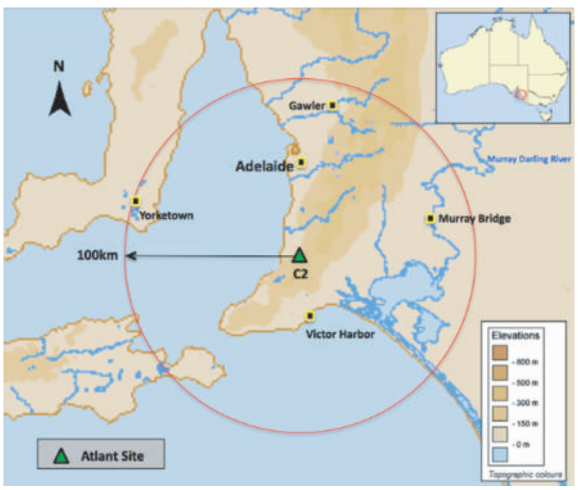

Figure 2. Land and water mass within a 100km radius about the trial site.

3.2 Trial Area Cloud

The incidence of cloud and rain in the trial area occur in association with frontal systems originating from low-pressure centres over ocean to the south of the trial area. On average they pass west to east approximately every 4-6 days during the trial period. Typically prefrontal altostratus moves in from the northwest and is replaced on the passage of the front by large cumulus degenerating to smaller cumulus coming from the west and southwest, stretching up to 200-300 km behind the boundary. The cumulus cloud bases average 500-1,000 meters with cloud top temperatures between 1 and -2°C. Eventually the weather clears from the west as the next high pressure system approaches. Freezing levels during August and September in the Adelaide Hills region will be in the 2,000-2,500 meter range rising to 4,000 meters and above in November. Typically post-frontal clouds are formed in a maritime air stream, below the freezing level and as such rain formed predominantly by the coalescence process. Based on the working hypothesis for how Atlant may modify the rain process, it was thought that cumulus and stratocumulus behind the frontal boundary would be most suitable for enhancement. However, as the technology is cheap to operate and suitable operating conditions not well defined, the operating protocol (described in section 3.3) was purposefully set to be very wide ranging to encompass the majority of cloud types including pre-frontal deep stratiform clouds which extend above the freezing level and likely produce rain by an ice-nucleation mechanism.

3.3 Operating Schedule

The trial ran for four months, from 9am on 1 August 2008 to 9am 1 December 2008, and was subject to an operating protocol. In particular, the operation of the Atlant technology was controlled by a team of meteorologists following a pre-described set of guidelines, which specified the meteorological parameters under which the Atlant system would be switched on. The main parameter for operation was forecast or observed significant cloud cover within the trial area (cloud depth of greater than 1km at any level in the atmosphere). The Atlant was operated three hours prior to the development or arrival of significant cloud cover within the trial area to ensure the Atlant-produced ions had sufficient time to disperse throughout the trial area through natural processes (wind, turbulence and convection). In some circumstances this lead-time was shorter than anticipated due to more rapid cloud development (on the order of 30 minutes). Significant cloud cover was typically inferred from model forecasts of wind, stability and moisture profiles as well as weather observations. Actual vertical profiles of the atmosphere taken at Adelaide Airport provided by the Australian Bureau of Meteorology (BOM) were used as a verification tool, as well as remotely sensed data from satellites. Operation of Atlant continued for a period of two hours after cloud had dissipated from the trial area. In the non-operating times, necessary system maintenance was conducted. Under some circumstances planned operation was not possible due to severe weather conditions or when the system was inoperable due to technical faults and damage.

3.4 Rainfall Data

The BOM maintains an extensive rain gauge and weather station network within the trial area. There were 159 BOM gauges that reported data during the trial period. Of these, 79 had daily rainfall data for the trial period (August to November) for the ten years 1999-2008. These gauges are referred to as historical BOM gauges in what follows. The BOM gauge data was supplemented by 54 ART weather stations that were programmed to record precipitation at 12-hourly intervals at 9am and 9pm daily. Figure 3 is a contour plot of gauge elevation for all 213 gauges that contributed data to the trial. The locations of the 79 historical gauges are identified in blue and the Atlant site location is shown as the intersection of the lines running north-south and east-west.

There were a substantial number of missing records as some gauges failed intermittently. The ART gauges were not in place until September 2008 and some were lost through the balance of the trial. On the basis of the records that were available, there were 7,915 'rain events' (gauge-days with rain) and 12,006 gauge-days with no rain recorded over the trial period. One of these, an isolated reading of 131.8mm on August 13 for the Inglewood Alert gauge, was excluded from the subsequent analysis. The distribution of daily rainfall observations in the trial area was strongly right skewed. Raw observations were therefore transformed using the natural logarithm. Since the logarithm of zero is not defined, this automatically resulted in the analysis being confined, for each gauge, to days when rainfall was recorded. In what follows, this transformed value is referred to as *LogRain*. The percentiles of distributions of *LogRain* from August though November 2008, is shown in Table 1.

It is reasonably clear that distributions of rainfall over the trial period for the historical and remaining gauges are not similar, highlighting the lack of geographic stationarity within the trial area. The mean and the median of the historical gauges are considerably higher than the corresponding mean and median of the remaining gauges and the interquartile range (25% to 75%) of the *LogRain* distribution for the historical gauges is wider than the corresponding range of the *LogRain* distribution for the remaining gauges. Consequently, we cannot use 1999-2007 rainfalls for the historical gauges as a temporal control for the 2008 rainfall observed in the trial.

Table 1. Percentiles of distributions of LogRain for the historical and the remaining trial rain gauges, August–November 2008.

Percentile	Historical gauges	Remaining gauges
100.0%	3.311	4.881
97.5%	2.653	2.625
90.0%	2.104	2.054
75.0%	1.569	1.435
50.0%	0.742	0.588
25.0%	-0.223	-0.511
10.0%	-0.916	-1.609
2.5%	-1.609	-1.609
0.0%	-2.708	-2.303
Mean	0.647	0.460
Std Dev	1.170	1.251
No. of Records	3399	4516

3.5 Secondary Data

Secondary data was obtained from the BOM. The data sets include daily meteorological observations from Adelaide airport and the location and elevation

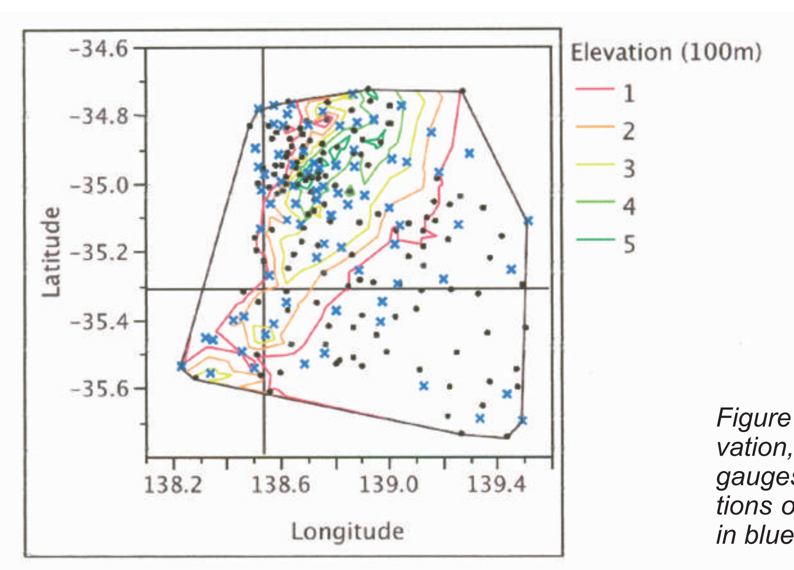

Figure 3. Contour plot of gauge elevation, showing spatial distribution of gauges across the trial area. Locations of historical gauges are shown in blue.

of BOM rainfall gauges. (The location and elevation of ART rain gauges were obtained using a hand-held GPS receiver.) Observations from Adelaide airport were available from 1999 through 2008. The observations were calculated as daily averages and included:

- wind speed (km/h) with separate readings at 500hPa, 700hPa and 850hPa;
- wind direction (degrees from due north, clockwise) with separate readings at 500hPa, 700hPa and 850hPa;
- air temperature;
- dew point temperature;
- mean sea level pressure.

Steering winds are associated with the general direction and speed in which clouds are moving and will vary with the height of the cloud layer(s). Steering wind direction and speed were approximated by an average of the 500hPa, 700hPa and 850hPa readings. The distributions of daily steering wind direction and speed for August–November 2008 on rain days, i.e. days when rain was recorded for at least one of the gauges in the trial area, are shown in Figure 4. Note the small variation in the steering wind direction distribution, with virtually all the readings concentrated in the SW quadrant (180° - 270°).

Over the 24-hour period in which rainfall was measured, wind direction and speed will vary. Consequently, the boundaries of any downwind effect will be fuzzy. However, steering wind directions on rain days in the trial period did fall within a limited range (Figure 4) and variation in wind direction and speed would be expected to be less within a 24-hour period. As a consequence, the number of rainfall gauges which are downwind of the Atlant site for at least part of a day is likely to fall within an even more limited range. Observations of vertical wind profiles at Adelaide airport are available on a six-hourly basis. The adjusted daily ranges in wind direction (i.e. the range in the absolute values of wind direction minus 180°) were therefore calculated on a 9am to 9am basis. The distributions of these adjusted daily ranges of wind directions at 700hPa and 850hPa over the trial period are shown in Figure 5.

4. HISTORICAL OROGRAPHIC ANALYSIS

A historical orographic analysis was conducted by fitting a random intercepts linear model to *LogRain* values from August–November for each of the years 1999-2008 for the historical gauges. This is a model of the form:

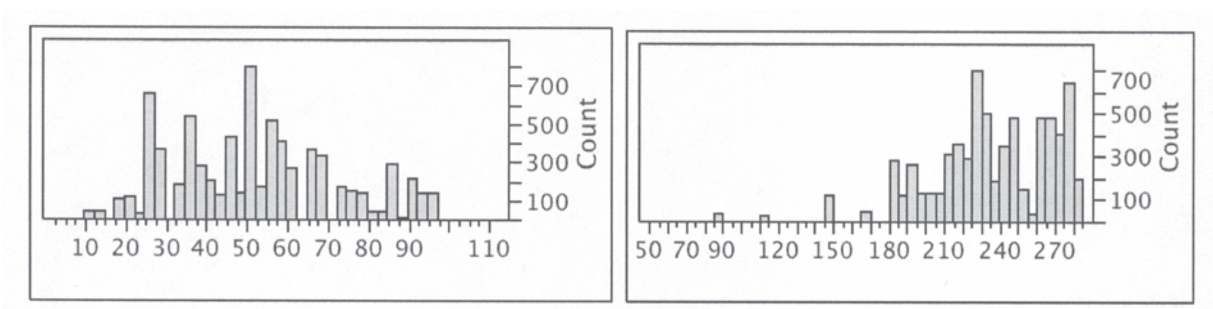

Figure 4. Gauge values of daily steering wind speed (left) and wind direction (right) on rain days.

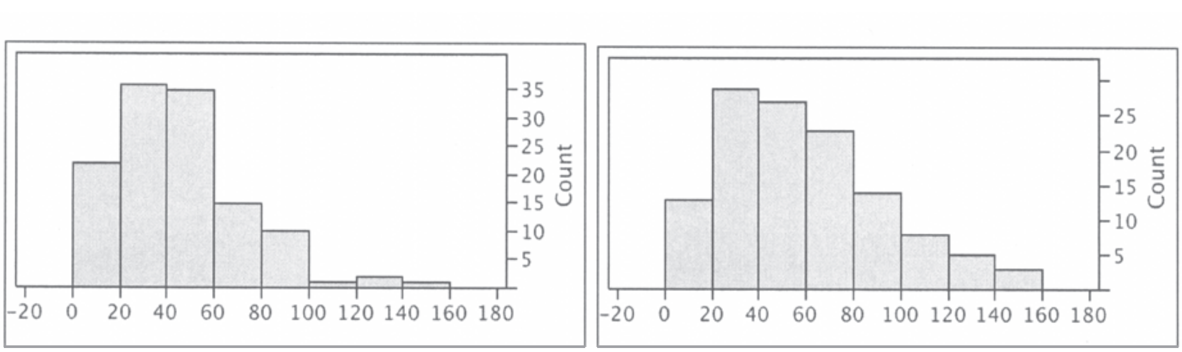

Figure 5. Distributions of the adjusted daily range in wind directions over the trial period at 700 hPa (left) and 850 hPa (right).

$$LogRain_{it} = \alpha^T x_i + \beta^T y_t + \gamma_i + \varepsilon_{it} \quad (1)$$

where *i* denotes gauges and *t* denotes the day within a year, α and β are coefficient vectors, *x* is a vector of orographic covariates that are specific to gauge locations, *y* is vector of meteorological covariates that vary over time, γ is a vector of gauge specific random effects and ε is a random error that varies between gauges and over days. The choice of a random intercepts model allows for an unobserved or unmeasured time invariant independent of orographic effects at each gauge site. The overall orographic effect in the model is therefore a linear combination of what can be explained by the orographic covariates and this gauge specific random effect:

$$\alpha^T x_i + \gamma_i. \quad (2)$$

Two issues arose when attempting to control for the influence of orographic effects on rainfall. These were:

- the predominant southwest wind direction and the topography of the Mount Lofty ranges, which gives rise to a strong declining rainfall gradient extending from west to east across the trial area; and
- the potential interaction between meteorological conditions, particularly wind speed and direction, topography and rainfall. That is, the distribution of gauge specific random effects in the model may vary from day to day.

While elevation is an obvious orographic covariate, the elevation of a gauge may not provide much information about the neighboring topography. Geographic location can also serve as proxy for orographic influences in the vicinity of a gauge. This can be controlled for by the inclusion of a factor in the rainfall model (1) that allows a different average rainfall to be observed in different parts of the trial area, though it leaves open questions concerning the shape and size of these sub-areas. In the results shown below we divided the trial area into nine sub-areas based on gauge locations. Figure 6 is a contour plot of gauge elevation for the 79 historical gauges, showing nine sub-areas (dotted lines) as well as the location of the Atlant site (intersection of the solid lines). The estimated orographic effect for a particular gauge is then a function of its elevation and the sub-area in which it is located. Operationally, the nine sub-areas shown in Figure 6 are defined in terms of the cross-classification of three latitude and three longitude zones:

- Southern Latitude Zone (SLaZ): Latitude < -35.3
- Middle Latitude Zone (MLaZ): $-35.3 \leq$ Latitude < -35.0
- Northern Latitude Zone (NLaZ): Latitude $\geq$ -35.0
- Western Longitude Zone (WLoZ): Longitude < 138.6

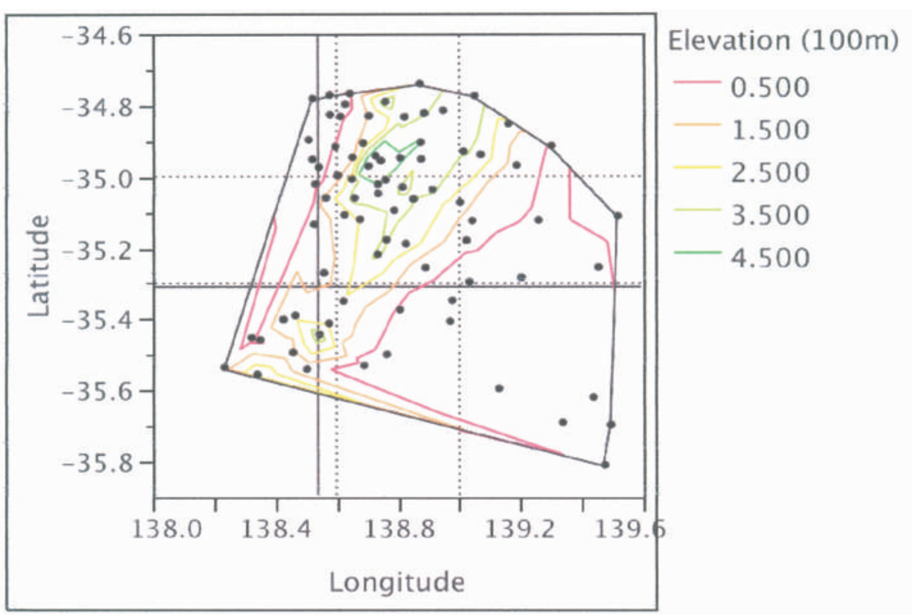

Figure 6. Contour plot of gauge elevation showing locations of 79 historical gauges within the nine sub-areas, as well as relation to the Atlant site (intersection of solid lines).

- Middle Longitude Zone (MLoZ): 138.6 ≤ Longitude < 139.0
- Eastern Longitude Zone (ELoZ): Longitude ≥ 139.0.

The model was fitted for each year from 1999 though 2008 using rainfall and meteorological data for the months of August through November. The model-fitting method was Restricted Maximum Likelihood (REML) (Patterson and Thompson 1971) and the resulting fits are summarized in Table 2. Estimates that are significant at the 5% level are bolded. The variability in the significant coefficient estimates from year to year provides an indication of the lack of temporal stationarity in the data. Seasonal effects, which are represented by an indicator variable that takes on the value of one in a given month and zero otherwise, are significant in each year. The effects of elevation are also significant in each year. The majority of the metrological covariates are significant, including meteorological conditions on the previous day. The lagged meteorological covariates were included as a proxy for persistent conditions that were not measured directly. The sub-area effects are generally not significant at the 95% confidence level, indicating that at this level of spatial aggregation of gauge locations, elevation accounts for most of the variation in rainfall explained by the fixed orographic effects within the model.

Table 2. Parameter estimates for year-specific models for LogRain with random gauge effects (bolded text indicates significant at 5% level, L1 denotes a one day lag).

Term	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Intercept	**56.08**	**25.81**	**65.98**	**68.95**	**59.64**	**32.49**	**79.96**	**21.76**	**38.57**	**32.52**
August	**-0.498**	**0.230**	**-0.314**	**-0.137**	**-0.019**	**-0.329**	**-0.062**	**-0.262**	**-0.725**	**0.429**
September	**-0.173**	**-0.514**	**0.121**	**0.018**	**-0.273**	**-0.285**	**-0.332**	**0.261**	**-0.040**	**-0.034**
October	**0.126**	**0.283**	**-0.070**	**-0.349**	**0.060**	**0.135**	**0.067**	**-0.114**	**0.004**	**-0.457**
Elevation (100m)	**0.095**	**0.102**	**0.112**	**0.119**	**0.118**	**0.093**	**0.131**	**0.094**	**0.084**	**0.084**
Geographic Zone SLaZ	0.000	0.075	0.033	**0.164**	0.069	**0.080**	0.033	0.006	**0.237**	**0.141**
Geographic Zone MLaZ	-0.022	-0.015	-0.004	0.076	0.020	0.026	0.047	0.067	**-0.081**	0.014
Geographic Zone WLoZ	0.061	0.100	**0.119**	**0.118**	0.026	0.047	**0.161**	0.063	0.057	0.005
Geographic Zone MLoZ	0.011	-0.007	0.074	**0.132**	0.030	0.068	0.075	**0.117**	**0.118**	0.068
SLaZ & WLoZ	-0.027	0.005	0.008	-0.051	-0.040	**-0.126**	-0.004	0.060	-0.046	-0.014
SLaZ & MLoZ	0.026	**-0.152**	-0.108	-0.128	-0.012	-0.099	-0.042	0.016	**-0.133**	0.007
MLaZ & WLoZ	0.061	0.137	0.093	0.013	0.148	0.081	0.033	0.014	0.105	0.059
MLaZ & MLoZ	-0.081	0.035	0.002	-0.020	-0.043	-0.052	-0.007	-0.034	0.027	-0.051
Wind Speed 500	**0.011**	**-0.012**	0.002	-0.002	**0.004**	**0.009**	**-0.010**	**0.006**	**-0.010**	-0.002
Wind Speed 500 L1	0.001	**-0.005**	**-0.008**	0.001	0.000	0.012	**0.009**	**0.007**	**0.018**	**0.004**
Wind Direction 500	**-0.007**	**0.003**	**-0.006**	-0.002	**0.006**	**0.006**	**-0.002**	**-0.007**	**0.029**	**-0.006**
Wind Direction 500 L1	**0.003**	**0.003**	**0.004**	0.011	**0.007**	-0.001	0.001	**-0.005**	**-0.005**	**0.007**
Wind Speed 700	**-0.030**	**0.034**	**0.005**	-0.022	**-0.009**	**-0.017**	**0.010**	**-0.019**	0.002	0.002
Wind Speed 700 L1	**-0.023**	**-0.013**	**-0.015**	0.003	**-0.005**	**-0.034**	**-0.014**	**-0.008**	**-0.039**	**-0.016**
Wind Direction 700	**-0.004**	0.000	-0.002	-0.001	**-0.010w**	**-0.010**	**-0.007**	0.004	**-0.031**	0.001
Wind Direction 700 L1	0.001	**-0.006**	**0.005**	**-0.002**	**-0.004**	**0.011**	**0.009**	**0.010**	**0.013**	**0.004**
Wind Speed 850	**0.037**	**0.008**	**-0.004**	**0.037**	**0.011**	**0.021**	0.003	**0.032**	**0.028**	-0.001
Wind Speed 850 L1	**0.048**	**0.042**	**0.053**	**0.013**	**0.019**	**0.041**	**0.030**	**0.016**	**0.023**	**0.024**
Wind Direction 850	**-0.002**	**-0.011**	**-0.002**	**-0.007**	**-0.002**	**0.001**	0.000	-0.001	0.000	**0.001**
Wind Direction 850 L1	**0.001**	**0.007**	**-0.001**	**0.003**	0.000	-0.004	**-0.009**	-0.001	**0.001**	**-0.002**
Air Temperature	**-0.207**	**-0.093**	**-0.200**	**-0.175**	**-0.189**	**-0.250**	**-0.237**	**-0.144**	**-0.306**	**-0.145**
Dew Point	**0.132**	**0.082**	**0.072**	**0.084**	**0.126**	**0.071**	**0.181**	**0.092**	**0.085**	0.017
Sea Level Pressure	**-0.052**	**-0.026**	**-0.063**	**-0.067**	**-0.057**	**-0.031**	**-0.075**	**-0.021**	**-0.037**	**-0.032**
R-Squared	49.4%	48.2%	44.4%	44.8%	33.1%	50.0%	46.5%	39.0%	47.4%	33.9%
Random Effects	3.1%	2.9%	2.9%	4.9%	3.4%	1.8%	2.1%	3.7%	1.5%	2.3%
Residual Effects	96.9%	97.1%	97.1%	95.1%	96.4%	98.2%	97.9%	96.3%	98.5%	97.7%

The summary statistics include the percentage of variation in rainfall accounted for by all the covariates in the model (R-Squared). The unexplained variation is decomposed into the percentage attributed to random gauge effects and a residual balance. On average the model explains over 43.7% of the gauge level variation in *LogRain*. The random gauge effects (estimated via REML) account for approximately 3% of the unexplained variation in gauge level rainfall, on average. This indicates that any fixed independent orographic effects that are not captured by the orographic covariates included in the model are relatively small. It also suggests that elevation captures the majority of the fixed orographic effects and that a finer regional resolution would not greatly improve the model specification.

Non-fixed orographic effects

By fitting the model each year we can see how stable the estimated orographic effects are. This is important because the distributions of wind speed, wind direction and other meteorological variables vary from year to year. A lack of stability would suggest that orographic effects are dependent on prevailing meteorological conditions. The order of magnitude of the estimated elevation coefficient in the model is stable over time but the estimates do range from a low of 0.084 to a high of 0.131 with an average over the 10 years of 0.103. The individual coefficient estimates for the sub-area covariate vary significantly between years. This was confirmed by fitting a model in which the estimates of the orographic effects were constrained to be the same in each year. This model was clearly rejected in favor of a model that allowed the effects to vary between years.

As the estimated orographic effects, assumed to be fixed within a year, vary over time, the random effects model does not fully control for potential orographic influences. This does imply a significant increase in rainfall could be observed relative to an arbitrary location due to unaccounted-for orographic effects. That is, the choice of the Atlant site could matter. Looking at the variation in the random effects provides some insight about the strength of these effects. By construction the random gauge effects have a mean of zero in any given year. The variance of the random effects is not constant and, while the variance of the random effects is a small proportion of the total variance in *LogRain*, it is still related to the mean as well as the variance of actual rainfall. In standard mean and variance notation:

$$\mu_{Rain} = \exp\{\mu_{LogRain} + 1/2(\sigma^2_{RandomEffect} + \sigma^2_{Residual})\} \quad (3)$$

The mean level effect on rainfall of the variance of the random effects for *LogRain*, expressed in percentage terms, is simply:

$$\textit{mean effect} = 100\,\{\exp(1/2\sigma^2_{RandomEffect}) - 1\} \quad (4)$$

Over the 10-year period the mean effect on observed rain ranged from 0.7% to 2.2%. Again the range of these effects is small.

5. ANALYSIS OF THE ATLANT TRIAL

The analysis of the trial data was carried out in three stages. First, a descriptive analysis was used to investigate marginal relationships between observed rainfall and wind direction, elevation, location and distance from the Atlant site. The purpose of this analysis was to examine evidence for an apparent Atlant effect in the raw data. Second, a statistical model for *LogRain* that simultaneously controlled for gauge-to-gauge and day-to-day variation in meteorological and orographic covariates was fitted to gauge-day data in order to estimate the influence of the Atlant system on rainfall after accounting for these factors. In the final stage, the level of Atlant-induced rainfall enhancement achieved during the trial was estimated.

5.1 Descriptive Analysis

The Atlant system generates a passive plume of ions that relies on the uplift at the site and low-level atmospheric turbulence to carry charged particles to the cloud layer. The conveyance model is analogous to a cold plume emitted from a point source. This leads to the following hypotheses regarding the enhancement effect:

- the primary effect will be downwind of the Atlant site;
- the effect will dissipate laterally and in the downwind direction as the concentration of the particles or aerosols within the plume declines; and
- the rate of lateral versus downwind dissipation is likely to be influenced by wind speed.

The adjusted daily range in wind direction tends to be 120° or less, particularly in the higher elevation winds. We therefore took a 120° arc centered about the average daily steering wind direction and extending downwind from the Atlant site as defining the extent of the downwind area of Atlant effect within the trial area. We defined for any day that rain was recorded at any gauge:

- Downwind Rain = recorded daily rain for gauge when it is within this 120° arc on the day, otherwise missing;

- Cross/Upwind Rain = recorded daily rain for gauge when it is not within this 120° arc on the day, otherwise missing.

Averages and medians of non-missing gauge-day values of Downwind Rain and Cross/Upwind Rain over both a 24h and a 48h period were then calculated for four different levels of intensity of Atlant operation over the preceding 48h, defined by allocating each rain day of the trial to one of the following groups:

- Atlant operational between 0 and 12h in the preceding 48h;
- Atlant operational between 12 and 24h in the preceding 48h;
- Atlant operational between 24 and 36h in the preceding 48h;
- Atlant operational between 36 and 48h in the preceding 48h.

Values of these averages and medians are shown in Table 3. In general, increased hours of Atlant operation are associated with an increase in Downwind Rain relative to Cross/Upwind Rain. The pattern is reasonably consistent for rainfall values measured over both 24h and 48h periods. The median level differences in Downwind Rain versus Cross/Upwind Rain are larger, in percentage terms, than the mean level differences. This suggests that the observed differences are not simply due to a few large outlying observations.

In the previous table, the set of downwind gauges (i.e. those inside the 120° arc centered about the average daily steering wind direction and extending downwind from the Atlant site) changes from day to day; a downwind gauge one day can be a cross/upwind gauge on another day. In what follows we therefore compare a fixed set of gauges based on the percentage of rain days that they are downwind gauges. A contour plot showing the spatial distribution of these downwind percentages for all 213 of the gauges involved in the trial is shown in Figure 7. This is consistent with the location of Atlant and the general SW to NE wind directions observed over the trial period.

Each gauge in the trial area was classified into one of three groups based on the frequency with which it was downwind of the Atlant site on rain days:

- less than 30%;
- greater than or equal to 30% but less than or equal to 70%; and
- greater than 70%.

Average and median levels of Downwind Rain and Cross/Upwind Rain over the preceding 24h and 48h were calculated for gauges in each group. These results are summarized in Table 4. Higher rainfall levels are associated with a greater frequency of days that a gauge is located downwind of the Atlant site.

Table 3. Average and median values of 24h and 48h Downwind Rain and Cross/Upwind Rain classified by hours of Atlant system operation in the preceding 48 hours.

Operating Hours	***Obs***	***Average Rainfall (mm)***			***Median Rainfall (mm)***		
		Downwind	***Cross/ Upwind***	***Δ%***	***Downwind***	***Cross/ Upwind***	***Δ%***
Over Preceding 24 hours (9am – 9am)							
0 - 12	732	2.85	3.17	-10.1	2.2	2.6	-15.4
12 - 24	1917	3.04	2.13	42.7	2.0	1.0	100.0
24 - 36	3637	3.64	2.90	25.5	2.2	1.6	37.5
36 - 48	1219	3.75	2.76	35.9	2.2	1.0	120.0
Over Preceding 48 hours (9am – 9am)							
0 - 12	732	4.43	3.96	11.9	2.8	3.4	-17.6
12 - 24	1917	3.92	3.06	28.1	2.2	1.6	37.5
24 - 36	3637	5.57	3.79	47.0	4.0	2.0	100.0
36 - 48	1219	7.78	5.26	47.9	6.2	2.8	121.4

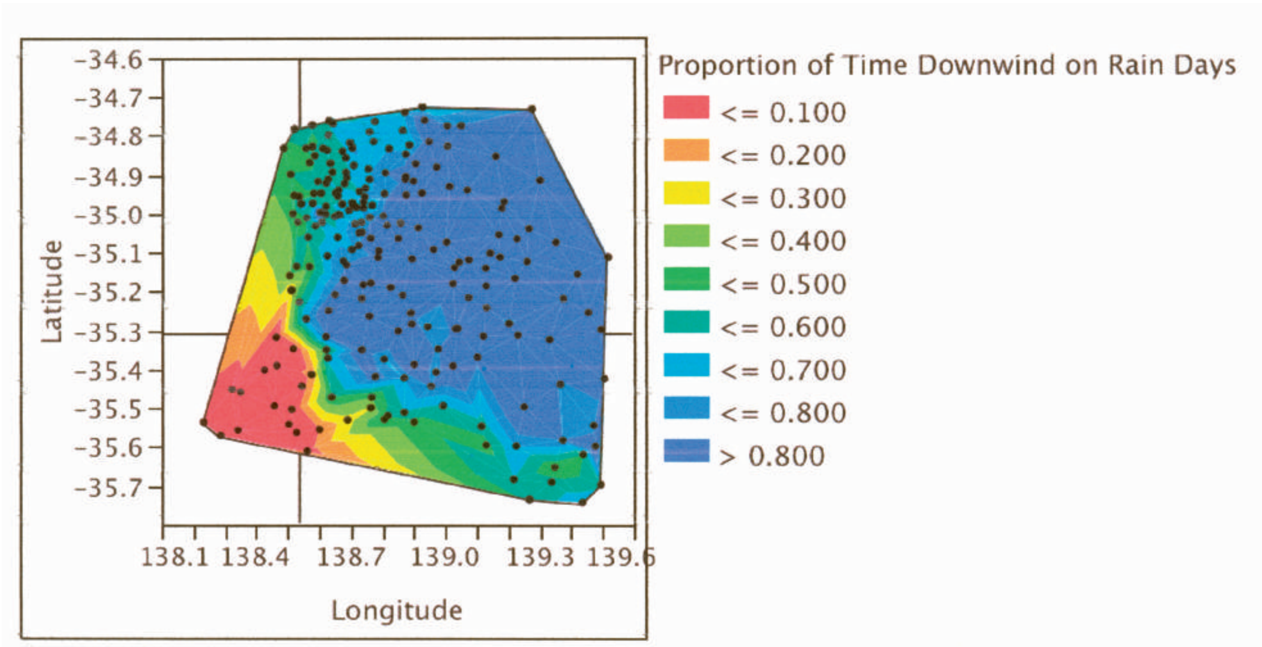

Figure 7. The distribution of gauge locations showing the proportion of rain days that a location was downwind of the Atlant site (identified by intersection of solid lines).

Table 4. Average and median Downwind Rain versus Cross/Upwind Rain for gauges classified by the frequency of rain days that they are downwind of the Atlant site.

Downwind Frequency		***Average Rainfall (mm)***			***Median Rainfall (mm)***		
	Obs	***Downwind***	***Cross/ Upwind***	***Δ%***	***Downwind***	***Cross Upwind***	***Δ%***
24 hours (9am – 9am)							
<30%	20	3.12	3.64	-14.3	2.2	2.07	6.3
30% - 70%	91	3.42	2.44	40.2	2.2	1.35	63.0
>70%	102	3.33	2.28	46.1	2.05	1.55	32.3
48 hours (9am – 9am)							
<30%	20	3.27	6.48	-49.5	2.4	4.68	-48.7
30% - 70%	91	5.06	3.07	64.8	3.38	1.6	111.3
>70%	102	5.28	2.68	97.0	3.4	1.8	88.9

The results displayed in Table 3 and Table 4 can be extended to show how average values of Downwind Rain and Cross/Upwind Rain vary as a continuously distributed variable. Similarly, the distance of the gauge from the Atlant site also varies. In this case we used spline scatterplot smoothers to show how the average values of Downwind Rain and Cross/Upwind Rain vary with this distance. We restrict the analysis to gauges that were downwind of the Atlant site between 30% and 70% of the time. Spline smoothes based on the data for average 24h and 48h rainfall are shown in Figure 8. Note that in both plots the left axis is rainfall in mm and the bottom axis is distance from the Atlant site in degrees (1° = 91km).

Rainfall levels are substantially higher downwind of the site but only over a limited range. The downwind and cross/upwind curves begin to diverge at distances of around 12km downwind. The curves re-converge at about 82km downwind. The effect is more pronounced with 48h rainfall compared with 24h rainfall.

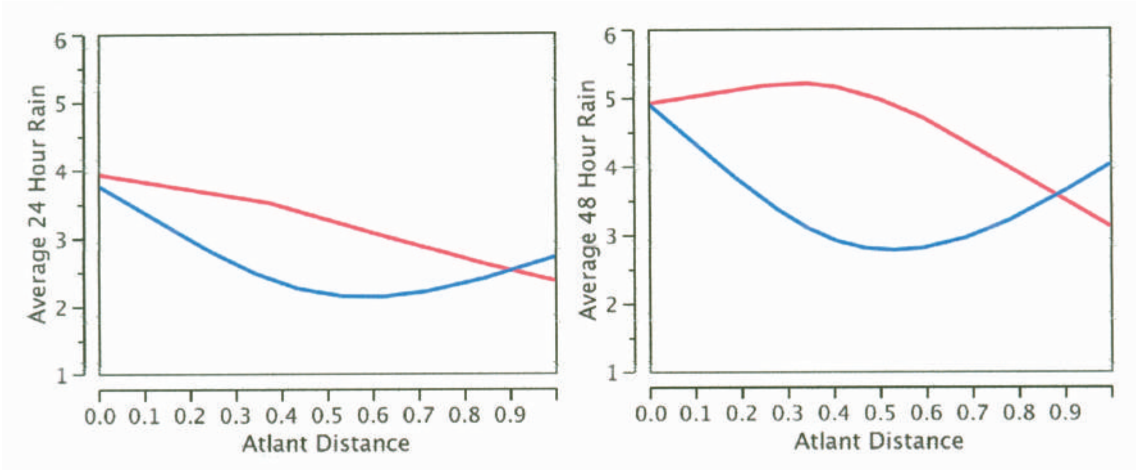

Figure 8. Spline smoothes of average 24h (left) and 48h (right) Downwind Rain and Cross/Upwind Rain as functions of distance from the Atlant site, restricted to gauges that are downwind between 30% and 70% of the time on rain days: Downwind (Cross/Upwind) Rain smooth is in red (blue).

On the basis of the preceding analysis, there appears to be evidence for an association between operation of the Atlant and elevated levels of rainfall. Further, the potential range of the Atlant effect appears to end at around 0.9° or just over 82km. However, we cannot ascribe the differences between Downwind Rain and Cross/Upwind Rain that are evident in our results so far purely to the operation of Atlant. This is because most gauges are downwind of Atlant more than 50% of the time and the orographic effects due to the changing topography of the trial area are from west to east, which was also the most prevalent wind direction. Consequently, before ascribing any differences in rainfall to the operation of Atlant, we must first control for meteorological and orographic effects (particularly gauge elevation, wind direction and wind speed) that also influence the spatial distribution of rainfall. A model for *LogRain* that includes these controls is the focus of the analysis described in the following sub-section.

5.2 Model-based Evaluation

The model (1) for *LogRain* only needs to be modified slightly for the purpose of evaluating the trial data. In particular, we model these data using a random intercepts specification of the form:

$$LogRain_{it} = \alpha^T x_i + \beta^T y_t + \lambda^T z_{it} + \delta^T s_{it} + \gamma_i + \varepsilon_{it} \qquad (5)$$

where λ and δ are vectors of coefficients, *z* is a vector of Atlant covariates and *s* is vector of dynamically specified gauge locations.

The Atlant covariates included:

- the duration, in hours, that the system was operational in a 24h period, starting at 9am. This corresponds with the daily rainfall measurement period used by the BOM. This covariate was used in lagged form in the model, with values ranging from L0 (operating hours in the 24h period up to 9am on the day) to L6 (operating hours in the 24h period up to 9am six days previously);

- the distance in degrees from a rainfall gauge to the Atlant site.

The dynamic specification of gauge locations was done on the basis of the average daily steering wind direction, and corresponded to a categorical variable that identified the dynamic orientation of each gauge relative to the direction of steering wind flow on the day:

- Wind Flow Sector 1–downwind–the gauge is 30° or less away from the steering wind direction;

- Wind Flow Sector 2–downwind–the gauge is between 30° and 60° away from the steering wind direction;

- Wind Flow Sector 3–crosswind–the gauge is between 60° to 90° away from the steering wind direction;

- Wind Flow Sector 4–crosswind–the gauge is between 90° and 135° away from the steering wind direction; and

- Wind Flow Sector 5–upwind–the gauge is more than 135° away from the steering wind direction.

Note that a gauge is classified as being downwind on a particular day if it is in either in Wind Flow Sector 1 or Wind Flow Sector 2 on the day. The random effects model (1) was then fitted via REML, with results summarized in Table 5.

Overall, the model accounts for nearly 50% of the daily gauge variation in *LogRain*. Consistent with the historical orographic analysis the random effects are small, accounting for only around 4% of the residual variation in *LogRain*. The monthly or seasonal effects are highly significant. As with the historical orographic analysis, gauge elevation is highly significant but the fixed sub-area effects are mainly not significant, and are small compared to the overall average. In general the meteorological covariates are highly significant. The exceptions are the higher-level wind speeds at 500hPa and 700hPa.

The Atlant covariates are generally significant. The effect due to distance from Atlant is negative and significant at the 95% confidence level. The main effects for the first two dynamically defined Wind Flow Sectors, i.e. for the downwind gauge-days, are positive and significant at the 99% level. The main effects for the two sectors corresponding to crosswind gauge-days (Wind Flow Sectors 3 and 4) are not significant. Note that Wind Flow Sector 5 (upwind gauge-days) is the reference group for these estimates, so the coefficient for its main effect (-0.301) is obtained as the negative of the sum of the estimated coefficients of the main effects for the other sectors. Note also that a number of the interactions of distance from the Atlant site (Atlant Distance, measured in degrees) with Wind Flow Sector are significant. These interactions are based on mean corrected Atlant Distance, so the positive signs for their coefficients indicate enhanced rainfall further away from the Atlant site.

The main effects for the Atlant hours of operation (Atlant Hours) are highly significant and exhibit a very pronounced lag structure. This phenomenon was also observed in the second Atlant trial at Paradise Dam (Beare and Chambers 2008). A number of the interactions of Atlant Hours with Atlant Distance are also significant. Since both variables are mean corrected in these interactions, we can see that gauges closer to Atlant benefit more from extended hours of operation of Atlant in the last few days. These lagged effects may be due to the operating rules used to switch the system on and off. These rules were based on forecast and observed cloud cover. To the extent that cloud cover and the conditions on which forecasts are based are linked to cyclical conditions affecting rainfall, a lag effect could be generated. Such effects might also be captured by lagged rainfall. However, the inclusion of lagged rainfall in the model did not substantially improve the model fit or change the Atlant operating hours lag structure.

Lagged operating hours as well as the distance from the Atlant site could serve as a proxy variable for relevant but excluded factors influencing rainfall. The coefficient estimates for the lag and distance covariates may therefore in part capture these proxy effects. The extent of this excluded variable bias is unknown and may be positive or negative. As a check, an alternative model for *LogRain* was fitted which did not include lagged operating hours or distance effects. While this alternative model accounts for less variation in *LogRain*, inferences about the extent of Atlant rain enhancement based on it are not substantially different from corresponding inferences based on the model specified in Table 5.

As gauge-level rainfall is spatially correlated it is reasonable to expect that the residual variation in *LogRain* will also be spatially correlated. As a consequence the '*t*' ratios reported in Table 5 may be overstated. This issue is discussed in more detail below, where we discuss how the model fit specified in Table 5 can be used to estimate the level of Atlant-induced rain enhancement.

5.2.1 Measuring rainfall enhancement

Our aim is to decompose the observed rainfall for a gauge *i* on day *t* when rainfall is observed at the gauge as:

$$Observed\ Rainfall_{it} = Latent\ Rainfall_{it}\,(1 + Enhancement\ Effect_{it}) \qquad (6)$$

Here $Latent\ Rainfall_{it}$ is the natural rainfall that would have been observed at gauge *i* if Atlant had not been operating when rain fell at the gauge on day *t*. Since we cannot observe latent rainfall while the Atlant system is operating, we derive estimates of the log scale values of the components of the decomposition (6) using the model (5). In order to do so we note that (6) implies an additive relationship on the log scale:

$$LogRain_{it} = LatentLogRain_{it} + LogAtlantEffect_{it}. \qquad (7)$$

Here $LatentLogRain_{it}$ is the logarithm of $Latent\ Rainfall_{it}$ and $LogAtlantEffect_{it}$ is the logarithm of 1 + $EnhancementEffect_{it}$. Given that (1) is an appropriate model for log scale latent rainfall, $LatentLogRain_{it}$ is then obtained by eliminating (1) from (5). Equivalently

$$LogAtlantEffect_{it} = \lambda^T z_{it} + \delta^T s_{it}. \qquad (8)$$

Table 5. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Term	Estimate	t Ratio	Prob>|t|	F Ratio	Prob > F
Intercept	16.982	4.71	<.0001		
Month[8]	0.947	24.20	<.0001	234.07	<.0001
Month[9]	-0.076	-3.23	0.0012		
Month[10]	-0.549	-18.42	<.0001		
SLaZ	0.254	7.85	<.0001	32.96	<.0001
MLaZ	-0.050	-1.57	0.1171		
WLoZ	-0.032	-0.67	0.5011	0.25	0.7810
MLoZ	0.006	0.20	0.8434		
SLaZ & WLoZ	0.034	0.67	0.5041	0.24	0.9202
SLaZ & MLoZ	-0.009	-0.20	0.8419		
MLaZ & WLoZ	-0.004	-0.08	0.9394		
MLaZ & MLoZ	-0.013	-0.34	0.7378		
Elevation (100m)	0.082	5.85	<.0001		
Wind Speed 500	0.000	0.20	0.8388		
Wind Speed 750	-0.001	-0.60	0.5459		
Wind Speed 850	-0.008	-4.37	<.0001		
Wind Speed 500 L1	0.011	11.94	<.0001		
Wind Speed 750 L1	-0.018	-10.26	<.0001		
Wind Speed 850 L1	0.022	14.44	<.0001		
Wind Direction 500	-0.008	-17.50	<.0001		
Wind Direction 750	0.002	4.37	<.0001		
Wind Direction 850	0.002	4.58	<.0001		
Wind Direction 500 L1	0.006	9.96	<.0001		
Wind Direction 750 L1	0.006	9.28	<.0001		
Wind Direction 850 L1	-0.005	-14.59	<.0001		
Air Temperature	-0.098	-10.86	<.0001		
Dew Point Temperature	0.051	6.73	<.0001		
Sea Level Pressure	-0.017	-4.84	<.0001		
Atlant Distance	-0.426	-2.27	0.0239		
Wind Flow Sector 1	0.137	4.63	<.0001	11.17	<.0001
Wind Flow Sector 2	0.174	6.07	<.0001		
Wind Flow Sector 3	0.030	0.99	0.323		
Wind Flow Sector 4	-0.040	-1.15	0.2499		
Atlant Distance * Wind Flow Sector 1	0.016	0.12	0.9052	5.31	0.003
Atlant Distance * Wind Flow Sector 2	0.390	2.92	0.0035		
Atlant Distance * Wind Flow Sector 3	0.493	3.58	0.0003		
Atlant Distance * Wind Flow Sector 4	0.089	0.53	0.5966		

*Note that a highly a significant p-value indicates a low Standard Error. These can be calculated by the ratio of the estimate and the t-ratio.

Table 5 cont. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Term	Estimate	t Ratio	Prob>|t|	F Ratio	Prob > F
Atlant Hours L0	0.030	19.05	<.0001		
Atlant Hours L1	-0.033	-18.57	<.0001		
Atlant Hours L2	-0.016	-10.35	<.0001		
Atlant Hours L3	0.030	19.33	<.0001		
Atlant Hours L4	-0.010	-6.51	<.0001		
Atlant Hours L5	-0.015	-11.27	<.0001		
Atlant Hours L6	-0.008	-4.73	<.0001		
Atlant Hours L0 * Atlant Distance	0.024	3.36	0.0008		
Atlant Hours L1 * Atlant Distance	-0.029	-4.61	<.0001		
Atlant Hours L2 * Atlant Distance	-0.005	-0.75	0.454		
Atlant Hours L3 * Atlant Distance	-0.026	-3.94	<.0001		
Atlant Hours L4 * Atlant Distance	0.010	1.54	0.1243		
Atlant Hours L5 * Atlant Distance	0.019	3.04	0.0023		
Atlant Hours L6 * Atlant Distance	0.007	1.07	0.2825		

Table 5 cont. Estimated coefficients defining fit of model (5) to the 2008 trial data.

Random Effect	Variance Component	Per Cent of Total
Gauge Location	0.038	4.76
Residual	0.772	95.23

Summary Statistic	Value
R-Squared	0.4952
Adjusted R-Squared	0.4916
Root Mean Square Error	0.8785
Observations	7138

We can estimate $LogAtlantEffect_{i,t}$ from the 2008 trial data, by substituting the coefficient values displayed in Table 5 into (8). Since the expected values of $LatentLogRain_{i,t}$ and $LogAtlantEffect_{i,t}$ are not separately identifiable under (7), we force the average value of the estimated log scale Atlant effects defined by (8) to be zero by mean correcting them. This has the effect of moving the expected value of the log scale Atlant effects into the corresponding expected value of the log scale latent rainfall, which is a conservative approach to dealing with this issue. Estimated values of $1{+}EnhancementEffect_{i,t}$ are then obtained by exponentiation. That is, our estimate of the Atlant enhancement for a particular gauge on a day when rainfall is observed is:

$$Enhancement\ Effect_{it} = k \exp\,(LogAtlantEffect_{it})\text{-}1 \quad (9)$$

The corresponding estimate of Latent Rainfall is obtained from (6) as:

$$LatentRainfall_{it} = k^{-1} \exp\,(\text{-}LogAtlantEffect_{it}) \times Observed\ Rainfall_{it}. \quad (10)$$

Finally, the estimated increase (or decrease) in rainfall attributed to Atlant at a gauge on a day when rainfall is observed is:

$$Atlant\ Attribution_{it} = Observed\ Rainfall_{it} \text{-} Latent\ Rainfall_{it}. \quad (11)$$

The constant k in (9) above corrects for the bias that is inherent in using exponentiation to move from log 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. To make the correction, a simple mean adjustment (k) is made so that the mean of the regression predictions when back-transformed from logarithm, equals the mean of the observed rainfall.

The last methodological issue is determining the precision of the total estimated Atlant attribution (11) for domains defined by specified gauge-days. To estimate proper confidence intervals we need to take into account the gauge level correlation in latent rainfall, which includes the variation in rainfall that is not explained by the model. The current procedure used to calculate standard errors is based on an assumption of spatial independence, however. In an attempt to define conservative estimates of the true standard errors, these naïve standard errors were therefore inflated by 100%. Confidence intervals were then calculated on the basis that errors associated with the estimated Atlant attribution are normally distributed. Subsequent bootstrap analysis indicated that the adjustment was conservative, in the sense that the bootstrapped standard errors that took into account spatial correlation, were uniformly smaller than those implicit in Table 5 and stated in Table 6.

5.2.2 The estimated enhancement effect

The estimated enhancement effects described in the previous section were calculated on a gauge by day basis. Table 6 summarizes the corresponding estimates of latent rainfall (10) as well as rainfall attributable to operation of the Atlant system (11) for all gauge-days for which model (6) can be fitted, as well as for those gauge-days corresponding to the downwind and cross/upwind parts of these data. The overall estimated Atlant attribution within the trial area over the trial period is 10.3%. More importantly, nearly all of this is due to enhanced rainfall for gauge-days that are downwind of the Atlant site, which is consistent with the hypothesized wind driven model for how the Atlant system operates. It is also consistent with results of the descriptive analysis presented in section 5.1. The estimated overall downwind attribution (i.e. for a downwind arc of 120°) is 15.8%, with approximate confidence intervals as shown in Figure 9. The 80% confidence bounds range from a low of 13.2% to a high of 18.4%. A contour plot showing the geographic distribution of the enhancement effect is shown in Figure 9. Comparing this with Figure 6, we see that the enhancement effects are reasonably well correlated with the predominant wind direction over the entire trial.

Table 6. The estimated contributioni of Atlant System to rainfall in the trial area.

Scope (No. of Gauge-Days with Rainfall)	Total Observed Rainfall (mm)	Total Latent Rainfall (mm)	Total Atlant Attribution (mm)	Attribution %	Standard Error on Attribution %
All (7138)	22008	19951	2058	10.3	1.6
60º Downwind Arc (2472)	8003	6997	1006	14.4	2.6
120º Downwind Arc (4458)	14792	12771	2021	15.8	2.0
Upwind-Crosswind (2680)	7216	7179	37	0.5	2.4

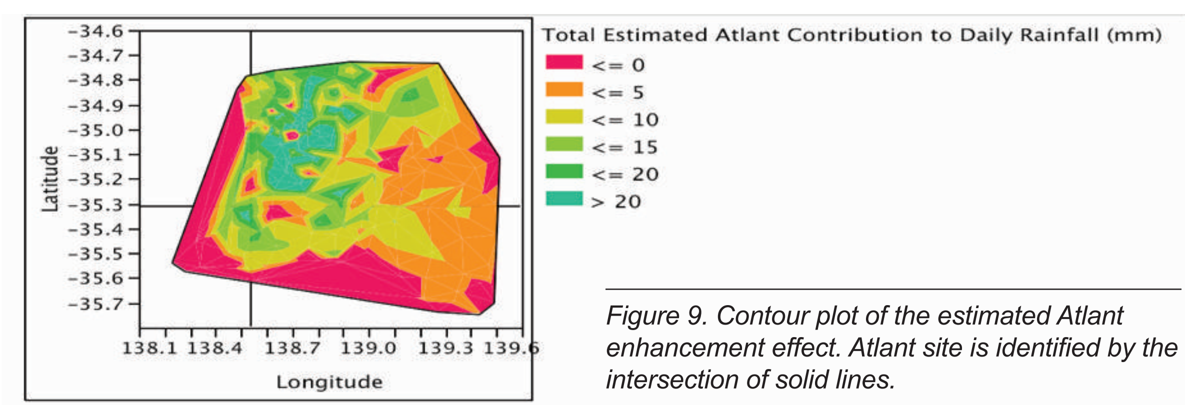

Figure 9. Contour plot of the estimated Atlant enhancement effect. Atlant site is identified by the intersection of solid lines.

6. CONCLUDING COMMENTS

Subject to the caveat that the trial was not randomized in any way, rainfall over the trial period was significantly higher downwind of the Atlant site over periods when the site was in operation. The estimated 15.8% downwind enhancement effect translates into 2,021mm (Table 6). This is the equivalent of an average of 0.4533mm per downwind gauge day.

Comparison of crosswind and downwind rainfall suggests that the observed Atlant effect had a range of approximately 80km. The 120° downwind area, on any given day, was 10,000km^2 or 1,000,000ha. One hundred mm of rainfall falling on one hectare equates to a volume of one megalitre. Given the average of 0.4533mm per downwind gauge day, this equates to 4,588ML per rainfall day. There were 65 days during the trial period where greater than 1mm fell in the trial area. This gives an approximate yield in the downwind area of 298GL for the trial. The corresponding estimate for a 60° downwind arc is a total of 132GL for the trial. This is slightly less than half of the 120° effect as estimated Atlant contribution for this area is slightly lower. However, the difference is not statistically significant (as can be seen in Table 6).

The statistical approach taken reflects two underlying objectives. The first was to establish whether the trial data supported the conclusion that the operation of the Atlant system was associated with a significant increase in rainfall in the trial area. The second was to measure the rainfall that could be attributed to the operation of the Atlant system. The latter objective imposed an important restriction on the analysis as this required interactive effects between the Atlant and meteorological covariates to be excluded. By definition, interactive effects generate joint attribution. It would be reasonable to expect such interactions to exist since the same number of Atlant operating hours should have a different rainfall impact depending on the weather conditions, but this impact should vary depending on the actual number of Atlant operating hours. The inclusion of interactive effects may not only improve the fit of the model but would help to better understand the conditions under which the system operates most effectively. However, by not including interactive effects it was possible to partition the rainfall data into latent rainfall and enhanced rainfall and thus more clearly identify any Atlant effect. If interactive effects were included, then the data would have to be broken into latent, enhanced and mixed rainfall.

In general, the results indicate that operating the Atlant for longer periods (>24hrs) is associated with a larger effect. However, this is only indicative as we had only a small number of observations at shorter operating intervals. While operating the Atlant system and determining when it would be operational at any given time were decided from a set of prescribed guidelines, the fact that they were related to meteorological conditions still generated a sub-optimal experimental design. This may have been justified given the trial had an underlying objective of generating rainfall during a period when there was a critical shortage in the local availability of water resources. Nevertheless, it reduced the extent to which an Atlant Effect could be accurately identified. This trial design issue was addressed in the second South Australian trial, run from August to December 2009.

A randomized trial design was applied to the 2009 trial, where the 2008 Atlant site and a second Atlant site, suitably separated and similar in terms of meteorological and topographic conditions, were operated on a randomly predetermined rotation basis throughout the trial with no breaks. The operation schedule chosen was followed irrespective of any predicted rainfall or meteorological events. The two sites were operated in a randomized asynchronous alternating schedule. One Atlant site was operated on a randomized alternate day on/day off sequence, while the other was operated on a randomized 2-day on/2-day off sequence. The advantage of this approach was to ensure that each combination was scheduled for an equal number of days. Similar statistical modeling analysis to that presented in this paper will be carried out. As in the 2008 trial, the aim of the 2009 trial is not to establish a causal link between operation of Atlant and enhanced rainfall, but rather to concentrate on a more rigorous statistical assessment of any effect of Atlant on rainfall quantity, which will add significant confidence to any results.

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APPENDIX: DETERMINING DOWNWIND SECTOR

Each Wind Flow Sector is defined in terms of two distinct arcs of a circle centered at the Atlant site and including all gauges in the trial area. The two arcs that correspond to a particular Wind Flow Sector are of the same length and are symmetrically placed on opposite sides of the radial vector defined by the downwind direction of the daily steering wind flow at the Atlant site. Thus, the arcs defining Wind Flow Sector 1 lie on either side of this vector, those that define Wind Flow Sector 2 lie further along the circle on either side and so on. By combining these arcs sequentially on either side of the radial vector we define a set of increasing segments (wedges), each uniquely defined by an angle θ (measured in radians) relative to the steering wind flow or wind direction, which is itself defined by an angle ω (also measured in radians) relative to due north. A rainfall gauge at a location (*lat*, *long*) is then at an angle θ relative to the direction of wind flow on the day if θ is the angle defining the smallest such wedge that includes the location of the gauge. That is, θ is the smallest value between 0 and π such that both the following conditions hold:

$$\sin(\theta - \omega)\,(lat - lat_A) + \cos(\theta - \omega)\,(long - long_A) < 0$$

$$\sin(\theta + \omega)\,(lat - lat_A) - \cos(\theta + \omega)\,(long - long_A) < 0$$

where lat_A and $long_A$ denote the latitude and longitude respectively of the Atlant site. Note that θ can take any value between 0 and π, so a gauge does not need to be downwind of the Atlant site in a literal sense. For values of θ greater than 135° the gauge is in fact upwind of the Atlant site, while for values of θ between 60° and 135° it can be considered to be located crosswind relative to the Atlant site.