Accounting for Spatiotemporal Variation of Rainfall Measurements when Evaluating Ground-Based Methods of Weather Modification

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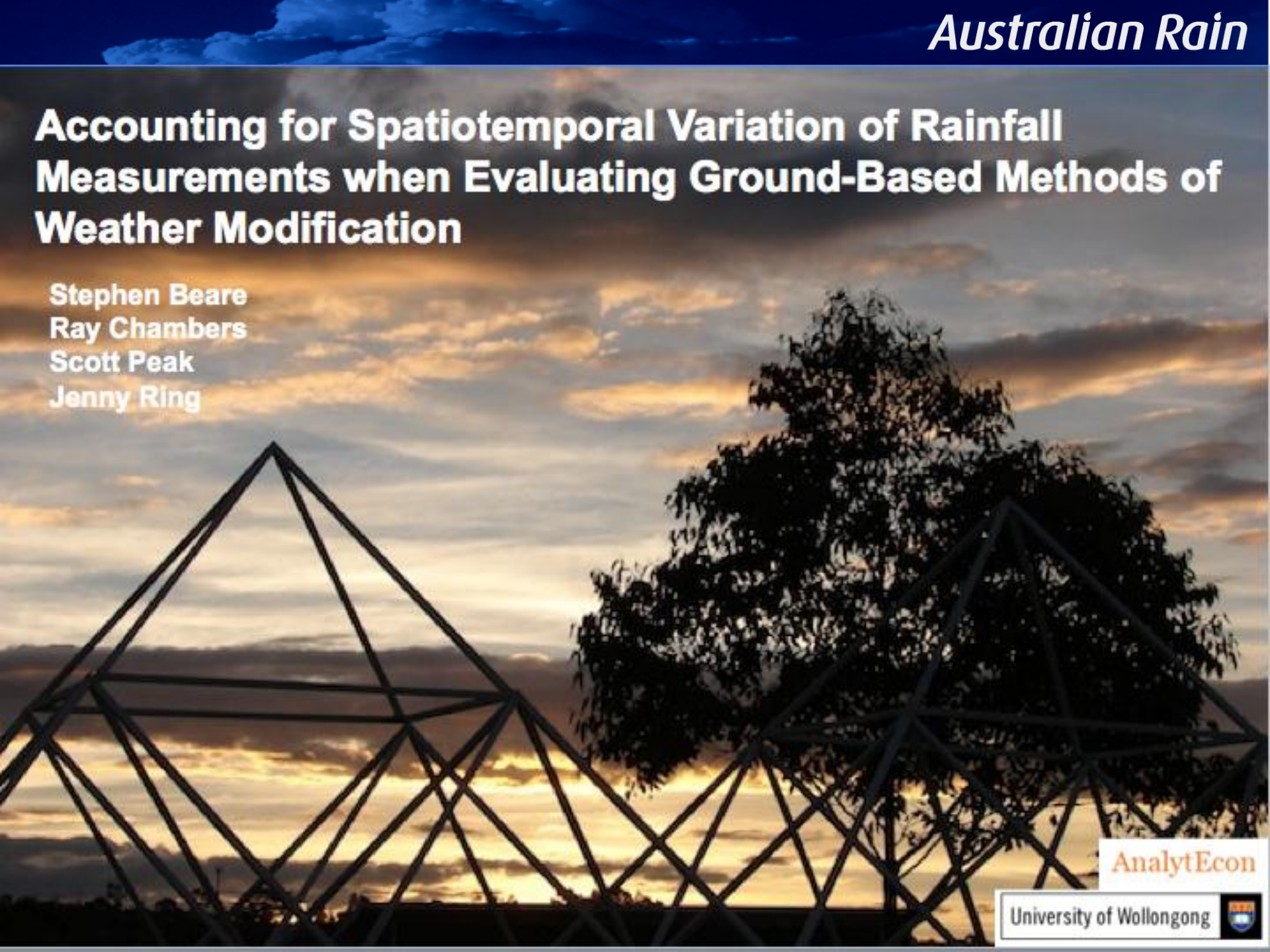

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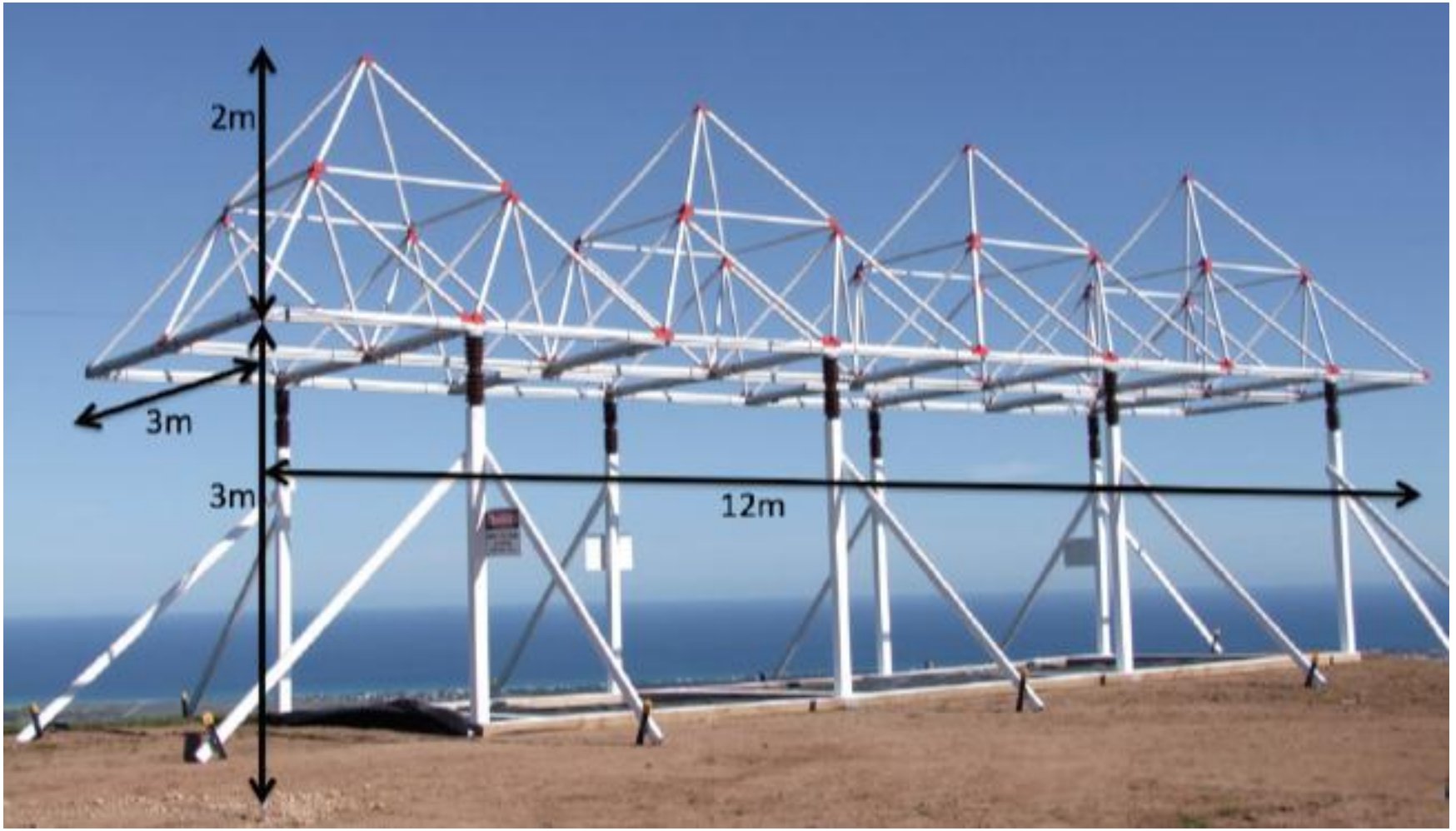
Atlant



Atlant Working Hypothesis

- 1. Negative ions are generated from a HV 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 will be conveyed to the higher atmosphere by wind, atmospheric convection and turbulence.
- 4. The electric charges on these particles, will be transferred to cloud droplets. The electrostatic forces on droplet interaction aids the coalescence of the cloud droplets, resulting in enhanced rain drop growth rate and ultimately increasing rainfall downwind from the Atlant

Exposure and the Working Hypothesis

- There is no physical evidence to indicate that Atlant delivers charged droplets into the cloud layer.
- Testing the hypothesis directly is difficult, primarily due to tracing the chemical interactions involving the ions after their release
- However it provides a working definition of rain gauge exposure on which we can conduct a conditional observational analysis:
  - A site is operational;
  - Cloud moisture is present; and
  - Within a conceptual downwind plume. The latter depending on uplift, wind direction and wind speed.

Challenges of Statistical Evaluation

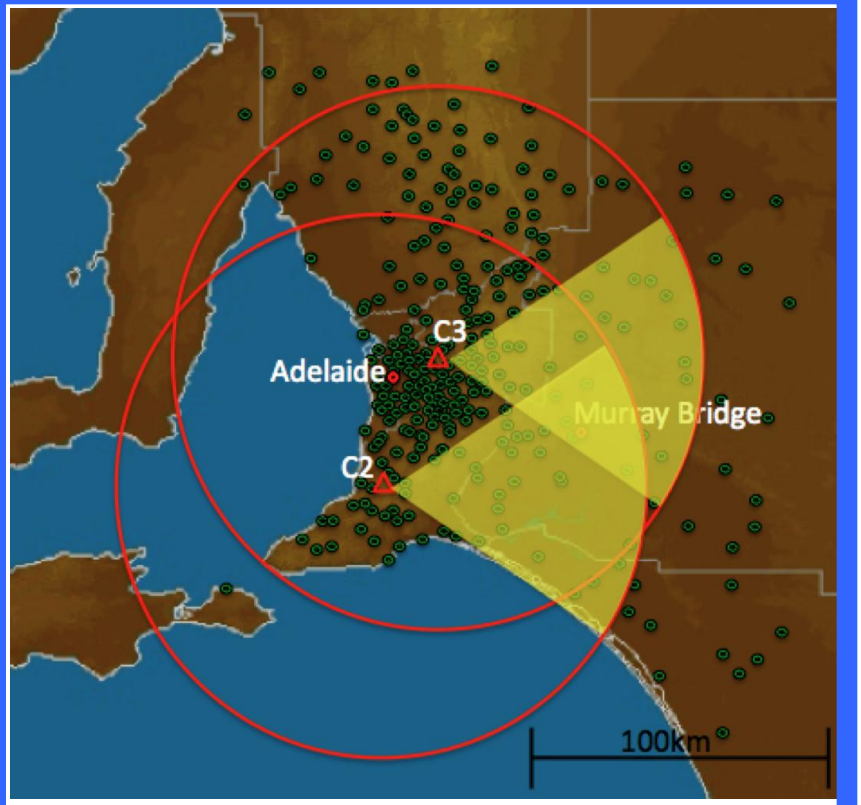
- Large scale temporal and spatial variation in rainfall relative to the potential enhancement signal;
- Non-stationary weather patterns over time; which
- Limits the applicability of historical, static spatial controls;
- Places a premium on real time controls as opposed to pure randomisation:
  - Blocking
  - Conditional or statistical modelling; though
- Neither of these strategies are without subjectivity.

Statistical Modeling

- Two stages
  - Probability of observing a gauge level rainfall event;
  - The level of rainfall given a rainfall event is observed;.
- Introduce daily meteorological and gauge level orographic covariates
- Introduce spatial and temporal random effects to capture systematic but unobserved (latent) effects;
- Characterisation of the Atlant effects – operational status, downwind and cross wind distance
- Randomised cross-over design allows the same gauge to be subject to different potential levels of exposure
- Account for residual spatiotemporal correlation between gauge measurements when calculating attribution statistics.

Trial Area

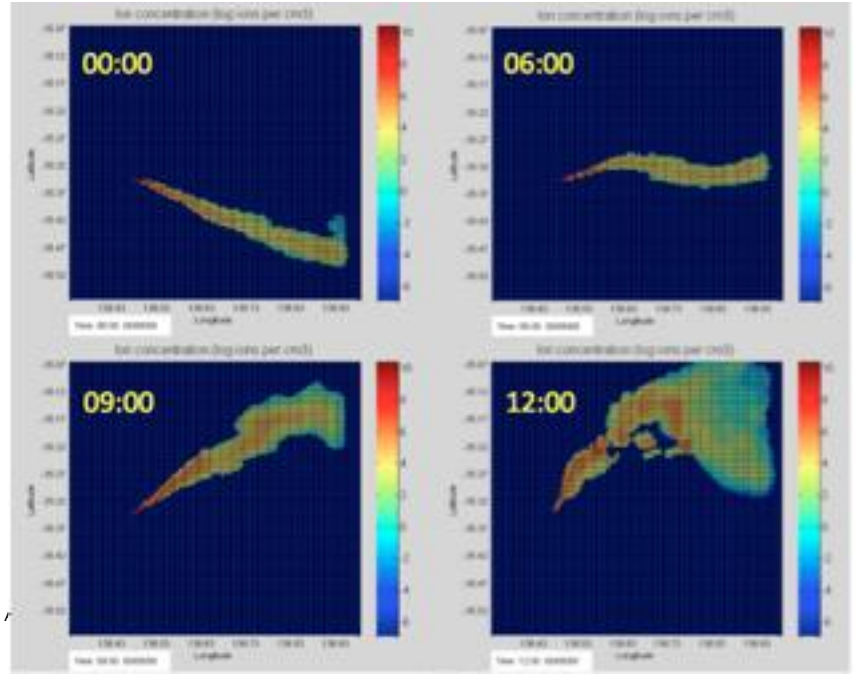
- Exposed to prevailing weather.
- Two sites 58 km apart
- Upslope provides lifting of any ion plume.
- Frontal passage west to east approximately every 4-6 days during the trial period.
- 1 Aug – 01 Dec 2009
- 282 rain gauges.
- Correlation of just under 80 per cent between daily average rainfall for gauges downwind of C2 and gauges downwind of C3.



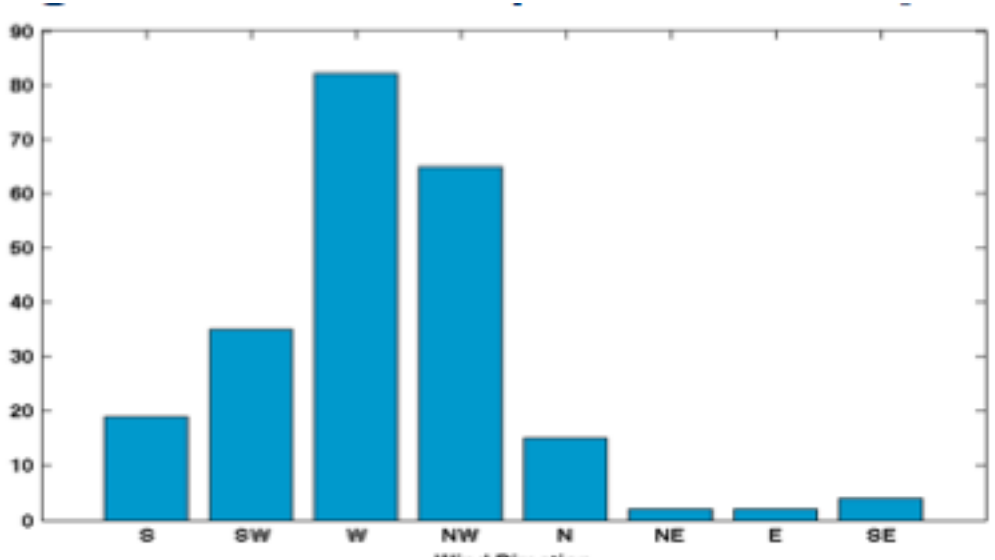
The rain gauges used in the trial are indicated by green dots. The circles centered on the Atlant sites have a radius of approx 90 km. Downwind sectors (yellow) are shown for a westerly wind.

The dynamic ‘downwind’ target area

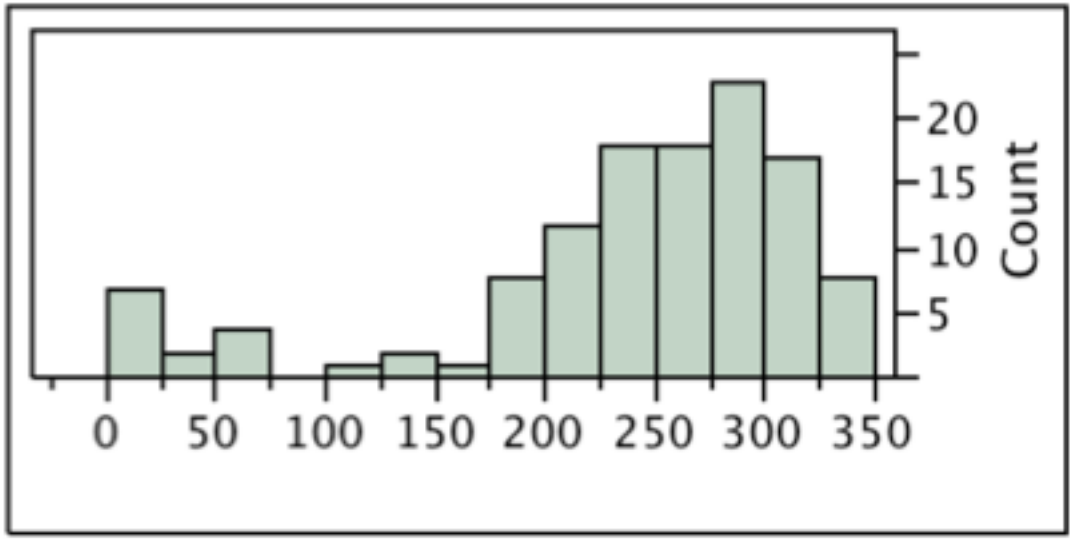
- Wedge-shaped area extending **downwind** from the Atlant site on a day;
  - defined by angle θ relative to the direction of the **steering wind.**
  - Daily steering wind = Vector average 850 and 925 hPa winds from radiosonde data from Adelaide airport
- MM5 modelling study of 2008 trial (0.6 km, 30 min, 23 vertical levels).
- HYSPLIT (0.005 degree, 10 min, 12 levels) indicated wedge angle 60˚



Daily Steering Wind at Adelaide Airport 2008 and 2009



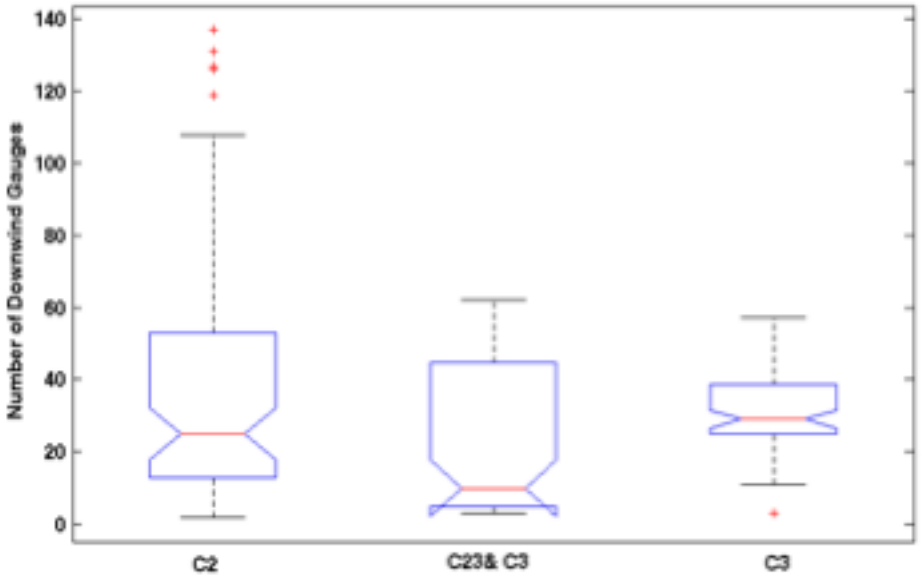
2009



2008

Exposed That Environmental Data Is Often Problematic

- Daily downwind averages can have very different:
  - Sample sizes; and
  - Orographic composition.
- Presents problems for ratio tests and daily analysis more generally



Dynamic double ration analysis

- The effect of seeding (Atlant operation) can then be assessed using the value of the root double ratio (RDR)

$$RDR = \sqrt{\frac{C2_{AtlantOn}}{C2_{AtlantOff}} \times \frac{C3_{AtlantOn}}{C3_{AtlantOff}}}$$

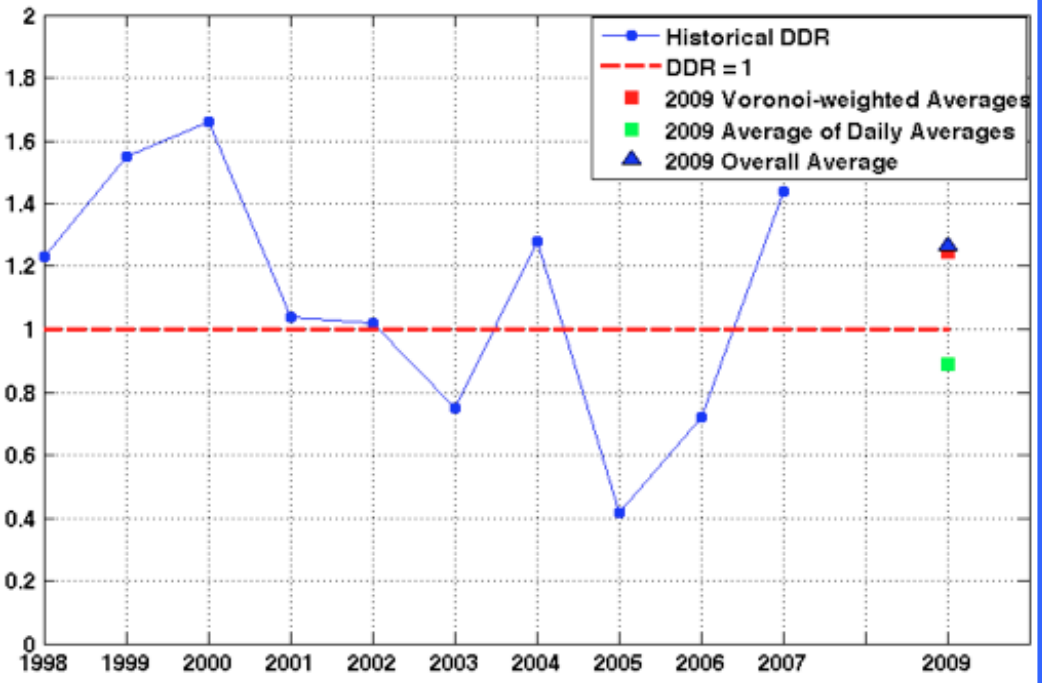
- A variant of the double-ratio statistic was computed for the trial period. This is referred to below as a dynamic double-ratio (DDR) statistic, because it reflects the fact that the target and control areas were redefined each day depending on wind direction and did not overlap.

$$DDR = \sqrt{\frac{Downwind\ C2\ only_{C2on/C3off}}{Downwind\ C3\ only_{C2on/C3off}} \times \frac{Downwind\ C3\ only_{C2off/C3on}}{Downwind\ C2\ only_{C2off/C3on}}}$$

- *Downwind C2 only*$_{C2on/C3off}$ denotes the ‘average rainfall’ recorded by gauges that were downwind of C2 but not of C3 on days when C2 was operational but C3 was not.

Historical DDR analysis

- In order to examine the underlying variability in these DDR statistics, we examined the inter-annual variation in the DDR statistic based on overall downwind area averages, as this should be the least variable estimate.
- There is a high level of year-to-year variability in the DDR statistic, with three out of the 10 historical observations exceeding the trial result.
- We have elected to pursue a conditional approach that estimates Atlant effects using regression models based on meteorological and orographic covariates .



Historical DDR statistics based on gauge-day average rainfall, 1998-2009

Gauge Level Regression Model

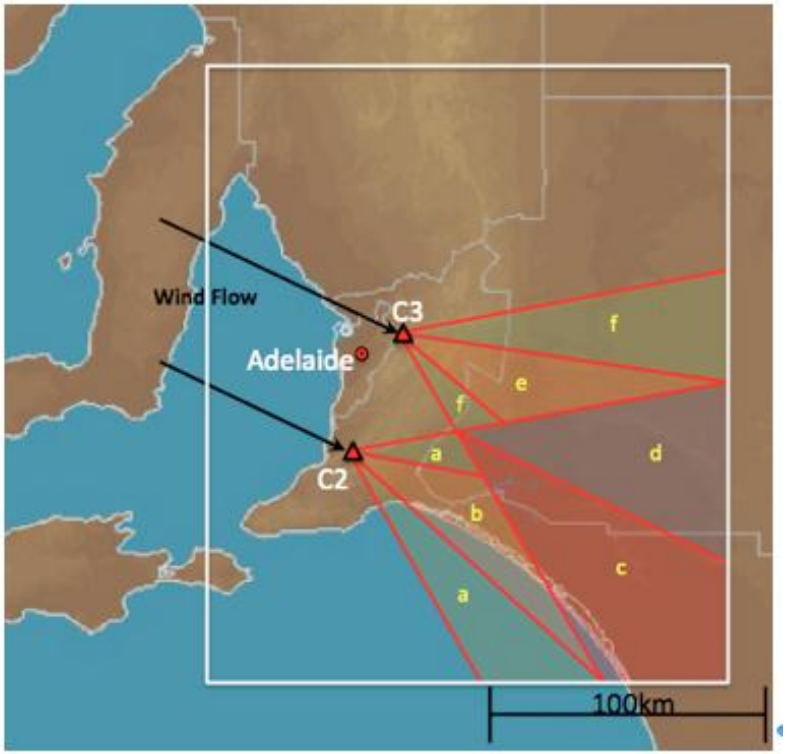
- **Decompose observed rainfall into:**
  - A latent measure of natural rainfall derived from;
    - Fixed effects excluding only the system effects;
    - The random effects;
  - Rainfall transformed to natural logs
  - A positive or negative Atlant contribution associated with the fixed system effects;
  - The attribution being the percentage difference between observed rainfall and the estimate of natural rainfall
    - This is not a unique formulation but should be the most conservative, in absolute value terms, as all mean level effects are attributed to natural rainfall
    - Complex statistic

Gauge-level regression model covariates

- Meteorological (concurrent and lagged)
  - Wind direction (three levels)
  - Wind speed (three levels)
  - Sea level pressure
  - Dew Point Depression
  - Temperature
  - Upwind precipitation
- Orographic
  - Elevation
  - Downwind distance
  - Crosswind angle
- **System**
  - Operating status by location
  - Location and operating status interactions

Random effects

- Random effects are typically used to allow for correlations in the data that are not captured by the model covariates – a source of false inference
- Purely temporal correlations were not significant;
- Purely spatial correlations were not very significant;
- Spatiotemporal correlations were highly significant



Areas covered by radial classes in a north-west wind

Probability of a rain event

- There was no suggestion that the operation of Atlant had any influence on the probability of observing a rainfall event.
- That is, rainfall would have to be a precondition for enhancement
- Spatial and temporal correlation has not been taken into account and the inflated significance level of other variables is clear

Parameter	Estimate	Standard Error	P-Value
Intercept	0.6352	9.9020	0.9489
August/September	-0.1700	0.1208	0.1592
WRE	0.4684	0.3288	0.1543
Upwind Rainfall	5.7195	0.1974	0.0000
Wind Speed 700	-0.0152	0.0035	0.0000
Wind Speed 700 – L1	0.0177	0.0034	0.0000
Wind Speed 850	0.0362	0.0073	0.0000
Wind Speed 850 – L1	-0.0114	0.0062	0.0660
Wind Speed 925	-0.0089	0.0068	0.1931
Wind Speed 925 – L1	0.0003	0.0053	0.9509
Wind Direction 700	-0.7120	0.4543	0.1171
Wind Direction 700 – L1	-0.4384	0.3865	0.2567
Wind Direction 850	1.2205	0.6971	0.0800
Wind Direction 850 – L1	-0.2299	0.6104	0.7064
Wind Direction 925	-0.3616	0.4260	0.3960
Wind Direction 925 – L1	-1.2559	0.3701	0.0007
Air Temperature	-0.0929	0.0224	0.0000
Dew Point Depression	-0.0175	0.0190	0.3556
Sea-level Pressure	-0.0007	0.0097	0.9432
Elevation	0.2534	0.0252	0.0000
Distance C2	-1.5233	0.7100	0.0319
C2θ	0.0007	0.0018	0.7188
Distance C2 * C2θ	0.0065	0.0034	0.0584
C2θ – L1	-0.0035	0.0013	0.0048
Distance C2 * C2θ – L1	-0.0006	0.0032	0.8575
Distance C3	-1.0923	0.7229	0.1308
C3θ	-0.0005	0.0009	0.5663
Distance C3 * C3θ	-0.0021	0.0033	0.5183
C3θ – L1	-0.0016	0.0009	0.0755
Distance C3 * C3θ – L1	0.0115	0.0032	0.0003
C2 On	-0.4163	0.2101	0.0475
Distance C2 * C2 On	0.6550	0.2842	0.0212
C2 On – L1	-0.4223	0.2086	0.0429
Distance C2 * C2 On – L1	-0.0476	0.2727	0.8613
C3 On	-0.0184	0.2028	0.9277
Distance C3 * C3 On	0.0908	0.3914	0.8166
C3 On – L1	-0.2142	0.1637	0.1905
Distance C3 * C3 On – L1	-0.4286	0.3012	0.1548

Log rainfall model

- 71 per cent of the variation in gauge level rainfall accounted for
- Highly significant spatiotemporal random effects - substantially tempered the significance of the fixed effects
- Meteorological and orographic and still account for a large proportion of the variation
- Operating effects significant

Parameter	Estimate	Standard Error	P-Value
Intercept	29.7520	9.9115	0.0027
August/September	-0.5116	0.1188	0.0000
WRE	1.0761	0.1551	0.0000
Upwind Rainfall	2.3431	0.1841	0.0000
Wind Speed 700	-0.0049	0.0036	0.1737
Wind Speed 700 – L1	0.0089	0.0033	0.0070
Wind Speed 850	0.0032	0.0069	0.6395
Wind Speed 850 – L1	-0.0018	0.0059	0.7578
Wind Speed 925	0.0070	0.0064	0.2763
Wind Speed 925 – L1	-0.0057	0.0051	0.2645
Wind Direction 700	-0.6828	0.4688	0.1461
Wind Direction 700 – L1	0.0447	0.4297	0.9171
Wind Direction 850	-0.4951	0.7340	0.5004
Wind Direction 850 – L1	0.2796	0.6176	0.6510
Wind Direction 925	0.4223	0.4283	0.3248
Wind Direction 925 – L1	-1.2170	0.3549	0.0007
Air Temperature	-0.0243	0.0243	0.3170
Dew Point Depression	-0.0128	0.0211	0.5448
Sea-level Pressure	-0.0295	0.0097	0.0026
Elevation	0.1410	0.0124	0.0000
Distance C2	0.1559	0.4626	0.7361
C2θ	0.0032	0.0011	0.0033
Distance C2 * C2θ	-0.0004	0.0021	0.8552
C2θ – L1	-0.0020	0.0008	0.0093
Distance C2 * C2θ – L1	-0.0026	0.0020	0.1888
Distance C3	-0.7602	0.4789	0.1125
C3θ	-0.0013	0.0005	0.0085
Distance C3 * C3θ	0.0042	0.0021	0.0434
C3θ – L1	-0.0010	0.0005	0.0248
Distance C3 * C3θ – L1	0.0088	0.0019	0.0000
C2 On	0.4523	0.1448	0.0019
Distance C2 * C2 On	-0.5654	0.1608	0.0004
C2 On – L1	0.1176	0.1384	0.3961
Distance C2 * C2 On – L1	-0.4978	0.1570	0.0015
C3 On	-0.0608	0.1593	0.7029
Distance C3 * C3 On	0.5149	0.2307	0.0257
C3 On – L1	0.2863	0.1141	0.0126
Distance C3 * C3 On – L1	-0.1463	0.1504	0.3308

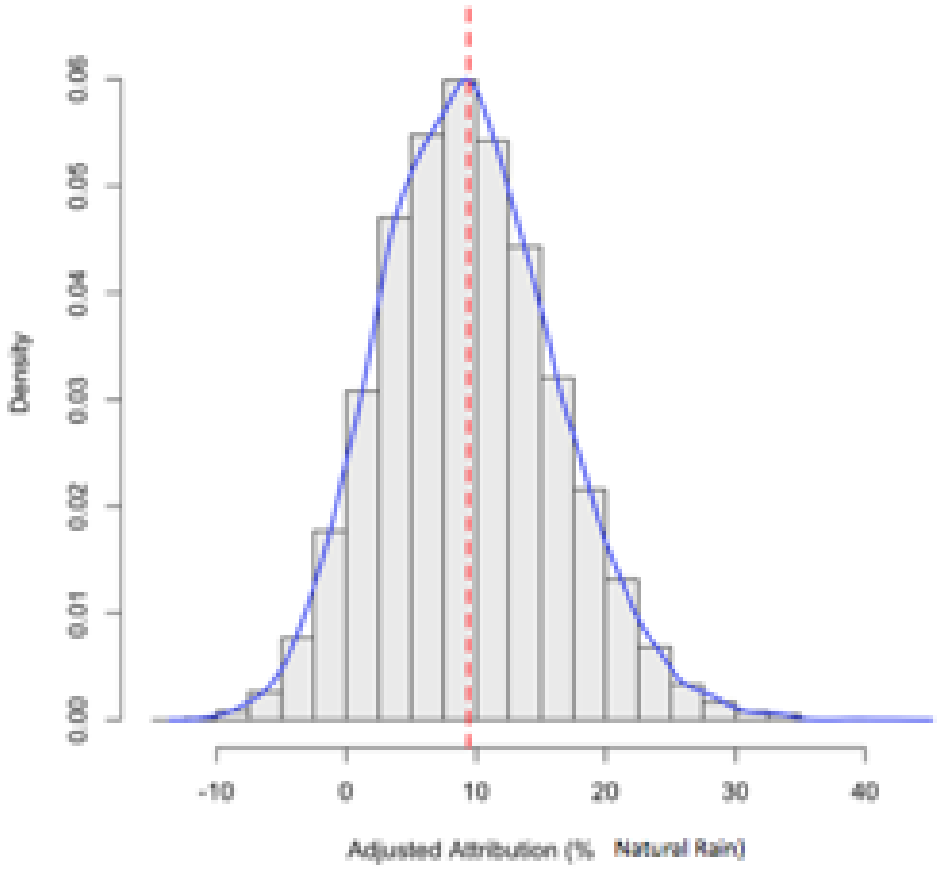
Variance Component Estimates		
Random Effect	**Component**	**Percentage**
Spatio-temporal	0.30587	31.870
Residual	0.65386	68.130

Atlant Attribution	
Actual Rainfall (mm)	13640
Estimated Natural Rainfall (mm)	12465
Attribution (% actual rainfall)	8.6
Attribution (% natural rainfall)	9.4

Spatial Correlation

- Estimating the precision of the estimated attribution requires bootstrapping
  - Repeated estimation of the model and attribution levels using random samples of the data with replacement
- Standard errors are understated if there is spatial correlation in the model errors;
- This can be measured and corrected for, in large part, by repeated sampling of the errors within overlapping spatiotemporal clusters;
  - Design of the clusters and the overlap scheme is at the cutting edge of applied statistics;
  - Will always have a degree of subjectivity.

Distribution of the Atlant Attribution



Conclusions from the trial analysis

- This analysis showed an overall positive enhancement effect
- Spatio-temporal bootstrap simulations showed significant at over the 90 per cent one-sided confidence level
- **However**, the investigative nature of the analysis, does mean that these results suggest a positive Atlant effect rather than prove its existence.
- Nevertheless, the statistical techniques developed for the analysis of data collected in the trial provides a powerful set of tools for similar statistical investigations of WM activities
  - A spatio-temporal modelling approach at the gauge-level can more effectively identify a signal in weather modification experiments when compared to traditional double-ratio tests.
  - Semi-parametric block bootstrap methods can be used to account for the correlation between gauges and provide a robust assessment of the precision with which rainfall enhancemnet effects can be measured.

Issues for the Future

- Investigation into physical processes
- Expanded set of meteorological covariates, including stability parameters
- Application of statistical technique to other weather modification trials