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OMAN RAIN ENHANCEMENT TRIAL

FINAL REPORT

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Main Section	52
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EXECUTIVE SUMMARY

Oman is one of most water-stressed countries in the world, with the northern part of Oman expected to face decreases in average annual rainfall in the coming decades of up to 40%. Thus any technology that can increase rainfall or mitigate projected future reduction is of considerable interest. Trading and Investment Establishment (TIE) contracted Australian Rain Technologies (ART) to oversee the operation of a rainfall enhancement trial using the ATLANT™ technology in the Hajar Mountains, with an independent evaluation of the results of this trial by the National Institute for Applied Statistics Research Australia (NIASRA) at the University of Wollongong.

The trial operation ran for 170 days from 15 May to 31 October 2013. This period was chosen to capture the reported high incidence of convective storms over the Hajar Mountains with consistently suitable microphysical conditions for rainfall enhancement operations. Two ATLANT™ locations were used to target the Batinah/Dakhliyah Region of Oman. This region was chosen considering synoptic and local wind flows, cloud types, widespread uplift, and moisture availability. Such features affect the delivery of charged particles or aerosols to the cloud layer and potential subsequent rainfall enhancement. The trial area included 120 rain gauges and two automatic weather stations installed by TIE, as well as weather stations and upper soundings at Seeb international airport provided by the Oman Directorate General of Meteorology and Air Navigation (DGMAN).

The trial employed a randomised crossover design with the two ATLANT™s operated in a pre-determined randomised alternating schedule and a nominal switching time at 7am (local Oman time) on the designated days. Statistical spatio-temporal modelling was used to analyse the trial data. The aim of the modelling is to reduce the natural rainfall variation by using covariates to predict or explain the natural variation independently of the rainfall itself, facilitating the prediction of the level of rainfall that would have occurred if the ATLANT™ system were not operating.

The methodology was developed for weather modification trials in Australia based on defining the ATLANT™ 'footprint' dynamically in terms of target and control areas corresponding to two overlapping 60° arcs (or 'wedges') emanating from each of the ATLANT™ sites and oriented downwind in the direction of the steering wind. However, given that there are substantive differences in the prevailing weather conditions at the two ATLANT™ sites and that the available meteorological data about the behaviour of steering winds over the course of a day is limited, it was decided that this was not the most robust model for defining a footprint in the Oman trial. A simple alternative was therefore developed as part of the Experiment plan prior to analysing the rainfall, which defined this footprint in terms of 'corridors' placed symmetrically about each ATLANT™ site and oriented downwind along the axis defined by the steering wind direction. The statistical analysis was conducted using a dynamic 60° downwind arc footprint model and a 30km dynamic downwind corridor footprint model based on daily steering wind direction, as specified in the pre-analysis plan. In all cases these footprints extended out 75km the ATLANT™ sites.

Overall, a positive and significant rainfall enhancement effect attributable to the operation of the ATLANT™ systems was observed over the course of the trial. The total attribution (enhancement effect) in the trial area defined by the 60º arc model, as a percentage of estimated natural rainfall, is estimated to be 11.7 per cent with a bootstrap standard error of 9.1 per cent. Furthermore, the bootstrap analysis indicates that this attribution is significantly greater than zero at a 90 per cent level of confidence, with a lower bound of 0.5 per cent for the bootstrap 90 per cent confidence interval for this attribution. Overall total attribution (enhancement effect) in the trial area defined by the 30 km corridor model, as a percentage of estimated natural rainfall, is estimated to be 18 per cent with a bootstrap standard error of 8.4 per cent. The bootstrap analysis indicates that this attribution is significantly greater than zero at a 99 per cent level of confidence, with a lower bound of 1.1 per cent for the bootstrap 90 per cent confidence interval for this attribution. The results are summarised below.

Model	Mean level rainfall enhancement effect	Standard Error	Confidence level enhancement effect > 0
30 km Corridor	18.0 %	8.4 %	99 %
60° Arc	11.7 %	9.1 %	90 %

While there was a positive ATLANT™ attribution at the two ATLANT™ sites, the attribution was substantially higher at H1 as opposed to H2 and the local attribution at H2 was not statistically significant. Detecting a significant enhancement effect at the individual sites is more difficult than for the trial area as whole. However, the difference in the effects at H1 and H2 may be due to factors such as the topography of the two sites and insufficient geographic separation of the downwind target and control areas when H1 was in operation. These issues require further investigation. Based on these positive results, further trials are recommended with the following suggested improvements in design: Increasing the number of gauges in the prospective downwind target and control area that could in part be achieved by relocating upwind gauges; relocating one or both of the ATLANT™s in order to provide a greater degree of separation of their footprints; expanding the trial to include two or more additional ATLANT™s; and installing upper air wind readings at H1 and H2.

1. INTRODUCTION

Oman is one of most water-stressed countries in the world, with Intergovernmental Panel on Climate Change (IPCC) simulations showing that the northern part of Oman is expected to face decreasing average annual rainfall in the coming decades of up to 40% (Charabi, 2013). Any technology that can increase rainfall or mitigate projected future reduction is therefore of considerable interest.

1.1 Project Overview

Trading and Investment Establishment (TIE) contracted Australian Rain Technologies (ART) to train their personnel and assist in the operation of a rainfall enhancement trial using the ATLANT™ technology in the Hajar Mountains in 2013. The trial was managed from a local TIE project headquarters in Oman including the coordination of the operations of the ATLANT™ sites and data instrument arrays across the trial region. ART monitored the operation of the trial remotely from their headquarters in Australia, as well as conducting regular monitoring visits during the trial. ART coordinated an independent assessment of the effect of the ATLANT™ technology based on rainfall and meteorological measurements recorded during the trial, conducted by the National Institute for Applied Statistics Research Australia (NIASRA) at the University of Wollongong.

The 2013 Oman Rainfall Enhancement Trial builds on the series of ATLANT™ trials undertaken in Australia 2007-2010 (Beare et al. 2010; 2011; Chambers et al. 2012). The rain gauge data obtained from the trial has been analysed using robust statistical analysis methods, which adds significant confidence and rigour to the results of the trial.

1.2 Hypothesis

The hypothesis that was tested in the trial is:

> ***That the operation of the ATLANT™ system in the assessment region leads to increased rainfall in the expected field of influence of the ATLANT™, compared with rainfall outside the expected field of influence of the ATLANT™.***

Statistical modelling and analysis is used to test the null hypothesis that there is no effect on rainfall. If this is rejected because of strong evidence of rainfall enhancement, then a statistically significant rainfall enhancement value is said to have been observed.

It is important to note that the aim of this trial is not to establish a causal link between operation of ATLANT™ and enhanced rainfall, but rather to concentrate on a rigorous statistical assessment of any effect of ATLANT™ on rainfall quantity.

2. BACKGROUND

2.1 Regional Climate

The Climate in the Sultanate of Oman varies from one region to another and from one season to another but can be divided mainly into two seasons, with transition months separating, namely:

- Winter or Northeast Monsoon (December-March)
- Transition Northeast-Southwest Monsoon (April-May)
- Summer or Southwest Monsoon (June-September)
- Transition Southwest-Northeast Monsoon (October-November)

Past climatological studies have identified the winter season (December through March) as accounting for the bulk of rain in flat and coastal areas in northern Oman. Troughs, depressions, and the occasional tail end of cold fronts move through the region from the west and northwest resulting in large-scale systems that can provide significant rainfall. However the occurrence and amount of rainfall is highly variable, not occurring at all in some years, and provides few opportunities for regular rainfall enhancement operations. During the summer season (June through September), convective rainfall over the Oman Mountains is a phenomenon that is known locally and has been recently studied. The reported high occurrence of convective storms over the Oman Mountains with consistently suitable microphysical conditions makes it the most suitable time for rainfall enhancement operations (Figure 2-1).

Figure 2-1 Convection along Hajar Mountains 10 July 2004 (source: Al Brashdl 2007).

3. TRIAL SET-UP

3.1 Trial Schedule

Due to delays in the installation of the ATLANT™ sites the rain enhancement operation phase of the 2012 trial was postponed until 2013 convective season. The operational schedule of the main activities is set out below:

- 01 Sep 2012 – 31 April 2013: Planning, transport, set up, testing of ATLANT™
- 15 May – 31 October: Operation of ATLANT™s, collection of field data
- 01 – 31 October: Preliminary analysis of August and September data
- 01 November: Presentation of preliminary results to TIE
- 01 November – 31 December: Analysis of final data and preparation of final report
- 31 December: Presentation of final results to TIE.

3.2 Trial Location

Two ATLANT™ locations were be used to target the Batinah/Dakhliyah Region of Oman (Figure 3-1). This region was chosen considering synoptic and local wind flows, cloud types, widespread uplift, and moisture availability. Such features affect the delivery of charged particles or aerosols to the cloud layer and potential subsequent rainfall enhancement. In addition, optimal rainfall enhancement operations would then occur in areas with a high frequency of suitable clouds located where irrigation flow and ground water recharge occurs. In Oman, groundwater recharge is found to be most prominent in the Wadis (dry river beds) that cut through the mountains.

Figure 3-1 Trial domain (shown by red box)

3.3 Targeting the Hajar Mountains

The Hajar Mountain range is a key factor in inducing a significant amount of rainfall during summer months. These steep mountains have peaks of over 3000 metres, and run parallel to the coast of the Gulf of Oman. Convective clouds form over the mountains creating a regular occurrence of showers and thunderstorms over a limited area in northern Oman during the summer months. The active weather is generally of short duration and intense. Orographic forcing, the advection of moisture from the south-western parts of the Arabian Sea or via sea breeze from the Gulf of Oman and large scale lifting are important factors in determining the occurrence of cloud and rainfall.

On days with no rain potential, dry north-westerlies converge (over the mountains) with the sea-breeze from the Gulf of Oman. Conversely on days with cloud and/or rain development, the sea-breeze converges with moisture flow advected from the Arabian Sea. A dry desert air will lead to moist convection being suppressed, whereas moist air advected from the Arabian Sea will enhance moist convection. Moisture advection from the Arabian Sea in a column of at least 1 kilometre in depth is required for proper convection (Al-Maskari et al. 2006). The stronger the flow from the Arabian Sea and the deeper the column of the moist air, the heavier the precipitation. Generally clouds that develop over the mountain peaks dissipate as they move west. As such, two ATLANT™ systems were located on the north side of the Hajar Mountains, designated Hajar 1 (H1) and Hajar 2 (H2) (see Figure 3-2).

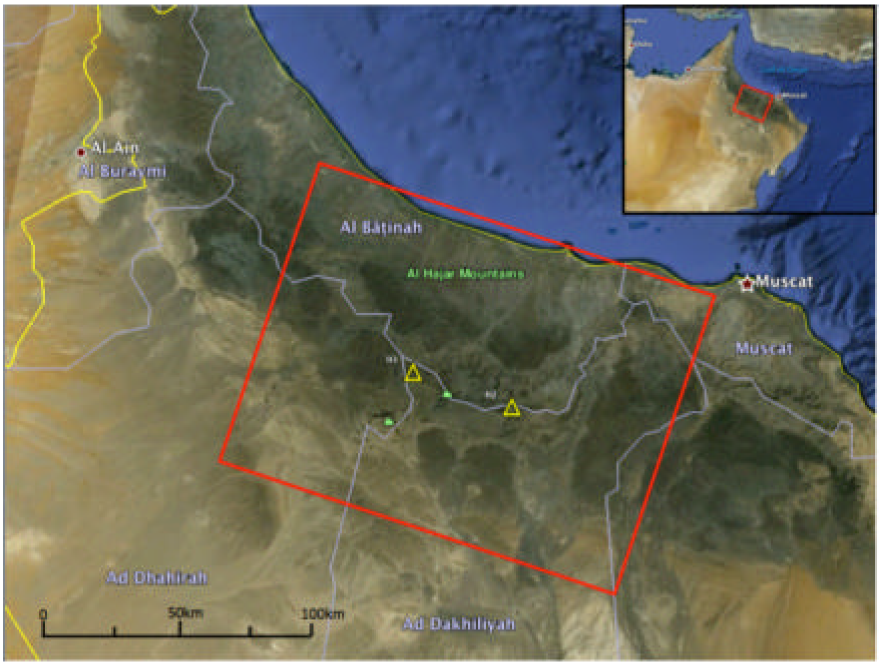


Figure 3-2 Trial Area (red line), ATLANT™ Sites (yellow triangles)

3.4 ATLANT™ Sites

The sites were chosen based upon the following criteria:

- The sites were as similar as possible, in terms of meteorological conditions, and elevation
- The ATLANT™ systems were separated sufficiently from each other, such that their areas of influence did not significantly overlap
- The sites are located such that a line joining them runs at 90° to the major wind direction and so are located to take advantage of orographic lifting of ion plume (see Figure 3-3)
- Surface-based measurements exist in the expanded trial area (i.e. rain gauge sites)
- Upper air wind profiles are located in the trial area and are generally representative of the conditions over the trial area.

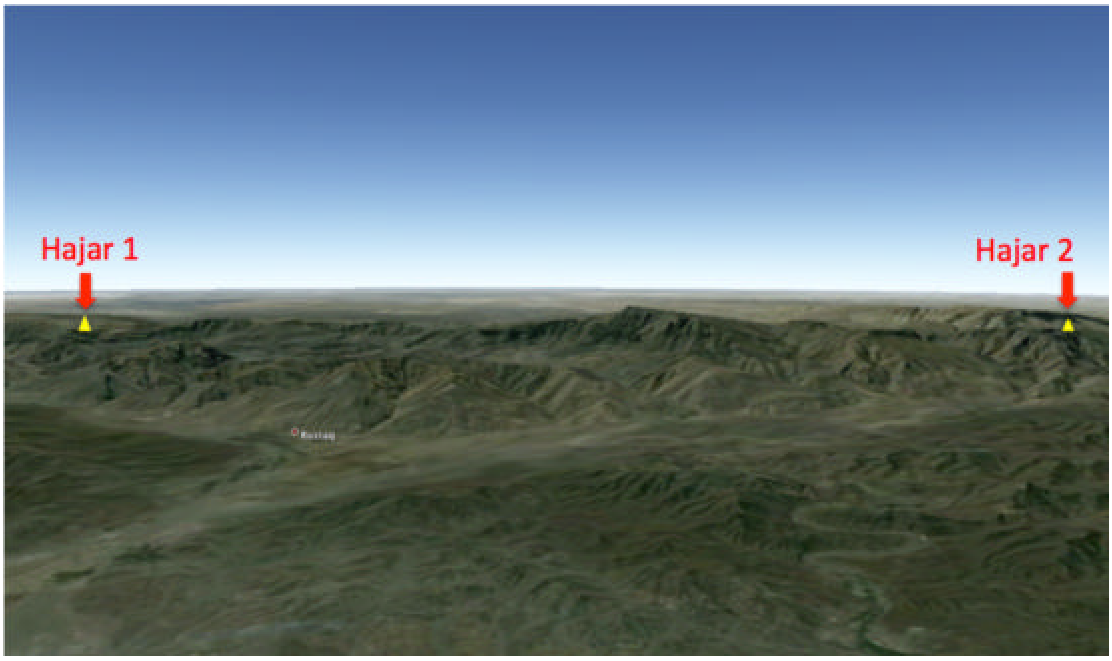


Figure 3-3 ATLANT™ sites looking South West towards the Hajar Mountains from the coast.

3.4.1 ATLANT™ Site Hajar 1 (H1)

Based on the above criteria, Hajar 1 was chosen as the first site for the trial (see Figure 3-4).

- Latitude: 23°19'21.74"N
- Longitude: 57° 7'23.15"E
- Elevation: 2670 m

Figure 3-4 The ATLANT™ at Hajar 1 Site

3.4.2 ATLANT™ Site Hajar 2 (H2)

Hajar 2 was chosen as the second site for the trial (see Figure 3-5).

- Latitude: 23°14'17.99"N
- Longitude: 57°36'33.22"E
- Elevation: 2157 m.

Figure 3-5 The ATLANT™ at Hajar 2 Site

3.5 Experiment Design

The trial employed a randomised crossover design. A crossover design is one in which the two sites are operated in a predetermined randomised sequence, each acting as both a target, and control for the other. Crossover designs are common for experiments in many scientific disciplines. This design is applicable as it has the following advantages:

First, the influence of confounding covariates is reduced because each crossover target serves as control for the other. A confounding covariate is a variable, unrelated to level of treatment, whose difference in distribution between a treatment group and a control group influences the observed response. Good experimental design for assessing treatment effects seeks to reduce this influence by ensuring that the distributions of potential confounders is the same, or approximately the same, in both groups. In a non-crossover study, even randomised, it can be the case that even after careful matching, target and control areas differ with respect to the distribution of some covariates. This is particularly the case for time-varying covariates. In a randomised crossover design the impact of differences in time varying covariates are averaged out (unless these covariates follow substantially different regimes in the target and control areas during the study).

Second, a crossover design is statistically efficient, in that on average it ensures approximately equal numbers of "seeded" cases and "non-seeded" cases. In addition, assuming no crossover effects, it doubles the number of seeded and unseeded cases compared to a non-crossover study. Consequently it requires a shorter trial period than would be the case for a non-crossover design.

The crossover design was applied to the trial with the two ATLANT™ sites operated on a randomly predetermined rotation basis throughout the trial with no breaks.

3.5.1 Randomised Operating Schedule

The two sites were operated in a randomised alternating schedule. Rather than randomly generating the schedules for Hajar 1 and Hajar 2 and then combining them, a schedule was constructed from the 170 1-day groups containing 85 days Hajar 1 on and Hajar off; and 85 days Hajar 2 on and Hajar 1 off. The advantage of this approach is that it ensures that each combination is scheduled for an equal number of days. The 170 1-day groups were then randomly sequenced giving an operating schedule commencing 15 May 13 and completing 31 October 2013.

The groups were randomly sequenced using the 'permrand' function in the Statistical package Matlab, which generates a random permutation of the integers from 1 to 'n', where 'n' was the 170 1-day groups. It uses the 'rand' function to generate pseudo-random values drawn from a uniform distribution on the unit interval. The function uses the Mersenne Twister algorithm by Nishimura and Matsumoto (1998). For a full description of the Mersenne-twister algorithm, see:
http://www.math.keio.ac.jp/~matumoto/emt.html.

For the trial operation covering the period 15 May to 31 October inclusive, the full random sequence yielded 85 days when Hajar 1 would be on and Hajar 2 would be off; and 85 days when Hajar 2 would be on and Hajar 1 would be off. The actual operation that was achieved is detailed in Table 3-1. No breakdown or significant operation stoppages occurred. The full achieved randomised operating schedule is set out in Appendix A.

Table 3-1: Summary of operation achieved

ATLANT™	Operating days
Hajar 1 (H1)	85
Hajar 2 (H2)	85
Total	170

3.5.2 Defining Switch Time

A few underlying principles on the selection of an appropriate operating "switch time" for the trial are:

- to alternate on small time scales (compared with the total experiment time)
- to establish buffers around target and control time periods and area between sites
- to limit interactions between sites.

The ATLANT™s were switched on and off in accordance with a nominal switching time at 7am (local Oman time) on the designated days. This was to ensure that enough time elapsed before the onset of convective cloud development, allowing ATLANT™ generated ions to be transported across the target areas. The Oman Directorate General of Meteorology and Air Navigation (DGMAN) advised that convective cloud development in the Hajar mountains generally begins earliest at 10am local and dissipates approximately at 8pm local. In addition, switching at 7am was operationally convenient, in that it approximated the start of a working day.

A 30-minute 'temporal buffer" was also added to the switch time, so that the ions from the off-going ATLANT™ had time to clear the area before switching on the ongoing ATLANT™. Thus with a nominal switch time at 7am, the operating ATLANT™ was turned off at 6.30am to let the ions clear away. The ongoing ATLANT™ was then turned on at 7am. All daily data used in the statistical analysis of the trial was therefore computed on a 7am to 7am basis, with YearDay (07:00) used to denote the corresponding day of the year

3.5.3 Target/Control area definition

The determination of whether a gauge is exposed to the ion plume generated by the ATLANT™ technology is a challenge 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. A detailed description of the target/control definition is given in Section 6.

4. METEOROLOGICAL INFRASTRUCTURE AND DATA

4.1 Upper air sounding data

The Oman Directorate General of Meteorology and Air Navigation (DGMAN) operates a radiosonde at Seeb International Airport.

- Designator: 41256 Seeb Intl/Muscat
- Latitude: 23.35N
- Longitude: 58.17E
- Elevation: 8 m

This provides daily vertical soundings that were used to provide representations of the vertical wind profiles at the sites. Hajar 1 is located approximately 114km to the west-southwest of the airport. Hajar 2 is located approximately 75km southwest of the airport. The launch occurs at 00z daily (4am local time) and generates graphic and textual output at pressure levels during the balloon ascent (Figure 4-1).

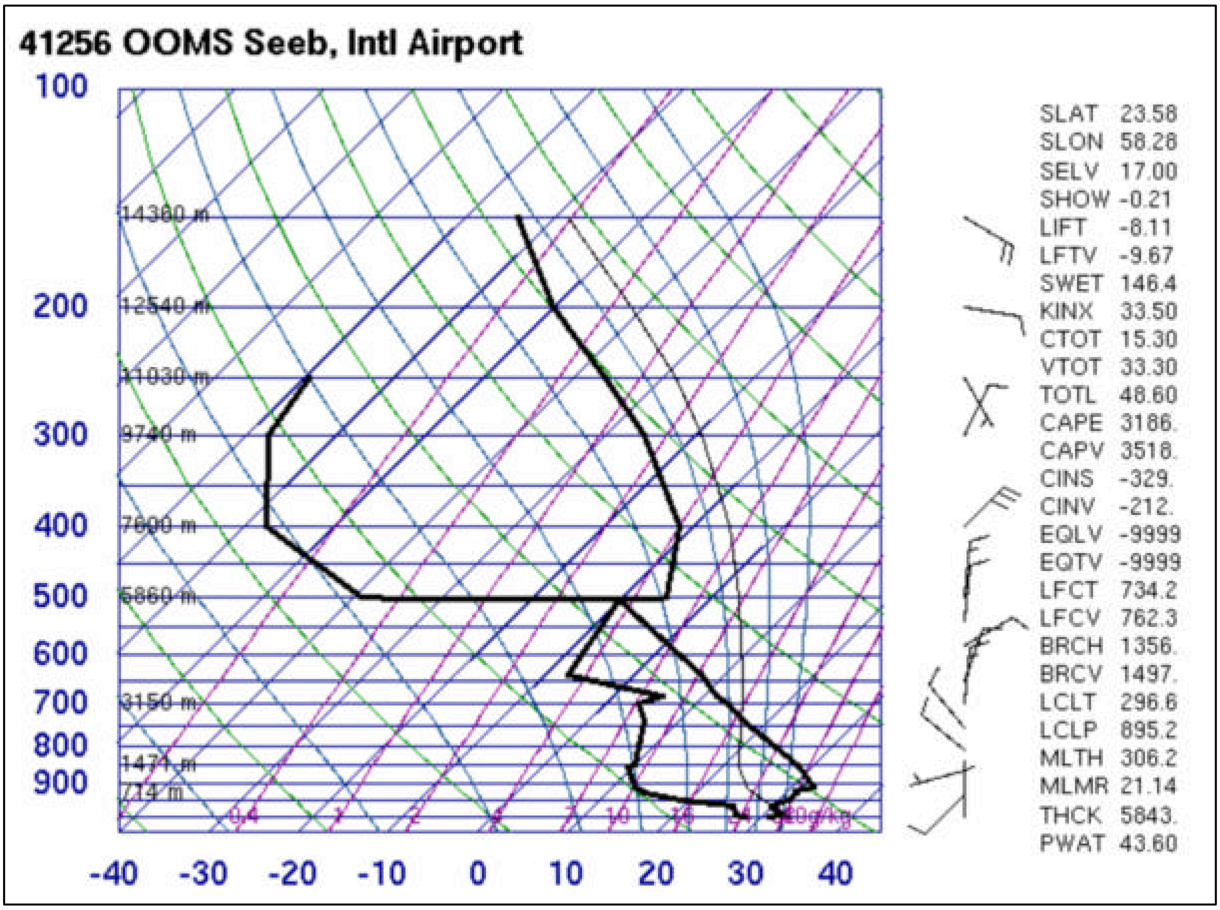


Figure 4-1 00z 21 Aug 13 Seeb radiosonde

4.2 Surface meteorological data

The Oman Directorate General of Meteorology and Air Navigation (DGMAN) operates a number of meteorological stations throughout the trial area. Hourly observations were available from these manned and automatic weather stations that belong to DGMAN, including those at Seeb International airport.

In addition, TIE installed two Automatic Weather Stations at the Atlant sites (see Figure 4-2). These stations recorded the following data:

- Rain amount
- Air Temperature
- Air humidity
- Wind Direction
- Wind Speed
- Air pressure
- Radiation
- Evaporation

Figure 4-2 TIE Automatic Weather Station at H2

4.3 Rain gauge data

Rain gauges operated by the Oman Directorate General of Meteorology and Air Navigation (DGMAN) in the trial area are co-located with their weather observation sites, and hence limited in number. Due to the localised and short-lived nature of rainfall throughout the trial area, an extensive array of quality rain gauges was installed by TIE to supplement those operated by the DGMAN. 120 new gauges were installed on an approximate 10 km regular grid throughout the trial area. Figure 4-3 shows one of the TIE gauges installed in the trial area. These gauges provided rainfall data on an hourly basis.

Figure 4-3 TIE rain gauge installed in the trial area

4.4 Radar

Radar-estimated rainfall amounts are sometimes used in support of ground precipitation data. In extreme circumstances, radar-estimated rainfall amounts can be used in lieu of the gauge data. However no weather radars are installed in Oman, though they are planned for 2014 and would be important source of data for any future operations.

Previous atmospheric studies in the region employed a variety of radars operated at sites in the UAE including at Al Ain. The National Centre for Climatology and Seismology in the UAE operate a network of C-band radars. Since the Al Ain radar covers only a limited portion of the trial area, it was not of use in the trial. Al Ain is located approximately 170 km from Hajar 1 and 214 km from Hajar 2.

4.5 Final Instrument Array

All the meteorological instruments described above collected data during the operating period. The full instrument array is depicted in Figure 4-4.

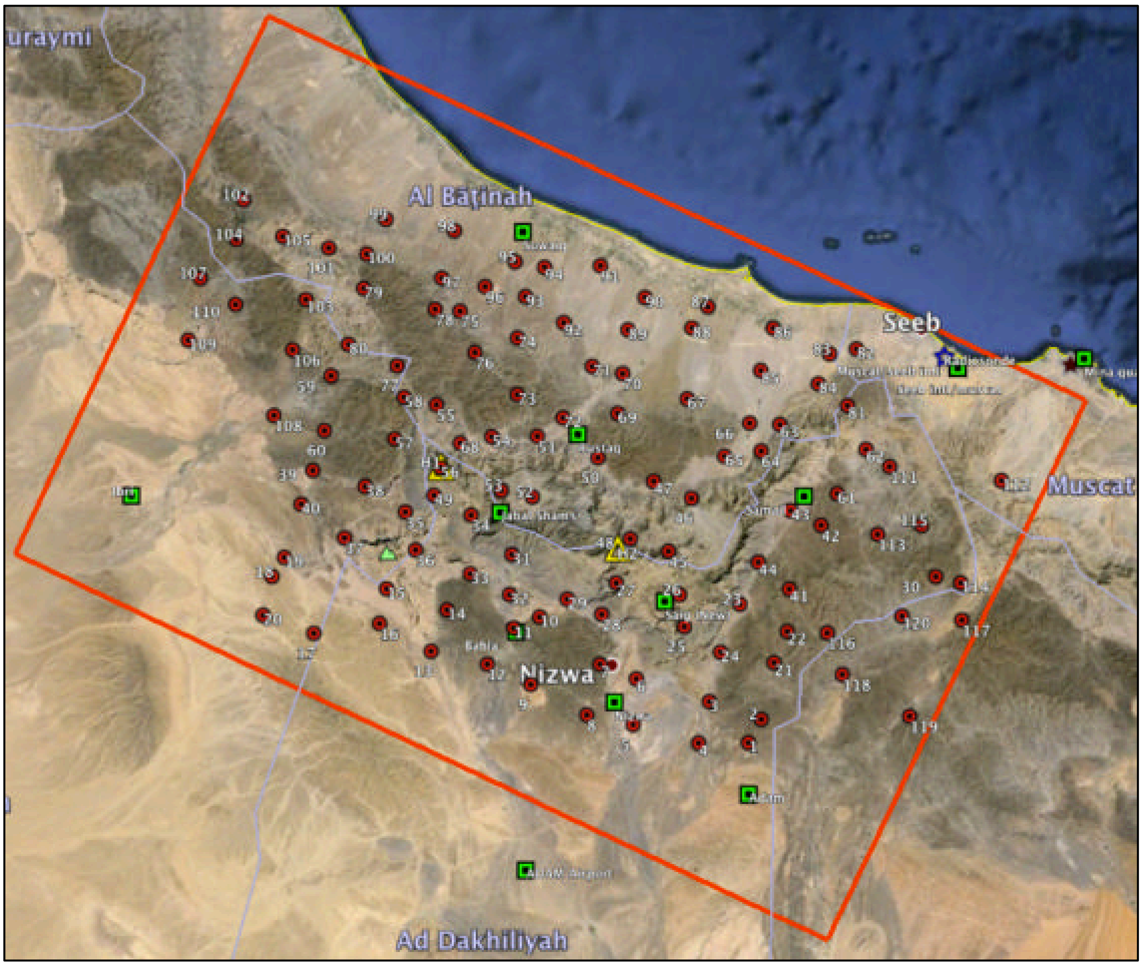


Figure 4-4 Instrument array. (Rain gauges - red circles. Surface weather stations- green squares. Radiosonde – blue star. ATLANT™s - yellow triangles).

The data recorded and available for use in the analysis is detailed in Table 4-1.

Table 4-1 Final data

Instrument	Parameter	Frequency	Notes
TIE Rain Gauge	Rain total	Hourly	120 Gauges no missing data
H1 Weather station	Wind Speed	Hourly	15 May – 31 October
	Wind Direction	Hourly	15 May – 31 October
	Temperature	Hourly	15 May – 31 October
	Humidity	Hourly	15 May – 31 October
	Evaporation	Hourly	15 May – 31 October
	Radiation	Hourly	15 May – 31 October
H2 Weather station	Wind Speed	Hourly	17 May – 31 October
	Wind Direction	Hourly	17 May – 31 October
	Temperature	Hourly	17 May – 31 October
	Humidity	Hourly	17 May – 31 October
	Evaporation	Hourly	17 May – 31 October
	Radiation	Hourly	17 May – 31 October
Seeb Radiosonde	Wind Speed Wind Direction Total totals LCL CAPE Lifted Index Precipitable-Water	Daily	4am (500 Hpa/700 Hpa) 15 May – 31 October 24 days missing
DGMAN Stations Saiq Saiq_New Suwaiq Al_Amerat, Al_Mudhebi Smail Nizwa Bahla Jabal Shams Muscat_Seeb	Rain total Wind Speed Wind Direction Temperature Humidity Evaporation Radiation	Hourly	15 May – 31 October Some missing data but over 90% complete

4.6 Derived Indices

In addition to the upper air wind speed and direction measurements obtained via the Seeb radiosonde, it also possible to use the data from this source to derive daily moisture and stability indices. The following indices were therefore calculated and used in the statistical analysis.

4.6.1 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.

4.6.2 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.

4.6.3 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.

4.6.4 Convective Available Potential Energy (CAPE)

CAPE =Convective Available Potential Energy. A measure of the amount of energy available for convection. CAPE is directly related to the maximum potential vertical speed within an updraft; thus, higher values indicate greater potential for severe weather. Observed values in thunderstorm environments often may exceed 1000 joules per kilogram (J/kg), and in extreme cases may exceed 5000 J/kg. It is a measure of instability. Rules of thumb refer to "weak instability" (CAPE less than 1000 Jkg-1), "moderate instability" (CAPE from 1000-2500 Jkg-1), "strong instability" (CAPE from 2500-4000 Jkg-1), and "extreme instability" (CAPE greater than 4000 Jkg-1).

4.6.5 Lifted Condensation Level (LCL)

The LCL (Lifting Condensation Level) is the level at which a parcel of air becomes saturated. Consider a parcel of air that is lifted adiabatically such as through forced ascent over mountainous terrain (which is equivalent to expanding), cools as it expands. As the parcel expands, the dew point of the parcel also changes in response to the pressure change. When the temperature of the air parcel and the dew point temperature are equal, condensation will occur, and a cloud will form. The height at which a parcel is lifted adiabatically and cools to the dew point temperature is known as the LCL. It is thus a reasonable estimate of cloud base height.

5. DESCRIPTIVE ANALYSIS OF THE TRIAL DATA

An Automatic Weather Station was located at each ATLANT™ site. Comparison of the data collected by these stations at each site was used to assess the similarity of the meteorological conditions at each site. Noting that ideal alternating target/control sites have highly correlated observations.

5.1 Trial Area Daily Convective Period

Over the trial area, on days with no rain potential, dry north-westerlies converge (over the mountains) with the sea-breeze from the Gulf of Oman. Conversely on days with cloud and/or rain development, the sea-breeze converges with moisture flow advected from the Arabian Sea. A dry desert air will lead to moist convection being suppressed, whereas moist air advected from the Arabian Sea will enhance moist convection. Moisture advection from the Arabian Sea in a column of at least 1 kilometre in depth is required for proper convection (Al-Maskari et al. 2006). The stronger the flow from the Arabian Sea and the deeper the column of the moist air, the heavier the precipitation. Generally clouds that develop over the mountain peaks dissipate as they move west.

The Oman Directorate General of Meteorology and Air Navigation (DGMAN) advised that convective cloud development in the Hajar mountains generally begins earliest at 10am local and dissipates approximately at 8pm local. Hence for the purpose of this analysis meteorology will be analysed over this daily period, as generally outside this period there is no rain potential.

5.2 ATLANT™ Site meteorology Data

Meteorological data at each ATLANT™ site was assessed on an hourly and a daily average basis. Pressure data was found to be well outside expected observation range returning values as low 700hPa. Consequently Pressure was not used in the statistical analysis and TIE is investigating the original calibration of the recorder. Air temperature, relative humidity, radiation and day to day change in evaporation were within expected observation ranges (see Figure 5-1 for daily averages). Air temperature, relative humidity, evaporation and radiation were all well correlated, both on an hourly and on a daily average basis (see Appendix B Figure B-3 and Figure B-4).

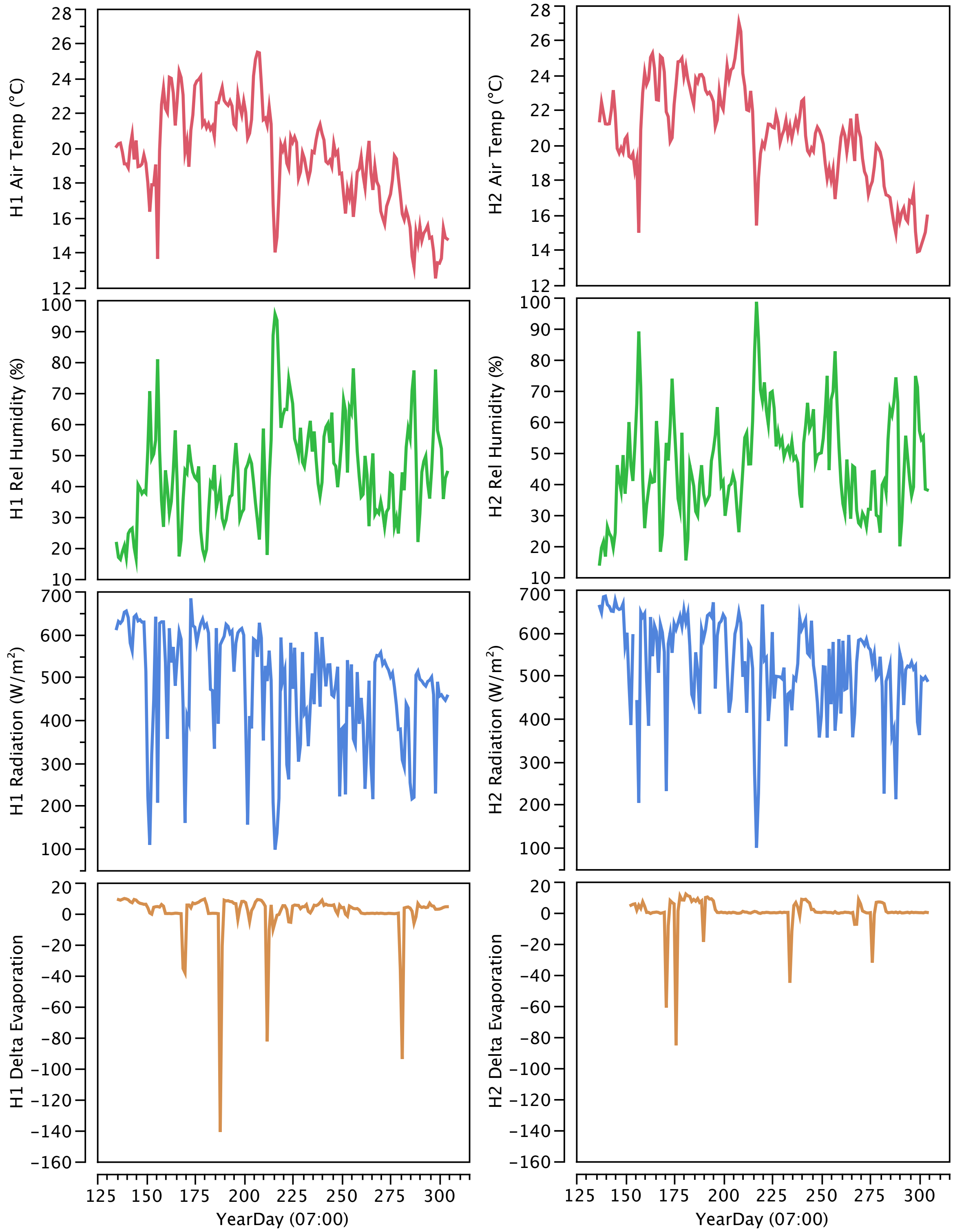


Figure 5-1: Daily average ATLANT™ site meteorology (Left panels H1 ; Right panels H2)

5.3 Wind data

Wind Direction and Speed data from the ATLANT™ sites, as well as Steering Wind calculated from Seeb radiosonde data are plotted in Figure 5-2. These data indicate that there are significant differences between the three sites, further highlighted in the daily wind distributions in Figure 5-3 and Figure 5-4. Of particular note is that the observed Seeb steering wind had 24 days when data are missing. These missing observations have been replaced by the median of the non-missing values from the three previous days and the three following days; they are referred to as the imputed Seeb steering wind direction (SWD) and steering wind speed (SWS) values in the plots making up the last row of Figure 5-2. TIE investigated the missing data issue with DGMAN, but the data were not recoverable.

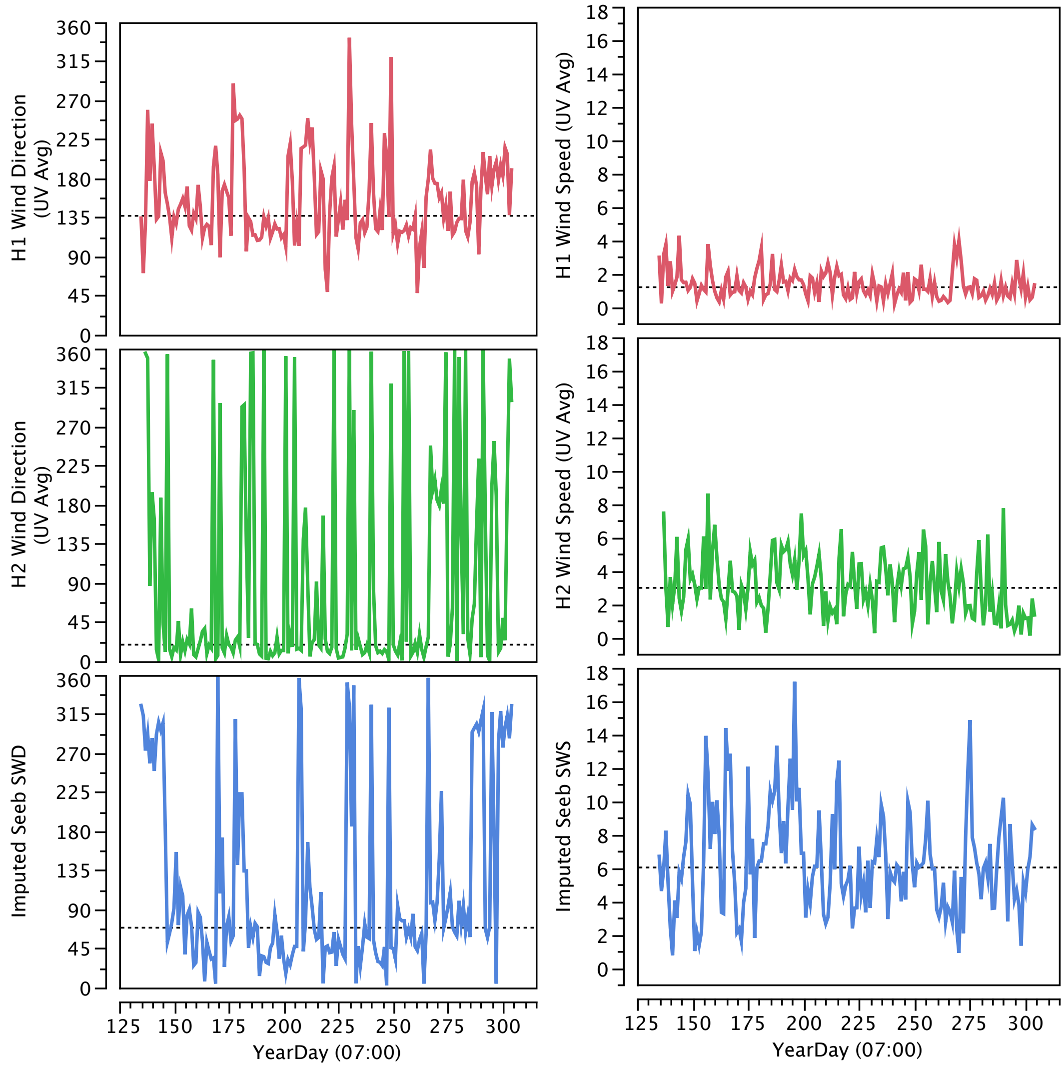
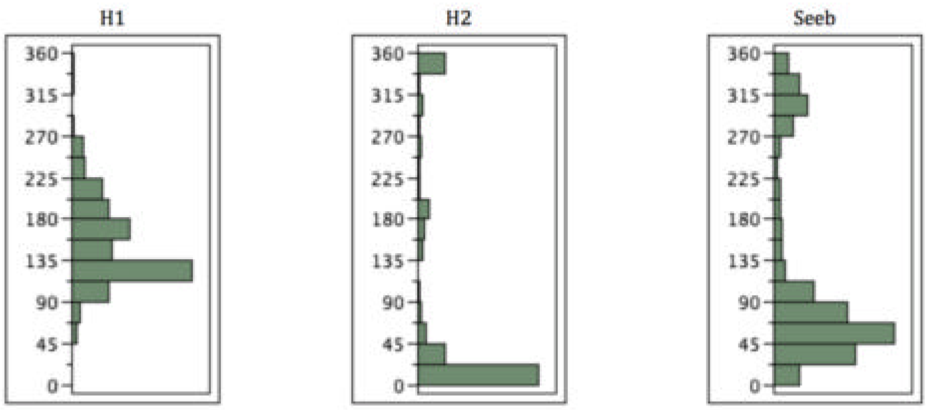


Figure 5-2: Daily Steering Wind Directions (SWD, left panels) and Steering Wind Speeds (SWS, right panels) at H1, H2 (1000-2000hrs) & Seeb (0400hrs). Dotted horizontal line is the median value.



H1

100.0%	maximum	342.23
97.5%		257.30
90.0%		218.32
75.0%	quartile	182.11
50.0%	median	137.12
25.0%	quartile	119.93
10.0%		109.34
2.5%		75.75
0.0%	minimum	48.02
Mean		154.77
Std Dev		48.48
N		170

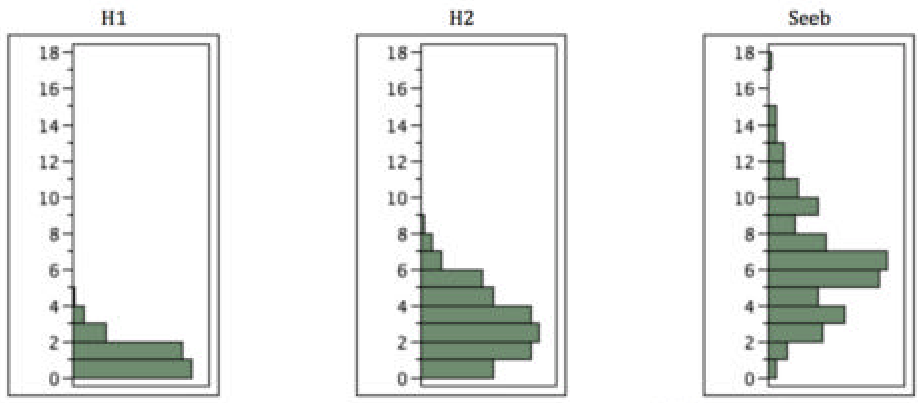
H2

100.0%	maximum	359.99
97.5%		359.11
90.0%		350.14
75.0%	quartile	167.29
50.0%	median	20.11
25.0%	quartile	10.57
10.0%		5.39
2.5%		1.69
0.0%	minimum	0.21
Mean		91.03
Std Dev		123.23
N		168

Seeb

100.0%	maximum	358.47
97.5%		350.67
90.0%		309.13
75.0%	quartile	168.87
50.0%	median	70.19
25.0%	quartile	46.38
10.0%		28.85
2.5%		4.64
0.0%	minimum	2.50
Mean		117.76
Std Dev		105.92
N		170

Figure 5-3: Distributions of Daily Steering Wind Directions at H1, H2 and Seeb. Note 24 days are missing from Seeb and are imputed



H1

100.0%	maximum	4.2618
97.5%		3.7250
90.0%		2.4798
75.0%	quartile	1.7263
50.0%	median	1.1694
25.0%	quartile	0.6996
10.0%		0.4034
2.5%		0.2651
0.0%	minimum	0.1794
Mean		1.3243
Std Dev		0.8301
N		170

H2

100.0%	maximum	8.6267
97.5%		7.2750
90.0%		5.5347
75.0%	quartile	4.3923
50.0%	median	2.9647
25.0%	quartile	1.7651
10.0%		0.8053
2.5%		0.2922
0.0%	minimum	0.0914
Mean		3.1057
Std Dev		1.7659
N		168

Seeb

100.0%	maximum	17.1708
97.5%		13.7558
90.0%		10.3779
75.0%	quartile	7.8526
50.0%	median	6.0628
25.0%	quartile	4.0783
10.0%		2.7417
2.5%		1.3336
0.5%		0.7498
0.0%	minimum	0.7498
Mean		6.3481
Std Dev		3.0486
N		170

Figure 5-4: Distributions of Daily Steering Wind Speeds (m/s) at H1, H2 and Seeb. Note 24 days are missing from Seeb and are imputed

5.4 Rainfall data

The ATLANT™s were switched on and off in accordance with a nominal switching time at 7am (local Oman time) on the designated days. This is to ensure the enough time to elapse before the onset of convective cloud development, so that the ATLANT™ generated ions are transported across the target areas. Rainfall was thus analysed in Figure 5-5 as total measured rainfall over the period from 7am to 7am, commencing on designated day of operation. In the statistical analysis, these days are denoted by YearDay (07:00) and measured on a day of year basis.

Clearly evident in the rainfall records is that the majority of rainfall fell between late July and mid-September. Evidence for this is the abrupt change from around August 1 (YearDay (07:00) = 213) in the proportion of the 120 TIE gauges that recorded rainfall, as shown in the first row of Figure 5-5). The second row of this Figure shows average gauge level rainfall by day for these gauges, while the third shows the daily averages over the trial period of the variable LogRain, defined as the logarithmic transform of gauge level rainfall. Note that since the logarithm of zero is not defined, values of LogRain only occur when there is rain recorded by a gauge, and so the daily averages for this variable are over gauges that reported rain that day. This means that on days when no rain was reported, there is no value for average LogRain, leading to missing data in the last row of Figure 5-5.

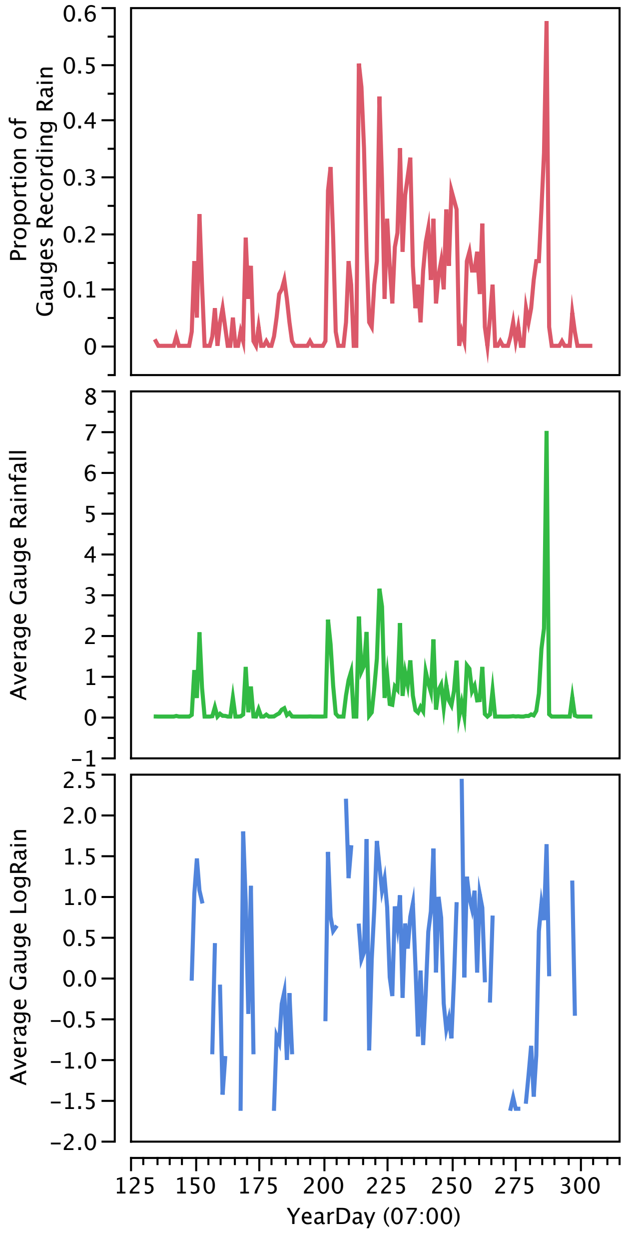


Figure 5-5: Gauge Averages by Day: Daily (07:00 - 07:00) Rainfall / LogRain / Rainfall Recorded

The daily rainfall patterns displayed in Figure 5-5 were then split according to days when H1 was operated vs. days on which H2 was operated. These two sets of patterns can be compared using the plots in Figure 5-6. Here we see that, contrary to the expectation that use of a trial design that randomised across days should lead to very similar patterns for H1 days vs. H2 days, there is some evidence that on days when H1 was operated rainfall was more prevalent, and was heavier. This means that any simple statistical comparison of rainfall between the two sites that does not take into account day to day variation in meteorological conditions will be non-robust.

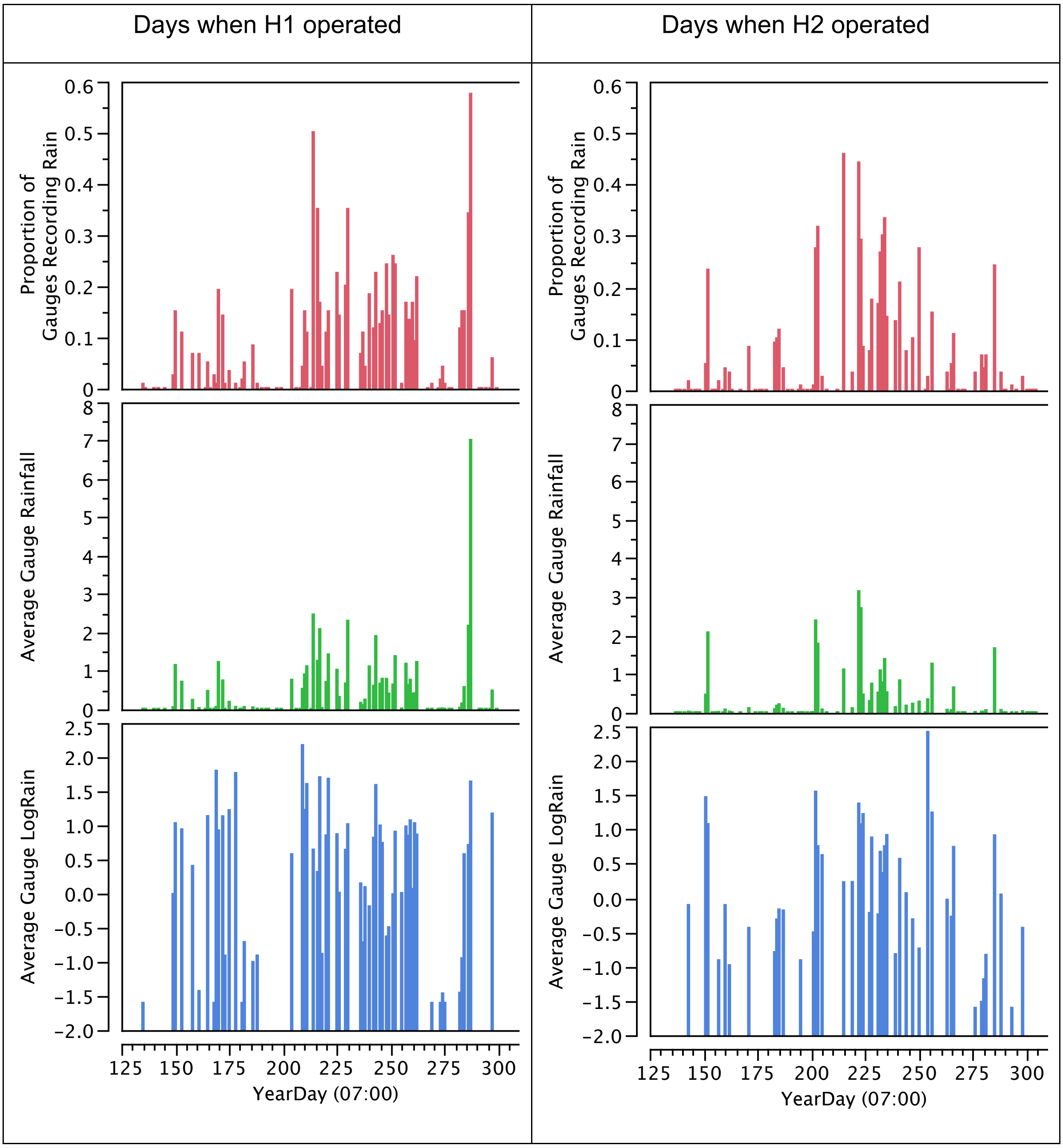
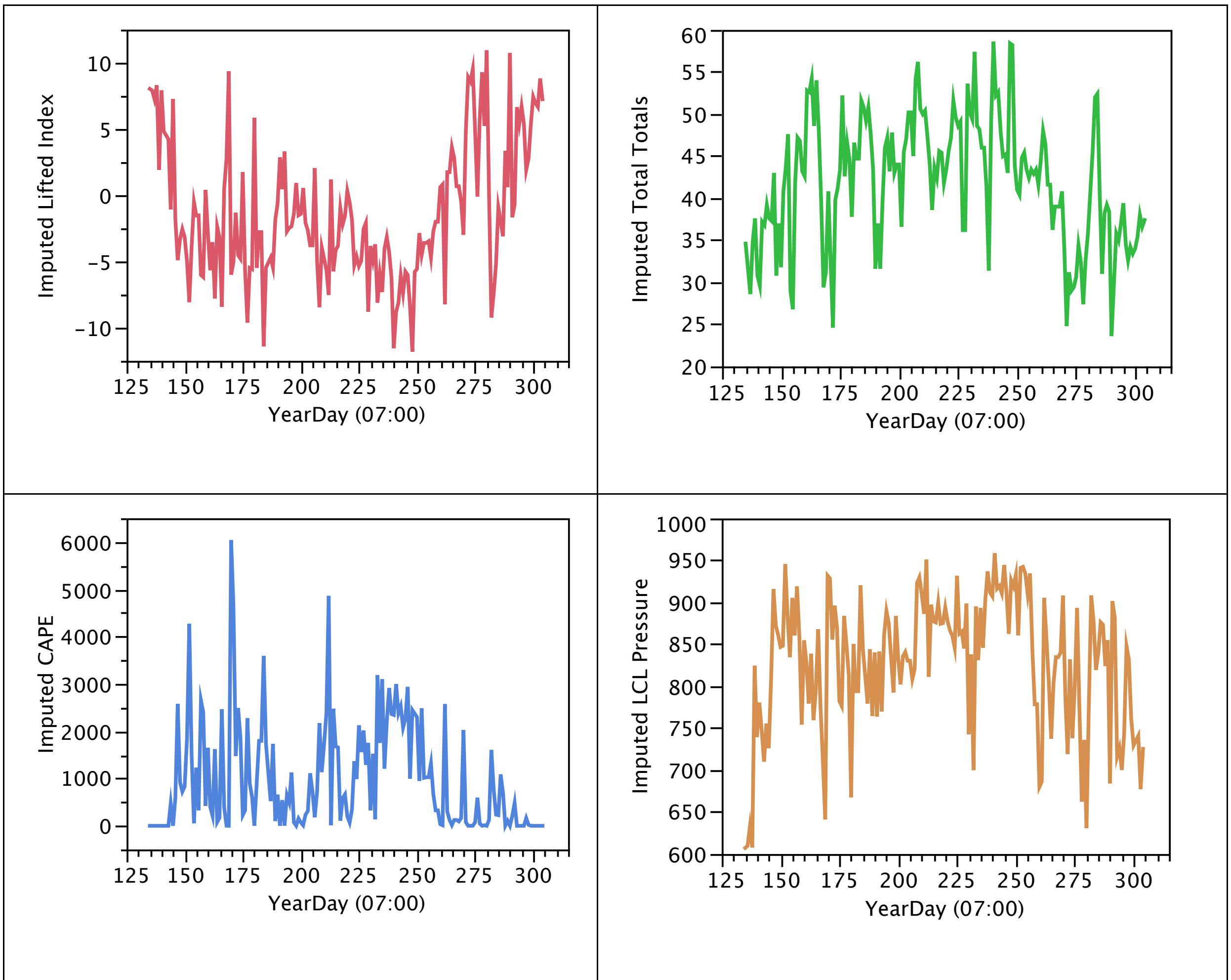
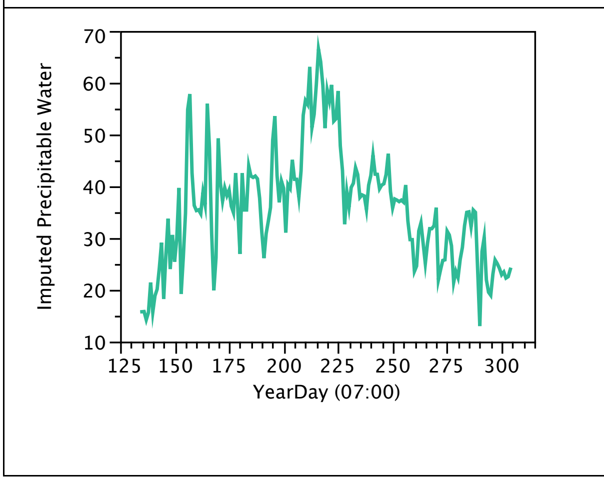


Figure 5-6 Rainfall patterns on days when H1 was operated vs. days on which H2 was operated

5.5 Stability and Moisture indices

The daily changes in the indices imputed from the Seeb radiosonde over the trial period are displayed in Figure 5-7.





Correlations

	Lifted Index	Total Totals	CAPE	LCL Pressure	Precip Water
Lifted Index	1.00	-0.72	-0.71	-0.78	-0.64
Total Totals	-0.72	1.00	0.33	0.38	0.61
CAPE	-0.71	0.33	1.00	0.68	0.47
LCL Pressure	-0.78	0.38	0.68	1.00	0.64
Precip Water	-0.64	0.61	0.47	0.64	1.00

Figure 5-7 Stability and Moisture Imputed Indices

5.6 DGMAN station meteorology

There were ten DGMAN weather stations with complete data over the trial period. These were Saiq, Saiq_New, Suwaiq, Al_Amerat, Al_Mudhebi, Smail, Nizwa, Bahla, Jabal Shams and Muscat_Seeb. Hourly measurements of Dry Temperature, Dewpoint Temperature and Relative Humidity between 10am and 8pm from these stations were averaged and compared. There was general agreement in these values after making allowances for the location and elevation of these stations. Consequently, their First (Component 1) and second (Component 2) principal components were calculated and used to characterise general meteorological conditions across the trial area on a day by day basis. These daily values are displayed in Figure 5-8.

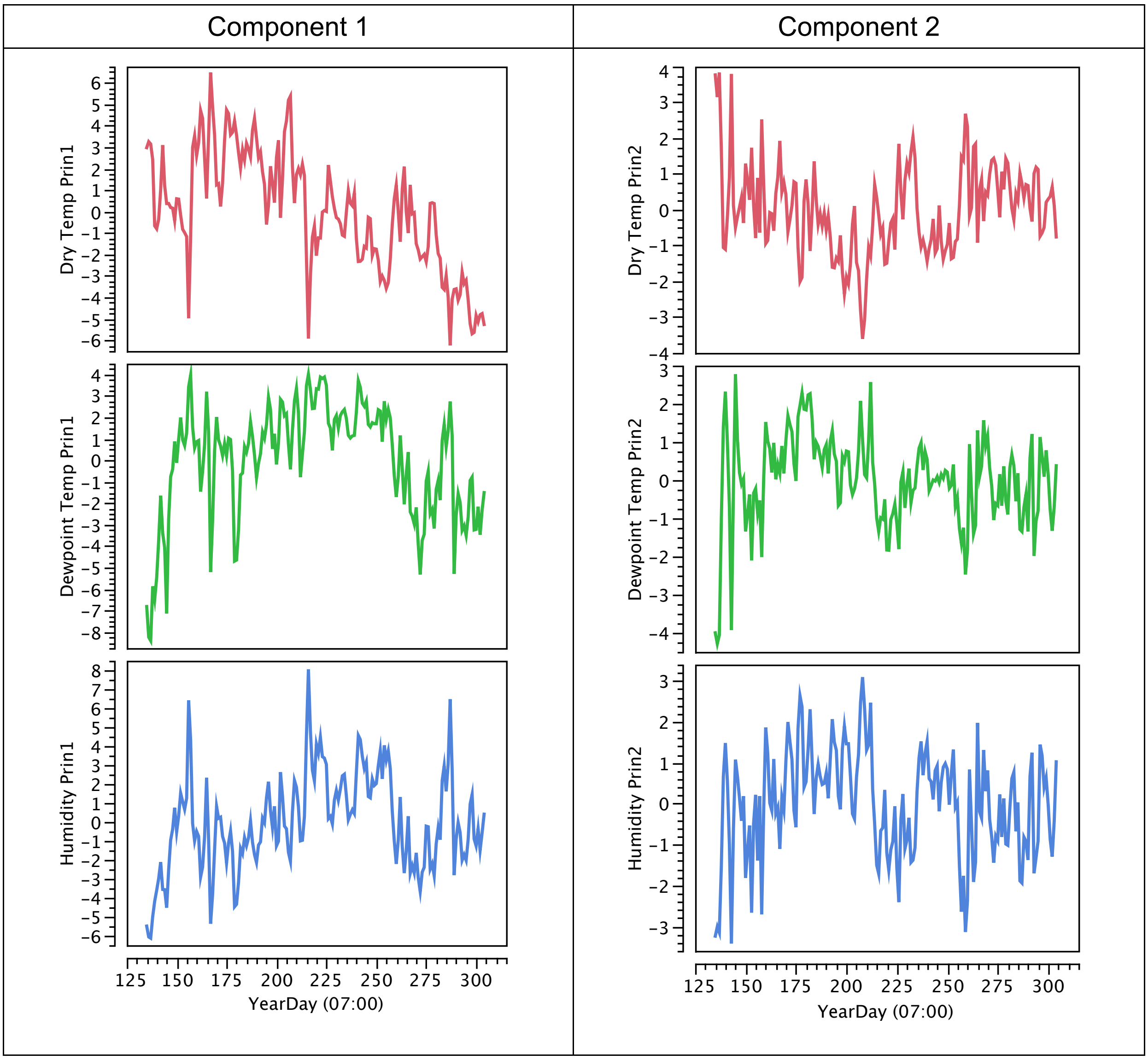


Figure 5-8 Principal components of DGMAN meteorology observations

6. SPECIFICATION OF THE STATISTICAL ANALYSIS

The objective of this section is to set out the conceptual specification of the statistical analysis prior to conducting the analysis and modelling of the rainfall data from the Oman ATLANT™ trial.

6.1 Conditional Experiment Design

The experimental design of the trial followed the format of the 2009 and 2010 Mount Lofty Ranges ATLANT™ trials. The statistical methodology used to analyse 2010 trial data is the starting point for the Oman trial. However, there are substantive differences in the prevailing weather conditions and available meteorological data available that need to be considered.

The plan is based on a review of the topography of the trial area and prevailing meteorological conditions over the trial period. The location of the ATLANT™ sites and rainfall gauges were analysed in conjunction with wind directions and speeds at the ATLANT™ sites and stations maintained by the Oman Directorate General of Meteorology and Air Navigation (DGMAN). The review raised questions that had to be addressed before the statistical analysis could proceed. Below we set out the process that was used to resolve them.

These were two critical elements the design of the statistical analysis that needed to be established.

1. The designation, based on wind direction and speed, of the rainfall gauges as a target, control or external to the trial area. Observations from external gauges that are upwind of the trial area are covariates that may help predict rainfall in the trial area independent of the status of the ATLANT™ systems.
2. The unit of analysis, which will be gauge-level rainfall over a specified time period. The continuous recording of rainfall in the trial area allows the frequency and duration of the time period to be aligned with the proposed design of the statistical model.

The principal issues that therefore needed to be resolved were to do with external sources of meteorological information. While weather observations provided by the DGMAN are essential, and other sources useful, to the design of the statistical model, the extent, frequency and location of the observations can present problems and impose constraints on the statistical analysis.

It was decided that the statistical methods used to model the data should, as a modelling strategy, follow those used in the 2010 Mount Lofty Ranges trial. This includes:

- Modelling gauge-level data
- Using covariates to control for variation in natural rainfall over time and location
- Transforming rainfall data to a scale consistent with the conditions that allow statistical estimates of reliability to be made

- Accounting for temporal, spatial and spatiotemporal correlation in the data to avoid substantive overstatement of the precision of the resulting estimates.

6.2 A Comparison of the Mount Lofty Ranges and Oman ATLANT™ trial sites

The use of publicly available rainfall data within the Mount Lofty Ranges trial area restricted the analysis to daily rainfall measurements. Thus the unit of analysis was a gauge day. This was taken as the starting point for the Oman trials as there are conditions that would need to be met if the unit analysis was moved to a finer time scale.

A key component of the experimental design and analysis is that exposure of rainfall gauges to the ATLANT™ is assumed to depend on wind direction and speed at and above the ion generator. Depending on the relative location of a rainfall gauge to an active ATLANT™ site, a gauge can be classified as a target (exposed) or a control (unexposed). This was the approach adopted in previous Atlant trials conducted in Australia. Daily rainfall measurements in that case were classified as target or control observations on the basis of the speed weighted average wind direction. This was a steering wind direction, calculated from wind direction and speed measurements at pressure levels of 850hPa and 925hPa at Adelaide airport taken four times daily (at 03:00, 09:00, 15:00 and 21:00). These pressure levels were selected in order to measure wind speed and direction at the heights that would direct the movement of the cloud layer. A downwind arc from an ATLANT™ site was then defined with the midline given by the steering wind direction at the site and a fixed interior angle that was set so as to capture both the lateral dispersion of an ion plume as well as shifts in wind direction during the day, while limiting the overlap created when gauges were classified as being downwind of both sites. A 60-degree angle provided a good compromise. The downwind extent of the arc was largely determined by the availability of rainfall gauge information, but analysis of data from previous ATLANT™ trials had indicated that this should be between 75km and 100km. Upwind gauges observations (where upwind is defined as being simultaneously upwind of both ATLANT™ sites) were used in the statistical modelling as covariates to account for potential differences in the propensity for rainfall to occur downwind of the two ATLANT™ sites.

This basic strategy has been maintained in the analysis of the Oman ATLANT™ trial data. Steering wind directions can be calculated from upper wind level observations made at 4am daily at Seeb airport. However, there are a number of sharp contrasts in trial conditions for Adelaide versus Oman. Notably:

- The physical processes that generate precipitation in the Oman trial area are extremely different from the widespread winter dominant rainfall patterns over the Mount Lofty Ranges. The summer rain season in the Hajar Mountains is dominated by warm convective clouds that generates precipitation, usually patchy in terms of geographic extent, in the afternoons (refer to section 5.1). An average of 400mm falls between June and September in the higher elevations. As clouds are carried over the desert they dry with little to no rainfall falling at the lower elevations of the desert plateau.
- The Mount Lofty Ranges run parallel to the coast (northeast to southwest) with prevailing steering winds ranging from the southwest, over the Southern Ocean, to northwest over

continental Australia. The Hajar Mountains run parallel to the coast (northeast to southeast) with a predominant prevailing wind direction of east-northeast coming over the Indian Ocean in the summer months. Steering winds are roughly perpendicular to the range throughout most of the trial period. The downwind extent of the trial area, define by the western edge of the Hajar Mountains, is roughly 50km, which is also the approximate distance between H1 and H2. The distance between the ATLANT™ sites in Adelaide was roughly 70 km.

- Surface wind direction and speed at the ATLANT™ sites in the Mount Lofty Ranges and Hajar Mountains are affected by the local topography. There was strong correlation between steering winds at the Adelaide airport and surface winds at the ATLANT™ sites when storms were tracking through the trial area. There are only weak to moderate correlations between steering wind directions at Seeb airport and the surface winds at the ATLANT™ sites (H1 and H2) in the Hajar Mountains (see Appendix B, Figure B-5). Surface winds in the afternoon at H1 and H2 are, in contrast to the steering wind at Seeb, quite variable (see Figure 5-3 and Figure 5-4 previously).
- The ATLANT™ sites in the Mount Lofty Ranges were situated at the top of ridgelines at elevations of less the 400 metres. The ATLANT™ site in the Hajar mountains are also at the top of ridgelines but at elevations of above 2,000 meters.

6.3 Implications for the analysis of the Oman trial

The differences outlined above have implications for the unit of analysis and the designation of gauges and other aspects of the statistical analysis of the trial data. First; while the ATLANT™ systems are operated on an alternating 24-hour schedule, the relevant period of operation are those hours in which there is a substantive probability that given sufficient atmospheric moisture, precipitation will occur. With a reasonable buffer this is in a window between 10am and 10pm. The designation of gauges should reflect to the best extent possible wind conditions prevailing within this period.

The radiosonde observations of upper level winds at Seeb airport take place at 4am, well outside this rainfall window. The problem is exacerbated by the fact that these upper levels wind observations are missing on 24 days between 15 May and 31 October. This raises two issues that needed to be resolved:

- Is there sufficient correlation between early morning and afternoon readings of upper wind levels, and
- The best way to impute the missing observations.

The consistency of the steering winds was verified by comparing the 4am Seeb wind reading to satellite imagery when there is afternoon cloud cover, as cloud bands are the product of steering winds (see Figure 6-1 for example). This established:

- An average steering wind direction when cloud cover is present.
- 4am measurements at Seeb are a reasonable predictor of this steering wind direction when cloud cover is present.

- Imputation of the missing 4am upper wind observations at Seeb should be carried out using Seeb data, rather than data from H1 or H2 (or a combination).

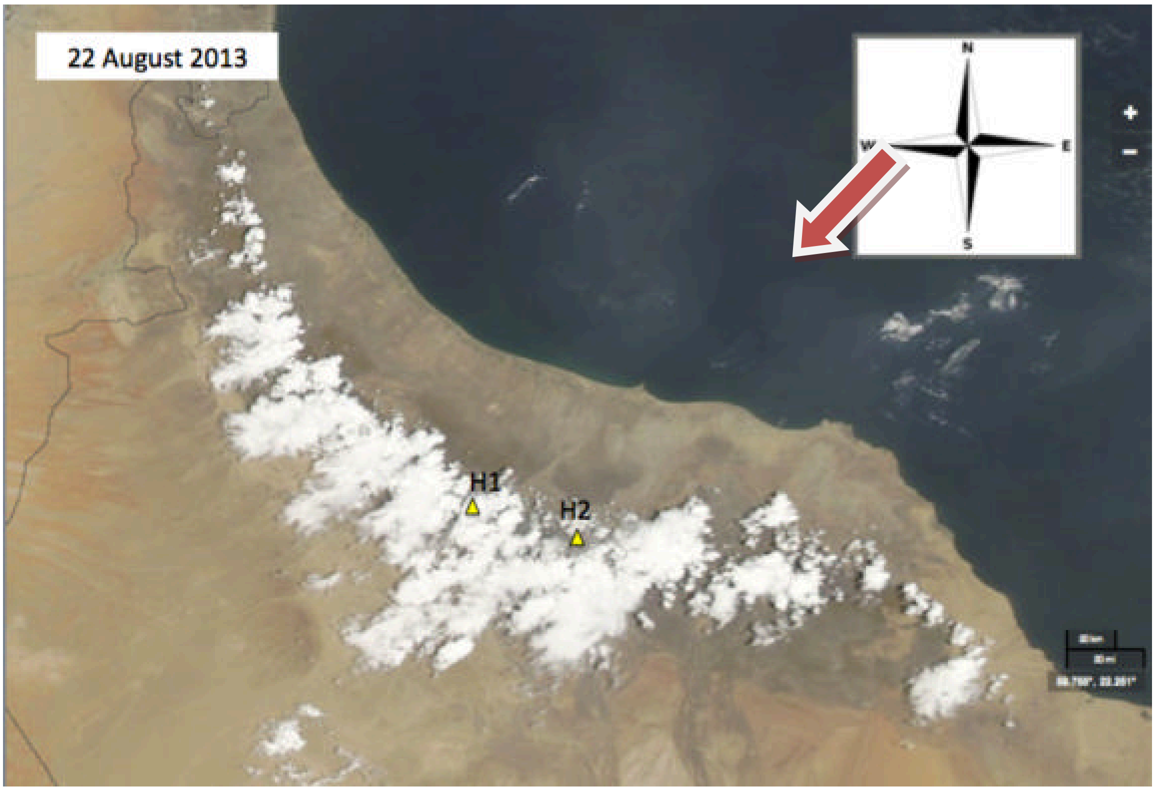


Figure 6-1: Visible Satellite image with Seeb steering wind overlay on 22 August with Steering wind at Seeb (048 degrees) from the NE (red arrow).

The imputation of missing or the complete replacement of upper wind observations at Seeb is a necessary condition for defining target and control gauges dynamically on the basis of wind direction. This would be advantageous as there is sufficient variation in upper wind levels at Seeb to justify dynamic designation of gauges as target and controls. As the wind direction shifts the gauges that are downwind of a particular site can change. Hence, defining the status of a gauge on the basis of current as opposed to an average wind direction and status is potentially more informative.

The replacement of upper wind observations at Seeb with more frequent ground level observations is necessary if the unit of analysis were to shift from a gauge to a finer time interval. However, there would need to sufficient variation in wind direction within the rainfall window to justify the resulting added complexity. That is, there would need to be changes in the composition of target and control gauges within the rainfall window on any given day to generate information over that provided by a fixed set of gauges for that day.

There is greater variability in the surface winds at H1 and H2 compared to the steering wind directions at Seeb. Furthermore, there is no significant correlation between surface winds at H1 and Seeb, and only moderate correlation of these winds at H2 and Seeb (see Appendix B, Figure B-5). This implies that dispersion of ions from the sites will be difficult to predict. The ions might initially move in one direction for period of time and then abruptly change direction as they are carried up to higher elevations.

It is reasonable to think of the effect of ground winds as a shift in the location of the ATLANT™ system in the direct of the surface wind. How large this shift is depends on wind speed and the time taken by the ion plume to enter the upper wind stream. The median wind speed over the trial period was about 5 km/hour at H1 and 12 km/hour at H2. The 90th percentile wind speeds were around 9 km/hr at H1 and 21 km/hr at H2 (see Figure 5-4 previously). Given the elevation of the ATLANT™ sites, the time required for the ions to reach the upper wind levels may be short and so taking account of the wind shift affect would not have a great impact on gauge designation. Some initial experiments with balloons suggested this might very well be the case with transit times of only a few minutes. However, further experiments with flares (due to their more neutral buoyancy) remain to be conducted.

Overall, it became clear before the trial data had been analysed that the use of an ATLANT™ 'footprint' defined by an arc (or 'wedge') emanating from the ATLANT™ site in the direction of the (assumed) steering wind is perhaps not the most robust model for designating target vs. control status of gauges on a day given the variability of surface winds at H1 and H2. A simple alternative that was therefore developed is to define this footprint in terms of 'corridors' that bisect the downwind trial area:

- At the midpoint between H1 and H2;
- Along the axis defined by the steering wind direction;
- With a fixed length;
- With a fixed width either side of the axis.

This corridor model is illustrated in Figure 6-2.

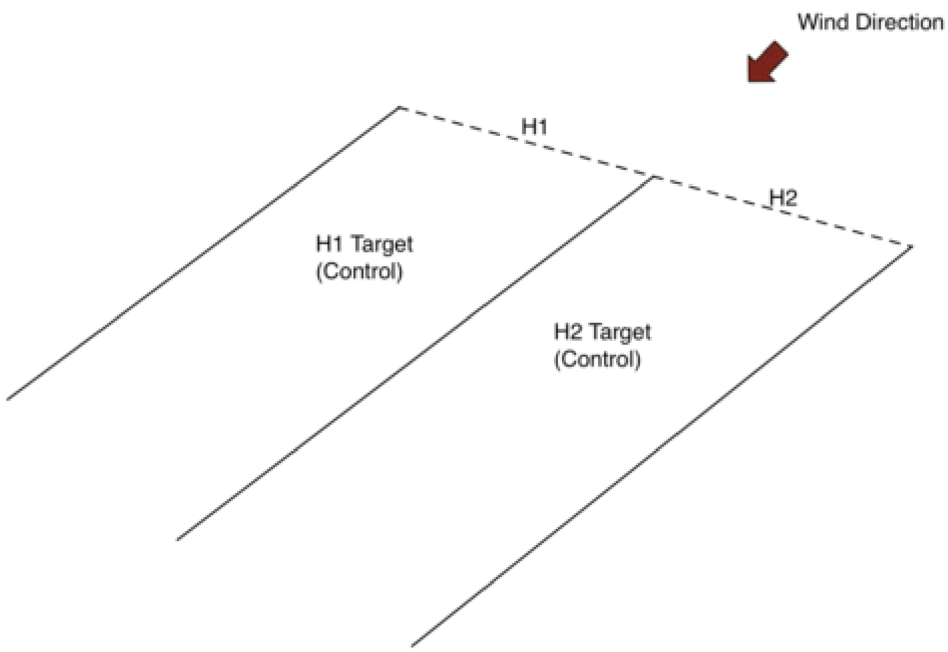


Figure 6-2: A stylised corridor model for designating target and control gauges

Depending on the chosen width and length of the 'corridor', this approach has two additional advantages:

- It increases the potential number of downwind gauges classified as either as target or control,
- It reduces overlap in the classification of gauges, that is, downwind of the active and the inactive ATLANT™ sites.

The corridor design is most efficient when the direction of the steering wind is at a 90° angle to the orientation of a direct line connecting the two sites, and its width is equal to the distance between the sites. In this case a H1 (H2) target gauge will always be physically located closer to H1 (H2) than to H2 (H1). This will also be true for a H1 (H2) control gauge. Given the locations of H1 and H2, this wind direction condition is (approximately) satisfied when the winds are out of the northeast, i.e. the prevailing wind direction over the summer months. A fixed north east oriented corridor design is less efficient however when the steering winds run more in line with the two sites. In this case some H1 (H2) target gauges may in fact be physically closer to H2 (H1), thus reducing the number of control gauges. There will also be H1 (H2) target gauges that are in fact not downwind of H1 (H2), thus adding variability to the analysis but no extra information. The problem occurs most often in September and October when the steering winds are more out of the north to north west.

The potential number of downwind gauges is also an issue in the Oman trial. When a 60º downwind arc is used to designate the target and control areas (as was the case in the Mount Lofty Ranges trial), the average daily number of gauges is about 11 in each (see Figure B-1 and Figure B-2 in Appendix B illustrating what happens on August 12 given this definition). With these smaller numbers of gauges (compared to the Mount Lofty Ranges trial), it would take a larger difference between the target and control areas to achieve the same level of confidence in any estimate derived from the statistical analysis. A corridor model with, for example, a width of 50 km, a downwind length of 75 km and a fixed orientation equal to 60º (the average steering wind direction at Seeb May to August) increases the number of downwind gauges (target and control) from 23 in the 60º downwind arc to 33 per day.

In the end, we decided to conduct analyses using both a dynamic 60° downwind arc footprint model and a dynamic downwind corridor footprint model based on daily steering wind direction as well as a static corridor footprint model based on a fixed 60° steering wind direction.

7. RAINFALL MODELLING ANALYSIS

7.1 Overview

The ATLANT™ trial utilised a randomised operating schedule (randomised design) in order to eliminate potential experimental bias arising, for example, if the system were operated when conditions were more favourable for natural rainfall to occur. The trial made use of two sites operated on an alternating schedule to create a randomised crossover design. This purpose of the crossover design is to improve statistical efficiency as opposed to further reducing experimental bias.[1] In the context of the ATLANT™ trial the factor that limits the effectiveness of the crossover design is the overlap in exposure, that is, where control gauges (i.e. gauges downwind of a non-operational ATLANT™) may still be influenced by the active ATLANT™ system.

Regardless of the design, the ability to detect a signal is difficult when the effect is small relative to the natural variation in the process being measured. The objective of constructing a statistical model is to reduce this natural variation by using covariates to predict or explain natural variation independently of the phenomenon of interest itself. In the context of the ATLANT™ trial, the objective of the statistical modelling is to predict the level of rainfall that would have occurred if the ATLANT™ system were not operating. The covariates are observations on, for example, temperature and humidity, which are correlated with rainfall but independent of whether:

- The ATLANT™ system is operating or not, and
- A gauge is designated as a target or control.

While there are many elements of choice in the development of a statistical model, the key concern is with the introduction of bias in the estimated:

- Effect of the ATLANT™ system, and
- Precision with which that effect is measured.

The estimator of the effect will be biased if there is an unmeasured influence on rainfall that is correlated with the operating status, which would be coincidental (and unlikely given the use of randomisation in the trial design), or the designation of target and control gauges, which may be systematic. While this possibility cannot be eliminated, it can be reduced by the introduction of what are referred to as random effects. Random effects are random values associated with the distribution of categorical variables, such as the day or gauge location, that represent significant sources of variation in rainfall that have nothing to do with

[1] This is in contrast to clinical trials where crossover designs allow the same patient to serve as target and a control, eliminating a potential bias in patient selection. The alternating operating schedule of the ATLANT™ systems is sufficient to allow individual rainfall gauges serve as both target and controls.

operation of ATLANT™, but have no obvious reason beyond that to be included as covariates in the rainfall model. Partitioning the residual variability in observed rainfall (i.e. remaining variability after allowing for the independent variability associated with the model covariates) into effects associated with day and with gauge for example then allows more efficient estimation of a potential ATLANT™ effect by sweeping out the natural variability due to changes in average rainfall from day to day and from gauge to gauge over the trial period.

The precision of the estimated effect of the ATLANT™ system will be overstated (biased) when prediction errors of the model are correlated over time or between gauge locations. The former may occur if unique weather conditions at a particular gauge location tend to persist from day to day. This is allowed for in the model through meteorological covariates and day specific random effects. The latter is more likely since it may occur if gauges are sufficiently close so as to be subject to similar weather conditions on a day. These correlations can be accounted for when estimating the standard error (precision) of an effect by resampling the data from blocks or clusters so as to reflect the correlation structure of concern and then re-estimating the effect (referred to as a block bootstrap). Resampling the data in this way and re-estimating the effect a large number times gives a more robust measure of the variability in the estimate that reflects any remaining correlation within a cluster (Chambers and Chandra, 2013). In all cases the bootstrap results quoted in this report are based on 10,000 bootstrap replications.

7.1.1 Regression Diagnostics

One issue with statistical models is that there are many possible choices of covariates to include, the scale on which to measure them, and the functional form of the relationship to be estimated (as for example, whether this relationship is linear or non-linear). Regression diagnostics are tools to help guide these choices. They include:

- **Goodness of fit (R-Square).** This is a general measure of how well a model fits the data relative to the so-called 'null' model, i.e. one with no covariates. Specifically, it is the percentage of variation in observed rainfall explained by the effects included in the model.
- **Statistical significance (P Value).** This is a measure of whether, given the estimated effect of a covariate, the actual effect could just as well be zero. A P Value lies between 0 and 1, and a low P Value generally 0.05 or less, is usually taken as evidence that the corresponding effect is unlikely to be zero, and so the covariate should be included in the model. Covariates that are not associated with the operating status of the ATLANT™ system, and with high P Values, are said to be insignificant and can be eliminated from the model, leading to a simpler and potentially more robust model specification. Insignificant covariates have generally (but not always) been excluded in the modelling results presented later in this section. In particular, we have retained insignificant covariates in some cases in order to allow comparability across models.

- **Measures of leverage.** These indicate how much influence individual observations have on the overall fit of the model and the estimated value of a model coefficient. These measures are particularly important in the context of the ATLANT^{TM} trial. Given a single trial of relatively short duration it is quite possible that a few rainfall events can have a substantial effect on the outcome. These highly influential events may have occurred in the target or control area simply by chance. Ideally, the influence of leverage of any given observation is low. However, it may be sometimes necessary to consider removing highly influential observations from the data that, if leading a more positive outcome, lead to perception of analytical bias. All modelling results reported in what follows have been evaluated to ensure that leverage diagnostics are acceptable.

7.2 Model Specification

There are five elements of the overall model specification:

- Defining target and control gauges on the basis of operating status and wind direction;
- Selecting the covariates and random effects;
- Selecting the functional form of the model;
- Defining the blocks or clusters for the bootstrap.

We present modelling results in the Report for two ATLANT^{TM} 'footprint' models. These were used to designate target and control gauges on a daily basis:

1. A 60 degree downwind arc oriented in the direction of the steering wind measured 4am daily at Seeb airport and extending 75 km downwind.
2. A 30km wide rectangular corridor oriented in the direction of the steering wind measured 4am daily at Seeb airport and extending 75 km downwind.

Both footprint models generated approximately the same number of downwind gauges (23) each day, differing mainly in the way that they modelled ion transport downwind of an active ATLANT^{TM}. Note that analysis was also carried out using a 50km wide and 75km long downwind corridor oriented at a fixed 60º at each site (i.e. a static footprint). However, the diagnostics for the rainfall models (both downwind and upwind) fitted using this definition were inferior to those for the dynamic footprint models above, and so estimates based on it are omitted. In large part, this decision was based on the fact that use of a static footprint could not be justified given that steering winds at Seeb shifted significantly northwards in September and October.

Depending on the direction of the steering winds there is some overlap in both the footprints defined above. We considered a gauge in the overlap area as a target gauge since it is, by definition, exposed to an active ATLANT^{TM}. With H2 being south east of H1 and with the predominant winds ranging from north to northeast, this would tend to reduce the number of control gauges at H2 when H1 is on. In addition, given the proximity of the sites to each other, the designated control gauges when H1 is on may be less clear-cut that when H2 is on. This would tend to reduce the effectiveness of the crossover design. The covariates initially included in the modelling process were:

- Indicator variables for each month of the trial
- Gauge elevation, latitude and longitude
- Meteorological effects, including first and second principal components of average daily measurements of air temperature, dew point temperature and relative humidity at the DGMAN weather stations, general meteorological indices reflecting rainfall propensity (see Section 5), average daily values of relative humidity, radiation temperature and change in evaporation at the ATLANT^{TM} sites, and steering wind speed at Seeb airport.
- An indicator variable for the operating status of the ATLANT^{TM} at H1 and H2.

A few points of clarification are needed as far as the meteorological covariates are concerned. First, there are missing observations for steering wind direction and speed from Seeb airport. These missing values were imputed using the median of non-missing values from the three days either side of the day in question. Second, temperature and humidity measurements were available from ten weather stations within the general vicinity of the trial area. These measurements are highly correlated between locations. Using the first two principal components of these ten measurements removes this correlation while preserving the information in the data. This leads to a more stable model for the purpose of predicting rainfall. Lastly, temperature, humidity and radiation measurements at H1 and H2 were also highly correlated. Using their average and their difference instead of the actual values from each site removes this correlation, while preserving the information from each site.

Random effects for each trial day and each gauge were initially included in the modelling process. However, inclusion of gauge random effects did not change results of the modelling. Consequently they were dropped from the model results presented in this Report.

7.2.1 The statistical modelling process

The objective of the statistical modelling is to allow estimation of the potential contribution, or attribution, of the ATLANT^{TM} systems to rainfall, measured as the estimated percentage increase in observed rainfall compared with natural rainfall. This estimation is carried out in three stages.

1. The first stage involves construction of the instrumental variable that correlates with the expected amount of natural rainfall at a gauge on a day. In this first stage, a model for LogRain is fitted to gauge level rainfall upwind of the target and control areas. Note that all modelling is based on the logarithm of rainfall in order allow for the extreme skewness of gauge level rainfall measurements (relatively many very small positive measurements and very few large measurements). This also means that the model is for the amount of rain given that rainfall occurs, since all zero rainfall measurements are excluded. Note, however, that rainfall propensity (i.e. whether or not rain is recorded at a gauge) is allowed for when assessing the significance of the estimated amount of rainfall attributed to the operation of the ATLANT^{TM} system. This upwind model specification is then used to predict gauge level rainfall in the target and control areas. Different covariates were significant in the upwind models for the 60º arc footprint and the 30km corridor footprint. In the former, Month, Elevation,

Latitude, Seeb steering wind speed, Lifted Index, Dry Air Temperature (both Component 1 and Component 2), and Dewpoint Temperature (Component 1) were all significant; whereas in the latter a much smaller set of covariates (Elevation, Seeb steering wind speed and Lifted Index) were significant. Overall, the model fit diagnostics for the upwind model associated with the 30km corridor footprint were superior. The predicted values generated by the upwind model specifications in the target and control areas define the instrumental variable values used in the second modelling stage.

2. A second model is then used to predict rainfall in the downwind (i.e. target and control) area. Again, for the same reasons as set out in the preceding paragraph, this model is for LogRain. Here, in addition to the instrumental variable, the model includes humidity and radiation measurements at H1 and H2 (temperature measurements were not significant) and gauge elevation. Note that radiation serves as a proxy for cloud cover during the afternoon, the time period over which significant summer rainfall occurs. Five covariates were therefore used to estimate the potential ATLANT^{TM} effect on rainfall:
   - The instrumental variable (Upwind Effect) derived from the upwind rain model
   - Average humidity at H1 and H2
   - Radiation at H1 and H2 (expressed as an average and a difference)
   - Gauge elevation
   - Site specific (H1 or H2) target status for a gauge on a day, i.e. an indicator for whether the rainfall data were obtained from a gauge that was downwind of an operational ATLANT^{TM}
   - The interactions between target status (H1 or H2) and gauge elevation, allowing potential site-specific ATLANT^{TM} effects to vary with elevation.

3. The third stage involves using the downwind model for LogRain to estimate how much of an increase (or decrease) in observed rainfall at a gauge should be attributed to the operation of the ATLANT^{TM} system. Here the component of the downwind model predicted value for LogRain that depends on whether the gauge is a target gauge or not is back transformed to the rainfall (mm) scale (with a correction for the ensuing back transformation bias). This is the estimated ATLANT^{TM} effect. Dividing the observed rain at the gauge by this estimated effect then gives an estimate of the natural rainfall, which is subtracted from the observed rainfall to provide an estimate of the ATLANT^{TM} attribution for the gauge on the day. These gauge by day attribution estimates are finally summed over the gauges reporting rainfall over the trial to provide an overall estimate of the change in the amount of downwind rainfall observed over this period due to operation of the ATLANT^{TM} system. This is referred to as the ATLANT^{TM} attribution

The ATLANT™ attribution is a complex nonlinear statistic, and its mean, standard error and significance cannot be calculated directly from the model parameter estimates. We resolve this issue by using the block bootstrap method discussed previously. As an aside, we note here that when we resample the data using the block bootstrap, we also allow for the large number of zero rainfall readings that are observed in practice. This is done by using another model for the probability of observing rainfall at a gauge to randomly generate similar amounts of zero rainfall data in the bootstrap simulations. Finally, we constrain the bootstrapped rainfall data (including zeros) so that the total amount of rainfall is within realistic limits for the downwind gauges. In particular, we these totals are constrained to be between 1000mm and 8000mm over the entire period of the trial. These limits can be compared with the actual total rainfall of 2478 mm observed in the 60º downwind arc over the trial, and the actual total rainfall of 3204 mm observed in the 30 km downwind corridor over the same period.

7.3 Results For The 60º Downwind Arc

Under this model, a gauge by day observation is designated as upwind if the gauge is no more than 75km from at least one ATLANT™ site, and is upwind of both on the day (i.e. makes an angle of at least 180º with the downwind vectors at both sites). Similarly, a gauge by day observation is classified as downwind if it is in either (or both) of the 60º downwind arcs emanating out to 75 km from each site. A downwind gauge by day observation is then further classified as a target observation if it is downwind of an active ATLANT™ on the day. Otherwise it is classified as a control. Summary statistics for the gauge designations are shown in Table 7-1. There is a reasonable balance between the numbers of positive rainfall observations classified as either target or control, with the larger number of target observations due to overlap of the downwind arcs. The target:control distribution of downwind observations is 54%:46%, while the corresponding distribution of positive rainfall observations is 56%:44%, indicating a slightly higher propensity for rainfall to be measured at target gauges. There is also an indication that the average amount of rainfall for a target observation is a little larger than that for a control, but the difference is non-significant, and vanishes when this average is computed over positive rainfall values. Rainfall is much lighter and much less frequent for upwind gauges, due to the fact that prevailing wind directions mean that these are usually at a much lower elevation, closer to the coast and more southerly.

Table 7-1 Summary statistics for the 60 º arc gauge designations

Observation Status	Zero Observations	Positive Observations	Average Rainfall in mm (Std Err)	Average Non-Zero Rainfall in mm (Std Err)
Control	1591	217	0.60 (0.07)	5.03 (0.46)
Target	1864	277	0.65 (0.07)	5.01 (0.50)
Upwind	8148	444	0.19 (0.02)	3.74 (0.30)

The parameter estimates for the upwind LogRain model are presented in Table 7-2. These estimates used to construct the instrumental variable used in the downwind LogRain model. The overall fit is weak, with the R-Square indicating that about one third of the variation in rainfall is accounted for by the covariates. Note that the reported P-Values in the table do not account for any residual spatial correlation between observations. However, residual temporal correlation is accounted for by the inclusion of an independent random effect for each day of the trial. As a consequence the significance of the model covariates may be slightly overstated, though they still provide a relative indication of the more important covariates. Collectively the seasonal covariates (month) are only moderately significant, elevation and the lift index are significant but negative and longitude is highly significant. This suggests that the 60º upwind sector may be too wide and is consistent with the earlier observation that this sector includes a large number of gauges that are influenced by coastal meteorology as opposed to conditions in the trial area. The parameter estimates for the downwind LogRain model (i.e. the one based on the target and control gauge rainfall) used to measure the potential ATLANT^{TM} contribution to natural rainfall is shown in Table 7-3.

Table 7-2 Estimates for upwind LogRain model for the 60° arc

Parameter	Estimate	P Value
Intercept	35.7090	0.0587
May	0.5750	0.2017
June	-0.0653	0.8046
July	0.7827	0.0189
August	-0.2771	0.1499
September	-0.6283	0.0031
Elevation	0.0004	<.0001
Longitude	-0.1537	0.4939
Latitude	-1.1493	0.0012
Seeb Steering Wind Speed	-0.1208	0.0003
Lifted Index	0.0584	0.0279
Temperature (Component 1)	-0.1735	0.0290
Dew Point (Component 1)	0.3520	0.0006
Temperature (Component 2)	0.3300	0.0076
Dew Point (Component 2)	0.2132	0.1408
R-Square = 36.9%	**Observations = 444**	
Random Effects	**Value**	**% Variation**
Day	0.1396	7.9
Observation Within Day	1.6325	92.1

Table 7-3 Estimates for downwind LogRain model for the 60° arc

Parameter	Estimate	P Value
Intercept	-3.1125	<.0001
Average Humidity H1 and H2	0.0280	0.0003
Average Radiation H1 and H2	0.0034	0.0006
Radiation H1 - H2	-0.0019	0.0075
Upwind Effect	0.3370	0.0151
Elevation	0.0005	0.0520
H1 Target	0.7960	0.0108
H2 Target	0.2971	0.3816
H1 Target * Elevation	-0.0009	0.0182
H1 Target * Elevation	-0.0005	0.2331
R-Square = 24.5% Observations = 493		
Random Effects	**Value**	**% Variation**
Day	0.1628	8.4
Observation Within Day	1.7823	91.6

As with the upwind model, we see that there is large proportion of unexplained variation in LogRain, with an R-Square value of less than 25 per cent. However, this is not surprising given the underlying processes that generate rainfall in the trial area.

Average humidity and radiation at H1 and H2 are significant. The latter is a proxy for cloud cover, and is a significant differential effect between H1 and H2, with cloud cover at H1 contributing more to downwind rainfall than H2. This might be due to differences in moisture content of the cloud cover and/or differences in the orographic (topography affecting rainfall) at H1 and H2.

Despite the possible issues with the instrumental variable (Upwind Effect) it is still a significant covariate. The random day effects sweep out over 8 per cent of variation in rainfall not explained by the fixed effects of the model covariates. This is relatively small and indicates that rainfall in the trial area is highly variable within a day.

The operating status of H1 and its interaction with elevation are significant at the 95 per cent confidence level. While the same caveats with respect to spatial correlating between gauge level observations and significance, it is clear that the operating status of H2 and its interaction with elevation is not significant.

While the parameter estimates in Table 7-3 indicate that there appears to be a significant effect at H1 and not H2, the total attribution in the trial area defined by the 60º downwind arc, as a percentage of estimated natural rainfall in this area, is estimated to be 11.7 per cent with a bootstrap standard error of 9.1 per cent. Furthermore, the block bootstrap analysis indicates that this attribution is significantly greater than zero at a 90 per cent level of confidence, with the lower bound of 0.5 per cent for the bootstrap 90 per cent confidence interval for this attribution.

7.4 Results for the 30km Corridor Model

Under this model, a gauge by day observation is designated as upwind if the gauge is no more than 75km from at least one ATLANT™ site, and is inside the upwind sector of either one (or both) of two 30km wide corridors that are located symmetrically either side of H1 and H2 and oriented downwind on the day. Similarly, a gauge by day observation is classified as downwind if it is in either (or both) of the downwind sectors of these corridors out to a distance of 75km from at least one site. A downwind gauge by day observation is further classified as a target observation if it is downwind of an active ATLANT™ on the day. Otherwise it is classified as a control. Summary statistics for the gauge designations are shown in Table 7-4.

Table 7-4 Summary statistics for the 30km corridor gauge designations

Observation Status	Zero Observations	Positive Observations	Average Rainfall in mm (Std Err)	Average Non-Zero Rainfall in mm (Std Err)
Control	1684	275	0.74 (0.08)	5.27 (0.48)
Target	1766	324	0.84 (0.08)	5.41 (0.44)
Upwind	4324	234	0.28 (0.04)	5.39 (0.70)

At 51%:49%, the relative distribution of the number of target and control rainfall readings for the downwind corridor model is more balanced than that for the 60º downwind arc, ,with a corresponding relative distribution of 54%:46% for positive rainfall readings. Average rainfall is greater for target gauges, both when zero readings are included and when they are excluded. However, as with the 60º arc, these differences are not significant. The parameter estimates for the upwind corridor LogRain model are presented in Figure 7-5. The overall fit is substantially better than that of the corresponding 60º arc model, with an R-Square of 42 per cent. Nevertheless, the proportion of unexplained variation associated with the upwind gauges is still high. Seasonal and gauge latitude and longitude effects were not significant and are excluded from the model. The effect of elevation is highly significant, as is the effect associated with Seeb steering wind speed. Of the remaining meteorological effects, the Lifted Index is significant, while the other effects included in the model are moderately significant. Although the caveats with respect to significance still apply, the generally good diagnostics associated with this model imply that its use as an instrumental variable for the downwind values of LogRain is likely to be more successful than in the 60º arc situation.

This expectation is confirmed when we examine the parameter estimates for the downwind LogRain model presented in Table 7-6. Again, although we see that the overall fit of this model still explains under 25 per cent of observed downwind rainfall, we also see that the instrumental variable (Upwind Effect) is now highly significant, while average radiation remains significant. Now, however, the radiation difference between the sites and humidity are only moderately significant. The directions of the effects (negative or positive) are the same as the 60º arc model. The random day effects sweep out over 11 per cent of variation in LogRain not explained by the model covariates. This is still relatively small, and again suggests that rainfall in the downwind corridor is highly variable within a day.

The operating status of H1 and its interaction with elevation are now highly significant. However, as with the 60º arc model, the operating status of H2 and its interaction with elevation are not significant.

Overall total attribution in the trial area defined by the two downwind corridors, as a percentage of estimated natural rainfall in this area, is estimated to be 18 per cent with a bootstrap standard error of 8.4 per cent. The block bootstrap analysis indicates that this attribution is significantly greater than zero at a 99 per cent level of confidence, with a lower bound of 1.1 one per cent for the bootstrap 90 per cent confidence interval for this attribution.

Table 7-5 Estimates for LogRain model for the 30km upwind corridor gauges

Parameter	**Estimate**	**P Value**
Intercept	0.6108	0.0576
Elevation	0.0005	0.0004
Seeb Steering Wind Speed	-0.1807	0.0001
Lifted Index	0.0870	0.0228
Dewpoint (Component 1)	0.1960	0.1464
Humidity (Component 1)	0.1430	0.1230
Temperature (Component 2)	0.1986	0.1214
R-Square = 42.5% **Observations = 234**		
Random Effects	**Value**	**% Variation**
Day	0.2201	10.8
Observation Within Day	1.8222	89.2

Table 7-6 Estimates for the 60 degree arc downwind gauges

Parameter	Estimate	P Value
Intercept	-1.8740	0.0149
Average Humidity H1 and H2	0.0131	0.0946
Average Radiation H1 and H2	0.0028	0.0049
Radiation H1 - H2	-0.0013	0.0789
Upwind Effect	0.5731	0.0002
Elevation	0.0003	0.1845
H1 Target	0.8351	0.0022
H2 Target	0.2351	0.4437
H1 Target * Elevation	-0.0007	0.0064
H2 Target * Elevation	-0.0004	0.1558
R-Square = 24.5% **Observations = 599**		
Random Effects	**Value**	**% Variation**
Day	0.2402	11.2
Observation Within Day	1.906	88.8

7.5 The Difference in ATLANT™ Response at H1 and H2

The differences in significance of the estimation results for target gauges associated with H1 compared with those associated with H2 under both a 60º arc and a 30km corridor model for the ATLANT™ footprint are striking, and constitute the main driver for the attribution estimates reported above. This result is consistent with the size of an ATLANT™ effect depending on local orography. However, it may also be due to there being:

- Substantially greater levels of natural rainfall falling downwind of H1 when H1 was in operation;
- Greater unexplained variability in rainfall at H2, making it more difficult to isolate and measure an ATLANT™ effect at this site.

Some summary statistics for the H1 and H2 corridors are presented in Table 7-7 to facilitate the consideration of these alternatives.

The first point cannot be fully discounted given the short length of the trial, nor can its corollary that the lack of a significant effect at H2 is due to variation in natural rainfall. Similar but lower levels of rainfall fell downwind of H1 and H2 when H1 was off and H2 was on. Greater levels of rainfall fell downwind of H1 and H2 when H1 was on and H2 was off. However, the extent of rainfall (the proportion of gauges recording rain) was substantially higher (32% as opposed to 28%) and the level of rainfall about six per cent higher at H1 compared to H2 when H1 was on. Leverage analysis of the 30km corridor model results indicated that there were no isolated events that made an overly large contribution to the model fit or the parameter estimates. This suggests there is no obvious source of bias in the estimated effects for H1 or H2.

There was no apparent difference in the variability of rainfall incidence (the proportion of gauges recording rainfall) between H1 and H2. The level of variability in rainfall, expressed as a percentage of the mean, was lower when H2 was in operation for gauges that recorded positive rainfall. This suggests that the unexplained variability in natural rainfall at H1 and H2 are similar.

The issue of overlapping target and control gauges has been referred to earlier, and represents a source of reduced estimation efficiency if there is substantial consequent reduction in the number of control gauges. Given that the prevailing winds are from the north east, see Figure 7-1 an overlap is more likely to occur when H1 is on. Furthermore, confounding of target and control status is possible when a gauge ostensibly designated as a control is in fact exposed to an active site. This can occur with both the 60º arc and the 30km corridor footprints and is most likely when winds are tending more from the north when H1 is active. This could make it more difficult to detect an enhancement signal at H2 because of the consequent boost to control values obtained downwind of this site on these days, since H2 is then not operational. Since exposure to an active site is inferred, as opposed to being observed, this confounding is possible but not verifiable. Greater separation between the

ATLANT™ sites seems desirable if there is a reasonable probability that winds will be more northerly during the trial period.

The results from the corridor model were also used to estimate ATLANT™ -attributed rainfall downwind of H1 and H2 separately. The estimated attribution (relative to estimated natural rainfall) was 24.9 per cent downwind of H1 and 9.1 per cent downwind of H2. The standard error of these corridor-specific estimates will both be greater than the estimate of 8.4 per cent recorded for all target gauges. Even with this lower overall standard error, however, the estimated attribution downwind of H2 is not significantly different from zero. A smaller enhancement effect at H2, if it does in fact exist, will therefore be more difficult to detect, requiring more extensive trials.

Table 7-7 Table Summary statistics for the H1 and H2 corridors

Corridor	Status	Rainfall Measure	Mean	StandardDeviation
H1	On	Rainfall (mm)	1.95	5.86
	Off		1.27	4.05
	On	Rainfall > 0 (mm)	6.15	9.08
	Off		4.76	6.67
	On	Per Cent Days with Rain Recorded by at least one gauge	31.7	0.47
	Off		26.7	0.44
H2	On	Rainfall (mm)	1.25	3.96
	Off		1.61	5.92
	On	Rainfall > 0 (mm)	4.69	6.56
	Off		5.83	8.76
	On	Per Cent Days with Rain Recorded by at least one gauge	26.6	0.44
	Off		27.7	0.45

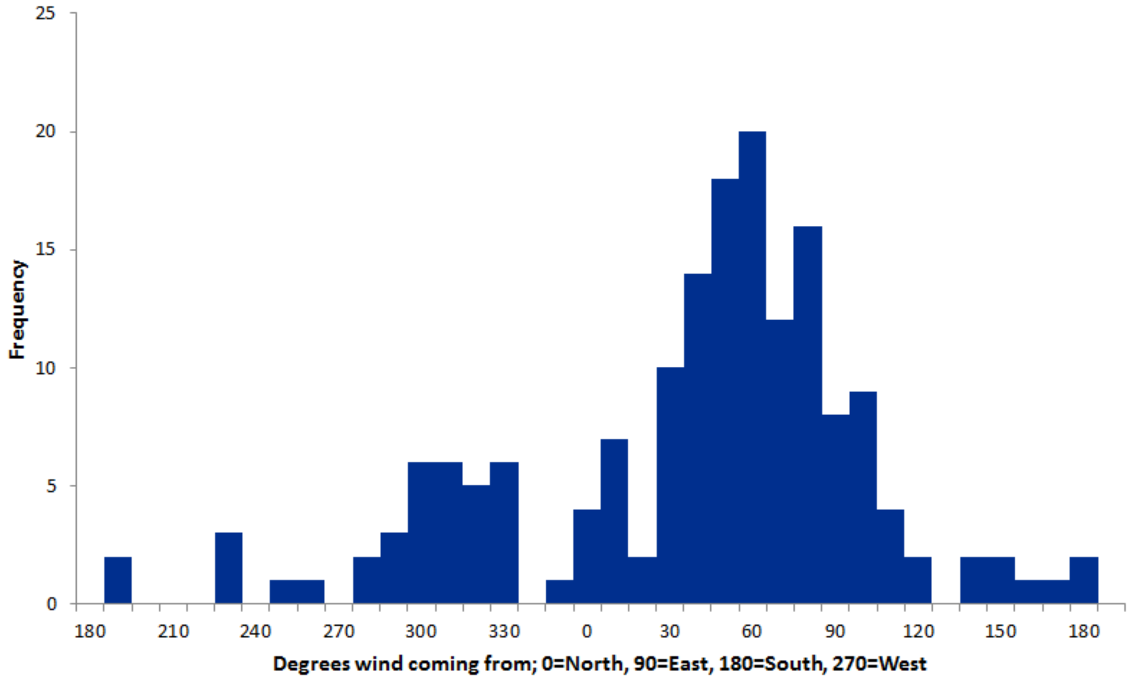


Figure 7-1 Steering wind directions at Seeb Airport

7.6 Further Considerations

The question of whether the lower attribution downwind of H2 can be explained by other factors remains open. One possibility is this is due to the complex orographic effects that can occur in mountain ranges. The topography at and around the H2 site is quite different from that at and around H1. This can be seen in Figure 7-2 in which the location and elevation contours of the rainfall gauges used in the trial are shown. The upper elevation contours, downwind of the north to northeast prevailing winds, are much more extensive at H2. Given this topography, the interaction between an ion plume generated form a point source and the cloud layer generated by uplift and convergence of moist and hot dry air may be quite unpredictable.

Gaining a better understating of the orographic effects associated with site selection would require the deployment of additional ATLANT^{TM} sites with operating schedules that ensure adequate separation between target and control gauges. Shifting the current location of H2 further south might also be considered. Site selection would be aided by a better understanding of the effect of topography in the Hajar mountain ranges. Here it would be useful to draw on expertise built from work done in other mountainous environments. In any case, the deployment of the rainfall gauge network in the existing and a possible expanded trial creates the opportunity to investigate the broader processes that generate Oman summer rainfall directly in the environment of interest.

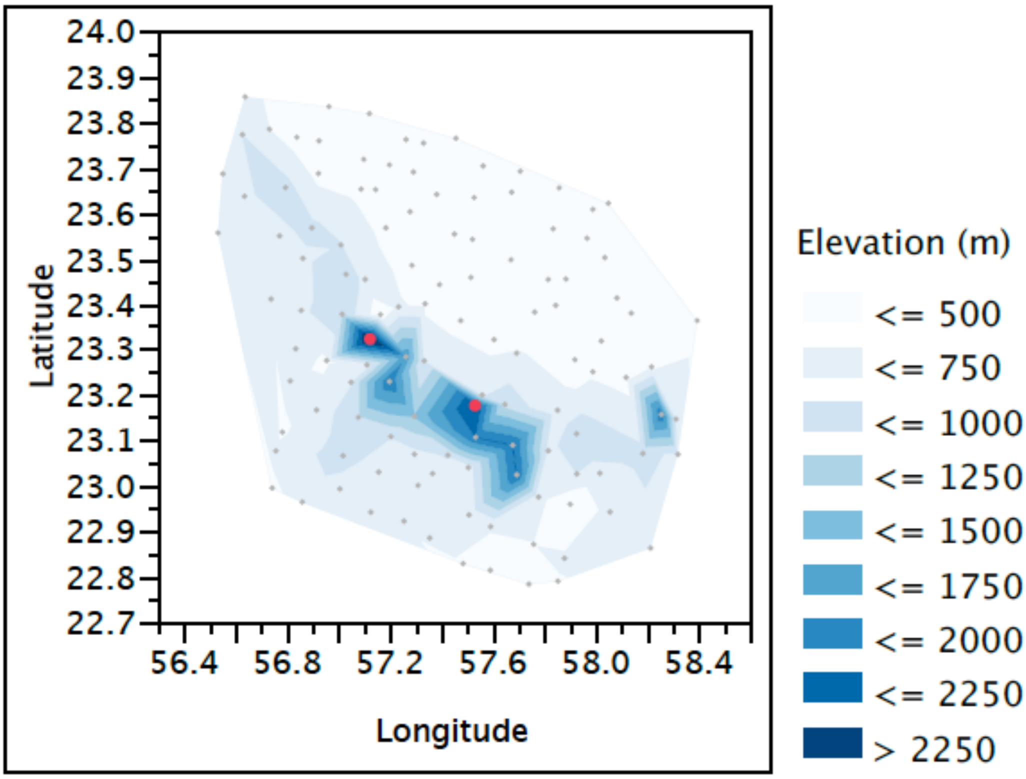


Figure 7-2 Elevation of the trial area (ATLANT^{TM} sites shown as red dots)

8. SUMMARY OF RESULTS

Overall, a positive and significant rainfall enhancement effect was observed, attributable to the operation of the ATLANT^{TM} systems. The total attribution (enhancement effect) in the trial area defined by the 60º arc model, as a percentage of estimated natural rainfall, is estimated to be 11.7 per cent with a bootstrap standard error of 9.1 per cent. Furthermore, the bootstrap analysis indicates that this attribution is significantly greater than zero at a 90 per cent level of confidence, with a lower bound of 0.5 per cent for the bootstrap 90 per cent confidence interval for this attribution. Overall total attribution (enhancement effect) in the trial area defined by the 30 km corridor model, as a percentage of estimated natural rainfall, is estimated to be 18 per cent with a bootstrap standard error of 8.4 per cent. The bootstrap analysis indicates that this attribution is significantly greater than zero at a 99 per cent level of confidence, with a lower bound of 1.1 per cent for the bootstrap 90 per cent confidence interval for this attribution. These results are summarised below.

Model	Mean level rainfall enhancement effect	Standard Error	Confidence level enhancement effect > 0
30 km Corridor	18.0 %	8.4 %	99 %
60° Arc	11.7 %	9.1 %	90 %

While there was a positive ATLANT^{TM} attribution at the two ATLANT^{TM} sites, the attribution was substantially higher at H1 as opposed to H2 and the local attribution at H2 was not statistically significant. Detecting a significant enhancement effect at the individual sites is more difficult than for the trial area as whole. However, the difference in the effects at H1 and H2 may be due to factors such as the topography of the two sites and insufficient geographic separation of the downwind target and control areas when H1 was in operation. These issues require further investigation.

9. RECOMMENDATIONS FOR FUTURE TRIALS

Based on the positive results summarised in the previous Section, further trials are recommended with the following suggested improvements in design: Increasing the number of gauges in the prospective downwind target and control area that could in part be achieved by relocating upwind gauges; relocating one or both of the ATLANT™s in order to provide a greater degree of separation of their footprints; expanding the trial to include two or more additional ATLANT™s; and installing upper air wind readings at H1 and H2. These improvements are further discussed following.

Increasing the number of gauges in the prospective target and control areas should have the greatest priority for any future trials. Particularly in the downwind areas. This could in part be achieved by relocating upwind gauges that were not (are not expected in the future) to provide helpful data for the analysis.

Expanding the trial to include two or more additional ATLANT™ s will facilitate the capacity to untangle the possible interaction of the hypothesised ATLANT effect with local orography. Aside from the (small, given the randomised design used) possibility that natural rainfall increased when H1 was operated, this is the most likely explanation for the identification of a strong ATLANT™ effect at H1 and virtually no effect at H2 in the 2013 trial. It will also allow a more strategic placement of the ATLANT™ devices, ensuring that the pattern of winds tending northwards over the summer does not lead to any substantial confounding of target and control gauges, thus ensuring a more efficient statistical analysis. Preliminary discussions with TIE identified suitable ATLANT™ sites in the trial area vicinity shown in Figure 9-1.

The real time instrumentation of the Oman trial is a major improvement in the experimental deign, with continuous measurement of wind direction at the sites and rainfall at the gauge locations. This allows consideration of a more precise classification of gauges into target or control classes or even a continuous measure of exposure. However, this may require a modification of the future experimental designs in two important ways:

1. Scheduling changes in operation of ATLANT™ devices within the rainfall window
2. Taking upper level wind readings at H1 and H2.

The most effective strategy will again depend heavily on the variability in steering wind direction. Low variability would favour the first options, high variability the second.

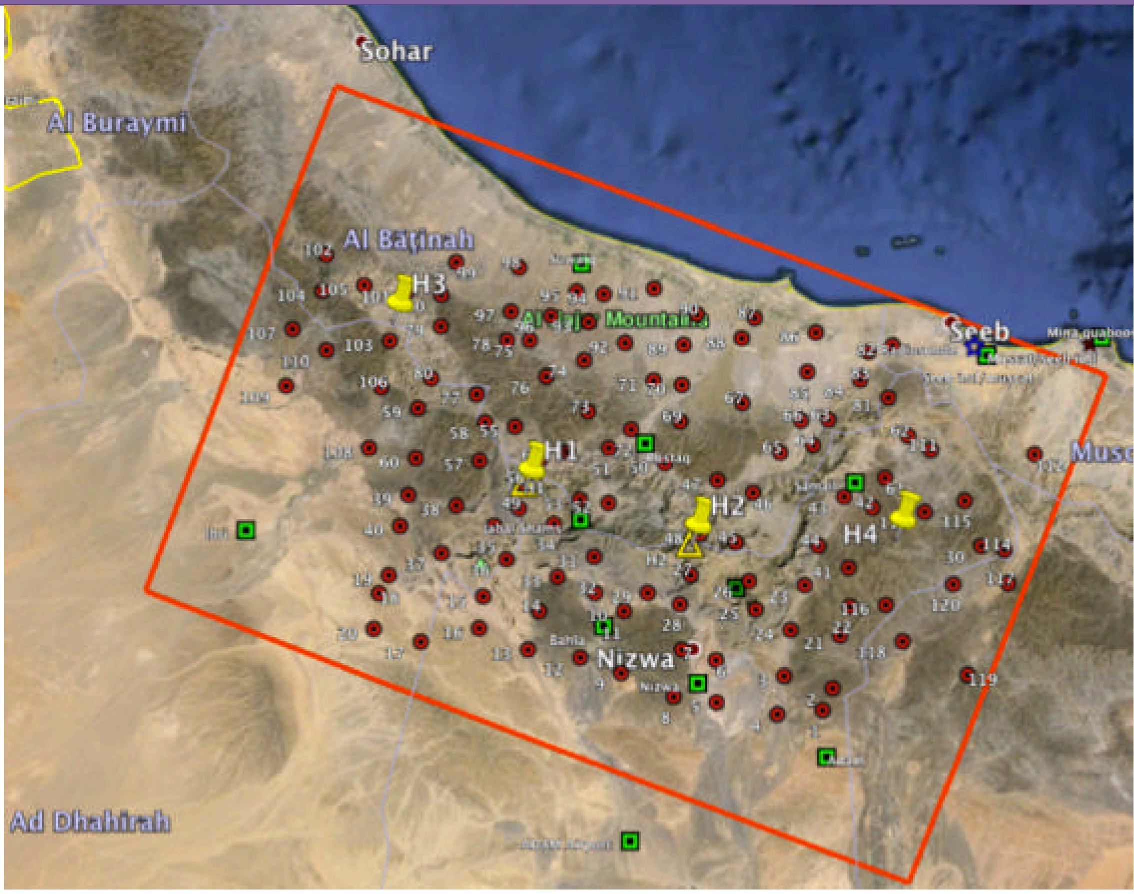


Figure 9-1 Possible future additional ATLANT™ sites

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APPENDIX A COMPLETED ATLANT OPERATION

Date	Year Day	Experiment	Hajar 1	Hajar 2
05/15/2013	135	1	1	0
05/16/2013	136	2	1	0
05/17/2013	137	3	0	1
05/18/2013	138	4	0	1
05/19/2013	139	5	0	1
05/20/2013	140	6	1	0
05/21/2013	141	7	0	1
05/22/2013	142	8	1	0
05/23/2013	143	9	0	1
05/24/2013	144	10	0	1
05/25/2013	145	11	1	0
05/26/2013	146	12	0	1
05/27/2013	147	13	0	1
05/28/2013	148	14	0	1
05/29/2013	149	15	1	0
05/30/2013	150	16	1	0
05/31/2013	151	17	0	1
06/01/2013	152	18	0	1
06/02/2013	153	19	1	0
06/03/2013	154	20	0	1
06/04/2013	155	21	0	1
06/05/2013	156	22	0	1
06/06/2013	157	23	0	1
06/07/2013	158	24	1	0
06/08/2013	159	25	0	1
06/09/2013	160	26	0	1
06/10/2013	161	27	1	0
06/11/2013	162	28	0	1
06/12/2013	163	29	0	1
06/13/2013	164	30	1	0
06/14/2013	165	31	1	0
06/15/2013	166	32	1	0
06/16/2013	167	33	0	1
06/17/2013	168	34	1	0
06/18/2013	169	35	1	0
06/19/2013	170	36	1	0
06/20/2013	171	37	0	1
06/21/2013	172	38	1	0
06/22/2013	173	39	1	0
06/23/2013	174	40	0	1
06/24/2013	175	41	1	0

06/25/2013	176	42	0	1
06/26/2013	177	43	0	1
06/27/2013	178	44	1	0
06/28/2013	179	45	0	1
06/29/2013	180	46	1	0
06/30/2013	181	47	1	0
07/01/2013	182	48	1	0
07/02/2013	183	49	0	1
07/03/2013	184	50	0	1
07/04/2013	185	51	0	1
07/05/2013	186	52	1	0
07/06/2013	187	53	0	1
07/07/2013	188	54	1	0
07/08/2013	189	55	0	1
07/09/2013	190	56	1	0
07/10/2013	191	57	0	1
07/11/2013	192	58	1	0
07/12/2013	193	59	1	0
07/13/2013	194	60	0	1
07/14/2013	195	61	0	1
07/15/2013	196	62	0	1
07/16/2013	197	63	1	0
07/17/2013	198	64	0	1
07/18/2013	199	65	1	0
07/19/2013	200	66	0	1
07/20/2013	201	67	0	1
07/21/2013	202	68	0	1
07/22/2013	203	69	0	1
07/23/2013	204	70	1	0
07/24/2013	205	71	0	1
07/25/2013	206	72	1	0
07/26/2013	207	73	0	1
07/27/2013	208	74	1	0
07/28/2013	209	75	1	0
07/29/2013	210	76	1	0
07/30/2013	211	77	1	0
07/31/2013	212	78	0	1
08/01/2013	213	79	1	0
08/02/2013	214	80	1	0
08/03/2013	215	81	0	1
08/04/2013	216	82	1	0
08/05/2013	217	83	1	0
08/06/2013	218	84	1	0
08/07/2013	219	85	0	1
08/08/2013	220	86	1	0
08/09/2013	221	87	1	0

08/10/2013	222	88	0	1
08/11/2013	223	89	0	1
08/12/2013	224	90	0	1
08/13/2013	225	91	1	0
08/14/2013	226	92	1	0
08/15/2013	227	93	0	1
08/16/2013	228	94	0	1
08/17/2013	229	95	1	0
08/18/2013	230	96	1	0
08/19/2013	231	97	0	1
08/20/2013	232	98	0	1
08/21/2013	233	99	0	1
08/22/2013	234	100	0	1
08/23/2013	235	101	0	1
08/24/2013	236	102	1	0
08/25/2013	237	103	1	0
08/26/2013	238	104	1	0
08/27/2013	239	105	0	1
08/28/2013	240	106	1	0
08/29/2013	241	107	0	1
08/30/2013	242	108	1	0
08/31/2013	243	109	1	0
09/01/2013	244	110	0	1
09/02/2013	245	111	1	0
09/03/2013	246	112	1	0
09/04/2013	247	113	0	1
09/05/2013	248	114	1	0
09/06/2013	249	115	1	0
09/07/2013	250	116	0	1
09/08/2013	251	117	1	0
09/09/2013	252	118	1	0
09/10/2013	253	119	0	1
09/11/2013	254	120	0	1
09/12/2013	255	121	1	0
09/13/2013	256	122	0	1
09/14/2013	257	123	1	0
09/15/2013	258	124	1	0
09/16/2013	259	125	1	0
09/17/2013	260	126	1	0
09/18/2013	261	127	1	0
09/19/2013	262	128	1	0
09/20/2013	263	129	0	1
09/21/2013	264	130	0	1
09/22/2013	265	131	0	1
09/23/2013	266	132	0	1
09/24/2013	267	133	1	0

09/25/2013	268	134	0	1
09/26/2013	269	135	1	0
09/27/2013	270	136	0	1
09/28/2013	271	137	0	1
09/29/2013	272	138	1	0
09/30/2013	273	139	1	0
10/01/2013	274	140	1	0
10/02/2013	275	141	1	0
10/03/2013	276	142	0	1
10/04/2013	277	143	1	0
10/05/2013	278	144	1	0
10/06/2013	279	145	0	1
10/07/2013	280	146	0	1
10/08/2013	281	147	0	1
10/09/2013	282	148	1	0
10/10/2013	283	149	1	0
10/11/2013	284	150	1	0
10/12/2013	285	151	0	1
10/13/2013	286	152	1	0
10/14/2013	287	153	1	0
10/15/2013	288	154	0	1
10/16/2013	289	155	0	1
10/17/2013	290	156	0	1
10/18/2013	291	157	1	0
10/19/2013	292	158	1	0
10/20/2013	293	159	0	1
10/21/2013	294	160	1	0
10/22/2013	295	161	0	1
10/23/2013	296	162	1	0
10/24/2013	297	163	1	0
10/25/2013	298	164	0	1
10/26/2013	299	165	1	0
10/27/2013	300	166	0	1
10/28/2013	301	167	0	1
10/29/2013	302	168	0	1
10/30/2013	303	169	0	1
10/31/2013	304	170	0	1

APPENDIX B ADDITIONAL FIGURES

This appendix contains tables and figures referenced in and supporting the main body of the Preliminary report. However for brevity reasons they are not included in the main body.

B.1. Example Gauge Status on 12th Aug (YearDay = 224) (H1 off / H2 on)

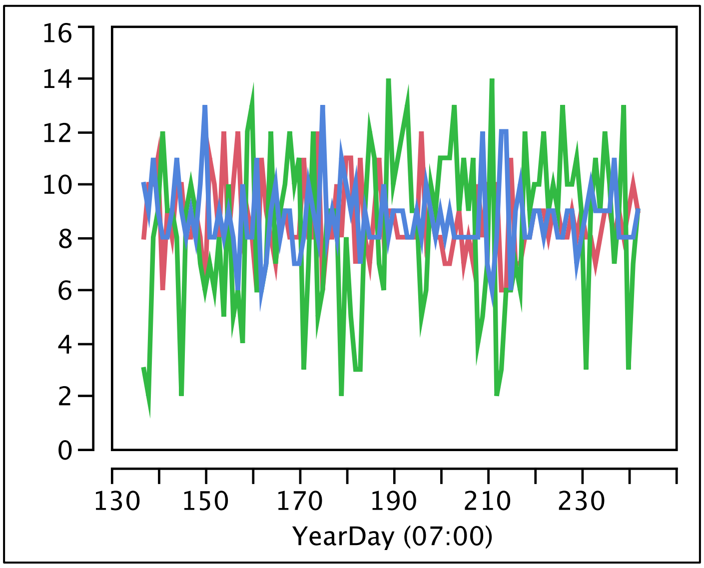


Figure B-1: Day to Day Variation in Total Numbers of Gauges by Sector. Sector based on Average Steering Wind Direction 30 degrees (Red = Target, Blue = Control, Green = Upwind)

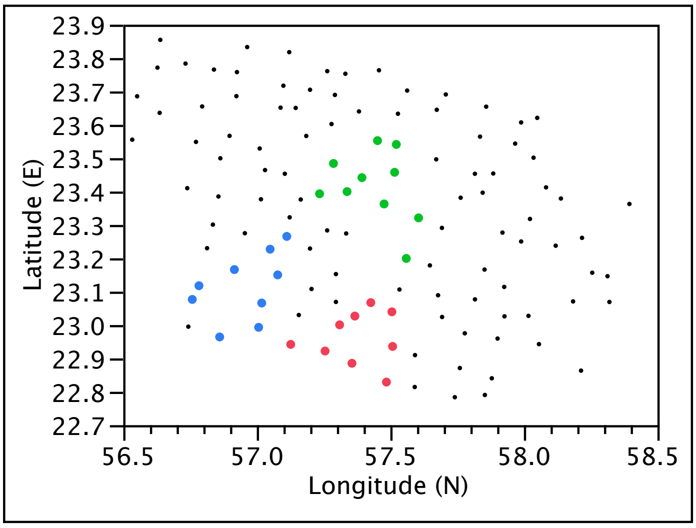
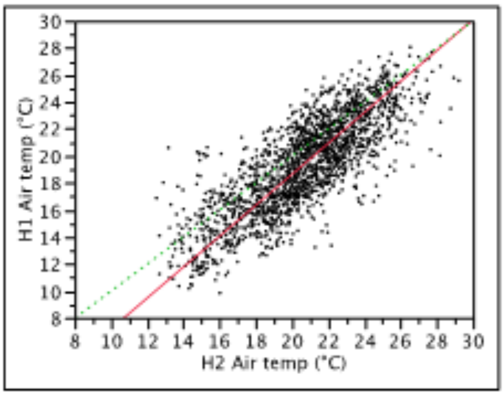
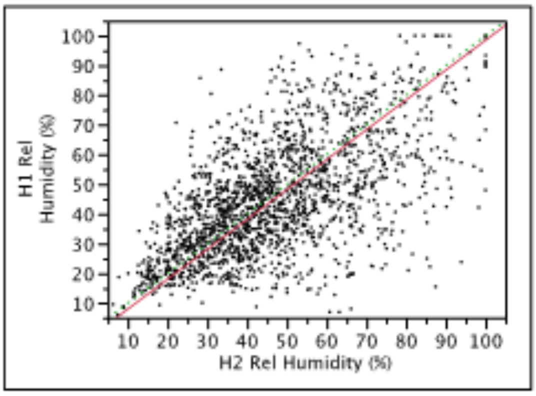


Figure B-2: Spatial distribution of Gauge Status. Steering wind Direction 30 degrees, sector angle 60 degrees. (Red = Target, Blue = Control, Green = Upwind)

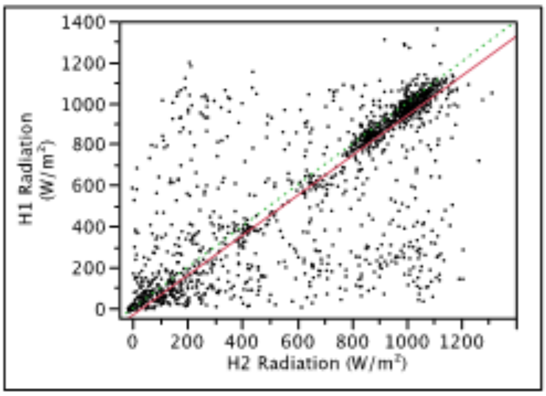
B.2. Correlation of ATLANT site meteorology



Variable	Mean	Std Dev	Correlation
H1 Air Temp (°C)	19.38	3.48	0.8003
H2 Air Temp (°C)	20.65	3.04	

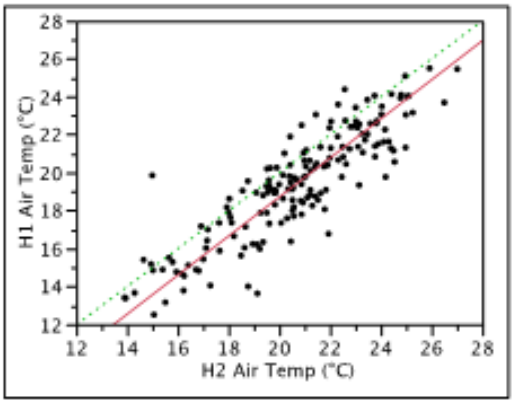


Variable	Mean	Std Dev	Correlation
H1 Rel Humidity (%)	44.60	18.96	0.6037
H2 Rel Humidity (%)	46.29	18.84	

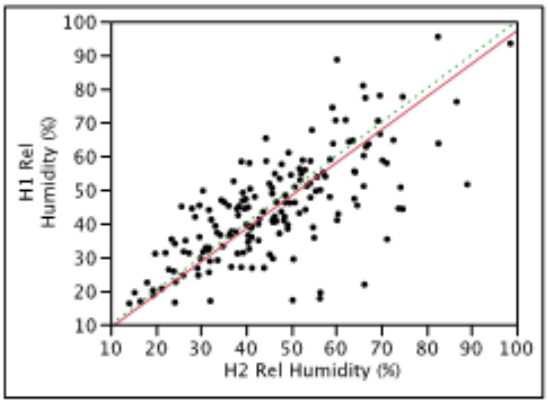


Variable	Mean	Std Dev	Correlation
H1 Radiation (W/m^2)	477.03	419.64	0.8239
H2 Radiation (W/m^2)	526.72	433.06	

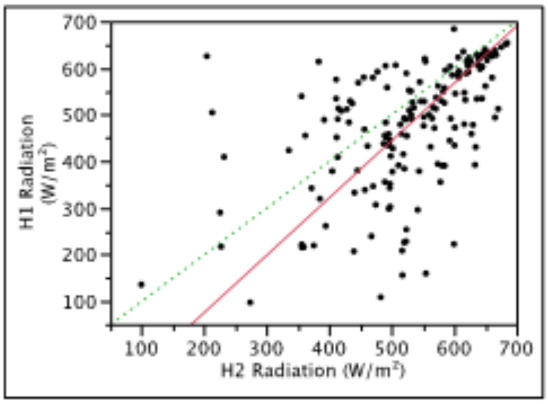
Figure B-3: Correlation of Hourly (1000 - 2000 hrs) ATLANT site meteorology. Red solid line minimises distance to the points, green dotted line is y=x line.



Variable	Mean	Std Dev	Correlation
Mean(H1 Air Temp (°C))	19.39	2.89	0.8754
Mean(H2 Air Temp (°C))	20.64	2.83	



Variable	Mean	Std Dev	Correlation
Mean(H1 Rel Humidity (%))	44.30	15.83	0.7128
Mean(H2 Rel Humidity (%))	46.35	16.03	



Variable	Mean	Std Dev	Correlation
Mean(H1 Radiation (W/m²))	478.73	133.15	0.5312
Mean(H2 Radiation (W/m²))	525.83	108.17	

Figure B-4: Correlation of daily (170 days, averaged over 1000 - 2000 hrs) ATLANT site meteorology. Red solid line minimises distance to the points, green dotted line is y=x line.

B.3. Correlation of ATLANT site wind data

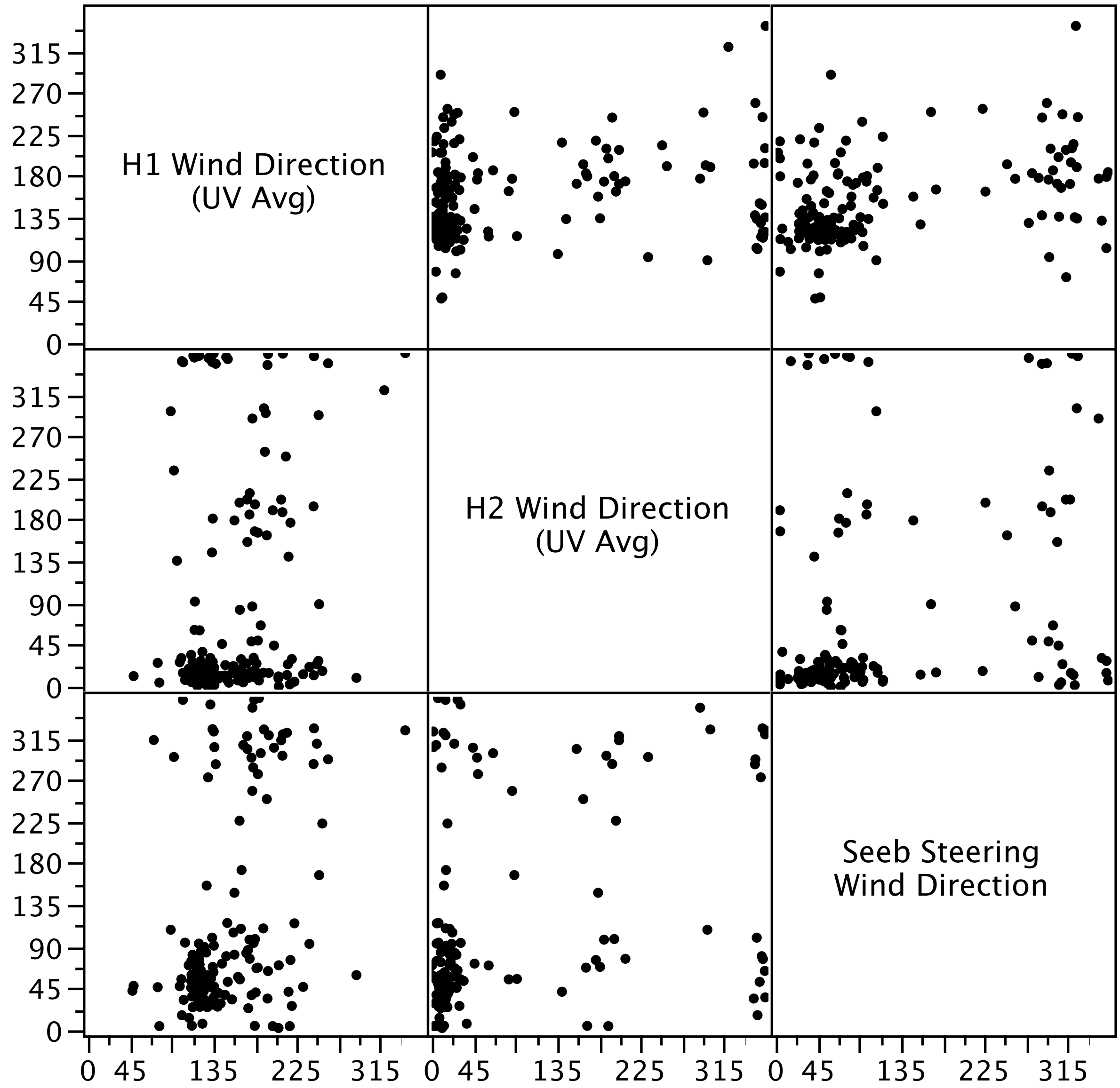


Figure B-5: Scatterplot Matrix Comparing Daily Steering Wind Directions at H1, H2 and Seeb (diagonal cell identifies row/column variable) (1000-2000 hrs)