# 2013 - 2018 Oman Rainfall Enhancement Trial

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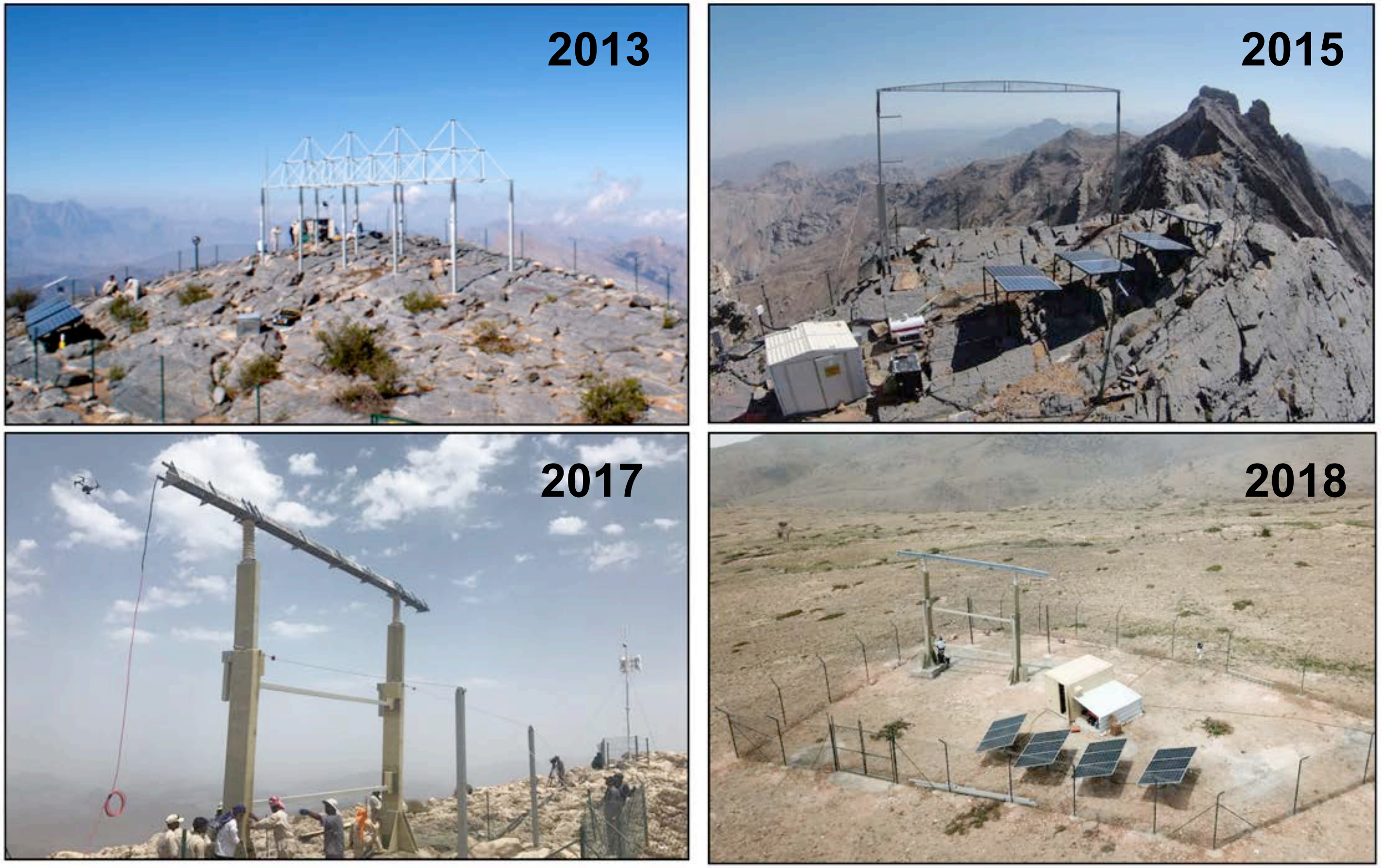
# + Introduction

- Oman is one of most water-stressed countries in the world.
- Rainfall enhancement trials using ART (Australian Rain Technologies) Atlant technology were carried out in the Hajar Mountains of northern Oman 2013 - 2018, and in the Salalah region in 2018.
- Trials were managed by TIE (Trading and Investment Establishment) in Muscat, Oman.
- Meteorological data sourced from DGMAN (Oman Directorate General of Meteorology and Air Navigation).
- Assessment carried out by NIASRA (National Institute for Applied Statistics Research Australia) at the University of Wollongong.
- This presentation summarises the final report prepared for the trial.
    - An analysis of the entire six-year data set collected 2013 - 2018.

# + Ground-Based Ionization

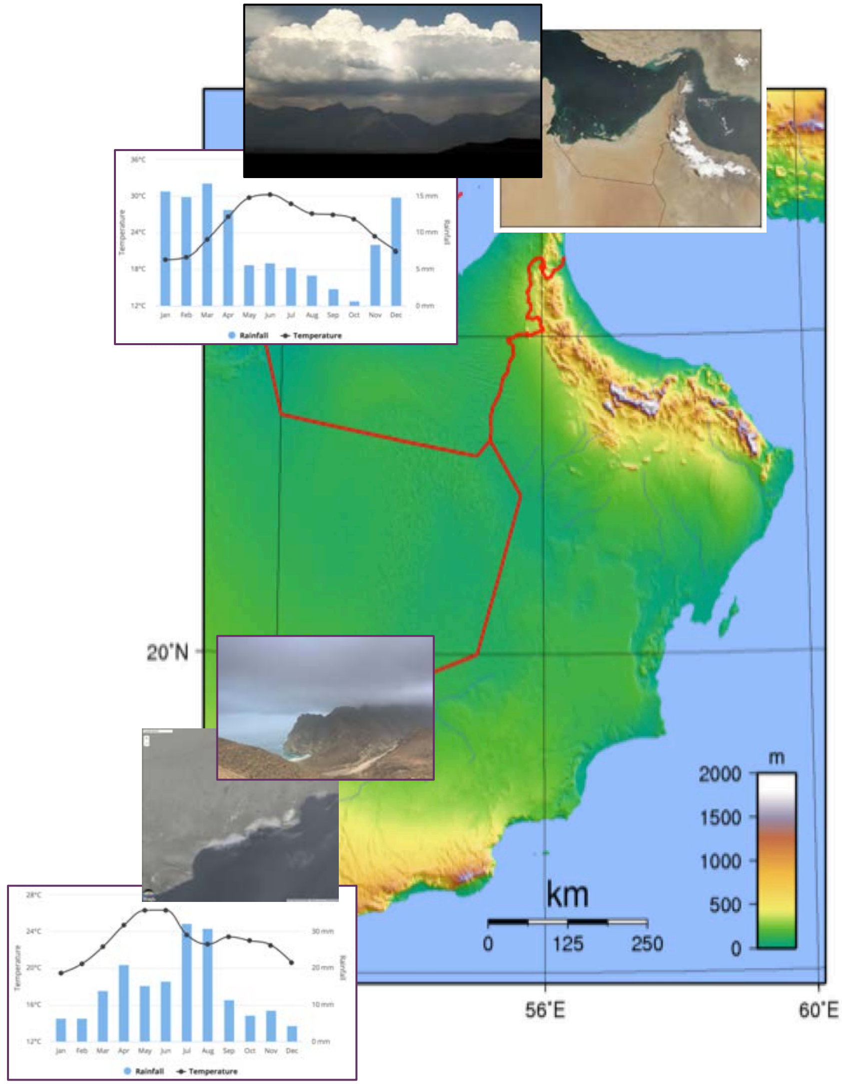
- Atlant is a ground-based ionization technology, and three generator designs were employed in the Oman trials.
  - These reflect design improvements aimed at greater ion generation efficiency, durability and maintainability.



# + Geography and Climate

- During the summer season (June through September), convective rainfall occurs over the Hajar Mountains.
  - Most suitable time for rainfall enhancement operations.
  - This weather is generally of short duration and intense.
- Lighter summer  rainfall with less convection occur around the Dofar mountains inland of Salalah.
  - Less favourable for rainfall enhancement.

**Convection clouds along the Hajar Mountains**

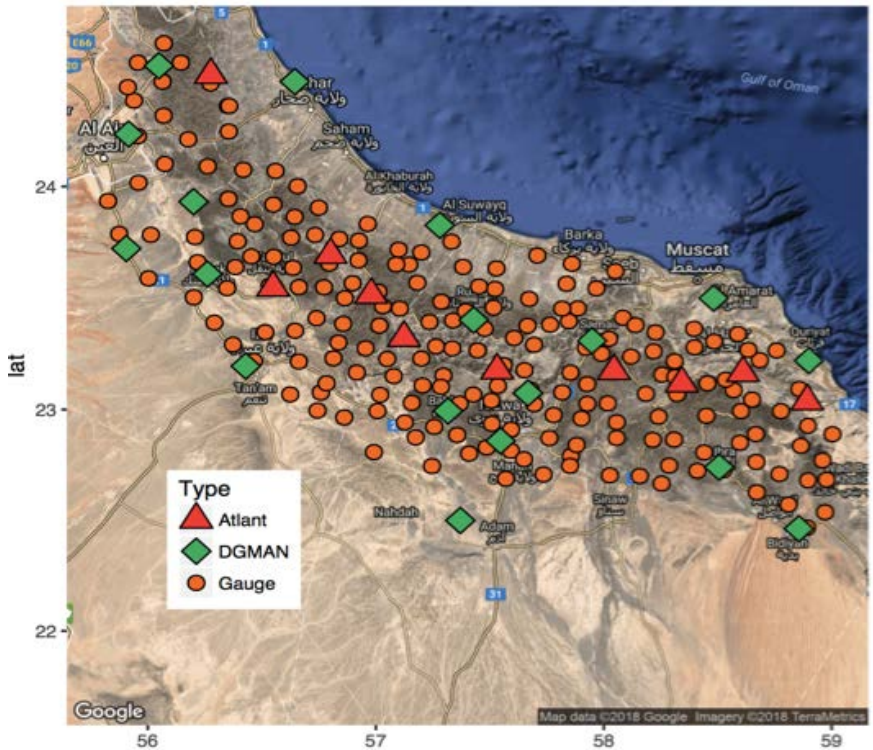



**Clouds along along the Dofar Mountains**

# + Trial Areas and Instrumentation

- Hajar Mountains trial area: H1 and H2 deployed in 2013. An extra two systems were then deployed each subsequent year up to 2017. These systems were labelled sequentially H3 – H10.
- Salalah trial area: H11 and H12 deployed in 2018.

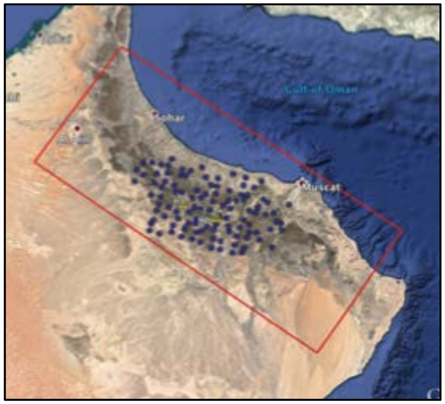
- Atlant sites chosen so that
  - Areas of influence did not significantly overlap.
  - Covered the main north-west to south-east range of peaks in the Hajar Mountains area.
  - Effectively placed along a line running at 90◦ to the main NE wind direction.

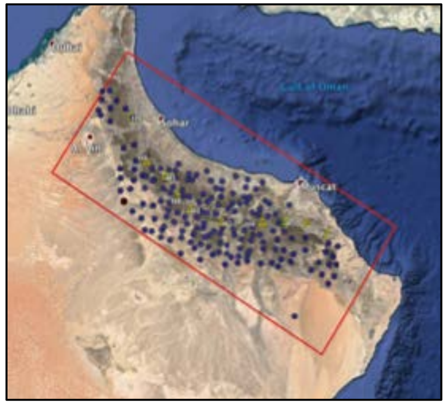



**Instrument locations - Hajar Mountains trial area 2017**

# + Trial Areas and Instrumentation

- **Deployment of Rain Gauges**
- Extensive array of 120 rain gauges installed by TIE prior to the start of the 2013 trial.
  - On an approximate 10 km regular grid.
  - Further gauges added as more Atlants deployed.
  - 201 gauges installed in Hajar Mountains trial area by 2017, with 19 more gauges installed in Salalah trial area in 2018.




| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|
| **No. of gauges** | 120 | 149 | 179 | 191 | 201 | 201 (Hajar)<br>19 (Salalah) |

**Size of rain gauge network by year, 2013 - 2018**

# + Trial Areas and Instrumentation

- **DGMAN Automatic Weather Stations (AWS)**
- Hourly observations from these stations were used to characterise prevailing weather conditions on the day.
- The main measurements collected from each AWS were:
  - Wind speed (m/s);
  - Dry air temperature (℃);
  - Dew point temperature (℃);
  - Relative humidity (%);
  - QFE air pressure (hPa);
  - QNH air pressure (hPa).

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|
| No. of AWS | 10 | 11 | 17 | 17 | 18 | 17 |

**Number of DGMAN AWS contributing data, 2013 - 2018**

# + Trial Areas and Instrumentation

- **Radiosonde Data on Meteorological Conditions**
- DGMAN radiosonde at Muscat International Airport provides:
  - Daily data on vertical wind profiles (direction and speed).
  - Derived values of key meteorological indices.
- Measurement of steering wind direction and speed is crucial for identifying where an operating Atlant has a rainfall enhancement effect.
  - High quality radiosonde data are essential for the analysis of the trial data.

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|
| Muscat radiosondes (time) | 1 (4am) | 1 (4am) | 2 (4am, 4pm) | 1 (4am) | 2 (4am, 1pm) | 1 (4am,1pm) |
| No of days with actual or imputed radiosonde data | 170 | 140 | 127 | 125 | 108 | 70 |

**Number of radiosondes and number of days with radiosonde data 2013 - 2018.**

# + Trial Areas and Instrumentation

- **Atlant Operating Schedules**
- A randomised operating schedule was defined each year before commencement of operations for that year, and was strictly followed, irrespective of weather patterns.
  - The only exceptions were due to mechanical or electrical failure.
  - Atlants H7 and H8 suffered weather-related damage after commencing operation on July 1 2016. The times set out below for 2016 are the actual operating periods for these Atlants after they were repaired.
  - All Atlants were operational July 1 - Oct 31 2017. But there was missing radiosonde data July 1 - July 15.
  - All Atlants were operational July 1 - Oct 31 2018. But there was missing radiosonde data Aug 24 - Sep 30 and Oct 17 - Oct 31.

| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|
| **Trial Period** | 15/5 - 31/10 | 1/6 - 18/10 | 14/6 - 18/10 | H1-H6<br>1/6 - 31/10<br>H7<br>6/8- 31/10<br>H8<br>29/7 - 31/10 | **16/7 - 31/10** | **1/7 - 23/8**<br>**1/10 - 16/10** |

**Effective trial periods 2013 - 2018 for the Hajar Mountains trial**

# + Trial Areas and Instrumentation

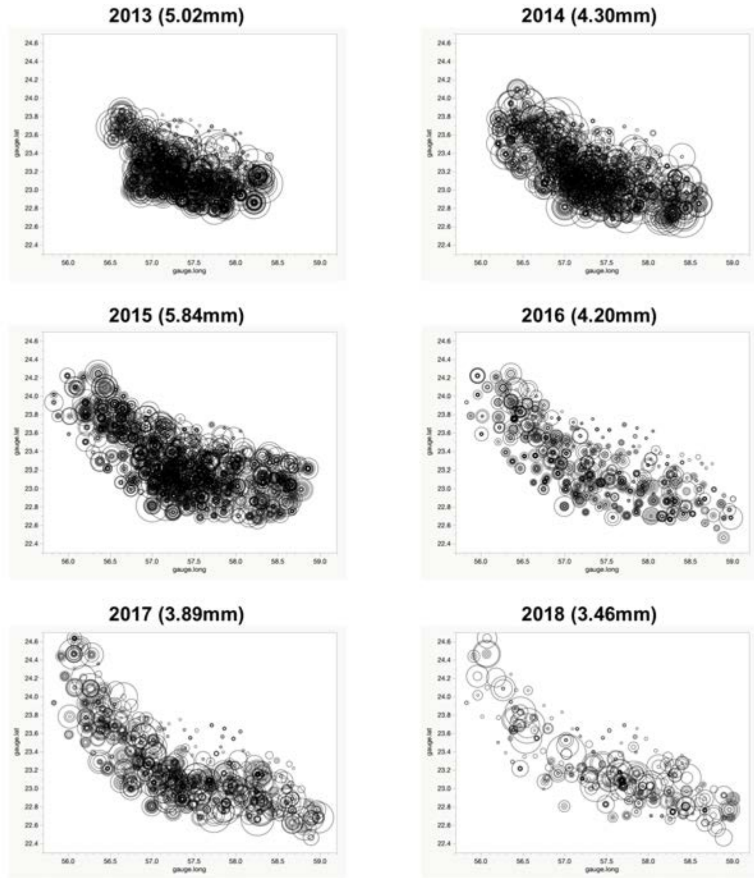
- **Design of the Atlant Operating Schedules**
- Hajar Mountains trial (2013 – 2018).
  - 2013: H1 and H2 were operated on a randomised crossover schedule.
  - 2014: Randomised paired crossover scheme used with H1 - H4.
  - 2015 onwards: Operating schedule randomly chosen subject to the spatio-temporal balance constraints
    - Equal number of operational and non-operational Atlants each day;
    - No more than two "adjacent" Atlants operated together on the same day;
    - No Atlant was operated more than two days in succession.
- Salalah trial (2018) used a randomised crossover schedule.
- Atlants switched on/off at 7am (local Oman time) on their designated operating days.

# + Meteorological Conditions 2013 - 2018

- **Rainfall 2013 - 2018**

- 122,259 gauge-day rainfall measurements were recorded for Hajar Mountains trial.
  - Gauge-day rainfall = total rainfall recorded at a gauge on a day.

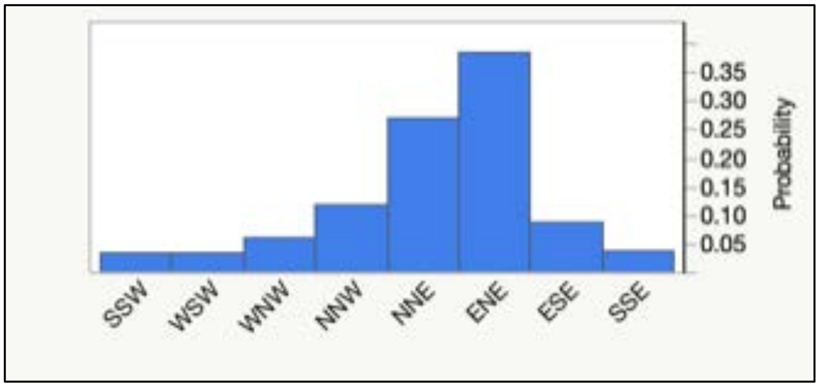
- 740 days of data collected.
  - 92.5 per cent of gauge-day rainfall values were zero.
  - Average gauge-day rainfall = 0.35mm.
  - Average gauge-day **positive rainfall** = 4.74mm.

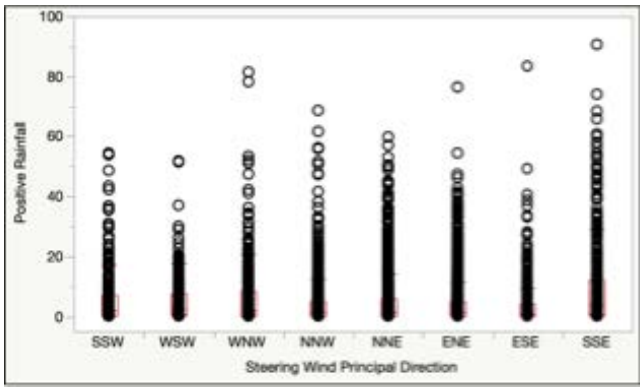



**Bubble plots of gauge locations showing 2013 - 2018 spatial distributions of gauge-day values of <u>positive</u> rainfall (annual average gauge-day positive rainfall in parentheses)**

# + Meteorological Conditions 2013 - 2018

- **Steering Winds (Hajar Mountains)**
- Daily steering wind direction defined as the speed-weighted average of the wind directions between 700hPa and 500hPa as measured by the 4am Muscat radiosonde.
- The most common principal wind directions were NNE and ENE, i.e. the prevailing steering winds were from the NE.
- Heaviest rainfall values were associated with the SSE direction and were most likely monsoonal.




**Hajar Mountains Trial Area: Distribution of gauge-days by principal steering wind directions 2013 - 2018 with corresponding distributions of gauge-day positive rainfall values in boxplots on right.**

# + Meteorological Conditions 2013 - 2018

- **Meteorological Indices Derived from Radiosonde Data**

- Four main daily meteorological indices with complete data 2013 - 2018
  - Lifted index (lifted.index);
  - Total totals (total.totals);
  - LCL Pressure (hPa) (lcl.pres);
  - Precipitable Water (mm) (prec.water).

- Correlation with both the occurrence and the amount of actual rainfall is not strong, averaging between 30 to 40 per cent in absolute value.
  - Highest correlation (0.485) is between Precipitable Water and Positive Rainfall.

| | lifted.index | total.totals | lcl.pres | prec.water | Rainfall Event | Positive Rainfall |
|---|---|---|---|---|---|---|
| lifted.index | 1.000 | -0.745 | -0.671 | -0.697 | -0.394 | -0.414 |
| total.totals | -0.745 | 1.000 | 0.267 | 0.655 | 0.416 | 0.395 |
| lcl.pres | -0.671 | 0.267 | 1.000 | 0.615 | 0.202 | 0.335 |
| prec.water | -0.697 | 0.655 | 0.615 | 1.000 | 0.388 | 0.485 |

**Correlation matrix defined by daily values of meteorological indices, proportion of gauges reporting rainfall (Rainfall Event) and average gauge-day positive rainfall (Positive Rainfall) on days when there was rainfall.**

# + Meteorological Conditions 2013 - 2018

- **Meteorological Indices Derived from AWS Data**
  - First and second principal components defined by daily values of AWS variables were used to provide indicators of background daily rainfall potential across the trial area.
  - With the exception of the first principal component of relative humidity (relh.1), these variables generally appear to correlate less with both actual rainfall propensity (Rainfall Event) and amount of rain (Positive Rainfall) than the meteorological indices from Radiosonde data.

| | temp.dry.1 | temp.dry.2 | relh.1 | relh.2 | pres.1 | Rainfall Event | Positive Rainfall |
|---|---|---|---|---|---|---|---|
| temp.dry.1 | 1.000 | -0.042 | -0.519 | 0.078 | -0.849 | -0.141 | -0.115 |
| temp.dry.2 | -0.042 | 1.000 | -0.271 | -0.724 | 0.190 | 0.118 | -0.068 |
| relh.1 | -0.519 | -0.271 | 1.000 | 0.002 | 0.144 | 0.465 | 0.519 |
| relh.2 | 0.078 | -0.724 | 0.002 | 1.000 | -0.119 | -0.186 | -0.034 |
| pres.1 | -0.849 | 0.190 | 0.144 | -0.119 | 1.000 | -0.029 | -0.098 |

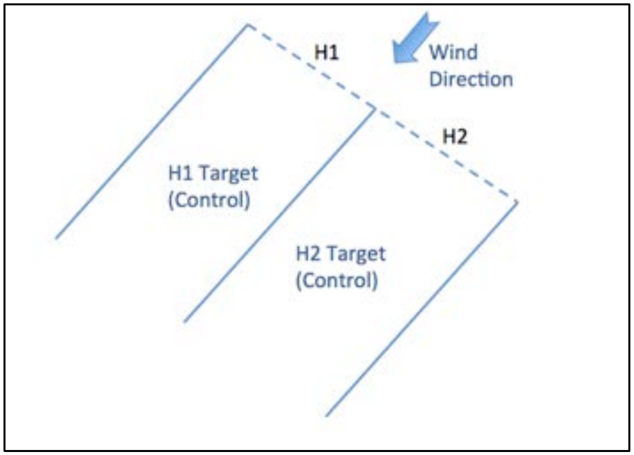
**Correlation matrix defined by daily values of the first and second principal components of dry air temperature (temp.dry.1, temp.dry.2), relative humidity (relh.1, relh.2) and the first principal component of QFE air pressure (pres.1), proportion of gauges reporting rainfall (Rainfall Event) and average gauge-day positive rainfall (Positive Rainfall) on days when there was rainfall.**

# + Statistical Analysis 2013 - 2018

- **Introduction**
- Combined analysis of the Hajar Mountains gauge-day data from 2013 - 2018.
  - An exploratory analysis of the 2018 Salalah trial.
- Fundamentals of statistical methodology unchanged from those specified at start of trial in 2013.
  - Description of the methodological process;
  - Summary analyses of rainfall;
  - Statistical modelling of the logarithm of daily positive rainfall measurements recorded by gauges, with subsequent estimation of enhancement effects;
  - Corroborative analysis of daily average positive rainfall;
  - Distribution and spatial analysis of gauge average attribution.

# + Statistical Analysis 2013 - 2018

- **Methodology**
- Daily footprint of an Atlant site is a 30km wide and 75km long corridor starting at the Atlant site and oriented downwind from it in the direction of the steering wind.
- Regression modelling is applied to the positive gauge-day rainfall in all footprints defined by the direction of the steering wind on a day.
- Modelling is used to estimate the rainfall enhancement, i.e. the extra rainfall in the daily footprints caused by operation of the Atlants.
  - Atlant attribution is the total rainfall enhancement expressed as a percentage of the corresponding estimate of the natural rain in these footprints over the same period.



# + Statistical Analysis 2013 - 2018

- **Methodology**

**Model Covariates**

- Used to control for the variation in natural rainfall.
- Include gauge elevation, year of measurement, daily steering wind speed, daily meteorological indices and principal components of daily DGMAN AWS measurements.
- Used in the specification of the upwind model.
- Fitted values generated by the upwind model fit are used as the main covariate measuring expected rainfall (i.e. non-Atlant related rainfall) in the downwind model.

# + Statistical Analysis 2013 - 2018

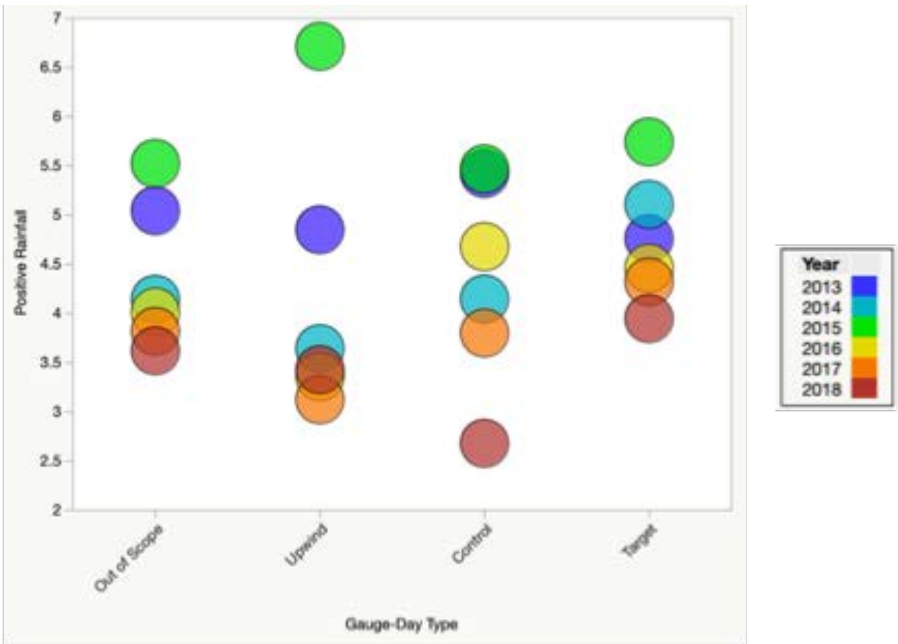
- **Methodology**

**Confidence Levels**

- Unexplained temporal and spatial variability can lead to overstated confidence levels
  - A random day effect is added to both the downwind and upwind models in order to allow for imperfect model specification.
  - A two-stage block bootstrap resampling strategy that accounts for zero as well as positive rainfall observations that are spatially correlated in space and time is used to assess the significance of the estimated attribution given the actual operating schedule.
  - A non-parametric permutation test in which the actual operating schedule is compared to a large number of random permutations of that schedule is used to further assess the significance of the estimated attribution in the context of the observed rainfall.

# + Statistical Analysis 2013 - 2018

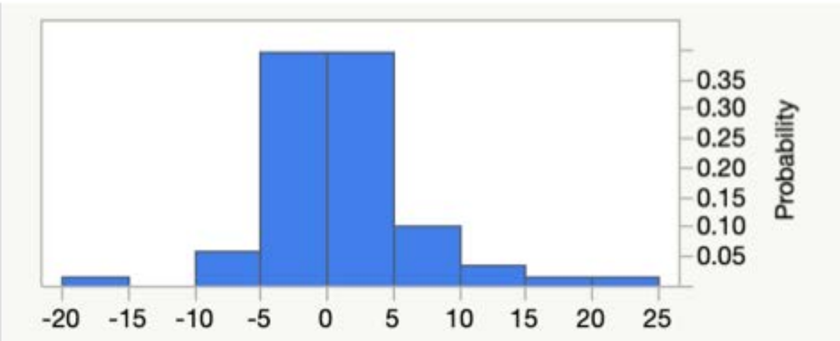
- **Average Target and Control Rainfall**
- Rainfall measurements classified by whether they were downwind, upwind or out of scope on the day.
    - Downwind observations further classified:
        - A target observation is downwind of at least one operating Atlant;
        - A control observation is downwind of non-operating Atlants only.



# + Statistical Analysis 2013 - 2018

- **6-year Gauges**

- There were 101 gauges that provided complete data for the same location for the entire six-year trial period.
  - Average elevation of 592m compared with average elevation of 531m for all gauges.
  - More tightly clustered in the central part of the Hajar Mountains trial area.
  - 92 gauges with both target and control data used to compute gauge-specific target-control average differences over 2013 – 2018.




| | |
|---|---|
| 100.0% | 21.300 |
| 90.0% | 6.397 |
| 75.0% | 2.215 |
| 50.0% | 0.233 |
| 25.0% | -1.542 |
| 10.0% | -3.429 |
| 0.0% | -17.600 |
| **Mean** | **0.947** |
| Std Err Mean | 0.545 |
| N | 92 |

**Histogram and associated key points in the distribution of gauge-specific differences (target-control) in average downwind positive rainfall (mm) for 6-year gauges with both target and control values.**

# + Statistical Analysis 2013 - 2018

- **Regression Modelling of LogRain (Logarithm of Gauge-Day Rainfall)**
- Regression model first fitted to the upwind gauge-day values of LogRain.
  - This fitted model is used to define a predictor of the downwind gauge-day values of "natural" LogRain.
- Another regression model then fitted to the downwind gauge-day values of LogRain
  - Very simple specification, with only upwind model-based predicted LogRain, gauge elevation and Atlant target status indicators as covariates.
  - Estimated values of the model parameters for these target status indicators provide measures of the influence of the different Atlants on downwind rainfall.
- Modelling using data from a single year does not lead to a consistent picture of how operation of the Atlant sites influences rainfall enhancement. We have to accumulate data across years.

# + Statistical Analysis 2013 - 2018

| Control Variable | 2013-2014 | | 2013-2015 | | 2013-2016 | | 2013-2017 | | 2013-2018 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Est | t val | Est | t val | Est | t val | Est | t val | Est | t val |
| | Upwind model estimates (expected rain for downwind model) | | | | | | | | | |
| (Intercept) | 0.498 | 0.765 | -0.689 | -1.257 | -0.988 | -1.968 | -1.535 | -3.646 | -1.447 | -3.593 |
| gauge.elev | 0.535 | 4.734 | 0.516 | 5.921 | 0.488 | 6.015 | 0.464 | 6.077 | 0.446 | 6.011 |
| wind.sp | -0.176 | -4.608 | -0.115 | -3.983 | -0.111 | -4.521 | -0.086 | -4.005 | -0.092 | -4.487 |
| total.totals | -0.004 | -0.288 | 0.017 | 1.451 | 0.024 | 2.273 | 0.033 | 3.798 | 0.032 | 3.814 |
| temp.dry.2 | 0.304 | 2.921 | 0.158 | 2.132 | 0.180 | 2.652 | 0.151 | 2.718 | 0.144 | 2.722 |
| relh.1 | 0.300 | 5.028 | 0.245 | 7.906 | 0.206 | 7.679 | 0.176 | 7.420 | 0.179 | 7.966 |
| pres.1 | -0.113 | -2.433 | -0.097 | -3.206 | -0.080 | -3.060 | -0.054 | -2.421 | -0.053 | -2.614 |
| No. gauge-days | 442 | | 1041 | | 1285 | | 1454 | | 1545 | |
| No. days | 104 | | 174 | | 219 | | 259 | | 292 | |
| | Downwind model estimates | | | | | | | | | |
| (Intercept) | 0.367 | 3.148 | 0.270 | 3.166 | 0.238 | 3.154 | 0.279 | 4.162 | 0.280 | 4.368 |
| gauge.elev | -0.009 | -0.078 | -0.067 | -0.748 | -0.033 | -0.415 | -0.127 | -1.811 | -0.140 | -2.120 |
| expected rain | 0.709 | 8.393 | 0.777 | 10.954 | 0.829 | 12.298 | 0.878 | 14.306 | 0.883 | 15.035 |
| H1 target | 0.566 | 2.769 | 0.434 | 2.595 | 0.423 | 2.758 | 0.307 | 2.208 | 0.298 | 2.189 |
| H2 target | 0.517 | 2.605 | 0.403 | 2.711 | 0.424 | 3.104 | 0.300 | 2.369 | 0.254 | 2.074 |
| H3 target | 0.425 | 2.479 | 0.396 | 3.155 | 0.360 | 3.422 | 0.264 | 2.806 | 0.236 | 2.551 |
| H4 target | -0.255 | -1.454 | -0.213 | -1.765 | -0.130 | -1.256 | -0.205 | -2.177 | -0.153 | -1.721 |
| H5 target | | | 0.615 | 2.673 | 0.490 | 3.085 | 0.465 | 3.236 | 0.437 | 3.318 |
| H6 target | | | -0.449 | -2.001 | -0.303 | -1.731 | -0.218 | -1.453 | -0.197 | -1.320 |
| H7 target | | | | | 0.025 | 0.075 | 0.371 | 1.660 | 0.228 | 1.216 |
| H8 target | | | | | -0.038 | -0.192 | 0.081 | 0.620 | 0.063 | 0.494 |
| H9 target | | | | | | | 0.556 | 1.737 | 0.499 | 1.633 |
| H10 target | | | | | | | 0.304 | 1.376 | 0.039 | 0.234 |
| elev*H1 target | -0.441 | -2.133 | -0.327 | -1.884 | -0.285 | -1.739 | -0.119 | -0.807 | -0.096 | -0.669 |
| elev*H2 target | -0.540 | -2.804 | -0.347 | -2.326 | -0.394 | -2.873 | -0.271 | -2.182 | -0.211 | -1.772 |
| No. gauge-days | 1370 | | 2447 | | 3219 | | 3905 | | 4168 | |
| No. days | 194 | | 286 | | 369 | | 435 | | 488 | |

**Cumulative years modelling for LogRain.**

# + Statistical Analysis 2013 - 2018

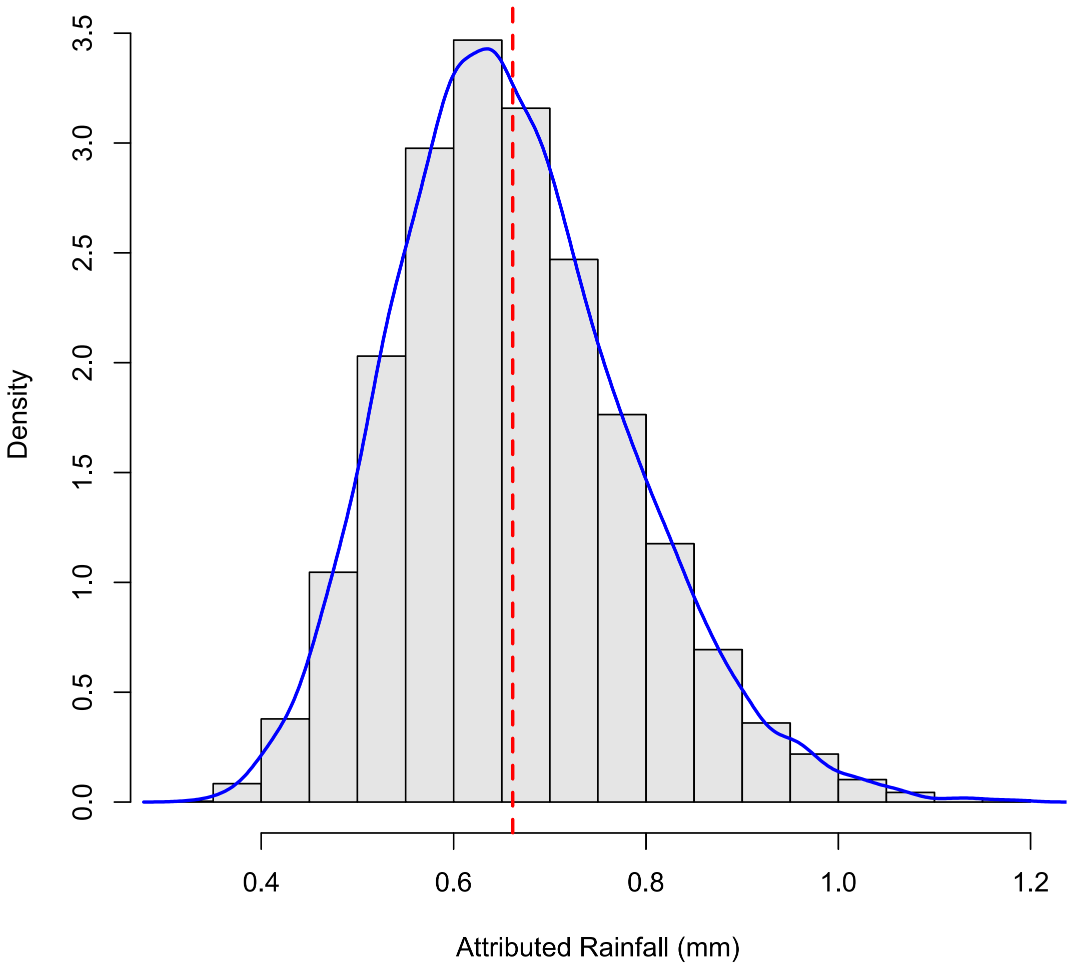
- **Atlant Enhancement of Downwind Gauge-Day Rainfall**

| Data period | 2013-2014 | 2013-2015 | 2013-2016 | 2013-2017 | 2016-2018 | 2013-2018 |
|---|---|---|---|---|---|---|
| Total rainfall (mm) | 16249 | 30961 | 36951 | 41572 | 12294 | 43254 |
| Average positive rainfall (mm) | 4.65 | 5.15 | 4.96 | 4.82 | 3.96 | 4.74 |
| Total downwind rainfall (mm) | 6587 | 12615 | 16136 | 18954 | 7232 | 19846 |
| Average positive downwind rainfall (mm) | 4.81 | 5.16 | 5.01 | 4.85 | 4.20 | 4.76 |
| | **Bootstrap estimates** | | | | | |
| Total natural downwind rainfall | 5516 (829) | 10583 (1550) | 13379 (1723) | 15930 (2080) | 6182 (1260) | 17089 (2116) |
| Attributed downwind rainfall | 1071 (344) | 2031 (487) | 2757 (510) | 3024 (546) | 1050 (183) | 2757 (506) |
| %attribution | **19.67** (6.31) | **19.39** (4.53) | **20.76** (3.76) | **19.13** (3.35) | **17.19** (1.77) | **16.25** (2.91) |
| % positive attributions | 99.99 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

**Bootstrap estimates of aggregated attribution for downwind corridors defined by daily steering winds (bootstrap standard errors in parentheses).**

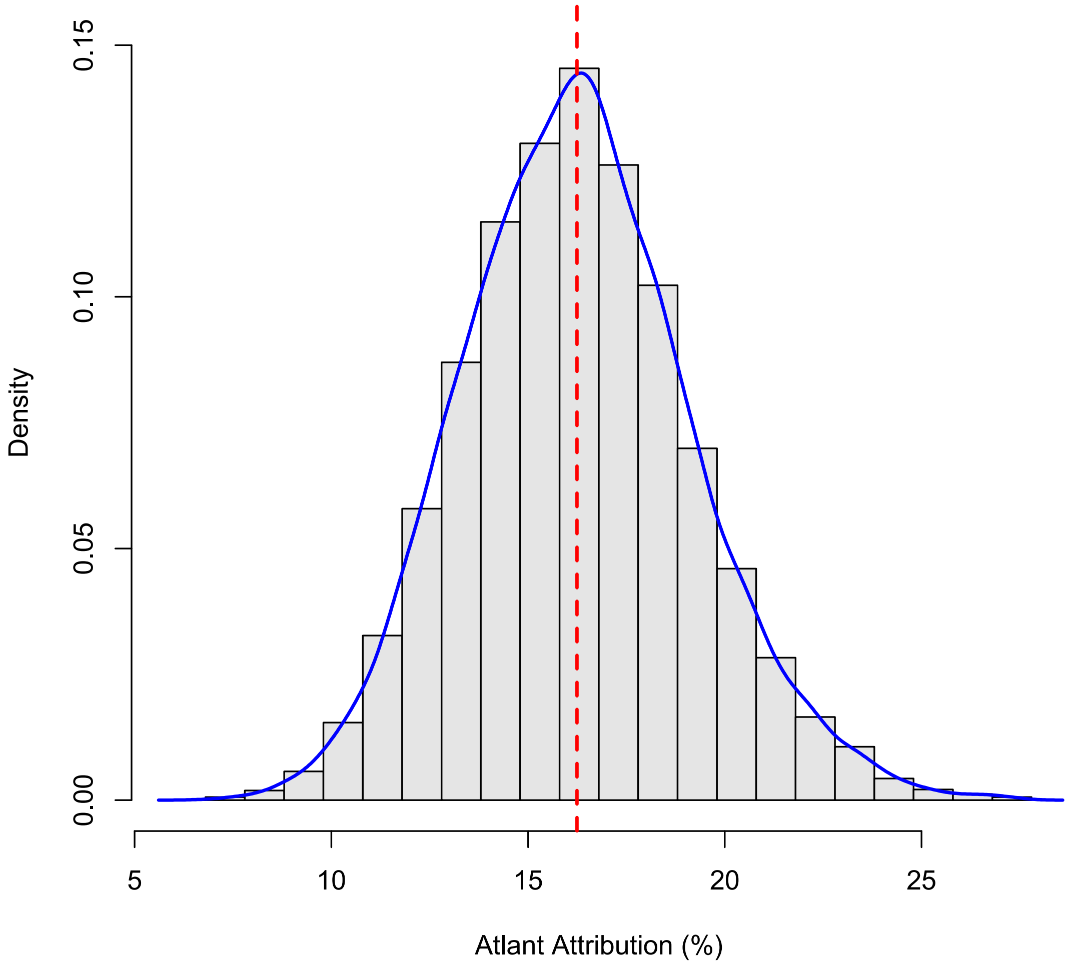
# + Statistical Analysis 2013 - 2018

- **Bootstrap Distribution of Average Downwind Gauge-Day Attribution (mm) 2013 - 2018**



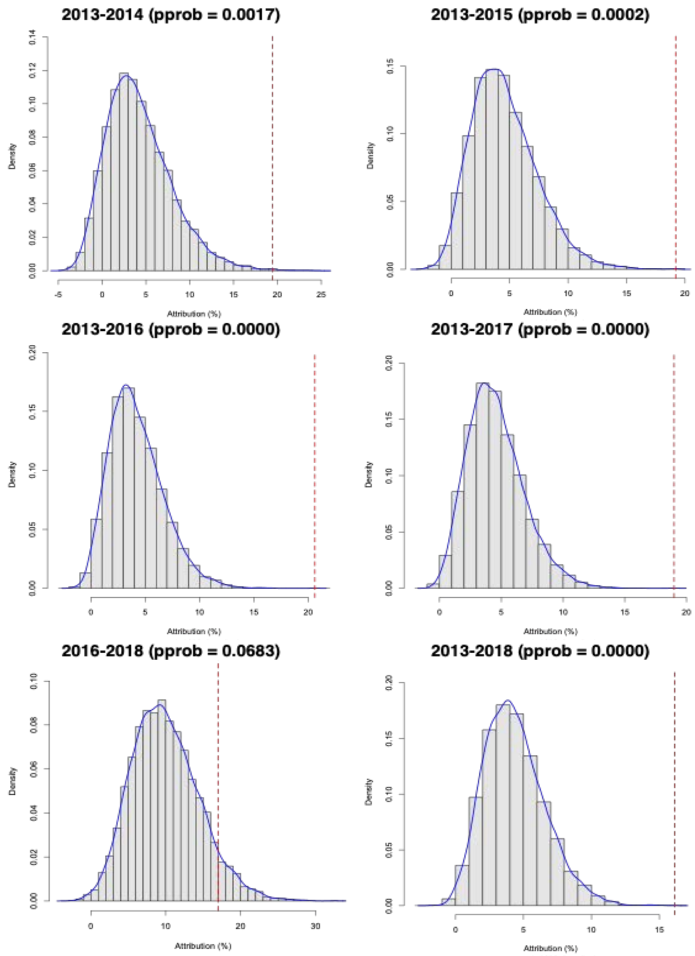
# + Statistical Analysis 2013 - 2018

- **Bootstrap Distribution of Atlant Attribution (%) 2013 - 2018**



# + Statistical Analysis 2013 - 2018

- Possible that by sheer chance Atlants were more often operated when rain was likely.
- Permutation test is based on the premise that if Atlant operation does nothing to enhance rainfall, then the actual Atlant operating sequence has no impact on attribution, and so the observed attribution is not likely to be very different from the attribution one would obtain if one replaced this operating sequence by a permuted version.
  - Permutation process is carried out a large number of times (10,000), and the resulting distribution of permuted attribution estimates is compared with the actual attribution estimate.




**Cumulative years permutation distributions for attribution. Actual attribution is vertical red dotted line. Value of pprob is permutation p-value.**

# + Statistical Analysis 2013 - 2018

- Site-Specific Attribution
- Assess impact of individual Atlant installations on attribution by just looking at rainfall in the upwind and downwind corridors they defined.
  - Gauges downwind of an operating Atlant are targets, and gauges downwind of the same Atlant when it is switched off are controls.
  - Controls that are also not downwind of any other operating Atlant on the day are pure controls.
  - Positive rainfall ratio is average positive rainfall for targets divided by average positive rainfall for controls.

| | Average Positive Rainfalls (mm) | | | | Positive Rainfall Ratios | | Estimated Attributions | |
|---|---|---|---|---|---|---|---|---|
| Atlant Site | Upwinds | Targets | All Controls | Pure Controls | Targets + All Controls | Targets + Pure Controls | Targets + All Controls | Targets + Pure Controls |
| H1 | 5.4 | 5.3 | 4.7 | 4.8 | 1.12 | 1.10 | 8.7 | 7.6 |
| H2 | 4.7 | 5.1 | 4.8 | 4.7 | 1.05 | 1.07 | -0.3 | -1.5 |
| H3 | 5.5 | 5.9 | 4.3 | 4.3 | 1.37 | 1.38 | 29.6 | 32.9 |
| H4 | 5.1 | 3.8 | 4.5 | 4.3 | 0.85 | 0.89 | -4.1 | -2.7 |
| H5 | 5.9 | 5.2 | 5.3 | 5.1 | 0.98 | 1.03 | 62.8 | 64.9 |
| H6 | 4.6 | 4.3 | 6.3 | 6.8 | 0.69 | 0.64 | -3.9 | -5.2 |
| H7 | 2.5 | 5.3 | 3.8 | 3.8 | 1.40 | 1.39 | 24.1 | 43.1 |
| H8 | 3.2 | 3.7 | 4.3 | 3.5 | 0.86 | 1.07 | 3.1 | 11.7 |
| H9 | 5.4 | 3.3 | 4.8 | 4.8 | 0.69 | 0.69 | -2.4 | -2.4 |
| H10 | 3.7 | 4.8 | 3.8 | 4.0 | 1.25 | 1.20 | 9.4 | 16.9 |

# + Statistical Analysis 2013 - 2018

- **Average Downwind Positive Rainfall**

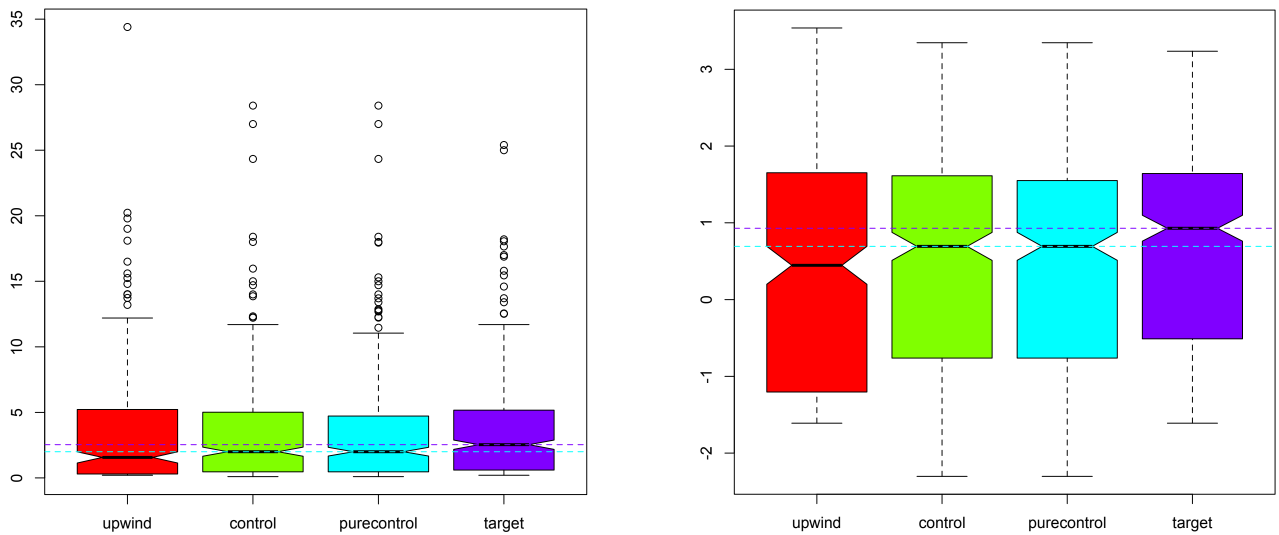
- Traditional approach to evaluating enhancement.
- Differences in average rainfall between targets and controls.
- Averages are often based on wildly varying numbers of rainfall events, and so cannot be considered comparable.
- Ignore this issue, and compare averages of target and control values of daily gauge-level positive rainfall for all 740 days making up 2013-2018 trial.

| Scale of Positive Rainfall | Average of Daily Averages | | | | Median of Daily Averages | | | |
|---|---|---|---|---|---|---|---|---|
| | Upwinds | Targets | All Controls | Pure Controls | Upwinds | Targets | All Controls | Pure Controls |
| Actual (mm) | 3.40 | 3.55 | 3.32 | 3.32 | 1.56 | 2.53 | 2.00 | 2.00 |
| Log(Actual) | 0.33 | 0.55 | 0.49 | 0.47 | 0.45 | 0.93 | 0.69 | 0.69 |
| Log Scale Average | -0.03 | 0.15 | 0.08 | 0.09 | 0.02 | 0.30 | 0.21 | 0.20 |

# + Statistical Analysis 2013 - 2018

- **Distributions of Daily Average Downwind Positive Rainfall Values**

- Boxplots shows distributions of daily averages (left) and logarithms of daily averages (right) of downwind positive rainfall across all 740 days.
  - Body of “box” for each group shows middle 50% of values for the group, with outliers shown outside “fence”.
  - “Notch” shows median of distribution, with size of notch indicating 95 per cent confidence interval, so groups with non-overlapping notches are significantly different.
  - Target distribution (actual and log scale) of daily average positive rainfall has larger median than control distribution, but variability in these simple averages too great to establish a significant difference (tvals = 1.23, 1.27 respectively for paired t-tests of target - purecontrol)



# + Statistical Analysis 2013 - 2018

- **Site-Specific Daily Averages of Downwind Positive Rainfall Values**

- Compute daily averages for "profiles" of gauges in daily downwind corridors.
  - 1664 “profiles” defined by gauges that are all downwind of the same Atlant site(s) on a day and such that at least one gauge records rainfall.
  - Sample sizes of profiles vary widely, with most based on one or two positive rainfall measurements, and with a few based on more than 10 positive rainfall measurements.
  - Profile average positive rainfall defined as a target value if gauges making up profile all downwind of an active Atlant. Otherwise classified as a control.

| Status | Count | Mean | SE | 10% | 25% | Median | 75% | 90% |
|---|---|---|---|---|---|---|---|---|
| Control | 748 | 3.74 | 0.20 | 0.20 | 0.50 | 1.93 | 4.88 | 9.43 |
| Target | 916 | 4.19 | 0.19 | 0.20 | 0.60 | 2.29 | 5.60 | 10.46 |

Summary data for the distribution of profile average positive rainfall, classified by target and control status

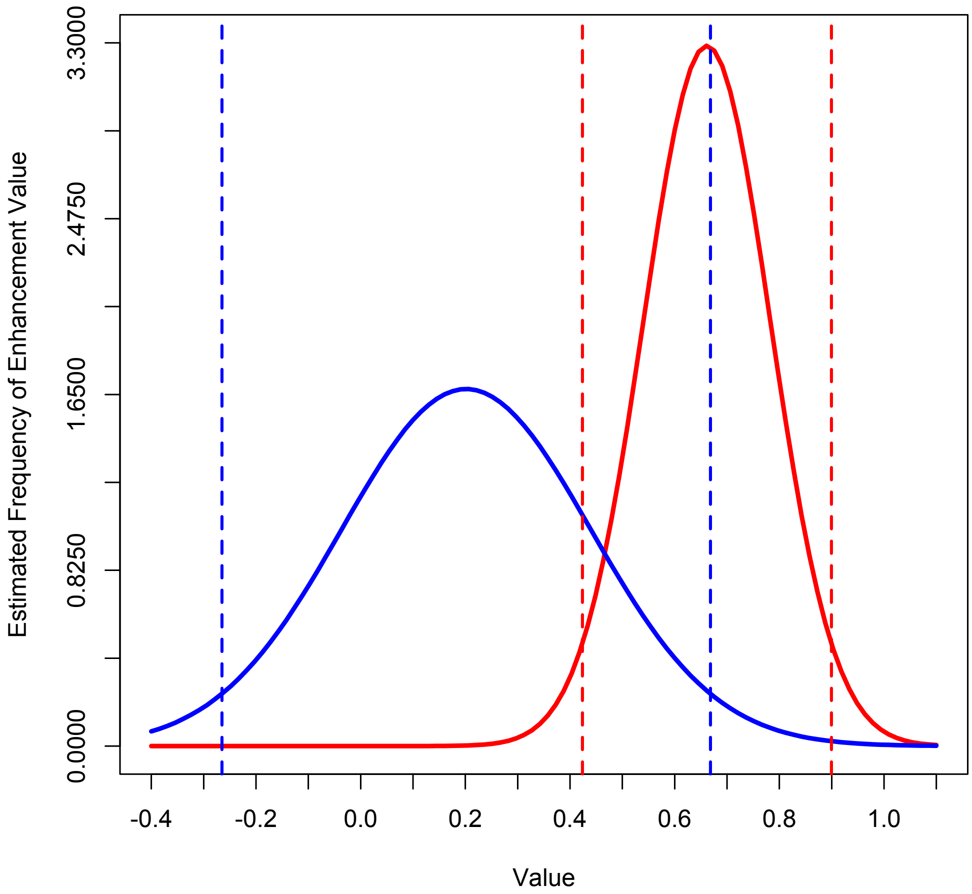
# + Statistical Analysis 2013 - 2018

- **Regression Analysis of Average Downwind Positive Rainfall for Profiles**

| Term | Estimate | t value |
|---|---:|---:|
| Intercept | 0.672 | 1.054 |
| year= 2013 | 2.010 | 3.560 |
| year=2014 | 1.100 | 2.365 |
| year=2015 | 1.177 | 2.702 |
| year=2016 | 1.189 | 2.740 |
| year=2018 | 0.382 | 0.734 |
| Average gauge.elev | -0.090 | -0.124 |
| Average expected rain | 1.616 | 11.922 |
| Target H1 | 0.532 | 1.228 |
| Target H2 | 0.118 | 0.265 |
| Target H3 | 1.516 | 3.022 |
| Target H4 | -0.249 | -0.489 |
| Target H5 | 1.462 | 2.104 |
| Target H6 | -1.059 | -1.302 |
| Target H7 | 0.957 | 0.991 |
| Target H8 | 0.115 | 0.181 |
| Target H9 | 0.621 | 0.415 |
| Target H10 | 0.643 | 0.807 |

# + Statistical Analysis 2013 - 2018

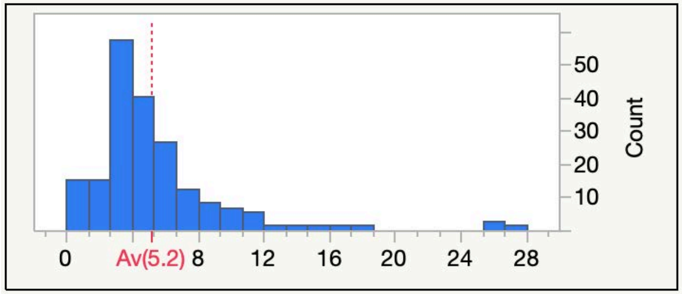
- **Comparison of Gaussian Approximations to Difference (Target – Control) Gauge-Day Positive Rainfall 2013 – 2018 (blue curve) and Model-Based Estimate of this Difference (red curve).**
  - Vertical dashed lines show 95% confidence limits for true value.



# + Statistical Analysis 2013 - 2018

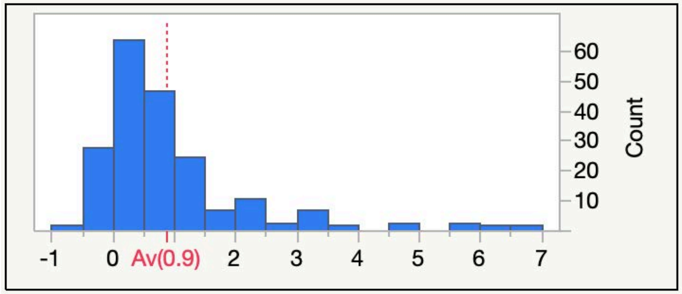
| | |
|---|---|
| Max | 27.55 |
| 90.0% | 9.31 |
| 75.0% | 5.80 |
| Median | 4.34 |
| 25.0% | 3.19 |
| 10.0% | 1.77 |
| Min | 0.20 |

Gauge Average Downwind Positive Rainfall (mm)



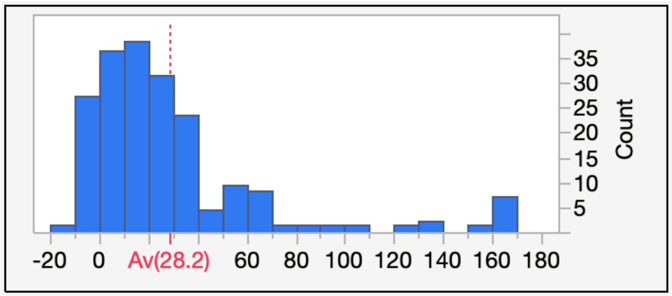

| | |
|---|---|
| Max | 6.54 |
| 90.0% | 2.34 |
| 75.0% | 1.07 |
| Median | 0.56 |
| 25.0% | 0.16 |
| 10.0% | -0.06 |
| Min | -0.52 |

Gauge Average Attributed Rain (mm)



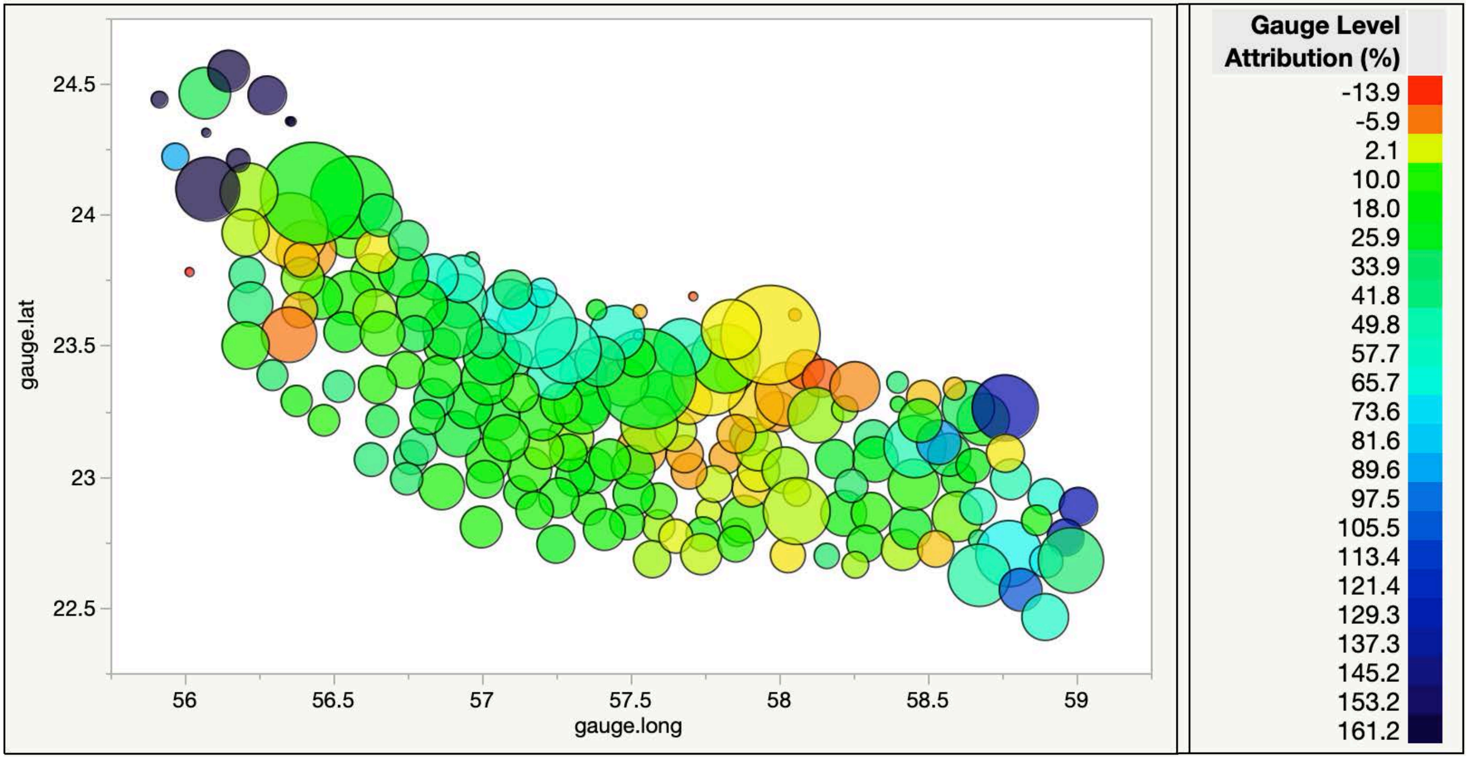

| | |
|---|---|
| Max | 161.15 |
| 90.0% | 62.21 |
| 75.0% | 34.93 |
| Median | 18.55 |
| 25.0% | 5.62 |
| 10.0% | -2.30 |
| Min | -13.86 |
| N | 192 |

Gauge Level Attribution (%)



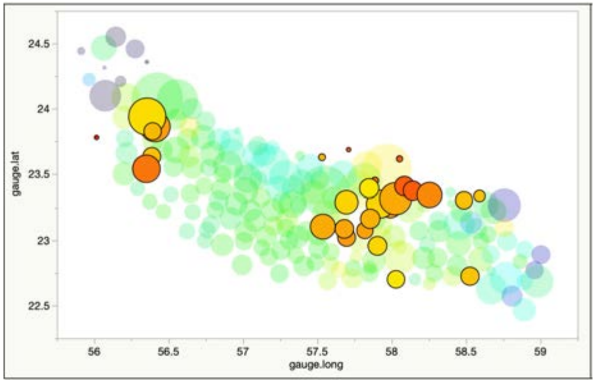
# + Statistical Analysis 2013 - 2018

Bubble Plot of Gauge Locations Showing Gauge Level Attributions Sized by Average Downwind Positive Rainfall

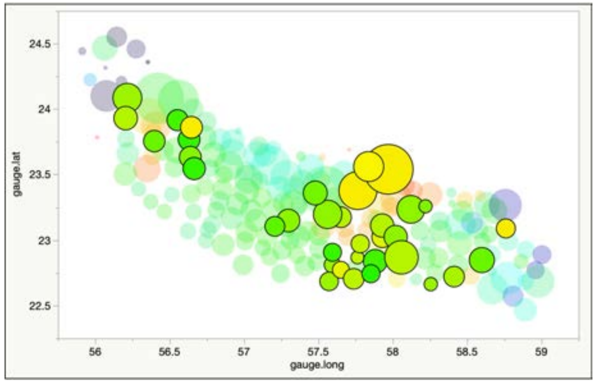


# + Statistical Analysis 2013 - 2018

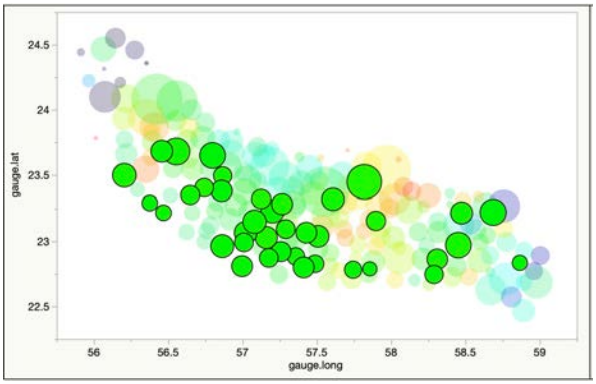
Attribution < 0



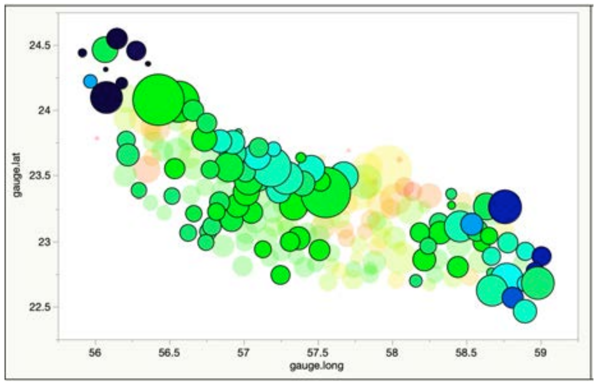

0 < Attribution < 10




10 < Attribution < 20




Attribution > 20



# + Exploratory Analysis of 2018 Salalah Trial

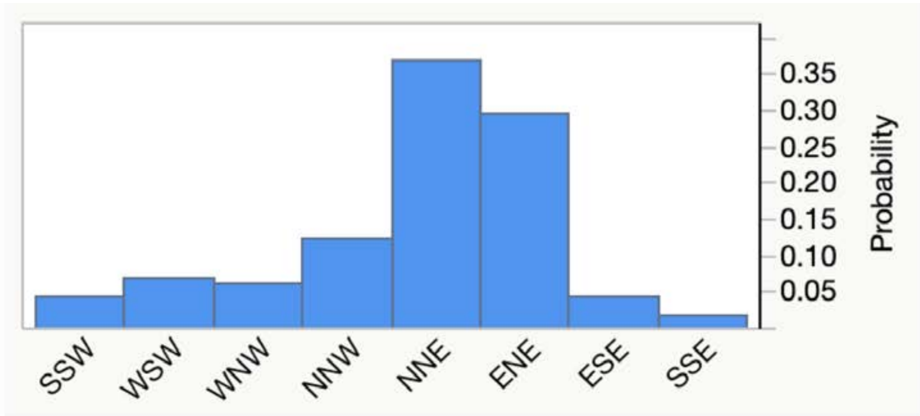
## Trial instrumentation and Implementation

- Salalah trial ran from July 1 to October 31, with H11 and H12 Atlants operating on a predefined randomised crossover sequence, with one turned on each day and the other turned off.

- Wind direction and speed information obtained from the 4am radiosonde at Salalah Airport.
  - Steering wind direction each day defined as the speed-weighted average of the radiosonde wind directions at 500hPa and 700hPa.

# + Exploratory Analysis of 2018 Salalah Trial

## Distribution of Salalah Steering Wind Directions




| Sector | Count | Prob |
|---|---|---|
| SSW | 5 | 0.04 |
| WSW | 8 | 0.07 |
| WNW | 7 | 0.06 |
| NNW | 15 | 0.12 |
| NNE | 45 | 0.37 |
| ENE | 36 | 0.29 |
| ESE | 5 | 0.04 |
| SSE | 2 | 0.02 |
| Total | 123 | 1.00 |

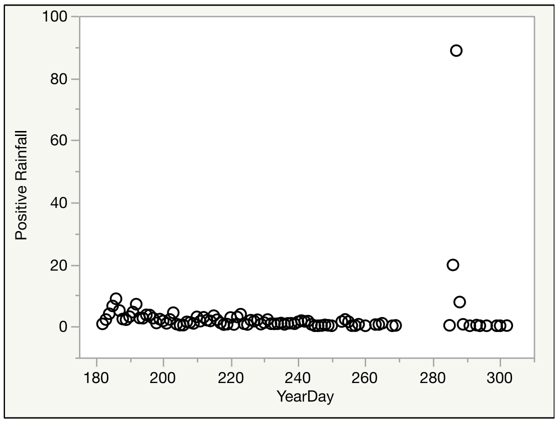
- No information on key meteorological indices from Salalah radiosonde.
- Daily Information on prevailing meteorological conditions available from the nine AWS operated by DGMAN in the region.
  - Reasonably complete hourly data on the three major meteorological variables (dry air temperature, relative humidity and QFE air pressure) that were found to be useful in rainfall modelling in the Hajar Mountains trial area.

# + Exploratory Analysis of 2018 Salalah Trial

- **Rainfall in the Salalah Trial Area 2018**
- More frequent than in the Hajar Mountains trial area
  - Approximately 19 per cent of the Salalah gauge-days recorded rainfall compared with under 8 per cent of the Hajar Mountains trial gauge-days.
- However, most of this Salalah rainfall was out of scope.
  - Approximately 73 per cent compared with just over 37 per cent in the Hajar Mountains trial
  - Major reduction in the relative amount of downwind rain.
  - Placement of rain gauges sub-optimal relative to the positioning of the Atlants and the prevailing steering wind directions.
- Large rainfall outlier in the Salalah region in 2018.

| Gauge-Day Type | No of gauge-days with rainfall > 0 |
|---|---|
| Out of Scope | 321 |
| Upwind | 56 |
| Control | 26 |
| H11 Target | 23 |
| H12 Target | 14 |

**Upwind and downwind frequencies, Salalah 2018.**




**Average positive daily rainfall (mm) in Salalah trial area, July 1 - Oct 31 2018.**

# + Exploratory Analysis of 2018 Salalah Trial

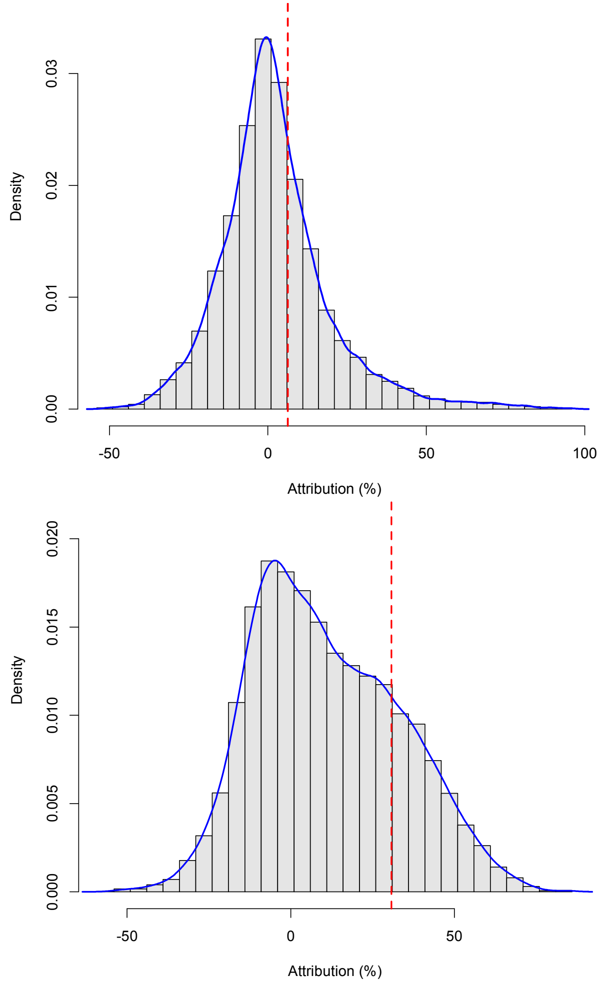
- **Attribution Analysis for Salalah 2018**
- Spatial balance is a crucial feature of a crossover design.
  - Allows rainfall recorded at target gauges on a day to be compared with rainfall recorded at control gauges on the same day.
- Could not be achieved in Salalah in 2018.
  - Of the 116 days of the trial when there were gauges downwind of either H11 or H12 or both, there was no rain measured on 66, with positive rainfall measured at just one downwind gauge on 42 of the remaining 50 days.
  - On most days (42 out of 50) when positive downwind rainfall was observed, it was either a control measurement or a target measurement.
  - Only partially controlled for by day to day variability in DGMAN AWS meteorological covariates.

# + Exploratory Analysis of 2018 Salalah Trial

- **Attribution Analysis for Salalah 2018**

| Control Variable | All data | | Rainfall > 40mm excluded | |
|---|---|---|---|---|
| | Est | t val | Est | t val |
| | **Upwind model estimates** | | | |
| (Intercept) | 1.339 | 1.930 | 1.572 | 2.341 |
| gauge.elev | -2.664 | -3.727 | -2.775 | -4.045 |
| wind.sp | 0.155 | 3.063 | 0.135 | 2.752 |
| temp.dry.1 | 0.474 | 2.742 | 0.495 | 2.989 |
| temp.dry.2 | -0.356 | -2.409 | -0.289 | -2.010 |
| relh.1 | 0.660 | 4.083 | 0.622 | 4.000 |
| No. gauge-days | 56 | | 55 | |
| No. days | 44 | | 43 | |
| | **Downwind model estimates** | | | |
| (Intercept) | 1.023 | 0.525 | 1.843 | 0.923 |
| gauge.elev | -0.826 | -0.464 | -1.841 | -0.982 |
| expected rain | 1.167 | 5.914 | 0.708 | 2.402 |
| H11 target | 0.009 | 0.019 | -0.198 | -0.435 |
| H12 target | 0.553 | 1.124 | 0.689 | 1.414 |
| No. gauge-days | 63 | | 60 | |
| No. days | 50 | | 48 | |
| Actual downwind rainfall (mm) | 572 | | 141 | |
| Natural rain | 538 | | 108 | |
| Attributed rain | 34 | | 33 | |
| %attribution (Std Error) | **6.3** (12.5) | | **35.2** (34.7) | |
| median %attribution | 3.9 | | 31.9 | |
| % +ve attributions | 64.7 | | 93.3 | |

**Attribution modelling results for Salalah 2018.**




**Permutation distributions for estimated attribution, Salalah 2018. Top panel uses all data, while bottom panel excludes four extreme gauge-day rainfall observations.**

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- Furthermore, this enhancement was consistent over the six years of the trial, which involved a variety of seasonal conditions ranging from favourable in the first half of the trial to unfavourable in the second half.

- By combining data from all six years, we see enhancement of between 15 and 18 per cent each year with an overall six-year enhancement of over 16 per cent and with negligible probability of there being no enhancement.
  - A permutation analysis of the randomised operating schedules used over the trial also shows that there is virtually zero probability that the observed attribution could have happened by chance.

# + Summary and Conclusions

| Analysis Period | Estimated Enhancement over Period | Standard Error of Estimated Enhancement | Bootstrap Probability of a Positive Enhancement over Period | Permutation Probability that Enhancement is Due to Chance |
|---|---|---|---|---|
| **2013-14** | 19.7 per cent | 6.3 per cent | 99.99 per cent | 0.17 per cent |
| **2013-15** | 19.4 per cent | 4.5 per cent | 100 per cent | 0.02 per cent |
| **2013-16** | 20.8 per cent | 3.8 per cent | 100 per cent | 0 per cent |
| **2013-17** | 19.1 per cent | 3.4 per cent | 100 per cent | 0 per cent |
| **2013-18** | 16.3 per cent | 2.9 per cent | 100 per cent | 0 per cent |

**Cumulative estimates of Atlant attribution 2013 - 2018.**

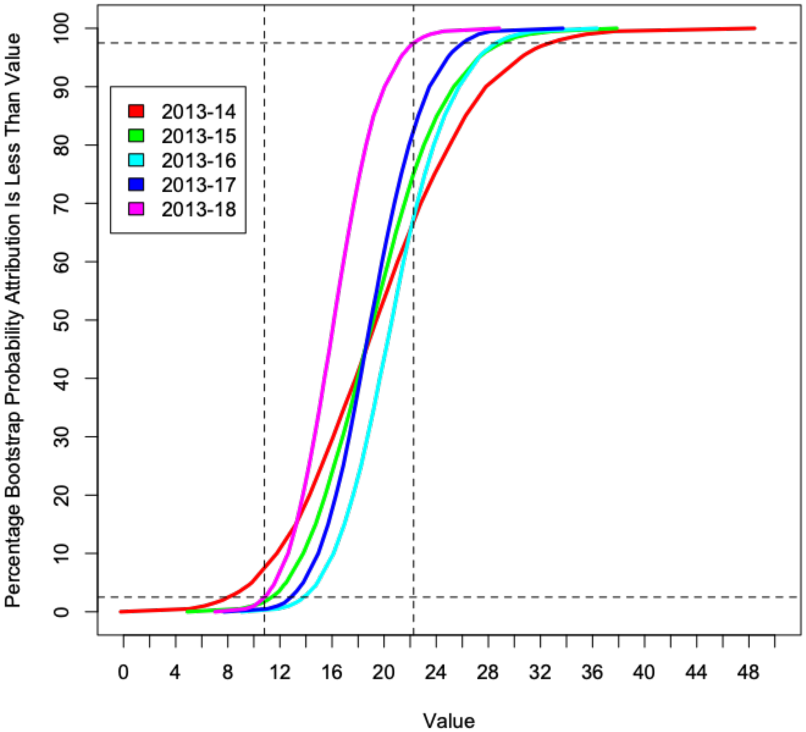
| Year | Estimated Enhancement for Year | Standard Error of Estimated Enhancement | Bootstrap Probability of a Positive Enhancement for Year |
|---|---|---|---|
| **2013** | 18.1 per cent | 1.7 per cent | 100 per cent |
| **2014** | 16.4 per cent | 2.6 per cent | 100 per cent |
| **2015** | 15.5 per cent | 2.7 per cent | 100 per cent |
| **2016** | 15.9 per cent | 2.6 per cent | 100 per cent |
| **2017/18** | 17.7 per cent | 9.9 per cent | 99.4 per cent |

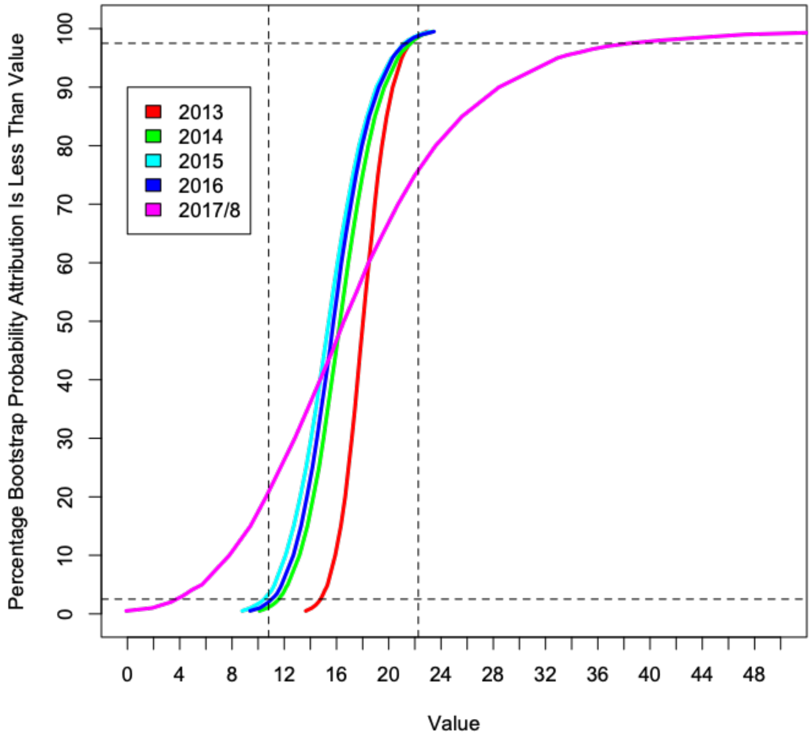
**Annual estimates of Atlant attribution 2013 - 2018.**

# + Summary and Conclusions

- Two graphs below allow one to read off the "risk" of claiming enhancement over this six year period was at least equal to a claimed value, and are obtained by cumulating the bootstrap distribution of attribution.

- There is virtually zero risk of being wrong in claiming positive enhancement each year, while there is considerable risk of being wrong if one tried to claim enhancement of 30 per cent or more. The area defined by the dotted lines in each graph is the 95 per cent bootstrap confidence region for 2013-2018 attribution.



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- There are alternative methods of rainfall enhancement (e.g. aerial cloud seeding). Although there is no argument that these methods can work, it seems clear that the use of ground-based ionization (e.g. via Atlant) currently offers a unique combination of:
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  - Scientifically demonstrated validity and efficacy.
    - In particular, no comparable results are currently available for alternative rainfall enhancement methods.

- However the climatic conditions that underpin summer rainfall in the Hajar Mountains of Oman are relatively unique. Ideally further experimentation using Atlant type (i.e. ground-based ionization) methods in different environments is necessary.

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  - Placement;
  - Operation; and
  - Improvements to the design of the Atlant technology.

- This investigation of increased efficiency should be driven by hydrological impact, i.e. increased rainfall that leads to significant contributions to local aquifers.
  - How does “interesting” rainfall in gauges become useful rainfall in the ground?

# + Summary and Conclusions

- **Next Steps**

- Preliminary results for the Salalah region in 2018 have been inconclusive, mainly because the experimental design used there in 2018 lacked sufficient power to identify an enhancement effect.

- There needs to be a significant commitment of resources to a more powerful design for this area, along the lines of that used in the Hajar Mountains, and over a similar time frame, if provision of conclusive evidence for an enhancement effect in this very different environment is the aim.