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Atmospheric moisture measurements explain increases in tropical rainfall extremes

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Key Points

1. Negative scaling in the tropics can be explained by the limitation of temperature due to evaporation.
2. Extreme rainfall is found to scale consistently with integrated water vapour regardless of location.
3. Global warming can be expected to bring higher extreme rainfall events in all locations, including the tropics.

Plain Language Summary

Rainfall scaling studies have been used to understand how we can expect extreme rainfall intensities to change under a warming global climate. Previous studies have consistently found negative scaling in the tropics which contradicts the expectations that higher temperatures will result in more extreme rainfall and greater flood risk. This study shows that the negative scaling rates calculated in previous research may be caused by a limitation of temperature especially in climates with a surplus of moisture. It is reasoned that when moisture is available, excess heat results in more evaporation as opposed to an increased air temperature, forcing temperature to remain below a nominal upper limit. The study was

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performed using satellite data for integrated water vapour to give an accurate relationship between extreme rainfall and atmospheric moisture, as well as between surface air temperature and atmospheric moisture.

Abstract

Anthropogenic climate change is increasing extreme rainfall as a result of increased water holding capacity of the atmosphere due to higher temperatures. However, the observed rainfall-temperature scaling relationships often differ from the theorised increases in moisture holding capacity. This discrepancy is most evident in tropics, where higher surface temperatures show a marked decrease in extreme rainfall intensity despite observed increases in extreme rainfall.

Here, we use atmospheric moisture measurements from NASA's Atmospheric Infrared Sounder (AIRS) with surface measurements to investigate the tropical rainfall-temperature scaling relationship. We show rainfall intensity scales positively with integrated water vapour in all regions. Further, integrated water vapour does not consistently scale positively with surface air temperature and its dependence on background temperature offers a physical explanation for the apparent negative scaling. We conclude the inconsistent relationship between surface air temperature and moisture is the reason for the 'apparent' negative scaling consistently found in the tropics.

1. Introduction

It is generally accepted that as our climate warms, extreme rainfalls will intensify (Craig, 2010). Such predictions are based on the physical reasoning that the atmospheric moisture holding capacity will increase at an exponential rate as governed by the Clausius-Clapeyron (C-C) relation (Trenberth et al., 2003). Due to this thermodynamic relationship between moisture and temperature, temperature has been used to infer how rainfall extremes may change with increasing temperatures (Agilan & Umamahesh, 2017; Allen & Ingram, 2002; Lenderink & Attema, 2015). With observational measurements of temperature and rainfall intensity, the observed rainfall can be paired with the concurrent temperature to calculate an observed scaling rate. This scaling represents a percentage increase in rainfall per degree increase in temperature and circumvents the need for extensive historical records. However, the observed scaling rate often differs from the exponential rate governed by the C-C relation.

Global studies using historical observations have consistently found that extreme rainfall decreases with near surface air temperature in the tropics and warmer climatic regions (Maeda et al., 2012; Utsumi et al., 2011; Wasko et al., 2016). These results are usually termed so-called ‘negative scaling rates’, meaning that extreme rainfall decreased with higher near-surface air temperature. Negative scaling rates challenge the notion that extreme rainfall will increase as near surface air temperature increases and contradict observational studies which have shown increased tropical precipitation extremes (O’Gorman, 2015). It is of interest to understand whether the extreme negative scaling observed for stream flows (more negative than that for precipitation) in the tropics could be a result of the use of an improper covariate (Sharma et al., 2018).

A unifying reason for why this negative scaling is observed has not yet been established. For example, the reversal from positive to negative in scaling above 26 degrees Celsius has been suggested to result from limited moisture availability (Hardwick Jones et al., 2010). This switch at high temperatures appears to be consistent in both the tropics and non-tropics (Wang et al., 2017). It has also been theorised that negative scaling is an outcome of the correlation between reduced rainfall and increased sunshine. The increased sunshine heats the surface soil, resulting in warmer surface air temperatures (Trenberth & Shea, 2005). The negative scaling is suggested to be the result of arid surface conditions (Drobinski et al., 2016). Surface air temperature was found to be a poor correlator of the atmospheric temperature of condensation. This disjoint is inflated in arid conditions and thus contributes to the lower rainfall intensity found at higher surface air temperature (Drobinski et al., 2016).

Others have suggested that the local cooling associated with the rainfall event is the cause of the negative scaling (Bao et al., 2017). It is shown that this local cooling effect is particularly pronounced in warmer climates as colder climates have typically more background variably in temperature. This ‘cooling effect’ has been mitigated by using the atmospheric temperature at 850hPa pressure from reanalysis products in place of the surface air temperature (Ali & Mishra, 2017), though the ‘cooling effect’ of rainfall events causing the apparent negative scaling has been refuted (Barbero et al., 2018). As the mechanism behind this switch in scaling relationship is not fully understood, alternatively, dew point temperature (DPT) has been used as a measure of the moisture of the atmosphere. This, to an extent, circumvents the inconsistent results obtained by scaling precipitation intensity with surface temperature with more positive scaling results obtained (Ali et al., 2018; Lenderink et al., 2011; Lenderink & Van Meijgaard, 2010; Panthou et al., 2014;Wasko et al., 2018).

A gridded observational study covering the European land mass demonstrated that the scaling rate of extreme daily precipitation with daily temperature is positive in winter, and negative in summer (Berg et al., 2009). Sub-daily data has been used to show that the negative scaling found at higher temperatures to be a result of shorter storm durations, but not a decreased intensity during those storms (Utsumi et al., 2011). Further it was found that embedded short duration storm bursts within longer storm durations will result in negative scaling (Wasko et al., 2015). Although the observed positive scaling rates have links to the increases in extreme rainfall (Westra et al., 2013), overall, the observed negative scaling in the tropics is in contrast to research that has found extreme rainfall to be robustly increasing in all regions across the world over the previous six decades (Donat et al., 2016), and a resulting increased flood risk (Hettiarachchi et al., 2017).

Rainfall scaling studies however may also identify scaling rates above C-C. For example, using a 99-year record of observations from a study site in the Netherlands, using sub-daily rainfall data retrieved at hourly intervals, a ‘super’ C-C scaling (above ~7%/°C) was observed. Multiple factors have been proposed to explain deviations in scaling rate above 7%/°C, such as storm intensification due to latent heat release (Lenderink & Van Meijgaard, 2008; Trenberth et al., 2003), or, a proportional shift to convective storm systems (Haerter & Berg, 2009). Also, a shift in rain type to increasingly convective storms at higher temperatures has been suggested, thus altering the expected scaling relationship (Berg et al., 2013).

Previous research on rainfall scaling has largely relied on ground observational data, climate models or reanalysis datasets to study extreme rainfall introducing possible artefacts in the scaling relationship. In this paper we retrieve the Atmospheric Infrared Sounder (AIRS) satellite data (Aumann et al., 2003; Susskind et al., 2014; Tobin et al., 2006) to obtain observational recordings for atmospheric moisture content. The AIRS satellite provides the unique opportunity, for the first time, to analyse observational atmospheric climate data to further our understanding of negative scaling. Previous research has relied on assumptions regarding the relationship between surface air temperature and the moisture holding capacity of the atmosphere to predict extreme rainfall.

The relationship between atmospheric water vapour and rainfall intensity has been previously examined to find a ‘peak’ relationship. Atmospheric radiation measurements have been analysed to show a dependence of rainfall on Integrated Water Vapour (IWV) (Neelin et al., 2009; Schiro et al., 2016). Other rainfall parameters were shown to increase with IWV such as mean cluster size and radius of gyration of the rainfall event (Peters et al., 2009) which supports the overall influence of IWV on rainfall.

In this paper, we directly investigate the relationship between Surface Air Temperature (SAT) and IWV, as well as the relationship between IWV and rainfall using observational measurements. Ultimately, this paper seeks to answer the question: Why do tropical extreme rainfalls scale negatively with higher temperatures?

2. Data and Methods

The Atmospheric Infrared Sounder (AIRS) satellite data (Version 6) provides a global coverage for both temperature and moisture. AIRS Data is publicly available for academic research at National Aeronautics and Space Administration (NASA), http://acdisc.gsfc.nasa.gov/opendap/Aqua_AIRS_Level3/. Moisture levels are recorded at 100 different pressure levels in the vertical air column. This has been combined into a Total Air Moisture, or Integrated Water Vapour (IWV) value for each grid square with units kg/m^2. The spatial coverage is a 1-degree by 1-degree grid over the earth’s surface. The satellite does two daily pole-to-pole passes at 1:30 and 13:30 local solar time, each day (Aumann et al., 2003; Susskind et al., 2014; Tobin et al., 2006) The AIRS data achieves 1K root mean squared errors in 1km layers below 100 hPa for temperature and 10% root mean squared errors for moisture concentration. Temperature and moisture observations agree with radiosonde measurements (Divakarla et al., 2006).

Each of the 109 ground weather stations used in this study are matched with the 1-degree latitude by 1-degree longitude grid square in which it resides with respect to the AIRS data. The two daily recordings of the AIRS data correspond to the two daily orbits of the AIRS satellite. The mean daily IWV is calculated as the average of the two swathes. This results in a database with corresponding average daily temperature, daily rainfall and average daily IWV.

This data is combined with daily surface rainfall and SAT data from the Australian Bureau of Meteorology weather stations. The weather station data retrieved was restricted to stations containing rainfall and temperature observations from 2002 to 2015 to match the AIRS data. Weather station data was required to contain over 97% of records flagged for acceptable quality control. This totalled 109 individual weather stations from mainland Australia. Our use of Australian data allows us quality data from a large variety of climates. This includes tropical, warmer regions in the north, temperate regions to the south and east, and arid, desert regions in central Australia. Station rainfall measurements are taken daily at 9:00 am. This value represents the rainfall that occurred at the station in the 24 hours preceding the measurement. Similarly, the daily average SAT is used. This has been calculated by averaging the maximum and minimum daily surface temperatures that occurred in the 24 hours preceding the 9:00 am measurement.

Quantile regression is used to assess the scaling relationships between climate variables (Wasko & Sharma, 2014). Quantile regression provides a statistical method to calculate the scaling rate that is unbiased to sample size. Quantile regression differs from linear regression as it minimizes the absolute deviation of the errors with a weighting of p for under prediction and $(1-p)$ for over prediction. The following description of quantile regression follows (Hao & Naiman, 2007):

Consider a set of data pairs (x_i, y_i) for $i = 1, .., n$ where x_i represents SAT observations and y_i gives rainfall. The quantile regression can be expressed as:

$$y_i = \beta_0^{(p)} + \beta_1^{(p)} x_i + \epsilon_i^{(p)}$$

where $0 < p < 1$ is the quantile and ϵ_i is an error term with zero expectation. The parameters $\beta_0^{(p)}$ and $\beta_1^{(p)}$ are chosen to minimize a cost function D, defined as:

$$D\left(\beta_0^{(p)}, \beta_1^{(p)}\right) = p \sum_{y_i \geq \beta_0^{(p)} + \beta_1^{(p)} x_i} |y_i - \beta_0^{(p)} - \beta_1^{(p)} x_i| + (1-p) \sum_{y_i < \beta_0^{(p)} + \beta_1^{(p)} x_i} |y_i - \beta_0^{(p)} - \beta_1^{(p)} x_i|$$

For this study the slope of the scaling relationship will be given by $\beta_1^{(p)}$. For rainfall, we have taken the log of the daily measurements in mm (Lenderink & Van Meijgaard, 2010). The slope $\beta_1^{(p)}$is transformed $100 \times (e^{\beta_1^{(p)}} - 1)$ to give the scaling rate as a % increase/decrease per degree Celsius when scaling rainfall against temperature. This methodology is also used to calculate a scaling between IWV and rainfall intensity as well as IWV and SAT.

3. Results

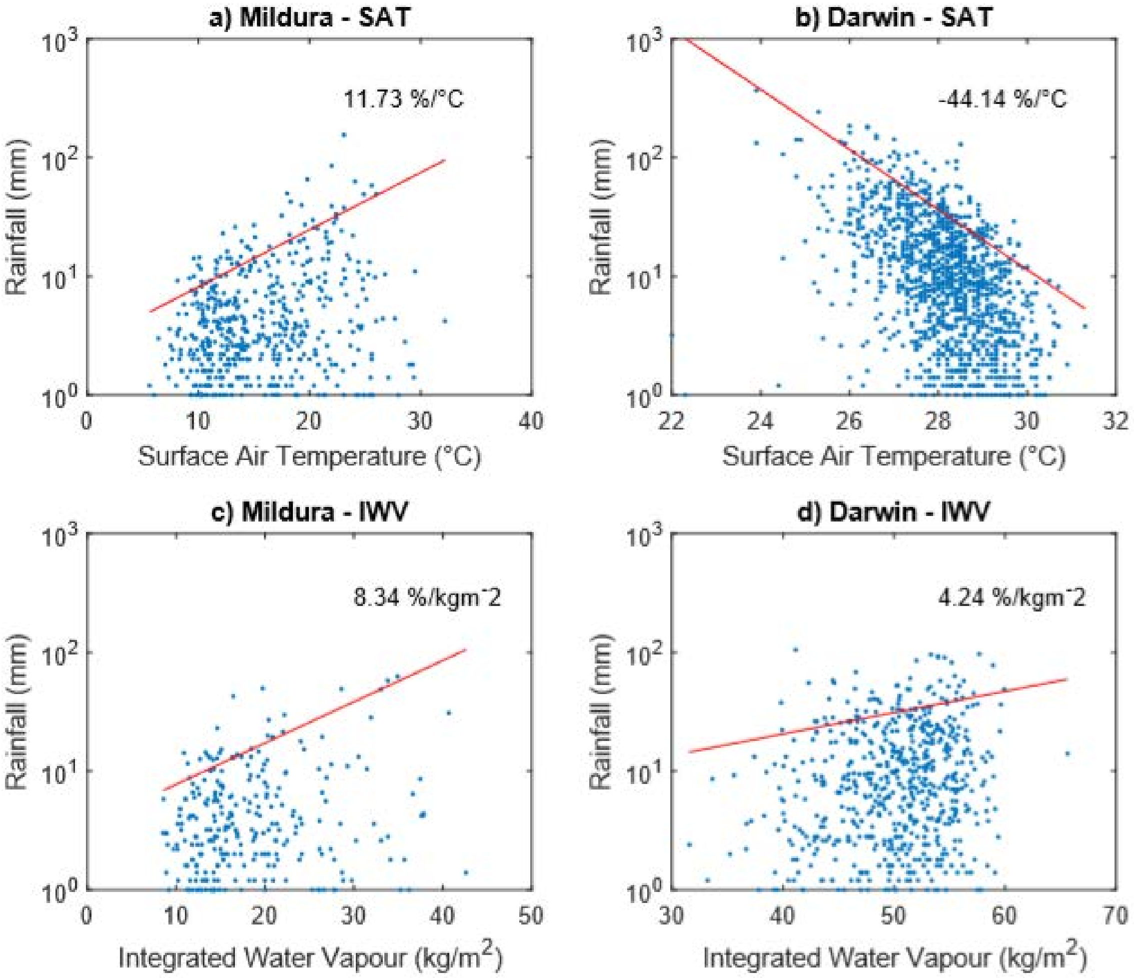

Figure 1. 90th percentile scaling of Rainfall against both SAT and IWV for Mildura Airport and Darwin Airport. a) Rainfall Intensity against SAT for Mildura Airport (%/°C). b) Rainfall Intensity against SAT for Darwin Airport (%/°C). c) Rainfall Intensity against IWV for Mildura Airport (%/kgm^2). d) Rainfall Intensity against IWV for Darwin Airport (%/kgm^2).

The scaling relationship between extreme rainfall intensity, SAT and IWV at two locations, one tropical (Darwin Airport, Stn:014015, Latitude: -12.4239°, Longitude: 130.8925°) and one non-tropical (Mildura Airport, Stn:076031, Latitude: -34.2358°, Longitude: 142.0867°)

are shown in Figure 1. Each plotted point represents a paired observation of daily rainfall volume and the corresponding daily averaged temperature. The red line shown in Figure 1 represents the calculated scaling rate. The Mildura Airport scaling for the 90th percentile between rainfall and SAT (Figure 1a) displays the typical expected positive relationship with a rate of 11.73%/°C increase in extreme rainfall intensity with each degree increase in temperature. However, at Darwin Airport (Figure 1b) the relationship is strongly negative (-44.14%/°C). This highlights the sharp decrease in extreme rainfall intensity with increasing temperatures we observe in tropical regions, which is in contrast to the observed increases in precipitation extremes in tropics.

Table 1. Percentage increase in mean yearly maximum daily rainfall from 1950-1980 to 1981-2014 for Mildura and Darwin Airport. Only days with rainfall exceeding 1 mm are considered for this analysis.

LOCATION	1950 – 1980	1981 - 2014	INCREASE
MILDURA AIRPORT	35.6 mm	38.9 mm	9.36 %
DARWIN AIRPORT	121.1 mm	144.9 mm	19.71 %

To highlight this, present extreme rainfall trends over time (Table 1). We find the yearly maximum rainfall intensity to be increasing in both Darwin and Mildura, consistent with previous research (Guerreiro et al., 2018). From the period 1950-1980 to the period 1981-2014, rainfall extremes increase at both locations. In our globally warming climate, such increases in rainfall extremes are observed in both the tropics and non-tropics (Donat et al., 2016). This opposes the relationship shown by scaling rainfall intensity against SAT, as, if it was to be used for prediction, a decrease in extreme precipitation intensity would result with higher temperatures.

To overcome the inconsistency of using SAT as a scaling covariate we have scaled rainfall intensity against IWV, derived using AIRS retrievals (Figure 1c, Figure 1d). The scaling ascertained for the 90th percentile (similar to the SAT results earlier) shows a positive scaling rate for both weather stations. Mildura Airport rainfall intensity scaled against IWV at a rate of 8.34%/kgm^{-2}. Darwin airport had a similarly positive rate of 4.24%/kgm^{-2}. It appears consistent that increased IWV results in higher extreme rainfall intensities across both locations of vastly varying climates. This is expected as a higher volume of integrated water vapor is intuitively a strong factor in the formation of extreme rainfall events.

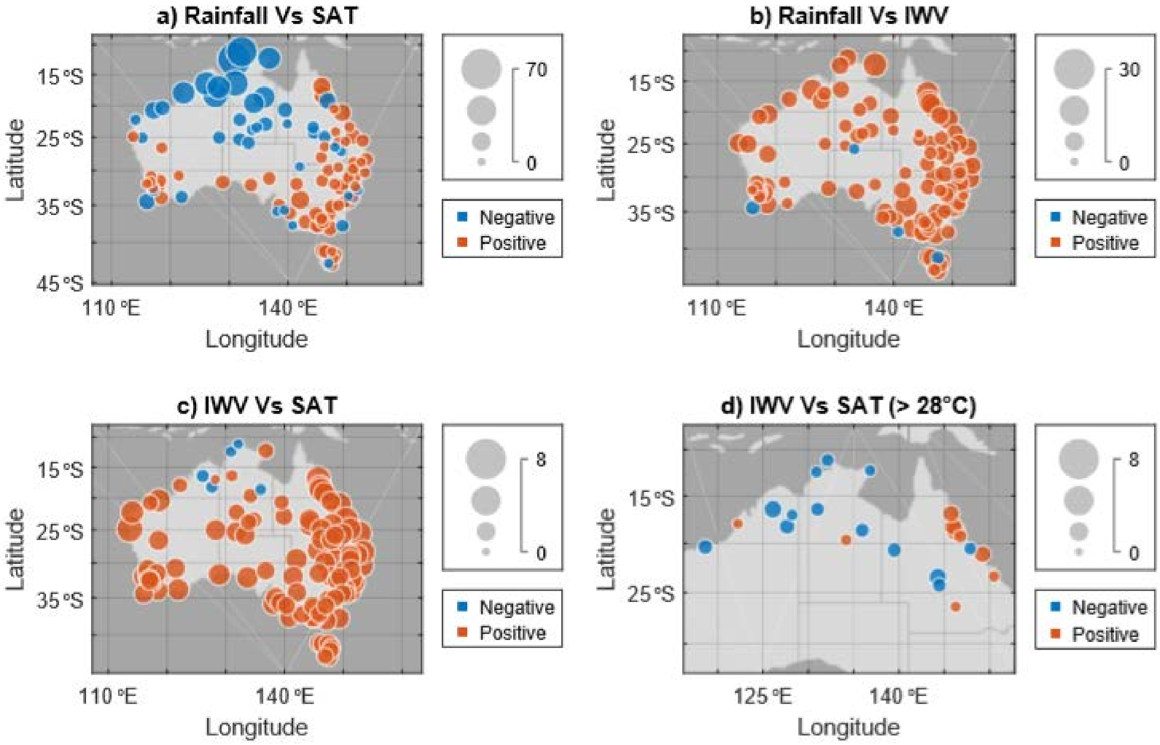

Figure 2. 90th percentile scaling of Rainfall, SAT and IWV for 109 weather stations in Australia from 2002 to 2015. a) Rainfall Scaling against SAT (%/°C). b) Rainfall Scaling against IWV (%/kgm^{-2}). c) IWV scaling against SAT (kgm^{-2}/°C). d) IWV scaling against SAT for daily SAT above 28°C (kgm^{-2}/°C) focused on tropical regions. Only days with rainfall exceeding 1 mm are considered. 100 wet days required for scaling rate to be shown in panel (d).

The 90th percentile scaling relationship between daily rainfall intensity and daily average SAT (Figure 2a) shows great variability over the 109 Australian weather stations. The magnitude of the sphere indicates the scaling rate and the colour gives the sign (positive or negative). The relationship between extreme rainfall and SAT is found to be in general agreement with previous studies (Wasko et al., 2016). Typically, a positive scaling rate has been observed in the colder subtropical regions and a negative scaling rate in hotter tropical regions. There is considerable variability in this plot, and the results are not consistent with the expected increase in rainfall extremes, thus not providing a reliable indication of the expected rainfall intensities with rising SAT.

The plot of rainfall intensity against IWV (Figure 2b) shows the relatively constant positive relationship between rainfall intensity and IWV. This relationship appears robust and independent of spatial location or local climatic temperature. It is also robust across arid, central location and the wetter coastal regions. This relationship appears consistent across Australia and confirms that a higher IWV is required for extreme rainfall to occur. The theory proposed to explain rainfall scaling outlines that higher SAT increases the moisture holding capacity of the atmosphere and will therefore result in an increased rainfall intensity (Soden & Held, 2006). In Figure 2b, Rainfall vs IWV shows atmospheric moisture and rainfall to scale positively in all locations, thus we can conclude that negative scaling observed in the tropics is likely a result of the relationship between SAT and atmospheric moisture.

IWV scales generally positively against SAT (Figure 2c) for the 90th percentile in the 109 weather stations analysed. However, a negative scaling rate with SAT is found for some stations located in northern Australia. For the negative scaling stations, a higher SAT corresponds to a lower IWV. When the scaling IWV against SAT is restricted to the days above 28 degrees Celsius (Figure 2d), we find a definite switch in the scaling relationship. This is evidence to where the relationship between extreme rainfall intensity and SAT breaks down. Figure 2d shows that at higher temperatures (>28 °C), an increase in SAT does not correspond to an increase in IWV, demonstrating that using SAT is responsible for negative scaling has been found across the tropics in past studies. Results for scaling against the 99th and 99.9th percentiles were found to be in general agreement with the 90th percentile scaling providing a broad analysis of extreme events. Extreme rainfall intensity is evidently an outcome of an increased IWV. At higher SAT's we observe a marked decrease in IWV, thus a decrease in overall precipitation. This physical relationship results in the apparent negative scaling found when scaling extreme rainfall against SAT in the tropics.

4. Discussion and Conclusions

SAT has been plotted against IWV in Figure 3 for all stations over the 13-year period. At lower temperatures, IWV capacity rises with SAT. However, for higher SAT, there is no longer an increase in IWV. This is congruent with the negative scaling shown in Figure 2d. There appears to be a limitation to the SAT and IWV relationship in warmer climates, thus creating the negative scaling observed between temperature and IWV for SAT's above 28 °C.

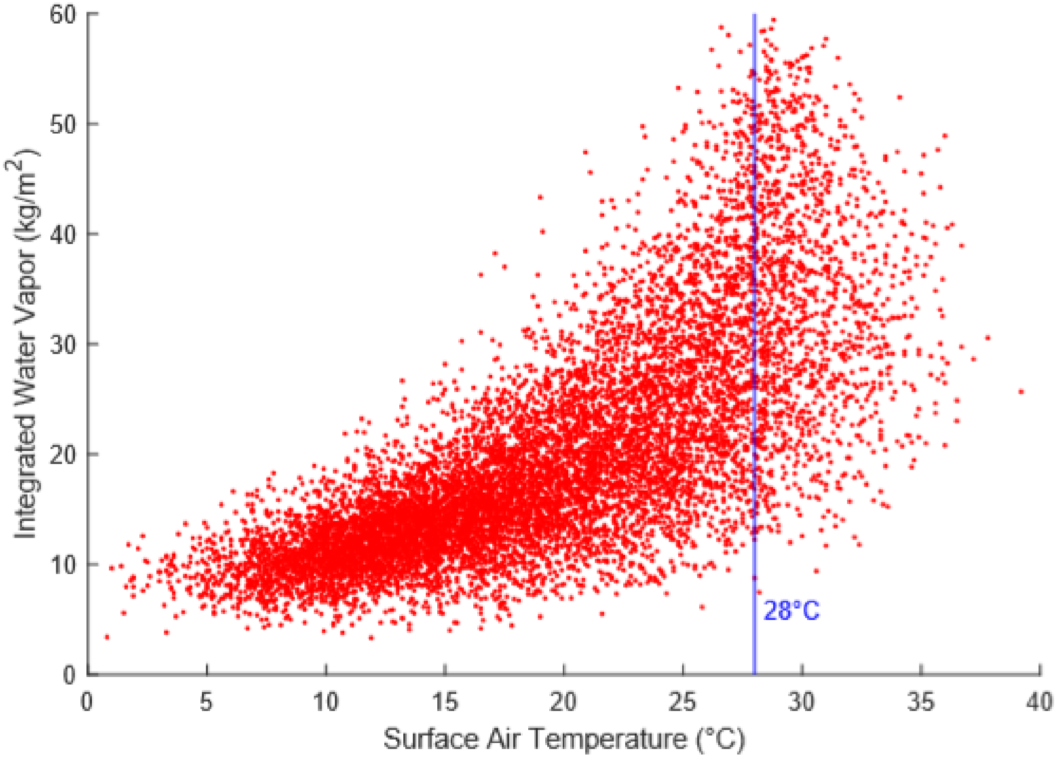

Figure 3. Scatter plot of IWV (kg/m2) against SAT (°C) for all 109 weather stations from 2002 to 2015.

As extreme rainfall is strongly correlated with increased IWV (Figure 2b) we can conclude that high temperature days have lower IWV and therefore less extreme rainfall. This reduction in rainfall intensity at higher temperatures results in the negative scaling rates found in warmer climates between temperature and rainfall consistent with previous studies (Hardwick Jones et al., 2010) which suggest that the negative scaling occurs above a specific temperature threshold.

This relationship between SAT and IWV can be explained by the limitations of temperature by evaporation in hot climates (Priestley, 1965). Priestley introduces the notion that temperature is limited in warmer climates by the balance of latent and sensible heat. When surface moisture is available, and SAT is elevated, temperature will remain relatively constant and additional heat will result in increased evaporation. Extreme temperature days are a result of insufficient surface moisture; therefore, additional radiation on very hot days is converted to sensible (and not latent) heat (Yin et al., 2014). This clarifies why higher temperature days often have lower IWV as there is insufficient surface moisture available for evaporation and thus less moisture in the air. The reduced IWV then leads to lower extreme precipitation and thus results in observational data of low rainfall on higher temperature days. This creates the apparent negative scaling found at higher temperatures. Our hypothesis aligns with Drobinski, who has attributed the negative scaling found at higher temperatures to be a result of arid surface conditions (Drobinski et al., 2016).

SAT does not appear to be a suitable surrogate for the prediction of future rainfall intensity as it opposes the observed increases in rainfall in the tropics (Bao et al., 2017; Donat et al., 2016). Several variables such as atmospheric temperature and dew point temperature have been considered and while performing better then SAT do not give a robust relationship to model future extreme rainfall (Ali & Mishra, 2017; Barbero et al., 2018). A new variable for future expected scaling should be investigated to forecast increasing rainfall intensities into the future. This covariate should follow a predictable relationship with rainfall intensity.

In this study, satellite measured atmospheric moisture was analysed to find that IWV increases with higher SAT, contrasting with the accepted observation that rainfall does not increase with SAT. The analysis here suggest that the negative scaling rates found in preceding research could be an outcome of the limitations of temperature in climates with a surplus of moisture (Priestley, 1965) and not reflective of future rainfall. Anthropogenic climate change will likely increase latent heat in the tropics, resulting in increased air moisture and thus increased extreme rainfall intensity.

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Surface rainfall and temperature data can be obtained from the Australian Bureau of Meteorology and can be found at www.bom.gov.au/climate/data/stations/. The AIRS data can be obtained from the NASA Goddard Earth Sciences Data Information and Services Center (GESDISC) and can be found at https://airs.jpl.nasa.gov/data/get_data

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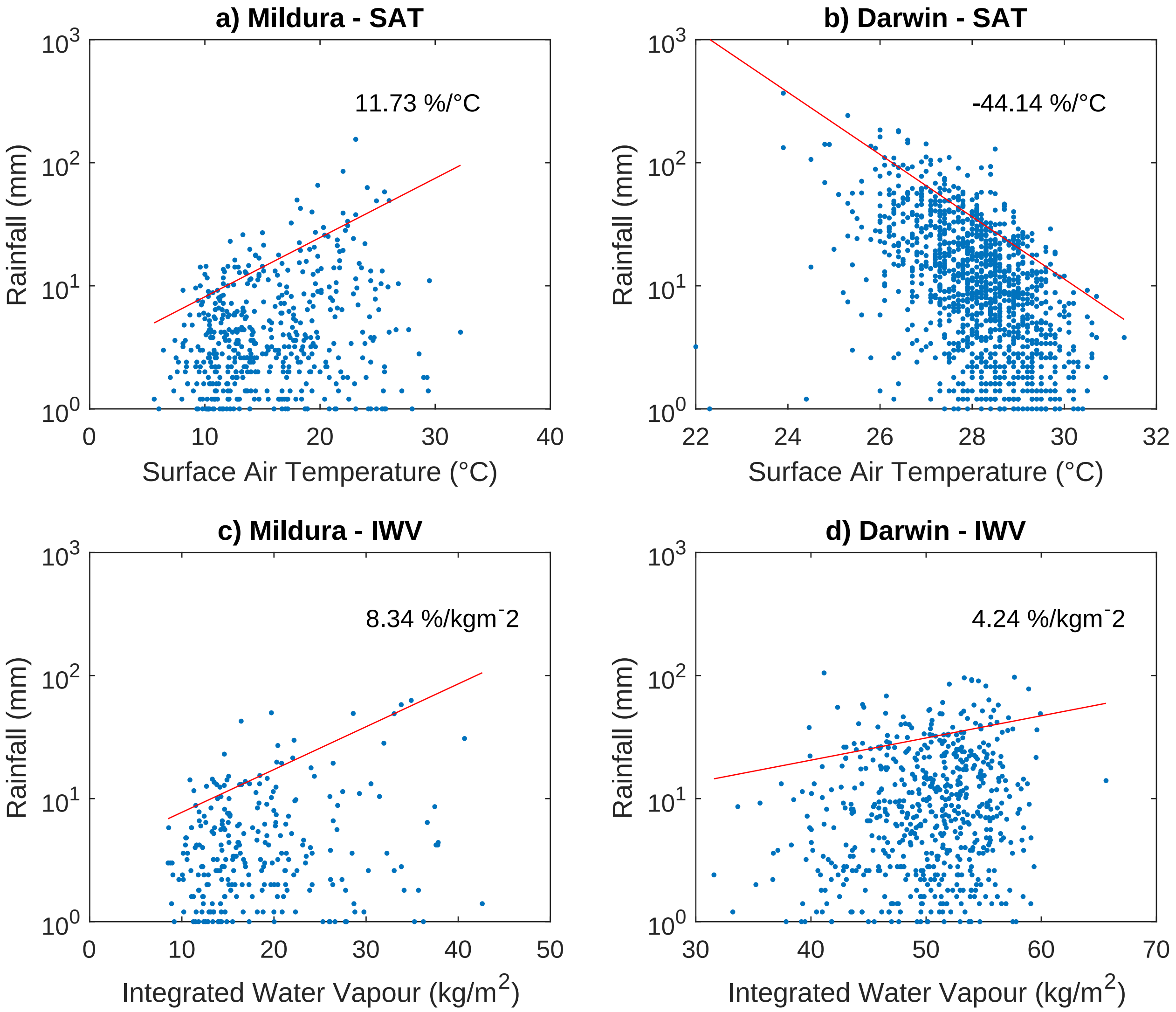
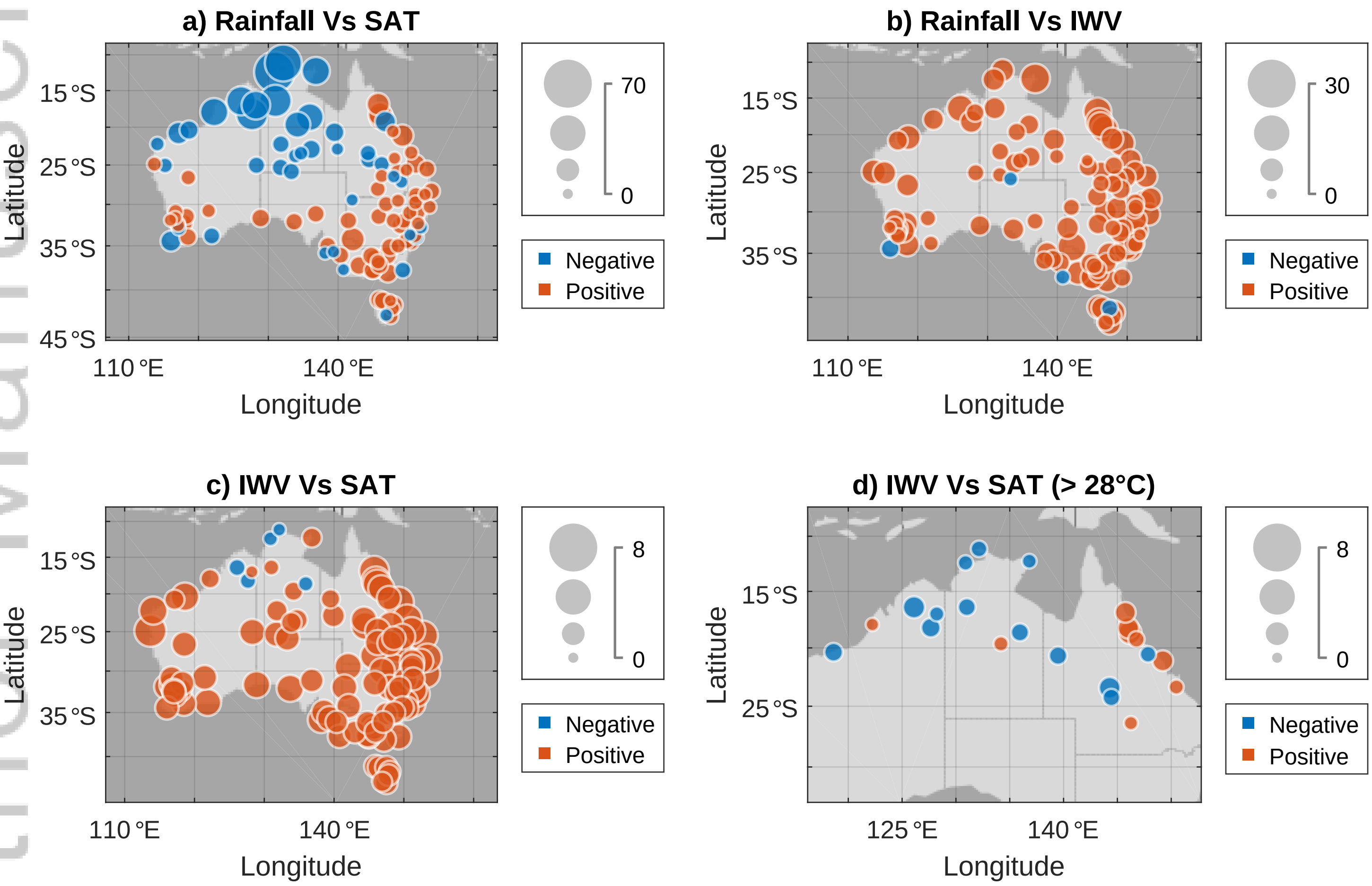
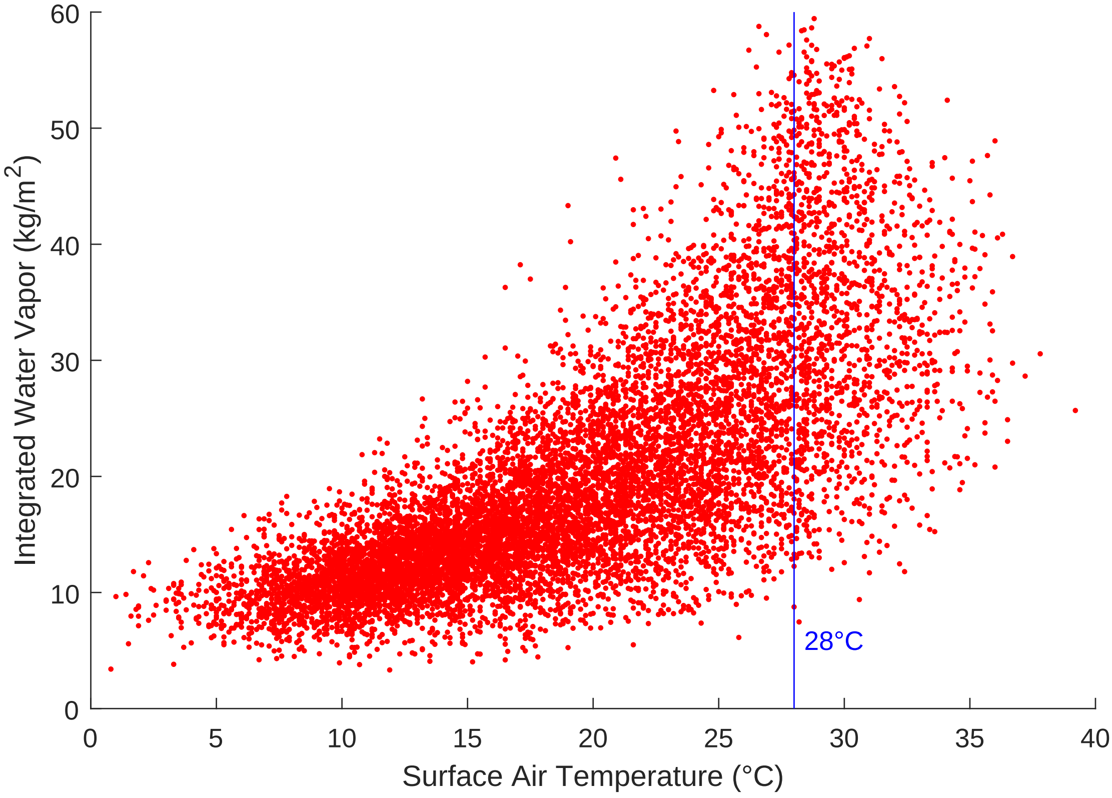

a) Mildura - SAT
11.73 %/°C
Rainfall (mm)
Surface Air Temperature (°C)
b) Darwin - SAT
-44.14 %/°C
Rainfall (mm)
Surface Air Temperature (°C)
c) Mildura - IWV
8.34 %/kgm-2
Rainfall (mm)
Integrated Water Vapour (kg/m2)
d) Darwin - IWV
4.24 %/kgm-2
Rainfall (mm)
Integrated Water Vapour (kg/m2)
10^0
10^1
10^2
10^3
0
10
20
30
40
50
22
24
26
28
30
32
60
70


a) Rainfall Vs SAT
15 °S
25 °S
35 °S
45 °S
Latitude
110 °E
140 °E
Longitude
70
0
Negative
Positive
b) Rainfall Vs IWV
15 °S
25 °S
35 °S
Latitude
110 °E
140 °E
Longitude
30
0
Negative
Positive
c) IWV Vs SAT
15 °S
25 °S
35 °S
Latitude
110 °E
140 °E
Longitude
8
0
Negative
Positive
d) IWV Vs SAT (> 28°C)
15 °S
25 °S
Latitude
125 °E
140 °E
Longitude
8
0
Negative
Positive


Integrated Water Vapor (kg/m^2)
Surface Air Temperature (°C)
28°C
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40