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Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity

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[1] Expected changes to future extreme precipitation remain a key uncertainty associated with anthropogenic climate change. Recently, extreme precipitation has been proposed to scale with the precipitable water content in the atmosphere, which assuming relative humidity stays constant, will increase at a rate of ~6.8%/°C as indicated by the Clausius-Clapeyron (C-C) relationship. We examine this scaling empirically using data from 137 long-record pluviograph and temperature gauges across Australia. We find that scaling rates are consistent with the C-C relationship for surface temperatures up to between 20°C and 26°C and for precipitation durations up to 30 minutes, implying that such scaling applies only for individual storm systems. At greater temperatures negative scaling is observed. Consideration of relative humidity data shows a pronounced decrease in the maximum relative humidity for land surface temperatures greater than 26°C, indicating that moisture availability becomes the dominant driver of how extreme precipitation scales at higher temperatures. **Citation:** Hardwick Jones, R., S. Westra, and A. Sharma (2010), Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity, *Geophys. Res. Lett.*, *37*, L22805, doi:10.1029/2010GL045081.

1. Introduction

[2] The changing nature of extreme precipitation as a result of anthropogenic climate change has been the subject of significant recent observational and modelling work [*Groisman et al.*, 2005; *Alexander et al.*, 2006; *Meehl et al.*, 2007; *Allan and Soden*, 2008; *O'Gorman and Schneider*, 2009]. Although many uncertainties remain, it is generally agreed that as temperatures increase, the intensity of heavy precipitation events also will increase in many regions globally, including some regions where average precipitation is expected to decrease [*Meehl et al.*, 2007]. Such projections are based in part on the physical reasoning that the water holding capacity of the atmosphere will increase at an exponential rate governed by the Clausius-Clapeyron (C-C) relationship, and that with only small changes in globally averaged relative humidity [*Soden and Held*, 2006] (see also *Sherwood et al.* [2010] for a discussion of regional changes), the moisture content of the atmosphere will scale at a similar rate [*Trenberth et al.*, 2003]. It furthermore has been argued that due to precipitation rates of individual storms significantly exceeding evaporation rates, moisture sources must be derived from water already in the atmosphere, such that precipitation intensity should also increase with atmospheric temperature at the rate dictated by the C-C relationship.

[3] Despite the obvious appeal of such an argument, trend detection and attribution studies show that while extreme trends appear to be increasing in most regions globally, such increases are not uniform in space [*Groisman et al.*, 2005; *Alexander et al.*, 2006] and thus likely to be driven as much by dynamical changes to circulation patterns as by the thermodynamics encapsulated in the C-C relationship. Furthermore, while the C-C scaling rate often has been used to define an upper-bound to how extreme precipitation might change, higher rates (so-called 'super' Clausius-Clapeyron scaling) have been described as physically plausible by *Trenberth et al.* [2003], and were found empirically by *Lenderink and van Meijgaard* [2008] at a location in De Bilt, the Netherlands, when relating rainfall intensity with land surface temperature. This has been attributed variously to the release of latent heat, which can intensify the storm system and expand the domain over which the storm sources its water [*Trenberth et al.*, 2003; *Lenderink and van Meijgaard*, 2008], or due to the increased prevalence of convective rainfall and decreased prevalence of large-scale rainfall as temperatures increase [*Haerter and Berg*, 2009].

[4] Interestingly, the scaling does not appear to be constant with land surface temperature, with *Lenderink and van Meijgaard* [2008] finding extreme hourly rainfall scaled at a rate consistent with the C-C rate for temperatures between −2°C and 12°C, with super (approximately double) C-C scaling occurring for temperatures between 12°C and 22°C. *Berg et al.* [2009] investigated seasonality of observed daily scaling relationships and the role of large scale vs. convective precipitation (modelled only), and also found significant seasonal variation, with monotonic C-C increases for large-scale events in winter, while moisture availability became increasingly limited in the summer months thus decreasing the scaling rates.

[5] In this paper we reproduce *Lenderink and van Meijgaard*'s [2008] methodology using 137 long pluviograph records located in a wide range of regions across Australia. This large dataset enables a range of outstanding questions to be addressed, including: how robust is the C-C scaling across tropical, sub-tropical, arid and temperature climates at temperatures ranging from ~5°C to >35°C (a much larger temperature range than has been examined in previous studies)? If C-C scaling can only be expected to hold for extreme events, how does the C-C relationship change with increased rarity of the event? And if the scaling only holds for individual storm systems, what is the duration for which this scaling relationship breaks down? Considering furthermore the role of moisture availability, does the assumption of constant relative humidity hold across all temperatures?

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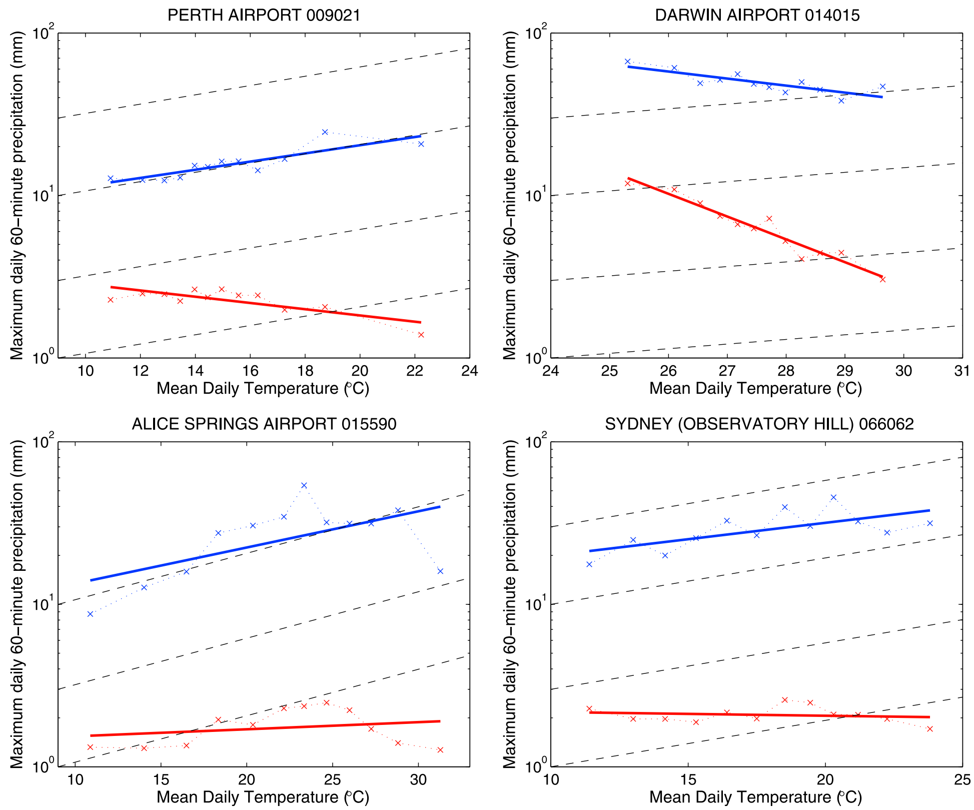

Figure 1. Fiftieth (red) and ninety-ninth (blue) percentile maximum 60-minute precipitation on wet days, showing raw data (dashed) and exponential regression (solid). Dashed black lines indicate C-C-like scaling of 6.8%.C$^{\circ-1}$.

Each of these questions will be considered in the sections that follow.

2. Data and Methods

[6] We analyse the Australian Bureau of Meteorology weather station dataset where both sub-daily pluviometer measurements of precipitation as well as temperature measurements are available. Measurements of relative humidity are also considered at certain stations. In total, this dataset includes observations from 1362 stations on mainland Australia and Tasmania. Our analysis focuses on the 137 stations which have precipitation records longer than 10 years and which are more than 90% complete after missing data or accumulations have been removed. The mean/median precipitation record length of these stations is 32.6/31.9 years, with a mean completeness of 94%. Measured precipitation depths are reported at 6-minute intervals.

[7] At each station for a given precipitation duration, the maximum recorded precipitation depth on each wet day (defined as >0.1 mm) is paired with the daily mean air temperature at 2 m above ground level. Maximum daily air temperature also was used, and the results found to be consistent with mean daily temperature and thus not reported further here. The frequency of temperature measurements varies from twice-daily to every three hours. The observed ranges of mean daily temperature were found to be primarily driven by seasonal variability. Where available, the mean relative humidity on wet days is also extracted. The precipitation-temperature pairs are placed in 12 bins according to temperature, with an equal number of samples in each bin, and therefore varying temperature ranges for each bin. The median temperature of the events in each bin is used as the representative temperature for that bin. This approach was preferred over using temperature bins of equal width, as it ensures a reasonable number of events across all bins, whereas the use of even-width temperature bins results in sparse sampling for bins in the upper- and lower-range of temperatures. The median number of recorded pairs for each station is 2800, corresponding to 233 events per temperature bin. Within each bin, precipitation intensities are ranked to determine the 50th and 99th percentiles.

[8] An exponential regression is applied to the precipitation values for each percentile (by fitting a least-squared linear regression to the logarithm of precipitation depth), where precipitation P is related to change in temperature ΔT as follows:

$$P_2 = P_1(1+\alpha)^{\Delta T}$$

such that $\alpha = 0.068$ is equivalent to Clausius-Clapeyron-like scaling of 6.8%.°C^{-1} at 25°C, obtained using the August-Roche-Magnus approximation for saturated vapour pressure, e_s:

$$e_s(T) = 6.1094 \exp\left(\frac{17.625T}{243.04+T}\right) \text{ for T in °C.}$$

This regression approach assumes a constant scaling across temperature – an assumption we will examine more closely in the following section.

3. Results

[9] Figure 1 illustrates the exponential regression fit for 99th and 50th percentile precipitation at selected sites. As an

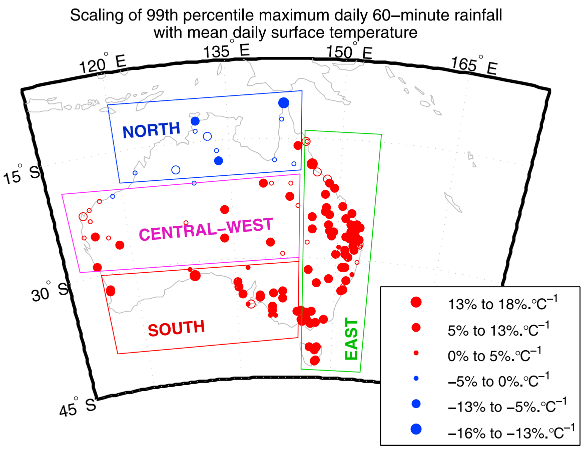

Figure 2. Regional variation of best-fit exponential scaling for 99th percentile maximum 60-minute precipitation on wet days with surface temperature. Red/black/blue indicates positive/neutral/negative scaling, and dot-size increases with the magnitude of the scaling exponent. Solid dots indicate a statistically significant relationship at the 95% confidence level.

initial approximation, the exponential regression appears to give a reasonable fit at most stations, such that the regression parameter α can be used to characterise the scaling and compared to the C-C relationship. Exceptions are noted across parts of central and western regions (e.g., Alice Springs), where the intensity peaks between 20°C to 25°C for both the 99th and 50th percentile and then begins to decline. We observe approximate C-C-like scaling for 99th percentile maximum 60-minute precipitation on wet days at Sydney, Perth and Alice Springs, but negative scaling at Darwin. In contrast, the 50th percentile precipitation shows either neutral or negative scaling. By constructing a spatial map of the fitted α values, we observe significant regional variations for all timescales analysed, with the sites from Figure 1 showing typical scaling behaviour for their region. This is shown in Figure 2, where for the 99th percentile maximum hourly precipitation, C-C like scaling is observed for most of eastern and southern Australia, with sub C-C scaling across central and western regions. Note that solid dots indicate statistically significant scaling at the 95% confidence level. Interestingly, in the tropical north we find that precipitation intensity reduces significantly with mean daily temperature, by more than 13%°C^{-1} at several stations. This negative scaling relationship at tropical locations is a robust feature across all precipitation timescales analysed, regardless of whether mean or maximum daily or instantaneous temperature is used as an indicator.

[10] We next present the intensity/temperature relationships for the 99th percentile maximum 60-minute precipitation for each location in Figure 3 (top), colour coded by region. A moving linear-fit smoother is also applied to summarise aggregate regional behaviour. We observe that there is a noticeable peak structure (similar to that observed by *Berg et al.* [2009]) with C-C scaling or possibly super-C-C

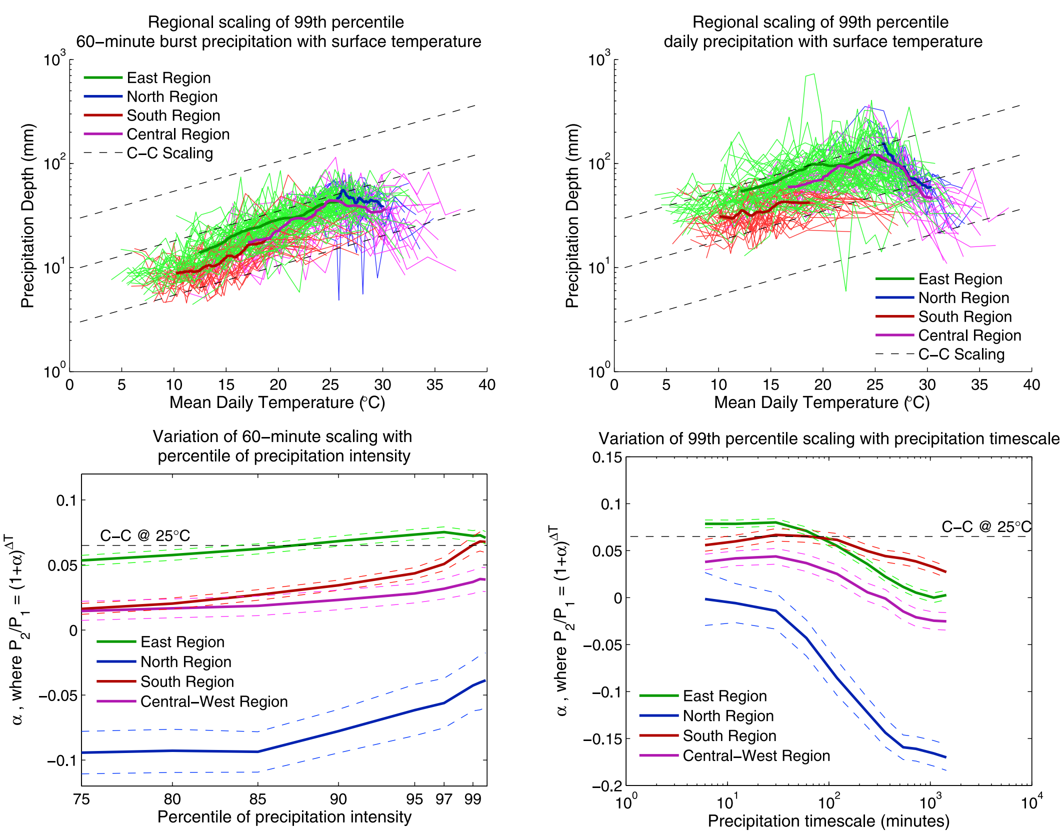

Figure 3. Regional scaling behaviour of (top right) 99th percentile daily precipitation and (top left) maximum 60-minute precipitation on wet days. Thick lines are smoothed regional averages. Variation of the regionally-averaged scaling exponent (bottom left) with percentile of precipitation depth and (bottom right) with precipitation timescale, with dashed lines showing 95% confidence bounds.

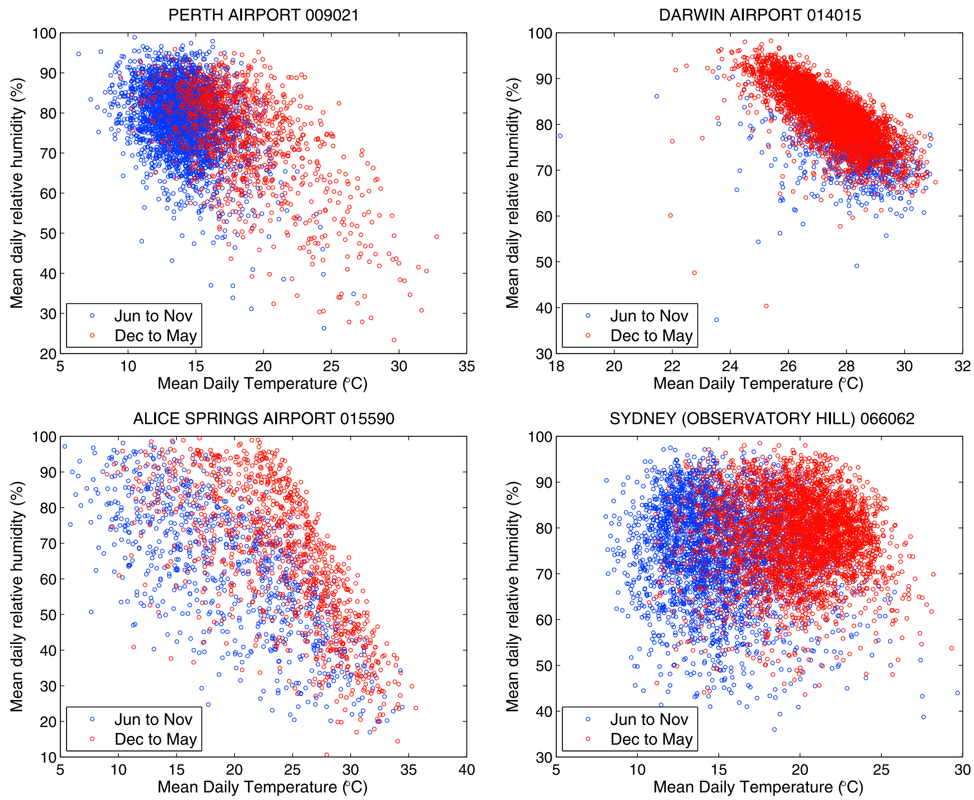

Figure 4. Relative humidity on wet days, separated into winter/spring (blue) and summer/autumn (red).

scaling in some regions for temperatures up to between 20°C and 26°C, and a negative scaling relationship for higher temperatures. The maxima of the smoothed regional precipitation intensity in the temperature range from 20°C and 26°C occurs across all durations and percentiles analysed, and in agreement with *Berg et al.* [2009] except that they find the inflection point at lower temperatures in the range from 15°C and 20°C.

[11] Figure 3 (bottom) shows the dependence of the scaling behaviour on precipitation timescale and percentile, obtained by taking the mean of the scaling parameter α across all stations in each region. Scaling is found to be roughly constant for durations from 6 minutes to 30 minutes and then reduces with longer storm durations. Furthermore, scaling is found to increase with increasing percentile. This result is perhaps to be expected, as for longer timescales or less extreme precipitation fully-saturated conditions are less likely to be present for the full duration of the event, and longer duration rainfall 'events' are more likely to contain dry periods interspersed with the rainfall.

[12] To better understand why negative scaling occurs with temperatures above approximately 20°C to 26°C, we plot relative humidity against temperature for each wet day (Figure 4). As can be seen, although there is significant variability in relative humidity values, at most stations there appears to be a general decrease in relative humidity associated with increasing temperature. Importantly, there appears to be a threshold temperature in the 20°C and 26°C range (with the warmer end of the range for more northerly locations in summer, and the cooler end in more southerly stations in winter), at which the upper bound of relative humidity begins to decline.

[13] It is likely that the observed decline in relative humidity can assist in explaining the negative scaling of extreme precipitation at high temperatures, with the point at which the maximum relative humidity values begins to decline occurring at the same temperature as the point of inflection in the scaling of rainfall intensity. This suggests that attention needs to be placed not only on how much moisture the atmosphere can hold, but on how much moisture is available in the first place. Given the importance of oceans in contributing approximately 85% of the water to the atmosphere [*Bigg et al.*, 2003] and the limited role of soil moisture recycling as a moisture source in arid regions such as for most of the Australian continent [*Koster et al.*, 2004], it is possible that the oceans play a dominant role in supplying the moisture needed to create intense precipitation extremes. The higher maximum temperatures of the land surface compared to the oceans during summer would explain the robust observed decline in maximum relative humidity values at high temperatures, as a saturated parcel of air in equilibrium with the ocean would become sub-saturated above a warmer land surface. This also would explain why both the point at which the maximum relative humidity value begins to decline, and the point of inflection of rainfall scaling with temperature, changes with latitude (ranging from about 20°C at high latitudes through to 26°C at lower latitudes), and with season (increasing by a mean of 3.9°C from winter/spring to summer/autumn, and larger seasonal variation further from the equator). This relationship between extreme rainfall and moisture source regions will require further investigation outside the scope of the present study, including dynamical modelling of extreme precipitation events and better accounting of the moisture source regions for individual storm events. The results presented

here do, however, highlight the limitations of using present day scaling relationships based solely on land-surface temperatures without regard for moisture source region as an indication of how regional extreme precipitation might change in a future climate, particularly in the context of the recent findings of differential warming between land and oceans resulting in a reduction in relative humidity over low- and mid-latitude land areas [*Simmons et al.*, 2010].

4. Discussion and Conclusions

[14] In this study we considered the scaling of wet day rainfall intensity against 2 m mean daily atmospheric temperature at 137 stations across Australia, spanning multiple climate zones. Building on the work of *Lenderink and van Meijgaard* [2008] and *Berg et al.* [2009], we find that while Clausius-Clapeyron scaling still may be useful in understanding the scaling behaviour between precipitation intensity and atmospheric temperature, the reality is likely to be much more nuanced. Specifically, it is evident that:

[15] 1. The scaling relationship varies with the rainfall percentile, with more extreme events showing greater sensitivity to temperature. Although this is unsurprising, as the theory behind C-C scaling is based on extremes rather than average events, the dependence of the scaling with the rarity of the event raises the question of whether greater scaling rates would be observed for the very rare (e.g., 1% annual exceedance probability) events which are often the greatest cause of flood damage.

[16] 2. The scaling relationship also varies with event duration, with a rapid decline with temperature for durations greater than approximately 30 minutes suggesting that such scaling only applies to individual storm cells. This is important as many of the global studies in changes to extreme rainfall focus on daily rainfall data for which long high-quality records are much more abundant, and these may not be expected to show strong trends to the extent expected of shorter-duration storm bursts.

[17] 3. The scaling does not appear to be constant over temperature. In particular, there is a point of inflection in the results shown earlier between about 20°C and 26°C above which the scaling becomes negative. An analysis of relative humidity shows a similar decline in moisture availability at these temperatures, reinforcing the conclusion by *Berg et al.* [2009] that moisture availability becomes increasingly important at higher temperatures.

[18] We conclude by emphasising that care needs to be taken in interpreting these results in the context of anthropogenic climate change. In particular, a relationship between temperature and precipitation intensity does not imply cause and effect, with warmer temperatures potentially being associated with different synoptic systems and thus different meteorological or precipitation regimes (see discussion by *Trenberth and Shea* [2005] in the context of monthly temperature and precipitation; or *Haerter and Berg* [2009] on the relative contribution of convective and large-scale rainfall with changing temperature). In addition, the possibility that moisture availability may act as a limiting agent in the scaling of extreme rainfall at high temperatures suggests that projections of future extreme rainfall intensity in a warmed climate need to consider both the thermodynamics of moisture holding capacity in the atmospheric column, and the dynamics of atmospheric circulation and moisture advection. Finally, the C-C scaling hypothesis considers only the intensity of rainfall events conditional to rainfall occurring, and the study of factors which influence the probability of rainfall occurrence likely will be equally important in governing changes to extreme precipitation in a future climate.

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