LETTER • OPEN ACCESS

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To cite this article: Conrad Wasko et al 2018 Environ. Res. Lett. 13 074031

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Relationship of extreme precipitation, dry-bulb temperature, and dew point temperature across Australia

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Abstract
Precipitation extremes are expected to intensify due to an increased moisture holding capacity in the atmosphere with higher temperatures; according to the Clausius–Clapeyron (CC) relation this increase is approximately 7% for every degree increase in temperature. Contrary to expectation, the relationship between precipitation extremes and surface temperature often differs from 7%/°C. Here, we explore this relationship further by estimating the sensitivity of precipitation with both dry-bulb temperature and dew point temperature across Australia.

A much better correspondence to the CC relation is obtained when surface dew point temperature is used for the calculation of precipitation-temperature sensitivities instead of surface dry-bulb temperature with most sites exhibiting sensitivities close to, or in excess of, the CC relation. The sensitivity obtained using dew point temperature is more consistent across climatic region, precipitation duration, and precipitation percentile. We conclude that dew point temperature is a better measure of precipitation changes due to increases in atmospheric moisture than dry-bulb temperature.

1. Introduction
It is generally accepted that climate change will result in warming in most regions around the world (Collins et al 2013, Meehl et al 2012) increasing the capacity of the atmosphere to hold moisture leading to increased precipitation extremes (Trenberth et al 2003, O’Gorman 2015). Predicted increases in extreme precipitation are generally based on the Clausius–Clapeyron (CC) relation which states that the moisture holding capacity of the atmosphere should increase by approximately 7% per degree increase in temperature, thus increasing extreme precipitation by a similar rate (Trenberth et al 2003, Westra et al 2014). The importance, and great interest, in calculating this relationship in observations of extreme precipitation stems from it providing a tool for debating how future precipitation extremes may vary due to an increase in temperature and what precipitation mechanisms may dominate in a future warmer climate (Boucher et al 2013).

For short duration precipitation extremes, most numerical model studies, including high resolution convection permitting models, simulate near CC sensitivities of extreme precipitation (Muller et al 2011, Chan et al 2016, Kendon et al 2014) despite observed sensitivities twice the CC relation (Lenderink and van Meijgaard 2008). The observation of sensitivities in excess of CC (termed super CC) suggests possible storm intensification (Trenberth et al 2003). Although super CC sensitivities have been observed in some model studies, large uncertainties remain (Bao et al 2017, Zhang et al 2017). Hence many authors focus on understanding how historical precipitation extremes respond to temperature to exploit the higher confidence modelled temperature predictions (Lenderink and Attema 2015, Wasko and Sharma 2017, Westra et al 2014).

A number of studies have calculated observed precipitation-temperature sensitivities for different geographical regions; for example central and western Europe (Lenderink and van Meijgaard 2008, Busuioc et al 2016, Molnar et al 2015, Berg et al 2009), the United Kingdom (Blenkinsop et al 2015), Australia (Hardwick Jones et al 2010, Wasko et al 2015, Herath et al 2018), North America (Mishra et al 2012, Panthou et al 2014, ...
Shaw et al (2011), Japan (Fujibe 2015), South Korea (Park and Min 2017), and India (Ali and Mishra 2017). Very variable sensitivities are presented with little consistency in the observed precipitation-temperature relationship. As precipitation can be caused by different phenomena such as orographic lifting, storm fronts, or local scale convection, the dominant type of precipitation for a region will affect the precipitation-temperature sensitivity (Mishra et al 2012, Berg et al 2013). It has also been shown that the relationship of extreme precipitation with temperature decreases with increasing storm durations (Panthou et al 2014, Wasko et al 2015) and increases with the more extreme precipitation percentile considered (Hardwick Jones et al 2010, Lenderink and van Meijgaard 2008). Sensitivities of extreme precipitation with temperature up to 14%/°C (or double CC) have been observed (Lenderink and van Meijgaard 2008). Despite the suggestion of statistical artefacts due to mixed sampling of convective and stratiform precipitation events (Molnar et al 2015, Haerter and Berg 2009) there is continued evidence for sensitivities in excess of the CC relation (Berg et al 2013, Moseley et al 2013, Lenderink et al 2017, Wasko et al 2015) pointing to storm intensification at higher temperatures (Lenderink and van Meijgaard 2008, Trenberth et al 2003, Wasko and Sharma 2015).

Many regions across the world, particularly warmer climates, exhibit a negative relationship between extreme precipitation and surface temperature (Utsumi et al 2011, Maeda et al 2012, Wasko et al 2016), usually above ~22 °C (Westra et al 2014). This has been attributed to various factors, from humidity limitations at higher temperatures (Hardwick Jones et al 2010, Berg et al 2009) to a positive correlation between days with less cloud and warmer soils increasing surface temperatures (Trenberth and Shea 2005). To overcome humidity limitations, dew point temperature has been used in preference to dry-bulb temperature for calculation of observed precipitation-temperature sensitivities (Lenderink and van Meijgaard 2010, Lenderink et al 2011) resulting in greater consistency with the CC relation (Barbero et al 2018). However, such studies are limited due to fewer dew point measurements (compared to dry-bulb temperatures) and have only been performed in a limited number of regions (e.g. Ali and Mishra 2017, Lenderink et al 2011, Lenderink and van Meijgaard 2010, Park and Min 2017, Panthou et al 2014).

Here, we fill the current gap in the literature of a large-scale study examining the relationship between precipitation and dew point temperature by using Australian precipitation and temperature data, which covers several climatic zones. Our aim is to answer the question: is the observed extreme precipitation-temperature sensitivity more consistent with the CC relationship when dew point temperature is considered instead dry-bulb temperature?

2. Data and methods

The dataset used was obtained from the Bureau of Meteorology of Australia. The daily precipitation data consists of over 17'770 stations, the sub-daily precipitation data consists of 1489 stations, and the sub-daily temperature data 1830 stations. Sub-daily precipitation is measured every six minutes and was accumulated to the duration of interest (up to daily). Average daily dry-bulb and dew point temperatures are an average of up to eight readings per day. For the purposes of this study, analysis was restricted to sites that had measurements of daily precipitation, sub-daily precipitation, dry-bulb temperature (referred to simply as temperature), and dew point temperature. Analysis was also restricted to sites that had no more than 25% data missing for any of the variables and had at least 100 data points per each temperature bin considered. In total 416 stations were used.

The above criteria ensured a large spread of stations across Australia covering a diverse range of climatic zones (Peel et al 2007). Australia consists of tropical regions in the north which are susceptible to cyclonic events where precipitation is summer dominant, through to southern Australia where the climate is dominated by cool/temperate climatic conditions and winter dominant precipitation. Inland the climate is arid desert dominated by dry conditions with little annual rainfall. Annual rainfall typically varies between up to 1800 mm along the eastern coast declining to near zero in the central deserts. Regions along the south-east coast are dominated by cold fronts and thunderstorms (Linacre and Geerts 1997). Although the majority of Australia is topographically flat, the east coast of Australia is dominated by a mountain range approximately 100–200 km inland which encourages orographic precipitation.

Many different methods exist for choosing precipitation-temperature pairs. Some studies use all non-zero precipitation data (Lenderink and van Meijgaard 2008) while others use the maximum intensity within a storm (Wasko and Sharma 2014, Molnar et al 2015). Precipitation is typically matched to average daily temperature, with precipitation-temperature pairs analyzed either using variants of quantile regression (Tan and Shao 2017, Wasko and Sharma 2014) or calculating extreme precipitation percentiles after binning on temperature (e.g. Hardwick Jones et al 2010, Lenderink and van Meijgaard 2008). Here, for daily precipitation, all wet days were used in the analysis. For sub-daily precipitation, events were separated by one hour of zero precipitation and the maximum one hour of precipitation within the event was chosen for analysis. Precipitation observations less than 0.1 mm were considered to be zero. Each precipitation observation was paired to average daily temperature and average daily dew point temperature. Each data pair was ordered from lowest temperature to highest tem-
temperature and assigned to a temperature bin. Based on a sensitivity analysis, a constant number of 12 temperature bins was used and the precipitation percentile was calculated on the precipitation that fell in this bin (Hardwick Jones et al. 2010). The target precipitation percentile was log-transformed and regressed against the average temperature per bin using a least-squares linear regression resulting in the following relationship:

\[ P_t = P_0(1 + a)\Delta t \] (1)

where \( P \) is precipitation, \( a \) is the sensitivity of precipitation per degree Celsius temperature change, and \( \Delta t \) is the difference in temperature between \( P_0 \), the reference precipitation and \( P_t \), the precipitation after a \( \Delta t \) temperature change.

3. Results

The relationship between daily precipitation with temperature and dew point temperature for the temperate Sydney (~33.8607°, 151.2050°) and the desert Alice Springs (23.7100°, 133.8683°) is presented in figure 1. Sydney’s daily average temperatures are below those where negative precipitation-temperature sensitivities are usually observed. However, for daily precipitation, the precipitation-temperature sensitivity is negative for the 50th percentile and approximately zero for the 99th percentile. The sensitivity is more positive for the more extreme 99th percentile, but remains well below the CC relation. Even in this region, where humidity appears to not be limited at higher temperatures (Hardwick Jones et al. 2010, Wasko et al. 2015) the precipitation-temperature sensitivity is contrary to what could be expected by considering the CC relation. This may be explained by the fact that there is less possibility of capturing a saturated atmosphere at longer durations, that is, shorter duration storms may be contained with the daily data (Wasko et al. 2015). For Alice Springs, a desert site, we see a clear negative relationship between precipitation and temperature, particularly above ~22 °C. For both the 50th and 99th percentile there is a hint of the classic hook-shape relationship where the sensitivity changes direction above ~22 °C (Drobinski et al. 2016). For the 99th percentile the observed precipitation-temperature relationship is more negative than that observed for Sydney. However, when dew point is used all these relationships become positive (bottom row of figure 1). The precipitation sensitivity with dew-point temperature is similar to 7%/°C for both the 50th and 99th percentiles for Sydney, while for Alice Springs increases of 9.1% and 12.8% are observed for the 99th and 50th percentiles respectively. These results reveal that dew point temperature can overcome the limitation of moisture availability as it is a more direct measure of moisture availability in the atmosphere than temperature alone (Lenderink and van Meijgaard 2010).

Figure 2 presents the sensitivity results of both dry-bulb and dew point temperature for the 50th and 99th percentiles for 416 stations across Australia. Inspecting figure 2(a) at least three broadly distinct regions can be identified: the northern tropical region where the sensitivity of precipitation and dry-bulb temperature is negative, the south-west region, which is largely arid and warm temperate, where again the precipitation-temperature relationship is negative, and the eastern seaboard which generally has values ranging from 0%/°C–10%/°C. For the 99th percentile (figure 2(b)) the results are broadly similar, however, now the south-west region is broadly consistent with CC, while the tropics remain negative. This increase is expected as the extreme precipitation is more likely to have a sensitivity closer to CC. The sensitivity of precipitation to dew point temperature is markedly different. For the 50th percentile (figure 2(c)) the majority of Australia exhibits a positive precipitation sensitivity with many stations exceeding the CC relation. Some exceptions remain with some isolated stations in the south remaining negative. For the 99th percentile, more consistent results are found. The majority of Australia exhibits approximately a 5%/°C–10%/°C sensitivity, with the only exception being NE Australia which exceeds CC. The shift in the distribution of these sensitivities is presented in figure 4. For the 50th percentile (figure 4(a)) the distribution shifts from centered on approximately zero when dry-bulb temperature is used to in excess of the CC relation (albeit with a large range) for dew point temperature. For the 99th percentile (figure 4(b)) a remarkably symmetric distribution centered just above CC is observed for dew point temperature, whereas the median dry-bulb sensitivity was close to zero. Use of dew point temperature appears to overcome humidity limitations with observed daily precipitation sensitivities close to CC, and in the case of the 99th percentile, the sensitivities are much more uniform across Australia.

The results presented in figure 2 are repeated in figure 3 using hourly precipitation maxima from storms separated by one hour of zero precipitation. The precipitation scaling is now closer to CC for both the 50th (figure 3(a)) and 99th percentile (figure 3(b)) across Australia. This is evidenced by the distribution shifts presented in figure 4. The distributions are overwhelmingly positive for dry-bulb temperature in figures 4(c) and (d). This could be expected for two reasons. Firstly, shorter duration precipitation is expected to be caused by convective mechanisms resulting in greater precipitation-temperature sensitivities (Berg et al. 2013). Secondly, it is more likely a saturated atmosphere is being captured at shorter durations and hence again, the extreme precipitation is more likely to match CC (Wasko et al. 2015). Notwithstanding, there remains a negative precipitation-sensitivity, even at the 99th percentile for these shorter durations,
Figure 1. Sensitivity of the 99th and 50th percentile daily precipitation with average daily temperature and dew point temperature at selected stations. Solid lines correspond to the raw data and dotted lines to the fitted regression.

Figure 2. Sensitivity of daily precipitation to dry-bulb and dew point temperature across Australia: (a) 50th precipitation percentile and average daily dry bulb temperature, (b) 99th precipitation percentile and average daily dry bulb temperature, (c) 50th precipitation percentile and average daily dew-point temperature, (d) 99th precipitation percentile and average daily dew-point temperature.
Figure 3. Sensitivity of hourly precipitation to dry-bulb and dew point temperature across Australia: (a) 50th precipitation percentile and average daily dry bulb temperature, (b) 99th precipitation percentile and average daily dry bulb temperature, (c) 50th precipitation percentile and average daily dew-point temperature, (d) 99th precipitation percentile and average daily dew-point temperature.

Figure 4. Density of daily and hourly precipitation sensitivities: (a) 50th daily precipitation percentile, (b) 99th daily precipitation percentile, (c) 50th hourly precipitation percentile, (d) 99th hourly precipitation percentile. Dry-bulb sensitivities are presented in red, dew point sensitivities in blue.
particularly in the tropics. The negative sensitivities (figures 3(a) and (b)) have been suggested to be due to declining moisture holding capacity at temperatures above ∼22°C (Westra et al 2014). When dew point temperature is used the negative sensitivities change to positive sensitivities for both the 50th (figure 3(c)) and 99th (figure 3(d)) percentiles, barring a few isolated exceptions. For the 50th percentile the hourly precipitation–dew point temperature sensitivities (figure 3(c)) exhibit closer correspondence to the CC relationship than the daily precipitation (figure 2(c)), with a median sensitivity of 8%/°C. This suggests that precipitation events are better defined at shorter durations. For the 99th percentile the results obtained using dew point temperature are similar regardless of whether daily precipitation (figure 2(d)) or hourly precipitation (figure 3(c)) is used. The distributions of the sensitivities are broadly similar (figures 4(b) and (d)), generally varying between 5%/°C–15%/°C across Australia, though the median precipitation–dew point temperature sensitivity for daily precipitation is closer to 7%/°C, whereas for hourly precipitation it exceeds this and is close to 10%/°C. The sensitivity is also greater for the 99th percentile (figure 4(d)), as compared to the 50th percentile (figure 4(c)).

Previous studies (e.g. Panthou et al 2014, Wasko et al 2015) observed that storm duration affects the precipitation sensitivity, hence, the analysis using dew point temperature was repeated across varying storm durations and event separations. The hours of zero precipitation required for selecting events was increased in increments from one hour up to 24 hours. Likewise, the storm event duration was also increased; events shorter than a specified duration were removed from the sample and the maximum one-hour storm burst from each event was selected. The precipitation–dew point sensitivity was subsequently calculated as per the methods above. Results for Sydney are presented in table 1.

For example, a sensitivity of 10.8%/°C was calculated for the maximum hourly precipitation burst within storms of duration greater than eight hours, separated by at least four hours of zero precipitation. Note that the sensitivity was not calculated when there was less than 100 points in each temperature bin. Regardless of the choice of inter-event separation or storm duration the results remain between 7 and 11%/°C. Similar types of variability were found for other sites. This suggests a very consistent relationship across storm durations, with the sensitivity close to, or exceeding, CC, when dew-point temperature is used for the calculation of precipitation sensitivities. Similarly, changing the number of temperature bins, or using temperature bins of a fixed sample size had little effect on the sensitivities calculated.

4. Discussion and conclusions

The sensitivity of precipitation with surface dry-bulb and dew point temperature was calculated for a range of durations and percentiles across Australia. The results presented demonstrate that calculated sensitivities of precipitation with dew-point temperature are closer to that expected from the CC relationship than those when dry-bulb temperature is used. In particular, it was shown:

1. The use of dew point temperature, as opposed to dry-bulb temperature, in calculating precipitation sensitivities to temperature provided results closer to, or in excess of, the sensitivity suggested by the CC relation, with 99th percentile hourly precipitation sensitivities generally in the range of 5%/°C–15%/°C.

2. A large variability across Australia was exhibited when precipitation sensitivities were calculated using dry-bulb temperature. Many regions presented negative sensitivities, particularly in the northern parts of Australia. The use of dew point temperature resulted primarily in positive precipitation sensitivities and less variability between sites and across regions.

3. Although the 50th and 99th percentile sensitivities using dew-point temperature for both daily and hourly precipitation were similar, in general, the 99th percentile of hourly precipitation sensitivities provided results with the greatest consistency across regions.

4. Regardless of the storm duration or precipitation percentile considered, the sensitivity of precipitation with dew point temperature remained similar.

The consistent precipitation–dew point sensitivities presented across different percentiles, rainfall durations, climatic zones, and storm durations support the assertion that dew point temperature is a better measure

| Event separation (hours) | Minimum storm duration (hours) |
|--------------------------|--------------------------------|
|                          | 1     | 2     | 3     | 4     | 6     | 8     | 12    | 18    |
| 1                        | 7.5   | 8.6   | 9.5   | 9.0   | 9.7   | —     | —     | —     |
| 2                        | 7.6   | 8.3   | 9.6   | 9.7   | 9.7   | 9.5   | —     | —     |
| 4                        | 8.3   | 8.7   | 9.5   | 10.2  | 11.3  | 10.8  | 8.6   | —     |
| 8                        | 8.7   | 9.2   | 9.9   | 9.5   | 10.3  | 10.3  | 10.0  | —     |
| 12                       | 9.1   | 9.4   | 9.8   | 9.8   | 9.9   | 9.9   | 10.0  | 9.1   |
| 24                       | 9.6   | 10.0  | 10.1  | 10.2  | 10.8  | 11.0  | 9.5   | 9.2   |
of increases in the moisture holding capacity of the atmosphere than dry-bulb temperature (Lenderink et al 2011). Despite the closer correspondence to the CC relation, and improved uniformity across climates, variability does remain. For example, for both hourly and daily precipitation, a number of stations on the north-east coast approach a sensitivity of 14%\(^\circ\)C. This isolated variability is one example of why doubt remains about the use of such sensitivities for extrapolation to a future warmer world and why further understanding of observed precipitation-temperature relationships is required (Zhang et al 2017). However, the sensitivities calculated here, along with their variability, match regional climate model simulated increases (5.7%\(^\circ\)C–15%\(^\circ\)C) remarkably well (Bao et al 2017). Hence, the results presented support the assertion that if such relationships are to be used to extrapolate change in precipitation extremes (Lenderink and Attema 2015) dew point temperature is a better measure of changes of increases in the atmospheric moisture holding capacity.

Acknowledgments

Data was obtained from the Australian Bureau of Meteorology and can be found at www.bom.gov.au/climate/data/stations/. Conrad Wasko receives funding from the University of Melbourne McKenzie Postdoctoral Fellowships Program. The authors sincerely thank the reviewers whose comments greatly improved the manuscript.

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