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Key Points:
- Across Australia more grids show increases than decreases across the wet day distribution with a relatively spatial uniformity of increase
- The spatial pattern of changes in total rainfall resembles the changes in frequency of wet days but not intensity changes
- Changes in wet day quantiles are sensitive to the underlying station network, while all day quantiles are sensitive to interpolation method

Supporting Information:
- Supporting Information S1

Correspondence to:
S. Contractor,
s.contractor@unsw.edu.au

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Intensification of the Daily Wet Day Rainfall Distribution Across Australia

Steefan Contractor[1], Markus G. Donat[1], and Lisa V. Alexander[1]

[1]Climate Change Research Centre and ARC Centre of Excellence for Climate Systems Science, UNSW, Sydney, New South Wales, Australia

Abstract In Australia and globally, changes in the entire distribution of daily precipitation are poorly understood. An analysis of spatiotemporal changes in the intensity and frequency of wet and all day Australian rainfall between 1958–1985 and 1986–2013 is presented using three different gridded data sets of daily precipitation based on varying underlying station data and interpolation methods. Our analysis method provides a complete picture of changes in the entire distribution as well as a coherent picture of the spatial changes across Australia. We find that the spatial pattern of changes in total rainfall is similar to the pattern of change in wet day frequency but not to change in wet day intensity. Furthermore, more grids across Australia show statistically significant increases than decreases in rainfall intensity throughout the wet day distribution. This means that when it rains (i.e., limited to the wet day distribution), whether it is light, moderate, or extreme rainfall, it rains more.

Plain Language Summary Rainfall has substantial impacts on our society, agriculture, urban environment, and industry and is strongly affected by climate change. However, understanding changes can be complex due to the variable nature of rainfall. For example, a region can receive fewer rainy days (rainfall frequency) even though the amount of rainfall when it rains (rainfall intensity) could be higher. Our study conducts a comprehensive analysis of rainfall changes by analyzing changes in the frequency and intensity of light, moderate, and heavy rainfall using daily gridded observational data sets for Australia between two 28-year periods, 1958 to 1985 and 1986 to 2013. We found that when it rained, it rained more intensely in the second period compared to the first irrespective of whether it was light, moderate, or heavy rainfall. However, changes in the frequency of rainfall varied regionally. Specifically, there are now more rainy days in northern Australia compared to the past, while in the east and south of Australia there are fewer rainy days. Finally, we also show that some aspects of rainfall are sensitive to the underlying station network, while others are sensitive to the gridding methodology of the data sets used.

1. Introduction

Significant increases in temperature have been observed over the past century and will likely continue into the future (Stocker, 2014). The Clausius-Clapeyron relationship states that the moisture holding capacity of air increases at the rate of around 7%/K. As a result there is an expectation that this increasing temperature may be accompanied by increasing rainfall. Australia, in particular, is affected by strong spatiotemporal rainfall variability, and a number of studies have sought to underpin expected changes by studying the observational record. However, it is still unclear what facets of rainfall are changing and how they are changing spatially. This is because previous studies have focused on a single index or statistic that is not indicative of changes in the entire distribution of rainfall (e.g., Alexander et al., 2007). Furthermore, the spatial changes are less understood because most studies use in situ observations, which provide an incomplete picture of the spatial distribution of rainfall (e.g., Gallant et al., 2007; Hennessy et al., 1999; Plummer et al., 1999). Studies that do use gridded data suffer from a low spatial resolution or lack description of changes in the entire distribution (e.g., Alexander & Arblaster, 2009; Donat, Alexander, Yang, Durre, Vose, & Caesar, 2013; Donat, Alexander, Yang, Durre, Vose, Dunn, et al., 2013; Smith, 2004). Understanding these changes in Australian rainfall is vital for minimizing their impact on Australian society, environment, and industry.

Among the studies that have investigated Australian rainfall, many have shown a decline in rainfall in southern Australia (south of 30°S) over the second half of the twentieth century (Gallant et al., 2007; Hope et al., 2006, 2015, 2010; Smith, 2004; Smith et al., 2000; Taschetto & England, 2009), mostly in the regions of

Southwest Western Australia (SWWA) and Southeast Australia (SEA). Although there is some expectation that the mechanisms behind the decline in SWWA are related to the decline in SEA (Hope et al., 2015), most studies investigate these two regions separately. There was an abrupt shift in the rainfall regime in the mid-1970s in SWWA leading to a drop in rainfall totals, while in SEA, studies have shown a more gradual downward trend in rainfall amounts. In general, the decline in southern Australia has been linked to two factors; first, the trend in the position and intensity of the subtropical ridge influenced by trends in Indian Ocean Dipole (Cai et al., 2011) and Southern Annular Mode (SAM; Nicholls, 2010), leading to the southward shift of the storm tracks; and second, trends in the frequency and intensity of closed low pressure systems such as cutoff lows (Risbey et al., 2013). Pezza et al. (2008) also proposed sea ice extent along with SAM in SWWA and SAM and El Niño–Southern Oscillation in SEA as another influencing factor on the storm tracks that bring rainfall to southern Australia. Pitman et al. (2004) proposed land clearance by European settlement as another cause of rainfall decline in SWWA. Risbey et al. (2013) found that one third of the rainfall reduction in SEA was due to the reduction in the amount of rain from frontal systems and two thirds from the decline in the number of most intense cutoff lows.

In the north, an increase in the rainfall amount in northwestern Australia (NWA) and a decrease in eastern Australia in latter twentieth century have been observed (Alexander et al., 2007; Taschetto & England, 2009). A number of driving mechanisms have been proposed for these changes. For NWA this includes enhanced sea surface temperatures (Shi et al., 2008) and an increase in anthropogenic aerosols from Asia (Rotstayn et al., 2007; Wardle & Smith, 2004). Tropical cyclones were also investigated as a possible cause for changes in NWA; however, it was found that they could only explain the changes in the narrow northern coast as their contribution to the rest of NWA is small (Lavender & Abbs, 2013; Ng et al., 2015). The changes in northeastern Australia remain more elusive, but a few explanations have been proposed including changes in atmospheric circulation inhibiting convective cloud formation (Taschetto & England, 2009).

Despite the abundance of studies on rainfall changes in various parts of Australia, an Australia-wide study that characterizes changes in the entire distribution of rainfall including the occurrence of rainfall (frequency of rain days), as well as a coherent picture of spatial differences of these changes, is yet to performed. Studies in the past have also relied on a single source of data (such as a single set of in situ observations or a single gridded data set), which does not characterize the affect of the observational uncertainties on their findings. Therefore, in this study, three gridded data sets based on differing underlying station data and interpolation methods are used to investigate changes in the frequency of wet days and the intensity of wet days at all intensity levels (from light, through moderate to extreme rainfall).

2. Methods

Daily gridded precipitation data for Australia were obtained from three data sets: (1) the Australian Water Availability Project (AWAP) data set (Jones et al., 2009) created and maintained by the Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, (2) Australian station data from the Global Historical Climatological Network-Daily data set (Menne et al., 2012) interpolated using Barnes Objective Analysis (BOA; Barnes, 1964), and (3) Australian station data from Global Historical Climatological Network-Daily interpolated using natural neighbor interpolation (NNI; Sibson, 1981). In the case of the latter two data sets, BOA and NNI methods were chosen as they were found to produce gridded output with the least artifacts (when comparing various interpolation methods) and are computationally inexpensive (Contractor et al., 2015).

For BOA and NNI, only those stations with at least 40 years of complete data were used where a year is considered complete if it contains less than 10 missing daily values. This completeness criterion minimizes artifacts related to variability in the underlying station network. AWAP on the other hand does not have a completeness criterion for their raw data.

We mask out an unreliable region in central Australia with low confidence in data quality (King et al., 2013). This mask is the same for AWAP and NNI; however, BOA has a slightly different mask as the interpolation method does not interpolate everywhere. This mask differs based on the interpolation parameters for BOA (see Contractor et al., 2015, for more information). As a result, for comparability, all spatial aggregation (e.g., for Figure 3) is done based on a combined AWAP/NNI and BOA mask.

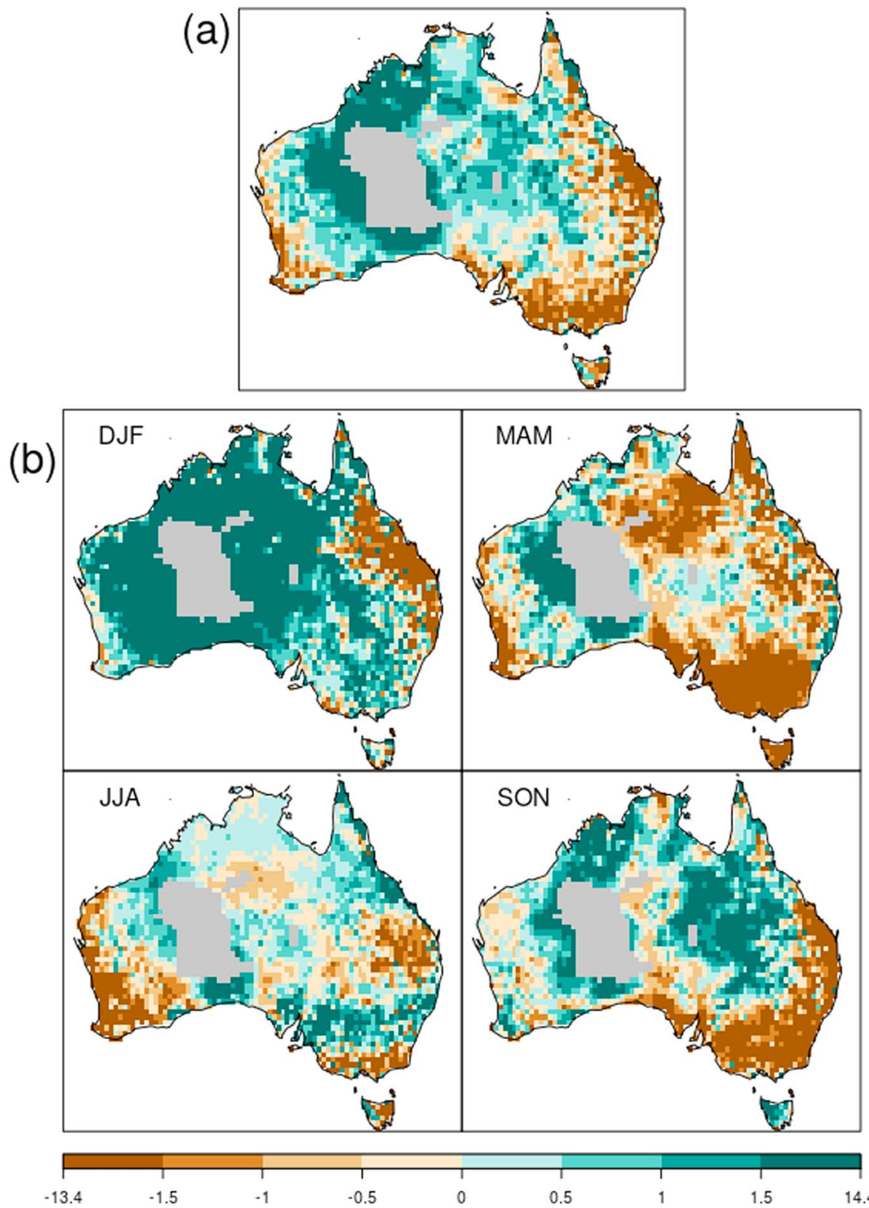

Figure 1. (a) Differences in percentages of wet days between period 1 (1958–1985) and period 2 (1986–2013) using natural neighbor interpolation. The gray shading in the center indicates areas that were masked out due to sparse data and artificial changes due to station network, similar to King et al. (2013). (b) Same as (a) but showing seasonal changes in proportions of wet days between period 1 and period 2. DJF = December–February; MAM = March–May; JJA = June–August; SON = September–November.

We focus on the period starting in 1958 (until 2013) because this is when the station network is most dense (Jones et al., 2009). The aim was to split the entire time period into sections long enough to determine statistically significant changes. For this reason each of the three data sets were split into two 28-year periods (i.e., 1958–1985 and 1986–2013) so that the daily rainfall distribution at each grid cell could be compared for these two periods for each data set. Although the raw station density peaks in early to mid-1970s, in general the raw station densities between the two periods are similar (Jones et al., 2009).

We use a nonparametric approach to study changes in probability density function as suggested by Ferro et al. (2005). The advantage of this approach is that no assumptions are made about properties of the probability density function. The main statistic calculated in this study is the relative change in quantiles, calculated by taking the difference between quantiles of the two periods and dividing by the mean of the quantiles. Therefore, a positive change indicates an increase of the quantile in period 2 and a negative change

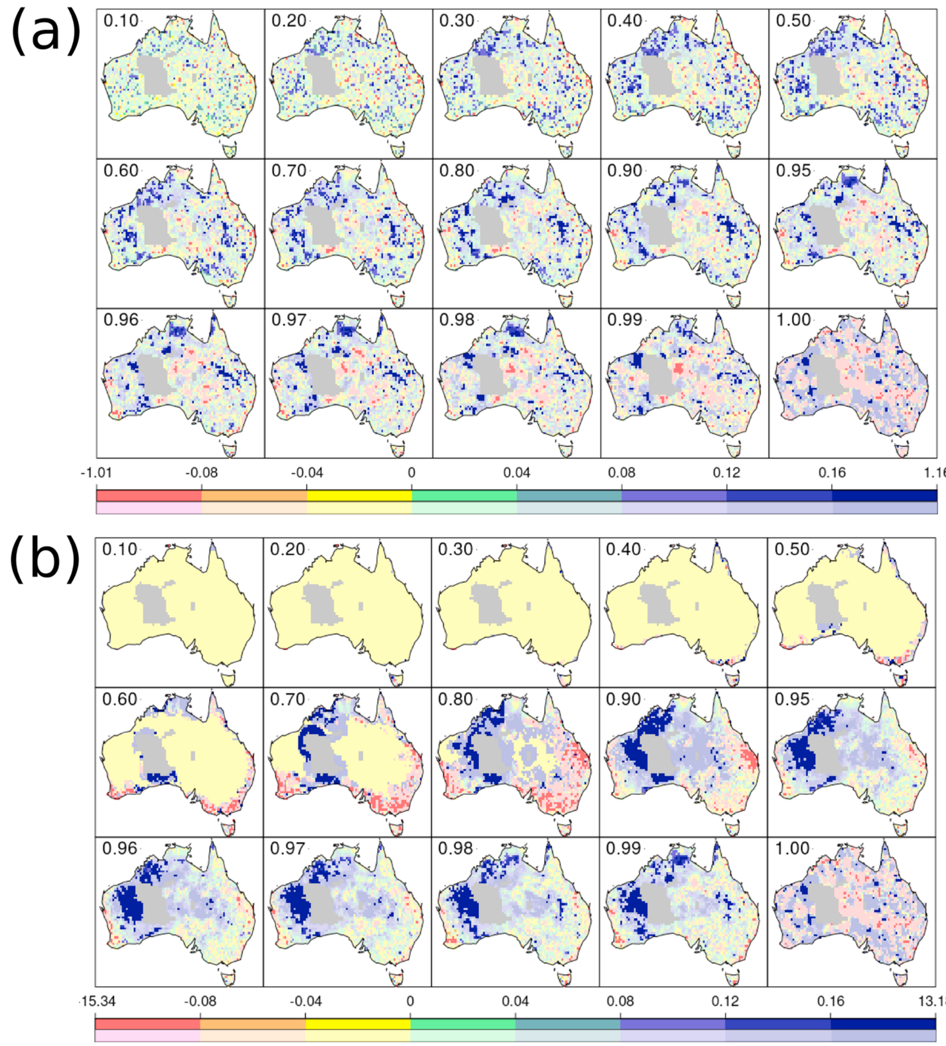

Figure 2. Maps of relative changes in various quantiles between periods 1 (1958–1985) and 2 (1986–2013) using natural neighbor interpolation. (a) Based on distributions of wet day (daily precipitation ≥ 1 mm) values of periods 1 and 2. (b) Based on all day distributions of periods 1 and 2. Each map shows the quantile indicated in the top left corner. Gray areas indicate masked out areas as in Figure 1. Grid cells with significant changes ($p \leq 0.1$) have a darker shade of color as indicated by the top color bar and the bottom color bar refers to the nonsignificant grid cells. Significance was estimated at $p \leq 0.1$ based on a 100 bootstraps (see section 2 for details).

indicates a decrease. The pth quantile is defined by the value (which has the same units as the sample data) that is expected to exceed a randomly picked sample of the data with a probability p. We calculate a total of 300 quantiles evenly spaced between 0 and 1. As a result, the lowest quantile and the interval between the quantiles is 0.0033. The aim was to balance obtaining as many quantiles as possible while maintaining the density of data needed for enough statistical power to calculate the quantiles at the upper end of the distribution. In section 3 we also present results for a quantile labeled 1.00, which refers to the maximum daily rainfall value in the 28-year period.

We show relative change based on both all day and wet day (≥ 1 mm) rainfall distributions. The objective is to determine the change in magnitude of rainfall, when it rains, based on the wet day results and compare those results with the all day quantiles to gain a comprehensive, unambiguous understanding of the entire distribution of rainfall. We also shed light on the correct interpretation of the results based on the two methods. All day quantiles were calculated by calculating 300 quantiles from the entire time series (including zeros) at each grid cell, whereas the wet day quantiles were calculated by calculating 300 quantiles after removing all samples less than 1 mm from each period time series. To avoid division by 0, we set the relative quantile change to 0 where both the quantiles are 0 mm.

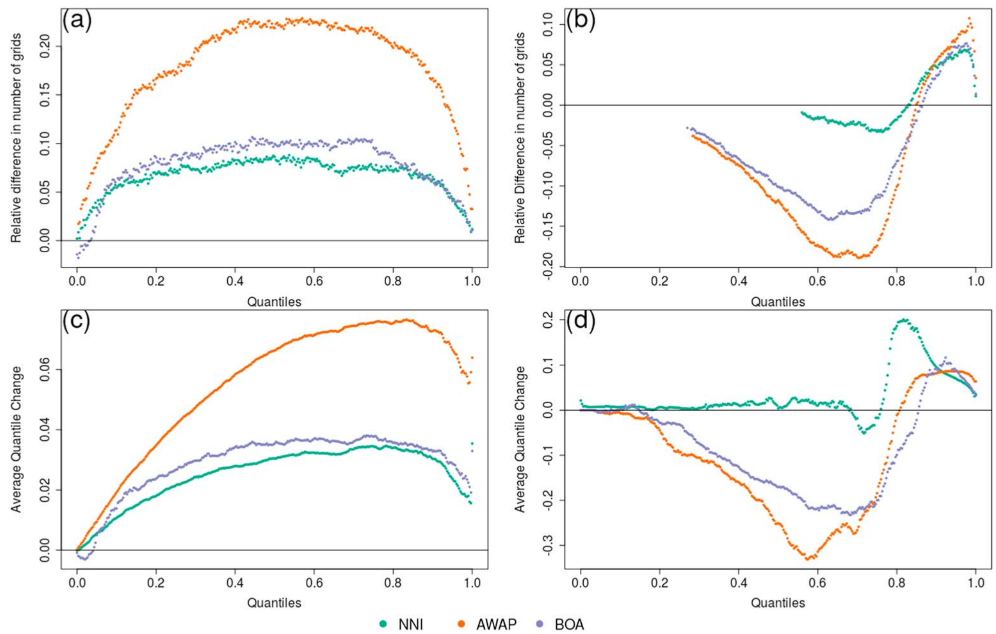

Figure 3. Relative difference between the number of grids (difference in the number of grids between the two periods divided by the total number of grids) with positive changes and those with negative changes (a and b) and spatially averaged relative quantile change (c and d) based on wet days (a and c) and all day samples (b and d). All panels show relative changes and are hence unitless. To calculate the spatially averaged relative quantile changes (b and d), the relative quantile change was calculated for each grid cell (as shown in Figure 2), which were then spatially averaged. The solid horizontal line refers to a relative difference of 0.0. Only significant grid cells were used in the calculation of the difference in number of grids (a and b), and all grid cells were used in the calculation of average quantile change (c and d).

To determine whether there is any statistically significant difference between the two time periods, we use block bootstrapping with replacement. Suppose $\{X_1, \ldots, X_m, X_{m+1}, \ldots, X_n\}$ are the original wet day precipitation samples from 1958 to 2013. Here m is the total number of wet days in period 1 and n is the total number of wet days in the entire 56-year period. Uniform resampling with replacement was performed on this original time series to create a new sample $\{X_1^*, \ldots, X_m^*, X_{m+1}^*, \ldots, X_n^*\}$. This sample was then split into two halves to create two time series, $\{X_1^*, \ldots, X_m^*\}$ and $\{X_{m+1}^*, \ldots, X_n^*\}$, corresponding to the first and second periods, respectively. To reproduce the intrinsic temporal and spatial dependence in the original sample, resampling was done in two yearly blocks and in the same order for each grid cell. Relative differences in quantiles were calculated between the first and second half of the resampled time series. This process was repeated a 1,000 times to create quantile ratios normally distributed around 0. The original quantile difference indicates a significant change if it can reject the null hypothesis that it can be drawn from the resampled distribution of quantile ratios at a 10% level; that is, the original quantile change is significant if it is greater than the 95th percentile or smaller than the 5th percentiles of the resampled quantile change distribution.

The methods used in this study are applicable to other parts of the globe with the exception of arid regions. This is because the occurrence of wet days in arid regions is often not sufficiently large to calculate significance by resampling. The next section describes the main results of this study. For brevity, unless mentioned otherwise, we show maps based on a single data set, NNI. Maps of the other data sets (BOA and AWAP) are shown in supporting information Figures S4–S7.

3. Results and Discussion

First, we examine changes in the frequency of wet days. Wet days here are days with greater than or equal to 1 mm of rainfall. Central northern Australia shows an increase in the number of wet days, while eastern, southeastern, and southwestern Australia show fewer wet days (Figure 1a). The changes in rainfall in these regions are well documented (Alexander et al., 2007; Hope et al., 2006; Gallant et al., 2007; Taschetto & England, 2009). The shift in the means of rainfall in SWWA occurred in mid-1970s, which is in the latter half of our first period (Taschetto & England, 2009). The other regions have shown a more gradual downward trend in rainfall amounts in the twentieth century. We note that the spatial pattern of the changes in frequency of wet days closely resembles the changes in daily mean and annual total rainfall between 1958–1985 and 1986–2013 (supporting information Figures S1 and S2). Results from BOA and AWAP are qualitatively similar (supporting information Figures S4 and S5).

To pinpoint the seasonal signature of the changes in frequency of wet days, Figure 1b shows the changes in the number of wet days by season (summer: December–February, autumn: March–May, winter: June–August, and spring: September–November) between the two periods. The increases in NWA seen previously are mainly due to an increase in the number of wet days in summer; however, slight positive changes can also be seen in spring. This is consistent with previous studies (Rotstayn et al., 2007; Shi et al., 2008; Wardle & Smith, 2004). We see a decrease in SWWA and SEA in all four seasons; however, the biggest change is seen in autumn and winter. The spatial extent of the decrease in SWWA is largest in winter, while the extent of the decrease in SEA peaks in autumn. This is consistent with Gallant et al. (2007), Taschetto and England (2009), and Alexander et al. (2007) who showed the strongest decreases (in mean annual, total annual, and mean rainfall, respectively) in autumn. Gallant et al. (2007) and Gallant and Karoly (2010) also showed downward trends in number of rain days in autumn in the southeast as well as in winter in the southwest in 1990s. Finally, a decrease in the number of wet days is seen in eastern Australia in all four seasons, but particularly in summer. Taschetto and England (2009) and Alexander et al. (2007) have also shown similar spatial patterns of seasonal decreases in rainfall amounts in eastern Australia.

When it rains, however, the majority of Australia experiences more intense rainfall in 1986–2013 compared to 1958–1985. This is seen in Figure 2a that shows maps of significant ($p \leq 0.1$) relative quantile changes of wet day precipitation between the first and the second period using NNI data. In general, we see more grid cells with an intensification of rainfall across Australia throughout the wet day distribution. The spatial distribution of grids with changes (increasing or decreasing) is relatively homogeneous across Australia, especially for the low quantiles (the first 3 deciles). These changes in rainfall become more pronounced and spatially clustered with increasing quantiles. There are regions, especially in central Australia, where higher quantile rainfall amounts have decreased; however, these regions are still fewer than those showing increases and are often statistically insignificant. Note that, due to the fewer number of wet days, changes in wet day rainfall amounts are less likely to be significant in drier regions. Hence, we advise caution when interpreting the results of this methodology for dry regions. Due to the larger variability in extreme rainfall amounts (compared to lower rainfall amounts), the number of statistically significant grids also reduces for the tail end of the distribution (>95th percentile). Using bootstrapping, we tested the significance of the number of grids with positive and negative changes against the null hypothesis of no change between the two periods. We use the same resampling procedure outlined previously only this time we create distributions of the number of positive and negative grids under the assumption of no change. We found that for all quantiles of the wet day distribution the number of grids with positive and negative changes is inconsistent with the no change hypothesis in a way that there are always more (fewer) grids with positive (negative) changes than the 95th (5th) percentile of the respective no change distribution. This indicates that there is a change signal across Australian data that points toward an intensification of rainfall across the wet day distribution. The magnitude of changes increases monotonically with the quantiles. In general, the spatial patterns of change in wet day rainfall magnitude for all quantiles (in particular, the 8th decile) resemble the spatial patterns in mean precipitation intensity (simple daily intensity index; supporting information Figure S3) and do not resemble the spatial patterns of annual total and daily average rainfall changes (supporting information Figures S1 and S2). We have also investigated the sensitivity of the wet day quantile changes to the choice of wet day threshold by changing the threshold to 2 mm (not shown) and found that the results are nearly identical. The finding that precipitation intensifies across more Australian regions than not is consistent with Donat et al. (2016, 2017), who reported that precipitation extremes are intensifying in regions with different rainfall characteristics (i.e., wet and dry regions) globally.

Schär et al. (2016) discussed differences in extreme precipitation indices, depending on whether the percentile thresholds were derived based on all days or wet days only. To compare the effect of the two different approaches of changes in the entire distribution, Figure 2b shows the relative change in various quantiles based on all day rainfall distributions. We no longer see more grids across Australia with an increase compared to a decrease in rainfall quantiles, with the exception of the upper extreme quantiles. This is because the spatial patterns of the low to upper-middle quantiles (until around 0.9) are more similar to changes in frequency of rainfall (Figure 1) and the upper extreme quantiles are more similar to rainfall intensity (supporting information Figure S3a). As a result the upper extreme quantiles show more grids with positive changes. Since, as shown earlier, the spatial patterns of the total rainfall changes are more similar to the frequency changes, the spatial patterns of changes in the upper-middle all day quantiles (in particular the 9th decile) are similar to average daily rainfall changes (supporting information Figure S1a). Furthermore, the changes in quantiles are more spatially coherent (less sporadic) for all day quantiles compared to wet day quatiles, and this coherence decreases with increasing quantiles. Once again, this is because the spatial pattern of changes in rainfall frequency is more coherent compared to the pattern of changes in intensity. Results from AWAP and BOA data (SI Figures S6 and S7) also show a similar spatial pattern of change, that is, an increase in wet day quantiles throughout the distribution across Australia and a spatial pattern resembling changes in frequency of wet days in the upper-middle all day quantiles and a pattern resembling simple daily intensity index changes in the upper extreme quantiles. This reduction of all day percentiles for intermediate precipitation events and an increase for heavy precipitation events have been observed in climate model simulations in other regions such as North America and Europe (Ban et al., 2015; Prein et al., 2016).

The intensification of wet day rainfall across more Australian regions compared to regions that do not show intensification is encapsulated by Figure 3. Based on all three data sets (NNI, BOA, and AWAP), there are both more grids with positive changes and positive spatially averaged quantile changes throughout the wet day quantiles (Figures 3a and 3c). This indicates that in general, throughout Australia, the rainfall amount when it rains has intensified. Note further that this pattern of intensification of rainfall amount is spatially homogeneous based on Figure 2a. The changes in most all day quantiles reflect changes in precipitation frequency; however, we still see an overall positive difference in the number of grids with positive and negative changes and spatial average of quantiles for the upper extreme quantiles (which reflect changes in precipitation intensity for these high quantiles as noted earlier) based on all three data sets.

Note that results from NNI and BOA are more alike for wet day quantiles (Figures 3a and 3c) and the results for AWAP and BOA are more alike for all day quantiles. NNI and BOA interpolate the same underlying station network of long-term stations, while AWAP interpolates all stations regardless of their record length. This indicates that wet day quantile changes are sensitive to the underlying station network. On the other hand, AWAP and BOA use the same interpolation method albeit with varying parameters. The differences between these two data sets and NNI indicate that all day quantile changes are more sensitive to the interpolation method.

4. Conclusion

We investigate changes in the intensity of daily rainfall for the entire distribution. Such a nonparametric approach avoids the need to assume a distribution for rainfall. Complemented by the analyses of the changes in frequency of wet days, such an approach provides a comprehensive picture of the rainfall changes and can be easily applied to other parts of the globe.

We conclude based on wet day quantiles that rainfall amounts, when it rains, have increased throughout Australia at all intensity levels, from light to heavy rainfall. The spatial pattern of intensification is homogeneous across Australia with high variability for lower quantiles and some spatial clustering for the higher quantiles. The magnitude of changes, however, is larger for the higher quantiles.

The frequency of wet days has decreased over the past 58 years in SWWA (in all four seasons but the largest changes are in winter), SEA (with the highest spatial extent of decreases in autumn and the lowest extent in summer), and other patches along the east coast. Wet days have increased in frequency in Northwest Western Australia particularly in summer. These spatial patterns of wet day changes are broadly similar to the patterns of changes in annual rainfall totals. While Taschetto and England (2009) reported a similarity between the spatial patterns of changes in annual rainfall totals and frequency changes of heavy events, our results show that the regional changes in rainfall totals across Australia are most similar to changes in the frequency of all wet day events. Hennessy et al. (1999) and Gallant et al. (2007) have shown concurrent reductions in total rainfall and frequency of rainfall in SEA and SWWA, but our study is the first to show that this relationship between rainfall totals and frequency of wet days is robust across Australia. In contrast, the spatial patterns of changes in quantiles of wet day rainfall are relatively homogeneous and less related to total rainfall.

Quantiles of both wet day and all day distributions are compared between 1958–1985 and 1986–2013 to show that wet day rainfall changes portray only the precipitation intensity changes. On the other hand, the upper-middle all day quantile changes portray the wet day frequency changes, and hence, the total rainfall changes and the upper extreme quantiles portray the spatial changes in intensity as well.

Finally, based on the comparison of three different data sets with varying underlying station data and interpolation methods, we show that changes in wet day distributions are sensitive to varying station networks, while changes in all day distributions are sensitive to the interpolation method. Despite this sensitivity, the conclusion that wet day rainfall has intensified across Australia remains robust, but the magnitude of intensification is uncertain depending mainly on the underlying station network used for interpolation. Therefore, we caution users of this methodology and other precipitation analysis methods to consider the sensitivity of their results to the underlying data set used.

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