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RESEARCH ARTICLE

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Temporally compounding heatwave–heavy rainfall events in Australia

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Abstract

Natural hazards often occur in combination with other natural hazards rather than as isolated events. While some combinations of hazards are well studied and their physical connection is increasingly understood, other combinations have received considerably less attention. High temperatures are known to be an important component for conditions that lead to heavy rainfall; however, sequences of heatwaves followed by heavy rainfall are not well understood, especially in a compound event context. Here, we analyse heatwave–heavy rainfall events across Australia using rainfall observations at hourly resolution. Our results show that heavy rainfall is more likely to occur if preceded by a heatwave, demonstrating that heatwave–heavy rainfall sequences should be seen as temporally compounding events. In particular, many regions in Australia experience both more frequent and more extreme wet days immediately following a heatwave. This behaviour is strongest in coastal regions, especially on the Australian east coast. These findings highlight the need for heatwave–heavy rainfall sequences to be studied as compounding events, as future changes in either hazard is likely to have impacts on related risks such as flash flooding.

KEYWORDS

Australia, compound events, GSDR, heatwave, heavy rainfall

1 | INTRODUCTION

The increased recognition that high-impact events tend to be "compound" in character (Leonard *et al.*, 2014; Zscheischler *et al.*, 2018) has led to a recent focus on the processes that connect different classes of natural hazards either in space, time and/or across multiple atmospheric variables (Zscheischler *et al.*, 2020). While a common typology is to recognize relationships within either "hot and dry" (Mazdiyasni and AghaKouchak, 2015; Sharma and Mujumdar, 2017; Miralles *et al.*, 2019) or "wet" categories (Zheng *et al.*, 2013; van den Hurk *et al.*, 2015; Wahl *et al.*, 2015), the connections between hot conditions and subsequent wet extremes have received less attention. The sequencing between "hot and wet" conditions nevertheless is important, particularly given the role of both antecedent catchment wetness conditions and heavy rainfall as determinants of flood risk.

There are numerous a priori reasons to suggest connections between these classes of extremes. At the large scale, drivers relevant to Australian conditions—such as the El Niño–Southern Oscillation or the Indian Ocean Dipole—provide a significant role in conditioning probabilities of localized weather conditions, influencing both hot (Marshall *et al.*, 2013; Parker *et al.*, 2014; Perkins *et al.*, 2015) and wet weather (England *et al.*, 2006; King *et al.*, 2013; King *et al.*, 2014; Ashcroft *et al.*, 2019). At the regional scale, land–atmosphere processes cause higher co-occurrences of droughts and heatwaves as a result of feedbacks involving changes in sensible and latent heat due to reduced moisture availability in soil and vegetation (Herold *et al.*, 2016; Hirsch *et al.*, 2019; Miralles *et al.*, 2019; Kong *et al.*, 2020). Hot temperatures, however, are also known to be a key component of atmospheric conditions that lead to localized heavy rainfall events. Significant research has been conducted on the influence of atmospheric temperature on rainfall intensity, with warmer atmospheres generally leading to more intense rainfall provided there is access to adequate moisture (Berg *et al.*, 2013; Westra *et al.*, 2014; Ali *et al.*, 2018; Guerreiro *et al.*, 2018; Ali *et al.*, 2021; Fowler *et al.*, 2021).

With the possibility of both large-scale as well as regional drivers influencing hot and wet extremes in the same location, we hypothesized that rainfall following heatwaves would be more extreme than normal, implying a temporally compounding relationship. To investigate this, we compared rainfall at subdaily timescales during, and immediately after, heatwaves to the climatological normal for rainfall for the time of the year.

Recent studies have started to investigate this link. Zhang and Villarini (2020) demonstrated that summer flooding events in the Central United Stated were often linked to prior hot and humid weather conditions, which they described as a "preconditioned compound event." For south China, Wu *et al.* (2021) showed that extreme precipitation events were often preceded by hot weather. Further, You and Wang (2021) introduced the concept of consecutive heat wave and heavy rainfall events and showed that a higher percentage of heatwaves in China was followed by heavy rainfall events within 7 days than what would be expected by chance. Direct comparisons between these studies themselves are difficult, as all three studies implement different definitions for extreme heat events and use different variables such as dry bulb temperature (Wu *et al.*, 2021; You and Wang, 2021) or wet bulb temperature (Zhang and Villarini, 2020). Dry bulb temperature is also referred to as "air temperature" and wet bulb temperature is the temperature a thermometer would show if covered by a wet cloth and can be derived from dry bulb temperature and relative humidity (Stull, 2011). All three studies have used rainfall data at daily resolution; however, we here examine rainfall events at hourly timesteps as it is more consistent with the timescales of convective storms (Trenberth *et al.*, 2017).

The processes behind temporally compounding heatwave–heavy rainfall events are largely unclear, providing uncertainty in how rainfall might differ in frequency and intensity following heatwaves in other regions. A better understanding of the link between heatwaves and subsequent heavy rainfall events—particularly how rainfall characteristics change if proceeded by a heatwave—is important due to the possibility of compounding and cascading impacts as well as the fact that heavy rainfall events have the potential to cause flooding events. Therefore, this paper examines the relationship between heatwaves and subdaily extreme rainfall events in different regions in Australia, offering insight into frequency and intensity of extreme rainfall events after heatwaves. In particular, relative to climatology we will investigate (a) how frequently heatwaves are terminated by rainfall, (b) if rainfall shortly after heatwaves is more extreme and (c) how hourly and daily rainfall extremes differ after heatwaves.

2 | DATA AND METHODS

2.1 | Data

Quality-controlled subdaily rainfall observations at hourly resolution were obtained from the Global Sub-Daily Rainfall Dataset (GSDR) (Lewis *et al.*, 2019). From the subset of Australian stations within the dataset, only stations that have a record length of at least 10 years and that have less than 20% missing data (regardless of their record length) were used. In six cases where a station provided hourly aggregated data from both 1-min and 5-min records, we removed the shorter record length. These criteria resulted in 701 stations across Australia being used for the analysis. The selected stations have an average record length of 28.3 years (median: 22.1 years) from first to last record (including missing data) and an average of 10.7% missing data (median: 10.5%).

Rainfall data has been aggregated to hourly resolution, and we define an hour with >0.1 mm rainfall as a wet hour. Aggregated to daily time steps, a day containing at least one wet hour is called a wet day in order to exclude cases where a wet day could contain no wet hours. Rainfall extremes are also defined on hourly timescales. For each station, an hourly rainfall extreme is defined as hourly rainfall exceeding the 95th percentile of all wet hours. To test the robustness of the results on the threshold selection, we also ran the analysis using the 90th percentile (Figure S5, Supporting Information) and 99th percentile (Figure S6) as a threshold for extreme wet hours instead of the 95th percentile; however, this did not significantly change the overall findings. Daily rainfall extremes, which in this study are only used for comparison, are defined as wet days with rainfall exceeding the 90th percentile of all wet days. These thresholds were selected to provide a balance between separating extreme from nonextreme rainfall events, while providing a statistically meaningful sample size for both categories. Different percentile thresholds have been chosen for hourly and daily rainfall to obtain a comparable frequency in extreme values in the dataset since the data lengths of wet hours and wet days differ.

In order to identify heatwaves, we use daily maximum and minimum temperature data (T_{max}, T_{min}, respectively) from the SILO climate database (Jeffrey *et al.*, 2001) as temperature data is not provided within the GSDR dataset. We chose against using rainfall data from the SILO dataset or another reanalysis product, as the quality-controlled GSDR dataset would provide the best representation of hourly rainfall extremes. SILO temperatures are based on observational data and are provided as an interpolated gridded dataset with 0.05° resolution (approximately $5\ km \times 5\ km$) that covers Australia and begins in 1889. For each station from the GSDR dataset, T_{max} and T_{min} are taken from the closest grid point, and heatwaves are only identified for times where rainfall records are available.

2.2 | Heatwave definition

Although numerous studies have focused on heatwaves, no universal definition exists (e.g., Perkins and Alexander, 2013). Most heatwave definitions are therefore specific to an impact or study purpose. While many studies use definitions that focus on the human impact or changes to heatwave properties like frequency or duration, we require a heatwave definition that enables accurate delineation of the start and especially the endpoint of a heatwave while still resembling common traits that are associated with heatwaves in the literature.

Therefore, we define a heatwave to have the following properties. For a given location, a heatwave is identified if

- The daily T_{max} lies above its yearly 95th percentile value for at least three consecutive days.
- The daily T_{min} lies above its yearly 95th percentile for at least the second and third day.

A heatwave ends when either T_{max} or T_{min} drop below their respective 95th percentile thresholds. The last day where the criteria above are still fulfilled is referred to as "Day 0." The previous days are counted in descending order with negative numbers (i.e., "−1," "−2," ...), and days after a heatwave are counted ascendingly with positive numbers (i.e., "1", "2", ...). Figure 1a illustrates the heatwave definition for a 4-day heatwave identified on the grid box close to a rainfall station (33.86°S, 151.21°E).

This definition slightly deviates from other heatwave definitions used in the literature. The Excess Heat Factor (Nairn and Fawcett, 2014), for example, also uses the 95th percentile (though for the mean daily temperature); however, the index is based on 3-day moving temperature averages. This, therefore, is not well suited to defining exact endpoints of a heatwave, with its primary purpose focused towards human impact. Heatwave definitions based on monthly temperature thresholds (e.g., Pezza *et al.*, 2011; Cowan *et al.*, 2014) are also not suitable for this study; we found that using these definitions led to heatwaves being predominately identified towards the end of a month when the average temperature was rising (during spring) or the beginning of a month when the average temperature was falling (autumn). Heatwave definitions based on daily thresholds (e.g., CTX90pct or CTN90pct), where the thresholds are based on 15-day windows (Perkins and Alexander, 2013), do not exhibit such biases. However, the threshold varies with the seasonal cycle, and thus involves identifying "warm spells" in a relative sense during nonsummer seasons, rather than focusing on absolute temperature. Since we also expect thermodynamical processes to contribute to end-of-heatwave rainfall, we chose to use an absolute threshold instead. To test the robustness of the results on the choice of heatwave definition, we also ran the analysis using the 90th percentile (Figures S1 and S3) instead of the 95th percentile for T_{max} and T_{min}, as well as the CTX90pct definition (Figures S2 and S4) for heatwaves.

Using the yearly 95th percentile means that, on average, ~18 days per year of T_{max} and T_{min} lie above the threshold. However, it is very unlikely that a location will experience 18 heatwave days in a given year since at least three consecutive days are required, as well as a temporal overlap of T_{max} and T_{min}. Averaged over all stations, the heatwave definition we use results in an average of 0.97 heatwaves per year per station. Though this is slightly lower than the daily percentile-based heatwave definitions analysed in Perkins and Alexander (2013), their setting allowed for heatwaves to occur during a 5-month period (November–March), while the absolute threshold used in this study identified heatwaves to occur mostly during a 3-month period from December to February, when average temperatures are at their highest (see Figure 1b). While we do not limit

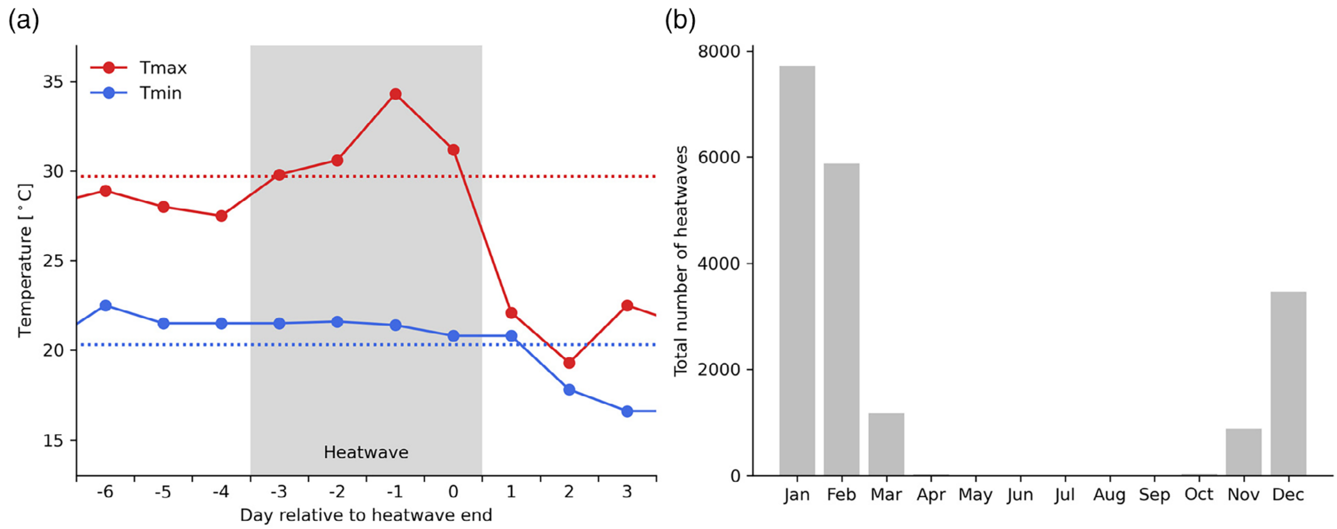

FIGURE 1 (a) Example of a heatwave from the SILO dataset, showing T_{max} (red solid line), T_{min} (blue solid line) and their respective 95th percentile temperatures (dotted lines with respective colours). The grey shaded region shows the days that have been identified as heatwave days. Day numbering on the x-axis is relative to the last day of the heatwave (see section 2.2). (b) Monthly distribution of heatwaves aggregated for all stations. If a heatwave spans over two separate months, it is allocated to the month in which the last heatwave day (Day 0) lies [Colour figure can be viewed at wileyonlinelibrary.com]

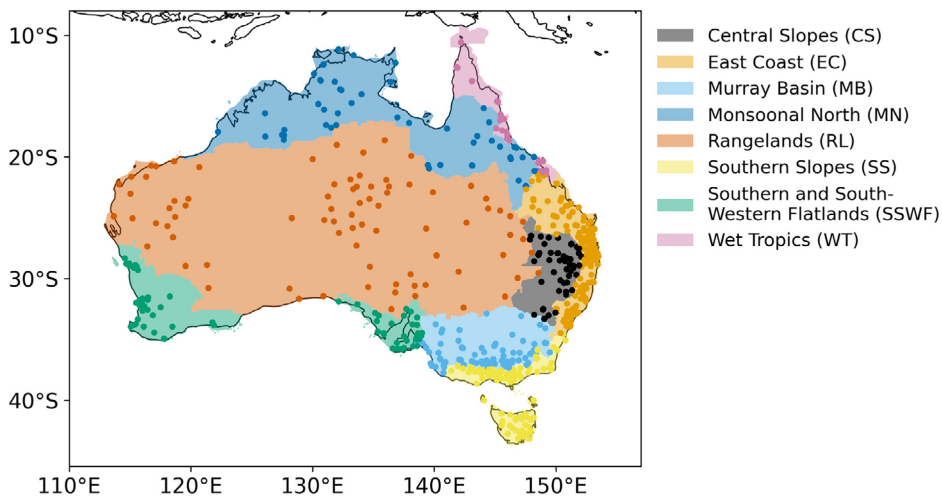

FIGURE 2 Eight subdivisions of Australia. Markers indicate locations of rainfall records used for the analysis [Colour figure can be viewed at wileyonlinelibrary.com]

heatwaves to be identified to a summer timeperiod, the vast majority of heatwaves is identified from November to March, with very few exceptions in October and April (Figure 1b).

2.3 | Methodology

Australia was chosen as the study area as the country has a good coverage of high-resolution rainfall observations, has many different climate zones and is known to experience many different kinds of hazards in short timeframes, including heatwaves, droughts, bushfires or floods (e.g., Kemter *et al.*, 2021).

We used the eight subdivisions for Australia provided by CSIRO and Bureau of Meteorology (2015, chap. 2) to account for differences in local climate. The subdivisions (regions), together with the locations of the rainfall stations used in this analysis, are shown in Figure 2. These are the Central Slopes (CS), East Coast (EC), Murray Basin (MB), Monsoonal North (MN), Rangelands (RL), Southern Slopes (SS), Southern and South-Western Flatlands (SSWF) and Wet Tropics (WT). Each subdivision contains between 30 (WT) to 174 (EC) stations.

In order to provide results for potential changes in rainfall that are characteristic for each region, we first calculate averaged values of all heatwaves at each

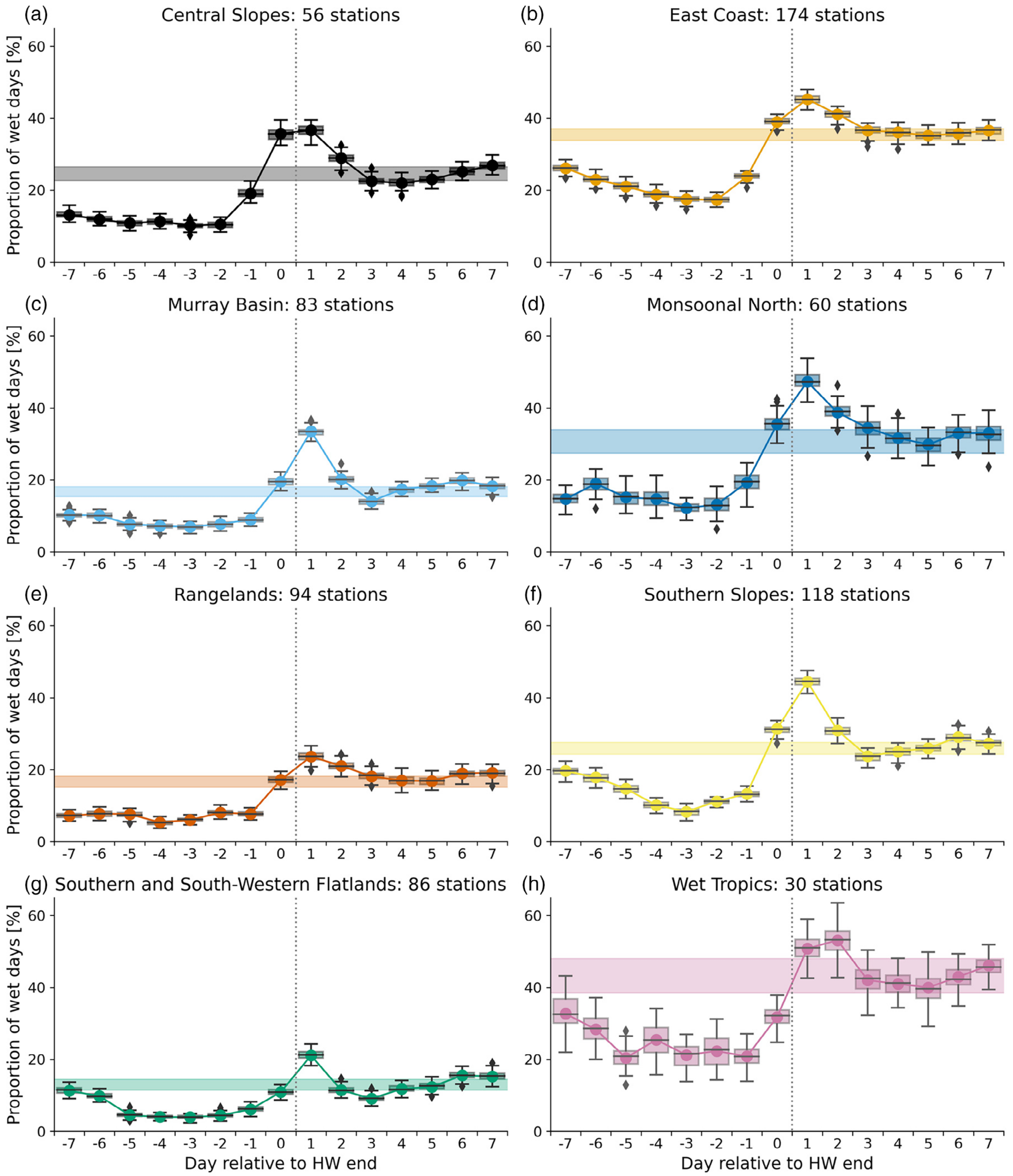

FIGURE 3 (a–h) Percentage of wet days across Australia relative to different days of a heatwave for the eight subdivisions. Continuous lines show station-averaged values for each day relative to the end of a heatwave. Coloured horizontal bars show the expected climatological 5th–95th percentile range obtained from resampling. Boxplots are calculated by randomly resampling 50% of the stations per region 100 times and indicate the uncertainty introduced by station-to-station differences. Connected dots show results for using all available stations. Dotted horizontal lines indicate the end of a heatwave [Colour figure can be viewed at wileyonlinelibrary.com]

individual station within a region. We then show the averaged results over all stations, weighting contributions from each station within a subdivision equally. We also tested weighting each station's contribution relative to the respective number of heatwaves detected. Although doing so slightly reduced the spread of the results, for simplicity we chose not to apply weights as the results did not show any significant changes.

The goal of this study is to determine if rainfall at the end of heatwaves is more extreme than its climatological mean. To obtain an estimate of average climatological rainfall conditions at similar times of year as the heatwaves, we use a resampling approach which ensures that resampled results are comparable to the original analysis. The method works as follows:

In our analysis, we only analyse rainfall during and after heatwaves. Therefore, rainfall properties during these events cannot be compared directly to average rainfall properties throughout the year since heatwaves occur predominantly during summer months and rainfall climatology in summer differs to that in the rest of the year. We therefore construct a resampled dataset which contains rainfall predominantly during summer months and functions as a comparative climatology to the original dataset. We do so by resampling an alternative date for analysing rainfall for each heatwave at each station in the original dataset. To ensure climatologically comparable conditions, we only sample from the same month as the heatwave (but any year). We chose to resample from the same month as the heatwave instead of the same day of the year as the heatwave, as doing so would have resulted in a very small pooling sample size. The resampled date from the same month of the heatwave could also coincide with the same or a different heatwave (i.e., resampling with replacement). Doing so ensures the resampled dataset preserves the climatological characteristics of rainfall during the heatwave months but effectively cancels out any potential influence of a heatwave itself. This process is repeated 1,000 times in order to represent the climate variability in the data.

3 | RESULTS

3.1 | Increase in wet days at the end of a heatwave

Figure 3 shows that the likelihood of rainfall, here expressed as the likelihood of a wet day occurring, varies strongly depending on the timing relative to a heatwave. For all subdivisions, wet days before and during a heatwave are far less likely than expected from climatology. This is in agreement with studies that show hot and dry conditions often occur simultaneously—potentially driven by positive land–atmosphere feedbacks and stable atmospheric conditions. Even in the tropical subdivisions (MN, WT) we find reduced wet day occurrence during and before a heatwave. For almost all locations, the number of wet days is below climatology even 7 days before the end of the heatwave, suggesting that the heatwaves are associated with reduced rainfall likelihood even prior to heatwave onset. During, and shortly after the end of, the heatwave, however, we find that wet day occurrence is higher than expected from climatology. As the results for all subdivisions lie outside their respective 5th to 95th percentile resampled climatological range, we consider this to be statistically significant compared to the climatological behaviour. Wet day occurrence in most regions peaks on the day after a heatwave with high values occurring from Day 0 up to Day 2. In subsequent days, wet day occurrences return to climatological levels.

3.2 | More hourly rainfall extremes in the last day of a heatwave

Following the result that the end of the heatwave is associated with rainfall more often than would be expected based on climatology, we now show that the rainfall that falls immediately following the end of a heatwave is often more extreme. In order to test if the accumulated heat of the heatwave affects the rainfall type or intensity, we choose a 36-hr time-window after 1200 LST (local time) on the last day of the heatwave. According to the heatwave definition, the temperature will have dropped by the end of the first day after the heatwave termination (Day 1) at the latest. Usually, T_{min} occurs in the early morning and thus before T_{max} occurs in the afternoon of the same day; however, the exact timing can vary. The drop in temperature which is associated with the end of a heatwave could therefore occur anytime between the measurement of T_{max} on Day 0 and T_{max} on Day 1. Assuming a cooling associated with rainfall occurs close to the timing of the rainfall, we chose an interval from 1200 LST on Day 0 to 0000 LST on Day 2 (36 hr) to ensure that any rainfall that co-occurred with a temperature drop is captured. The same intervals (starting at 1200 LST) are also chosen for resampling to ensure comparability in rainfall behaviour. We also tested a 60 hr time window starting at 1200 LST on Day 0; however, differences in rainfall intensity after a heatwave to climatology were smaller when averaging over the longer time window, further indicating the relationship between heatwaves and heavy rainfall is strongest immediately after the heatwave (Figure S7).

Figure 4 shows that rainfall occurring within 36 hr of midday on Day 0 contains a higher proportion of extreme

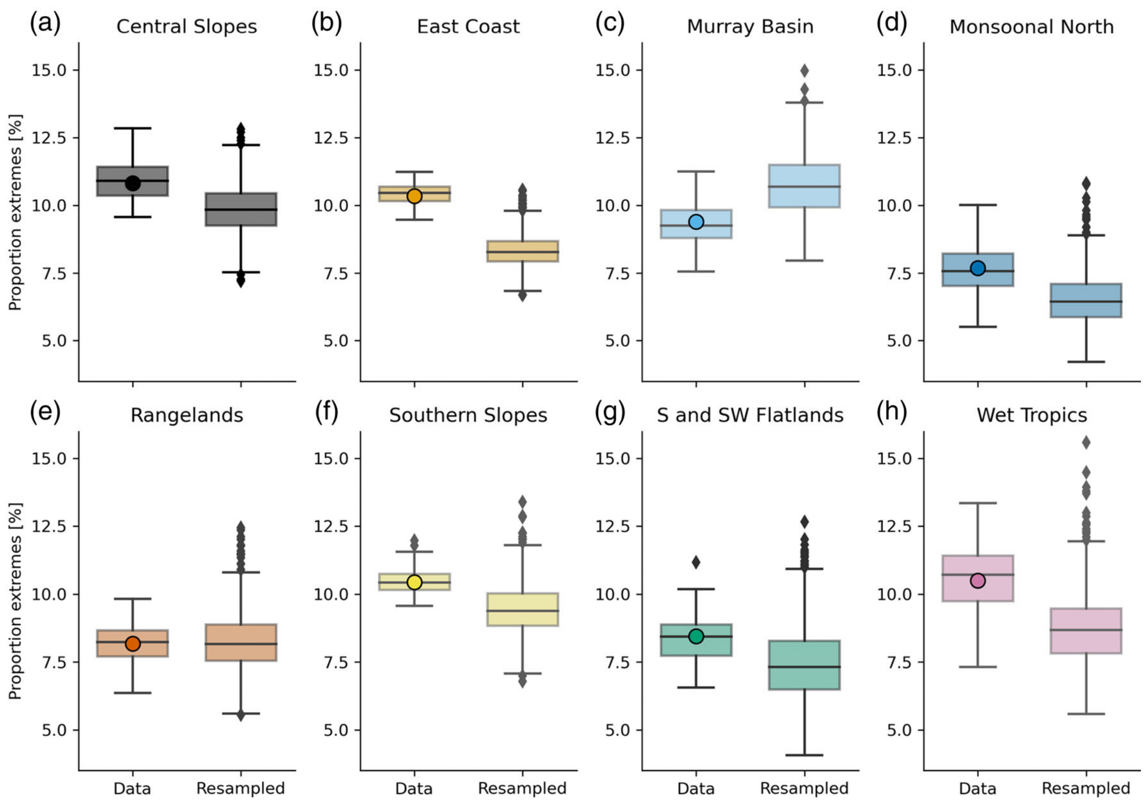

FIGURE 4 Proportion of extreme to nonextreme wet hours that occur within 36 hr of 1200 LST (local time) on Day 0 for the eight different subdivisions (a–h). Left boxplots show values obtained from randomly sampling 50% of stations per subdivision 100 times. Circles show fraction of extreme wet hours obtained from all stations within a subdivision. Right boxplots show climatologically expected fraction of extreme values which is obtained from 1,000 resamples during similar times of the year (see section 2.3) [Colour figure can be viewed at wileyonlinelibrary.com]

to nonextreme wet hours when compared to resampled data from similar times of the year. This is the case for most regions (except for MB and RL). The highest difference to the climatological mean occurs in the East Coast region, where the average proportion of extreme events increases from approximately 8.4–11.0% after a heatwave. According to our definition, wet hours are extreme if the rainfall amount lies above the 95th percentile of all wet hours for the respective station and month and we would therefore generally expect results from the climatology to lie around the 5% mark. For all regions however, the resampled means lie above 5%. We attribute this to the fact that more rainfall extremes occur during the summer months, and rainfall for the climatology has been sampled during months when heatwaves were occurred, which was predominately during summer months. Additionally, rainfall intensity in Australia tends to peak in the afternoon/evening due to mechanisms such as convection (Evans and Westra, 2012). Thus, a 36-hr window which contains two half days and one night would contain a higher-than-average proportion of extremes.

3.3 | Comparing hourly and daily rainfall extremes during and after heatwaves

The greater availability of daily rainfall data compared to subdaily rainfall data raises the question of what added-value subdaily records provide, as using daily rainfall data allows the use of more data with greater spatial coverage. You and Wang (2021) previously showed increases in daily rainfall extremes after heatwaves in China using daily gridded precipitation observations. To analyse any differences in results at daily and hourly scales, we accumulated the GSDR hourly rainfall data to daily timescales to compare hourly and daily rainfall extremes.

Figure 5 compares the proportion of extreme rainfall values to nonextreme values on hourly and daily timescales for several days relative to the end of a heatwave. We find that hourly and daily rainfall extremes especially differ in the timing of their highest occurrences. On an hourly timescale, the highest proportion of extremes is generally found on the last day of the heatwave, and this substantially exceeds the average climatology. The

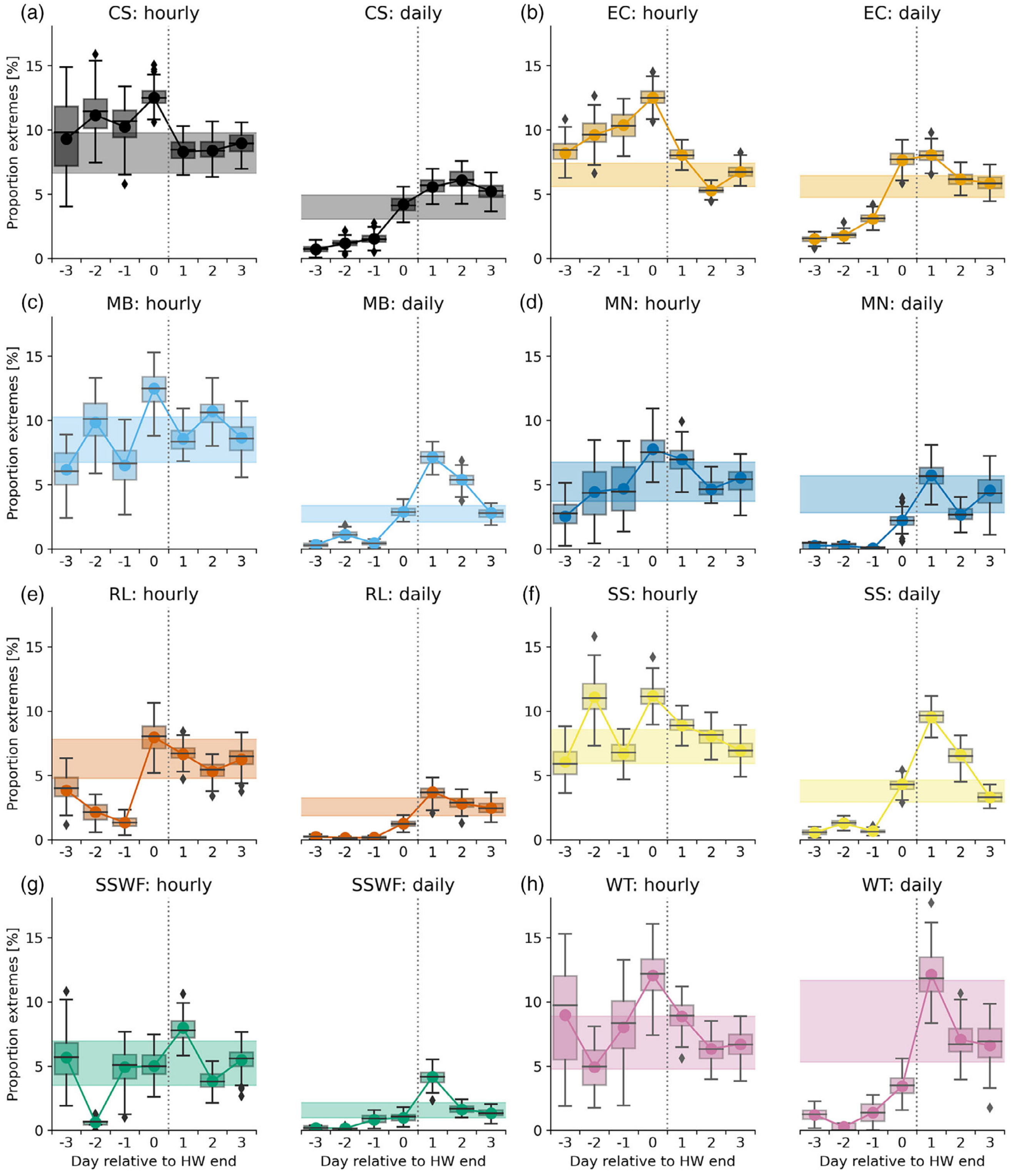

FIGURE 5 Comparison between proportion of hourly and daily rainfall extremes with respect to the last day of a heatwave for the eight regional subdivisions (a–h). Left plots for each region show proportion of extreme to nonextreme wet hours, right plots show proportion of extreme to nonextreme wet days. Continuous lines, coloured horizontal bars, boxplots, connected dots and dotted horizontal lines are derived analogue to Figure 3 [Colour figure can be viewed at wileyonlinelibrary.com]

proportion of extremes during the heatwave itself does not differ substantially from the average climatological behaviour, although it tends to be lower than the climatological average. The proportion of hourly extremes then decreases from the first day after the heatwave onwards to return to the climatology after 2 or

3 days. Using daily data, however, we find that the proportion of daily rainfall extremes to nonextreme wet days generally peaks on the first day after a heatwave, that is, 1 day after the peak is seen in the hourly data. The proportion of daily rainfall extremes during the heatwave also tends to be much lower than average climatology—a behaviour that is not consistently seen in the hourly data. This is likely due to the fact that daily extremes usually result from longer-duration (up to 24 hr) rainfall which would be more likely to terminate a heatwave than an hourly rainfall extreme which could result from a short-duration rainfall event such as a convective storm. After the peak on the first day after a heatwave, the proportion of extreme wet days tends to drop to, or below, the climatological average within a day or two. Notably, regions that exhibit peaks in the proportion of rainfall extremes that are substantially higher than the climatological average do so either for hourly (CS, EC, WT), or for daily (MB, SS, SSWF) suggesting potentially different dominant mechanisms for heatwave termination in the different groupings.

4 | DISCUSSION AND CONCLUSIONS

We have shown that, in Australia, rainfall at the end of heatwaves is often more likely and more extreme when compared to rainfall at similar times of the year during non-heatwave conditions (i.e., the climatological average). This results from an increase in wet days at the end of a heatwave as well as a higher proportion of extreme wet hours within 36 hr of the heatwave end. This increase in wet days at the end of a heatwave compared to climatology occurs in all regions of Australia. The intensification of rainfall immediately following the heatwave can be seen in all regions except for the central RL and MB, and especially on the East Coast (EC). However, the risk of these regions experiencing heatwave-breaking rainfall is still increased in absolute numbers due to higher wet-day frequency at the end of the heatwave.

The investigation of rainfall data at daily and hourly timescales offers different perspectives on the occurrence of extreme rainfall at the end of heatwaves. We find increases in the proportion of extreme to nonextreme events at the end of heatwaves for both hourly and daily rainfall, but the results differ in the timing of the peak proportion of extreme events, the extent of the increase relative to the climatological average and the behaviour during the heatwave. We show significant peaks in the proportion of hourly rainfall extremes on the last day of the heatwave in the Central Slopes, East Coast and the Wet Tropics. Peaks in the proportion of daily extremes are commonly found a day later, on the day after a heatwave terminates, and prominent in the Murray Basin, Southern Slopes, and the Southern and South-Western Flatlands. This could indicate differences in the mechanisms driving the heatwave termination in these regional groupings: clustered as North-Eastern regions (CS, EC, WT—peak hourly extremes on day of heatwave termination) and Southern regions (MB, SS, SSFL—peak daily extremes on day after heatwave termination). This suggests that the dominant mechanism for extreme rainfall terminating heatwaves in the North-Eastern regions is likely temperature-driven convection, while in the Southern regions the dominant mechanism may be synoptic variability.

While our study demonstrates a compounding relationship between heatwaves and rainfall extremes in Australia, we have not yet fully investigated the causal link between these extremes. However, it is likely that large-scale drivers and atmospheric synoptic-scale variability play the dominant role in providing rainfall to break the heatwaves in southern regions given the peak occurrence of daily extremes in the day after heatwave termination. Here, a reduction in temperature could be the result of cold air advection from a low-pressure system (Bao *et al.*, 2017; Visser *et al.*, 2020). However, in north-eastern regions the reduction in temperature may be a direct result of rainfall. Here, heatwave termination is associated with peaks of hourly extreme rainfall occurrence—localized high temperatures may favour convection causing intense short-duration bursts which lowers temperatures. Further research must be conducted to understand the regional interplay between heatwave termination and heavy rainfall.

The end of a heatwave is linked to an increase in wet days in all regions in Australia, and some regions, like the East Coast, additionally exhibit a high risk of short duration rainfall extremes during those wet days. As the East Coast region is highly populated, containing the cities of Brisbane and Sydney, and shows the strongest regional increase in hourly rainfall extremes after a heatwave, the potential impacts of temporally compounding heatwave–heavy rainfall events may be significant. Impacts might also become exacerbated in the future due to changes in hazards in a warming climate. As heatwaves are projected to become more frequent (e.g., Cowan *et al.*, 2014; Russo *et al.*, 2014; Trancoso *et al.*, 2020), this could have serious implications for potentially increasing the risk of heavy rainfall terminating heatwaves. More research is necessary to verify if this relationship holds true in a warming climate.

A benefit of recognizing extreme events as compound events is that it adds focus on potentially overlooked impacts, since high impacts often occur from a combination of hazards and/or drivers. However, the nature of possible impacts associated with compounding heatwave–wet extremes is poorly understood. One the one hand, heatwaves could reduce antecedent moisture conditions (Bennett *et al.*, 2018) in the soil profile and short-term water storages (e.g., stormwater retention stores) relative to climatology, and may potentially lower flood magnitude following a heavy rainfall event. On the other hand, a quick transition from hot (which often occurs with dry conditions) to extreme wet conditions may pose additional risks to sectors such as water resources management or agriculture from those resulting from individual hazards alone. Further impacts can also result if wildfires were present during or before the heatwave, as this can affect runoff and erosion (Moody *et al.*, 2013), as well as water quality (Murphy *et al.*, 2015). The effect of this compounding behaviour on other impacts such as implications on heat stress (e.g., Sherwood and Huber, 2010; Raymond *et al.*, 2020) and/or thunderstorm asthma (e.g., Taylor and Jonsson, 2004; Thien *et al.*, 2018) are similarly poorly understood.

Previous studies analysing temporally compounding hot-wet extremes have been focussing on hazards or definitions for hot extremes that deviate from those used in this study, such as: daily wet bulb temperature extremes followed by flood events (Zhang and Villarini, 2020), daily extreme heat followed by rainfall extremes (Wu *et al.*, 2021), or heatwaves based on maximum temperature followed by rainfall extremes (You and Wang, 2021). Due to these differences in hazards and definitions, it is not possible to draw direct comparisons between the results in this work and these studies. However, our results agree with the general findings of these studies, showing that hot events are often linked to an increase in subsequent wet extremes.

In conclusion, we show that in Australia there is evidence of temporally compounding hot-wet extremes. Although the implications of this compounding behaviour on impacts are not well understood, it is likely that interactions between heatwaves and heavy rainfall have the potential to significantly modify climate impacts and risks, and represents an important area for future investigation.

AUTHOR CONTRIBUTIONS

Christoph Sauter: Formal analysis; visualization; writing – original draft preparation; writing – review & editing. **Christopher J. White:** Conceptualization; funding acquisition; writing – review & editing. **Hayley J. Fowler:** Conceptualization; writing – review & editing. **Seth Westra:** Conceptualization; writing – review & editing.

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DATA AVAILABILITY STATEMENT

GSDR data can be obtained from the authors of Lewis *et al.* (2019). SILO data can be downloaded at https://www.longpaddock.qld.gov.au/silo/. Shape files for the Australian subdivisions are available at https://www.climatechangeinaustralia.gov.au/en/.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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