Intensifying Australian heatwave trends and their sensitivity to observational data

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Key Points:

- Australian heatwaves are becoming hotter, longer, frequent, occurring with excess heat, starting earlier and extending their season duration
- Australian heatwave trends are noticeably different amongst gridded and in-situ station datasets
- Heatwaves and severe heatwaves have increased rapidly in the recent decade compared to previous periods in the considered Australian cities.

Abstract

Heatwaves are an accustomed extreme event of the Australian climate and cause catastrophic impacts on human health, agriculture, and urban and natural systems. Heatwaves are measured by various metrics developed for the employment of different impact-based studies. We have analysed the trends in Australia-wide heatwave metrics (frequency, duration, intensity, number, cumulative magnitude, timing, and season duration) across 69 extended summer seasons (i.e., from Nov-1951 to Mar-2020). Our findings not only emphasise that heatwaves are becoming hotter, longer, and more frequent, but also signify that they are occurring with excess heat, commencing much earlier, and expanding their season over many parts of Australia in recent decades. We also investigated the heatwave and severe heatwave trends at a local city-scale using two different observational products (AWAP gridded dataset and ACORN_SATV2 station data) over selected time periods (1911 to 2019, 1911-64, and 1964-2019). Results suggest that heatwave trends are different amongst the two datasets. However, the results highlight that the severe heatwave cumulative magnitude and their season duration has been increasing significantly in recent decades over the southern coastal cities of Australia (like Melbourne and Adelaide). The climatological mean of the most heatwave and severe heatwave metrics is substantially higher in recent decades compared to earlier periods across all the cities considered. The findings of our study have significant implications for the development of advanced heatwave planning and adaptation strategies.

1 Introduction

The global anthropogenic emissions of atmospheric greenhouse gases in the most recent decade (2000-10) are the highest in the past observational record (Pachauri et al., 2014). Increasing greenhouse gas concentrations in the atmosphere leads to enhanced radiative forcing, which is estimated to result in mean warming of approximately 2.6 to 4.8 °C relative to 1986-2005 by the end of the 21st century under a high emission scenario (Collins et al., 2013). Rising global average temperatures are responsible for the increase in the likelihood of severe heat events such as heatwaves across the world, and the probability of these events is expected to increase towards the end of the 21st century (Cowan et al., 2014; Meehl & Tebaldi, 2004; Russo et al., 2014; Schoetter et al., 2015).

Heatwaves are an extended period of extremely hot days exceeding a relative or absolute threshold. Heatwaves can be both terrestrial (Perkins & Alexander, 2013) and marine (Hobday et al., 2016). However, we limit our analysis to terrestrial heatwaves, which have adverse societal impacts. Across the globe, there were more than 166,000 heat-related deaths during the period 1998-2017 (Wallemacq, 2018). In recent decades, many parts of the world have experienced frequent and severe heatwaves, some of which resulted in thousands of fatalities from a single event, including the 2003 European heatwave (García-Herrera et al., 2010), the 2010 Russian heatwave (Barriopedro et al., 2011) and the 2015 Indian heatwave (Pattanaik et al., 2017). The fatalities caused by Australian heatwaves are more than all other weather-related hazards combined (Coates et al., 2014). Coates et al. (2014) reported that over 4500 people lost their lives due to heat-related ailments during the period 1900 to 2010 in Australia. Australian heatwaves have other societal impacts on the productivity of crops and livestock (Asseng et al., 2011), infrastructure, and power supply (McEvoy et al., 2012). Heatwaves also play a critical factor in increasing bushfire risk (Clarke et al., 2013). While heatwaves are typical of the Australian climate, they are rare (by definition) in a stochastic climate.

Heatwaves are generally defined using meteorological variables such as maximum temperature, minimum temperature, and relative humidity, which are also used as an absolute or relative threshold. Steadman (1984) defined heatwaves using apparent temperature, which is calculated using both temperature and relative humidity. Many indices that define heatwaves developed by specific impact-based groups are complex to calculate over climatological scales (Mayer & Höppe, 1987). However, in Australia, most studies have defined heatwaves as a period of three or more consecutive hot days, where temperature exceeds relative thresholds (Cowan et al., 2014; Perkins & Alexander, 2013; Perkins et al., 2015). Furthermore, Fischer and Schär (2010) suggested four metrics to determine and analyse the characteristics of a heatwave. These include (1) heatwave frequency: total number of heatwave days, (2) heatwave duration: period of the longest heatwave, (3) heatwave amplitude: the hottest day of the hottest heatwave, and (4) heatwave number: number of heatwave events per season or year. Apart from these four, Perkins and Alexander (2013) also used a metric called heatwave magnitude to analyse the mean intensity of heatwaves in a season or year. Recently Perkins-Kirkpatrick and Lewis (2020) suggested that total intensity variations are better captured with the cumulative sum of extra heat during heatwaves (i.e., heatwave cumulative magnitude) rather than the original heatwave magnitude metric. Shiva et al. (2019) employed a new metric called heatwave season duration, which is the difference between the last day of the last heatwave in a season and the first day of the first heatwave in a season, and used to examine the heatwave seasonal changes. Most of these metrics are constructed for the use of various impact-based studies. The first heatwave of a season or year has more adverse effects on human health than the other heatwaves in later days with similar intensity (Habeeb et al., 2015). The intensity of a heatwave mainly affects human mortality (Hanna et al., 2011), and the timing and duration of heatwave have agricultural productivity impacts (Nuttall et al., 2012).

Heatwaves all over the world are mainly driven by the changes in synoptic systems (Meehl & Tebaldi, 2004; Pezza et al., 2012), land-atmosphere feedback (Hirsch et al., 2019), climate variability modes (Perkins et al., 2015) and global warming (Meehl & Tebaldi, 2004). In addition to these, increased urbanization in a future warmer world may also cause frequent and intense localised heatwaves across different climates (Habeeb et al., 2015). The added heating due to urban infrastructure contributes to the Urban Heat Island. Rogers et al. (2019) observed that the Urban Heat Island during heatwaves elevates nighttime temperatures, thus affecting heatwave intensity. The urban population, mainly in major Australian cities, is projected to increase from 66% in 2013 to 72% in 2053 (Australian Bureau of Statistics, 2014). Increasing urban population will result in an increase in the number of vulnerable people to heatwaves. Hence it is vital to understand the changes in intense heatwave characteristics in rapidly growing urban centres of Australia, which is not yet researched at the city scale.

Although many previous studies examined the changes in Australian heatwaves, they limit their analysis to certain characteristics, including heatwave frequency, intensity, and duration (Cowan et al., 2014; Perkins & Alexander, 2013; Trancoso et al., 2020). Analysis of all these metrics (heatwave frequency, duration, intensity, cumulative magnitude, timing, number, and total season duration) using the same heatwave definition provides a consistent, comprehensive understanding of Australian heatwaves, but until now such an analysis is lacking. The present study builds on the previous studies (e.g., Perkins & Alexander, 2013; Trancoso et al., 2020) by updating the trends of all heatwave characteristics (up to 2020) at a continental-scale (Australia wide). In addition, historical heatwave trends at in-situ locations for major Australian cities are presented, which has not been previously researched. Furthermore, at the city-scale, we compared heatwave trends between the gridded and in-situ station datasets. This comparison allows assessment of the sensitivity of heatwave trends to various observational data products. Thus, the present study provides a more comprehensive understanding of how heatwaves are changing at both the continental-scale and city-scale, which can help policymakers in designing better planning and adaptation strategies.

2 Materials and Methods

2.1 Data

The daily maximum and minimum temperature data used to calculate Australian heatwave trends are obtained from the observational gridded dataset generated by the Australian Water Availability Project (AWAP) (Jones et al., 2009). Due to computational restraints, we use the 0.25° × 0.25° gridded data instead of the original high resolution 0.05° × 0.05° data to compute the continental-wide trends. However, decreasing grid resolution does not affect the spatial pattern, magnitude, and significance of trends (Perkins & Alexander, 2013). The AWAP dataset is produced using high-quality station data by applying the hybrid gridding procedure (Jones et al., 2009). Many previous studies have used the AWAP data to analyse Australian heatwaves (Cowan et al., 2014; Herold et al., 2016, 2018; Perkins & Alexander, 2013; Perkins et al., 2015; Trancoso et al., 2020). However, the gridding procedure, the inputted non-homogenised data, and temporally and spatially varying station density can influence data quality, particularly where the station network is sparse, such as central Western Australia. Due to the sparse station network coverage before the 1950s (Jones et al., 2009), we limit our continental-wide trend analysis to 1951-2020 (i.e., Nov-1951 to Mar-2020). We also masked the grid points with no nearest station (< 2° radius), which have at least 30 years of data during the period 1951-2020. For masking the station locations are obtained from the station network used for producing the AWAP gridded dataset.

The present study mainly focuses on the top five densely populated Australian cities (Table 1). The city-scale temperature data is obtained from the high-quality station data provided by the ACORN-SATv2 (Trewin et al., 2020) (Table 1). Unlike AWAP, the ACORN-SATv2 is a homogenised dataset. The homogenisation is accomplished using the sophisticated percentile matching technique. ACORN-SATv2 dataset consists of 112 stations over the whole of Australia, out of which 110 stations have at least 50 years of data (Trewin et al., 2020). The city stations are selected based on the availability of long term temporally consistent data. In addition, the city-scale heatwave analysis is also carried out with high-resolution AWAP gridded (0.05° × 0.05°) data by selecting the nearest available grid point to each selected city station (Table 1). The AWAP data is available from 1911 to 2020 (i.e., July 2020). The ACORN-SATv2 data is available from 1910 to 2019 in all the selected stations except Brisbane airport, where it is available from mid-1949 to 2019. Hence, we limit our analysis in city-scale to the period of 1911-2019 except for Brisbane airport station (from 1950 to 2019).

Table 1. The chronological order of top five densely populated Australian cities with their corresponding station and its location

S.no	**City**	**ACORN-SATv2 Station** (Latitude (°S), Longitude (°E))	**Nearby AWAP grid (0.05° × 0.05°) location** (Latitude (°S), Longitude (°E))
1	Sydney	Observatory hill (-33.86, 151.21)	-33.85, 151.20
2	Melbourne	Olympic park (-37.83, 144.98)	-37.85, 145.00
3	Brisbane	Airport (-27.39, 153.13)	-27.40, 153.10
4	Perth	Airport (-31.93, 115.98)	-31.95, 116.00
5	Adelaide	Kent town (-34.92, 138.62)	-34.90, 138.60

2.2 Heatwave definitions

Despite no universal definition, most studies define heatwaves as a period of consecutive days with high daytime and (or) or nighttime temperatures exceeding an extreme threshold. However, heatwave definitions vary broadly across the world among different groups based on targeted sector-based applications (Perkins & Alexander, 2013). Perkins and Alexander (2013) note that percentile-based threshold indices are most relevant to study the climatology of extreme heat events. Nairn and Fawcett (2013) formulated the Excess heat factor (EHF) index, which considers a 3-day period temperature relative to preceding average monthly temperature and climatological percentile-based threshold temperature. The other most commonly used relative threshold heatwave indices are CTX90pct and CTN90pct, which are defined as the maximum and minimum temperatures exceeding the climatological 90th percentile for three consecutive days, respectively. Perkins and Alexander (2013) found that heatwave definition based on EHF is more appealing than others to analyse climatological heatwave metrics in the Australian context. The EHF index is formulated with daily mean temperature, which is calculated using maximum and minimum temperatures. The inclusion of daily minimum temperatures in the EHF formulation implicitly accounts for humidity variations (Nairn & Fawcett, 2013), which better allows for studying the heat-related impacts on human health. Many recent studies note that EHF is a better predictor of demand for emergency health services (Loridan et al., 2016; Scalley et al., 2015). We compute EHF according to Perkins et al. (2015), as follows:

$$T = \frac{(T_{max} + T_{min})}{2} \tag{1}$$

$$EHI_{sig} = \frac{(T_i + T_{i-1} + T_{i-2})}{3} - T_{90} \tag{2}$$

$$EHI_{acc} = \frac{(T_i + T_{i-1} + T_{i-2})}{3} - \frac{(T_{i-3} + \cdots + T_{i-32})}{30} \tag{3}$$

$$EHF = EHI_{sig} \times max(EHI_{acc}\,, 1) \tag{4}$$

where T_{max}, T_{min}, and T are the daily maximum, minimum, and mean air temperatures, respectively. T_i represents the daily mean temperature on the ith day, and T_{90} is the climatological 90th percentile temperature of the specified base period (1961-90).

T_{90} is calculated using the 15-day centred window for each day of the year for a selected base period and then smoothened using Savitzky-Golay 3rd order polynomial filter (Luo et al., 2005). The window-based daily relative threshold method of EHF calculation allows capturing all the changes in heatwave metrics throughout the year. The reference period 1961-90 is chosen because it is used by the previous heatwave focused studies (Herold et al., 2016; Perkins et al., 2015). EHI_{sig} and EHI_{acc} are represented as the significance and the acclimatisation excess heat indices, respectively. The EHI_{sig} indicates the deviation of the present 3-day period temperature corresponding to the climatological relative threshold. EHI_{acc} represents the current 3-day period temperature variation with respect to the previous month average temperature. In this study, we considered three or more consecutive positive EHF days as a heatwave.

In recent decades both the average and the extreme intensity of heatwaves is increasing rapidly over Australia (Cowan et al., 2014; Perkins-Kirkpatrick et al., 2016; Perkins-Kirkpatrick & Lewis, 2020; Trancoso et al., 2020). These intense heatwaves have adverse effects on human health (Nairn et al., 2018). To investigate the changes, particularly in severe heatwaves, we classified heatwaves into two categories according to the Nairn and Fawcett (2013) severity definition. They are low-intense, and severe category heatwaves. This classification facilitates recognition of events which have higher impacts on human health. The heatwave severity is formulated as follows:

$$Severity = \frac{EHF}{EHF_{85p}} \tag{5}$$

$$Heatwave = \begin{cases} Low - intense\ heatwave, & 0 \leq Severity < 1 \\ Severe\ heatwave, & Severity \geq 1 \end{cases} \tag{6}$$

Where EHF_{85p} is the 85th percentile of positive EHF values for the whole study period at a corresponding location. In this study, a heatwave with at least a day in its duration with EHF value greater than or equal to EHF_{85p} of the corresponding location is considered as a severe heatwave.

2.3 Heatwave metrics

Heatwaves are a discrete type of extreme, which can be further categorized by various metrics (Perkins, 2015). Most of these metrics are constructed for the use of various impact-based studies. The metrics considered for the analysis in the present study are computed according to previous studies (e.g., Perkins-Kirkpatrick & Lewis, 2020; Perkins et al., 2015; Perkins & Alexander, 2013; Shiva et al., 2019) and are expressed as follows

Heatwave frequency (HWF): total number of heatwave days in a season,
Heatwave duration (HWD): length of the longest heatwave in a season,
Heatwave number (HWN): total number of separate heatwave events in a season,
Heatwave amplitude (HWA): the hottest day of the hottest heatwave in a season (Perkins & Alexander, 2013),
Heatwave cumulative magnitude (HWC): seasonal sum across all heatwave days of the departure between the heatwave threshold and measured temperature (Perkins-Kirkpatrick & Lewis, 2020),
First heatwave timing (HWT): timing of the first heatwave day in a season (Perkins et al., 2015),
Heatwave season duration (HWS): the difference between last and first heatwave day in a season (Shiva et al., 2019).

All heatwave metrics in this study are computed for an extended summer season (Nov to Mar), where heatwaves have high societal impacts such as human mortality and agricultural productivity (Perkins & Alexander, 2013).

2.4 Approach

All metrics are calculated on a continental-scale using AWAP gridded data of 0.25° × 0.25° resolution and at the city-scale using ACORN-SATv2 station data and high-resolution AWAP gridded data (0.05° × 0.05°). In addition to these, the severe heatwave metrics are also computed at the city-scale for both observational products. The trends of all metrics across 69 extended summer seasons (i.e., from Nov-1951 to Mar-2020) are calculated using Sen slope (Sen, 1968) over the continental scale. Trend significance is assessed using the non-parametric Mann-Kendall test (Kendall, 1957; Mann, 1945). Heatwave metrics do not follow the normal distribution; hence the non-parametric Mann-Kendall test is appropriate for the present study to analyse the trends (Perkins & Alexander, 2013). City-scale trends are analysed from 1911 to 2019 (108 years), and in two sub-periods, one is the first half of the study period (54 years, 1911-64), and the other is the second half (54 years, 1965-2019). This trend analysis helps to answer the question, "Is there a shift in heatwave trends in recent decades over major populated Australian cities?". The climatological analysis of heatwave and severe heatwave metrics is performed at the city-scale for the four sub-periods each of 30 years except the last one (a. 1911-40, b. 1941-70, c. 1970-2000, and d. 2001-19). The 30-year period is chosen because it is the homogenised measure of mean climate across the regions, even considering natural climate variability (Perkins et al., 2015). The 30-year period is also recommended by the World Meteorological Organisation for the purpose of climatological analysis.

3 Results

3.1 Continental trend analysis of heatwave metrics

In this study, hereafter the heatwave metrics are referred as HWF, HWD, HWN, HWA, HWC, HWT, and HWS (heatwave frequency, duration, number, amplitude, cumulative magnitude, timing, and season duration, respectively), while severe heatwave metrics will be prefixed with HW_s. Figure 1 shows the trends of the considered heatwave metrics during the period 1951-2020 over the whole of Australia. The spatial trend pattern is much similar between heatwave metrics like heatwave frequency (HWF), heatwave duration (HWD), and heatwave number (HWN) and these results are consistent with Perkins and Alexander (2013). However, the trends of HWF are higher in magnitude compared to HWD and HWN. The statistically significant positive trends of HWF (2 - 3 days/decade), HWD (0.8 - 1.2 days/decade), and HWN

(0.4 - 0.6 number/decade) were seen in southeastern and southern parts of Australia, Queensland, and central parts of Western Australia. In these regions, the trends of heatwave amplitude (HWA) are also statistically significant. However, the higher trend magnitudes of HWA (around 2.5 °C^2/decade) are seen in southern and southeastern parts of Australia. The trends of heatwave cumulative magnitude (HWC), which is a measure of extra heat felt during heatwaves, are greater in the regions where HWA trends are stronger. This means that regions that have encountered increasing maximum heatwave intensity have also experienced increased excess heat during heatwaves.

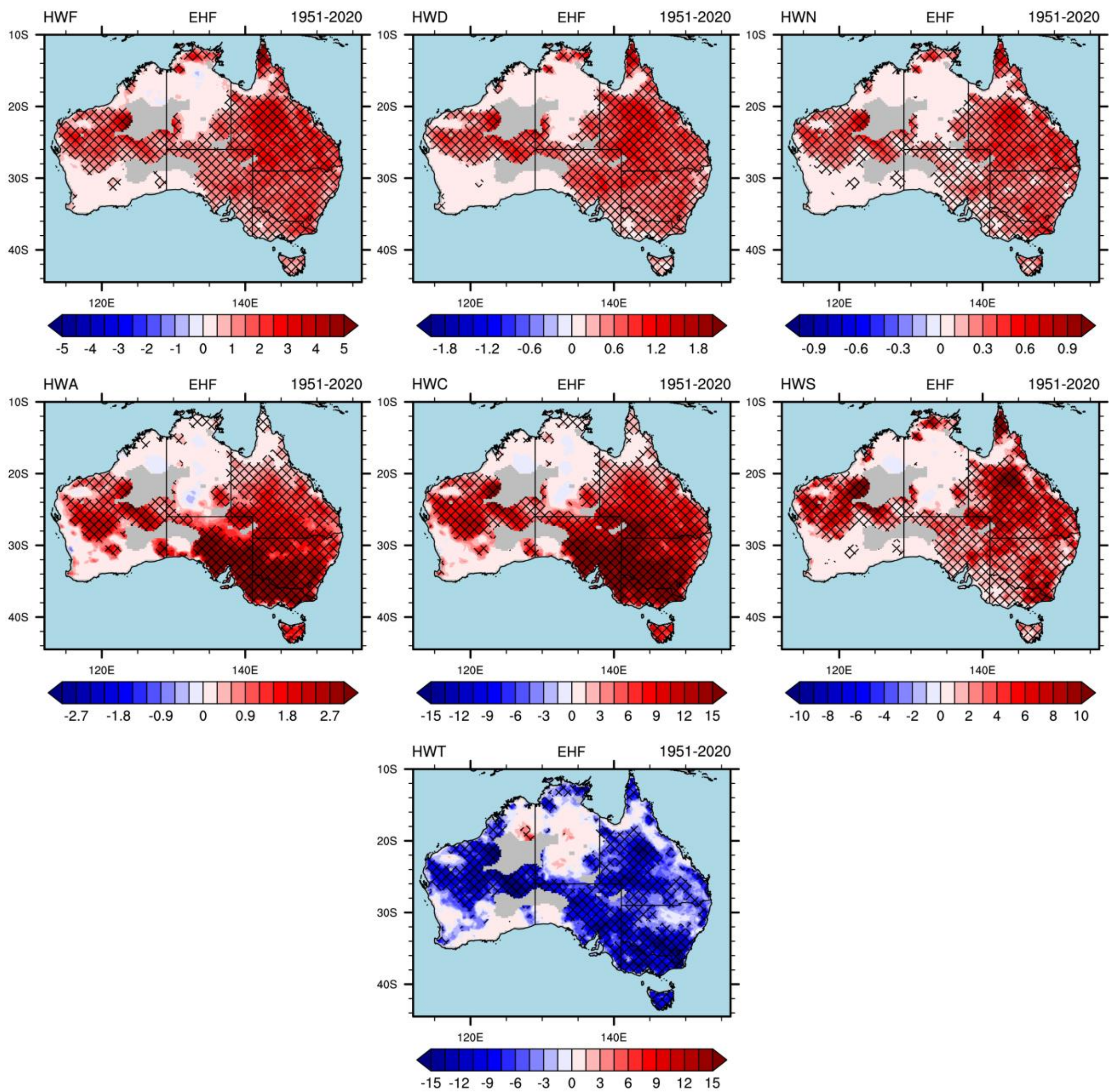


Figure 1. Decadal trends of all heatwave metrics considered in this study from 1951 to 2020 (it means from Nov 1951 to Mar 2020). The trend magnitude and significance are calculated by Sen slope and Mann-Kendall test, respectively. The hatched regions represent the trends at the 0.05 significance level. Grey areas represent the masked regions.

The spatial pattern of statistically significant trends of HWS is similar to the trend patterns of HWF. However, greater trend magnitudes are seen in southeastern parts of southeast Australia and northern parts of Queensland. In these regions, statistically significant higher negative trends of heatwave timing (HWT) are also observed. The negative trend values of HWT represents earlier onset of heatwaves in a season. No significant trends in the timing of the last heatwave in a season were observed in southeastern parts of southeast Australia, central parts of Western Australia, and northern parts of Queensland (not shown). This indicates that in these regions, the extended heatwave season duration is mainly due to the early onset of heatwaves.

3.2 City-scale trend analysis of heatwave and severe heatwave metrics

Here we present the results of the heatwave and severe heatwave metrics trend analysis in top five densely populated Australian cities (table 1). This trend analysis is carried out using both the station (ACORN-SATv2) (see in figs. 2 and 3) and gridded (AWAP) (see in figs. S1 and S2) datasets. The actual trend magnitude values are presented in tables S1, S2, and S3 for various selected study periods, respectively. It is expected that heatwave trends to be similar among the two considered observational datasets. On the contrary, our results suggest that heatwave trends are noticeably different amongst the two datasets. These differences are likely due to minor variations among temperature data (see in fig. S3). These minor variations in data caused the broader distributional changes like AWAP data is more variable in Sydney than ACORN-SATv2, ACORN-SATv2 data is more variable in Perth compared to AWAP, and the ACORN-SATv2 distributional curve is shifted right side in comparison with AWAP curve (see in fig. S3). However, the climatological calendar-day 90th percentile temperature threshold values are mostly similar with slight variations between the two datasets (see in fig. S4). The trend calculations of heatwave characteristics are sensitive to the temperature variations due to the definitional requirements of the heatwave (like 3-day minimum consecutive periods of high temperatures exceeding their threshold) (see in table S1). Additionally, the broader distributional changes of temperature data such as a shift in the overall curve towards warmer conditions and increased variability can greatly affect the frequency and intensity of extreme heat events like heatwaves (Perkins, 2015). This is because of their rarity (by definition) and their presence in the tails of the original distribution (Perkins, 2015). The slight temperature data deviations of the AWAP dataset compared to the high-quality ACORN-SATv2 data is likely due to the methods used in gridding procedure, time-varying station density, and non-homogenisation of data. Hence, the city-scale heatwave analysis is carried out using the ACORN-SATv2 data instead of AWAP.

Figures 2 and 3 show the trends of the heatwave and severe heatwave metrics for each of the cities considered, over the first half (1911-64), the second half (1965-2019), and full study period (1911-2019) using the ACORN-SATv2 data. Sydney shows statistically significant positive trends for most of the heatwave metrics (HWF, HWA, HWC, and HWS) and a negative trend for only HWT and HWT_s over the whole study period. However, no statistically significant trends for both the heatwave and severe heatwave metrics were observed during the first and second half of the study period. Similar to Sydney, in Melbourne most of the heatwave metrics exhibit statistically significant positive trends and a negative trend for HWT and HWT_s over the full study period. The second half period also shows statistically significant positive trends for HWF, HWA, HWC, HWC_s, and HW_s in Melbourne. Similar to Sydney and Melbourne, no significant trends were seen during the first half of the period for both heatwave and severe heatwave metrics. Due to data limitations, the trend analysis is carried out for only the second half of the study period in Brisbane. Only HWF and HWN show a statistically significant positive trend in Brisbane over the second half of the study period.

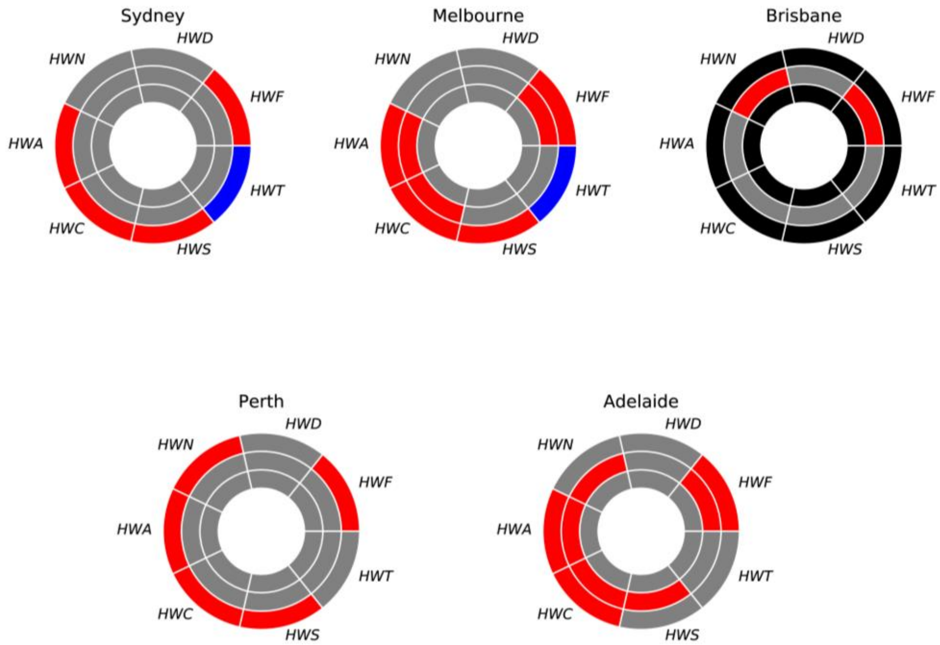


Figure 2. Trend donut plot of heatwave metrics of the corresponding cities using the ACORN_SATV2 data. Sen slope magnitude and Mann-Kendall significance test results of trends are represented as red (statistically significant increasing trend), grey (no statistically significant trend or no trend), blue (statistically decreasing trend), and black (no data). The outermost ring of donut represents the trends for the full study period (1911-2019), the innermost ring represents the trends for the first half period (1911-64), and the middle ring represents the trends for the second half (1965-2019). Each segment represents the respective heatwave metric.

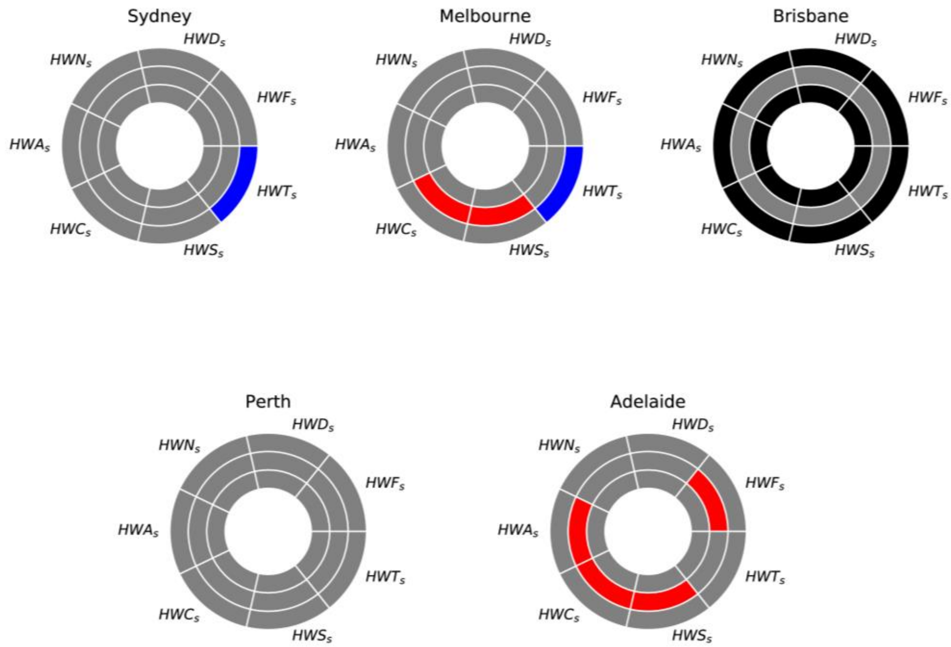


Figure 3. Same as fig. 2 but for the severe heatwave metrics

In Perth, most of the heatwave metrics show statistically significant positive trends over the full study period and no significant trends in the two half study periods. However, none of the trends of any of the severe heatwave metrics are significant in Perth over any of the selected study periods. Unlike other cities, Adelaide exhibits statistically significant positive trends for most heatwave and severe heatwave metrics during the latter half of the study period. This indicates that Adelaide experienced a greater number of intense and prolonged heatwaves in the most recent half of the study period compared to the former half.

3.3 City-scale climatological analysis of heatwave and severe heatwave metrics

Figures 4-8 display the variations of all considered heatwave and severe heatwave metrics over the four selected sub-periods for the five cities, respectively. In Sydney, mean heatwave and severe heatwave frequency, duration, amplitude, and cumulative magnitude during the recent period (2001-19) are greater than the 75th percentile value of the respective metric in the previous sub-period (1971-2000) (see in fig. 4). Similarly, in all of the other cities, the average value of both heatwave and severe heatwave metrics except HWT and HWT_s is substantially higher in the recent period (2001-19) compared to all other sub-periods (see in figs. 5-8). This indicates that all heatwaves, as well as severe heatwaves are more frequent, prolonged, intense, and seasonally extended in recent decades over all cities analysed here. Heatwave and severe heatwave timing values are earlier in the most recent period compared to the previous sub-periods in all five cities indicate the early onset of heatwaves and severe heatwaves. In all the selected cities, every heatwave metric shows a large amount of variability during the recent period (2001-19) compared to the other periods. This could be due to the effect of internal climate variability on heatwaves over shorter decadal timescales (Perkins-Kirkpatrick et al., 2017).

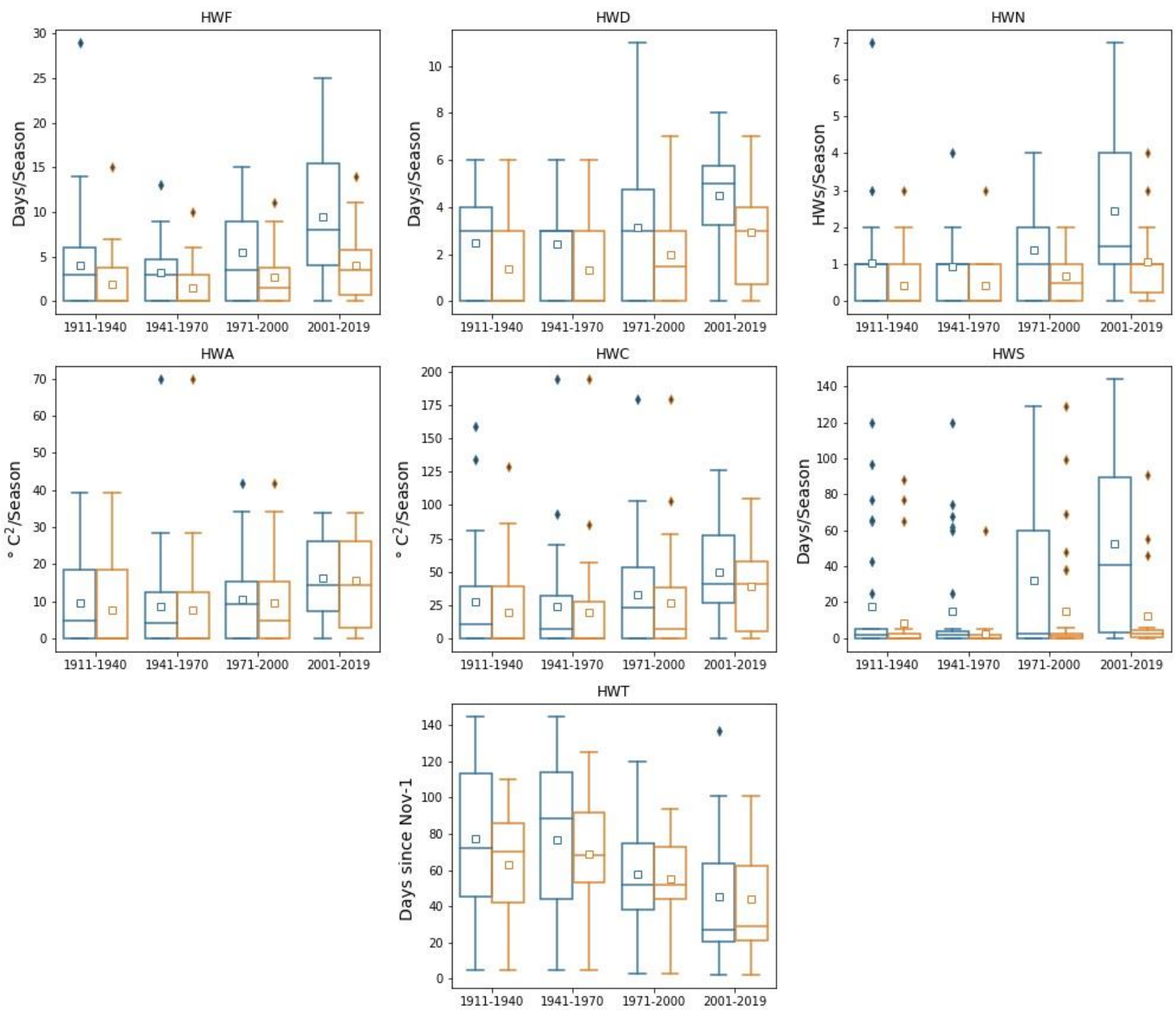


Figure 4. Box and whisker plot of heatwave metrics (all heatwaves – blue colour and severe heatwaves – orange colour) of Sydney for the sub-periods (1911-40, 1941-70, 1971-00, and 2001-19) using the ACORN_SATV2 dataset. The lower end and upper end of the box represent 25th and 75th percentile values, respectively. The whisker represents the 1.5 times of the

respective interquartile (25th and 75th) range. The small box and line represent the mean and median, respectively. Filled diamonds represent the outliers.

4 Discussion

In this study, we found that Australia-wide heatwave trends are substantially higher than those presented by Perkins and Alexander (2013), who computed the trends for the period 1951-2008, and Trancoso et al. (2020) who computed the trends for the period 1950-2016. Here for the first time over Australia, we have computed the trends of other important heatwave metrics (like heatwave season duration (HWS), heatwave cumulative magnitude (HWC), and heatwave timing (HWT)), which indicate conditions that can have severe impacts on human morbidity and mortality. Our results not only highlight that heatwaves are becoming more frequent, longer, and intense as was found in previous studies (Perkins-Kirkpatrick et al., 2016; Perkins-Kirkpatrick & Lewis, 2020; Perkins & Alexander, 2013; Perkins, 2015; Steffen et al., 2014; Trancoso et al., 2020) but also signify that the heatwave season is extending with the much earlier onset of heatwaves over many parts of Australia in recent decades. Our results also indicate that excess heat during heatwaves (HWC) and extreme heatwave intensity (HWA) are increasing at a rapid rate over the southern and southeastern regions of Australia compared to the other parts of Australia (fig. 1). The hotter heatwaves over the southern and southeastern Australian regions have severe implications for human health (Williams et al., 2018), agricultural productivity (Herold et al., 2018), the livestock industry (Henry et al., 2012), and other extreme events like bushfires (Sharples et al., 2016).

The present study is the first to systematically compute the heatwave and severe heatwave trends at a local city-scale (in selected Australian cities) using the two observational datasets. We found that heatwave calculations and the corresponding trends are very sensitive to minor variations in the underpinning temperature data. The minor variations in temperature data of AWAP dataset are likely due to the methods used in producing the data, the gridding procedure, non-homogenisation of data, and temporally varying station locations. These slight variations influence heatwave trends due to the constraints imposed by how heatwaves are measured (i.e. at least three consecutive extremely hot days). These minor variations in the distributions of underpinning data likely affected resulting heatwave events and subsequent trends. This is because like any extreme events, heatwaves are very sensitive to the broader distributional changes due to their existence in the extremities of the original distribution (Perkins, 2015). Overall, we suggest that heatwaves are better identified at a local scale using the station data instead of a gridded data product.

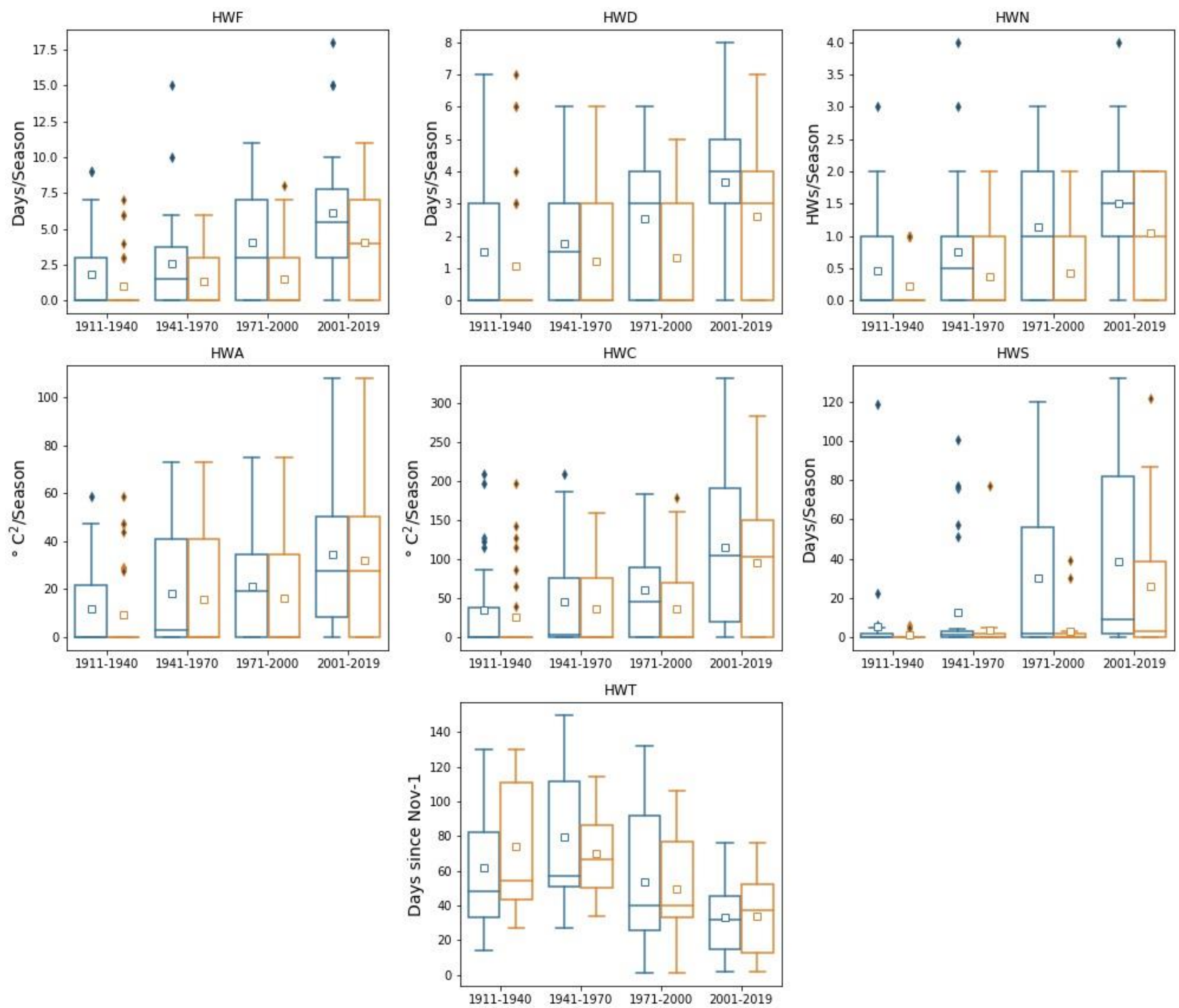


Figure 5. Same as fig. 4 but for Melbourne

The trends in heatwave and severe heatwave metrics vary across the cities considered since these metrics are affected by various factors such as synoptic systems (Pezza et al., 2012), rainfall (Perkins et al., 2015), land surface conditions (Hirsch et al., 2019), and topography. The severe heatwave trends show no significant trends in Sydney, Brisbane, and Perth over all the considered study periods (see in fig. 3). However, most of the heatwave metrics exhibit an increasing trend in Sydney, Melbourne, Perth, and Adelaide over the full study period (fig. 2). These increases in heatwaves over rapidly growing Australian cities will cause adverse impacts on the power supply, transportation, and construction. The city population is projected to rise from 66% in 2013 to 72% in 2053 (Australian Bureau of Statistics, 2014), which will increase the number of people prone to heatwaves. The rapid rise in heatwave-affected populations could overwhelm emergency health services (Lindstrom et al., 2013) and power supply system (McEvoy et al., 2012).

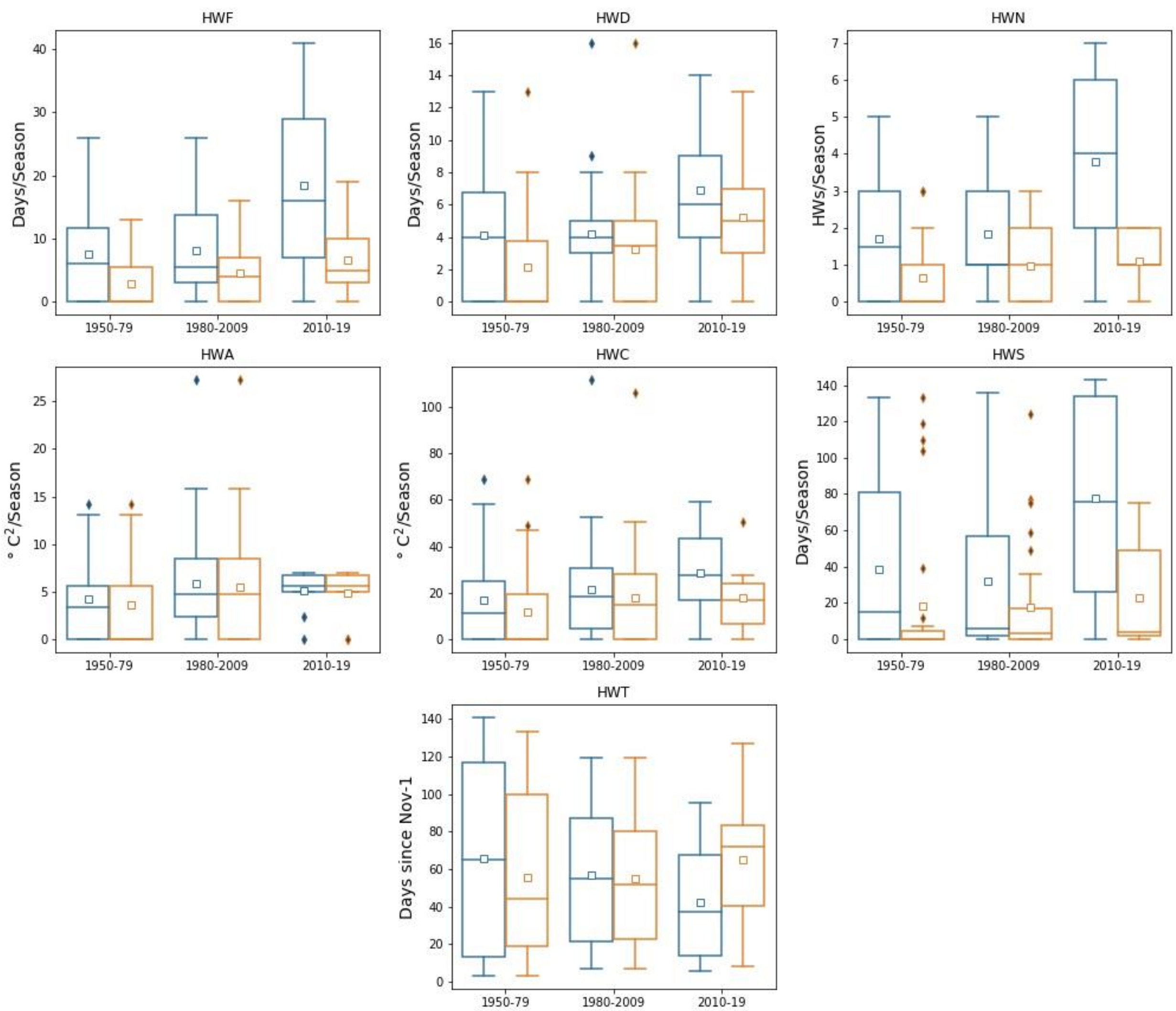
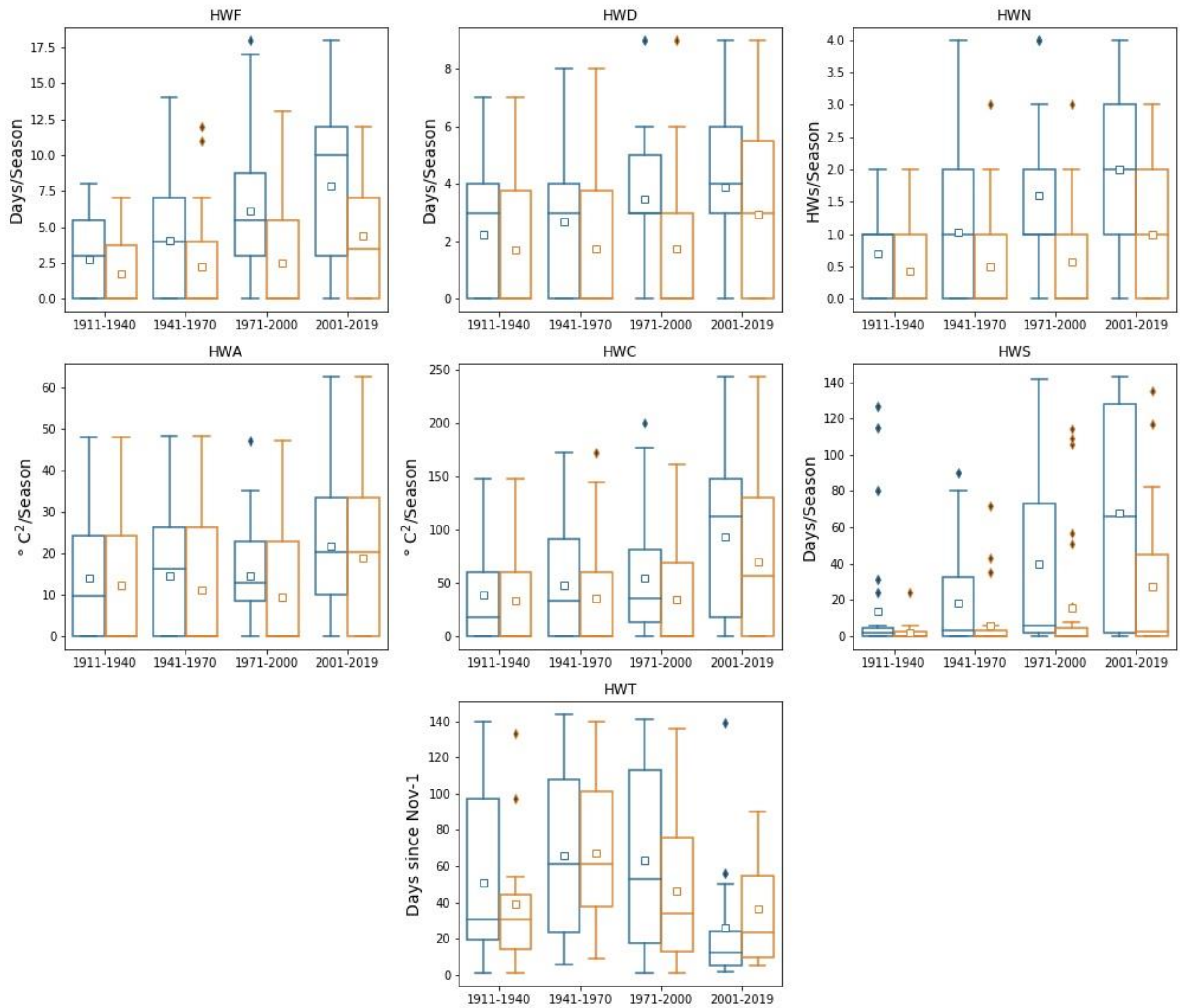


Figure 6. Same as fig. 4 but for Brisbane (with sub-periods: - 1950-79, 1980-09, and 2010-19)

In recent decades, both the heatwave and severe heatwave cumulative magnitude, extreme intensity, and season duration have increased rapidly, particularly in the southern coastal cities (Adelaide and Melbourne) of Australia. These increases could be due to the influence of global warming (Meehl & Tebaldi, 2004), synoptic systems (Pezza et al., 2012), natural modes of climate variability (Perkins et al., 2015), and increased urbanisation (Habeeb et al., 2015; Shiva et al., 2019). The increased urbanisation exacerbates the Urban Heat Island (UHI) effect, which can greatly affect the heatwave intensity in Melbourne and Adelaide (Rogers et al., 2019). Further research is required to quantify the effects of UHI on the other heatwave metrics. Increases in severe heatwave cumulative magnitude and season duration in a densely populated city like Melbourne will have serious implications for emergency health service and human mortality (Lindstrom et al., 2013). Results also highlight that trends in both the heatwave and severe heatwave timing are decreasing in Sydney and Melbourne over the full study period (see in fig. 2 and 3). This means that heatwaves and severe heatwaves are starting significantly earlier in these cities.

The variations in mean climatological heatwave metrics in all the cities considered over the selected study periods are consistent with the findings of Steffen et al. (2014). The greater increase in climatological mean and larger variability of all considered heatwave and severe heatwave metrics are seen in the recent period (2011-19) compared to the other periods over all selected cities (see in figs. 4-8). This larger variability of heatwave metrics in the recent period (2011-19) with shorter timescale is likely due to the influence of internal climate variability (Perkins-Kirkpatrick et al., 2017; Perkins-Kirkpatrick & Lewis, 2020). The greater increases in the heatwave and severe heatwave metrics could be due to the increased urbanisation and rapid rise in population growth over these cities in the recent decade.



432

433 **Figure 7.** Same as fig. 4 but for Perth

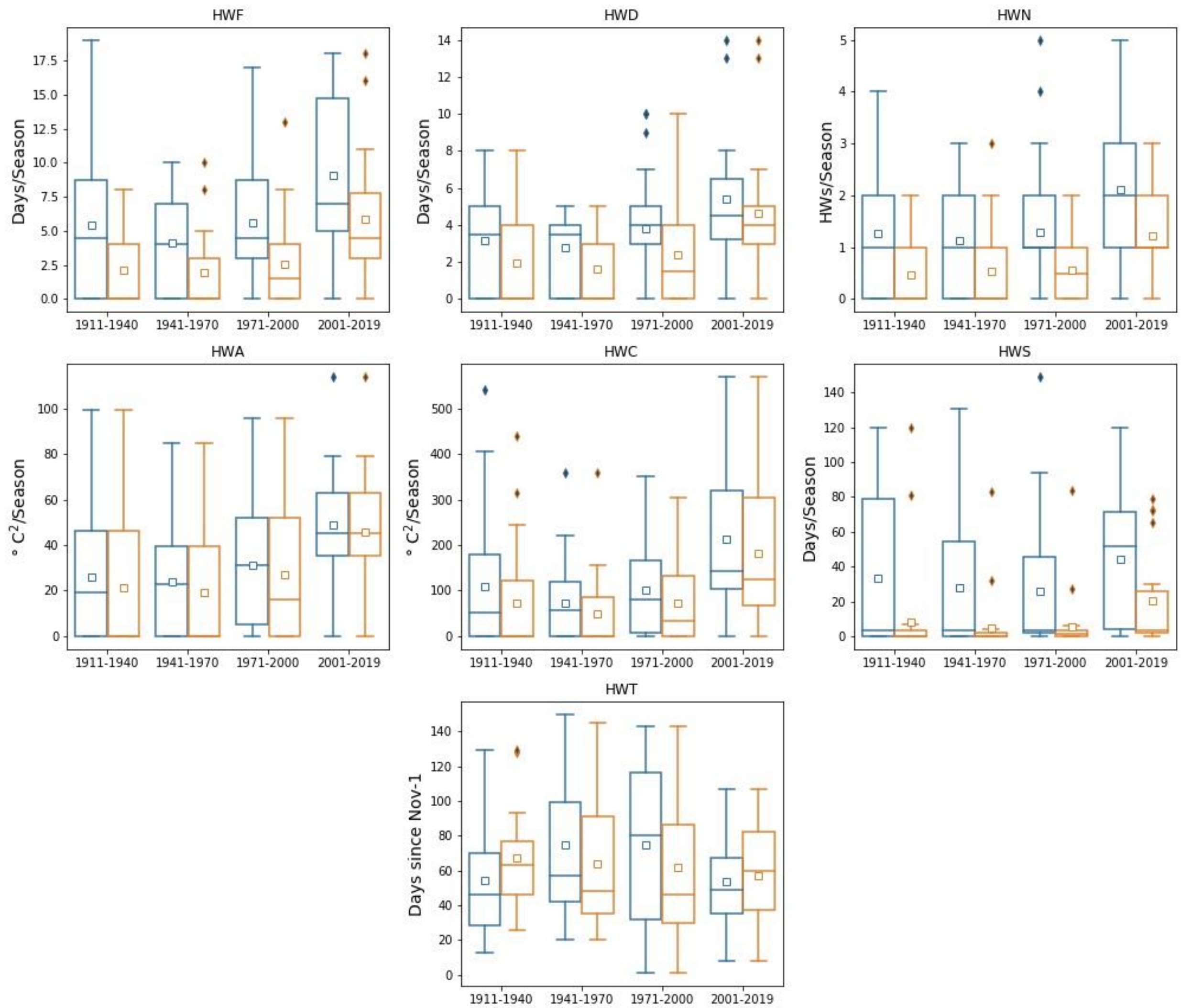


Figure 8. Same as fig. 4 but for Adelaide

5 Conclusions

Heatwaves are becoming more frequent, longer, and hotter as well as generating excess heat, and the season both extending and starting earlier over many parts of Australia during the period 1951-2020. Heatwave trends at a local city-scale are different among the two observational data products (gridded (AWAP) and station (ACORN-SATv2) data). This highlights the sensitivity of Australian heatwave trends to the slight variations in temperature data. Results emphasise that many of the considered heatwave metrics (such as heatwave frequency, amplitude, cumulative magnitude, and season duration) are increasing over most of the selected cities during the period 1911-2019. Results also highlight that severe heatwaves are becoming more frequent and hotter with prolonged season duration in Adelaide during the second half of the study period (1965-2019). The average value of most of the considered heatwave and severe heatwave metrics (such as frequency, duration, number, amplitude, cumulative magnitude, and season duration) is substantially higher in the recent period (2011-19) compared to the previous periods over all the selected cities. The results presented here have important implications for city planning and improved policy design. These results could help in the preparation of advanced heatwave plans for the major urban centres of Australia to mitigate human losses and the effects on infrastructure. Future work on analysing the future projected heatwave trends at a local city scale in increased greenhouse gas environment is needed for the development of better city planning.

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