On the Measurement of Heat Waves

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ABSTRACT

Despite their adverse impacts, definitions and measurements of heat waves are ambiguous and inconsistent, generally being endemic to only the group affected, or the respective study reporting the analysis. The present study addresses this issue by employing a set of three heat wave definitions, derived from surveying heat-related indices in the climate science literature. The definitions include three or more consecutive days above one of the following: the 90th percentile for maximum temperature, the 90th percentile for minimum temperature, and positive extreme heat factor (EHF) conditions. Additionally, each index is studied using a multiaspect framework measuring heat wave number, duration, participating days, and the peak and mean magnitudes. Observed climatologies and trends computed by Sen's Kendall slope estimator are presented for the Australian continent for two time periods (1951–2008 and 1971–2008). Trends in all aspects and definitions are smaller in magnitude but more significant for 1951–2008 than for 1971–2008. Considerable similarities exist in trends of the yearly number of days participating in a heat wave and yearly heat wave frequency, suggesting that the number of available heat wave days drives the number of events. Larger trends in the hottest part of a heat wave suggest that heat wave intensity is increasing faster than the mean magnitude. Although the direct results of this study cannot be inferred for other regions, the methodology has been designed as such that it is widely applicable. Furthermore, it includes a range of definitions that may be useful for a wide range of systems impacted by heat waves.

1. Introduction

It has been established in the scientific literature that effects of anthropogenic climate change extend beyond changes in the mean and encompass adverse shifts in extremes (Trenberth et al. 2007). Indeed, the subject of climate extremes is of great interest globally because of their high monetary, human, and physical impacts (see Karl and Knight 1997; Trigo et al. 2005; Karoly 2009; Cai et al. 2009; Coumou and Rahmstorf 2012). The scale of heat wave impacts highlights the necessity to be able to measure and study extreme events in an informative manner, which does justice to the geographical region affected, the communities impacted, and the climatic fields involved. The fact that dynamical model projections show increases in the frequency, intensity, and duration of temperature extremes over at least the next century (e.g., Kharin et al. 2007; Fischer and Schär 2010; Perkins et al. 2013) makes it all the more important to determine appropriate metrics of heat waves, particularly across various time frames (i.e., past, present, and future) and climatic conditions. However, it is this range of criteria that makes it difficult to determine universal and collective measures of any climate extreme, including heat waves. Therefore, clear and common definitions, at least for some types of extreme events, remain rare or nonexistent.

In the case of heat waves, the overall definition remains very broad in describing a period of consecutive days where conditions are excessively hotter than normal. Based on this definition, heat waves can be both summertime and annual events. This can include minimum temperature ($T_{\min}$) as well as maximum temperature ($T_{\max}$) since high nighttime temperatures can further exacerbate heat wave conditions (Pattenden et al. 2003; Trigo et al. 2005; Nicholls et al. 2008; Nairn et al. 2009). Apparent temperature (Ta), also known as the ''heat index,'' as defined by Steadman (1979, 1984) is calculated from temperature and relative humidity and might also be considered when studying concurrent extreme days

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(e.g., Deo et al. 2007). Many indices tend to be constructed with a certain impact group or sector in mind (e.g., human health, wildlife, agriculture, bushfire–wildfire management, transport, and electricity and power) and, due to their complexity, may not be transportable across more than one region or group. Furthermore, the methodology and variables required may not allow for the examination of changes in the index across long periods of time via climatological data (both modeled and observed). It is therefore understandable that a plethora of metrics (or indices) exists, all attempting to provide quantitative information on periods of extreme or excess heat.

A clear example of this are the indices used to measure human comfort during periods of excess heat. The predicted mean vote (PMV; Fanger 1970) and the physiological equivalent temperature (PET; Mayer and Hoppe 1987) have been employed on small temporal and spatial scales to examine heat stress and human morbidity (e.g., Matzarakis and Mayer 1997; McGregor et al. 2002; Pantavou et al. 2008). Both PMV and PET are based on the human energy balance and include a wide range of variables such as the metabolic rate and clothing factor of an individual. Such variables are difficult to approximate from climatological fields. Using Ta may provide an alternative to bridge the gap between the availability of climatological data and more specific human health heat wave indices (Karl and Knight 1997; Delworth et al. 1999; Robinson 2001; Fischer and Schär 2010; Fischer et al. 2011; Deo et al. 2007). Unfortunately for some regions, limitations exist in the availability and quality of relative humidity observations, mostly due to the quality of the climate variables from which the field is derived. We have illustrated the complexity and rigidness of sector-based heat wave indices using the example of human health; however, other heat wave indices used by specific industry groups show similar intricacy.

Since the complexity of sector-based heat wave indices eliminates their ability to be calculated on climatological scales, great emphasis is placed on temperature-based diagnostics, namely those that describe $T_{\min}$ and $T_{\max}$ extremes. While useful in their own right, many of these indices may not be representing many or even all aspects of heat waves appropriately. The World Meteorological Organization (WMO) Commission for Climatology (CCl)/Climate Variability and Predictability (CLIVAR)/ Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI) have up to eight indices that, either by themselves or combined, have been used for heat wave purposes (SU, TR, TXx, TNx, TX90p, TN90p, and WSDI; see http://etccdi.pacificclimate.org/list_27_indices.shtml). Examples on their use in both observed and modeling studies are vast and span many different regions (e.g., Alexander et al. 2006, 2007; Fischer and Schär 2010; Fischer et al. 2011; Perkins 2011; Avila et al. 2012; Jiang et al. 2012). However, the ETCCDI indices that measure extreme temperature only consider one aspect of a heat wave each, either event duration (WSDI) or frequency of days that *may* be (but are not necessarily) part of a heat spell (SU, TR, TXx, TNx, TX90p, and TN90p). Furthermore, some ETCCDI indices are based on absolute thresholds (SU and TR), which are not suitable in some regions (see Perkins 2011).

Alternatives to absolute thresholds are percentile-based thresholds, which look at occurrences of events that exceed a threshold relative to the area of interest. In the case of hot temperature events, exceedances are *above* the prescribed percentile and can be attained for both $T_{\min}$ and $T_{\max}$. Hot event ETCCDI indices that are based on relative thresholds include WSDI, TX90p, and TN90p. Both TX90p and TN90p focus on the frequency of individual *days*, whereas WSDI considers consecutive days where the threshold is exceeded. Other examples of percentile-based indices used over various regions include Huth et al. (2000), Meehl and Tebaldi (2004), and Fischer and Schär (2010). Huth et al. (2000) and later Meehl and Tebaldi (2004) employed two percentile thresholds to study periods of sustained excess heat in modeling and observational studies, respectively. The thresholds are used to dissect the time series of daily $T_{\max}$, such that a heat wave will only exist if three criteria based on the thresholds are met across a daily time window. This type of index thus allows for the analysis of heat wave duration and frequency via a single metric. Fischer and Schär (2010) also suggest a structure for studying multiple elements of a heat wave, considering more than just event duration and frequency. This framework includes the amplitude (HWA, hottest day of hottest yearly event), the number of events (HWN), their duration (HWD, length in days), and their frequency (HWF, sum of participating heat wave days), where a heat wave exists when at the $T_{\max}$ 90th percentile is exceeded for at least six consecutive days.

Another issue surrounding the measurement if heat waves is the annual occurrence of the events—are such events only a summertime phenomenon, or should anomalously warm events in other seasons also be considered? Indeed, the conditions that cause successive days of warm temperature differ between the seasons (e.g., blocking highs/Rossby wave breaking in summer and poleward advection of warm air during winter), with different communities impacted depending on when an event may occur (e.g., human health during summer and some agricultural sectors during winter). Some indices used for heat wave measurement include information about the entire annual cycle, where consecutive days and/or exceedances above a seasonal cycle of thresholds are considered. This means that thresholds exist for *all* seasons of the year, not just summer. Examples of these include the WSDI, TX90p, and TN90p ETCCDI indices, as well as some suggested by Fischer and Schär (2010). Other indices are geared toward a single (i.e., summer) season, where thresholds are set such that extreme conditions can only occur during warmer periods of the year (e.g., SU, TR, TNx, and TXx; see Huth et al. 2000; Meehl and Tebaldi 2004; Nairn et al. 2009). When considering the impacts of heat waves, which are of course, sector-specific, it is imperative to know how an index measures the events, as employing the wrong index for a specific purpose could result in incorrect information, resulting in poor adaptation and mitigation planning.

Because of the range of groups and sectors affected by heat waves it is, of course, impossible to obtain a single index that is appropriate across each group *and* can be calculated from readily available climatological data. It is possible, however, to define a set of metrics that can be readily calculated from climatological data and provide information on various aspects of heat waves. Such methods have great potential to be useful to many different sectors affected by heat waves, as well as being applicable to a broad range of climates. The present study attempts to achieve this, using Australia as a case study, given that numerous different climate regimes exist within a single region (Perkins et al. 2007). The impacts of heat waves are felt across all groups and sectors listed above, and little work to date has focused specifically on observed heat waves over this region. Previous extreme-based studies over Australia include trends in percentile-based indices (Torok and Nicholls 1996; Plummer et al. 1999; Collins et al. 2000; Alexander et al. 2007), the employment of the multivariate and nonparametric climate extremes index (Gallant and Karoly 2010), the use of reanalysis data to study periods of consecutive days above the 90th percentile (Tryhorn and Risbey 2006), and atmospheric dynamics behind heat wave occurrences (Pezza et al. 2012). Such studies have either used the observational record *or* focused on heat waves, and no study to date has specifically focused on observed heat waves over the Australian region. It is anticipated that heat wave indices that are deemed appropriate for Australia will also be as suitable for other regions across the globe.

This paper therefore has two main aims: 1) to investigate a range of heat wave and heat wave–related indices in terms of their feasibility across varying climates and 2) to provide a spatially uniform comparison of trends and occurrences of observed heat waves over Australia using the preferred indices outlined by the first aim. Section 2 will discuss the methods used and outline the preferred indices. Section 3 will present results of observed trends and occurrences for Australia, followed by a discussion in section 4 and conclusions in section 5.

2. Methods

a. Data

Given that one aim of the present study is to present spatially uniform information on observed Australian heat waves, an appropriate gridded dataset is required. The Australian Water Availability Project (AWAP) dataset provides daily gridded observations of $T_{\min}$ and $T_{\max}$, as well as vapor pressure and precipitation at $0.05° \times 0.05°$ resolution (Jones et al. 2009). Using a hybrid technique that combines empirical interpolation and function fitting, daily gridded observations are constructed from *all* available stations across the Australian continent (Jones et al. 2009). Available stations are all managed by the Australian Bureau of Meteorology, and are included for all points of time for which they have applicable data, meaning that stations may ''drop'' in and out of the gridding algorithm if their time series is not continuous. However, the use of all stations allows for far greater spatial coverage across the sparsely populated continent than has been achieved previously, permitting the analysis in the present study.

Because of computational constraints, all analysis was performed on a $0.5° \times 0.5°$ grid, created via bilinear interpolation from the original 5-km grid. The variables used are discussed below. To explore differences in resolution uncertainty, all experiments were also performed at $1° \times 1°$ and $2° \times 2°$; however, decreasing the resolution did not substantially affect the magnitude or spatial distribution of the results (not shown). All analysis was performed for 1951–2008 and 1971–2008 separately, to investigate whether different results exist for different time periods.

b. Heat wave indices—Aspects and definitions

To determine a set of applicable heat wave definitions and methods, a wide range of heat wave and extreme temperature indices already defined in the scientific literature were explored. Since this initial analysis is not central to the present study, the appendix provides a list of these metrics, a brief description of their method and the variables required, and the reference from which they were derived (Table A1); also, it illustrates why some of these indices are not appropriate for quantifying heat waves (Fig. A1). The rest of this section provides a more in-depth description of the heat wave indices presented in section 3, which were developed from the original indices studied. In this study we group the indices used into aspects and definitions, where an aspect represents a certain characteristic of a heat wave (e.g., frequency, duration, magnitude) and a definition refers to *how* the heat wave is obtained from the data. Therefore, for each heat wave definition used, all aspects are calculated.

In terms of the aspects, we adopt a similar methodology to Fischer and Schär (2010), when conditions above the criteria persist for a number of days. Based on the definitions below, we consider a heat wave to be an event of at least *three* consecutive days (Collins et al. 2000; Pezza et al. 2012), which differs from events of at least six days' length used by Fischer and Schär (2010) and the warm spell duration index (WSDI, defined by ETCCDI); and single (1 day) threshold exceedances used by other ETCCDI indices. Fischer and Schär (2010) focus on yearly values of HWF, HWN, HWD, and HWA for 30-yr time slices. Our methodology is also uses these heat wave aspects, but we also include the average heat wave magnitude (HWM). All five aspects are calculated yearly, such that HWM is the average daily magnitude across all heat wave events within a year; HWA is the hottest day (or peak) of the hottest yearly event; HWN is the yearly number of heat waves; HWD is the length (in days) of the longest yearly event; and HWF is the sum of participating heat wave days per year that satisfy the definition criteria. The three heat wave definitions are employed as described below:

1) CTX90pct—The threshold is the calendar day 90th percentile of $T_{\max}$, based on a 15-day window. That is, there is a different percentile value for each day of the year (thereby accounting for the seasonal cycle), where the window is centered on the day in question. Using a moving window accounts for temporal dependence while producing a reasonable sample size to calculate a realistic percentile value. The thresholds are calculated for each time period and grid box separately.
2) CTN90pct—The threshold is the calendar day 90th percentile of $T_{\min}$, as described for $T_{\max}$.
3) EHF—This stands for the Excess Heat Factor, as defined by Nairn et al. (2009). This index is based on two excess heat indices (EHIs):

$$\begin{aligned}\mathrm{EHI(accl.)} &= [(T_i + T_{i-1} + T_{i-2})/3] \\ &\quad - [(T_{i-3} + \ldots + T_{i-32})/30], \qquad (1)\end{aligned}$$

$$\mathrm{EHI(sig.)} = [(T_i + T_{i-1} + T_{i-2})/3] - T_{95}, \qquad (2)$$

where T_i is the average daily temperature for day i, and T_{95} is the climatological (i.e., non-time-varying) 95th percentile for the time period in question. The average daily temperature is defined as the average $T_{\min}$ and $T_{\max}$ within a 24-h cycle (0900-0900 LT). EHI(accl.) describes the anomaly over a 3-day window against the preceding 30 days, and EHI(sig.) describes the anomaly of the same window against an extreme threshold. Therefore, the respective EHI (sig.)–EHI(accl.) on day i is dependent on the previous two days; cool daily average temperatures on days $i - 1$ and $i - 2$ may reduce the overall average across the 3-day window, which will impact the climatological–acclimatization anomaly on the day of interest. Equations (1) and (2) are then combined to derive EHF:

$$\mathrm{EHF} = \max[1, \mathrm{EHI(accl.)}] \times \mathrm{EHI(sig.)}, \qquad (3)$$

where positive values of EHF define heat wave–like conditions for day i. Therefore, based on our criteria (heat wave–like conditions must persist for at least three days), EHF must be positive for at least i, $i + 1$, and $i + 2$. Nairn et al. (2009) defined the index for operational forecasts, and it has been used to study the impacts of extreme heat events on human health and mortality (PwC 2011). Because of the multiplication of the EHI(accl.) and EHI(sig.) indices, the unit of EHF is degrees Celsius squared.

These preferred definitions are chosen not only for the reasons described in section 3, but also because of their applicability to regions other than Australia, the quality of the data required to calculate them, and the feasibility of their methodology. A larger sample of heat wave indices, which included fixed thresholds, higher percentiles, and Ta, was also studied using the five-aspect methodology. However, these were found to be unsuitable from a climatological perspective (see the appendix). We make clear that while CTX90pct and CTN90pct measure events across the entire annual cycle, we only consider events that occur during a 5-month austral summer (November–March) for all three definitions. The season begins in either 1951 or 1971, thereby giving 57 or 37 years of heat wave analysis, respectively.

The 90th percentile for CTX90pct and CTN90pct was chosen because of an "adequate" population of measurable events. The appendix figure (Figs. A1c,f) shows that using the 95th percentile for $T_{\min}$ and $T_{\max}$ results in very few events being measured—although the 95th percentile corresponds to ~18 days yr^{-1}, the organization into blocks of at least three days is barely measurable. Conversely, the use of a smaller threshold (e.g., 80th/85th percentile) resulted in too many or too long events being measured (not shown). This resulted in the selection of the 90th percentile, where the balance of ''extreme'' versus ''measureable'' was determined to be optimum.

The summer season was analyzed in this study because of the high impacts of such events over Australia (Karoly 2009; Coumou and Rahmstorf 2012). However, using a similar suite of heat wave definitions, Perkins et al. (2012) demonstrate changes in bother summertime and annual events at the global scale. Furthermore, the calculations of HWA and HWM for CTX90pct and CTN90pct in this study are anomaly-based, where the summertime mean is subtracted from annual summer values of the aspect, removing the seasonality and depicting *how hot* heat waves are compared against expected summertime conditions. This information may be more useful from an impacts perspective than absolute values of HWA and HWM. Since EHF is anomaly-based by definition, a similar conversion of the respective heat wave aspects was not necessary.

Using the yearly values for each heat wave definition, the trend and the overall average was calculated per aspect (HWA, HWM, HWF, HWN, and HWD) for the two time periods. Trends were calculated per decade using Sen's Kendall slope estimator, which is nonparametric and is robust against outliers and nonnormally distributed data (Sen 1968; Zhang et al. 2005; Caesar et al. 2011). The ordinary least squares (OLS) method was also explored for fitting trends; however, it was found that the residuals where almost always not normally distributed, particularly for the HWN and HWD aspects. This means that parametric trend methods that assume normality, such as the OLS method, are inappropriate. Extreme events by definition occur within the tail of a distribution, thereby approaching an asymptotic regime, which violates the assumption of normality. Nonparametric methods are highly recommended for the trend estimation of all climate extremes.

Trends were estimated at a grid box when at least 20 years of data existed and statistical significance was computed at the 5% significance level. Regions where statistically significant trends exist are very similar for both the OLS and Kendall methods. Averages of HWA, HWM, and HWD were calculated for only those years where heat waves occurred, whereas averages of HWF and HWN were calculated across the whole time period. Trends are presented for both periods analyzed; however, climatologies are presented for 1951–2008 only, given the considerable similarity between the two time periods for all three heat wave definitions and their five aspects.

3. Results

This section explains the results of HWN (yearly number of heat waves), HWD (length of the longest yearly event), HWF (yearly sum of participating heat wave days), HWA (hottest day of hottest yearly event), and HWM (average magnitude of all yearly heat waves) for all three indices. For each heat wave definition, the climatological average of the respective aspect is presented for the period 1951–2008, as well as trends for 1951–2008 and 1971–2008. Differences in trends between the two periods are discussed, as well as differences in climatologies across the Australian continent.

a. HWN (yearly number of heat waves)

Figure 1 shows the climatologies and trends of the yearly number of heat waves (HWN) for each index. CTX90pct (Fig. 1a) measures 1.5–2 heat waves yr^{-1} for most of Australia, except for the southwest and southeast coast where the average number of events is no more than one per year. CTN90pct (Fig. 1d) tends to measure less events, averaging between 0.75 and 1.75 events yr^{-1}. The highest number of heat waves are measured by EHF (Fig. 1g), with 1.5–2 heat waves yr^{-1} measured for most of the continent and reaching 2.5 heat waves yr^{-1} in some eastern and central western areas. HWN climatologies are higher for CTX90pct (Fig. 1a) than for CTN90pct (Fig. 1d), which suggests that consecutive nights of extreme high $T_{\min}$ are less common over Australia than consecutive days of extreme $T_{\max}$. Given the dry climate of Australia, which induces little cloud cover, heat accumulated through solar forcing during the daytime may dissipate during clear nighttime conditions. Such circumstances may allow for consecutive extreme daytime temperatures while inhibiting consecutive nighttime extremes. These climatic conditions also impact the HWD (length of the longest yearly event; Fig. 2) and the yearly sum of participating heat wave days (HWF; Fig. 3) aspects of CTX90pct.

Although CTX90pct measures, on average, more heat waves than CTN90pct (i.e., there are more $T_{\max}$-based heat waves than $T_{\min}$-based heat waves), in some areas the numbers of CTN90pct events are increasing faster than CTX90pct events. Over 1951–2008 all indices show significantly positive trends (0.2–0.6 heat waves $decade^{-1}$) for central Western Australia, northeast Australia, and parts of southeast Australia, which extend over larger areas for CTN90pct (Fig. 1e) and EHF (Fig. 1h). EHF trend magnitudes are noticeably larger for 1971–2008 (Fig. 1i) over the same regions, with significant increases of at least 0.5 heat waves $decade^{-1}$. CTX90pct exhibits similar trends over the same regions

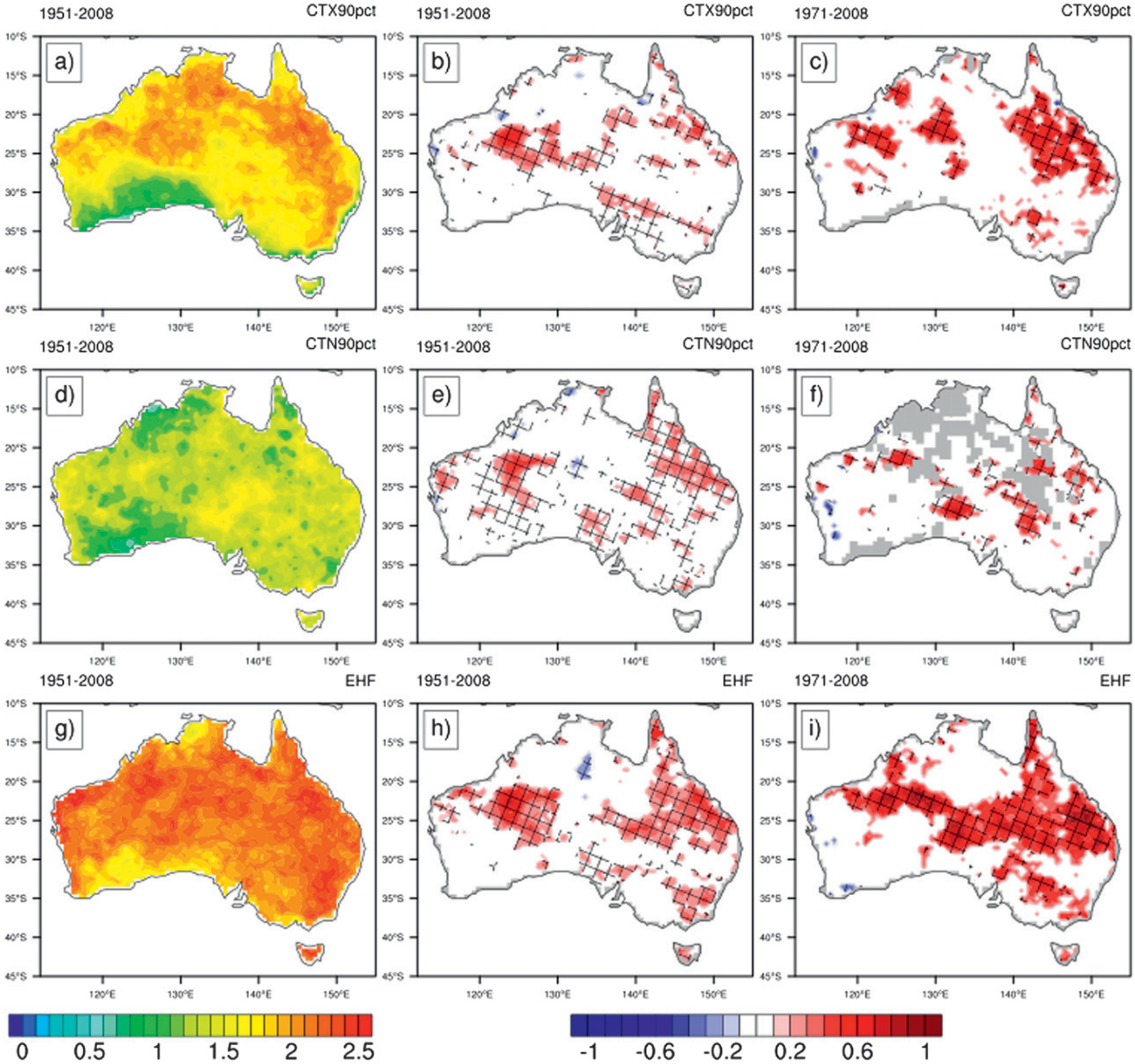

FIG. 1. Climatologies and trends for HWN (yearly number of heat waves): (a),(d),(g) the 1951–2008 climatologies for (top)–(bottom) CTX90pct, CTN90pct, and EHF, respectively; (b),(e),(h) the corresponding 1951–2008 trends computed by Sen's Kendall slope estimator; and (c),(f),(i) the corresponding 1971–2008 trends. Hatching indicates statistical significance of trends at the 5% level. Trends are calculated where at least 20 yr of data exist, leaving some areas shaded gray where trends could not be calculated, particularly for 1971–2008 trends of CTN90pct. Units are in occurrences per year for climatologies, and occurrences per decade for trends.

(Fig. 1c), although they are more confined (no trend exists in central northeast Australia). For CTN90pct (Fig. 1f) most trends are either insignificant or not computable; however, trends that are significant occur over similar regions to the 1951–2008 trends, albeit slightly larger in magnitude (0.4–0.7 heat waves decade^{-1}). For the rest of the continent, trends in HWN are approximately zero for each index and time period, suggesting that over these regions the yearly number of heat waves has not produced a measureable change.

b. HWD (length of the longest yearly event)

Figure 2 shows the climatologies and trends of the length of the longest yearly event (HWD) for each index (recall that for a heat wave to exist, conditions must persist for at least three days). Similar to HWN (yearly number of heat waves), the average is similar for each index across both time periods. CTX90pct (Fig. 2a) measures the longest heat wave length to be, on average, 6.5–8 days in the north and 3–4 days in the southwest and

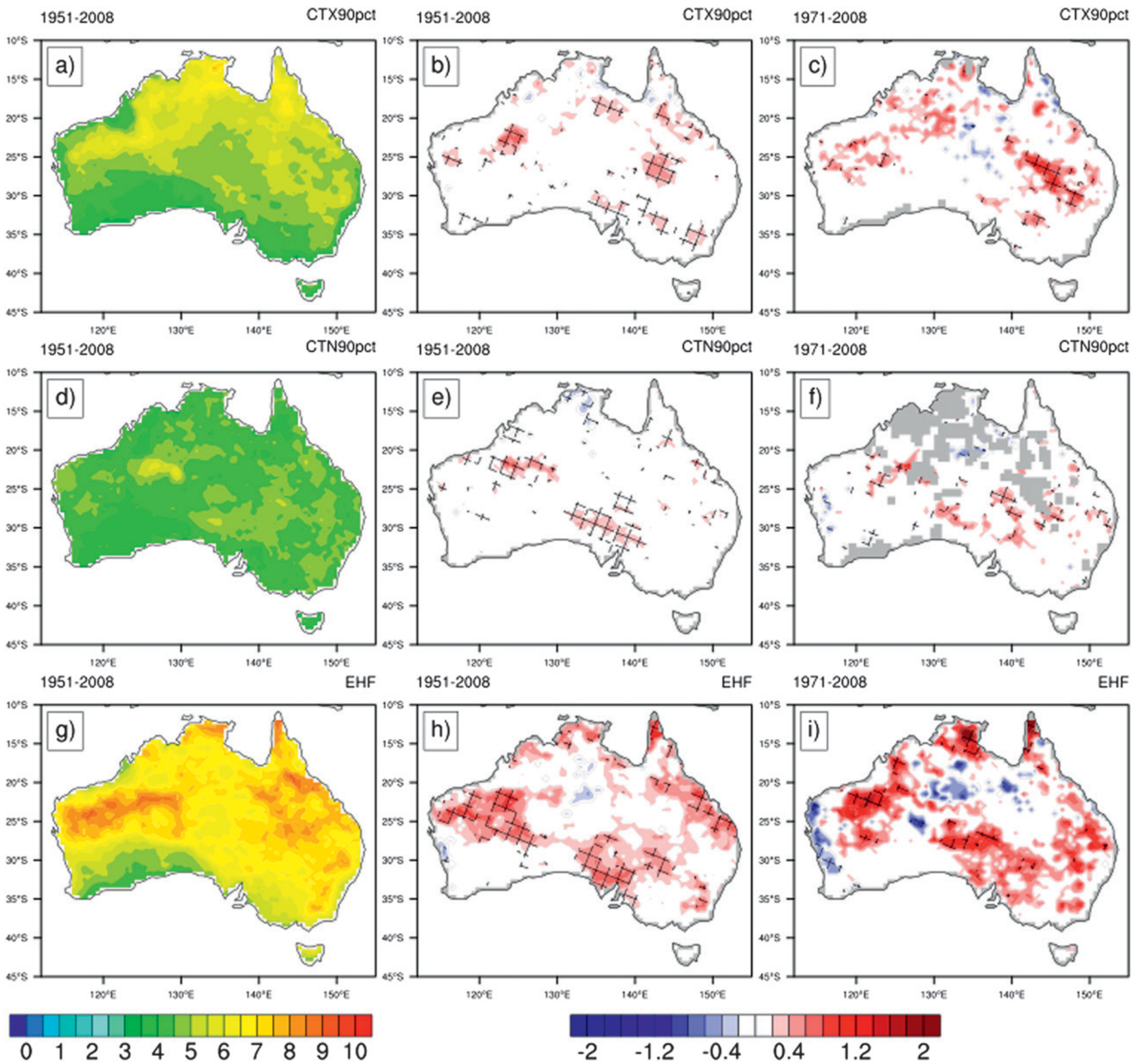

FIG. 2. As in Fig. 1, but for HWD (length of the longest yearly event). Units are days per year for climatologies and days per decade for trends.

southeast. Heat waves measured by CTN90pct (Fig. 2d) are of shorter duration for most of the continent to CTX90pct (4–5 days) but are of similar length in the southwest. Average HWD based on EHF (Fig. 2g) is 6.5–8 days for most of the continent, with smaller lengths of 3–5 days in the southwest and 5–6 days in the southeast.

Trends in HWD are less significant than HWN (yearly number of heat waves) trends (Fig. 1) for all three indices. For 1951–2008, statistically significant HWD trends are generally confined to smaller areas in the west, south, and east when compared to HWN trends. Such trends are no more than 0.4 days decade^{-1} for CTX90pct (Fig. 2b) and CTN90pct (Fig. 2e) and up to 0.6 days decade^{-1} for EHF (Fig. 2h). Trends in CTX90pct and CTN90pct are generally close to 0 for the rest of Australia, although EHF produces nonsignificant trends of 0.4 days decade^{-1} over some eastern and far northern areas. Fewer significant trends are measured for 1971–2008 for all three indices. This is despite an increase in trend magnitude for EHF (Fig. 2i). Decreasing (nonsignificant) HWD trends of up to 1.2 days decade^{-1} are evident along the central Western Australian coast and small areas of central Australia for EHF. Most HWN trends over 1971–2008 for CTX90pct (Fig. 2c) and CTN90pct (Fig. 2f) are generally close to 0 or slightly

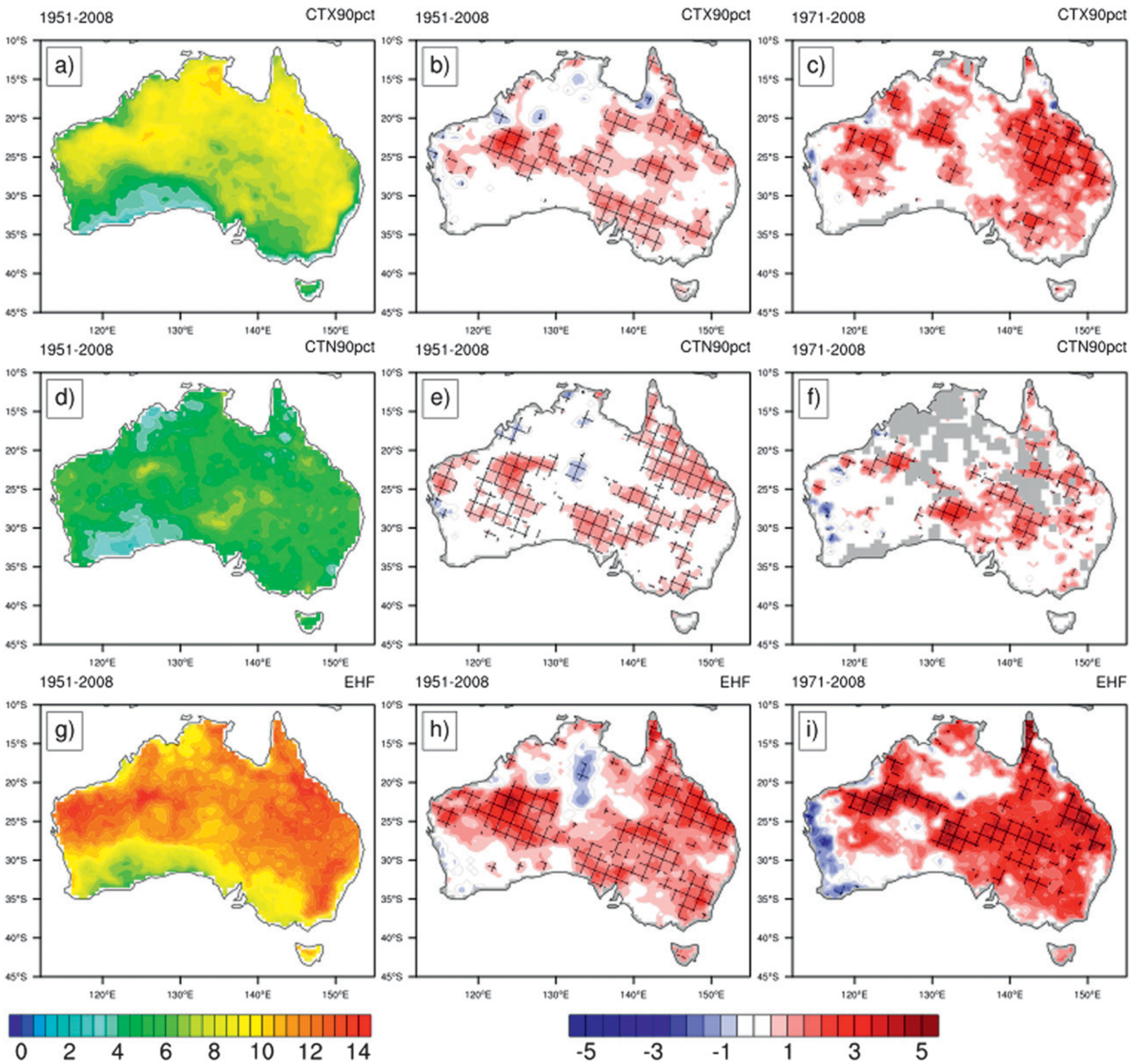

FIG. 3. As in Fig. 2, but for HWF (yearly sum of participating heat wave days).

positive (0.4 days decade^{-1}) or, in the case of CTN90pct, not measureable. It is interesting to note that while the general areas of significance for HWD and HWN are similar, they do not always directly overlap.

c. *HWF (yearly sum of participating heat wave days)*

Figure 3 shows the climatologies and trends of the yearly sum of participating heat wave days (HWF) for each index. The climatological patterns between the indices are similar for HWF as they are for HWD (length of the longest yearly event Fig. 2) and HWN (yearly number of heat waves; Fig. 1), since the number of heat wave days influences event duration and number (note that it is not simply HWF = HWD × HWN, as HWD measures the length of the *longest* event, not the average length). On average, CTX90pct measures 8–9 heat wave days yr^{-1} for much of the continent (Fig. 3a), decreasing to 3–4 days yr^{-1} in the southwest. CTN90pct (Fig. 3d) measures fewer heat wave days than CTX90pct, measuring 4–6 days yr^{-1} for most of Australia and 3–4 days yr^{-1} in the southwest. EHF (Fig. 3g) measures the highest amount of heat wave days per year, with at least 9 days yr^{-1} for most of Australia. Indeed, the number of heat wave days is at least 11 days yr^{-1} for much of the eastern, central and western regions. In the south and southwest, this number falls to 4–6 days yr^{-1}.

Trends in the yearly sum of heat wave days (HWM) show spatial patterns similar to those of HWN (yearly number of heat waves; Fig. 1) and HWD (length of the longest yearly event; Fig. 2) combined, respective to each index. That is, areas where trends are statistically significant for HWN and/or HWD are also statistically significant for HWF. Since the number of heat wave days is the base unit that directly influences event length and occurrence, a change in the number of days participating in heat waves (i.e., HWF) means that the duration of heat waves (i.e., HWD) and/or their yearly number (i.e., HWN) must also change accordingly. Across most of Australia, for all definitions and time periods, an increase in HWF results in an increase of HWN and HWD. Indeed, for all definitions the greatest similarity is between HWF and HWN, implying that changes in the number of participating heat wave days drive the overall number of heat wave events. Furthermore, the magnitudes of HWF trends are 3 times larger than for HWD. This means that when the sum of participating heat wave days increases by 2 days decade^{-1}, the average number of heat waves increases by 0.4 events decade^{-1}.

Trends in HWF for 1971–2008 (Figs. 3c,f,i) are greater than for 1951–2008 (Figs. 3b,e,h). For both time periods, EHF produces trends that are 1–2 days decade^{-1} greater than CTX90pct and CTN90pct; however, the spatial patterns of trends are very similar across all three indices. The exception to this is the southwest coast of Western Australia, where EHF produces (nonsignificant) declining trends of up to 2 days decade^{-1} for 1971–2008, analogous to declining HWD trends in Fig. 2i.

d. HWA (hottest day of hottest yearly event)

Figure 4 shows the climatologies and trends of the hottest day of the hottest yearly event (HWA) for each index. Both CTX90pct and CTN90pct are represented as anomalies against the respective 5-month summertime mean. Figures 4a and 4d show that the largest anomalies for these indices (up to 15°C) occur over southern areas of Australia, and are confined to the central southeast for CTN90pct. This means that the hottest day (night) of the hottest yearly heat wave is, on average, 15°C warmer than the summer mean $T_{\max}$ ($T_{\min}$). HWA anomalies decrease to 2°–3°C over northern Australia, where a tropical climate imposes less diurnal and seasonal variation in temperature than in the southern regions. The average HWA for EHF (Fig. 4g) shows similar patterns to CTN90pct, but with larger magnitude southward of 20°S. This is due to the calculation of EHF, where two anomaly-based indices are multiplied, resulting in units of degrees Celsius squared [recall Eq. (3)]. While this makes HWA measurements from EHF also anomaly-based, caution should exerted when comparing magnitudes to CTN90pct and CTX90pct, as EHF focuses on the *excess* heat felt during a heat wave, derived from two previously calculated indices [recall Eq. (3)].

Based on EHF, the northern half of Australia does not tend to experience extremely hot heat waves, as average peaks are no more than 12°C^2, for reasons similar to those explained above. In southern, more temperate regions, average peaks increase to up to 45°C^2 along the eastern side of the Great Australian Bight. It is interesting to note that areas of highest HWA values for EHF align with areas of blocking highs, which cause the tropospheric conditions required for extreme heat waves, such as the so-called "Black Saturday" event in February 2009 (Nairn et al. 2009; Pezza et al. 2012). These blocking highs bring persistent warm advection from inland areas with little nighttime relief (Pezza et al. 2012), and participating days would be extremely hot when compared to the climatological threshold, as well as to the preceding month. Since EHF is based on these measurements, it is able to measure important regional dynamical influences on heat waves that can have substantial impacts on heat wave intensity (Nairn et al. 2009) and also on duration (Pezza et al. 2012).

Similar to HWN (yearly number of heat waves), HWD (length of the longest yearly event), and HWF (yearly sum of participating heat wave days), larger trends in HWA occur during 1971–2008 (Figs. 4c,f,i) than in 1951–2008 (Figs. 4b,e,h) for all three definitions. For comparison across the three definitions, the square root of EHF was taken before trends were calculated, such that trends can be compared. All definitions exhibit similar areas of increasing trends over western, southern, and northeast Australia for both time periods. CTX90pct and CTN90pct produce the largest magnitudes, being at least 1°C decade^{-1} over western and southern Australia for 1971–2008. Corresponding trends in EHF are no more than 0.8°C decade^{-1}. This suggests that the rate of change in the intensity of a heat wave is reliant on whether seasonal adaptation is considered. The sign of the change, however, is broadly consistent across all heat wave definitions. For some areas, increases in the peak of a heat wave during 1951–2008 are slightly larger for CTN90pct than CTX90pct, suggesting that nighttime events are warming faster than warm daytime events for this time period. This result has been found over other global regions (e.g., Alexander et al. 2006) although global trends in the diurnal temperature range appear to have flattened since the 1980s (Trenberth et al. 2007; Vose et al. 2005).

Small areas of decreasing trends exist for each definition, which are generally consistent across the two time periods. Statistically significant HWA trends are

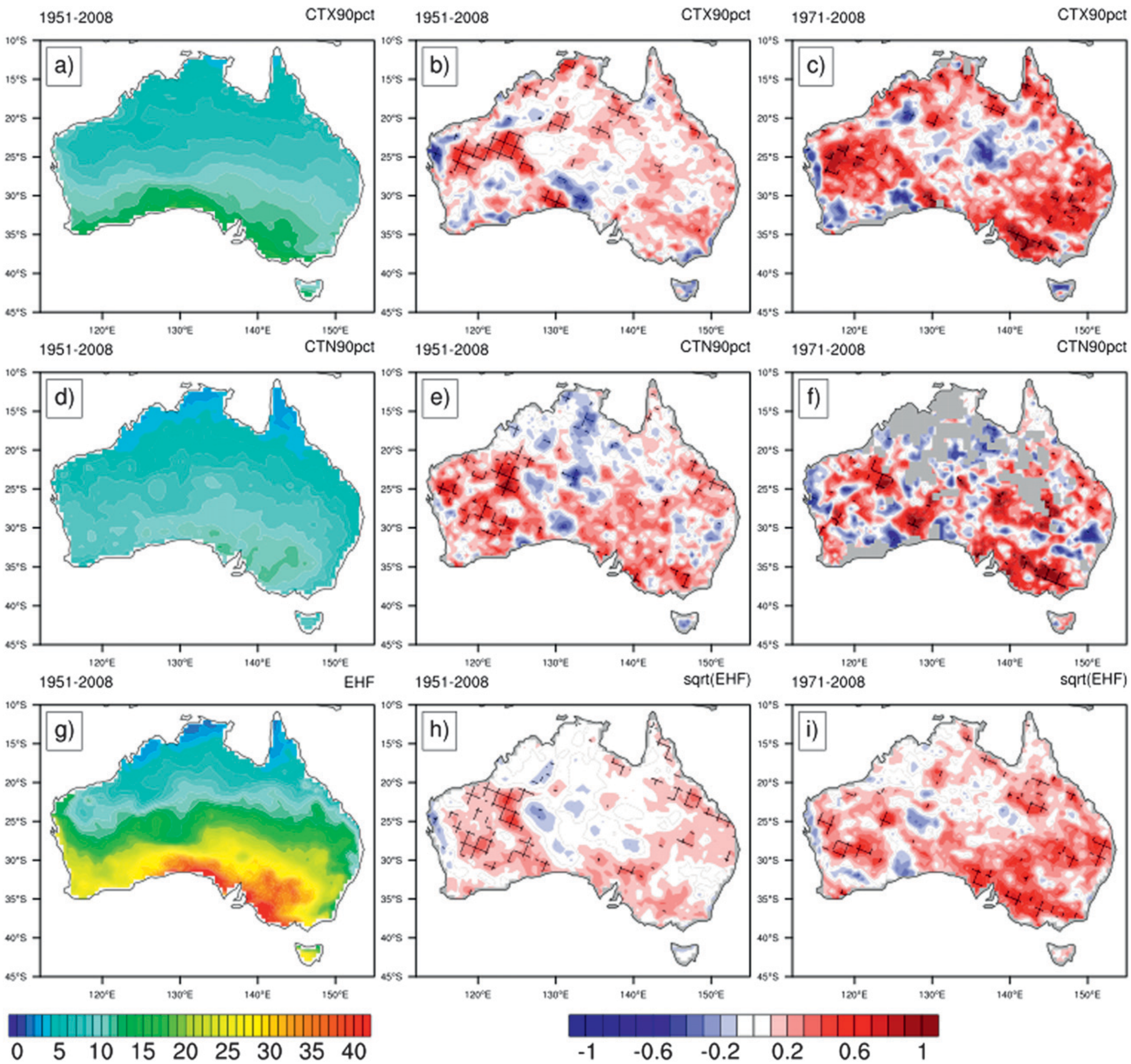

FIG. 4. As in Fig. 1, but for HWA (hottest day of hottest yearly event). Shown are CTX90pct and CTN90pct climatologies (°C) and trends (°C decade^{-1}), and are anomalies against the mean summertime temperature. Also shown are EHF climatology (°C^2) and trends (°C^2 decade^{-1}).

confined to the central west for all three definitions and the northeast coast for CTX90pct and CTN90pct during 1951–2008. Similar trend patterns exist during 1971–2008, but for more confined areas. The spatial patterns in trends of HWA for CTX90pct and EHF are similar to the results of Deo et al. (2007) in terms of the sign and regional significance.

e. HWM (average magnitude of all yearly heat waves)

Figure 5 shows the climatologies and trends of the average magnitude of all yearly heat waves (HWM) for each index. Similar to section 3d, HWM of CTX90pct and CTN90pct are anomalies against the respective summertime mean temperature. Spatially, the patterns are very similar to the respective HWA (hottest day of hottest yearly event) results in Fig. 4. For CTX90pct and CTN90pct (Figs. 5a,b) the climatology of mean heat wave magnitude is generally 2°–4°C less than the climatology of the peak magnitude (Fig. 4a). EHF mean magnitudes (Fig. 5g) are generally 6°C^2 smaller than EHF peak magnitude (Fig. 4g) northward of 30°S, but up to 30°C^2 smaller in the central southeast. The range of

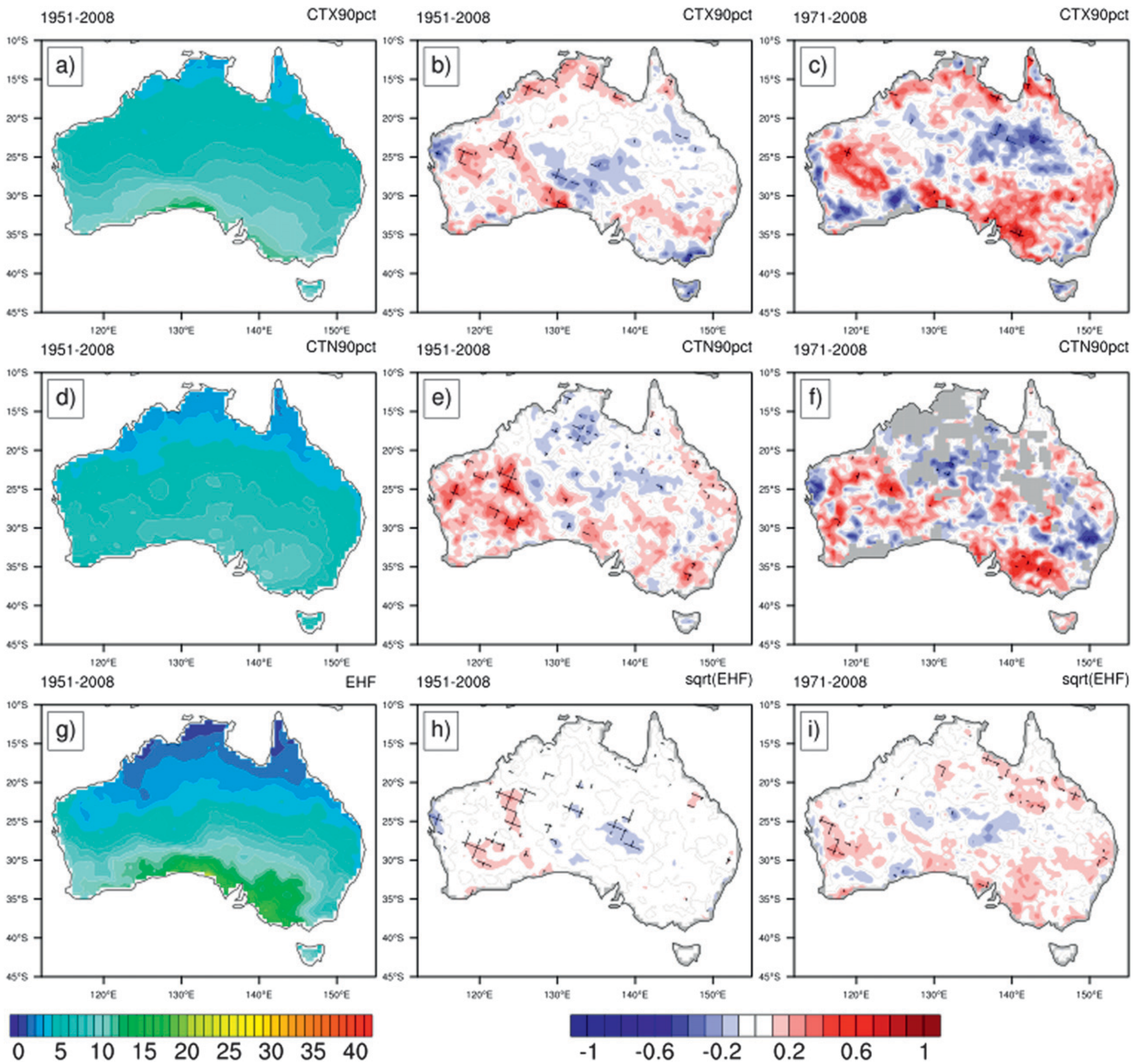

FIG. 5. As in Fig. 4, but for HWM (average magnitude of all yearly heat waves).

magnitudes (i.e., the difference between heat wave peak and mean) obtainable for a definition that considers anomalies and seasonal adaptation is much larger compared to single threshold-based indices. Furthermore, an individual heat wave based on EHF may have peak or mean magnitude values much greater than the respective HWA or HWN (yearly number of heat waves) climatologies (e.g., Nairn et al. 2009); however, the respective heat wave peak and mean anomaly of CTX90pct or CTN90pct heat waves may be very similar to each other, and to the respective climatologies presented in Figs. 4 and 5. The anomalies of HWA (hottest day of hottest yearly event) and HWM (average magnitude of all yearly heat waves) for CTX90pct (Figs. 4a, 5a) are slightly larger than for the respective CTN90pct aspects (Figs. 4d, 5d), indicating that heat waves based on T_{max} are hotter than T_{min} events, when compared to the relevant background conditions.

The spatial distribution of HWM (average magnitude of all yearly heat waves) trends is very similar to HWA (hottest day of hottest yearly event; Fig. 4) for each definition and time period; however, trend magnitudes of HWM are generally half the size of HWA. HWM defined by CTN90pct increases by 0.2°–0.4°C decade^{-1} over western Australia during 1951–2008 (Fig. 5e), and by 0.6°–0.7°C decade^{-1} over western and southeast

Australia during 1971–2008 for CTX90pct (Fig. 5c) and CTN90pct (Fig. 5f). There are also subregional areas of decreasing trends for CTX90pct and CTN90pct during 1971–2008. This highlights regional and temporal variation in the change of mean heat wave conditions per definition used and time period analyzed. Almost no visible trends occur during 1951–2008 for EHF measurements of HWM; however, trends of $0.2°C^2$ decade^{-1} occur over small regions for 1971–2008. Trends of HWM for all indices are generally not statistically significant.

4. Discussion

a. Comparison of heat wave definitions and aspects

For much of the continent, trends in all five heat wave aspects that are significant are increasing for all three definitions (Figs. 1–5, second and third columns). Furthermore, for each aspect, areas of significant trends among the three definitions are quite similar in both sign and spatial extent, particularly for 1951–2008. Such trends are also similar to those presented by Perkins et al. (2012), who employed the gridded daily Hadley Centre Global Historical Climatology Network (HadGHCND) dataset to study global observed trends. Regions where no trends are detected for each aspect (particularly for HWN, HWD, and HWF) are also comparable among the definitions. Actual trend magnitudes differ among the definitions, however, because of the different methodologies employed for CTX90pct, CTN90pct, and EHF. The most similar patterns among heat wave aspects are between HWF (yearly sum of participating heat wave days; Fig. 3) and HWN (yearly number of heat waves; Fig. 1) for each index pair, where areas of significant increases are very similar. That is, for regions where the annual sum of heat wave days increases so does the yearly incidence of heat wave events. Such results imply that significant (longer term) changes in HWF and HWN are robust across the indices used.

To a lesser extent, some regions also show an increase in the length of the longest yearly event (HWD; Fig. 2) as the number of available heat wave days increases. It is likely that the overall number of heat waves (and their duration) will increase when the number of participating days increases—more available heat wave days in a given year may therefore drive more heat wave events (and/or longer events) in that year. However, it is difficult to determine by how much HWN an HWD will change, based on changes in HWF alone. Such relationships are likely to be highly regional and may even depend on the dataset employed (see Tryhorn and Risbey 2006). The Australian case study results presented here may not necessarily apply to other global regions. It is therefore important to consider multiple heat wave aspects in order to understand the full extent of heat wave behavior for every region of interest.

There are some spatial similarities between trends in HWA (Fig. 4) and HWM (Fig. 5) per index; however, the change in the average temperature felt during a heat wave (i.e., HWM) is smaller than the change in the hottest day of the hottest yearly event (i.e., HWA). This may, at least in part, be explained by the lengthening of heat waves—while more days are consecutively exceeding the threshold, it may be only slightly so, thereby dampening any increase in HWM. Since HWA is based on a single day, it is not affected by an increase in the length of an event, provided it still occurs during an event of at least three days. However, this is still an important result as it indicates that, over Australia, the most extreme part of a heat wave is increasing. This may have considerable implications for many different sectors, as they may need to revise their preparedness strategies to account for changes in the most dangerous part of a heat wave. In general, however, trends of HWA and HWM are not significant over the time periods analyzed in this study.

Across all five heat wave aspects and both time periods there is an area of largest increasing trends over central Western Australia. However, caution is advised when interpreting trends for this region. Much of Western Australia has a sparse spatial distribution of observation stations, which means that data are heavily interpolated within this region (see Jones et al. 2009). For some heat wave aspects, there are areas of decreasing trends in the central north and the west Australian coast, surrounded by areas of opposite and equally large and/or larger trends (e.g., EHF on the western coast for HWN, HWD, and HWF, 1971–2008; Figs. 1i, 2i, 3i). Although it is certainly possible that decreasing trends are occurring in the real world, the spatial extent of these trends may not be correctly represented in the AWAP dataset for the reasons just described. It may be that one or two local stations *are* showing declining trends in heat waves, yet the calculation of AWAP sees this extended beyond its true spatial limits. However, at least for some variables, AWAP appears to do sufficiently well at representing trends and variability in extremes in areas with dense station coverage (King et al. 2013).

b. Closing the gap on heat wave definitions

Similarities and differences between the three preferred definitions of a heat wave have been highlighted above. Although it would be an attractive outcome, the authors are cautious not to select a single heat wave definition that is recommended for all applications.

It is hoped that this analysis will allow readers to determine which definition and methodology are best for their purposes, and how they compare to other heat wave definitions. For example, those in farming and agriculture may be more interested in $T_{\min}$-based heat waves, which can affect the growth and planting time of some crops (e.g., Peng et al. 2004; Liu et al. 2006; Lanning et al. 2011). Those in the engineering industry may only be interested in periods of consecutive extreme $T_{\max}$ days, which may impact the integrity of human structures such as buildings, power, and transport networks (Colombo et al. 1999; Pezza et al. 2012). Health experts, however, may require a combination of periods of $T_{\max}$ and $T_{\min}$ and anomalies that consider relative conditions, as the capability for nighttime relief and adaptation can have a profound impact on excess mortality and morbidity (Karl and Knight 1997; Meehl and Tebaldi 2004; Hansen et al. 2008; PwC 2011). Based on a wide range of extreme temperature indices within the scientific literature, the current study has determined a subset of heat wave definitions and a framework in which to analyze them that is applicable to a wide range of sectors.

From a purely climatological standpoint, the EHF index is the most appealing. One reason is the consideration of $T_{\min}$ and $T_{\max}$ within the same index. The CHT index proposed by Fischer and Schär (2010) also considered coincident extreme events of both fields; however, this was based on fixed thresholds. Pezza et al. (2012) employ relative thresholds for $T_{\min}$ and $T_{\max}$; however, they use the 90th percentile for each, based on monthly climatologies. Another reason why EHF is particularly appealing is that the conditions leading up to a given day (i.e., the previous two days) are also considered, which can therefore amplify or dampen heat wave amplitude. Lastly, the given day is also compared an extreme threshold (via the 95th percentile) to determine its climatological anomaly, and to the mean of the preceding month to determine the anomaly against recent conditions. This takes some account of ''acclimatization'' to the heat wave. The present study takes EHF an extra step further by analyzing consecutive days of positive anomalous conditions. This has resulted in the identification of the similarity between intense regional heat waves and the meteorological phenomena (Pezza et al. 2012) that may drive them. Given that large-scale circulation is an important element of the intensity and duration of heat waves for other global regions (e.g., Meehl and Tebaldi 2004; Trigo et al. 2005), an index that pays respect to this has more chance of fulfilling the ''universal'' criterion from a physical perspective. However, meteorological conditions are not the *only* cause of long and intense heat waves—further research exploring linkages among heat wave indices, dynamical components, and other factors such as low-frequency variability is intended to fully understand all factors of heat wave occurrence.

5. Conclusions

Because of the wide range of impacts across many different sectors, the definition of heat waves will most likely always be broad and ambiguous. With this in mind, the present study has researched a vast range of heat-related indices presented in the scientific literature to determine a set of widely applicable heat wave definitions and corresponding methodologies. This set includes the following: CTX90pct—periods of three or more consecutive days when each day exceeds the calendar-day 90th percentile; CTN90pct—periods of three or more consecutive nights when each night exceeds the calendar-day 90th percentile; and EHF—periods of three or more consecutive days when excess heat conditions are experienced. Each heat wave definition is analyzed with respect to five aspects—the yearly number of heat waves (HWN), length of the longest yearly event (HWD), the yearly sum of participating heat wave days (HWF), the hottest day of hottest yearly event (HWA), and the average magnitude of all yearly heat waves (HWM), all calculated yearly. By computing a range of heat wave aspects per definition, this framework allows for a more in-depth study of heat waves than what has been previously achieved within the climate science community. The methodology has been applied to gridded observation data over Australia in order to test the approach over various climatic types, and to produce an in-depth heat wave analysis where previous work is sparse and/or inconsistent. Given the versatility of each definition across all climatic types in Australia, it is anticipated that they will prove equally as useful over other regions. Two time periods were analyzed to determine if differing trends and climatologies were obtained when stations participating in the gridded product changed.

In summary, using Australia as a case study, we found the following:

- Across all definitions, greater significance exists for trends in occurrence-based aspects, that is, the yearly sum of participating heat wave days (HWF) and yearly number of heat waves (HWN).
- The number of available heat wave days drives the length of heat wave events.
- Some regions of Australia show little change in heat wave length or frequency over the time period analyzed.
- Because of the methodology, EHF is more sensitive in measuring heat wave aspects than CTX90pct and CTN90pct.

- Generally, regions of significant trends over 1951–2008 are similar across all three indices for yearly number of heat waves (HWN), the sum of participating heat wave days (HWF), and the length of the longest yearly event (HWD), indicating a level of robustness despite which index is used. This result diminishes for 1971–2008, mostly due to nondetectable trends for CTN90pct and the higher sensitivity of EHF.
- Climatologies across the three occurrence-based aspects show fewer and shorter heat waves when considering just nighttime conditions, and more frequent and longer heat waves when considering both variables and seasonal relevance.
- Trends in the hottest day of the hottest yearly heat wave (HWA) are larger than trends in the mean magnitude of all yearly heat waves (HWM), suggesting that the intensity of a heat wave is increasing faster than average heat wave conditions.
- In regions with sparse observational data, trends may be spurious because of the gridding procedure employed in a gridded dataset.

We acknowledge that more appropriate heat wave definitions may emerge in the future, and that more advanced methods may become applicable over continental regions (e.g., Furrer et al. 2010). This may be due to improved observational datasets particularly for fields such as vapor pressure and/or relative humidity, longer time periods that allow for continuous days of more extreme temperature (e.g., the 95th percentile), or even perhaps more clarity as to the definition of a heat wave. Nevertheless, the present study has defined a subset of broadly applicable heat wave definitions and analyzed them via a multiaspect structure based on Fischer and Schär (2010). The results of this study demonstrate that some commonly used extreme temperature and heat wave indices are not useful over various climatic types, most of which are fixed-threshold indices. We therefore advocate the use of percentile-based calculations, so long as the percentile is not set too low or too high.

We also support the use of the multiaspect framework so that a heat wave can be examined from multiple angles, not just duration or intensity, as is most commonly produced via other popular indices (e.g., Collins et al. 2000; Deo et al. 2007). Furthermore, this study has shown that considerable similarities exist in the trends of the same heat wave aspects of different definitions, thereby reducing some of the uncertainty in the methods that measure heat waves. Further research will focus on applying the definitions to other observational datasets and regions, with the aim to provide a consistent global analysis on the trends of heat waves and to explore interregional variations in climatologies and trends. The indices may also be used for the assessment of heat waves in modeling studies in order to determine their likely change under enhanced greenhouse gas conditions.

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APPENDIX

Heat Wave Indices Determined Unsuitable by this Study

In addition to the indices results presented in this paper (CTX90pct, CTN90pct, and EHF), a broader range of indices were assessed in their ability to measure heat waves via the five-aspect methodology for events of at least three consecutive days. These included the following:

1) TX95pct—the threshold is the calendar day 95th percentile of T_{max}, based on a 15-day window. That is, there is a different percentile value for each day of the year (thereby accounting for the seasonal cycle), where the window is centered on the day in question.
2) TN95pct—the threshold is the calendar day 95th percentile of T_{min}, as described for T_{max}.
3) TX35deg (TX40deg)—the threshold is fixed at 35°C (40°C) for T_{max}.
4) TN20deg (TN25deg)—the threshold is fixed at 20°C (25°C) for T_{min}.
5) Ta35deg (Ta40deg)—the threshold is fixed at 35°C (40°C) for Ta.
6) CHT—defined by Fischer and Schär (2010) as the occurrence of a hot day ($T_{max} > 35$°C), followed by a tropical night (TR; $T_{min} > 20$°C).
7) Ta90pct (Ta95pct)—the threshold is the calendar day 90th (95th) percentile of apparent temperature, as described for T_{max}; Ta is derived from the equation given by Fischer and Schär (2010). Since relative humidity is required for Ta but is not an original variable of AWAP, it is calculated as the ratio of the vapor pressure fields at 1500 LT and the saturation vapor pressure based on the daily T_{max}.

To illustrate *how* the above indices are unsuitable for multiple climatic zones, Fig. A1 displays the 1951–2008 climatological average for HWN (yearly number of heat waves) for indices 1 to 4 mentioned above, and HWA (hottest day of hottest event) for indices 5 and 7. Note that here HWA is an absolute measurement, not an anomaly. The indices in Figs. A1a–d are based on

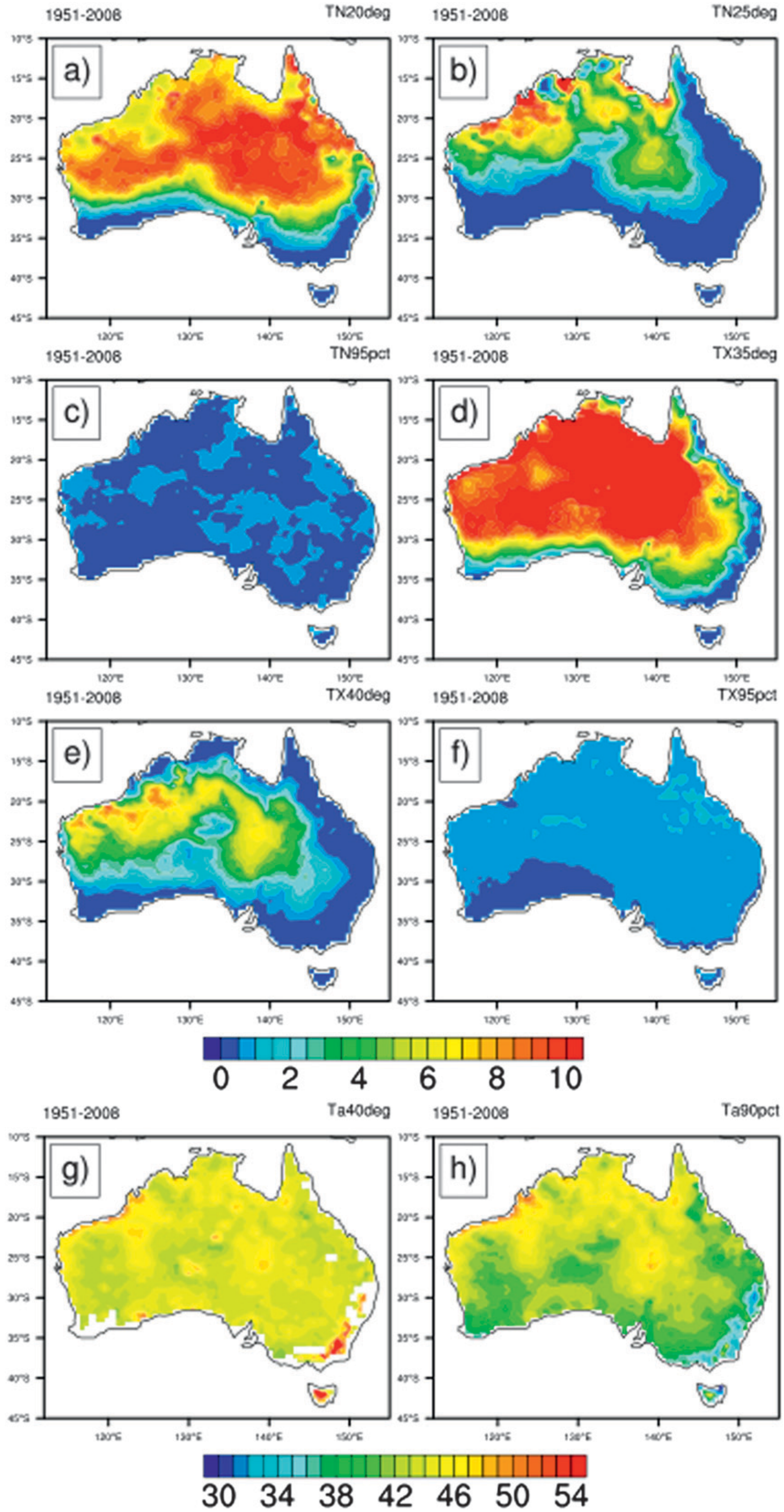

FIG. A1. Examples of aspects of unsuitable globally applicable heat wave indices. (a)–(f) HWN climatologies (occurrences yr^{-1}) for TN20deg, TN25deg, TX35deg, TX40deg, TN90pct, and TX95pct, respectively. (g),(h) HWA (°C) for Ta40deg and Ta90pct, respectively.

TABLE A1. List of extreme temperature indices that were initially calculated and were *not* discussed in the main body of the paper. All indices were calculated yearly. For the ETCCDI reference items, see http://etccdi.pacificclimate.org/list_27_indices.shtml.

Metric	Description	Reference
TX90p	Percent of days where T_{max} > calendar day 90th percentile, based on a 5-day window, for the entire time period	ETCCDI Alexander et al. (2006)
TN90p	Percent of days where T_{min} > calendar day 90th percentile, based on a 5-day window, for 1961–90	ETCCDI Alexander et al. (2006)
WSDI (warm spell duration index)	Annual count of days with at least 6 consecutive days when T_{max} > 90th percentile, based on a 5-day window, for 1961–90	ETCCDI Alexander et al. (2006)
HWDI (heat wave duration index)	Annual count of days with at least 6 consecutive days when T_{max} > mean(T_{max}) + 5°C	ETCCDI Alexander et al. (2006)
SU (summer days)	Annual count of days when T_{max} > 25°C.	ETCCDI Alexander et al. (2006)
TR (tropical nights)	Annual count of days when T_{min} > 20°C.	ETCCDI Alexander et al. (2006)
CHT (combined hot days and tropical nights)	Average number of days with T_{max} > 35°C and T_{min} > 20°C	Fischer and Schär (2010)
AT105F	Average number of days when Ta > 40.6°C (105°F)	Fischer and Schär (2010)
Deo_Ta index	Highest 3-day running mean of Ta	Deo et al. (2007)
Multiple threshold index	Longest period of consecutive days where T_{max} must be above T1 for at least 3 days, mean(T_{max}) of event is above T1, and T_{max} is T2 for every day of the event. T1 = 97.5th percentile of T_{max}; T2 = 81st percentile of T_{max}	Meehl and Tebaldi (2004)
Hot days/events	Frequency of T_{max} ≥ 35°C/Frequency of 3–5 consecutive days of T_{max} ≥ 35°C	Collins et al. (2000)
Hot nights/events	Frequency of T_{min} ≥ 20°C/Frequency of 3–5 consecutive days of T_{min} ≥ 20°C	Collins et al. (2000)
Warm days/events	Frequency of T_{max} anomalies ≥ 95th percentile/Frequency of 3–5 consecutive days of T_{max} ≥ 90th percentile	Collins et al. (2000)
Warm nights/events	Frequency of T_{min} anomalies ≥ 95th percentile/Frequency of 3–5 consecutive days of T_{min} ≥ 90th percentile	Collins et al. (2000)

absolute thresholds of T_{min} and T_{max}. The number of heat waves based on TN20deg can reach at least 10 yr^{-1} over much of central Australia; however, no heat waves are measured in the southwest or southeast coast, particularly over the Great Dividing Range (Fig. A1a). While the CHT index is not shown, it produces a pattern in the number of heat waves similar to that of TN20deg. This pattern is further exacerbated when using TN25deg as an index (Fig. A1b), where the measurement of any heat waves is confined farther north. Similar patterns in heat wave numbers can be seen in TX35deg (Fig. A1c) and TX40deg (Fig. A1d) compared to TN20deg and TN25deg, respectively. This indicates that using a single absolute threshold for a region where multiple climate regimes exist (such as Australia) cannot adequately represent heat wave occurrence across all such climates. This inference can also extend to other large regional or continental studies, such as over Europe, Asia, and the Americas where a broad range of climates exist; therefore, an absolute threshold applicable to one area may not be appropriate to the rest of the region. Absolute thresholds are sometimes necessary from an impacts perspective (e.g., concerning plant physiology or human health), but from a climatological perspective, they *may* only be suitable when studying heat waves in a small region or at a point source (e.g., where an observation station is located) when a single climate regime exists.

Figures A1e and A1f display instances of when a relative threshold is used but is set too high. TN95pct (Fig. A1e) produces an average of less than one heat wave per year, particularly in the southwest. Figure A1f also shows very small numbers of heat waves based on TX95pct, particularly in the southwest where no events are measured. The rest of Australia tends to experience no more than one heat wave per year on average based on this index. As in Fig. A1e, the use of a too-high relative threshold dampens the measurement of consecutive days where those conditions occur. The limitations of the T_{min} and T_{max} 95th percentile within this study may be partially explained by the dataset length—if a longer period were analyzed, there would be an increased chance that consecutive days above the 95th percentile would occur. However, given the lack of reliable extended observational datasets across the globe, there would be few regions where the 95th percentile would measure a reasonable number of heat waves. Similar to absolute thresholds explained above, the use of a very high relative threshold may only apply to small regions or point sources. We therefore advocate the use of the 90th percentile for measuring T_{min} and T_{max} heat waves, as it is applicable to the observational data available for most regions, while still being considered ‘‘extreme.’’

Figures A1g and A1h show the 1951–2008 climatological average of HWA for Ta40deg and Ta90pct, respectively. When considering fixed Ta indices (Ta40deg and Ta35deg; not shown) the amplitude of occurring heat waves for much of Australia is between 42° and 46°C, with slightly higher values on the northwest coast. Such conditions seem quite reasonable for periods of extreme heat. However, along the Great Dividing Range in the far southeast HWA can reach 60°C. This may be considered possible in arid humid climates (such as the Middle East), yet the Great Dividing Range has a cool, temperate climate. The occurrence of such high peaks is therefore due to the data from which Ta was calculated. The calculation of relative humidity from the saturated vapor pressure based on $T_{\max}$ and AWAP-provided vapor pressure may produce erroneous values over regions of high topography such as the Great Dividing Range. HWA for relative thresholds (Ta90pct and Ta95pct; not shown) produce more plausible peaks, especially over the southeast. However, given the highlighted setback with the calculation of Ta, even relative Ta indices cannot be used confidently, at least from this observational dataset. The use of Ta heat wave indices is therefore eliminated from the main analysis of this study, although it does have the potential to be explored further in other observational datasets, particularly over other global regions, so long as the required fields are in a reasonable condition.

All ETCCDI indices regarding hot temperature extremes were also analyzed (Table A1) but were deemed inappropriate when concerning the measurement of heat waves. The SU and TR indices reflect single exceedances above an absolute threshold for $T_{\max}$ and $T_{\min}$, respectively. While TX90p and TN90pct are based on relative calendar day thresholds, they also measure just single exceedances. Consecutive days of exceedances are measured by HWDI and WSDI; however, the HWDI uses an absolute threshold, and both indices measure events of at least six days’ length. It was found that events of this length were rarely identified in the observations, and that events of half this length can have impacts on many different sectors. Therefore, at least in their original format, these indices were found to be inapplicable in appropriately quantifying heat waves.

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