Atmospheric Research 164–165 (2015) 242–267

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Invited review article

A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale

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ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form 22 May 2015
Accepted 22 May 2015
Available online 29 May 2015

Keywords:
Heatwaves
Regional
Observations
Projections
Dynamics
Attribution

ABSTRACT

Heatwaves impose disastrous impacts over human, natural and industrial systems across the globe. Over a relatively short period of time, there has been considerable advancement in the scientific understanding of heatwaves. Such advancements include how heatwaves are measured, their driving mechanisms, observed and projected changes, and quantifying the anthropogenic influence behind these changes. This paper reviews these developments. There are however gaps in the scientific literature that should be filled in order to gain a more complete understanding of the changing nature of heatwaves. The conclusions of this paper propose that the global community should work toward a unified framework in which to measure heatwaves, reduce spatial and temporal gaps by increasing the global observation network, further research on how physical mechanisms interact for heatwave manifestation, and continual work and expansion of methods used for attribution studies on observed heatwaves and their trends.

Contents

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http://dx.doi.org/10.1016/j.atmosres.2015.05.014

1. Introduction

Since 1900 the global average temperature has warmed by 0.89 °C, with most of the warming due to anthropogenic activity (Hartmann et al., 2013). It has been discussed for some time in the climate science literature that small changes in average temperature can result in disproportionally larger changes in the intensity and frequency of extremes. Mearns et al. (1984) suggested this, and over time, was built upon by other studies, such as Katz and Brown (1992), Nicholls et al. (1996) and Boer and Lambert (2001). Fig. 1, extracted from the Intergovernmental Panel for Climate Change (IPCC) Special Report on Extremes (SREX, IPCC, 2012) summarizes how extreme temperature can change in response to a shift in mean temperature, or a change in variability. Extreme temperature can be categorized in many ways (see Section 2), depending on what elements of extreme temperature are of interest. This review paper is focused on a particular type of temperature extreme—heatwaves.

Heatwaves have disastrous impacts on many different systems. The first which many think about is impacts on human health. In 2003, an intense heatwave occurred over Western Europe, with temperatures the highest since 1500 (Luterbacher et al., 2004). This event was responsible for over 70 000 deaths (Coumou and Rahmstorf, 2012). The 2010 Russian heatwave, which lasted over a month, killed around 54 000 individuals (McMichael and Lindgren, 2011). In 2009 a heatwave over south eastern Australia killed 374 people, double that of the bushfire that followed (Victorian Department of Health, 2009). Indeed, heatwaves have been dubbed the “silent killer” (Loughnan, 2014), as their impacts on human health are not usually instantaneous. Heat stroke generally exacerbates underlying medical conditions, affecting mainly the elderly, the young, and those that work outside, with death generally occurring after a number of days. It can be exceptionally hard to properly attribute deaths to heat extremes, because admission to hospital is generally under the illness aggravated. Thus it is likely that the true number of heatwave-related deaths is underestimated. Moreover, it is not necessarily the daytime heat which is always responsible for morbidity and mortality, humans need lower nighttime temperatures to recuperate so that they can handle any extreme heat on the following day. In the most extreme heatwaves, such as the 2003 European heatwave, nighttime temperatures were abnormally high, which contributed largely to the final death toll (Trigo et al., 2005). Furthermore, the event does not necessarily have to last for an exceptionally long time. Generally human morbidity and mortality is quite low after a single day of extreme temperatures, however increases dramatically for prolonged events over 2 days (Pantavou et al., 2008).

Another system adversely impacted by heatwaves is human infrastructure. Australian heatwaves have caused railways to buckle (McEvoy et al., 2012) and put an enormous strain on power supply (Colombo et al., 1999), having knock-on effects to human health (e.g., Wrigley et al., 2006). Parts of the United States are projected to fall short of the required energy load by almost 20%, with increasing temperature extremes in the future mapped on to current infrastructure (Miller et al., 2008). Medical authorities will also be put under pressure, with the potential for increased ambulance callouts and hospital admissions. Agricultural industries are also adversely impacted by extreme

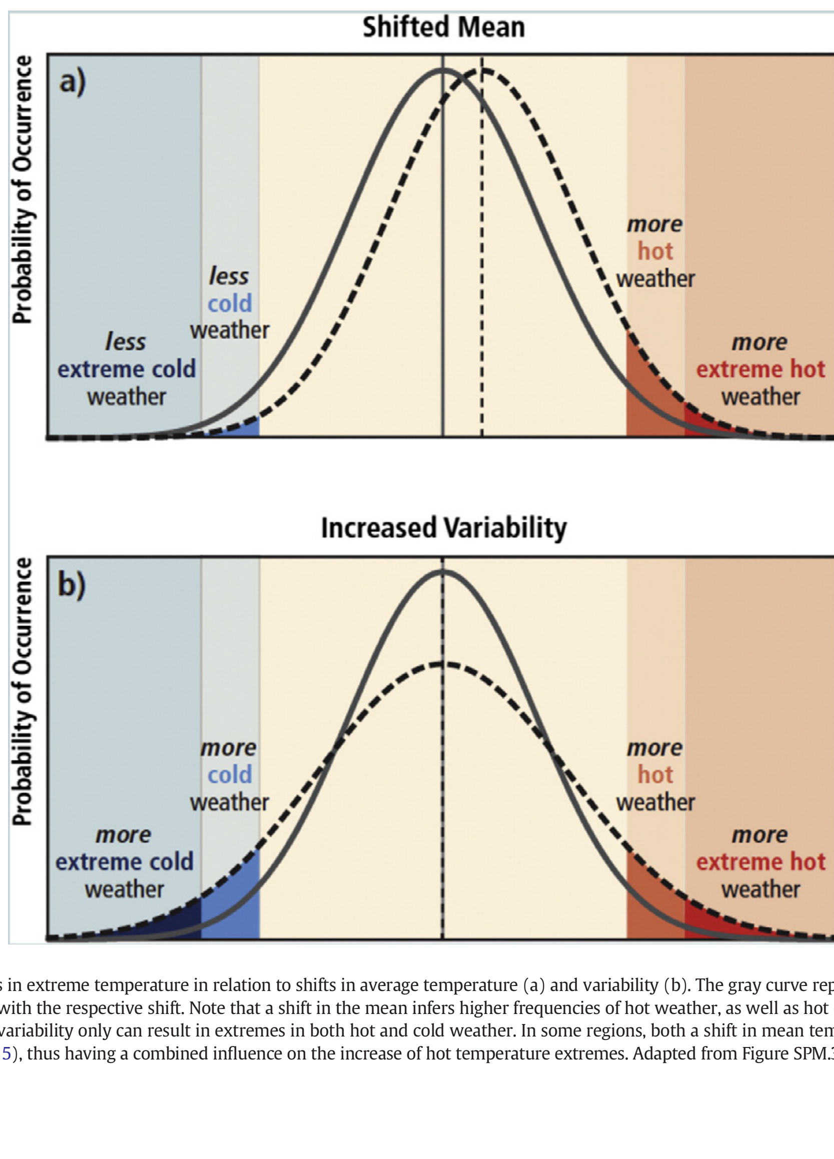

Fig. 1. Schematics showing changes in extreme temperature in relation to shifts in average temperature (a) and variability (b). The gray curve represents the current climate, the black dashed curve represents a climate with the respective shift. Note that a shift in the mean infers higher frequencies of hot weather, as well as hot extremes that were extremely rare in the original distribution. A shift in variability only can result in extremes in both hot and cold weather. In some regions, both a shift in mean temperature and variability are reported to be occurring (see Sections 4 and 5), thus having a combined influence on the increase of hot temperature extremes. Adapted from Figure SPM.3 of IPCC (2012).

heat. Russian grain harvests suffered a loss of 30% after the 2010 event (Barriopedro et al., 2011), due to sensitive tolerances that affect grain-filling and reproduction (Barlow et al., 2013). Other crops such as rice are also impacted by extreme temperatures (Lanning et al., 2011), as are bovine livestock and their milk production (Dunn et al., 2014).

Natural ecosystems are also finely in tune with their surrounding habitats, and are generally only tolerant to specific temperatures. For example, Australian flying-foxes, mostly lactating mothers and their young, literally fall out of trees once temperatures reach 42 °C. During a 12-year period, over 30 000 flying-foxes suffered heat-related deaths (Welbergen et al., 2008). Whole terrestrial ecosystems (as well as human property) are also at risk of increased fire danger during and directly after a heatwave. The intense temperatures further exacerbate the drying of vegetation, which, due to preceding conditions, is likely already very dry. Thus, the likelihood of combustion after ignition is increased. Extreme heat contributed to and exacerbated 500 wildfires over Russia in 2010, as well as the worst Australian bushfires on record during 2009 that resulted in 173 deaths and 3500 homes destroyed (Karoly, 2009). It is also worth remembering that heatwaves are not restricted to land, they can also occur in the ocean. A marine heatwave off Western Australia in 2010/2011 caused catastrophic damage to local seaweed populations, and the first-ever coral bleaching event on the local reefs (Smale and Wernberg, 2013; Wernberg et al., 2013). A 2012 Marine heatwave in the northwest Atlantic seriously impacted local fish species, inducing concern of increased frequency of similar events as the global climate continues to warm (Mills et al., 2013).

There cannot be any doubt that heatwaves incur widespread devastating impacts. But what else do we know about them? How are they measured? What drives heatwaves? How have they changed? How will they continue to change, and what is the role of anthropogenic activity behind these changes? This review seeks to clarify the current state of the scientific literature on these questions surrounding terrestrial heatwaves. The following five sections are themed around: a history on the measurement of temperature extremes and current definitions used by the climate science community; the underpinning physical processes of heatwaves; documented changes in temperature extremes and heatwaves the observational record; future projections from numerical climate models; and ascertaining the role of humans behind observed changes. By the end of this review, the reader should have a clear grasp on how heatwaves are distinctive, and have changed differently compared to other measures of temperature extremes; and the scientific development of understanding terrestrial heatwaves, particularly the comprehensive discoveries made in the last decade. There are, of course, gaps in the literature that if filled, would lead to a more complete understanding of these complex events. Therefore lastly, a summary is given that calls upon where future research on heatwaves should be focused.

2. History of the measurement of extreme temperatures and heatwaves

2.1. Preliminary measures of extreme temperature

While average temperature is relatively easy to derive and study, extreme temperatures have historically posed challenges, many of which still stand today. An important issue is definitions that can be derived from climate data, and provide important information on the intensity, severity and duration of temperature extremes required for impacts purposes across natural and human systems. Moreover, temperature extremes require high-quality daily data for their calculation, which, in terms of observations, does not openly exist for many areas of the globe. Since extremes are rare by their very definition, robust calculation is also a challenge—trends in rare events detected by linear methods over traditional temporal and regional scales are generally not significant (Manton et al., 2001; Frich et al., 2002).

Attempting to overcome these issues, Frich et al. (2002) proposed 10 climate indicators, 5 of which apply to temperature, with the purpose to be calculated at local observation centers (i.e., in-situ). This was in conjunction with the outcomes of multiple World Meteorological Organization (WMO) meetings, where the input of changes in extreme events into the 3rd IPCC report was discussed, and the use of pre-calculated indices was agreed upon. The choice if the indices by Frich et al. (2002) were limited to those that displayed robust results; had applications in a variety of impacts sectors, and could be calculated from available observations. These first five measures of extreme temperature are listed in Table 1 (Frich et al., 2002).

The metrics by Frich et al. (2002) were employed in other regional studies (e.g., Kiktev et al., 2003; Klein Tank and Können, 2003), and paved the way for the expansion and development of other extreme indices (Klein Tank and Können, 2003). The joint World Meteorological Organization Commission on Climatology (CCl)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (now known as ETCCDI) was established shortly after. ETCCDI facilitated the international coordination of a larger set of climate extreme indices, freely available software packages for end users for their own calculations, and numerous regional workshops that attempted to close gaps in data availability that hampered earlier work on extremes (Alexander et al., 2006). In all, 27 climate indices were developed by ETCCDI, 17 of which measure extreme temperature. Such work was a major development in the field of extreme event metrics, compared to the smaller repertoire of indices in previous studies (Frich et al., 2002; Klein Tank and Können, 2003). This updated list included a variety of percentile, absolute threshold, duration, and range-based temperature indices (see Table 2).

The expansion of this list from Frich et al. (2002) is owed largely to the pioneering work ETCCDI conducted in providing tools for consistent in-house calculations of the extremes locally, thus improving the global network. While some data-sparse regions remained, more coverage than ever over previously data-poor regions of India, South America and Africa was permitted, since regional authorities could keep the original observations, and only needed to surrender the pre-calculated indices.

Another milestone outcome of ETCCDI was Hadley Extremes database (HadEX), the gridded output of the indices over areas where sufficient data is present, which is freely available (Donat et al., 2013a; http://www.metoffice.gov.uk/hadobs/hadex2/). All indices were initially calculated for 1951–2003, allowing for a consistent measure on how (temperature) extremes had changed over a substantial period of time, with trends calculated using nonparametric methods (Sen, 1968; Alexander et al., 2006). This network of indices is continually expanding, and exists today in the form of the HadEX2 dataset (Donat et al., 2013a). Another gridded collection of the ETCCDI indices exist in the Hadley Centre/Global Historical Climatology Network (HadGHCND) extremes database (GHCNDEX), however in this dataset indices are calculated first before being gridded, and data is limited to stations part of the HadGHCND network (see Caesar et al., 2006; Donat et al., 2013b).

Some similarities and overlap clearly exist between Frich et al. (2002) and Alexander et al. (2006), although developments, particularly in the measurement of warm spells, were made. Alexander et al. (2006) noted that HWDI (see Table 1), due to its absolute threshold (daily mean temperature + 5 °C), could not be applied to all global regions. An example of this is demonstrated by Perkins (2011), where due to a small annual temperature distribution in the tropics and some tropical regions, HWDI is poor for measuring periods of extreme heat. Alexander et al. (2006) therefore introduce WSDI (see Table 2), which is relative to a particular location as well as the time of year (i.e. detects anomalously warm events during summer as well as winter), thus measuring heatwaves in the cooler months.

The ETCCDI indices have been, and still are, widely applied to observational and climate model data to understand previous and future changes in extreme events. In terms of regional temperature extremes, Alexander and Arblaster (2009) used a selection of the indices to

Table 1
The first 5 measures of extreme temperature, proposed by Frich et al. (2002). HWDI was the only index to measure heatwaves (prolonged periods of excess heat), however has now been superseded.

Index shorthand	Index name	Index definition
Fd	Total number of frost days	Count of days with minimum temperature <0 °C
ETR	Intra-annual extreme temperature range	Difference between the highest temperature observation of any given calendar year, and the lowest temperature reading of the same year
GSL	Growing season length	Period between when daily temperature is above 5 °C for at least five consecutive days, and below 5 °C for at least five consecutive days
HWDI	Heatwave duration index	Maximum period of at least five consecutive days where daily maximum temperature is above the 1961–1990 mean +5 °C
Tn90	(pronounced as shorthand)	Percent of time when daily minimum temperature is above the 90th percentile

evaluate models part of phase 3 of the Climate Model Intercomparison Project (CMIP3) against observations, and calculate future projections over Australia. Perkins (2011) employed a selection for future projections over the Pacific, also using CMIP3. You et al. (2011), Aguilar et al. (2009) and Vincent et al. (2011) used a selection of indices to explore observed changes in extreme temperature over China, parts of Africa and the Western Indian Ocean, respectively, during the second half of the 20th Century. Similar studies were conducted over North America by Peterson et al. (2008a), and the Indo-Pacific by Caesar et al. (2011). You et al. (2011) explored linkages to changes in atmospheric dynamics, and the work by Aguilar et al. (2009), Caesar et al. (2011) and Vincent et al (2011) resulted from further in-country ETCCDI workshops. More recently, work conducted by Sillmann et al. (2013a, 2013b), calculated the indices for CMIP5 for historical and future projections, making the output available to researchers who sought further analysis. Avila et al. (2012) investigated the effect of land cover change in dampening or enhancing change in 12 of the temperature indices at the global scale. The above list is by no means exhaustive, however gives a rounded indication on how broadly the ETCCDI indices have been applied, and therefore, the groundbreaking work achieved by this group in standardizing in the measurement of extreme (temperature) events (see Peterson and Manton, 2008; Zhang et al., 2011).

While the work by ETCCDI is by no means short of pioneering, the events that are measured are generally only considered "moderate extremes" (e.g., Klein Tank et al., 2009; Zhang et al., 2011). This in particular relates to the percentile-based indices, being based on the highest or lowest 10%. Moreover, the indices only measure one feature of extreme events (see Table 2), such as frequency (e.g., TX90p/WSDI), intensity (e.g., TXx) or duration (e.g., GSL). Is this enough information for the measurement of heatwaves, or are multivariate/multi-measurement indices required (Zhang et al., 2011)?

2.2. Heatwave definitions in the climate & impacts communities

It would appear that numerous climate-based studies have recognized that the appropriate measurement of heatwaves requires more than just counts above a threshold, or the magnitude of the hottest day in a month or year (see Table 3). Meehl and Tebaldi (2004) employ two heatwave definitions based on daily maximum and minimum temperatures to examine projected changes in their intensity, frequency and duration over North America and Europe. Fischer and Schär (2010) analyze changes in a range of heatwave indices over Europe—combined hot days/cold nights; an apparent temperature index, and a multi-measurement index. The latter defined a heatwave as a period where at least 6 consecutive days exceeded their respective calendar-day 90th percentile for maximum temperature. The index was then segregated into the total number of heatwave days in a summer season (June–August), the number of discrete events in a season, the mean magnitude over all seasonal heatwaves, and the hottest day of the hottest seasonal event (Fischer and Schär, 2010).

In a similar vein to Meehl and Tebaldi (2004), Fischer and Schär (2010), Vautard et al. (2013) analyzed both the amplitude and persistence of European heatwaves, based on the 90th percentile of daily mean temperature. Focusing on periods of at least 3 consecutive days above the 98th percentile of maximum temperature, Schoetter et al. (2014) examine the cumulative severity of a heatwave, based on its mean intensity, mean extent, and duration. A heatwave magnitude index is proposed by Russo et al. (2014), taking the maximum

Table 2
17 measures of extreme temperature proposed by ETCCDI (Alexander et al., 2006). WSDI was to replace HWDI, as it measured winter time heatwaves (i.e., warm spells) as well as summertime events. WSDI is also applicable to a wider range of climates than HWDI.

Index shorthand	Characteristic measured & timescales	Index definition
TN10p	Frequency; monthly & annual	Occurrence of cold nights (daily minimum temperature) below the 10th percentile
TN90p	Frequency; monthly & annual	Occurrence of warm nights above the 90th percentile
TX10p	Frequency; monthly & annual	Occurrence of cold days (daily maximum temperature) below the 10th percentile,
TX90p	Frequency; monthly & annual	Occurrence of warm days above the 90th percentile.
TXx	Intensity; monthly & annual	Maximum daily maximum temperature
TNx	Intensity; monthly & annual	Maximum daily minimum temperature
TXn	Intensity; monthly & annual	Minimum daily maximum temperature
TNn	Intensity; monthly & annual	Minimum daily minimum temperature
FD	Frequency; annual	Occurrence of frost days (minimum temperature below 0 °C)
ID	Frequency; annual	Annual occurrence of ice days (maximum temperature below 0 °C)
SU	Frequency; annual	Annual occurrence of summer days (maximum temperature above 25 °C
TR	Frequency; annual	Annual occurrence of tropical nights; (minimum temperature above 20 °C).
CSDI	Duration; annual	Cold spell duration indicator (count of days part of a 6-day window when minimum temperature is below the 10th percentile)
WSDI	Duration; annual	Warm spell duration indicator (count of days part of a 6-day window when maximum temperature is above the 90th percentile)
GSL	Duration; annual	Growing season length (as defined by Frich et al., 2002)
DTR	Range/spread; monthly	Diurnal temperature range (monthly mean difference between daily maximum and minimum temperature)
ETR (no longer part of ETCCDI framework)	Range/spread; monthly	Extreme temperature range (as defined by Frich et al., 2002)

Table 3
Examples of more recent specific heatwave indices proposed in the climate science literature. While there are some commonalities between the indices, no two studies have used the same index. This can make it very difficult to compare changes in heatwaves at regional scales, particularly when interested in a number of characteristics.

Study	Index description	Heatwave characteristic measured
Meehl and Tebaldi (2004)	"Worst" 3-day event:—the hottest 3 consecutive nights per year	Intensity
Meehl and Tebaldi (2004)	Exceedance index—longest period where maximum temperature is above the 97.5th percentile for at least 3 days; average daily maximum temperature across the event is over the 97.5th percentile; all days are above the 81st percentile.	Duration
Fischer and Schär (2010)	AT105F—number of days where apparent temperature (relative humidity and temperature combined) exceeds 40.6 °C	Frequency, intensity
Fischer and Schär (2010)	Multi-measurement index—periods of at least 6 days where maximum temperature exceeds the calendar day 90th percentile (15 day calendar window). Per summer, the total number of events; the hottest day of the hottest event; the length of the longest event; and the sum of all heatwave days are calculated	Frequency, intensity, duration
Fischer and Schär (2010)	CHT—combined hot days and tropical nights (see Table 1)	Frequency, intensity
Vautard et al. (2013)	Periods of various length where daily mean temperature is above the 90th percentile	Frequency, intensity, duration and persistence
Schoetter et al. (2014)	At least 3 days above the 98th percentile of maximum temperature	Cumulative intensity (calculated via mean intensity and extent, as well as duration)
Stefanon et al. (2013)	Exceedance of the calendar-day (21-days) 90th percentile of maximum temperature	Spatial extent, duration
Nairn and Fawcett (2013)	At least 3 consecutive days where temperature (the average of the maximum and minimum) exceeds the climatological 95th percentile, and is anomalously warm compared to the prior month	Intensity, duration, spatial extent

magnitude of events were at least 3 consecutive days is above the calendar-day 90th percentile for maximum temperature for 1981–2010. This index can then be broken down into sub-heatwaves, and various calculations of magnitude. Stefanon et al. (2013) use the 95th percentile of daily temperature, with sub-categories for the length of events and their spatial distribution. Coming from a meteorological perspective, Nairn and Fawcett (2013) combine daily minimum and maximum temperature into a single variable, and compare how anomalous a three-day averaged window is to the climatological 95th percentile, as well as to the prior month (see Table 3).

While it is evident that a large number of climate-based studies have identified heatwaves as multi-characteristic events, there are also studies that consider single characteristics, such as intensity (e.g., Hoerling et al., 2013), duration (e.g., Diffenbaugh, 2005; Diffenbaugh et al., 2005) or frequency (e.g., Della-Marta et al., 2007a) to represent heatwaves. Some studies even use monthly instead of daily temperature (e.g., Coumou and Rahmstorf, 2012), or the ETCCDI indices (see Table 2) to analyze heatwaves. Indeed, it seems that almost, if not every climatological study that looks at heatwaves uses a different metric.

Heatwave definitions within the impacts community are no better. 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, power), are generally too complex or specialized to be transportable across groups, or to climatological data. An example of this are indices within the human comfort and health sector. The Predicted Mean Vote (PMV; Fanger, 1970) and the Physiological Equivalent Temperature (PET; Mayer and Höppe, 1987) have been employed on small temporal and spatial scales to examine heat stress and human morbidity (e.g., Matzarakis et al., 1999; McGregor et al., 2002; Pantavou et al., 2008), and are, to the untrained eye, very similar. Both PMT 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. Apparent temperature, also known at the 'heat index' (Steadman, 1979, 1984) is calculated from temperature and relative humidity, allowing for the determination of what conditions *feel* like to a person undertaking minimal work. These indices have been tailored to this specific sector, and particularly in the case of PET and PMV, are neither useful for most others, nor can they be readily derived from climatological data (apparent temperature may be calculated for some regional climates). These traits are very similar across many sector-based indices.

Without consistency among impacts sectors or the general climatological community (let alone across these two groups), can we ever follow in the steps of ETCCDI, and move toward a consistent framework in which to measure heatwaves?

Most papers studying heatwaves state there is no universal definition in which to measure these events, however also state that they are prolonged periods where temperatures are excessively hotter than normal. Despite the plethora of metrics used to measure heatwaves, there are indeed some similarities across the board. Although an obvious one, all definitions consider at least one form of temperature (daily minimum, maximum or average). To consider prolonged events, the majority of studies, particularly modern ones require a number of consecutive days where a particular threshold is exceeded, and most of these thresholds revolve around the upper tail of a temperature distribution. An advantage of using relative-based thresholds such as high percentiles, allow for the measurement of heatwaves across all locations, and when using a calendar-day percentile, can be relative to the time of year (sometimes referred to as warm spells).

A general heatwave framework has been constructed by Perkins and Alexander (2013) and Perkins et al. (2012), seeking to reduce the plethora of metrics employed for measuring heatwaves and warm spells. The framework employs three separate baselines from which heatwaves are measured (daily minimum and maximum temperature, and the excess heat factor; Nairn and Fawcett, 2013) and use a calendar-day 90th percentile for all three baselines to determine at least three days in a row where the threshold is exceeded. Based on Fischer and Schär (2010), each definition is broken down into seasonal characteristics including the number of heatwave days, the number of discrete events, length of the longest event, the mean event magnitude and the highest magnitude. Fig. 2 presents a schematic of the heatwave characteristics suggested by Perkins and Alexander (2013). The framework is designed such that other characteristics may also be calculated if required (e.g., commencement of heatwave season, spatial extent). While no novel indices were proposed, this framework succeeds in reducing the amount of heatwave metrics in general, and balances what is available and required from the climatological and impacts sectors, respectively. For example, 3 days length is sufficient for impacts on particular sectors, (see Perkins and Alexander, 2013). While the definitions quantitatively differ and will therefore be most suitable for different impacts purposes, the qualitative information derived across all definitions (e.g., global trends) is similar (see Section 4; Perkins et al., 2012).

A restraint of the metrics used to measure heatwaves is very necessary, and while not necessarily perfect, has been proven possible via the work of Perkins and Alexander (2013). Using a consistent framework has an imperative advantage of measuring past, current and future changes in heatwaves in a comparable manner. However, heatwaves

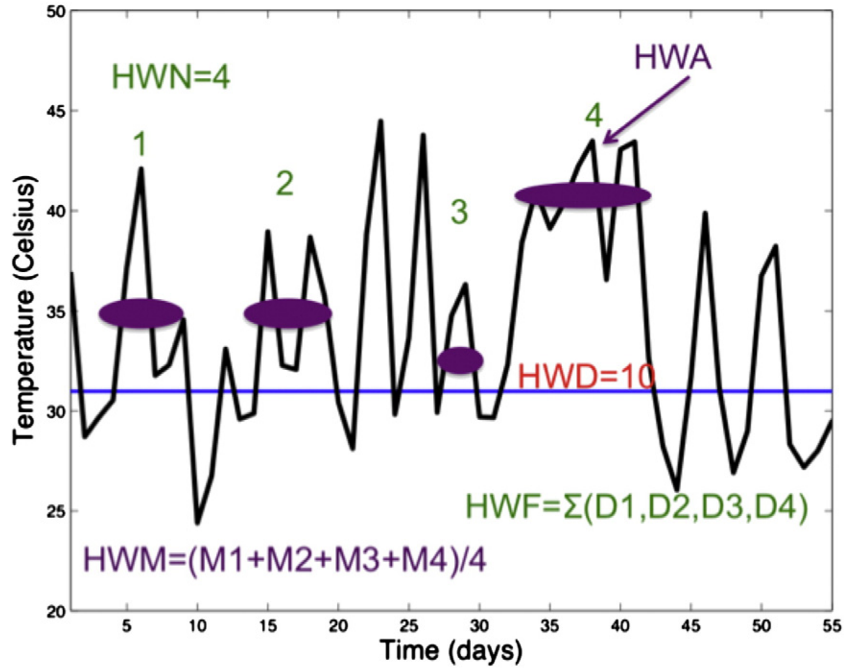

Fig. 2. Schematic illustrating The multi-characteristic framework outlined by Perkins et al. (2012) and Perkins and Alexander (2013). Each of the 5 characteristics here are calculated for three definitions of heatwaves—the EHF (Nairn and Fawcett (2013)), and separate definitions based for maxmimum and minimum temperature, relative to the calendar—day 90th percentile. A heatwave occurs when at least 3 days in a row are considered above the respective threshold. In this figure the threshold is represented by the blue line. There are 4 discrete events (HWN); the length of the longest event is 10 days (HWD); the number of heatwave days in the sum of the duration of all four events (HWF); the average heatwave magnitude is the average temperature across all for events (HWM); and the heatwave amplitude is the hottest day of the event with the hottest average (HWA). All 5 characteristics are generally calculated for a selected season (in this figure the season is 55 days), however are designed to be calculated annualy as well.

are inherently more complex events with a broad spectrum of impacts than their cousins measured by the ETCCDI framework. Therefore, attempting to contain all heatwaves in precisely the same manner with a universal definition is likely too ambitious. In the climate science community, we do however need to make a concerted effort to work together to reduce the plethora of metrics used, and balance them with what is useful to the many sectors impacted by these tremendous events.

3. Physical drivers of heatwaves

Before we can explore changes in heatwaves, a background on the mechanisms behind heatwaves should be given. It should be made clear that understanding the underlying physical mechanisms and their interactions on multi-characteristic heatwaves is an area of very active research, with many discoveries yet to be made, particularly in terms of how Sections 3.1–3.3 may be quantitatively linked. Therefore, in some cases we can only apply what we know about physical mechanisms behind temperature extremes in general. While specific relationships between physical drivers and heatwaves may differ from those with more general temperature extremes, the latter at least provides some background on what mechanisms may potentially need to be in place for the former to manifest. This section discusses these drivers in three main categories - synoptic systems, soil moisture and land surface interactions, and climate variability phenomena.

3.1. Synoptic systems of heatwaves

Although heatwaves can be studied from a climatological standpoint (e.g., Perkins et al., 2012), at the very core they are meteorological events. This is governed by the temporal and spatial scales they occur on. Most events usually last around a week or less, however the Russian heatwave of 2010 is a fine example of rarer, exceptionally longer event lasting for over a month (Matsueda, 2011). For all heatwaves the globe over, there is one common feature in their composition—a high-pressure synoptic system (otherwise known as anticyclones). Typically, such a system is known as a "blocking high" (Charney and DeVore, 1979; Coughlan, 1983)—a stationary system with a center of anomalously high pressure that remains in the same location for a longer period than what is usually expected. However, in recent publications there has been a shift toward calling these systems persistent highs (Marshall et al., 2014). This is because the responsible system for some heatwaves is not always positioned in the region were classical blacking highs, measured by the blocking index (e.g., Pook and Gibson, 1999) occur (see Charney and DeVore, 1979; Coughlan, 1983).

Traditional blocking highs occur when upper-level atmospheric winds split due to the meandering of the jet stream, allowing a region to be "blocked" from the zonal jet stream flow, usually for several days (Egger, 1978; Pezza et al., 2012). As such, cooler air from the poleward side cannot mix with hotter air in the equatorial side, and because of the "blocked" pattern, the warm air builds up. Classical blocking highs have been responsible for numerous extreme heatwaves, including the he Russian heatwave in 2010 (Matsueda, 2011), the 2003 European heatwave (Black et al., 2004; Vautard et al., 2013) and the 1995 Chicago heatwave (Meehl and Tebaldi, 2004). Indeed, the synoptic of these regions are conducive to classical blocking highs, due to the highly meandering northern polar jet stream, although Cassou et al. (2005) demonstrate that other circulation patterns can also be responsible for heatwave-causing high pressure systems over Europe.

Other persistent highs may not be caused by a split in the jet stream, and occur at lower latitudes (Marshall et al., 2014). These systems are generally located 10° equatorward of the typical blocking region, where the subtropical ridge sits during summer. Marshall et al. (2014) find that these types of persistent highs were responsible for numerous heatwaves over Australia, such as the southeastern 2009 event (Hudson et al., 2011a; Parker et al., 2014a, 2014b), and are highly represented in general Australian heatwave climatologies (Pezza et al., 2012; Boschat et al., 2015). These systems are not blocked from cooler air flow by the stubborn jetstream aloft, rather they remain stationary until a stronger (generally low pressure) system can shift it, usually associated with the movement of atmospheric rossby wave trains (Cassou et al., 2005; Della-Marta et al., 2007a; Parker et al., 2014a, 2014b; Boschat et al., 2015). While these high pressure systems also last for several days (thereby allowing a heatwave to occur), they have a smaller chance of lasting much longer than this, compared to classical blocking highs.

Whatever the type of the offending high pressure system, they work in the same way to cause and prolong a heatwave event, by advecting warm dry air to the region affected. Over Australia, the responsible persistent high pressure system sits adjacent to the area affected, advecting hot, dry air from the interior of the continent (Hudson et al., 2011a; Pezza et al, 2012; Marshall et al., 2014; Boschat et al., 2015). Responsible blocking highs in the Northern Hemsiphere are generally centered over the affected region (e.g., Black et al., 2004; Della-Marta et al., 2007a; Matsueda, 2011), with the direction of windflow guiding hot dry air from southerly deserts to this location. Fig. 3 depicts examples of typical heatwave causing systems over Australia at sea level.

The high pressure systems are not just situated at the surface, but extend vertically into the atmosphere, with high pressure anomalies consistently detected at the 500 and 250 hpa geopotential height levels (e.g., Meehl and Tebaldi, 2004; Pezza et al., 2012; Boschat et al., 2015; see Fig. 4). Low pressure systems typically sit adjacent, and are dynamically linked to the responsible high pressure system. These may include "omega" patterns, where lows either side of a blocking high help keep it stationary (Dole and Gordon, 1983; Degirmendžić and Wibig, 2007), low pressure systems part of a rossby wave train (Cassou et al., 2005; Pezza et al., 2012; Parker et al., 2014a, 2014b), or dynamical teleconnections with tropical lows and cyclones, which can assist in prolonging the persistent nature of the high pressure system (Cassou et al., 2005; Hudson et al., 2011b; Marshall et al., 2014; Parker et al., 2013).

3.2. The role of the land surface and soil moisture

While blocking/persistent high pressure systems are a necessary synoptic ingredient for heatwaves, coupling with the land surface is arguably more important. When the land surface has plenty of moisture, latent heat is the dominant flux over sensible heat, however this reverses when the soil is dry (Alexander, 2010; see Fig. 5), inducing a positive feedback between atmospheric heating and further drying of the soil. Studies examining coupling between the land surface and extreme temperature have shown that soil moisture/temperature interactions increase summer temperature variability, resulting in extreme temperatures when soil moisture is low (Seneviratne et al., 2006; Lorenz et al., 2010). Similar findings have been reported over other global regions

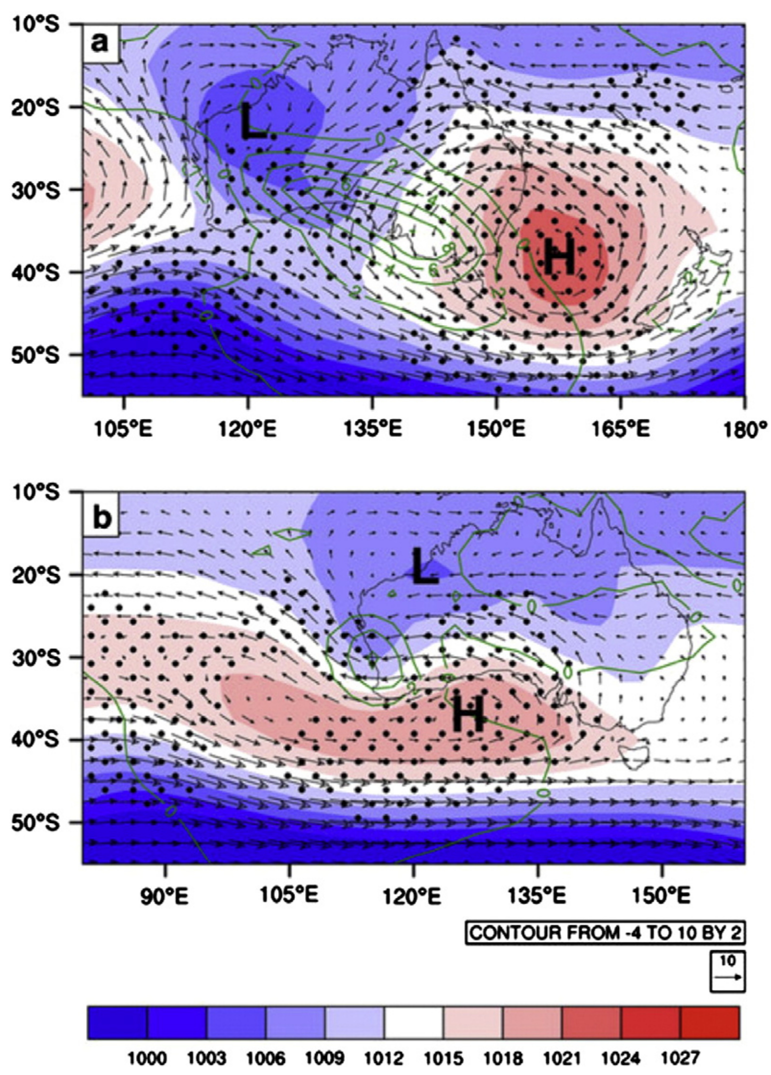

Fig. 3. Examples of sea-level persistent high-pressure systems that cause heatwaves, in this case over Australia, (a) for the southeast and (b) for the southwest. Note that the highs sit adjacent to the area affected, advecting warm air to the region. Units of the color scale are hPa, and for wind vectors are m s^{-1}, given by size. Taken from Fig. 4 of Pezza et al. (2012).

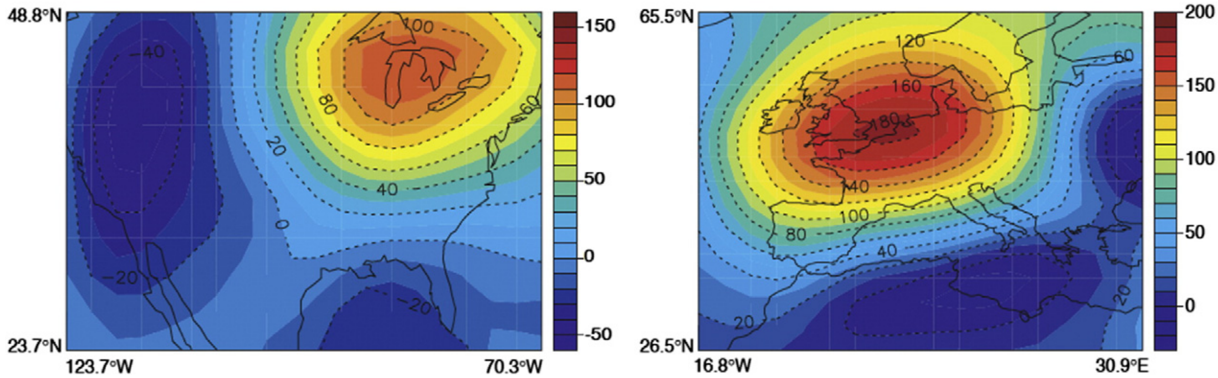

Fig. 4. Observed upper-level high-pressure anomalies (500 hPa) during the heatwaves of (left) Chicago in 1995 and (right) Europe in 2003. Both anomalies are calculated against the 1948–2003 monthly averages of July, and August, respectively, the month when the heatwaves occurred. Taken from Fig. 3 of Meehl and Tebaldi (2004).

(Mueller and Seneviratne, 2012), where the relationship is stronger where rainfall (and therefore soil moisture) is consistent and plentiful. When soil moisture decreases in these regions, extreme temperatures are more likely. In order for extreme summertime temperatures to occur over Europe, the preceding winter and spring must be dry (Durre et al., 2000; Quesada et al., 2012). This causes antecedent dry soil moisture conditions, and, when combined blocking highs, the positive feedback amplifies. Few hot days will occur if antecedent soil moisture is present but there is a lack of blocking highs, yet no hot days will occur if soil moisture is high, despite what weather systems occur (see Fig. 6).

This area of heatwave research has held a solid European focus. Dry conditions increased the 2003 heatwave intensity by up to 40% (Fischer et al., 2007a, 2007b), and a positive feedback situation between soil moisture, circulation (i.e., the resulting synoptics) and temperature has been detected for both individual events and climatological studies on European heatwaves (Fischer et al., 2007a, 2007b; Vautard et al., 2007; Zampieri et al., 2009). Specifically, large-scale advection during the daytime continues to dry out already desiccated soil, while entrainment allows for a continual build-up of heat in the vertical profile (Stefanon et al., 2013; Miralles et al., 2014; see Fig. 7). The strength of the coupling between dry soil and the atmosphere can vary dependent on the event (Miralles et al., 2012), however was also a fundamental ingredient in the "mega heatwaves" over Europe in 2003 and Russia in 2010 (e.g., Fischer et al., 2007a, 2007b; Miralles et al., 2012, 2014).

Longer lasting heatwaves also have a clear link to local soil moisture deficits (Lorenz et al., 2010). Furthermore, very dry antecedent conditions can exacerbate larger-scale influences on extreme heatwaves, such as oceanic influences (Ferranti and Viterbo, 2006). Quantifying the soil moisture/temperature is challenging, however this coupling is certainly much tighter for temperatures of rare occurrence (Hirschi et al., 2011)—that is, soil moisture deficit plays an integral role in reaching very extreme temperatures. Over North America, desiccated soil moisture is also found to have an influence on severe temperature extremes (Diffenbaugh et al., 2005). Specifically, a severe rainfall deficit contributed to the 2011 Texas drought, where rainfall 8 months prior to the summer was less than half of the long term average (Hoerling et al., 2013). A relationship between droughts and extreme temperatures, as well as antecedent soil moisture and heatwaves over Australia has also been identified (Nicholls and Larsen, 2011; Nicholls, 2012; Perkins et al., in review).

It is clear via the pioneering work conducted over Europe (and to a lesser extent North America) that the land surface has an integral role to play, in acting like a switch as to whether a heatwave will occur, as well as its length and intensity. However there remain large gaps in our knowledge on this topic, particularly regarding the quantification of land surface/heatwave coupling over other global regions. Given the large impacts of heatwaves (see Section 1), such focus should be high research priority, to better aid in the prediction and preparedness of these events.

3.3. Climate variability and large-scale teleconnections

The role of climate variability in heatwave manifestation is an area where specialized studies are largely still required. Indeed, there are only a handful of studies that investigate the relationships between climate variability and general temperature extremes at the global scale (Kenyon and Hegerl, 2008; Alexander and Arblaster, 2009; Arblaster

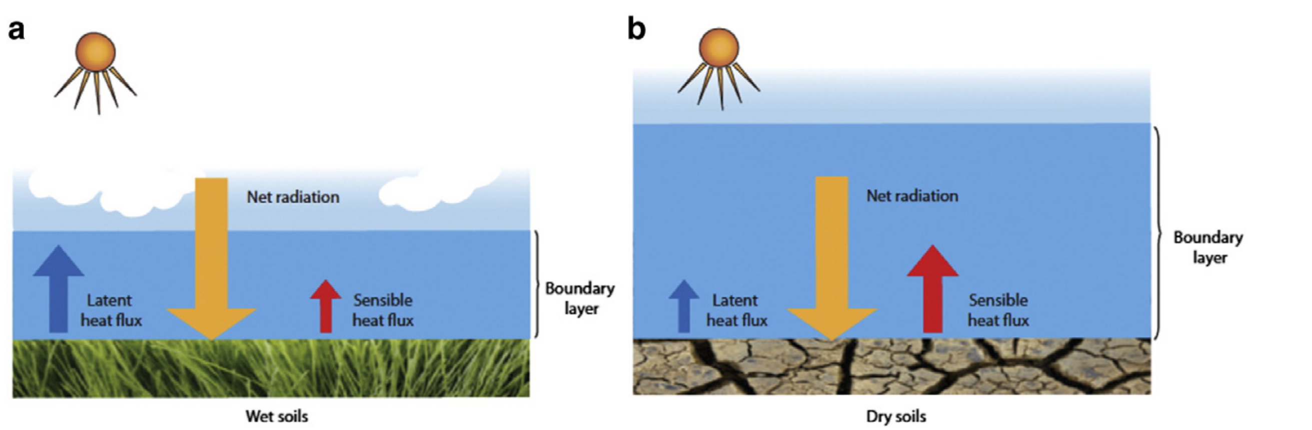

Fig. 5. Changes in the role of the land surface on temperature when soils are wet (a) and dry (b). A smaller boundary layer and sensible heat flux, and an enhanced latent heat flux occurs when soils are wet, however this is reversed under dry conditions. This explains in a simple context the coupling of drought and heatwaves. Taken from Fig. 1 of Alexander (2010).

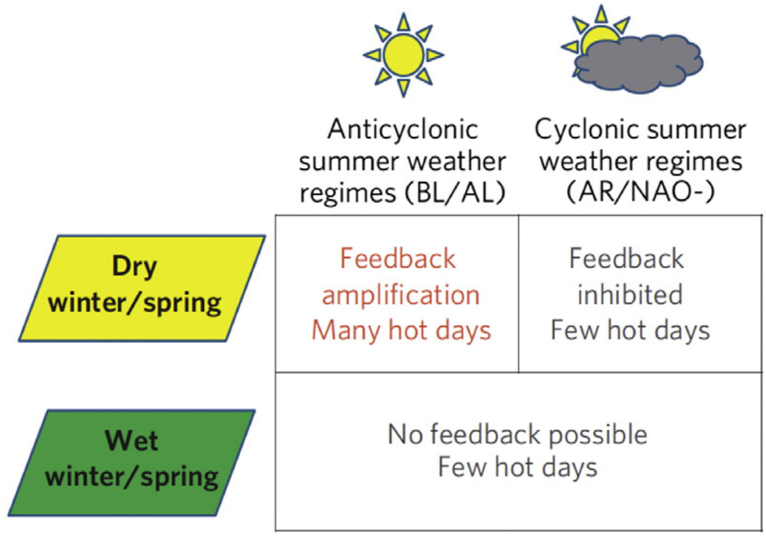

Fig. 6. Schematic explaining the relationship between rainfall in the months preceding summer and feedbacks with synoptic systems to cause hot days over Europe. Note that hot days are conducive to both little antecedent rainfall and anti-cyclonic weather. Taken from Fig. 4d of Quesada et al. (2012).

and Alexander, 2012). The global influence of the El Nino/Southern Oscillation (ENSO) is clear, however regional relationships dominate dependent on mode phase (i.e., El Nino or La Nina; Kenyon and Hegerl, 2008, Alexander and Arblaster, 2009; Arblaster and Alexander, 2012). The North Atlantic Oscillation (NAO) has a clear regional influence over Eurasia on temperature extremes, and the largest influence of the Pacific Decadal Oscillation (PDO) occurs over the northern Pacific Rim and North America (Kenyon and Hegerl, 2008). Given that climate modes can influence temperature distributions beyond a simple shift in the mean (Kenyon and Hegerl, 2008), further research in

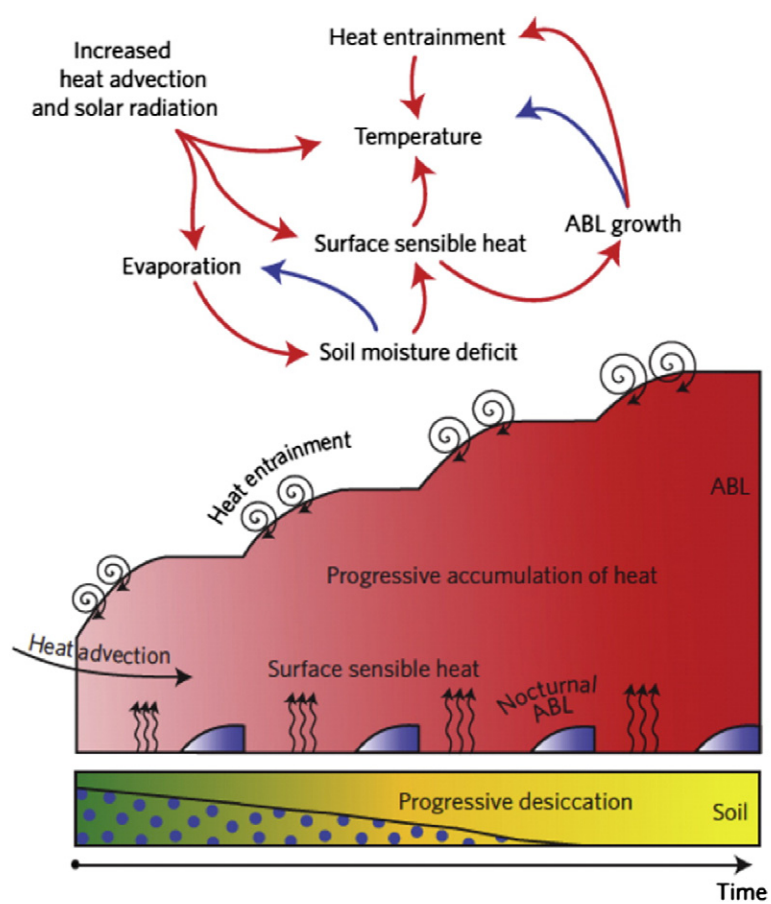

Fig. 7. Schematic illustrating the positive feedback between decreased soil moisture, which enhances sensible heat, the growth of the boundary layer and therefore heat entrainment. Increased advection decreases evaporation and contributes to a dryer soil. All processes work together to increase temperature, thus a heatwave occurs. Taken from Fig. 4 of Miralles et al. (2014).

understanding the interactions and changes in climate variability in relation to climate extremes at the regional scale is important.

As discussed in Section 3.2, much of the focus on European heatwave drivers has focused around land/atmosphere coupling via soil moisture, with many great developments made. Yet furthering this understanding to include large scale modes of variability and other teleconnection is quite sparse. This could be due to the fact that blocking highs are largely associated with the NAO (Della-Marta et al., 2007a), therefore such connections are implicit. Furthermore, research over this region has shown the dominating influence of soil moisture (Quesada et al., 2012) in heatwave intensity and frequency, which is likely important regardless of the larger-scale influence responsible for any one season of surplus/deficit. Despite this, connections have been made with the occurrence of heatwaves and the Atlantic Multidecadal Oscillation (AMO) via northern Atlantic sea surface temperatures (SSTs), as well as connections to high pressure anomalies over Scandinavia (Della-Marta et al., 2007a), suggesting that the drivers of European heatwaves can extend beyond local and shorter temporal mechanisms.

There are other global regions where climate variability and large scale teleconnections have significant influences. Over Australia, ENSO, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) have been shown to influence seasonal extreme temperatures (Nicholls et al., 1996; Min et al., 2013). Some attempts have been made in extending similar analyses specifically to heatwaves (Trewin, 2009; Parker et al., 2014b; Perkins et al., in review). Connections have been made in the physical development of southeastern heatwaves to La Nina phases of ENSO, positive phases of SAM and phases 3–6 of the Madden Julian Oscillation (MJO), due to the tropical convection interactions these phases govern (Parker et al., 2014b). In general, El Nino summers result in earlier heatwaves, longer and more intense heatwaves over much of Australia, with the exception of the far southeast (Trewin, 2009; Boschat et al., 2015; Perkins et al., in review). Large scale teleconnections to sea surface temperatures and atmospheric conditions have been suggested (Pezza et al., 2012; Boschat et al., 2015), thus linking persistent causing highs with larger scale climate variability.

Over North America, an ENSO influence has been identified, where La Nina patterns are coincident with warmer temperatures (Kenyon and Hegerl, 2008; Koster et al., 2009; Hoerling et al., 2013). It has been reported that a strong La Nina was largely responsible for the 2011 Texan heatwave/drought (Hoerling et al., 2013). Indeed, connections have been made with cooler Pacific conditions and enhanced evaporation regimes (Koster et al., 2009), highlighting a link between climate variability, the land surface and extreme temperature events for North America.

While the drivers of heatwaves have been discussed in separate sections in the present paper, it is clear that links exist between them. For example, clear links between climate variability and the land surface in the formation of heatwaves have been identified by Hoerling et al. (2013), while Quesada et al. (2012) address links between the land surface and synoptic systems. However, such analyses are sporadic in terms of the events and regions analyzed. While the climate community has a good general understanding in how synoptic systems, the land surface and larger-scale climate variability can contribute to heatwave development, there is a large gap in this quantification, as well the relative importance of the involved physical mechanisms. This will, of course, vary per region, but is vital for understanding in greater detail how and why heatwaves have changed. Moreover, a more comprehensive understanding on how heatwave are inextricably linked may aid in the better measurements of these high impact events in the future.

4. Observed changes and regional heatwaves

Due to the global effort in categorizing extreme temperatures, there is a wealth of literature analyzing how changes in the frequency and intensity of maximum and minimum temperatures have changed in the observational record (see IPCC, 2012). However, as discussed in Section 2, there are more to heatwaves than just the count of exceedances about the 90th percentile, or the highest annual intensity of maximum temperature. While this has been recognized (IPCC, 2012; Perkins and Alexander, 2013), literature on changes in specifically heatwaves is relatively scarce. As such, changes in general temperature extremes are first summarized. A discussion of global changes in heatwaves is then given, along with the challenges in detecting heatwaves at this scale. Regional changes as well as major regional events are also discussed.

4.1. changes in temperature extremes

Globally averaged, warming trends in annual maximum (minimum) temperatures were 0.14 °C (0.2 °C) per decade over 1950–2004 (Trenberth et al., 2007). Changes in observed temperature extremes have been detected since the turn of the millennium (e.g., Plummer et al., 1999; Easterling et al., 2000; Frich et al., 2002), though with regional variations. While fewer cooler extremes were detected over North America, fewer warm extremes were also measured toward the end of the 20th Century (DeGaetano and Allen, 2002). Similar trends have been measured via other studies, dubbing a “warming hole” for the central eastern United States (Pan et al., 2004; Portmann et al., 2009). However, over Australia and New Zealand both the frequency and intensity of warm maximum and minimum temperatures increased, with warm minimum temperatures showing greater trends (Plummer et al., 1999; Alexander and Arblaster, 2009), detectable over some areas as far back as 1910 (Torok and Nicholls, 1996). Over Europe, frost days have significantly decreased since the 1930s, due to large increases of winter minimum temperatures (Heino et al., 1999; Easterling et al., 2000). Over 1946–1999, a reasonably symmetric warming of minimum and maximum extremes was detected over Europe, though variations of the rate of warming occurred over shorter periods within this timeframe (Klein Tank and Können, 2003). The late 20th century warming over Europe, including the warming of extremes, placed this period warmer than any other in at least 500 years (Luterbacher et al., 2004). Other regional studies, which agree with those discussed here, can be found in IPCC (2012).

The first “global” analysis on observed changes in temperature extremes reported a significant change in most temperature indicators from 1946–1999, where the intensity and frequency of warm (cool) extremes increased (decreased) over most regions (Frich et al., 2002). However, changes in heatwaves were largely non-significant, yet were based on the now superseded HWDI index (see Table 1 & Fig. 8). The approach of this global study was in-house calculation of extremes by meteorological services so that they did not have to relinquish original data (see Section 2.1). However, large gaps still remained over Africa, India, and Central and South America (Frich et al., 2002). The creation of the ETCCDI network gave a much more comprehensive overview on observed changes in global extremes (Alexander et al., 2006). Over 70% (45%) of stations analyzed showed significant decreases (increases) in cold (warm) extremes over 1951–2003 (Alexander et al., 2006). As indicated by earlier studies, regional trends varied, where some regions (e.g., central and eastern Eurasia) exhibited large significant changes in the frequency of ETCCDI temperature indices, and others (e.g., the United States) showed little significant change (Alexander et al., 2006). Changes heatwaves were now detected via WSDI and not HWDI (see Table 1; Fig. 9). The observational network and resulting trends in ETCCDI indices are continually being updated, with a more recent assessment reporting significant increases in temperature extremes throughout all seasons during 1901–2010, although are generally larger during cooler months (Donat et al., 2013a). There is also evidence that the warming trends multiple indicators of temperature extremes have accelerated since the turn of the millennium (Seneviratne et al, 2014).

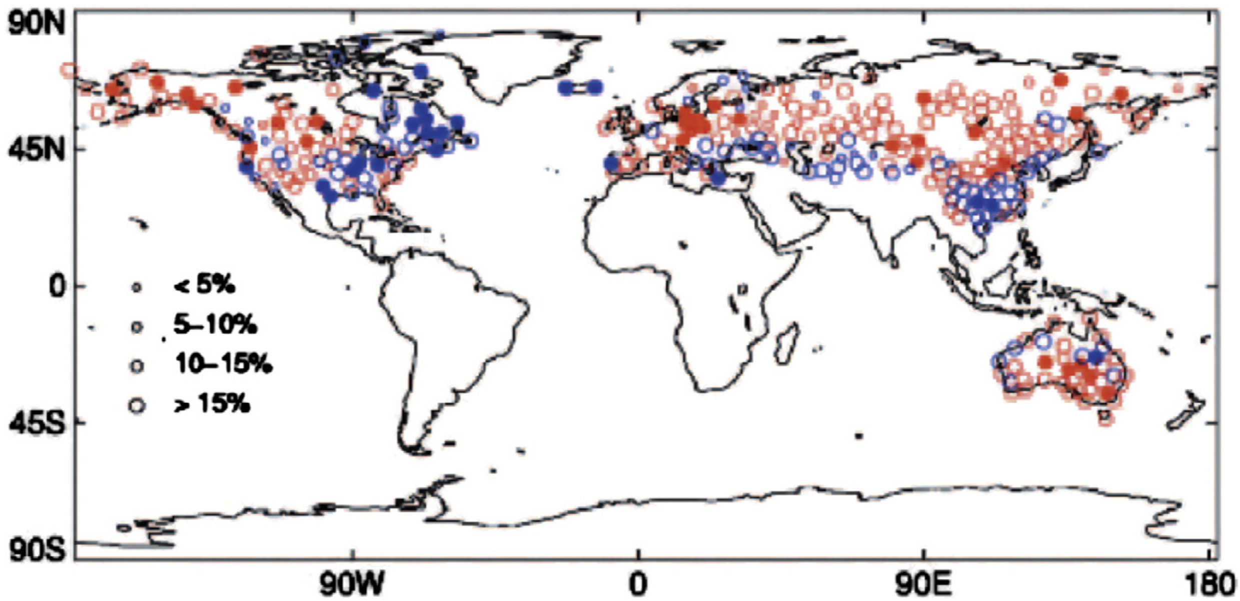

Fig. 8. The percentage of change between two multi-decadal averages in heatwaves during the 2nd half of the 20th century (1946–1999) of heatwave duration, as measured by HWDI for 144 stations. Filled circles indicate significant changes at the 5% level, with red (blue) indicating increases (decreases). Despite this being a global study there are still large regions not represented. Taken from Fig. 4a of Frich et al. (2002).

4.2. Global heatwave changes and hindering limitations

Given the inconsistency in heatwave definitions, until recently it has been difficult to document their changes at the global scale. Frich et al. (2002) and Alexander et al. (2006) provided some indication on how heatwave duration has increased (see Figs. 8 & 9), however one of the metrics is the previously discussed HWDI (see Section 2.1). A more recent study has presented updated global changes in heatwaves, using three relative definitions of heatwaves (see Fig. 2) and three characteristics—seasonal heatwave intensity, duration, and the number of heatwave days (See Section 2.2; Perkins et al., 2012). Since at least 1950, all three heatwave characteristics have been showing increasing trends in the global observational record, despite which underpinning definition of a heatwave is used (Figs. 10 & 11; Perkins et al., 2012). There is some regional similarity to changes other temperature extremes, such as the warming hole over the central United States (Perkins et al., 2012). Climate variability influences are evident globally, with the 1998 and 2009 El Nino's increasing the duration of heatwaves, and the series of La Nina's during the 1970s slightly decreasing the peak intensity of heatwaves during the respective years (Fig. 10, Perkins et al., 2012). However ENSO influences are only seasonal, with the long-term global trend indicating more heatwaves that are hotter and last for longer. Perkins et al. (2012) also showed that warm spells, which include heatwaves outside summer, are increasing faster in their frequency and intensity. This agrees with the existing literature on other measures of temperature extremes, in that warm temperatures relative to cooler

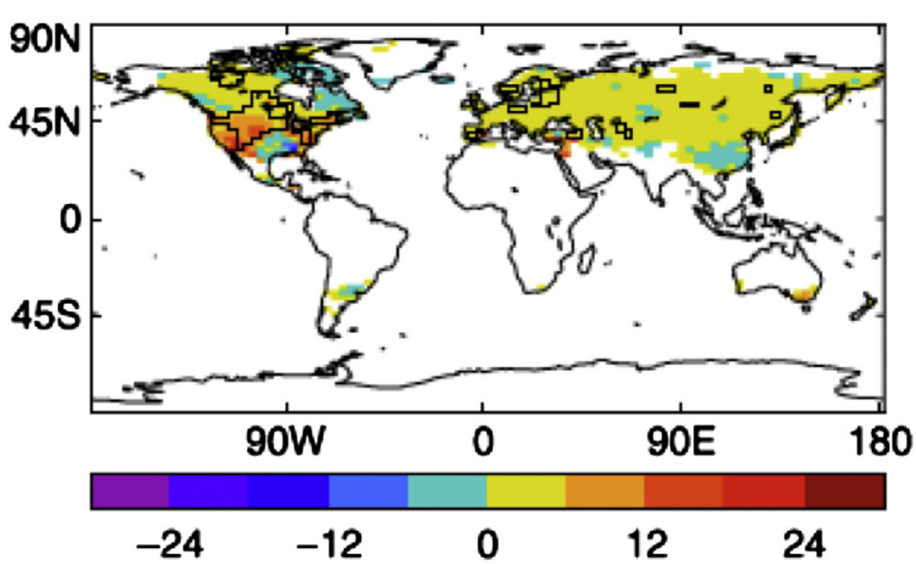

Fig. 9. Global changes in WSDI for 1951–2003. Units are in days/decade and areas within black boarders show significant trends at the 5% level. While there is some improvement with spatial coverage for some regions compared to Fig. 8, other regions are worse (e.g., Australia). This is likely due to the index not adequately representing heatwaves/warm spells over this region, rather than no heatwaves actually occurring. This is also likely a reason why trends in WSDI are smaller and less significant than other measures of extreme temperature in Alexander et al. (2006). Taken from Fig. 4a of Alexander et al. (2006).

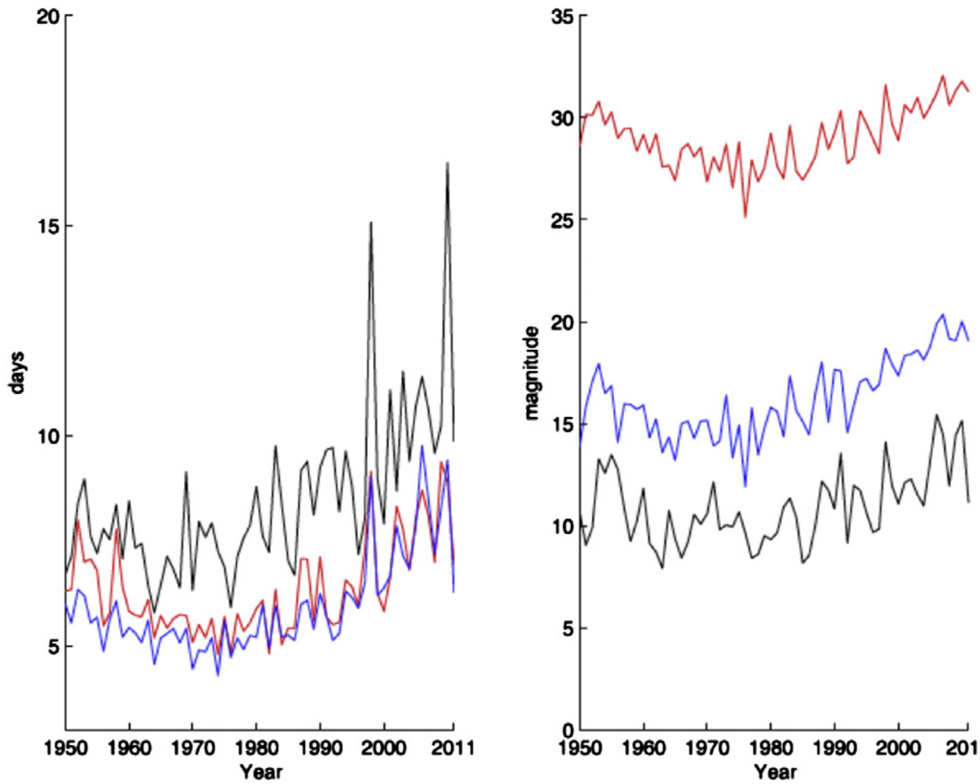

Fig. 10. Globally-averaged heatwave duration (HWD, left) and heatwave amplitude (HWA, right) from 1950–2011. Each line represents a different heatwave definition (see Perkins et al., 2012). Note that despite different quantitative results, all definitions have similar trends per characteristic. Moreover, seasonality is similarly represented. Taken from Fig. 2 of Perkins et al. (2012).

times of the year are increasing faster than similar extremes during warmer times if the year (e.g., Alexander et al., 2006).

Another challenge in the global assessment of changes in heatwaves is the underpinning data required. While some studies have calculated heatwaves and reported respective changes based on monthly data (e.g., Coumou and Robinson, 2013), the short timescales on which heatwaves occur and cause disastrous impacts means that daily data is essential in appropriately measuring them. Unfortunately, large gaps exist in the coverage and quality of the global observational network of daily temperature (Caesar et al., 2006), with areas of little to no coverage over Africa, central and south America, India, Greenland or Antarctica (Caesar et al., 2006; Perkins et al., 2012). Indeed, the data coverage in Perkins et al. (2012) is similarly lacking to Frich et al (2002), despite being a decade younger.

In the case of developing countries such gaps are partly explained by issues surrounding ownership of observational data. This limitation does not necessarily apply to other temperature extremes, due to alternative methods in their calculation (as discussed above). Moreover while other monthly global products of temperature go back as far as the late 1800s or early 1900s, the quality of daily data for many regions cannot be assured to a similar standard before 1950. Along with the previously inconsistent metrics used to measure heatwaves, the spatial and temporal limitations in daily observations has led the Intergovernmental Panel on Climate Change (IPCC) to declare only medium confidence in their changes at the global scale (IPCC, 2012). Such confidence will likely not change unless the quality of daily global observations is improved. Therefore until this time the assessment by Perkins et al. (2012) is as comprehensive as possible for a global analysis. Furthermore, as discussed below, (recent) regional studies on observed changes in heatwaves are mainly limited to regions with a comprehensive record – Europe, Australia and the United States.

4.3. Regional heatwave changes and remarkable events

While a dedicated and in-depth global assessment on heatwave changes has only recently been possible, research on European events has been underway for the last decade. While much of this has focused on the mega heatwaves over Western Europe and Russia (e.g., Stott et al., 2004; Otto et al., 2012), trends in European events have been measured from 1880 (Della-Marta et al., 2007b). The length of intense heatwaves has doubled over Western Europe between 1880–2005 (Della-Marta et al., 2007b; Fig. 12). It is estimated that an 11% increase in variance is responsible for a 40% increase in heatwave frequency (Della-Marta et al., 2007b). It has been suggested that the strong connections with the water cycle and land surface over Europe during summer (see Section 3.2) and the changes therein can explain some of the increases in summertime heatwaves, since more intense and longer heatwaves are much more likely after a dry winter over the Mediterranean (Vautard et al., 2007; Vautard and Yiou, 2009).

Both the 2003 European and 2010 Russian heatwaves are considered mega-heatwaves, due to their unprecedented nature in terms of their magnitude (Schär et al., 2004; Grumm, 2011) and in the case of the Russian heatwave, duration. The intensity of both events were at least 4 standard deviations greater than the observed temperature distribution (Schär et al., 2004; Grumm, 2011). Much of this research effort has been geared toward understanding why these events have occurred (e.g., Stott et al., 2004; Fischer et al., 2007a; Dole et al., 2011; Otto et al., 2012) and the likelihood of experiencing more in the future (e.g., Stott et al., 2004; Barriopedro et al., 2011). The contribution to changes in these events due to anthropogenic activity is discussed in Section 6. Interestingly, it is via these mega heatwaves that many developments have been made in understanding the role of the land surface and synoptic patterns in priming heatwave conditions (see Section 3). An extreme precipitation deficit, early excess

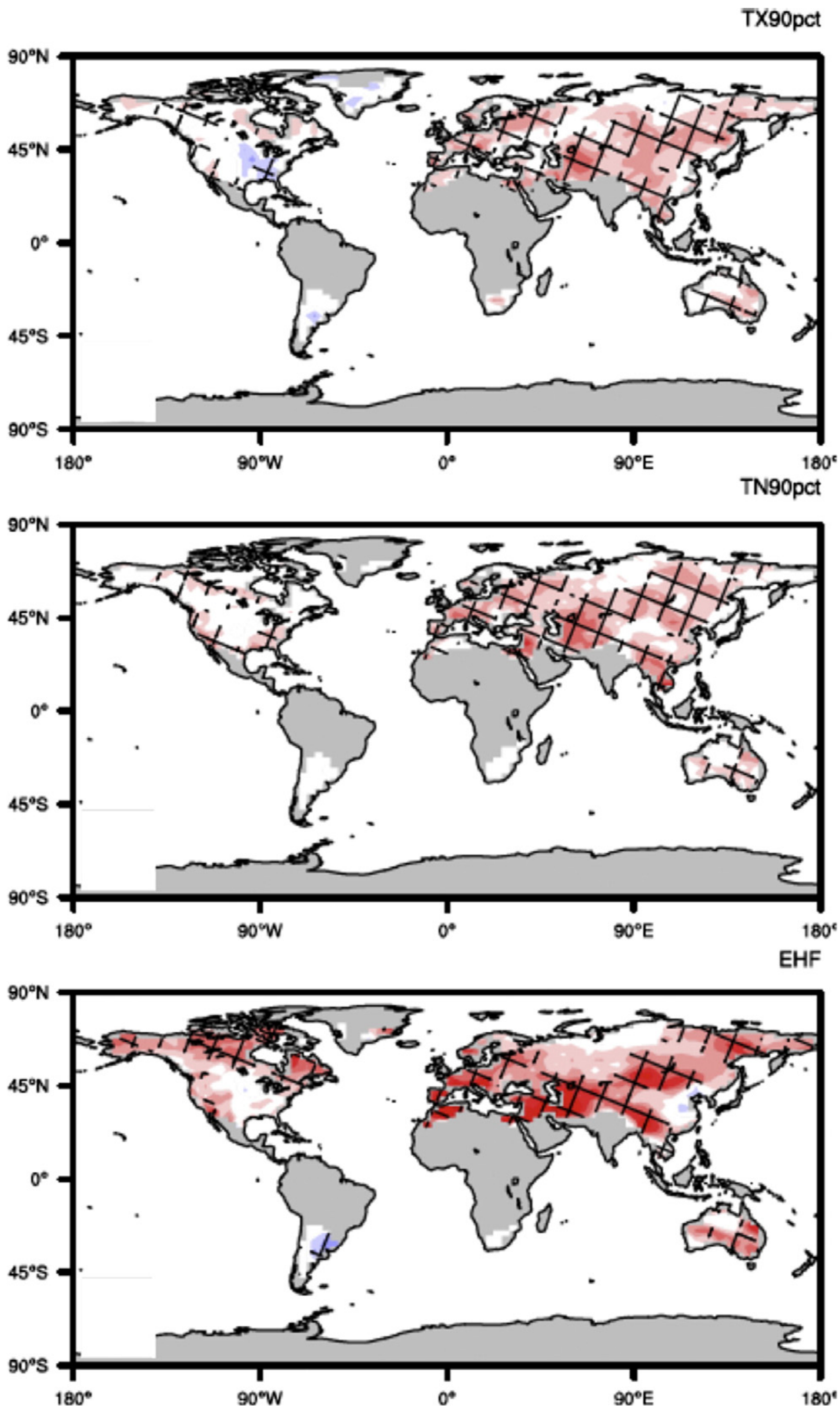

Fig. 11. Global trends in the frequency of summer heatwave days from 1950–2011 for three different definitions of heatwaves (see Perkins et al., 2012). Hatching indicates significance at the 5% level. Similar to Fig. 10, while quantitatively the indices differ, their respective regional trends are quite similar, along with areas of significance. Adapted from Fig. 1 of Perkins et al. (2012).

evapotranspiration and persistent blocking highs aided a positive feedback where latent cooling was heavily reduced, allowing the 2003 heatwave to be so extreme (Zaitchik et al., 2006; Fischer et al., 2007a). In retrospective studies, decreased soil moisture also increased the intensity of summer heatwaves in 1976, 1994 and 2005 (Fischer et al., 2007b). The longevity of the 2010 Russian heatwave was found to be mainly due to internal atmospheric processes that maintained a long-lived "omega" blocking event, while

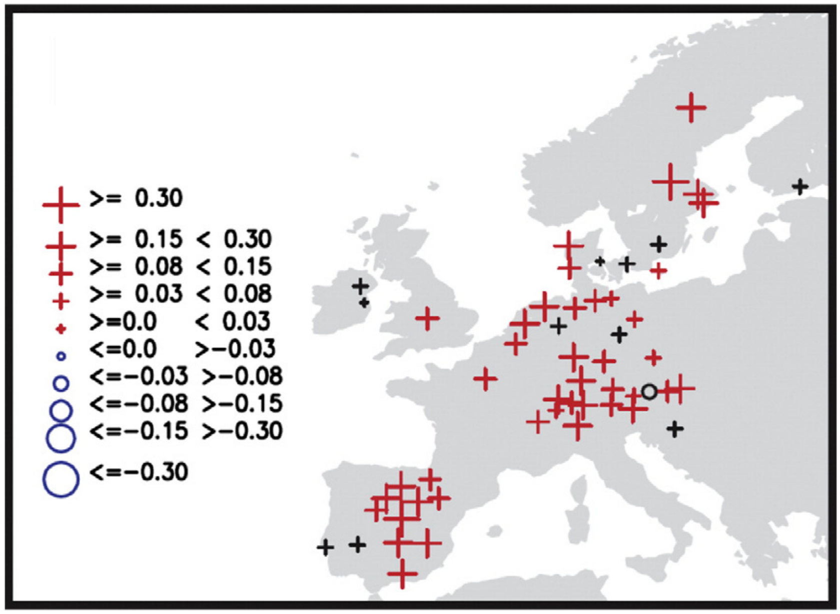

Fig. 12. Trends in the maximum summer heatwave length over Europe over 1880–2007. Red (black) indicate significant (nonsignificant) trends at the 5% level. Trends are in days/decade. Taken from Fig. 7d of Della-Marta et al. (2007b).

its intensity has been linked to the preceding drought (Dole et al., 2011; Matsueda, 2011; Grumm, 2011).

Over Australia, a small number of studies have addressed how heatwaves have changed over time. From 1950–2013 the number of heatwave days during each summer increased by 1–2 days/decade over much of the continent (Fig. 13), with trends further increasing during the latter 40 years (Perkins and Alexander, 2013; Steffen et al., 2014). The number of discrete events as well as heatwave duration has also increased, however by a lesser degree, since both rely upon a change in heatwave days. Significant increases in peak intensity were also detected for much of eastern Australia, and heatwaves occur earlier over many regions (Perkins and Alexander, 2013; Steffen et al., 2014). However, such changes are not uniform across the country, with some locations experiencing large increases in heatwave days, and others in intensity (Steffen et al., 2014). The most recent literature is qualitatively in agreement with earlier studies that employ different definitions and

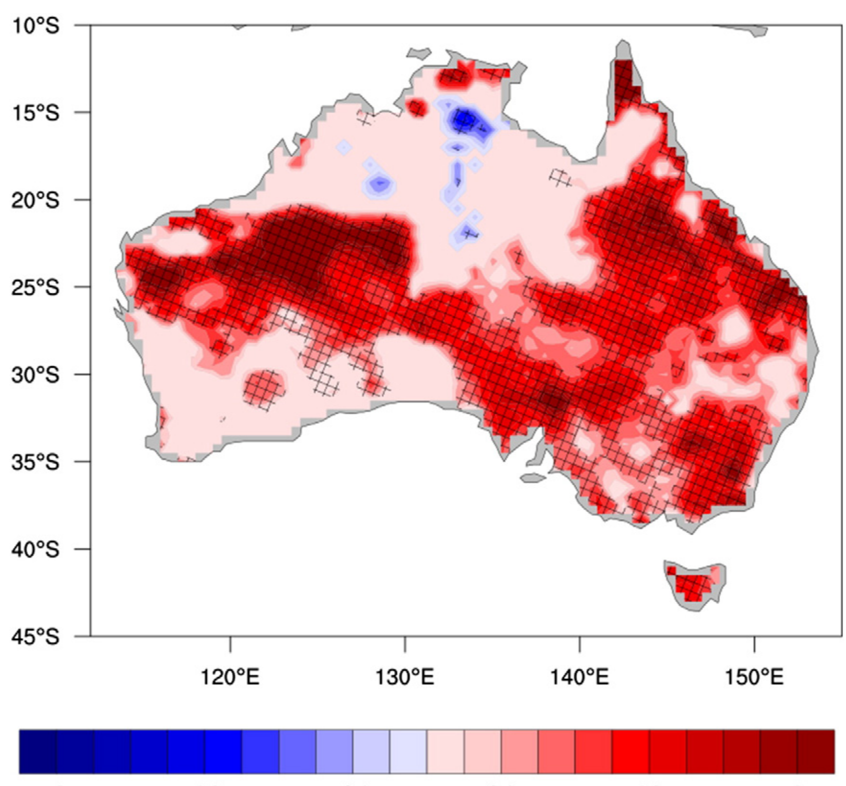

Fig. 13. Trends in the number of heatwave days (during November–March) over Australia between 1950–2013. Units are in days/decade, hatching indicates significance at the 5% level. This is an updated version of Fig. 3 h in Perkins and Alexander (2013).

characteristics (Tryhorn and Risbey, 2006; Trewin, 2009) as well as regional assessments on other temperature extremes (e.g., Plummer et al., 1999; Alexander and Arblaster, 2009). However some uncertainty lies around the observational datasets used. Coastal events exhibit higher intensities when measured from in-situ data compared to reanalysis, while trends in the number of heatwave days and average duration are larger in the latter (Tryhorn and Risbey, 2006).

In the last few years Australia has experienced numerous unprecedented heatwaves. A late spring heatwave occurred in 2012 over the southeast, where some areas recorded temperatures up to 12 °C higher than average (Bureau of Meteorology, 2012). This event preceded Australia's hottest summer on record, which was punctuated by an extensive heatwave during summer that impacted all of the country (Bureau of Meteorology, 2013a), a prolonged autumn heatwave over the southeast (Bureau of meteorology, 2013b), and relatively extreme heatwaves during spring (Bureau of Meteorology, 2013c). Central and southeast Australia were affected by a persistent high during January 2014 (Bureau of Meteorology, 2014a), and much of Australia experienced a long autumn heatwave, lasting almost 3 weeks in some locations (Bureau of Meteorology, 2014b). These events have broken many records across various locations, and have added to the increasing trends discussed above.

Compared to Europe and Australia, there is a lack of published literature on the investigation of recent changes in heatwaves over North America. This is likely due to the detection of the warming hole and its connections to changes in the regional hydrological cycle (Pan et al., 2004; Portmann et al., 2009) and/or changes in the phase of the PDO (Meehl et al., 2012), allowing assumptions to be extended to heatwaves. Indeed, larger numbers of heatwaves occurred in the central United States during the 1930s (Kunkel et al., 2008; Peterson et al., 2013), consistent with the dust-bowl drought (Hoerling et al., 2013). However a significant increasing trend in heatwaves has been detected since 1960 (Kunkel et al., 2008), and Alaska has experienced a high number of heatwaves during 2001–2010 (Peterson et al., 2013). There has however been two major American heatwaves that have received some attention in the climate science literature. In 1995 a severe heatwave occurred over Chicago, which was accompanied by a high dew point temperature (Karl and Knight, 1997; Kunkel et al., 1996) and was the most intense event in the region in 48 years (Kunkel et al., 1996). Another outstanding event is the Texan heatwave of 2011. The overall summer average temperature of 2011 was 2.9 °C above the climatological mean, with large ties identified to severe antecedent rainfall deficits and a very strong La Nina (Hoerling et al., 2013). This region of the United States has experienced other notable heatwaves, during the 1930s, 1980 (Greenberg et al., 1983) and 1998 (Hong and Kalnay, 2000), which, like European events, have strong connections to antecedent droughts (Hong and Kalnay, 2000). Lastly, over China, significant increases in heatwave length have been found since 1961, particularly in the northwest and southeast coast (Ding et al., 2010).

This somewhat detached assessment of observed changes in heatwaves reinforces the need for a unified framework. Much of the literature on observed heatwaves employ separate definitions, making it very difficult quantitatively to compare individual events and overall changes. While a prescribed framework similar to ETCCDI has been proposed (Perkins et al., 2012; Perkins and Alexander, 2013), such a tool will only be effective and, ideally improved upon, when widely used. The deployment of a unified heatwave framework similar to, or even part of the ETCCDI HadEX2 (Donat et al., 2013a) calculations would certainly help achieve this.

5. Future changes in heatwaves

5.1. Climate model background and their usefulness

Unlike the measurement of observed heatwaves, projected changes derived from numerical climate model simulations do not suffer from spatial and temporal issues, at least to the same degree. They do however suffer from the inconsistency of a unified heatwave definition with many studies employing their own, or using less appropriate ETCCDI definitions (similar to that of observed changes). Since the release of the Climate Model Intercomparison Project Phase 3 in 2005, many global climate models (GCMs) have provided daily data, which is key in the measurement of heatwaves. CMIP3 models with daily data produced only two time slices for future projections, based around 2046–2065 and 2081–2100, for a range of emissions scenarios (generally low, medium and high; see Meehl et al., 2007a). These limitations were mainly due to data storage and model run time, and allowed for a snapshot of the climate centered on the middle and the end of the 21st century.

The current version, CMIP5, has continuous 21st Century simulations for similar though not identical emissions scenarios (see Taylor et al., 2012), allowing for the analysis of trends and progressive changes in high-impact events such as heatwaves. Modern day climate model projections are also consistent through space, although the resolution of climate models can inhibit adequate projections of temperature extremes relative to observations. Climate models produce gridded data, where resolution can vary in size from 50–100 km^2 to 400 km^2 among different climate models. Each grid box is a representative for all conditions for the area it covers, thereby processes that occur on scales smaller than the resolution are parameterized (i.e., mathematically represented, and not actually simulated by the model). This can affect the representation of heatwaves since the driving processes (e.g., surface energy fluxes, soil moisture, synoptic systems) may not be adequately simulated, resulting in systematic biases such as overly persistent events (see Vautard et al., 2013).

Nevertheless, climate models are the best tools available for gaining understanding in how the climate will change under enhanced anthropogenic activity, and are extremely useful so long as their limitations are understood and taken into account. Moreover, multiple assessments have concluded that many contemporary numerical models provide sound projections of heatwaves and temperatures extremes (e.g., Perkins et al., 2009; Cowan et al., 2014; Zwiers et al., 2011). Encouragingly, there is also evidence that the latest generation of climate models in the CMIP5 archive have improved in simulating key processes for temperature extremes and heatwaves (e.g., Fischer et al., 2012; Purich et al., 2014; Loikith et al., 2015). Regional climate models (RCMs), which operate on finer resolutions than GCMs for a limited domain can also increase value to projections of temperature extremes (e.g., Di Luca et al., 2013; Perkins et al., 2014a), though the quality of downscaled projections is dependent on the driving GCMs (e.g., Vautard et al., 2013; Perkins et al., 2014a). All investigations of projections of heatwaves and temperature extremes conclude that the more greenhouse-gas enhanced the future climate is (represented via different emission scenarios), all temperature extremes are more intense and occur more often, and in the case of heatwaves, last for longer. The rest of this section discusses the current state of scientific knowledge on projected changes heatwaves at global and regional scales, as well as how an enhanced greenhouse gas future may affect heatwave mechanisms.

5.2. Projected global and regional changes

Recent comprehensive assessments of the climate science literature have stated it is very likely that increases in heatwave duration, intensity and frequency under enhanced greenhouse gas conditions (Meehl et al., 2007b; IPCC, 2012), though such increases have been reported for over a decade (Meehl and Tebaldi, 2004). Using a multi-member ensemble of a single GCM, the 2003 European and 1995 Chicago heatwaves are projected to occur more frequently under a business-as-usual scenario (i.e., no change in industry, greenhouse gas emissions continue to increase; Meehl and Tebaldi, 2004). A separate analysis over Central Europe also confirmed an increase in frequency of heatwaves similar to the 2003 event due to an increase in average temperature under enhanced greenhouse conditions (Beniston, 2004).

More modern RCM projections over Europe have shown spatial heterogeneity in increases of the intensity, frequency and duration of heatwaves (see Fig. 14; Fischer and Shär, 2009; Fischer and Schär, 2010). Larger increases in intensity and duration are projected for southern Europe, particularly over Spain and the Mediterranean, were heatwave days are projected to increase 20-fold by 2100 (Fischer and Shär, 2009; Fischer and Schär, 2010). Other projections over the Mediterranean include dramatic increases in the frequency hot temperature extremes and heat stress by between 200–500% by the end of the 21st century (Diffenbaugh et al., 2007). The frequency of a European mega-heatwave similar to 2003 is projected increase by 5–10 fold over the next 40 years (Barriopedro et al., 2011), with corresponding summer temperature anomalies becoming "the norm" by 2100 under a high emissions scenario (Fig. 15; Christidis et al., 2014). However, the 2010 Russian event was so extreme that the probability of a similar event occurring again does not increase for at least 50 years (Barriopedro et al., 2011) and is still considered a rare event by the end of the 21st century under a high emissions scenario (Russo et al., 2014).

Increases in heatwave intensity and frequency are projected by the CMIP3 ensemble and RCMs over the United States (see Fig. 16), with these signals detectable by 2030–2039 (Diffenbaugh and Ashfaq, 2010). Similar to Europe, projections are spatially heterogeneous, with larger increases in frequency over the southwestern states and Northern Mexico (Diffenbaugh and Ashfaq, 2010), yet the intensity of

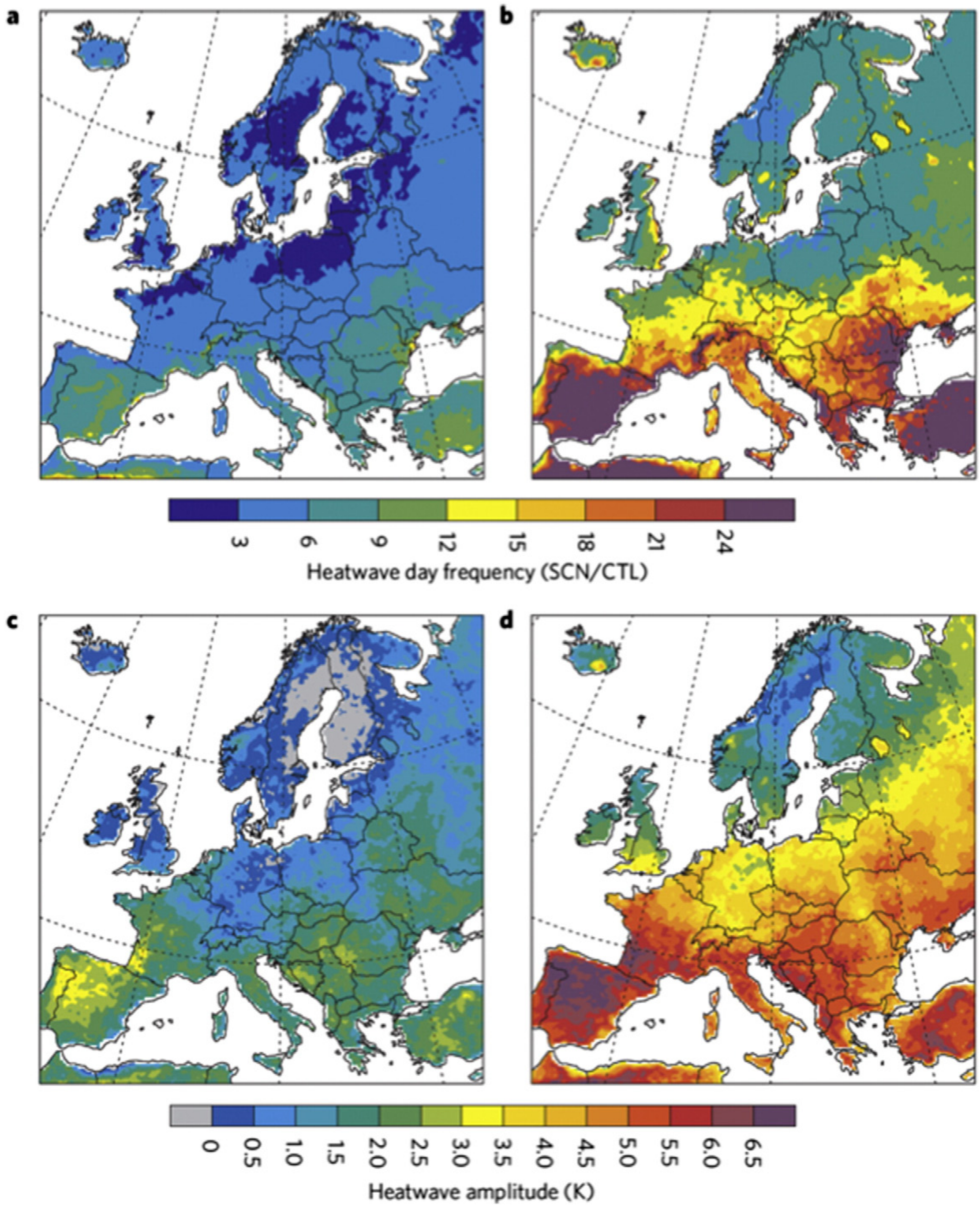

Fig. 14. Projected changes via an ensemble of RCMS of average European heatwave frequency (a,b) and amplitude (b,d) for 2021–2050 (a,c) and 2071–2100 (b,d), with respect to 1961–1990. Note the spatial heterogeneity, with smaller and sometimes negative changes further poleward. Taken from Fig. 2 of Fischer and Schär (2010).

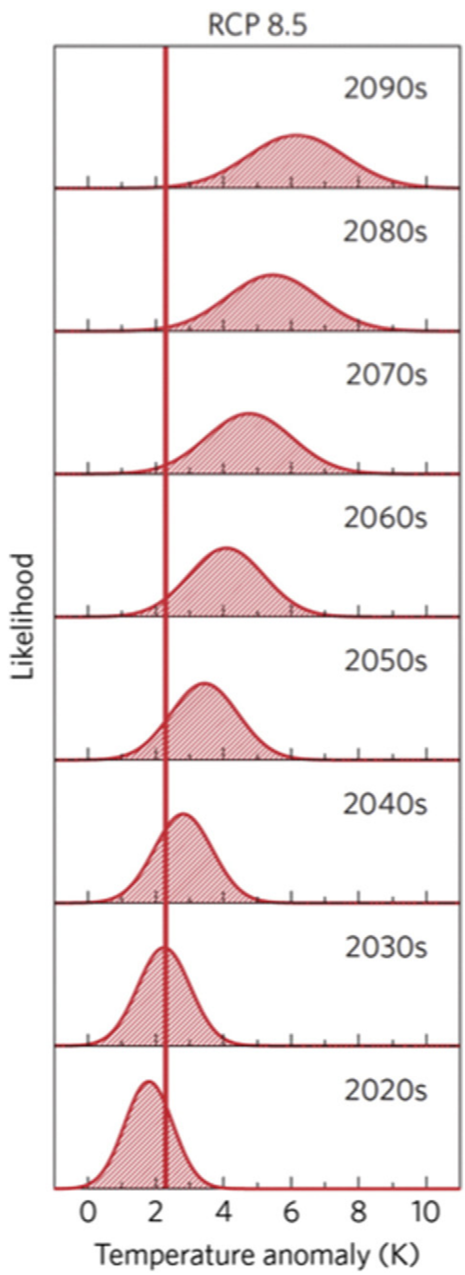

Fig. 15. Probability distributions of the European average summertime temperature anomalies relative to 1961–1990 for future decades under a nigh emissions scenario from the CMIP5 GCM ensemble. The vertical red line indicates the seasonal anomaly of the 2003 European heatwave. Note that by the end of the century, all European summers are projected to be at least as hot as 2003, indicating significantly more heatwaves. Adapted from Fig. 5 of Christidis et al. (2014).

temperature extremes show larger increases in the northeast, particularly under a high emissions scenario (Wuebbles et al., 2014). Under a medium emissions scenario, the number of hot extremes will outnumber cold extremes by 20 (50) times by the mid (late) 21st century (Meehl et al., 2009). Heat stress over the United States are projected to increase by many climate model ensembles and generations, largely driven by temperature increases since relative humidity is projected to decline (Wuebbles et al., 2014 and references therein).

Very large increases the duration of heatwaves are projected over the Tropical Pacific by the end of the 21st Century (Perkins, 2011). However, such projections should be interpreted with caution, as extreme temperature metrics are exacerbated in this region due to the small annual range temperature. Though despite this small annual range and relatively smaller projected temperature increase, it has been reported that heat stress show the largest projected increase over the Tropics than any other region by the end of this century (Delworth et al., 1999; Fischer et al., 2012).

Significant increases in Australian heatwave/warm spell duration was found to occur by the end of the 21st Century in a subsample of CMIP3 models (Alexander and Arblaster, 2009). This is consistent with earlier work, which also reported increases in heatwave frequency and intensity projected by a single GCM by (Tryhorn and Risbey, 2006). Modern analysis employing the CMIP5 models report increases in the intensity, frequency and duration of Australian heatwaves and warm spells by the end of the 21st century (Cowan et al., 2014). Significant increases in the number of heatwave/warm spell days and heatwave/warm spell duration are greatest over tropical Australia, particularly by 2100 under a high emissions scenario (see Fig. 17). The maximum amplitude of heatwaves and warm spells significantly increases over southern Australia (Cowan et al., 2014), which already experiences the most intense events of the continent (Tryhorn and Risbey, 2006; Perkins and Alexander, 2013). This asymmetric warming in events during cooler times of the year is consistent with observed changes (Perkins et al., 2012). At the local scale, significant changes in the number of heatwave days and event duration are projected for a selection of Australian cities, under a high emissions scenario (Cowan et al., 2014). Urban areas are projected so see larger increases in heat stress (heatwaves coupled with humidity), particularly at nighttime, compared to surrounding urban areas (Fischer et al, 2012).

While there is a significant amount of literature on future changes in regional heatwaves, some studies have also held a global focus. Increases in heatwave duration were projected by the CMIP3 and CMIP5 GCM ensembles, with greater increases under the business-as-usual scenario compared to lower emission scenarios, and statistically significant changes over land, with exception to the tropics (Tebaldi et al., 2006; Orlowsky and Seneviratne, 2012). The length of the average seasonal heatwave is projected to increase faster than maximum seasonal duration, and long events show faster increases during cooler seasons compared to warmer seasons (Fig. 18; Orlowsky and Seneviratne, 2012) Events with similar intensity to the 2010 Russian event are projected to occur as often as once every 2 years over Europe, the Americas, Africa and Indonesia by the end of the 21st century under a high emissions scenario (Russo et al., 2014). Projections from a perturbed physics ensemble show increases in heatwave intensity over the Northern Hemisphere, which are reasonably uniform across events of various duration, though the overall length of events are projected to have dramatic increases (Clark et al., 2006). Indeed, many global regions may likely reach a new permanent warm state by the middle of the 21st Century (Diffenbaugh and Scherer, 2011), thus increasing the intensity, severity and frequency of present-day events.

5.3. Changes in mechanistic drivers of heatwaves

It is abundantly clear from many different studies employing numerical models at regional and global scales that throughout the 21st century, heatwaves will occur more often, at higher intensities, and last for longer under enhanced greenhouse gas concentrations. But what exactly drives this change? Do the synoptic systems that govern heatwaves also change, is there any alteration to land surface fluxes and coupling, or is an increase in background temperatures solely responsible? Presently, there seems to be no clear answer on this, with different studies providing evidence in changes of different mechanisms.

Changes in the intensification of persistent highs were found to influence future increases in frequency of intense heatwaves similar to the 2003 European heatwave and 1995 Chicago heatwave (Meehl and Tebaldi, 2004). Increased frequencies of persistent highs have been projected over the United States, which, coupled with increased drying of the land surface, aids in the manifestation of heatwaves under enhanced greenhouse conditions (Diffenbaugh and Ashfaq, 2010).

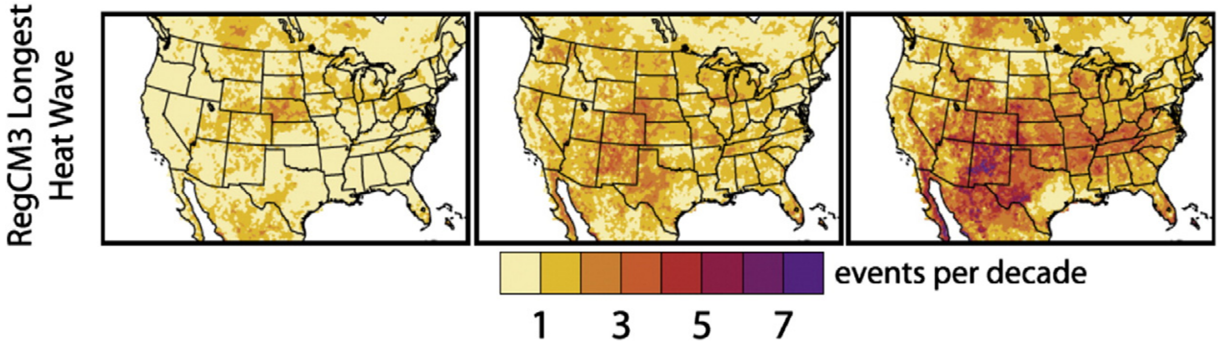

Fig. 16. Figure projections over the United States from an RCM on the occurrence of the hottest heatwave during 1951–1999 for 2010–2019 (left), 2020–2029 (middle) and 2030–2039 (right). Note that by halfway through this century, all of the United States will see more extreme heatwaves, particularly in the central states. Adapted from Fig. 1 of Diffenbaugh and Ashfaq (2010).

However, while the intensity of persistent highs is also projected to increase over Australia with more of these systems also occurring further poleward, the main driver for increased heatwave occurrence and duration is mainly due to an increase in average temperature (Cowan et al., 2014; Purich et al., 2014). This is in agreement with earlier work finding increases in the frequency of temperature extremes result mainly from increases in seasonal average temperature over most global regions (e.g., Barnett et al., 2006; Ballester et al., 2010). Similarly over Europe the CMIP3 ensemble provided no evidence to suggest changes in heatwave-driving synoptic systems throughout the 21st century (Cattiaux et al., 2012). Moreover, future events are projected to have similar governing synoptic systems compared to recent events (Cattiaux et al., 2012).

Simulations from RCMs project increased variability coupled with an increase in average temperature under enhanced greenhouse gas conditions. This increases the frequency of events similar to the 2003 and 2010 mega-heatwaves, though changes in "less extreme" heatwaves may result from increases in mean temperature only (Barriopedro et al., 2011). Many studies point toward increased temperature variability of around 100% over Europe over the next century, leading to larger increases in extremes compared to mean temperatures (Schär et al., 2004; Clark et al., 2006; Diffenbaugh et al., 2007; Fischer and Schär, 2009, 2010; Fischer et al., 2012). Temporal components of variability (seasonal, annual, interannual) are all projected to increase under enhanced greenhouse conditions, though by varying degrees over different European regions (Fischer and Schär, 2010; Fischer et al., 2012). There is evidence that the projected increase in temperature variability is connected to soil moisture and other land surface interactions, with higher heatwave magnitudes expected under increases in average temperatures combined with enhanced soil moisture deficits (Clark et al., 2006; Seneviratne et al., 2006; Diffenbaugh et al., 2007; Fischer et al., 2011). Indeed, a preferential heating of the upper tail of the temperature distribution, thus increasing variability, is largely governed by soil moisture feedbacks (Diffenbaugh et al., 2007; Fischer et al., 2012). Both conditions are projected under enhanced greenhouse gas conditions over Europe (e.g., Seneviratne et al., 2006; Fischer et al., 2011), though there are no similar studies to date exploring future land surface changes and heatwaves over Southern Hemisphere regions.

Over the last decade, a huge amount of work has been undertaken to understand how temperature extremes and heatwaves will change under enhanced greenhouse gas conditions. While heatwave intensity, frequency and duration increase over time (particularly under high/business as usual scenarios), they are projected to change at different rates and over different spatial scales. Moreover, much of the work in understanding how the drivers of heatwaves will change has largely been conducted over Europe. Such changes in temperature variability and land surface coupling may not necessarily apply to other regions, at least to the same extent. Thus, there is a great need for more research on how anthropogenic activity may cause changes in the physical mechanisms behind heatwaves. There may also be other mechanisms that may change in a future climate but have not yet been thoroughly researched, such as land use change and the corresponding effects of atmosphere/land surface coupling (e.g., Hirsch et al., 2014). Progress in climate modeling is also continuous and develops further as we learn more about the climate system and its interactions, and the climate community is able to make use advances in computational resources. Thus, continuing research into the understanding of future changes in heatwaves will continue to be necessary, at least for the foreseeable future.

6. Role of humans behind heatwave changes—can we do it?

Despite a lack of a consistent heatwave metric, an increase in the intensity, frequency and/or duration of these high-impact events have been detected over many global regions. The occurrence of record-breaking events since the turn of the millennium is also disturbing. While such changes are consistent with what is expected under enhanced greenhouse conditions, is it possible to quantify whether human activity is responsible for these changes, and/or the occurrence of a particular event? Indeed, this is a question often bestowed on climate scientists during or directly after a heatwave (or another high-impact event) occurs (Stone and Allen, 2005). And while we cannot categorically answer "yes" or "no", we can determine whether the likelihood, or chance of a particular heatwave occurring has changed due to human influence on the climate. In other words, do we now see more heatwaves that are longer and more intense, because of anthropogenic climate change?

6.1. Fraction of Attributable Risk

A probabilistic method commonly used to answer this question is named Fraction of Attributable Risk (FAR), which works by comparing the occurrence of a specific event over a given region between two samples (Allen, 2003; Stone and Allen, 2005). In the case of climate change research, this involves large ensembles of climate model simulations. This method is frequently used to study changes in a meteorological event from a climatological perspective (Hulme, 2014), that is, is a meteorological event of a certain intensity changing in its relative frequency, because the climate is changing? The probability of the event of interest is computed in climate model experiments where observed greenhouse gas emissions are prescribed, and are compared to the probability of the same event occurring in experiments where greenhouse gasses are not included. The exact details of models used and experimental design may vary (e.g., see Lewis and Karoly, 2013; Christidis et al., 2013), however the method has been successfully employed for

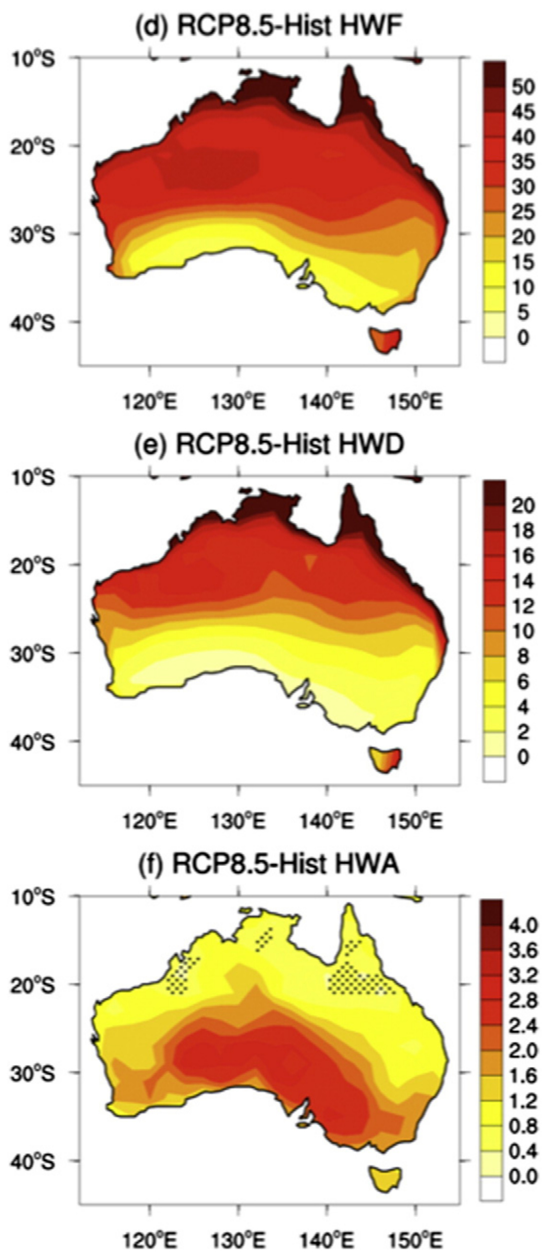

Fig. 17. Projected changes of Australian summer heatwave days (HWF), duration (HWD) and hottest day of hottest event (HWA) using the CMIP5 GCM under a high emissions scenario for 2081–2100 compared to 1950–2005. Units for the top to panels are days, for the bottom panel in °C. Stippling indicates where changes are not significant at the 5% level. Adapted from Fig. 3 of Cowan et al. (2014).

over a decade to determine probabilistic changes in the odds of various observed extreme events under current atmospheric greenhouse gas levels (e.g., Stott et al., 2004). Fig. 19 shows the relationship between FAR values and changes in risk. For example, a FAR value of 0.5 corresponds to a doubling of risk, a FAR value of 0.7 corresponds to a quadrupling, and so on.

One of the first FAR studies conducted investigated the change in likelihood of the 2003 European heatwave (Stott et al., 2004). In this attribution study, the event was characterized by a summertime mean temperature anomaly of 2.3 °C over the domain of Western Europe. The frequency of this area-averaged summertime anomaly was then determined for model simulations that included natural climate forcings and anthropogenic emissions, and compared to the frequency of the same event in a simulation where only natural forcings were included. By using a bootstrap resampling procedure to estimate uncertainty, it was concluded with 90% confidence that the odds of a summertime anomaly of 2.3 °C over Western Europe had at least doubled due to anthropogenic activity (Stott et al., 2004). However, updated studies report this estimate as very conservative, due to a continuing increase in European temperatures, and more advanced modeling tools (Barriopedro et al., 2011; Christidis et al., 2014). Moreover, the estimate in risk is only valid for the point in time that it is estimated for. As the climate continues to change because of anthropogenic activity, risks in high-impact events will also change. So in the case of the 2003 European heatwave, the risk of a similar event occurring will only increase as the planet continues to warm.

Using the CMIP5 model ensemble, Lewis and Karoly (2013) performed a similar study on the 2012/2013 Australian summer, the hottest on record. Their analysis revealed a 2.5 fold increase in the odds of an Australian summer this hot by the early 2000s, and at least a 5-fold increase by 2020. Very similar results were also found for the increase in risk of the 2014 autumn heatwave (Perkins, in review). Indeed, there have been multiple studies that have examined the contribution of anthropogenic climate change to Australia's hottest year using various methods. Knutson et al. (2014) and Lewis and Karoly (2014) computed FAR values of near 1.0 (i.e., almost impossible to have occurred without human influence) for various prolonged extreme temperatures that occurred during 2013, with Arblaster et al. (2014) and King et al. (2014) noting such links with anthropogenic climate change have manifested in reduced moisture availability an anomalous circulation patterns. More specifically Perkins et al. (2014b) found at the intensity and frequency of heatwaves that occurred during the 2013 Austral summer had doubled and trebled in these odds of occurrence, respectively, due to anthropogenic climate change.

Similar studies have also been conducted for other regional events across the globe. Diffenbaugh and Scherer (2013) found a 4-fold increase in the extreme July temperatures and associated dynamics across the United States. An extreme summer also occurred over Asia during 2013, with FAR analyses revealing a 10-fold increase over Korea (Min et al., 2014). Anthropogenic climate change also increased the probability of heatwaves similar to respective 2013 events over Japan (Imada et al., 2014) and China (Zhou et al., 2014). The likelihood of extremely warm European summers has increased by 2–4 fold (Christidis et al., 2012a), while extremely warm years have increased by at least a factor of 2 over many global regions (Christidis et al., 2012b). European autumn temperatures of similar magnitude to 2011 have also increased 62-fold in occurrence, compared to a climate without anthropogenic influence (Massey et al., 2012).

In the last decade, understanding the human contribution on smaller regional and spatial scales has become pertinent, particularly from an impacts perspective. While the limitations of GCMs could inhibit attribution analyses on finer scales (Stott et al., 2010), a systematic intra-model relationship between temporal and spatial scales has been identified in the attribution of temperature extremes (Fig. 20; Angélil et al., 2014). Thus, while most "extreme" attribution studies currently focus on seasonal or annual temperature anomalies over continental scales, the same general findings of these studies likely apply to shorter scale events (i.e., heatwaves), at least until targeted research is undertaken.

6.2. Other approaches and inherent attribution issues of heatwaves

There are also other, though perhaps less widely used methods that can be used to understand the anthropogenic influence behind changes in heatwaves. A statistical model employing Monte Carlo simulations was introduced by Rahmstorf and Coumou (2011), assessing changes in risk similar to FAR, though employed no numerical climate models, rather incorporating random sampling and trend estimation from observations. Via this method it was found that the occurrence of the Russian heatwave had increased by 5-fold during the last decade

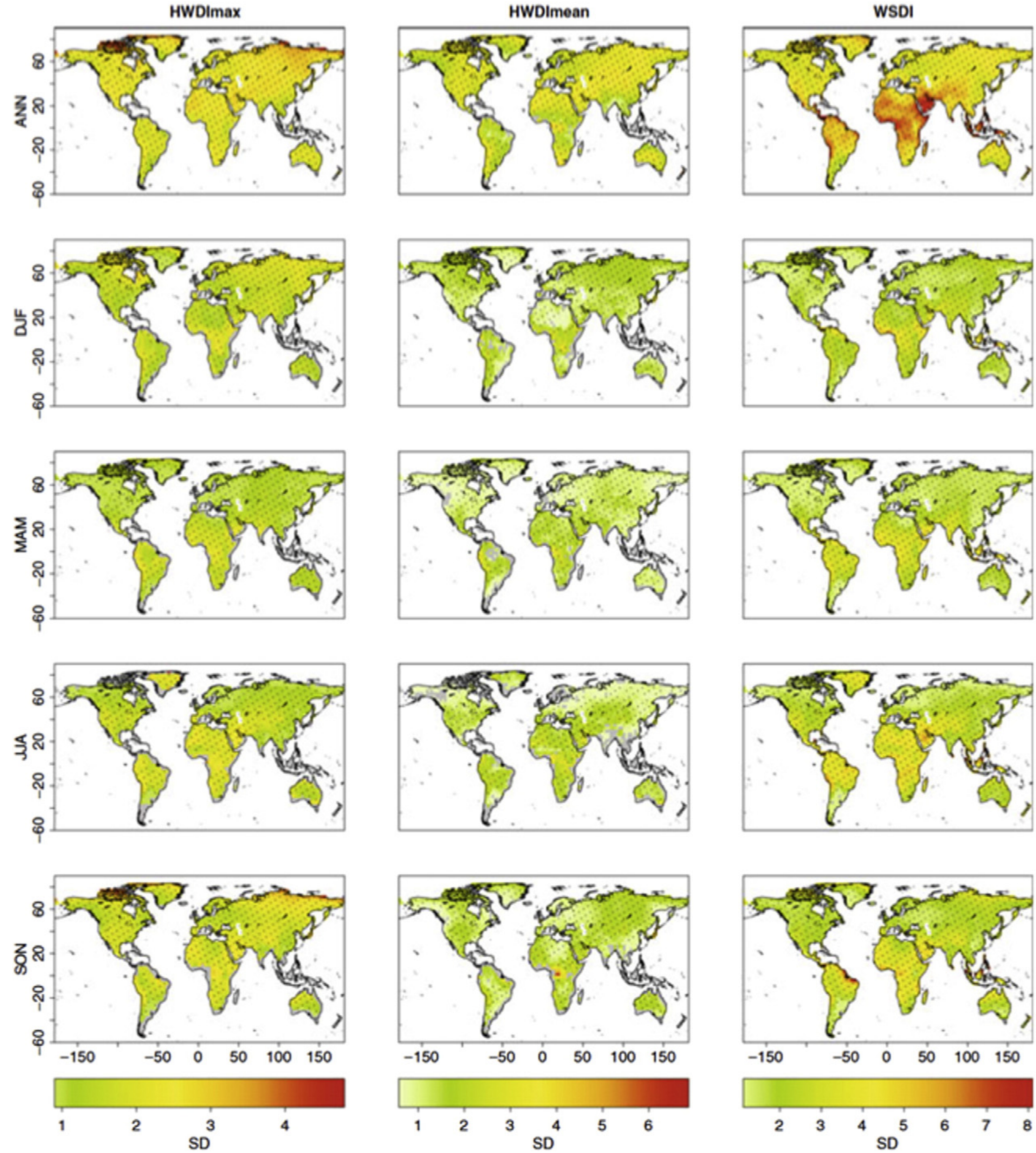

Fig. 18. Global projections of Annual (1st row), Dec–Feb (2nd row), Mar–May (3rd row), Jul–Aug (4th row), and Sep–Nov (5th row) of maximum heatwave duration (1st column), average heatwave duration (2nd column) and warm spell duration (3rd column) using the CMIP3 GCMs. Note the seasonal and regional heterogeneity of changes. Taken from Fig. 5 of Orlowsky and Seneviratne (2012).

(Rahmstorf and Coumou, 2011). Dole et al. (2011) made use of the CMIP3 model ensemble to ascertain any contribution of human activity on the Russian heatwave, and employed multi-member model ensembles to understand the role of atmospheric and oceanic influences. Since no trend was detected for western Russia temperature extremes in the CMIP3 models and observations, and weather patterns were similar to other heatwaves for the region, it was concluded that human activity did not contribute to the intensity of the 2010 Russian heatwave, rather that atmospheric mechanisms and land–atmosphere feedbacks were mostly responsible (Dole et al., 2011). It is interesting that despite analyzing the same event, the above two studies seem to contradict each other.

This raises the important point of the attribution question that is posed. What appears to be contradicting statements on the role of anthropogenic climate change behind a specific heatwave may be equally plausible, so long as the context is clear. Otto et al. (2012), who conducted a separate analysis on the Russian heatwave, find neither study wrong. Instead, the importance of question framing is emphasized—the magnitude of the Russian heatwave is primarily driven by internal dynamics, as outlined by Dole et al. (2011), however the probability in the occurrence if this particular event over the region of interest has increased when anthropogenic climate change is accounted for (Rahmstorf and Coumou, 2011; Otto et al., 2012). This is a crucial point that must be remembered in any analysis determining the

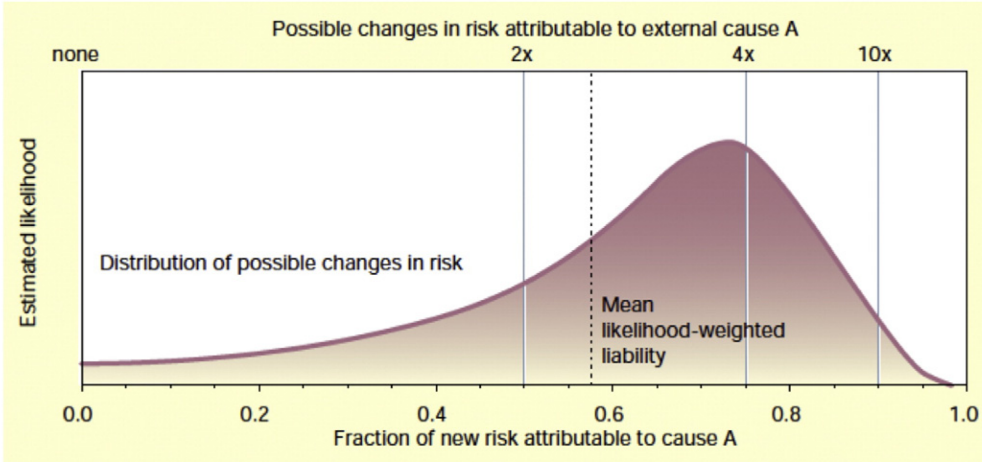

Fig. 19. Schematic showing the relationship between the fraction of attributable risk of a specific to an external cause, and the corresponding change in risk. Taken from Fig. 1 of Allen (2003).

contribution of humans toward a specific event—the explicit statement of the characteristic being analyzed and its context.

It is also quite likely that in many cases the different driving mechanisms of a heatwave are affected by anthropogenic climate change in different ways, thus complicating the resulting attribution statements. An example of this is the 2011 Texan heatwave, which was coupled, and likely amplified, by a preceding extreme drought (Hoerling et al., 2013). The drought itself was largely driven by natural variability through an extreme La Nina. And while increases in the frequency of temperature records were marginally attributed to human activity, attribution to natural variability was much higher. An overall average warming from 1981–2010 was attributed to human activity, however over longer temporal periods the assessment is difficult, due to a lack of temperature trend over this region. Hoerling et al. (2013) emphasize the importance of assessing the physical mechanisms in conjunction with event attribution, and the conclusion that natural variability was largely responsible was also supported by Cattiaux and Yiou (2013), who found little detectable change in atmospheric flow in response to anthropogenic activity.

Optimal fingerprinting is another method to disclose the human contribution behind observed changes (Allen and Tett, 1999). This method employs climate model simulations to estimate internal variability, and scaling estimates are applied to historical model trends to best match observed trends (Allen and Tett, 1999; Allen, 2003). Thus,

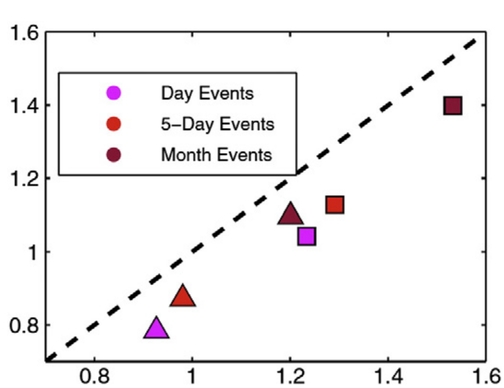

Fig. 20. The relationship between the length of time an extreme temperature event lasts (colors) and the size of the spatial domain it occurs on (x and y axes) for its risk of occurrence. The triangles and squares each represent a different RCM. Such relationships suggest that changes in the risk of temperature extremes (i.e., heatwaves) at finer scales can be estimated from changes in risk at larger scales. However, the estimated absolute changes in risk do differ dependent on the model used. Adapted from Fig. 3a of Angélil et al. (2014).

the result depicts the contribution of human activity toward trends in a certain event, accounting for influences of internal climate variability. A significant contribution of anthropogenic forcing toward increasing warm years has been detected over many global regions (Christidis et al., 2012b). At the regional level, an anthropogenic influence has contributed to European seasonal temperature trends (Stott et al., 2004; Christidis et al., 2012a). In terms of extremes, optimal fingerprinting has found that increasing trends in extremely warm nights over Australia, the United States and Northern Eurasia can be attributed toward human activity (Christidis et al., 2005). Later work detected an influence on extremely warm days over similar regions (Christidis et al., 2012b), which, along with other measures of extreme temperatures, has been extended to other regions (Zwiers et al., 2011). Indeed in most cases, trends in temperature extremes would have decreased since 1950 if forcings on the climate system were only from natural sources (see Christidis et al., 2005, 2012b). However, despite significant trends being detected over numerous regions (Perkins et al., 2012), formal fingerprinting on heatwaves specifically has yet to be established.

It is clear from the discussion above that while it is certainly achievable to ascertain the influence of human activity behind a heatwave (or any other event of interest), there are some limitations that must be remembered. Firstly, the results of an assessment like this are highly specific—they depend on the intensity of the event, its spatial and temporal scale, the regions of interest, and the specific time period on which the analysis is performed. Thus, while links of attribution statements between spatial and temporal scales have been identified for temperature extremes (Angélil et al., 2014), in order to ascertain the correct change in risk, at least at this stage, an attributional study is required for each individual event. Moreover, changes in likelihood are not stationary in time, and need to be re-established for different temporal periods. There are also issues surrounding the specificity of the attribution question, which influences the analysis and the interpretation of the assessment. Previous and current modeling tools used for attribution may also become superseded, which could compromise then-relevant statements.

These issues, however, should not prevent the undertaking of heatwave attribution studies, but rather facilitate in their development. A large communication effort is certainly required to ensure statements are interpreted correctly, and not misunderstood by the greater scientific or even general communities. Provided this occurs, and attribution methods are developed further and applied to physical mechanisms, many benefits could arise from this type of knowledge. Near- or even real-time attribution could be determined as a heatwave occurs, or perhaps even as part of a weather forecast. This would highlight the current impact of anthropogenic climate change, and accelerate the discussion of liability (Allen, 2003) in social constructs. Attribution of heatwaves may also provide important adaptation and mitigation information; by understanding how an event is changing compared to a natural baseline, appropriate policies may be drawn up to lessen the impacts of these events—for example the impacts of heatwaves on human health. Moreover, while variability exists in the exact quantification of human contribution behind heatwaves, the vast majority of studies point toward increases in the frequency of high-impact events, due to anthropogenic climate change.

7. Closing remarks and future heatwave research priorities

It should be clear that an enormous amount of research has been conducted by the climate science community, particularly in the last 10 years, in order to further scientific understanding of heatwaves. This work has focused on the definition of a heatwave, driving physical mechanisms, observed and future changes, and the contribution of anthropogenic climate change behind these changes. Fig. 21 provides a schematic on how the five heatwave topics addressed in this paper relate and interact with one another. No one topic stands alone, yet future changes (i.e., Section 5) a wholly reliant on the other four. Moreover, all five topics undoubtedly have strong influences on any resulting heatwave events, and their impacts.

In terms of the measurement of heatwaves, progress has been made from non-flexible duration indices and counting days above a particular threshold (e.g., Frich et al., 2002; Alexander et al., 2006), to mutli-definition and characteristic frameworks (Perkins and Alexander, 2013) as well as metrics that combine multiple heatwave characteristics (e.g., Russo et al., 2014), all of which are based around the premise of consecutive days of extreme heat. There is a substantial amount of knowledge of the driving mechanisms of heatwaves, including persistent high pressure systems (e.g., Black et al., 2004; Matsueda, 2011; Pezza et al., 2012), land surface interactions and moisture fluxes (e.g., Fischer et al., 2007b; Hirschi et al., 2011; Quesada et al., 2012), and seasonal climate variability (e.g., Kenyon and Hegerl, 2008; Hoerling et al., 2013). Many studies have consistently reported observed increases in heatwaves and related temperature extremes at global and regional scales (e.g., Alexander et al., 2006; Della-Marta et al., 2007a; Ding et al., 2010). There are also differences in how heatwave characteristics (e.g., intensity frequency and duration) have changed over different global regions (Perkins et al., 2012). Observed increases are projected

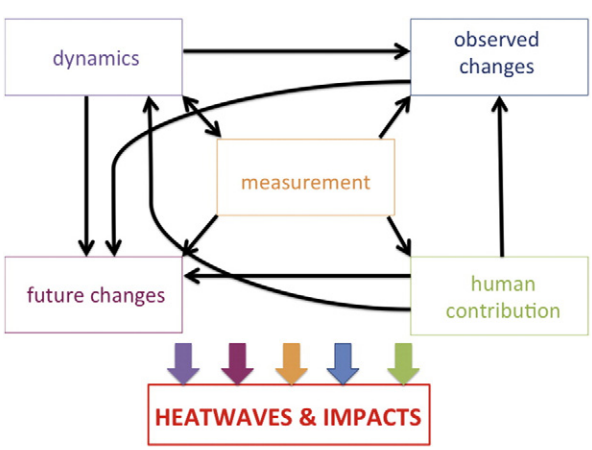

Fig. 21. Schematic showing the interrelationships between the 5 heatwave topics discussed in this literature review. All topics are interrelated, indicating that further development and research on heatwaves can't be conducted separately under these topics. Future changes in heatwaves rely on a sound understanding of the 4 other topics, and all 5 topics have a profound impact on corresponding heatwave events and the resulting impacts.

to continue well into the future by numerical climate models (e.g., Meehl and Tebaldi, 2004; Cowan et al., 2014; Russo et al, 2014), particularly if anthropogenic activity continues on the current trajectory. Moreover there is already a detectable influence of anthropogenic climate change on the frequency of numerous observed events across the globe (e.g., Lewis and Karoly, 2013; Christidis et al., 2014). Such research efforts have certainly accelerated our understanding of a high impact and complex event that has global ramifications across many systems. However gaps still exist in our knowledge of heatwaves, which should hold priorities for future research directions.

Despite several attempts, there is still a lack of a unified metric or framework in which to measure heatwaves. A single unified metric is likely too ambitious, due to the large range of heatwave impacts, which are driven by different characteristics to different extents. However it is certainly feasible to have a unified framework, although there may be issues with disseminating its application to the climate, meteorological and impacts communities, since they are already established in their own metrics. It would be a potentially laborious, yet worthwhile exercise for all communities affected by heatwaves to work together toward a common framework, perhaps even using ETCCDI as a model. From all vantage points discussed in this paper, it is clear that more certainty would exist around our understanding of heatwaves, in particular their changes, if a common framework of their measurement was employed.

It has nevertheless been established that anthropogenic activity is causing increases in heatwave intensity, frequency and duration over the globe. From an impacts perspective (see Section 1), such results are extremely concerning and should be taken seriously. However, most measures of heatwaves and temperature extremes use a static base period, centered on a particular point in time (e.g., Alexander et al., 2006; Nairn and Fawcett, 2013; Perkins and Alexander, 2013) to maximize common data between observations and models, adequately sample natural climate variability, and to be as representative of a stochastic climate with as little anthropogenic influence as possible. Therefore, such reference periods do not take into account possible long-term acclimation to rising temperatures. Climatologically speaking changes in heatwaves will certainly still occur and are extremely concerning, but adaptive capacity over decadal timescales may reduce the impacts of increases in heatwave intensity and duration (Cowan et al., 2014). Indeed, under the case of no mitigation and continual global warming a threshold of human heat stress tolerance will eventually be reached (Sherwood and Huber, 2010). Moreover it is feasible that humans have a higher adaptive capacity than other organisms and systems. Yet there is a large research gap in determining whether the extent of impacts aligned with future heatwave projections will be just as severe as the projections themselves.

It is also evident that there are large gaps in our understanding of observed changes in heatwaves, both spatially and temporally. This is of course not an issue endemic to heatwaves, but also affects other extreme events. In developing countries analog records may exist, however have not been digitized. In other parts of the world large gaps exist where recordings were paused, or stations were removed for some reason. It is certainly the case that in many locations such issues cannot be rectified, simply because there is not enough data. Reanalysis products help in producing consistent pictures where and when observations are lacking, however they reduce in skill during periods and over regions where observations do not exist, as the numerical model employed by the product is required at greater lengths. Other interpolation tools used to “fill gaps” of observational records should be used with caution. The digitization and/or quality control of records would aid in our understanding of how regional changes in heatwaves may differ, as well as increasing confidence and certainty around global projections. Such a task would be no easy feat and would certainly require global efforts. Though past efforts (e.g., Alexander et al., 2006; Donat et al., 2013a) are evidence of the many benefits this would dispose on the climate science community in understanding changes in extremes.

In the last decade, considerable developments have been made on the physical mechanisms responsible for heatwave manifestation. A combination of persistent high-pressure systems, low soil moisture and teleconnections from climate variability all play a role in the intensity, frequency and duration of heatwaves. This research, however, has been quite segregated. Many advances on the role of the land surface and soil moisture has taken place in central Europe (Fischer et al., 2007a, 2007b; Lorenz et al., 2010; Hirschi et al., 2011; Quesada et al., 2012). Understanding the driving synoptic systems has also had great focus in this region (e.g., Cassou et al., 2005; Della-Marta et al., 2007b; Vautard and Yiou, 2009), but has also started to extend to other regions (Pezza et al., 2012; Parker et al., 2013, 2014a). To a lesser extent, and mainly for temperature extremes, influences of climate variability have been assessed globally (Kenyon and Hegerl, 2008), and for some regions (e.g., Parker et al., 2014b; Boschat et al., 2015). There is however a lack of understanding on how extremes such as heatwaves may change if not only mean temperature and variability change, but also the skewness of the underpinning distribution (IPCC, 2012). A future research priority for the global heatwave community would be to fill these gaps. That is, develop a comprehensive understanding on how these physical mechanisms contribute to heatwave development over as many global regions as possible. It is extremely likely that all three types of mechanisms apply over all regions, however their relative rolls would differ. Moreover, despite a few exceptions, studies investigating the dynamical links *between* these mechanisms are largely missing.

Physical studies on heatwaves are also mainly focused on summertime events; quantifying the dynamics of cooler season warm spells and their changes has remained relatively untouched. While the lack of observational data may hamper such analyses in some regions (as discussed above) there are certainly more studies that could be conducted where observational data is of high quality. Given the strong interactions between heatwaves and the land surface, future research on the coupling between heatwaves and droughts would also be beneficial. Desiccated soil moisture is also a clear indicator of drought-like conditions, and so the interactions between heatwaves and droughts cannot go undetected. This research has been attempted (e.g., Mueller and Seneviratne, 2012), but further developments, particularly at regional scales remain relatively untouched. Indeed, because of their tight coupling, there may even be room for overlapping metrics between the two phenomena. These proposed studies have great potential to be useful in short- and long-term forecasting of heatwaves, which in turn, will aid in preparedness measures of these high-impact events.

Lastly, the greater heatwave community would significantly benefit from improved detection and attribution studies. There has been a large number of event attribution analyses on individual heatwaves, however this is a distinctly case-by-case basis, usually occurring sometime after the event occurs. Working toward real-time attribution would not only allow for an automated process, but may also aid in communicating that anthropogenic influence is *already* having an influence on the extremes we experience today. There is some evidence that this has been attempted (e.g., Lewis et al., 2014), however more studies are required, since different attribution statements will stand for different events over different regions. There is also a need to test the sensitivity of the FAR method to the experimental design, as model setup (e.g., mutli-model or multi-member ensembles) could yield different quantitative statements. Lastly, optimal fingerprinting has not yet been performed on trends of regional heatwaves; there is room for interesting and relevant research on whether anthropogenic influence has had different contributions on the trends of heatwave intensity, frequency, and duration, respectively.

As this review paper has demonstrated, scientific research in understanding the measurement, occurrence and changes in heatwaves has made remarkable progress in a short period of time. This knowledge is invaluable to the greater community, particularly toward heatwave preparedness, adaptation, and perhaps even mitigation. However, research in this field is by no means complete—there is still work to be done the unified measurement of terrestrial heatwaves, a greater understanding of their observed changes, how physical mechanisms interact for a heatwave to occur, and furthering our ability to quantify human influence. Such work will surely be a global effort, but will prove invaluable in gaining a deeper understanding of this complex extreme event, and thus mitigating various devastating impacts of heatwaves worldwide.

Acknowledgments

S.E. Perkins is supported by the Australian Research Council grant number DE140100952.

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