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A review of recent studies on heat wave definitions, mechanisms, changes, and impact on mortality

Adrian PITICAR[1*], Sorin CHEVAL[1, 2], Maria FRIGHENCIU[3]

[1] Faculty of Aeronautical Management, Henri Coandă" Air Force Academy, 160, Mihai Viteazul Street, Brașov, Romania
[2] National Meteorological Administration, 97, București-Ploiești Street, Bucharest, Romania
[3] Faculty of Sciences, Department of Geography, University of Craiova, 13, Alexandru Ioan Cuza Street, Craiova, Romania
* *Corresponding author*: adrian.piticar@gmail.com

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Abstract

Heat waves (HWs) represent a major danger to society and natural environment. The increasing occurrence of high magnitude and impact HWs has raised concerns worldwide and has attracted an increasing interest on this issue among climatologists over the past decade. In this review the research from 2007-2018 period on HWs definitions, driving mechanisms, present changes, future changes, and impact on human mortality is summarized. By reviewing the recent literature, it was found that whilst the atmospheric dynamic is considered to be the primary driver in HW occurrence, the sea surface temperature (SST) and land surface conditions are also essential driving components. The vastness of HW-definitions raises difficulties in selecting the appropriate methodology to identify heat episodes and to compare results from studies which used different definitions. However, by analyzing a sample of 109 papers, a preference for percentile-based definitions was observed. Therefore, 71.6% of the analyzed articles used only percentile-based definitions to identify HWs. Despite the wide variety of definitions, the analysis of changes in HWs converged to similar results. Thus, the existing recent literature provided extensive evidence of significant increase in HWs characteristics across large regions of the planet. Available scientific literature indicated that HWs have been responsible for a considerable increase in mortality in many regions of the world. In the future HWs are predicted to increase in their main characteristics leading to a greater impact on human mortality. Nevertheless, the implementation of rigorous adaptation measures can mitigate the negative impact on mortality. In conclusion, it was noted that a substantial progress has been done in the HW research, but there are still important gaps in this issue which need to be addressed.

Keywords: *climate change, extreme temperatures, heat wave, excess heat factor*

Rezumat. O revizuire a studiilor recente privind definițiile, mecanismele, schimbările undelor de căldură și impactul asupra mortalității

Valurile de căldură (HWs) reprezintă un pericol major pentru societate și mediul înconjurător. Creșterea frecvenței HWs cu magnitudine și impact ridicate a generat preocupare la nivel global și a atras interes asupra problemei în rândul climatologilor în ultimul deceniu. În articol sunt inventariate studiile realizate în perioada 2007-2018 privind definiţiile HWs, factorilor declanșatori, schimbărilor prezente și viitoare și impactul asupra mortalității. Prin inventarierea literaturii de specialitate recente, a fost evdențiat că deși dinamica atmosferei este principalul factor generator al HWs, temperatura apei de suprafață (SST) și condițiile date de suprafața terenurilor sunt de asemenea factori generatori importanți. Diverstatea definițiilor atribuite HWs determină dificultăți în selectarea unor metodologii potrivite pentru identificarea fenomenelor respectve și compararea rezultatelor unor studii care utilizează definiții diferite. Totuși, analizând un eșantion de 109 lucrări, a fost observată o preferință asupra unor definiții bazate pe percentile. Așadar, în 71.6% din articolele analizate au fost utilizate doar definiții bazate pe percentile pentru identificarea HWs. În ciuda marii varietăți de definiții, rezultatele analizelor au fost similare. Astfel, literatura recentă furnizează dovezi ample care atestă o creștere semnificativă a caracteristicilor HWs pe suprafeţe extinse ale planetei. Literatura științifică indică faptul că HWs au fost unul dintre factorii responsabili pentru creșterea mortalității în multe părți ale lume. În viitor este anticipată o amplificare a caracteristicilor HWs, conducând la o creștere a impactului pe care acestea îl vor avea asupra mortalității. Cu toate acestea, prin implementarea unor măsuri riguroase de adaptare, poate fi diminuat impactul negativ care conduce la mortalitate. În concluzie, a fost remarcat faptul că s-a realizat un progres substanţial în cercetarea HWs, rămânând însă lacune importante care necesită abordare.

Cuvinte-cheie: *schimbări climatice, temperaturi extreme, val de căldură, factorul excesului de căldură*

Introduction

Over the last decade heat waves (HWs) received increasing attention from climatologists. Thus, a large number of climate studies focused on analyzing these events. The main aims identified in these studies were understanding the mechanisms and synoptic conditions behind HW occurrence and persistence, analysis of changes in their main characteristics (frequency, duration, intensity), and assessing the impact on mortality. The majority of these studies found important changes in the frequency, duration, intensity, and other indices related to these parameters (Perkins et al., 2012; Perkins and Alexander, 2013; Acero et al., 2017; Allen and Sheridan, 2016; Ceccherini et al., 2016; Ceccherini et al., 2017; Panda et al., 2017; Piticar et al., 2017;

Zhang et al., 2017a). It was estimated that as global warming progresses these changes will continue at even higher rates in the future. Therefore, we can expect HWs that are more frequent, longer, and more intense. This can have serious negative consequences on society. Zacharias et al. (2015) estimated that more frequent, longer, and more intense HWs may kill 5 times more people from ischemic heart diseases by the end of the century compared to the present. However, if 50% acclimatization approach will occur, excess mortality will be attenuated to a factor of 2.4 (Zacharias et al., 2015).

The abundance of HW studies in the last years could have been triggered among devastating high impact events such as that of the summer of 2003 (with estimated heat related deaths varying between 25000 and 70000 in Europe) (D'Ippoliti et al., 2010; Amengual et al., 2014), or that of 2010 in central Russia in which exceptional heat and poor air quality due to wildfires led to a high death toll (Dole et al., 2011). Another example, is the extreme HW of the summer of 2008/2009 in Australia which was followed by the most devastating bushfires in the Australian history (Perkins-Kirkpatrick et al., 2016). Moreover, a record-breaking persistent HW spanned over the Australian continent was unprecedented spatially and temporally lasting for seven consecutive days with maximum temperature above 39 °C and setting a new national temperature record of 40.33 °C (Perkins-Kirkpatrick et al., 2016).

The increasing occurrence of high magnitude and impact HWs in the last two decades (e.g. Europe in 2003, southern and southeastern Europe in 2007, Australia in 2009, and Russia in 2010) has raised concerns worldwide and has outlined the importance of understanding present changes and predicting future changes of these events. Anthropogenic influences played a leading role to their magnitude, forcing HW trends towards unprecedented rates of increase (Weaver et al., 2014; Perkins-Kirkpatrick et al., 2017). For instance, Australia's HW frequency and intensity during the 2012/2013 summer increased by two and three fold due to anthropogenic greenhouse gas emissions (Perkins-Kirkpatrick et al., 2016).

Extended periods of unusually high temperature are stressful to biologic systems. HWs have a negative impact on plant growth and development; they can damage plants, and cause illness or even death to animals and humans (Anandhi et al., 2016). A significant relationship between certain HW parameters and human mortality was observed in many parts of the world Son et al., 2012; Ma et al., 2015; Dong et al., 2016; Lee et al., 2016; Guo et al., 2017a).

Such events have also many ecological, hydrological, and socioeconomically negative consequences (Liu et al., 2015; Anandhi et al., 2016). For instance, HWs can induce changes in the growing season, milk production, and have implications on the water cycle and its quality (Liu et al., 2015; Anandhi et al., 2016). The number of HWs was found to be significantly correlated with the fire occurrences in western Turkey (Unal et al., 2013). In terms of regional distribution, the number of fires had slightly higher correlations with the number of HWs over the inlands regions than the coastline (Unal et al., 2013). In the Nanjing metropolitan region (China) the major issues caused by high temperature and HWs were energy consumption, power shortage, human health and human habitat deterioration (Liu et al., 2015). Heat episodes can also have a serious impact on the local or regional economy. Herbel et al. (2017) assessed the potential economic loss during HWs in the city of Cluj-Napoca (Romania) and estimated a loss of about 2.5 mil. EUR for each HW day in summer. In Zaragoza (Spain), the cost of heat events in terms of health-related impacts alone was estimated at approximately 100000 USD per year (Roldán et al., 2016, cited by Horton et al., 2016). A higher demand for energy (around 0.15 MW) is noticed in Serbia when air temperature is above 30 °C, mostly during HWs with a maximum electricity consumption during daytime (Savić et al., 2014). Moreover, HW episodes put pressure on health services and emergency call lines. Hospital admissions increase during HWs (WMO and WHO 2015). Another negative consequence of heat episodes is the major threat to global crop production with implications that go as far as food security and economy (Horton et al., 2016).

For extreme temperature events related to heat, including HWs, there are review articles already available in the existing literature to which readers may refer at a regional (Rusticucci, 2012; Bittner et al., 2013; Schubert et al., 2014; Grotjahn et al., 2016; Perkins-Kirkpatrick et al., 2016) or a global scale (Coumou and Rahmstorf, 2012; Xu et al., 2014; Perkins, 2015; Horton et al., 2016; Mora et al., 2017; Song et al., 2017).

The aims of this paper are to summarize the mechanisms behind HW formation and the factors that maintain such events, changes in their characteristics (frequency, duration, and intensity), impact on human mortality, and to address the issue of HW definitions by synthesizing recent studies published in the 2007-2018 period in peer-review journals.

This article is organized as follows: Section 2 addresses the issue of HWs definitions. In Section 3 the physical mechanisms that causes and sustain HWs are described. Section 4 is dedicated to changes in HW characteristics. Section 5 focuses on the relationship between HWs and mortality. Conclusions are provided in section 6.

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Definitions of heat waves

The purpose of this section is to address the issue concerning the various definitions related to HWs. Generally, a HW is defined as a prolonged period of excessive heat (D'Ippoliti et al., 2010; Perkins-Kirkpatrick and Gibson, 2017; Yan et al., 2017). Depending on the data availability, and the region and sector of interest (i.e. human health, agriculture, infrastructure) there are many ways to statistically define a HW. Typically, HWs can be identified and investigated based on daily maximum (TX) and minimum (TN) temperature separately or by combining these variables. Beside temperature data, other human impact orientated studies took in consideration supplementary variables as well. For instance, Basarin et al., (2016) assessed HWs and cold waves (CWs) in Serbia by employing physiologically equivalent temperature (PET) which incorporates air temperature, vapor pressure, wind velocity, and mean radiant temperature. This definition also includes information about clothing insulation, human activity and height and weight. Unal et al. (2013) analyzed HWs over western Turkey based on apparent temperature as a function of daily TX and relative humidity.

Based on the data availability and purpose of the study, a HW can typically be identified by a combination of duration and intensity thresholds. Thus, the duration thresholds can vary from a minimum of two to six or even more consecutive days (Ringard et al., 2016; Piticar et al., 2017). Some definitions take into consideration 1 or 2 days of no HW conditions included within a longer event, while others eliminate or break it into two or more events (Piticar et al., 2017). Intensity thresholds can take the form of relative (i.e. 90 – 99th percentile, deviation above n °C from the normal local climate) or fixed (i.e. 30 – 40 °C) thresholds. The most common approach to identify a HW is based on the exceedance of a relative or absolute threshold for daily temperature for a period of at least n consecutive days (usually 2 – 6 days). Although fixed thresholds can have some advantages they are limited to specific areas. Percentile thresholds are more flexible, allowing comparisons among regions with different climates and geographical features and identifying warm events which are not dependent on the warm season.

Although, there is no universal method for HW identification, by analyzing a sample of 109 articles published in the 2007-2018 period a preference for percentile-based definitions was observed (Fig. 1). Thus, 71.6% of the analyzed articles used only percentile-based definitions to identify and examine HW events and their characteristics. Definitions based on fixed thresholds were selected in the case of 11.9% papers. The WMO definition (when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5 °C, the normal period being 1961-1990) was used in 3.7% studies. Both percentile and fixed or WMO definitions were employed to analyze HWs in 3.7% articles. In the case of 9.2 % of articles, HWs were identified based on more complex definitions which could not be included in any class (percentile-based, fixed, WMO, and mixed definitions). For instance, Guo et al. (2017b) analyzed projection of HWs over China using a definition based on a combination of a percentile threshold and a fixed threshold. Thus, a HW was defined as a consecutive period of at least 3 days during which the daily TX exceeded the 95th percentile of the 1971-2000 reference period and where the percentile threshold was no less than 30 °C.

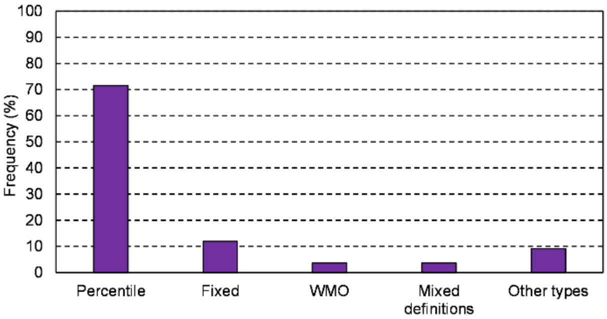

Fig. 1. Frequency of definition types identified in a sample of 109 studies published from 2007 to 2018 period.

The preference for definitions based on percentile thresholds could be explained by the advantages they offer, the effort of the Expert Team on Sector-Specific Climate Indices (ET-SCI) of the World Meteorological Commission for Climatology and Indices (CCI) to introduce a standardized set of definitions which are based on percentile thresholds, and the significant contribution of Perkins et al. (2012) and Perkins and Alexander (2013) that proposed the use of a set of HW definitions based on percentile thresholds in order to reduce the large number of metrics employed to measure these events (Perkins, 2015).

Understanding the role of using different definitions to analyze various aspects in HWs studies (i.e. changes, projections, impact) is crucial in selecting the appropriate methodology of HWs identification. In particular, the selection of HW-definitions is very important in human impact studies, since researchers suggested that they could affect mortality differently (Lee et al., 2016).

Beyond all these statistical definitions which indubitably have a strong physical basis, there are the driving physical mechanisms which generates and maintain such events. Thus, in the following section the main drivers which generate and maintain HWs are described.

Physical mechanisms responsible for the heat waves formation and persistence

General considerations

Much effort was put into understanding the mechanisms that cause and sustain HWs in different regions of the world. Previous studies have indicated the significant role of large-scale atmospheric circulation and sea surface temperature (SST) on HWs occurrence (Cerne and Vera, 2011; Parker et al., 2014; Wang et al., 2017).

Persistent and intense anticyclone systems are the central components that generate and sustain HW events (Geirinhas et al., 2017; Kueh et al., 2017; Tomczyk and Sulikowska, 2017; Wang et al., 2017). These systems are also called blocking highs or persistent highs (Perkins, 2015). They occur when upper-level atmospheric winds split as a consequence the meandering of the jet stream (Pezza et al., 2012; Perkins, 2015). Other persistent highs may have other causes and occur at lower latitudes than the typical blocking region (Perkins, 2015). Such persistent highs were responsible for numerous HWs over Europe, Australia, and other regions of the planet (Purich et al., 2014; Perkins, 2015). The high anticyclone structures are extended vertically from the surface into the atmosphere with high pressure anomalies detected at the 500 and 250 hPa geopotential height levels (Loikith and Broccoli, 2012; Bumbaco et al., 2013; Perkins, 2015; Hafez and Almazroui, 2016). Blocking highs which generate HWs in the Northern Hemisphere are generally centered over the affected area, with the direction of wind flow guiding warm and dry air from south over the region in cause (Perkins, 2015). Blocking anticyclones through their persistence and stationarity or slow moving allow HWs the time to build (Horton et al., 2016). Over a recent period of time, the occurrence of mid-latitude anticyclone systems related to atmospheric blocking and climate change process increased (Morabito et al., 2017) leading to a higher frequency of HWs.

SST positive anomalies can also significantly contribute to HW formation and persistence (Feudale and Shukla, 2011; Jia et al., 2016) and can be a good predictor of their occurrence. For example, SST over the south sea of the Korea/Japan is warming about a week before HWs occur in Korea (Ham and Na, 2017). Understanding the relation between HWs and large-scale atmospheric circulation and SSTs is important for predicting these events.

Another fundamental element which contributes to HW development and severity are surface heating and soil moisture (Loughran et al., 2017; Wang et al., 2017). Dry soil tends to intensify HWs and extend their duration. For example, the 2003 HW over Europe was up to 40% more intense as a result of dry conditions (Fischer et al., 2007b; Perkins et al., 2015; Horton et al., 2016).

Furthermore, the intensity of HWs is built by regional land surface feedback and intense radiation. Fischer et al. (2007a) investigated major summer HWs of 1976, 1994, 2003, and 2005 in Europe conducting regional climate simulations with and without land-atmosphere coupling. The results of the experiment revealed that land-atmosphere coupling was an important factor in the evolution of the investigated HWs both trough local and remote effects. Soil moisture-temperature interactions increased the analyzed HWs duration and account for 50 - 80% of the number of hot summer days. This effect occurred mainly due to the limitation of evaporation caused by drought conditions. Moreover, it looks like spring precipitation deficits could enhance the strength of summer HWs (Fischer et al., 2007a, 2007b).

Teng and Branstator (2017) investigated linkages between HWs in the Northern Hemisphere and the quasi-stationary planetary wave anomaly produced by atmospheric internal variability based on the 12000-year integration of a climate model. The main findings suggested that when circulation anomalies had unusually high projections onto circumglobal teleconnection patterns, the probability of HWs can be increased/decreased over much of the hemisphere by a factor of 4, both concurrently and in the following two weeks. These circumglobal teleconnection patterns are quasi-stationary, through their influence on the likelihood of HWs and therefore they provide a viable source of predictability of HWs on subseasonal timescales (Teng and Branstator, 2017).

Regional considerations

Europe

In Europe HWs are closely linked to the atmospheric blocking regime and SST anomalies (Purich et al., 2014). In Western Europe, HWs are strongly related to the high pressure centers over Scandinavia and central Western Europe (Della-Marta et al., 2007; Wang et al., 2017). For instance, SST anomalies and convection processes in the Atlantic Ocean associated with the Rossby wave train system and downstream atmospheric blocking lead to summer HW formation across Europe and Russia (Della-Marta et al., 2007; Purich et al., 2014). In the United Kingdom (UK), Sanderson et al. (2017) showed that higher numbers and lengths of HWs are related with the positive phase of the Atlantic Multidecadal Oscillation (AMO), while negative phases of the AMO moderate the number and duration of such events. However, there are other atmospheric modes and weather conditions which can exacerbate HWs even when negative phases of the AMO are in progress. For example, the long HWs of 1975 and 1976, were exacerbated most likely because of the simultaneously manifestation of drought (Sanderson et al., 2017). The same study also suggested that the summertime North Atlantic Oscillation (NAO) moderates the number and duration of HWs. Tomczyk and Sulikowska (2017) indicated that the occurrence of HWs in northern Germany was related to a ridge of high pressure over Europe with a local anomaly of high-pressure in the Baltic Sea center. In Serbia almost 84% of the longest HW days were possible under anticyclonic conditions and southerlies major types of Grossweterlagen patterns (GWL) (Unkašević and Tošić, 2009). Unkašević and Tošić (2009, 2015), also indicated that the severe HWs of summers of 2007 and 2012 in Serbia occurred as a consequence of warm and dry air advection from North Africa. The synoptic conditions generating HWs in Greece consist in the Subtropical Jet Stream (STJ) shifting northward to the North of the Greek area resulting in warmer than normal temperatures at the surface thus facilitating conditions for the North-African warm air masses to invade Greece and move northward over the Balkans (Theoharatos et al., 2010). The displacement of STJ can be determined by low-pressure systems over southwestern England and Northern Biscayan Gulf areas, combined with ridges projected from Africa towards the Mediterranean (Theoharatos et al., 2010). This type of mechanism causes a powerful intrusion of heat in the Balkan region (Theoharatos et al., 2010). In eastern Europe, HWs are strongly related to warmer SSTs in the Mediterranean and Black Sea which reinforces upper-level anticyclonic flow (Unal et al., 2013).

Asia

The stationary Rossby waves play a key role in the development of HWs in the Northern Eurasian region, including events such as the one in 2010 in Russia (Schubert et al., 2014). Mid-latitude heat episodes are often associated with strong Rossby wave activity in the upper troposphere (Fragkoulidis et al., 2018). A study over West Asia indicated that severe HWs in Georgia are attributed to negative sea level pressure (SLP) anomalies over southern Scandinavia and Red and Black Sea, and positive SLP anomalies across western Asia in association with mid-tropospheric anticyclonic conditions (Keggenhoff et al., 2015b). This atmospheric configuration blocks westerlies, and allows warm air from the Southeast to cause extreme high temperature over Georgia (Keggenhoff et al., 2015b). Moreover, high atmospheric stability, intense insolation, and pronounced soil dryness contribute to the increased severity of HWs in this region (Keggenhoff et al., 2015b).

HW occurrence over India is related with large scale atmospheric anomalies connecting sub-tropical high quasi-stationary Rossby waves over the mid-latitudes, pronounced soil dryness, and clear sky (Rohini et al., 2016). Moreover, Rohini et al. (2016) also suggested that SST anomalies of the Indian Ocean and of ENSO events have a large contribution on Indian HWs and changes in these features are expected to have consequences on the frequency and the duration of extreme heat episodes. Based on observed patterns and the statistical analyses of the TX variability Ratnam et al. (2016) identified two types of HWs over India. The first type is specific to north-central India and was found to be associated with blockage over the North Atlantic which results in a cyclonic anomaly in the western region of North Africa at upper levels. The stretching of vorticity generates a Rossby wave source near the entrance of the African Jet. The generated quasi-stationary wave train along the jet has a positive phase over India causing anomalous sinking motion and thereby HW conditions over this region. The second type of HWs is common to coastal eastern India and is generated by the anomalous Matsuno-Gill response to the anomalous cooling in the Pacific. Thus, the Matsuno-Gill response results in northwesterly anomalies over the land reducing the land-sea breeze, conducting in HWs occurrence.

Wang et al. (2017) identified three leading modes governing the spatiotemporal distribution of extreme heat episodes in China: interdecadal (ID), interannual-tripole (IA-TR), and interannual-dipole (IA-DP) modes. ID pattern generated more frequent, longer and stronger events over North China. The IA-TR structure underlines a tripole anomaly pattern with positive (negative) anomalies centered on north and south China and negative (positive) anomalies in central China. The IA-DP mode exhibits a meridional dipole pattern with anomalies of opposite signs between the north and most of the southern areas of China (Wang et al., 2017). Wang et. al (2017) also emphasized the important role of SST anomalies on HWs genesis over China. Thus, the considerable SST warming over Tropical Western Pacific (TPWP) leads to convective processes. The positive and negative SST anomalies over the tropical western and eastern Pacific strengthen Walker circulation resulting in intense convective processes over TPWP in the case of the IA-DP and IA-TR patterns. Furthermore, the increase of TPWP diabatic heating associated with the convection triggered northward, propagates Rossby wave trains leading to an anomalous descending motion and less precipitation over the high pressure nodes influencing HWs in China. Luo and Lau (2017) analyzed HWs in southern China and indicated that these events are accompanied by anomalous surface high pressure and anticyclonic circulation. The dominant anomalous northwesterly flow reduces moisture advection from sea to land. Thus, the region is dominated by dry and warm conditions and along with clear sky, which prolongs sunshine duration and enhances the solar radiation leading to a greater solar heating. The SLP and temperature anomalies are associated with the westward displacement of the western North Pacific subtropical high (WNPSH), suggesting that westward circulation of this system is partially responsible for the occurrence of HWs in south China (Luo and Lau, 2017). In Yangtze River valley approximately two third of the total HW variability in the July-August interval can be attributed to anomalous SST forcing, whereas the other one third is due to internal variability (Chen and Zhou, 2017). ENSO also plays an important role in the SST forcing. Wang et al. (2017) suggested that intensity of HWs in China could be strongly enhanced by the deficiency of soil moisture.

A recent study over Taiwan indicated that HW events over this region are associated with abnormal warming and drying atmospheric conditions controlled by enhanced WNPSH (Kueh et al., 2017). The drying magnitude is suppressed by surrounding waters which serve as a vast moisture source (Kueh et al., 2017). The WNPSH, a key component of the East Asian summer monsoon system, is a major regulatory element of the summer monsoon rainfall and tropical storm activities over the western North Pacific (Kueh et al., 2017). The anomalous WNPSH is a major cause of weather extremes, HWs included, in the region (Wang et al., 2016; Kueh et al., 2017; Luo and Lau, 2017). HWs in East Asia were attributed to the variation of WNPSH and could be further enhanced by the ENSO and the tropical Indian Ocean warming (Kueh et al., 2017). However, there still are gaps in the scientific analysis of the physical causes which generate extreme heat events in this region.

Lee and Lee (2016) found that the number of HWs in South Korea are related to a north – south dipole pattern between the South China Sea and Northeast Asia. When this large-scale circulation configuration facilitates deep convection in South China Sea, it tends to weaken moisture advection from this region to Northeast Asia. Intense deep convection in the South China Sea triggers a Rossby wave train along southerly winds which lead to the formation of positive geopotential height anomalies around Korea and Japan, accompanied by large-scale subsidence and therefore providing favorable conditions for extreme hot and dry days in Korea.

Africa

Summer HWs in Northern Africa are related to a cyclonic anomaly activity in central Sahel favoring the monsoon eastward to 0° longitude and a midlevel anticyclonic anomaly over the Western Sahara, increasing southward the flux divergence associated with the African Easterly Jet (Fontaine et al., 2013). In the March–May period, two to three HWs propagate toward east. They are preceded by an abnormal warm cell over Libya and southwesterlies over the West Sahara. Midtropospheric subsidence and anticyclonic rotation associated with a large trough which stagnates over North Atlantic reinforce across the continent, then moves toward the Arabian Peninsula. These signals are spatially coherent and might suggest the role of short Rossby waves with an eastward group velocity and a baroclinic mode, possibly associated with jet stream deformation (Fontaine et al., 2013). In spring, heat episodes are also connected to midlevel cyclonic rotation over Morocco associated with a Rossby wave pattern, lessening the Harmattan (Fontaine et al., 2013).

Another important driver which generates HWs (day-time events) in the western Sahel region is the increased shortwave radiation and a reduction in cloud cover (Oueslati et al., 2017). Nigh-time events are explained by the greenhouse effect of water vapor increasing longwave radiation (Oueslati et al., 2017). Atmospheric circulation has an important role in sustaining these warm anomalies during the night by transporting moisture from the Atlantic Ocean and the Guinean coasts into Sahel. ENSO is also a key factor in the occurrence and variability of HWs in Sahel, favoring high TN and increased event frequency (Oueslati et al., 2017).

The African Intertropical Convergence Zone (ITCZ) is also an important element of HW occurrence in North Africa. An outstanding significant positive correlation between the abrupt shift of ITCZ position and HW occurrence was found in Egypt in the summer of 2015, suggesting that the southerly movement of the eastern African ITCZ controls the weather over this country and led to the extreme HWs (Hafez and Almazroui, 2016). The geopotential height at a 500-hPa anomaly becomes positive for the duration of a HW over Egypt for the summer season (Hafez and Almazroui, 2016). The stability conditions of high pressure system in the upper atmosphere over this area create lower inversion of temperature near the surface and cause the heat accumulation (Hafez and Almazroui, 2016).

We could not identify any study between 2007 and 2018 which analyzed mechanisms that generated HWs over the southern half of the African continent. Therefore, future research should identify the key mechanisms which generate and maintain such events in this area of the globe.

Australia

In Australia as in the case of other continents, both large-scale atmospheric circulation and land surface conditions are some of the most important drivers in the HW genesis and persistence (Pezza et al., 2012; Gibson et al., 2017). Australian HWs conditions of occurrence can roughly be described as a consequence of a high pressure system of the subtropical ridge advecting warm air from the North (Loughran et al., 2017). The high pressure system is often embedded in a stationary Rossby wave. Loughran et al. (2017) found that ENSO has a great influence on HWs in Australia, especially on frequency days, duration, and number in northern and northeastern areas of the continent.

The fundamental mechanism of HWs in southern Australia was identified as a transient pulse arriving from the Indian Ocean which resonates with the Australian continent projecting a very strong ridge towards the south (Pezza et al., 2012). Events in Southern Australia are also related with feedbacks between SST anomalies and atmospheric variability and interactions with tropical variability (Purich et al., 2014). In southeastern Australia extreme heat events occur under persistent subtropical high pressure systems associated with northerly winds, while in the southwestern part of the continent high pressure systems in the Great Australian Bight produce easterly winds which can induce conditions for HWs formation (Purich et al., 2014). Parker et al. (2014) have also analyzed the physical mechanism behind HW formation in southeastern Australia and found that these events are accompanied by a slow-moving transient surface anticyclone over the Tasman Sea to the East, which directs warm continental air over this region. Also, summer HWs over southeastern Australia seemed to be related with heavy rainfall in the northeastern areas of the continent (Cowan et al., 2014; Parker et al., 2014). The mechanism behind this dipole of extreme heat in the southeast and heavy rainfall in the northeast and adjacent waters is generated by upper-level cyclonic potential vorticity troughs which rainfall by vertical motion, high instability, and modification to moisture flux (Parker et al., 2014).

North America

Extreme heat episodes in North America are associated with anomalous circulation at 500 hPa geopotential height (positive anomalies) and SLP anomalies (Loikith and Broccoli, 2012). These episodes are accompanied as in the case of other areas on the globe by quasi-stationary mid-latitude Rossby waves (Teng et al., 2013). Other processes, such as low soil moisture content can be an important component of HW formation in this area as well (Loikith and Broccoli, 2012). Some of the most severe high impact HWs in the North America occurred in relation to low-humidity and drought conditions (Peterson et al., 2013).

It was found that HW frequency over this region is dominated by two distinct modes. (i) The interdecadal mode primarily depicts a HW frequency increasing pattern over most of North America except some western coastal areas (Wu et al., 2012). (ii) The interannual mode resembles a tripole anomaly pattern with three centers over the northwestern, central, and southern continent. The interdecadal mode is closely associated with the prior spring SST anomaly in the tropical Atlantic and tropical western Pacific that can persist during the summer, whereas the interannual mode is related to the development of ENSO. For the interdecadal mode the tropical Atlantic sea surface anomaly can induce a Gill-type response which extends to North America, while the northwestern Pacific sea surface anomaly excites a Rossby wave train propagating eastward towards the continent. These two circulation patterns jointly contribute to the formation of the large-scale circulation anomalies associated with the interdecadal mode. For instance, SSTs over the North Atlantic, Tropical Atlantic, tropical Pacific, North Pacific, and uniform global SST warming contributed to the 2012 summer warm temperature anomalies over large areas of the US (Jia et al., 2016). In the case of interannual mode, the corresponding circulation anomalies are similar to a Pacific-North America pattern. The subsidence associated with high-pressure anomalies warms and dries the boundary layer, inhibiting cloud formation. The resulting surface radiative heating further warms the surface (Wu et al., 2012). Moreover, some patterns suggest influence from other large-scale teleconnections, such as Arctic Oscillation and the Pacific-North American mode (Loikith and Broccoli, 2012). The orientation, physical characteristics, and spatial scale of these circulation patterns vary based on latitude, season, and proximity to major geographic features such as mountains, coastlines and others (Loikith and Broccoli, 2012).

Bumbaco et al. (2013) analyzed day-time and night-time HWs in the Pacific Northwest and found that stronger 850 hPa winds, higher 500 hPa geopotential heights, and larger SLP gradient associated with TX events over the region indicated that downslope warming across the west side of the Cascade Mountains is more important for the day-time events. Moreover, this finding was supported by a positive relationship between the strength of the 500 hPa anomalies and the magnitude of the TX regional anomalies. On the other hand, nigh-time events had a less pronounced 500 hPa ridge and a weaker 850 hPa easterly winds, a weaker SLP gradient, and there was no relationship between the strength of the 500 hPa Z and the regional anomaly.

Hence, the atmospheric dynamics, land initial conditions, SSTs, and radiative forcing are all important drivers, and source of predictability for North America HWs (Jia et al., 2016).

South America

One important characteristic of South America HWs is that they are less common and intense compared to the Northern Hemisphere ones (Rusticucci, 2012). A study over subtropical South America found that 73% of HWs which occurred in this region were related to an active South Atlantic Convergence Zone (SACZ) associated with the strengthening of an anticyclonic anomaly in the subtropical region (Cerne and Vera, 2011). Moreover, the high anticyclonic activity over this area is embedded in a large-scale Rossby wave train extended along the South Pacific Ocean which was found to be linked with intraseasonal changes of the convective processes at the equatorial western and central Pacific Ocean (Cerne and Vera, 2011). Jacques-Coper et al. (2016) also found similar results in southeastern Patagonia in respect to the relation of HW events to convective conditions in the SACZ (two thirds of the HWs in southeastern Patagonia were related to SACZ). A low number of HWs (7 of 26 identified in the 1979-2003 period) were not related with active SACZ (Cerne and Vera, 2011). They occurred under warmer than normal conditions over the subtropical regions. These conditions are sustained by the persistence of advections of very warm and moist air promoted into the region by a quasi-stationary frontal system located at the southern tip of South America (Cerne and Vera, 2011). Therefore, HWs in the subtropical South America occur even when the activity of the SACZ is suppressed (Cerne and Vera, 2011; Rusticucci et al., 2016). Over Brazil, HWs can be induced by a westward migration of the South Atlantic Subtropical high in association with SST anomalies over the South Atlantic Ocean (Geirinhas et al., 2017). In the equatorial areas, HWs are related to the migration of the Intertropical Convergence Zone (ITCZ) northward and warmer SST over the North Tropical Atlantic Ocean and also with the ENSO (Geirinhas et al., 2017). The radiative balance at the surface has been also found to be an important driver for the development of HWs in some locations of Brazil (Geirinhas et al., 2017).

Changes in heat waves across the globe

Observed changes

Even though there is a wide variety of definitions, the analysis of changes in HWs converged to similar results: increase in frequency, duration and intensity. Globally averaged, HWs (analyzed by the warm spell duration indicator - WSDI) have increased by approximately 8 days since the middle of the twentieth century (Donat et al., 2013). The increase was more evident since 1990. Conversely, the duration of cold spells (analyzed by the cold spell duration indicator - CSDI) has significantly decreased over large areas, by circa 4 days since 1950 (Donat et al., 2013). Thus, these results indicated that the warming process at a global scale is reflected more in HWs than in CWs. Large areas of the globe experienced significant increasing trends in WSDI for the 1951-2010 period. However, these changes are not uniform from a spatial and temporal point of view. The most affected regions seemed to be Europe, almost the entire surface of Asia and Australia, Southern Africa, the northern half of North America, and sparse regions of South America located in the north, west, and south (Donat et al., 2013). These results are similar with those reported by Perkins et al. (2012) which analyzed HWs at a global scale by employing three different definitions: TX above the 90th percentile for at least three days, TN above the 90th percentile for at least three days, and excess heat factor (EHF). Moreover, the global area affected by HWs has increased in recent decades (Russo et al., 2014).

In all of the regions of the planet, short-term downward trends in HWs are followed by a rise in their metrics within 5 – 10 yr, indicating that those areas will experience an increase within the next decade (Perkins-Kirkpatrick et al., 2017). Changes in the metrics of these events are highly sensitive to changes in mean global-scale warming (Horton et al., 2016; Perkins-Kirkpatrick and Gibson, 2017). Thus, limiting the global warming to 2 °C as recommended by the Paris agreement can avoid considerable changes in HWs (Perkins-Kirkpatrick and Gibson, 2017).

Regional changes

Europe

The European continent faced many extreme heat events in the last decades. A considerable number of studies showed an important increase in HW frequency, duration, and intensity over large regions of Europe. Thus, these changes were observed in: Spain (Acero et al., 2017), Northern Europe (Tomczyk et al., 2017), lowland Germany (Tomczyk and Sulikowska, 2017), the Carpathian Region (Spinoni et al., 2015), Ukraine (Shevchenko et al., 2014), Romania (Croitoru et al., 2016; Piticar et al., 2017), and Serbia (Unkašević and Tošić, 2015; Basarin et al., 2016). Long-term changes analysis showed that the duration of intense HWs has doubled in Western Europe between 1880-2003 (Della-Marta et al., 2007). Sanderson et al. (2017) found some positive trends in the number and duration of HWs at some stations in the United Kingdom. However, for some stations in the south-eastern of England, the duration of very long events (over 10 days) had decreased since 1970s, whereas the duration of shorter events (up to 10 days) had slightly increased.

Asia

Trend analysis of HWs over western Asia (Georgia) demonstrated a significant increase in the frequency, duration, and intensity of these events (Keggenhoff et al. 2015a, 2015b). Unal et al. (2013) also found increasing trends in the frequency and duration of HWs in western Turkey. Important changes were found in HW variables related to frequency, duration, and intensity in China, pointing out towards more severe events (Dian-Xiu et al., 2014; Liu et al., 2015; Chen et al., 2017; Chen and Li, 2017; Luo and Lau, 2017; Wang et al., 2017; Yan et al., 2017; Zhang et al., 2017a). Rohini et al. (2016) and Panda et al. (2017) found statistically significant increasing trends in HW frequency, total duration, and maximum duration in India, especially in central and northwestern regions.

Africa

For the African continent the situation is similar to Europe and Asia in respect to changes in HWs. Thus, the number of HWs increased both in day-time and night-time events in the 1981-2015 period over Africa (Ceccherini et al., 2017). Russo et al. (2016) indicated that in the recent years Africa experienced hotter, longer, and more extent HWs than in the last two decades of the 20th century. The annual number of diurnal and nocturnal events increased over the coastal regions of the Gulf of Guinea in the second half of 20th century, becoming more accelerated after 1980s period (Ringard et al., 2016). Oueslati et al. (2017) also reported that over the last three decades, HW frequency, duration, and intensity increased in the Sahel region. In southern Africa, a shift toward higher heat wave frequency in recent years occurred (Lyon, 2009).

Australia

Significant changes were also found across large areas of Australia in different HW parameters which measured frequency, duration, and intensity (Perkins and Alexander, 2013; Parker et al., 2014; Nairn and Fawcett, 2015; Perkins-Kirkpatrick et al., 2016).

Greater statistical significance was found in frequency-based indices (Perkins and Alexander, 2013). In terms of intensity-based indices, the results of the same study showed that changes are more substantial in the highest intensity values than in average ones.

North America

North America experienced an increase of the number of HWs (Keellings et al., 2018). Peterson et al. (2013) indicated that over the last decades HWs are generally increasing in the US. Smith et al. (2013) have also found positive trends in HWs indices over most of the US territory. Only few significant negative trends were found in portions of the Southwest, Northwest, and Great Plains (Smith et al., 2013). Anandhi et al. (2016) found a general increase in the number of warm spells (WSs) in winter in Kansas and a decrease over the whole year. In Florida HWs have become more frequent and intense (Keellings and Waylen, 2014). The duration and intensity of HWs have increased in summer in Mexicali City (Mexico) (Cueto et al., 2010). Allen and Sheridan (2016) analyzed spatio-temporal changes in HWs in 55 US metropolitan areas over the 1948-2012 period and found that across many locations these events have become more frequent, longer, and earlier occurring. Mazdiyasni and AghaKouchak (2015) showed a substantial increase in concurrent droughts and HWs across most areas of the US and a statistically significant shift in the distribution of concurrent extremes. Bumbaco et al. (2013) noted that a significant increasing trend in the frequency of nighttime HWs is the only significant increasing trend in the Pacific Northwest.

South America

The analysis of changes in HWs in South America also showed that these events became more frequent, more intense, and longer. Ceccherini et al. (2016) revealed an increase in the intensity and frequency of HWs in South America. Rusticucci et al. (2016) found increasing frequency in HWs in Argentina over the 1961-2010 period. Geirinhas et al. (2017) revealed the existence of positive and significant trends in HW frequency in Brazil, particularly for the cities of São Paulo, Manaus, and Recife.

Future changes

Projections of HWs indicate that these events will continue to increase in the future at higher rates in terms of frequency, duration, and intensity compared to the present situation and at a greater magnitude than the global mean temperature (Amengual et al., 2014; Perkins, 2015; Perkins-Kirkpatrick and Gibson, 2017). HWs as defined by present-day standards, will have an extraordinary duration which will vary from several weeks (under the optimistic B2 scenario) to months (under the A2 scenario) (Zittis et al., 2016). These changes could lead to increased discomfort and mortality, especially among elderly, children, and people with health problems if appropriate adaptation measurements will not be considered.

At a global scale, model predictions indicated an increase in the probability of occurrence of extreme and very extreme HWs in the coming years, in particular, by the end of the century (Russo et al., 2014). HWs of the same severity as those in Russia in the summer of 2010 are projected to occur as often as every 2 years in southern Europe, North America, South America, Africa, and Indonesia under the most severe IPCC AR5 scenario (Russo et al., 2014). However, the extreme Russian heat event can still be considered a rare event in the future under the less severe scenarios (RCP2.6 and RCP4.5) (Russo et al., 2014).

Amengual et al. (2014) analyzed HW projections with high impact on human health in Europe over the 21st century and concluded that the population will be exposed to higher health risk related to these events. Other studies also found that until 2100 HW variables may increase drastically in Europe (Ballester et al., 2010; Fischer and Schär, 2010; Jacob et al., 2014; Lelieveld et al., 2014; Schoetter et al., 2015; Zacharias et al., 2015; Ouzeau et al., 2016). However, changes in HW metrics are estimated to vary considerably across different regions of the continent. The most pronounced changes are projected to occur in southernmost Europe for frequency and duration, in further north for amplitude, and in low-altitude southern regions for health-related indicators (Fischer and Schär, 2010).

As in the case of European continent, large areas of Asia will face more severe heat episodes. Zittis et al. (2016) indicated that all variables that characterize HW severity are estimated to strongly increase compared with the control period of 1961-1990 in the eastern Mediterranean and the Middle East. The Northern Eurasia region will experience more HWs especially by the second half of the 21st century (Schubert et al., 2014). The Indian subcontinent is expected to experience more intense, longer, higher numbers of HWs, and earlier occurrence across the year (Murari et al., 2015). Moreover, Southern India, currently not influenced by HWs, is expected to be severely affected by the end of the century (Murari et al., 2015). Guo et al. (2017b) analyzed the projection of HWs over China using 12 CMIP5 models and found that as global temperature will cross the 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 °C targets, HWs would become more frequent, longer, and more intense. HWs are also forecast to become more severe in the future in Taiwan (Kueh et al., 2017). Coupled Model Intercomparison Project Phase 3 (CMIP3) models projected that the number of HW days will increase in northern, eastern, and western Japan (Nakano et al., 2013). Also, the duration of HW days is estimated to increase in areas in which HW days frequency will increase as well (Nakano et al., 2013).

In a recent review article, Perkins-Kirkpatrick et al. (2016) indicated that observed increasing trends in HW metrics in Australia are projected to continue at higher rates until the end of the century. CMIP5 projections over this continent showed more frequent, hotter, and longer summer HWs and winter WSs by the end of the century with more extreme conditions under RCP8.5 compared to RCP4.5 (Cowan et al., 2014).

50% of regional climate projections over Africa suggest that HWs which are unusually severe under the present climate will occur on a regular basis by 2040 under the RCP8.5 scenario (Russo et al., 2016). The Gulf of Guinea, the Horn of Africa, the Arabian Peninsula, Angola, and the Democratic Republic of Congo are expected to face, every two years, HWs of a length comprised between 60 and 120 days under the RCP8.5 scenario (Dosio, 2017).

Over North and South America HWs are estimated to increase considerably in frequency and duration during the 21st century (Lau and Nath, 2012; Marengo et al., 2014; Grotjahn et al., 2016; Li et al., 2017; Angeles-Malaspina et al., 2018).

The impact of heat waves on mortality

HWs have a considerable impact on various systems. Nevertheless, the most direct and brutal societal impact is death (Perkins, 2015; WMO and WHO, 2015). A significant impact on mortality has been clearly demonstrated in numerous studies (D'Ippoliti et al., 2010; Barnett et al., 2012; Lee et al., 2016; Guo et al., 2017a; Zhang et al., 2017b and many others). The most illustrative example is the HW of the 2003 summer that caused between 25000 and 70000 excess deaths in 12 European countries (D'Ippoliti et al., 2010; Amengual et al., 2014; WMO and WHO, 2015). HWs have been responsible for more deaths in Europe, US, and Australia than any other natural hazard (Nairn and Fawcett, 2015).

Extreme heat episodes can also have a serious impact on humans from a health perspective causing heatstroke, heat exhaustion, heat cramps, heat syncope, heat oedama, and heat rush (WMO and WHO, 2015). Heat is also responsible for severe dehydration, acute cerebrovascular accidents, and contributes to thrombogenesis (WMO and WHO, 2015). Moreover, HWs can aggravate chronic pulmonary and cardiac conditions, kidney disorders, and psychiatric illness (WMO and WHO, 2015). In Korea it was found that cardiovascular hospitalizations were significantly associated with high temperature during HWs, particularly in women and younger persons (Son et al., 2014).

A comprehensive study analyzed the impact of HWs on mortality in 18 countries in different regions of the globe using 12 HW-definitions (each 90th, 92.5th, 95th, and 97.5th percentile intensity thresholds combined with duration thresholds above 2, 3, and, 4 days) and found significant association in all countries for all types of HWs (Guo et al., 2017a). The same study indicated that HWs had a higher association with mortality in moderate cold and moderate hot areas than cold and hot areas. Barnett et al. (2012) found that HWs generally increased the risk of death in the US. The largest increase was found for the most extreme temperatures (Barnett et al., 2012). Linares et al. (2015) showed that the impact of heat on daily mortality was greater than that of cold in Spain. Other factors such as interaction between HWs and air pollution from wildfires substantially increase the number of deaths as was the case of Russian mega-HW in 2010 (Shaposhnikov et al., 2014).

HWs impact on mortality can vary according to their characteristics and severity. Thus, variables such as duration and intensity, and their degree of severity correlate and affect differently the number of deaths.