Issues and challenges in defining a heat wave: a Mediterranean case study

Elena Barcena-Martin[a], Julian Molina[b], Jose Damian Ruiz-Sinoga[c*]

[a]*Statictics and Econometry Department. University of Málaga, Spain.*

[b]*Mathematics Department. University of Málaga. Spain.*

[c]*Geography Department. University of Málaga. Spain.(email: sinoga@uma.es Telf: 0034-952131710)*

Abstract

We evaluated three definitions of heat wave (HW), and demonstrate that selection of the reference period and air temperature threshold used in the definition can affect the reported frequency of HWs. First, we propose an alternative definition of HW that is based on a moving reference period and specific air temperatures threshold for each calendar date. Then, we present a case study using data from 5 observatories in Malaga Province (Spain) from 1971 to 2016. We assessed the effect of a moving reference period (rather than a fixed reference period) and the definition of daily air temperatures threshold on the identification of anomalies in the definition of a HW. The results indicate that HWs can occur throughout the year. Finally, we propose incorporation of minimum daily air temperatures in two alternative definitions of HW. Our results indicate a high frequency of HWs in the summer months, in which HWs are mainly due to anomalous high Tmin and more frequent HWs in which maximum and minimum daily air temperature are exceeded from 2014 onwards. These new methods of defining a HW provides more accurate assessments of thermal discomfort.

Key words: daily threshold, heat waves, maximum air temperature, minimum air temperature, moving reference period.

1. Introduction

There is increasing attention devoted to changes in climate variability and in the extremes of weather and climatic events (Houghton *et al.*, 2001). Relative to changes in mean climatic variables, changes in extreme climatic events have a greater impact on human activities, the natural environment, agriculture, and insurance coverage (Kunkel *et al.*, 1999). More specifically, changes in the frequency or/and intensity of extreme events have affected human health directly (*via* heat and cold waves) and indirectly (*via* floods or pollution) (Zwiers and Kharin, 1998).

The term ‘heat wave’ (HW) originates from the first descriptions of hot periods recorded in the 1930s in the United States, and one of the first HWs mentioned in scientific papers occurred in Saint Louis in 1936 (Ellis and Nelson, 1978). Until the 1970s, most research concerning HWs were carried out in the United States. Over the next few years, the first descriptions of HWs and extreme air temperature values in Europe appeared (Kuchcik, 2006). Increasing interest in the occurrence of observed HWs is substantial and not solely because of global warming. Persistent periods of very high temperature have a strong impact on human health (Tomczyk and Bednorz, 2016).

Nonetheless, there is no one objective and uniform definition of HW (Tomczyk et al., 2017a). In China, heat warnings are issued when maximum temperature is forecast to exceed 35ºC on any one day, while in the United Kingdom, regionally varying thresholds of maximum and minimum temperature must be exceeded for two consecutive days and an intervening night. The Netherlands meteorological bureau issues warnings to health services when maximum temperatures are predicted to exceed 25º C for at least 5 days of which at least 3 days threaten temperatures above 30ºC. In the United States, the National Weather Service suggests early warning when the daytime heat index (including adjustment for humidity) reaches 40.6ºC and a nighttime minimum temperature of 26.7ºC persists for at least 48 h. (Gershunov et al., 2009). The scientific community considers a summer HW event as a prolonged sequence of days of excessive heat over a large area (Chen *et al.*, 2017) or as an isolated episode in the summer with an extremely high near-surface air temperature that lasts several days or more (Robinson, 2001; Lau and Nath, 2012; Shevchenko *et al*., 2014).

The number of HWs has increased worldwide in recent decades (Shevchenko *et al*., 2014), and there were extreme HWs in Western and Southwestern Europe during June and August of 2003 (Fink *et al*., 2004; Rebetez *et al*., 2006) and during June and July of 2006 (Fouillet *et al*., 2008; Gosling *et al*., 2009; Rebetez *et al*., 2009; Kyselý, 2010; Monteiro *et al*., 2013). A particularly extreme HW occurred during July and August of 2010 in Eastern Europe and Western Russia (Barriopedro *et al*., 2011; Grumm, 2011; Rahmstorf and Coumou, 2011; Otto *et al*., 2012; Shevchenko *et al*., 2014). From 2011-2015, no HW had an impact as extreme as the 2003 HW in Central Europe or the 2010 HW in the Russian Federation, although there were intense HWs during that period (WMO, 2016). In Eastern and Central Europe, the most serious HW since 2003 was during the first half of July in 2015. According with Hoy et al., (2017) the extreme summer of 2015 was characterized by very intensive heat episodes with extreme or even record high temperatures in large parts of Europe. A study on extreme European summer heat waves by Russo et al. (2015) ranked the 2015 heat event as sixth severe since 1950, combining heat intensity and spatial extent. At that time, Germany had national record air temperature of 40.3°C; several weeks later, there were unprecedented record high air temperatures in Spain, France, and Switzerland. This was the longest recorded HW in Spain, which experienced the warmest July since the beginning of record keeping, and there were similar events in Switzerland and Austria.

There were also significant HWs in different parts of Europe during the summers of 2012, 2013, and 2014 (WMO, 2016).

It is likely that the frequency of HWs has increased in Europe, Asia, and Australia since 1950, according to Intergovernmental Panel on Climate Change (IPCC) (2013). Other research indicates that HWs will become more frequent and intense in the future due to global warming (Meehl and Tebaldi, 2004; Christidis *et al*., 2005; Hansen and Sato, 2012; Coumou and Robinson, 2013; Watanabe *et al*., 2013; Lee and Lee, 2016, Chen *et al*., 2017). These forecasted changes have motivated weather forecasters to develop more accurate methods to identify and predict HWs, so that society can mitigate their impact (WMO, 2011; Coumou and Rahmstorf, 2012; Lee and Lee, 2016).

Statistical analyses of the characteristics of HWs examined data from many countries including China (Tan *et al*., 2007), Czech Republic (Kyselý, 2002), France (Fouillet *et al*., 2008), Portugal (Monteiro *et al*., 2013), Spain (Díaz *et al*. 2006), and the USA (Gershunov *et al*., 2009), particularly after extreme events (Shevchenko *et al*., 2014). However, these studies of anomalies only considered data from the summer months.

HWs are a natural hazard, and much is known about their effects on the human body (Kovats and Hajat, 2008). In particular, they have significant impacts on the well-being, efficiency, and health of humans, and can lead to marked short-term increases of morbidity and mortality (Kovats and Ebi, 2006; Basu, 2009; Gosling et al., 2009), and their effects are particularly significant in cities (Shevchenko et al., 2014). The adaptation and vulnerability of the population to heat waves depend on the local average temperatures and on the frequency of heat waves (Donaldson et al. 2003; Pascal et al., 2006). Deadly heat waves have always been associated with elevated night-time temperatures (Besancenot 1990a; Diaz et al. 2002a, 2002b).

The total impact of a HW, which can jeopardize human health and lead to losses in economic sectors such as agriculture and forestry, depends on its magnitude and timing and also on the adaptability of humans and public health responses (Shevchenko *et al*., 2014). The impact of such events is greater when there are extreme weather conditions over extended periods, and this is the reason for the increased focus on HWs.

An improved understanding of the dynamical and physical processes of HWs is needed to improve our ability to predict these phenomena, and to develop strategies that can reduce their impact on human health and agriculture (Lee and Lee, 2016). Robinson (2001) concluded there is no consensus regarding a strict definition of HW. Current definitions of HWs from Spain's State Meteorological Agency (AEMET) only consider air temperatures during July and August, relative to a fixed reference period, to establish a common air temperature threshold for air temperature anomalies on any calendar date. These criteria do not consider air temperature anomalies at other times of the year, what are referred as warm spells (Tomczyk et al. 2017b). Moreover, because of the increase in mean air temperatures over time, the threshold for a HW may need to be modified. Other definitions of a HW, such as that from the IPCC, attempt to overcome some of the drawbacks of the AEMET definition, but most continue to rely upon a fixed reference period.

We propose an alternative definition of HW that is based on a moving reference period and specific air temperatures threshold for each calendar date, and then evaluated the frequency of HWs according to this new definition. We also suggest two more definitions of HW that consider maximum and minimum daily air temperatures, and are based on a moving reference period and specific threshold air temperatures for each calendar date. Then we determined the annual HW series at five observatories in Malaga Province (Spain), and compared these series to the HW series determined by the

AEMET and IPCC definitions.[1] We also analyzed the monthly frequency distribution of HWs throughout the year according to each proposed definition.

2. Factors used to define heat wave: first proposal

We analyzed the effect of the reference period and the definition of threshold air temperature on the identification of air temperature anomalies used to define HWs. The criteria used to define a HW often depend on the aims of a study and the available meteorological data (Gershunov *et al*., 2009; Antics *et al*., 2013; Pascal *et al*., 2013). AEMET currently defines a HW as "a spell of at least three consecutive days, in which at least 10% of the observatories considered are above the 95th percentile of its series of daily maximum air temperatures (Tmax) of the months of July and August of the period 1971-2000." There are other definitions of a HW, such as that from the IPCC that defines a HW as a period of more than 5 consecutive days with daily Tmax of 5°C or more above the mean daily Tmax for the normal climatic period 1961–1990 (Frich *et al*., 2002; Radinovic and Curic, 2012).[2]

We propose modification of 2 aspects of the definition of AEMET, so the term HW can provide a more meaningful measure of current weather conditions. First, the AEMET definition relies on daily Tmax values over a fixed 30 year time period. The World Meteorological Organization (WMO) mandates each member nation compute 30-year averages of meteorological quantities at least every 30 years (1931–1960, 1961–1990, 1991–2020, etc.), but it also recommends an update every 10 years (Arguez and Russel, 2011).

The use of daily Tmax distribution in the definition of HW is intended to detect patterns in the data that deviate from expected patterns. However, the expected patterns

[1] Please, refer to the Appendix for further comparisons.
[2] Please, refer to the Appendix for further definitions.

change over time. In particular, climate change has led to increased average air temperature, a shift of the natural limits, and more frequent high air temperature anomalies (Trenberth *et al*, 2012). Due to climate change, use of a specific reference period may lead to misleading results. Therefore, it is necessary to frequently update the reference period to provide a more meaningful indicator of current weather conditions, as the WMO recommends.

The reference period clearly affects the identification of a HW, and yet the official definition of a HW uses a fixed reference period. Therefore we evaluated the extent to which the reference period affects the identification of anomalous air temperatures. In particular, we compared the results from use of the 1971-2000 fixed reference period with use of a 30-year moving reference period (in which the reference period is continuously updated).

Second, we also propose to change the period during which the threshold air temperature is computed. Following AEMET's definition of HW, the threshold air temperature is the 95th percentile of the series of daily Tmax values for the months of July and August. This definition means that a HW outside of the summer months (warm spells) is highly improbable. Nonetheless, non-summer air temperatures may be much warmer than expected, but still not exceed this limit. We are interested in detecting anomalously warm data in a specific context ("contextual anomalies"), so propose defining a specific threshold for each day that is computed in accordance with its context. Thus, we do not use a common threshold air temperature for all Julian days, and neither does IPCC definition of HW, but IPCC maintain the same daily threshold for many years (30).

Instead, for each Julian day, we propose calculation of a running average of the Tmax of the specific day with the two adjacent days (this reduces day-to-day fluctuations) for all 30 previous calendar dates. The upper daily threshold air temperature for each day is the 95th percentile of the corresponding Tmax series. Climatologists commonly use this criterion to determine the threshold of climate variables (Manton et al. 2001, Labajo et al. 2008).

Formally, we define $Tmax_{i,t}$ as the Tmax of the i Julian day of year t and $\widetilde{Tmax}_{i,t}$ as the Tmax series of the Julian day i and the two adjacent days ($Tmax_{i-1,t}$ $Tmax_{i+1,t}$) during the previous 30 years.

Therefore

$$\widetilde{Tmax}_{i,t} = \{Tmax_{i,\mathrm{j}}, Tmax_{i-1,\mathrm{j}}, Tmax_{i+1,\mathrm{j}} | \mathrm{j} = t-30, t-29, \ldots, t-1\}$$

We also define $P95_{max,i,t}$ as the 95th percentile of $\widetilde{Tmax}_{i,t}$.

Definition of HW based on moving reference period and daily threshold (MRDT): a period of at least 3 consecutive days in which $Tmax_{i,t} > P95_{max,i,t}$.

The Tmax threshold in this definition varies with the Julian day (this filters out seasonality, so no correction of values measured directly at an observatory is necessary) and year (this detrends the threshold, and updates it to current conditions), so it incorporates the two key features proposed above.

3. Data

We used daily air temperature data from five observatories from the official network of observatories of the Spanish state in Malaga Province (Spain), which represent a variety of geographical settings (coastal, mountain and inland), for analysis of our alternative definition of HW (Figure 1). The air temperature data at these observatories (Algarrobo, Bobadilla, Cortes de la Frontera, Guadalhorce, Málaga airport) are highly reliable for the period 1971-2016. All data were from AEMET. Mediterranean basin ecosystems are a hotspot of the world’s biodiversity and supply numerous services to people, including clean water, flood protection, carbon storage, and recreation. A specific climate zone that has significant inter-annual variability in precipitation and air temperature. In recent decades, there has been severe economic damage and loss of life due to droughts, flooding events, and heat or cold waves, and these may have been exacerbated by increases in population and construction (Easterling *et al*., 2000). Alpert *et al*. (2002) analyzed observational databases from several areas of the Mediterranean basin using data from the 20th century, and reported an increase in extreme events. The rate of increase in the temperature of the Mediterranean due to the global change in the Planet has accelerated alarmingly in the last 5 to 10 years, at a rate of 0.75 degrees per year, despite the fact that it had been increasing one degree Celsius each 25 years (Guiot and Cramer, 2016).

We analyzed the frequency of HWs for 2001-2016, because 1971-2000 data is used as a reference period for computation of Tmax thresholds during the first year (2001), and the reference period is updated for all subsequent years. There were 16790 daily values at each of the 5 observatories.

4. Results and discussion

We evaluated the sensitivity of the identification of air temperature anomalies with our proposed definition of HW in the data from 5 observatories in Spain. The main features of our new HW definition are that it uses a moving reference period (instead of a fixed reference period) and it uses a specific threshold air temperature for each calendar date (instead of a common fixed threshold air temperature for all dates).

Figure 2 compares the number of HWs based on the AEMET definition, our first proposed definition (MRDT), and the IPCC definition.[3] We modified the IPCC

[3] Please, refer to the Appendix for further comparisons.

definition to make it comparable with the MRDT and the AEMET definitions by considering a period of more than 3 consecutive days and by considering the 1971-2000 reference period (as in AEMET).

There are two main results shown in this figure: first and obvious, there were significantly more HWs using the MRDT definition than the AEMET definition; and second, there were more HWs using the IPCC definition than the MRDT definition. We used the t-test to determine if the difference between the mean number of monthly HWs detected by two measures was significantly different from 0. Therefore, H0 is that two measures had the same result, and H1 is that one of the measures had more HWs than the other. The corresponding t-statistic are respectively, -5.91 $p < 0.0001$; and 2.08 $p = 0.0191$.

Figure 3 shows that AEMET only identifies HWs in July, August, and September, whereas the IPCC and MRDT definitions identify HWs in all months of the year also called warm spells, with the greatest frequencies in May and October. Thus, it is more meaningful to define a HW by comparison of daily Tmax with the expected air temperature for the specific Julian day.[4]

We propose computing the threshold as the 95th percentile of the series of daily Tmax for the specific Julian day. This allows identification of a Tmax that is warmer than expected for the specific time of the year, but not warmer than the threshold air temperature calculated in the months of July and August (as in the AEMET definition).

Figure 4 shows the daily evolution of the threshold for the year 2016 at the Cortes de la Frontera observatory based on the MRDT definition. Note that our methodology does not impose a common threshold air temperature for the same day of

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[4] We have investigated and conclude that these results are not due to a rearrangement of the anomalies. The differences in number of HWs are consistent with a difference in the number of anomalies. We thank an anonymous referee for proposing this verification.

different years, in contrast to the IPCC definition that changes the threshold from day to day but it remains fixed for a specific day until the reference period is updated.

Figure 4 shows that the thresholds for the IPCC and our proposed method change during the year, and an anomaly is only identified when Tmax is higher than this threshold. Thus, the IPCC and our proposed method identify anomalous high Tmax values that are not identified by AEMET (horizontal line), many of which are in non-summer months.

As noted above (Figure 2), the number of HWs based on the IPCC definition is greater than the number from our MRDT proposal, possibly due to differences in their definitions of threshold. IPCC defines an anomaly as any Tmax that is more than 5ºC above the mean daily Tmax. In contrast, we define an anomaly as any Tmax that exceeds the $P95_{max,i,t}$ of the $T\widetilde{max}_{i,t}$. We question whether use of a constant difference with respect to the mean (as in the IPCC definition) is the best method to define the threshold. Depending on the distribution of the daily Tmax, 5ºC can represent a high or low percentage of the observations.

We are trying to identify outliers in our Tmax data (air temperature anomalies), yet outliers skew the mean. Thus, we did not use the mean to identify outliers, because the mean does not represent typical behavior in the presence of outliers. On the contrary, use of the 95th percentile is robust to the presence of extreme outliers.

Finally, the MRDT thresholds and the IPCC thresholds change from day to day, adapting to context, but the AEMET threshold is the same for all days. Furthermore, the MRDT and IPCC methods for computing daily threshold are not as stringent as the AEMET method for non-summer months, because the AEMET confines its computation to the months of July and August. In addition, our threshold adapts to the specific context of the day of the year, and also to the overall trend of the series. We propose updating the reference period each year, although the IPCC only updates the reference period every some years.

Figure 5 shows the change of the threshold for one specific day (19 May) at the Malaga observatory, calculated using the 3 different definitions of HW, from 2001-2016. It shows that although IPCC uses a different threshold for each day (as in the MRDT definition) and therefore adapts to the context of the Julian day, it does not regularly update the reference period. In contrast, our daily threshold adapts to the history of the 30 previous years. Therefore, we eliminate the arbitrariness of when to update the reference period and avoid abrupt changes in the air temperature thresholds due to the update of the period every 30 or 10 years. Changes in the threshold could make classify a Tmax as anomalous if a reference period is considered, but not if the reference period is updated. These changes are more abrupt the longer the time between updates. Nonetheless, our proposal allows for a continuous change in the air temperature thresholds, avoiding abrupt changes in the thresholds as compared with the updating every 30 years

We observed in Figure 5 that the MRDT threshold increased over time. This is because updating of the threshold considers the increment in the daily Tmax for the 19 May during the 30 previous years. We believe that use of a moving reference period provides a more meaningful characterization of HWs, because it detrends the time series, and this is important when interpreting weather phenomena. Figure 6 shows the difference of the daily MRDT thresholds from 2001 to 2016 at the Malaga observatory on all 365 Julian days, where positive values mean there was an increase in the MRDT threshold from 2001-2016. Moreover, this figure shows that most of the values were positive (76.4%, 279 out of 365) and the mean difference was also positive (0.504°C).

In other words, there was an increase of the MRDT thresholds from 2001-2016 due regular updating.

5. Expanded definition of heat wave: second proposal

As have been shown the HW activity has received considerable attention, especially following the European heat waves in 2003 (Beniston and Diaz 2004; Schar *et al*. 2004; Stott *et al*. 2004; Meehl and Tebaldi 2004; Gershunov and Douville 2008). Most studies have focused on local extreme temperature magnitudes and durations associated with heat waves (Beniston 2004; Beniston and Diaz 2004; Schar *et al*. 2004). However, heat waves are inherently regional phenomena with regional impacts. Therefore, the spatial scale of heat waves amplifies the event's stressful effects by spreading them over broader sectors of ecosystems, society, and infrastructure (Gershunov *et al*., 2009)

A more precise and useful description of heat wave activity should include an explicit and separate quantification of daily and nightly temperature extremes. During a persistent daytime heat wave, cool nights provide respite from the stressful effects of heat on the health and general well-being of plants and animals, as well as for the energy sector, and prepare society and nature to face another day of scorching heat. Health impacts of nighttime heat are less well known, but there are indications that high minimum temperatures during heat waves enhance morbidity and mortality (Hémon and Jougla 2003; Grize *et al*. 2005; Gosling *et al*. 2008; Gershunov *et al*., 2009).

To describe the spatial extent of heat waves and differential symptoms during day and night, we start with maximum and minimum daily air temperatures (Tmax and Tmin, respectively) recorded at the 5 representative observatories from the province of Málaga. The minimum and maximum temperatures were hence collected as pertinent indicators of the potential impact of the HW, according with the described methodology.

HWs were always characterized by a steep increase of maximum and minimum temperatures and duration of several days. The final choice of a combined indicator "Tmin and Tmax" is consistent with the literature. Indeed, it has already been observed that the maximum temperature alone was not sufficient to estimate the health risk. An elevated by-night temperature not allowing the body to rest is also a key risk factor (Besancenot 2002; Pascal *et al.*, 2006).

Taking in account these evidences, we also propose a second method to define a HW, which incorporates analysis of minimum daily air temperatures (Tmin). We propose two alternative definitions based on a moving reference period and two daily thresholds (for Tmax and Tmin), so we designate it as MR2DT. According to the MR2DT(OR), a HW is a period of at least 3 consecutive days in which the Tmax is above the 95th percentile of the series of daily Tmax for the specific Julian day, or in which the Tmin is above the 95th percentile of the series of daily Tmin for the specific Julian day. In the same line, MR2DT(AND) imposes that both thresholds should be exceeded simultaneously.[5] MR2DT(AND) defines a HW as the period of at least 3 consecutive days in which the Tmax is above the 95th percentile of the series of daily Tmax for the specific Julian day, and in which the Tmin is above the 95th percentile of the series of daily Tmin for the specific Julian day.

These definitions thus consider maximum and minimum air temperatures, and the Tmax and Tmin thresholds vary with the Julian day and year. The MR2DT(OR) and MR2DT(AND) therefore incorporate the two novelties we first proposed.

($Tmin_{i-1,t}$ $Tmin_{i+1,t}$) during the previous 30 years:

$$\widetilde{Tmin_t} = \{Tmin_{i,j}, Tmin_{i-1,j}, Tmin_{i+1,j} | j = t-30, t-29, \ldots, t-1\}$$

And $P95_{min,i,t}$ is the 95th percentile of $\widetilde{Tmin_t}$

***Definition of HW based on moving reference period and two alternative daily thresholds (MR2DT(OR))*:** a period of at least three consecutive days, in which $Tmax_{i,t} > P95_{i,t}$ or $Tmin_{i,t} > P95_{i,t}$.

***Definition of HW based on moving reference period and two simultaneous daily thresholds (MR2DT(AND))*:** a period of at least three consecutive days, in which $Tmax_{i,t} > P95_{i,t}$ and $Tmin_{i,t} > P95_{i,t}$.

Figure 7 shows the number of HWs per year according to the MRDT, MR2DT(OR) and the MR2DT(AND). Obviously, the MR2DT(OR) definition identified more HWs than the MRDT definition because it considers Tmax or Tmin alternatively, while the opposite takes place for the MR2DT(AND) definition, that identified less HWs than the MRDT definition, because it considers Tmax and Tmin simultaneously. Additional interesting results from comparison of the MRDT and MR2DT(OR) definitions are that the HWs in 2007 were mostly due to high Tmax values, the HWs in 2004 were mostly due to high Tmin values, and 2015 had many HWs with high Tmax and Tmin values. MR2DT(AND) shows that in 2010 and from 2014 onwards there were more frequency of HWs where Tmax and Tmin threshold temperatures were exceeded.

Figure 8 shows the same information with aggregation by month. The MRDT definition identified fewer HWs in the summer months than the MR2DT(OR), especially during June (due to the many high Tmin values in June). The MR2DT(OR) also identified more HWs than the MRDT in July, August, and October, months that also had many anomalous high Tmin values. Nonetheless, MR2DT(AND) identified more number of HWs that exceeds Tmax and Tmin thresholds simultaneously, in March, July, November and December.

6. Conclusions

This study shows that modifying some of the criteria used to define a HW provides a more meaningful analysis of monthly and annual changes in HWs. Our evaluation shows that bias is introduced when the definition of a HW is based on a fixed reference period and when the threshold air temperature is the same for all months. Thus, we first suggest use of a moving reference period and a daily Tmax threshold to define a HW (MRDT definition). This allows a more meaningful identification of HWs, because it considers the daily context and long-term changes in climate. Therefore we eliminate the arbitrariness of when to update the reference period, because we propose a continuous update and avoid abrupt changes in the air temperature thresholds due to the update of the period every 30 or 10 years. We further propose defining a HW by analysis of daily Tmax and Tmin, because Tmin provides a more accurate assessment of thermal discomfort.

According to the first definition of a HW (MRDT), there were HWs in all years from 2001-2016, and the greatest number of HWs was in 2015 (20 HWs). Moreover, our analysis of HWs throughout the year shows that HWs do not only occur during warm periods (as with the AEMET definition). In fact, the months with the most HWs (warm spells) were May and October.

According to our second definition of a HW (MR2DT(OR)), the greatest number of HWs was in 2015 (42 HWs). In addition, based on the MR2DT(OR) definition of HW, there were more HWs during the summer months, with HWs mainly due to anomalous high Tmin. Being more restrictive, a third definition (MR2DT(AND)) imposing two simultaneous thresholds (one for Tmax and other for Tmin) shows that more HWs are identified from 2014 onwards.

7. Acknowledgements

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8. Appendix. Robustness analysis

In this section we first compare the results of the analysis using the definition MRDT proposed in this paper with the one that use an alternative threshold: the 90th percentile centered on a 5-day window (P90-5) instead of the 95th centered on a 3-day window (P95-3) in order to check the robustness of the conclusions obtained in section 4.

The comparison of the daily thresholds P90-5 and P95-3 for one observatory is shown in Figure A1. We observe that evidently when imposing a threshold based on the 90th percentile the threshold is lower. This obviously has an impact over the number of HWs reported by year and month. The comparison of the annual number of HWs reported by MRDT(P95-3) and MRDT(P90-5) in Figure A2 shows an 123% overall increase in the number of HWs reported in the period under MRDT(P90-5) compared to MRDT(95-3).

The conclusions obtained from Figure 3 in the manuscript and in Figure A3 shows similar conclusions. That is, as we report in the manuscript the IPCC and MRDT(90-5) definitions identifies HWs in all months of the year, with the greatest frequencies in May and October. Conclusions still applies for the comparison of the two definitions proposed, MRDT(P90-5) and MR2DT(P95-3).

We now evaluate the sensitivity of the identification of air temperature anomalies with our proposed definition of HW, MRDT, with the definition used in the Warm Spell Duration index (WSDI). For this purpose, we adapt MRDT and WSDI definition to make them comparable. We impose a common threshold based on the WSDI definition, the 90th percentile of the series of the Tmax of Julian day i and the four adjacent days (5 day window), named $P90-5_{max,i,t}$, for each day i. We define a HW as a period of at least three consecutive days in which $Tmax_{i,t} > P90-5_{max,i,t}$. We adapt the definition of MR2DT(OR) and MR2DT(AND) accordingly.

We first compare the number of HWs based on the MRDT(P90-5), MR2DT(OR), MR2DT(AND) and WSDI definition (Figure A4) All definitions use the P90-5 threshold, but the three former use a moving reference period while the latter a use a fixed referenced period anchored in 1971-2000.

We observe that WSDI and MRDT (P90-5) report similar number of HWS but with some differences due to the continuous update of the threshold in MRDT(P90-5) definition. Conclusions regarding to MR2DT(OR) (P90-5) and MR2DT(AND) (P90-5) remain. The first definition report significantly greater number of HWs than the second. It is evident the increase in the number of HWs when considering the MR2DT(OR) (P90-5) definition for 2015, so they are mainly due to the increase in this year of Tmin.

Figure A5 shows that WSDI and MRDT(P90-5) definitions identify HWs in all months of the year, with the greatest frequencies in May and October.

We conclude from the comparison of both definitions that WSDI report greater number of HWs from May to August while the opposite takes place during the rest of the year. This result must derive from the update of the thresholds that have increased from May to August, while they have reduced from September to April; that is, daily Tmax temperature are higher from May to August than in the period 1971-2000 (Figure A6).

Figure A6 shows that although WSDI uses a different threshold for each day (as in the MRDT definition) and therefore adapts to the context of the Julian day, it does not regularly update the reference period) the daily threshold does not change in the period 2001-2016. In contrast, our daily threshold adapts to the history of the 30 previous years, so it changes every year. Our proposal allows for a continuous change in the air temperature thresholds, avoiding abrupt changes in the thresholds as compared with the updating every 30 years. This change has made the MRDT (P90-5) threshold from May to August to be higher than the WSDI, therefore reporting a smaller number of HWS during these months.

Summing up, we can conclude that the P90-5 threshold is an easier to cross limit, and therefore it reduces its ability to identify extreme situations and would entail very frequent heat warnings. That is why we propose the 95th percentile in a 3-day window threshold that updater every year.

9. References

Alpert P, Ben-Gai T, Baharad A, Benjamini Y, Yekutieli D, Colacino M, Diodato L, Ramis C, Homar V, Romero R, Michaelides S, Manes A. 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophys. Res. Lett. 29, 31.1–31.4.

Antics A, Pascal M, Laaidi K, Wagner V, Corso M, Declercq C, Beaudeau P. 2013. A simple indicator to rapidly assess the short-term impact of heat waves on mortality within the French heat warning system. International Journal of Biometeorology 57: 75–81. DOI: 10.1007/s00484-012-0535-9

Arguez A, Russel S. 2011. The Definition of the Standard WMO Climate Normal: The Key to Deriving Alternative Climate Normals. Bulletin of the American Meteorological Society 92(6). DOI: 10.1175/2010BAMS2955.1

Barriopedro D, Fischer EM, Luterbacher J, Trigo RM, García-Herrera R. 2011. The hot summer of 2010: redrawing the temperature record map of Europe. Science 332: 220–224. DOI: 10.1126/science.1201224

Basu R. 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environmental Health 8: 40. DOI: 10.1186/1476-069X-8-40

Beniston M and Diaz, HF 2004. The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. Global Planet. Change, 44, 73–81. DOI:10.1016/j.gloplacha.2004.06.006

Beniston M. 2004. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys. Res. Lett., 31, L02202, DOI: 10.1029/2003GL018857.

Besancenot JP. 1990a. L´organisme humain humain face à la chaleur. Sécheresse, Science et changements planétaires 1:98–104

Chen, Y, Hu Q, Yang Y, Qian W. 2017. Anomaly based analysis of extreme heat waves in Eastern China during 1981–2013. International Journal of Climatology 37: 509-523. DOI: 10.1002/joc.4724

Christidis N, Stott P, Brown S, Hegerl G, Caesar J. 2005. Detection of changes in temperature extremes during the second half of the 20th century. Geophys. Res. Lett. 32: L20716, DOI: 10.1029/2005GL023885.

Coumou D, Rahmstorf S. 2012. A decade of weather extremes. Nat. Clim. Change 2: 491–496, DOI: 10.1038/NCLIMATE1452.

Coumou D, Robinson A. 2013. Historic and future increase in the global land area affected by monthly heat extremes. Environ. Res. Lett. 8: 034018. DOI: 10.1088/1748-9326/8/3/034018

Díaz J, García R, Velazquez de Castro F, Hernández E, López C, Otero A. 2002a. Effects of extremely hot days on people older than 65 years old in Seville (Spain) from 1986 to 1997. Int. J. Biometeorol. 46, 145–149.

Díaz J, García-Herrera R, Trogo RM, Linares C, Valente MA, de Miguel JM, Hernández E. 2006. The impact of the summer 2003 heat wave in Iberia: how should we measure it? International Journal of Biometeorology 50: 159–166. DOI: 10.1007/s00484-005-0005-8

Díaz J, Jordán A, García R, López C, Alberdi JC, Hernández E, Otero, A. 2002b. Heat waves in Madrid 1986–1997: Effects on the heath of elderly. Int. Arch Occup Environ Health 75, 163–170.

Donaldson GC, Keatinge WR, Nayha S. 2003. Changes in summer temperature and heat-related mortality since 1971 in North Carolina, South Finland, and Southeast England. Environ Res 91:1–7. DOI: 10.1016/S0013-9351(02)00002-6

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO, 2000. Climate extremes: observations, modeling and impacts. Science 289, 2068– 2074.

Ellis FP, Nelson F. 1978. Mortality in the elderly in a heat waves in New York City, August 1975. Environ. Res. 15: 504 –512.

Fink A, Brücher T, Krüger A, Leckebusch G, Pinto J, Ulbrich U. 2004. The 2003 European summer heatwaves and drought – synoptic diagnosis and impacts. Weather 59: 209–216. DOI: 10.1256/wea.73.04

Fouillet A, Rey G, Wagner V, Laaidi K, Empereur-Bissonnet P, Le Tertre A, Frayssinet P, Bessemoulin P, Laurent F, De Crouy-Chanel, P, Jougla E, H´emon D. 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. International Journal of Epidemiology 37: 309–317. DOI: 10.1093/ije/dym253

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylovk M, Klein Tank AMG, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Research 19: 193–212

Gershunov A, Cayan DR, Iacobellis SF. 2009. The great 2006 heat wave over California and Nevada: signal of an increasing trend. Journal of Climate 22: 6181–6203. DOI: 10.1175/2009JCLI2465.1

Gershunov A, and Douville H. 2008: Extensive summer hot and cold extremes under current and possible future climatic conditions: Europe and North America. Climate Extremes and Society, Diaz HF and Murnane RJ Eds., Cambridge University Press, 74–98.

Gosling SN, Lowe JA, McGregor GR, Pelling M, Malamud BD. 2009. Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Climatic Change 92: 299–341. DOI: 10.1007/s10584-008-9441-x

Grize L, Huss A, Thommen O, Schindler C, and Braun-Fahrlander C. 2005. Heat wave 2003 and mortality in Switzerland. Swiss Med. Wkly., 135, 200–205.

Grumm RH. 2011. The Central European and Russian heat event of July - August 2010. Bulletin of the American Meteorological Society 92: 1285–1296. D O I : 10 .117 5 / 2

011B A M S 3174 .1

Guiot J and Cramer W. 2016. Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. Science VOL 354 ISSUE 6311 DOI:10.1126/science.aah5015

Hansen J, Sato M, Ruedy R. 2012. Perception of climate change. Proc. Natl. Acad. Sci. 109: E2415–E2423. DOI: 10.1073/pnas.1205276109

Hémon D, Jougla E. 2003. Surmortalité liée à la canicule d'août 2003. Rapport d'étape (1/3). Estimation de la surmortalité et principales caractéristiques épidémiologiques. INSERM. 1–59. 2003. INSERM, Paris

Houghton JT, Ding Y, Noguer M, 2001. Climate Change 2001: The scientific basis. Cambridge University Press, 881 pp.

Hoy A, Hänsel S, Skalak P, Ustrnul Z, Bochnícek O. 2017. The extreme European summer of 2015 in a long-term perspective. Int. J. Climatol. 37: 943–962. DOI: 10.1002/joc.4751

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker TF, Qin D, Plattner, G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds). Cambridge University Press: Cambridge, UK and New York, NY, 1535 pp, DOI: 10.1017/CBO9781107415324.

Kovats RS, Ebi KL. 2006. Heatwaves and public health in Europe. European Journal of Public Health 16: 592–599. DOI: 10.1093/eurpub/ckl049

Kovats RS, Hajat S. 2008. Heat stress and public health: a critical review. Annual Review of Public Health 29: 41–55. DOI: 10.1146/annurev.publhealth.29.020907.090843

Kuchcik M. 2006. Fale upałów w Polsce w latach 1993 – 2002 (Heat waves in Poland over the period 1993 – 2002). Prz. Geogr. 78(3): 397 –412 (in Polish).

Kunkel KE, Pielke RA, Changnon SA, 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: a review. Bull. Am. Meteorol. Soc. 80, 1077–1098. DOI: 10.1175/1520-0477(1999)080<1077:TFIWAC>2.0.CO;2

Kyselý J. 2002. Temporal fluctuations in heat waves at Prague-Klementinum, the Czech Republic, from 1901–97, and their relationships to atmospheric circulation. International Journal of Climatology 22: 33–50. DOI: 10.1002/joc.720

Kyselý J. 2010. Recent severe heat waves in central Europe: how to view them in a long-term prospect? International Journal of Climatology 30: 89–109. DOI: 10.1002/joc.1874

Labajo JL, Martín Q, Labajo AL, Piorno A, Ortega MT and Morales C. 2008. Recent trends in the frequencies of extreme values of daily maximum atmospheric pressure at ground level in the central zone of the Iberian Peninsula. International Journal of Climatology 28: 1227-1238. DOI: 10.1002/joc.1631

Lau N-C, Nath MJ. 2012. A model study of heat waves over North America: meteorological aspects and projections for the twenty-first century. Journal of Climate

25: 4761–4784. DOI: 10.1175/JCLI-D-11-00575.1

Lee W-S, Lee M. 2016. Interannual variability of heat waves in South Korea and theirconnection with large-scale atmospheric circulation patterns. International Journal of Climatology 36: 4815–4830. DOI: 10.1002/joc.4671

Manton MJ, Della-Marta PM, Haylock MR, Hennessy KJ, Nicholls N, Chambers LE, Collins DA, Daw G, Finet A, Gunawan D, Inape K, Isobe H, Kestin TS, Lefale P, Leyu CH, Lwin T, Maitrepierre L, Ouprasitwong N, Page CM, Pahalad J, Plummer N, Salinger MJ, Suppiah R, Tran VL, Trewin B, Tibig I and Yee D, 2001. Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961-1998. International Journal of Climatology, 21, 269-284. DOI: 10.1002/joc.610

Meehl GA, Tebaldi C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305: 994–997. DOI: 10.1126/science.1098704

Monteiro A, Carvalho V, Oliveira T, Sousa C. 2013. Excess mortality and morbidity during the July 2006 heat wave in Porto, Portugal. International Journal of Biometeorology 57: 155–167. DOI: 10.1007/s00484-012-0543-9

Otto FEL, Massey N, van Oldenborgh GJ, Jones RG, Allan MR. 2012. Reconciling two approaches to attribution of the 2010 Russian heat wave. Geophysical Research Letters 39: L04702. DOI: 10.1029/2011GL05042

Pascal M, Laaidi K, Ledrans M, Baffert E, Casério-Schönemann C, Le Tertre A. 2006. France's heat health watch warning system. Int J Biometeorol 50:144–153. DOI: 10.1007/s00484-005-0003-x

Pascal M, Wagner V, Le Tertre A, Laaidi K, Honore C, Benichou F, Beaudeau P. 2013. Definition of temperature thresholds: the example of the French heat wave warning system. International Journal of Biometeorology 57: 21–29. DOI: 10.1007/s00484-012-0530-1

Radinovíc D, Curíc M. 2012. Criteria for heat and cold wave duration indexes. Theoretical and Applied Climatology 107: 505–510. DOI: 10.1007/s00704-011-0495-8

Rahmstorf S, Coumou D. 2011. Increase of extreme events in a warming world. PNAS 108: 17905–17909. DOI: 10.1073/pnas.1101766108

Rebetez M, Dupont O, Giroud M. 2009. An analysis of the July 2006 heatwave extent in Europe compared to the record year of 2003. Theoretical and Applied Climatology 95: 1–7. DOI: 10.1007/s00704-007-0370-9

Rebetez M, Mayer H, Dupont O, Schindler D, Gartner K, Kropp, JP, Menzel A. 2006. Heat and drought 2003 in Europe: a climate synthesis. Annals of Forest Science 63: 569–577. DOI: 10.1051/forest:2006043

Robinson PJ. 2001. On the definition of a heat wave. Journal of Applied Meteorology 40: 762–775.

Robinson, P.J. 2001. On the definition of a heat wave. Journal of Applied Meteorology and Climatology, 40, 762-775.

Russo S, Sillmann J, Fischer EM. 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10(12): 124003. DOI: 10.1088/1748-9326/10/12/124003

Schar CP, Vidale L, Luthi D, Frei C, Haberli C, Liniger MA, and Appenzeller C. 2004. The role of increasing temperature variability in European summer heatwaves. Nature, 427, 332–336. DOI:10.1038/nature02300

Shevchenko O, Lee H, Snizhko S, Mayer H. 2014. Long-term analysis of heat waves in Ukraine. International Journal of Climatology 34: 1642–1650. DOI: 10.1002/joc.3792

Stott PA, Stone DA, and Allen MR. 2004. Human contribution to the European heatwave of 2003. Nature, 432, 610–613. DOI:10.1038/nature03089

Tan J, Zheng Y, Song G, Kalkstein LS, Kalkstein AJ, Tang X. 2007. Heat wave impacts on mortality in Shanghai, 1998 and 2003. International Journal of Biometeorology 51: 193–200. DOI: 10.1007/s00484-006-0058-3

Tomczyk AM, Bednorz E. 2016. Heat waves in Central Europe and their circulation conditions. Int. J. Climatol. 36(2): 770–782, DOI: 10.1002/joc.4381.

Tomczyk AM, Półrolniczak M, Bednorz E. 2017a. Circulation Conditions' Effect on the Occurrence of Heat Waves in Western and Southwestern Europe. Atmosphere 2017, 8, 31; DOI: 10.3390/atmos8020031

Tomczyk, A, Piotrowski P, Bednorz E. 2017b. Warm spells in Northern Europe in relation to atmospheric circulation. Theor. Appl. Climatol. 128 (3-4), 623-634, DOI: 10.1007/s00704-015-1727-0

Trenberth KE, Meehl J, Masters J, Somerville R. (2012): Heat Waves and Climate Change. A Science Update from Climate Communication.

Watanabe M, Shiogama H, Imada Y, Mori M, Ishii M, Kimoto M. 2013. Event attribution of the August 2010 Russian heat wave. SOLA 9: 65–68. DOI: 10.2151/sola.2013-015

World Meteorological Organization. 2011. Weather extremes in a changing climate: hindsight on foresight. WMO Publication No. 1075, Geneva, Switzerland.

World Meteorological Organization. 2016. Statement on the State of the Global Climate in 2016. WMO Publication No. 1189, Geneva, Switzerland

Zwiers FW, Kharin VV, 1998. Changes in the extremes of the climate simulated by CCC GCM2 under CO2 doubling. Journal of Climate, 2200–2222.

Figure captions:

Figure 1. Observatories in Malaga Province (Spain).

Figure 2. Number of HWs per year, under different definitions.

Note: AEMET: AEMET definition of HW; IPCC: IPCC-adapted from the IPCC definition of HW; MRDT: moving reference, daily threshold definition of HW (proposed in this paper).

Source: Based on AEMET daily Tmax data.

Figure 3. Aggregate number of HWs in different months, under different definitions.

Note: AEMET: AEMET definition of HW; IPCC: IPCC-adapted from the IPCC definition of HW; MRDT: moving reference, daily threshold definition of HW (proposed in this paper).

Source: Based on AEMET daily Tmax data.

Figure 4. Daily thresholds for a HW in 2016 at Algarrobo, under different definitions.

Note: AEMET: AEMET definition of HW; IPCC: IPCC-adapted from the IPCC definition of HW; MRDT: moving reference, daily threshold definition of HW (proposed in this paper).

Source: Based on AEMET daily Tmax data.

Figure 5. Thresholds for a HW at the Malaga observatory on 19 May, under different definitions.

Note: AEMET: AEMET definition of HW; IPCC: IPCC-adapted from the IPCC definition of HW; MRDT: moving reference, daily threshold definition of HW (proposed in this paper).

Source: Based on AEMET daily Tmax data.

Figure 6. Difference between the MRDT thresholds in 2001 and 2016.

Note: A positive value means the MRDT threshold increased from 2001 to 2016; in other words, there was warming trend during this period.

Figure 7. Number of HWs per year, based on the MRDT and MR2DT definitions.

Note: MRDT: moving reference, daily threshold definition of HW (proposed in this paper). MR2DT: moving reference, daily threshold definition of HW considering Tmax and Tmin (proposed in this paper). Source: Based on AEMET daily Tmax data.

Figure 8. Aggregate number of HWs in different months, under MRDT, MR2DT(OR) and MR2DT (AND) definitions.

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Note: MRDT: moving reference, daily threshold definition of HW (proposed in this paper). MR2DT: moving reference, daily threshold definition of HW considering Tmax and Tmin (proposed in this paper). MR2DT(OR): moving reference, daily threshold definition of HW considering Tmax and Tmin (proposed in this paper), at least one of the threshold (for Tmax or Tmin) is trespassed. MR2DT(AND): moving reference, daily threshold definition of HW considering Tmax and Tmin (proposed in this paper), both thresholds (for Tmax and Tmin) are trespassed.

Source: Based on AEMET daily Tmax data.

Figure A1. Daily thresholds under the different alternatives in observatory 21 for 2016.

Note: P90-5: daily thresholds using the 90th percentile centered on a 5-day window. P95-3:daily thresholds using the 90th percentile centered on a 5-day window.

Figure A2. Evolution of the frequency of HWs by year under MRDT(P95-3) and MRDT(P90-5).

Note: MRDT(P90-5) moving reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MRDT(P95-3) moving reference, daily threshold definition of HW using the 95th percentile centered on a 3-day window.

Figure A3. Evolution of the frequency of HWs by month (aggregated data for the period 2001-2016)

Note: MRDT(P90-5): moving reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MRDT(P95-3): moving reference, daily threshold definition of HW using the 95th percentile centered on a 3-day window.

Figure A4. Evolution of the frequency of HWs by year under alternative definitions

Note: WSDI fixed reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MRDT(P90-5) moving reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MR2DT(OR) (P90-5): moving reference, daily threshold (P90-5) definition of HW considering Tmax and Tmin, at least one of the threshold (for Tmax or Tmin) is trespassed. MR2DT(AND) (P90-5): moving reference, daily threshold (P90-5) definition of HW considering Tmax and Tmin, both thresholds (for Tmax and Tmin) are trespassed.

Figure A5. Evolution of the frequency of HWs by month (aggregated data for the period 2001-2016)

Note: WSDI fixed reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MRDT(P90-5) moving reference, daily threshold definition of HW using the 90th percentile centered on a 5-day window. MR2DT(OR) (P90-5): moving reference, daily threshold (P90-5) definition of HW considering Tmax and Tmin, at least one of the threshold (for Tmax or Tmin) is trespassed. MR2DT(AND) (P90-5): moving reference, daily threshold (P90-5) definition of HW considering Tmax and Tmin, both thresholds (for Tmax and Tmin) are trespassed.

Figure A6. Daily thresholds for WSDI and MRDT(P90-5) during the period 2001-2016

Note: WSDI fixed reference, daily threshold using the 90th percentile centered on a 5-day window. MRDT(P90-5) moving reference, daily threshold using the 90th percentile centered on a 5-day window.

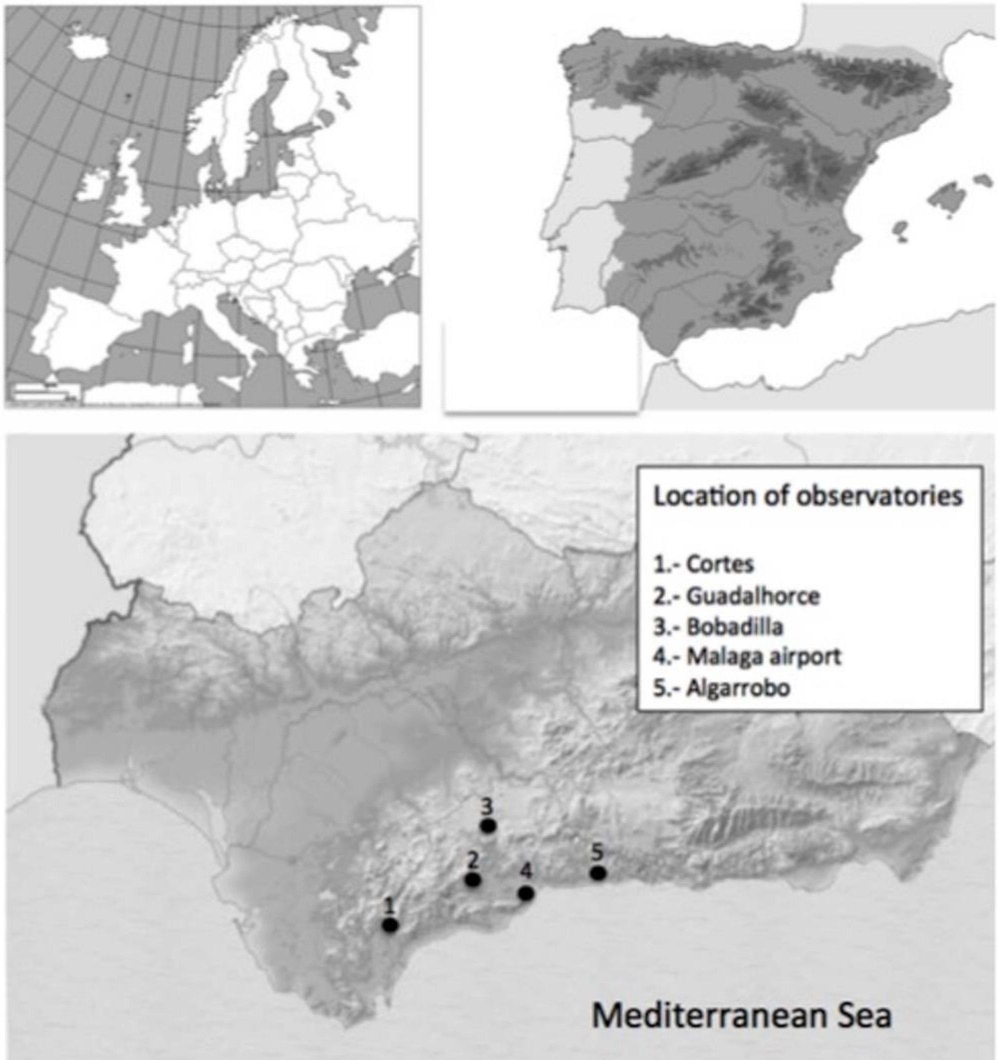
Location of observatories
1.- Cortes
2.- Guadalhorce
3.- Bobadilla
4.- Malaga airport
5.- Algarrobo
1
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Figure 1.

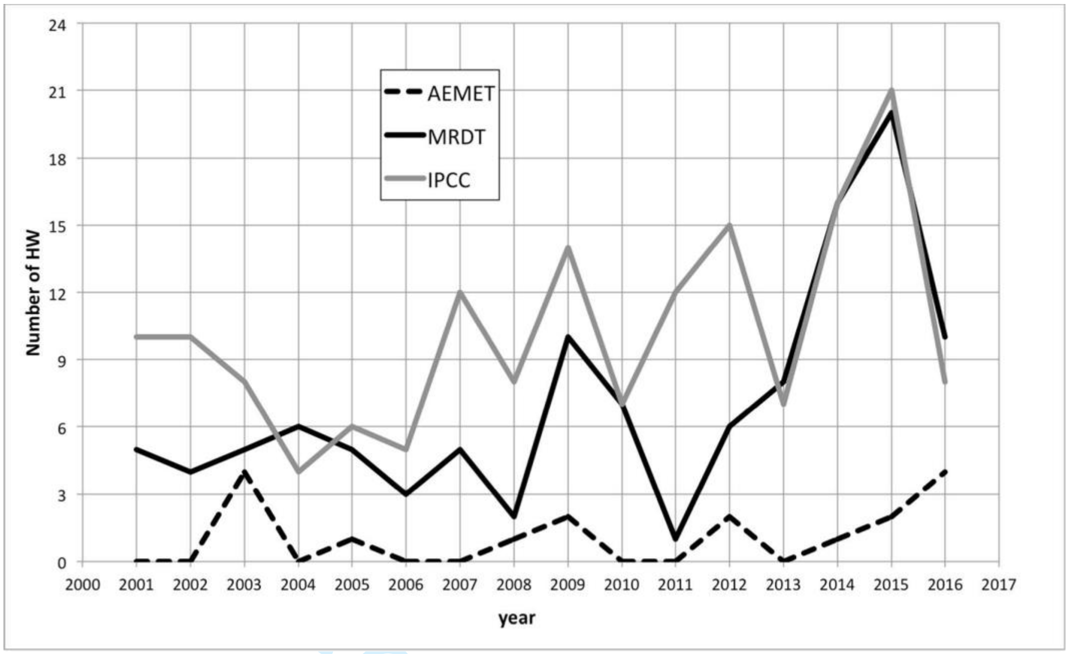


Figure 2. Number of HWs per year, under different definitions.

Figure 3. Aggregate number of HWs in different months, under different definitions.

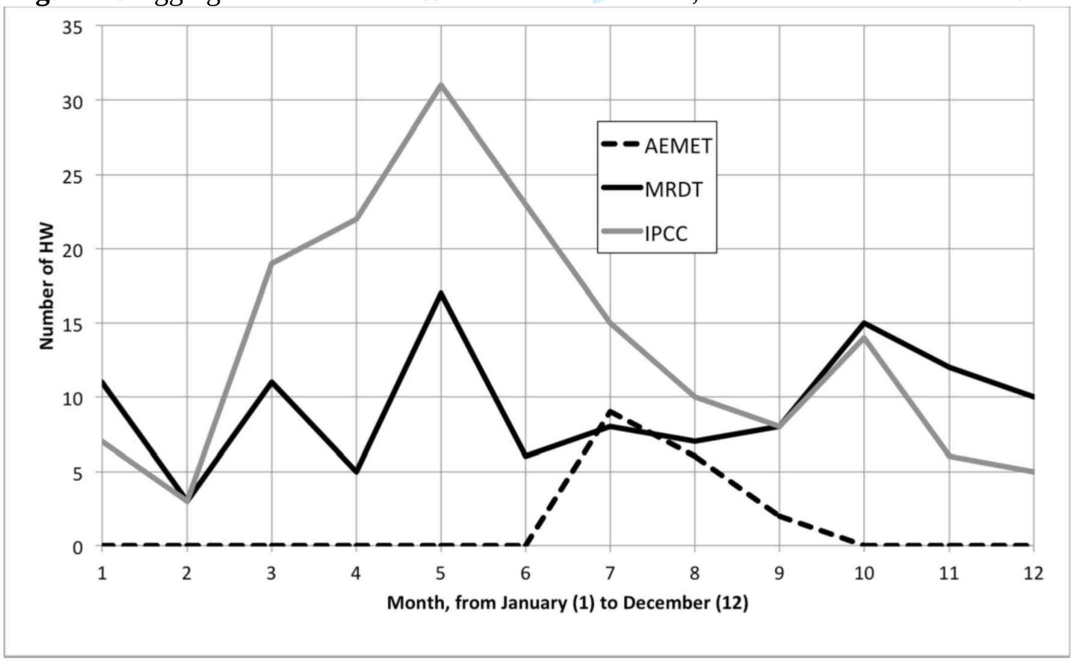


Figure 4. Daily thresholds for a HW in 2016 at Algarrobo, under different definitions

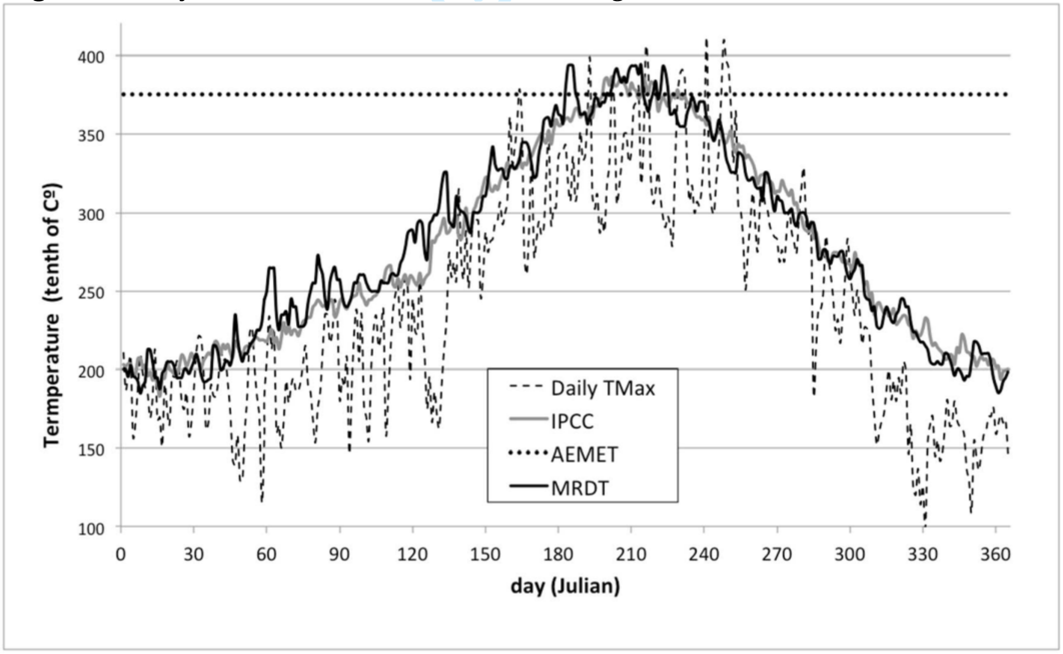


Figure 5. Thresholds for a HW at the Malaga observatory on 19 May, under different definitions.

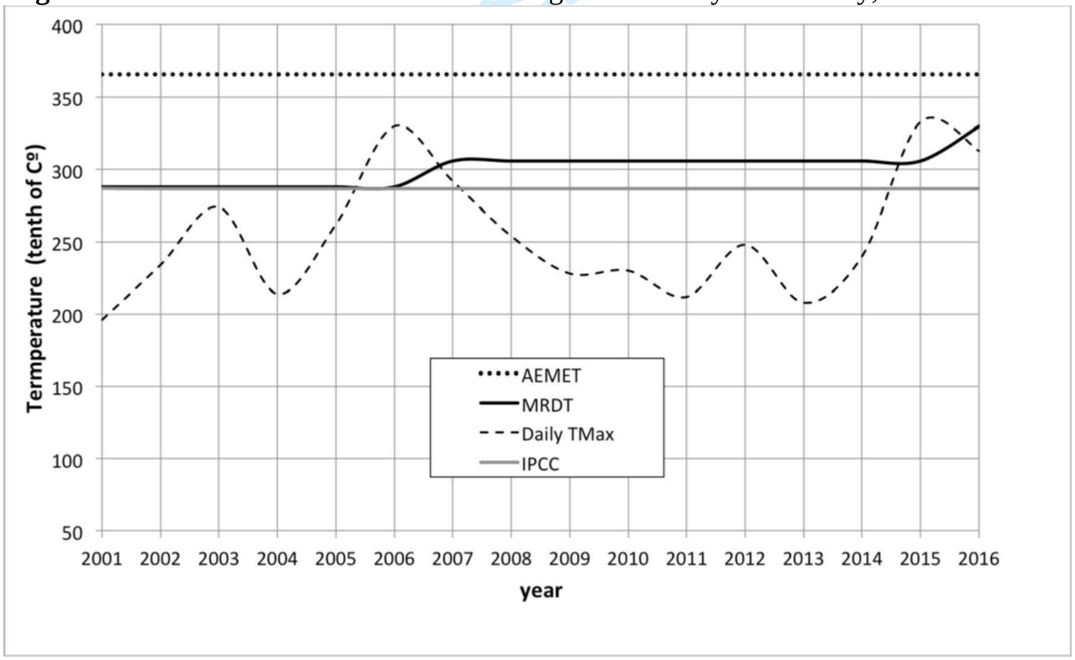
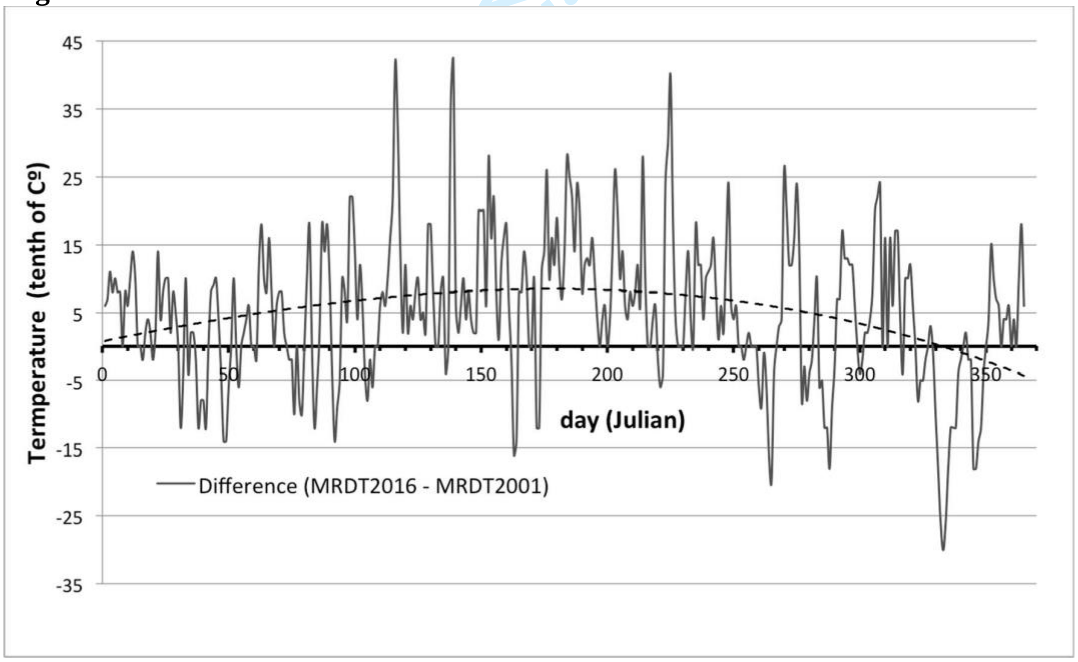


Figure 6. Difference between the MRDT thresholds in 2001 and 2016.



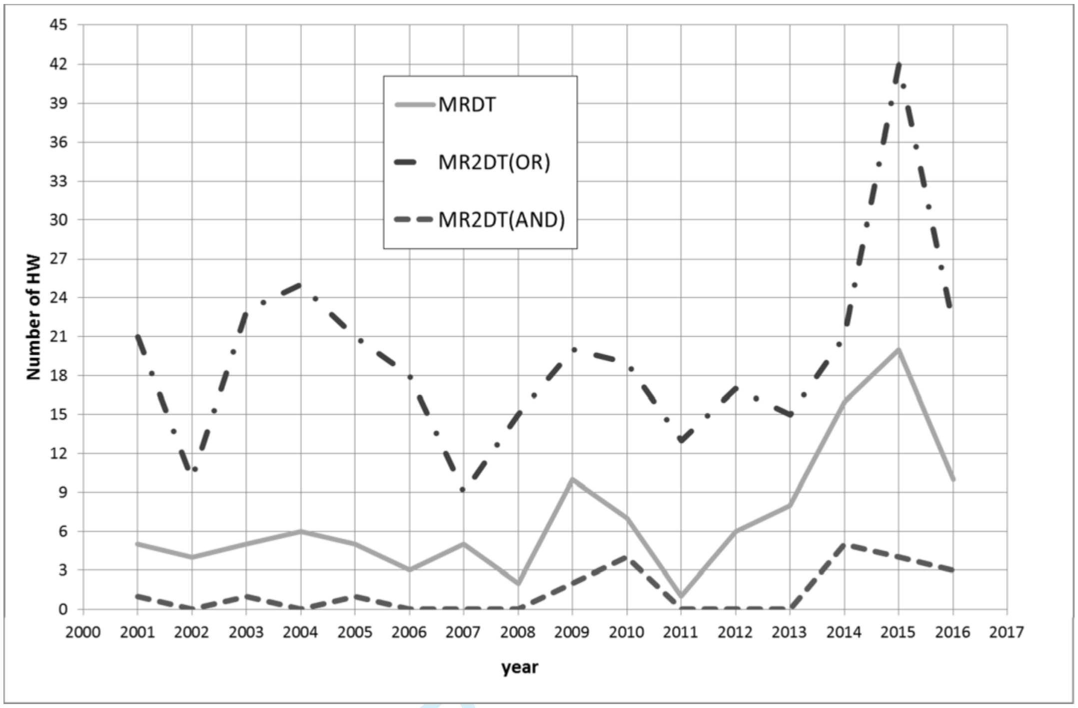


Figure 7. Number of HWs per year, based on the MRDT, MR2DT (OR) and MR2DT (AND) definitions.

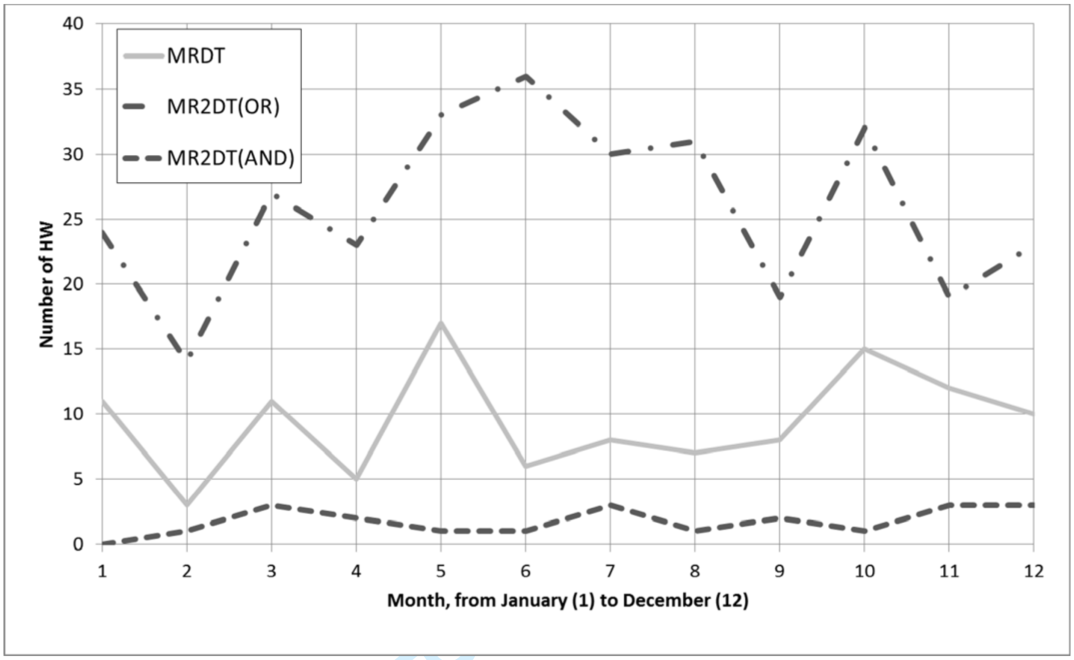


Figure 8. Aggregate number of HWs in different months, under MRDT, MR2DT (OR) and MR2DT (AND) definitions.

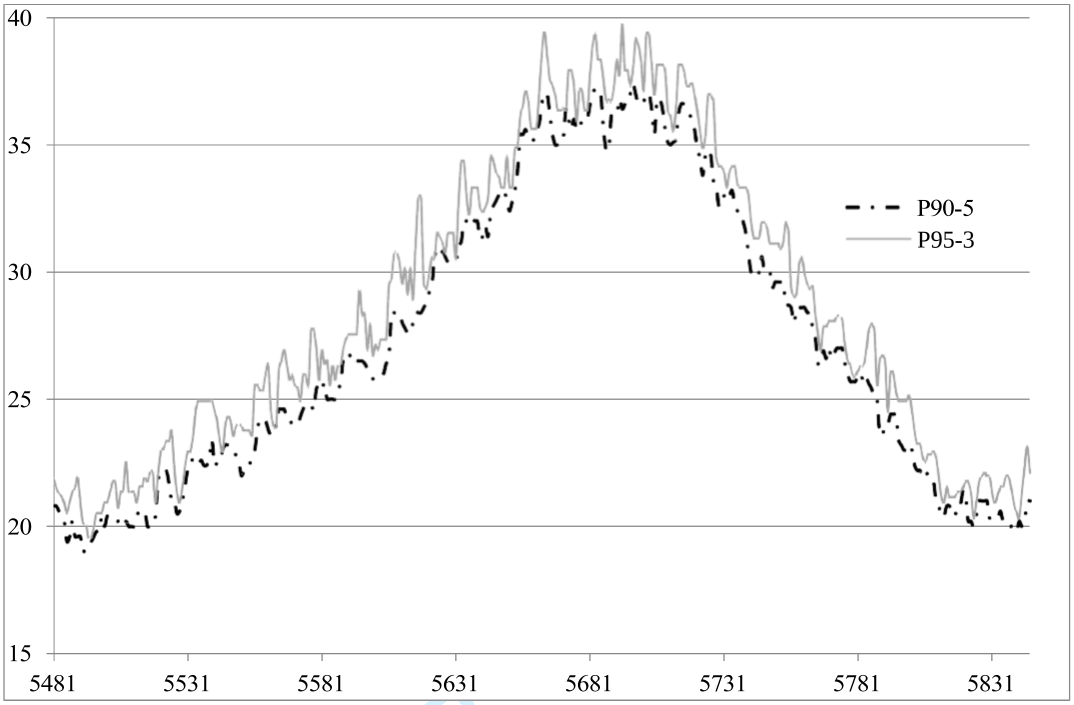


Figure A1. Daily thresholds under the different alternatives in observatory 21 for 2016.

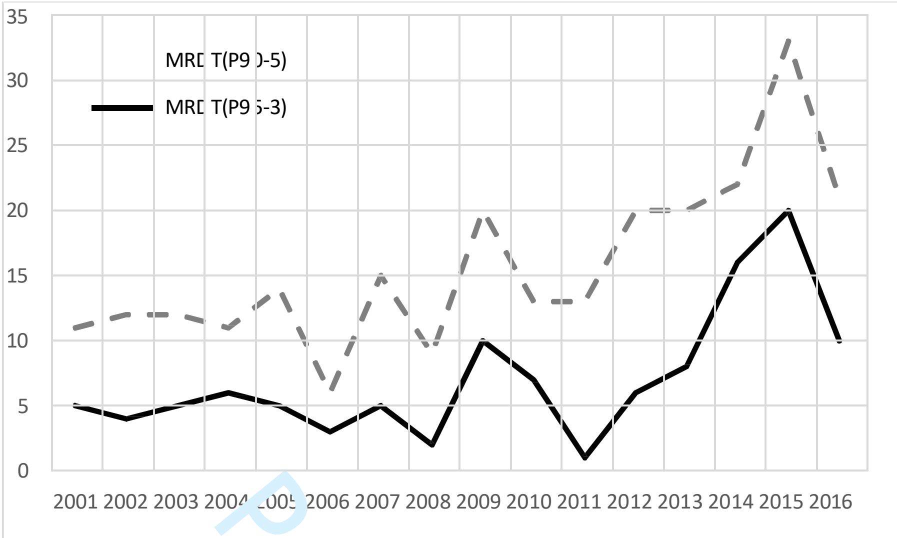


Figure A2. Evolution of the frequency of HWs by year under MRDT(P95-3) and MRDT(P90-5).

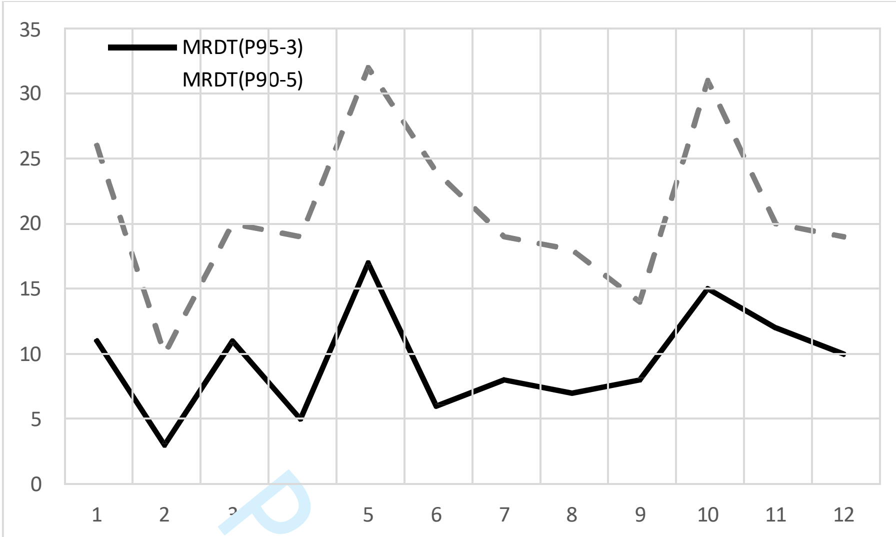


Figure A3. Evolution of the frequency of HWs by month (aggregated data for the period 2001-2016)

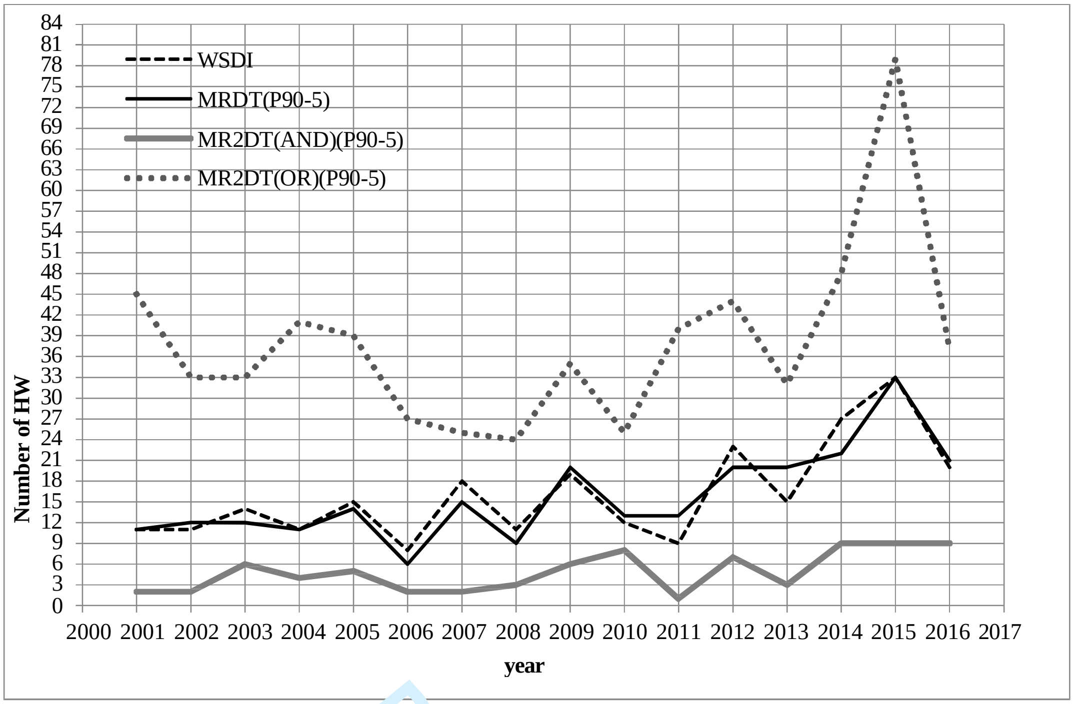


Figure A4. Evolution of the frequency of HWs by year under alternative definitions

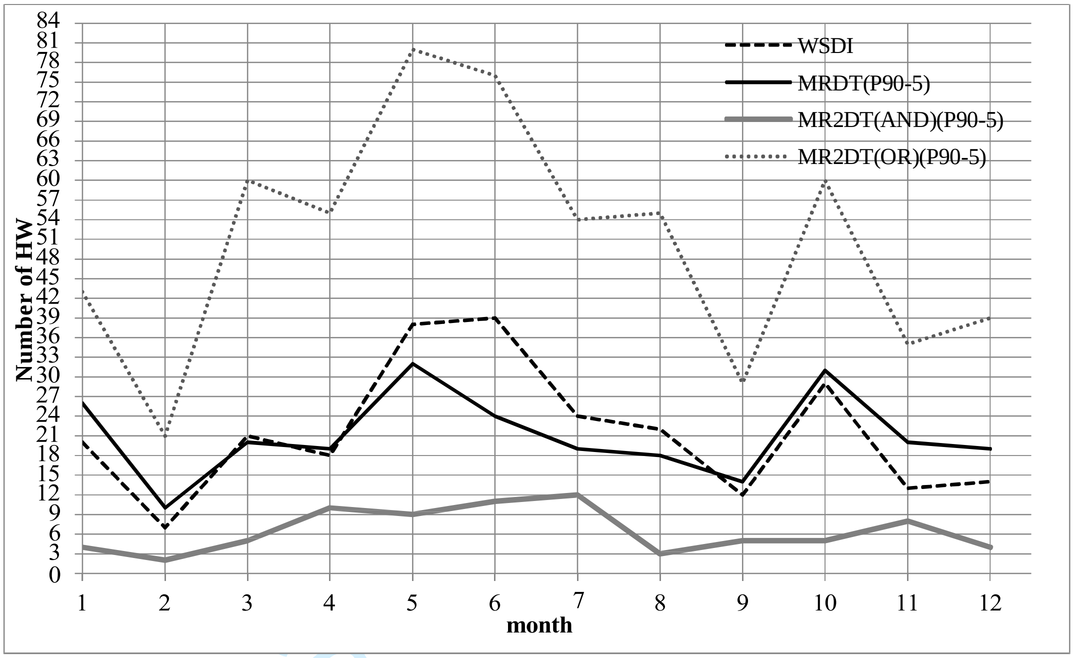


Figure A5. Evolution of the frequency of HWs by month (aggregated data for the period 2001-2016)

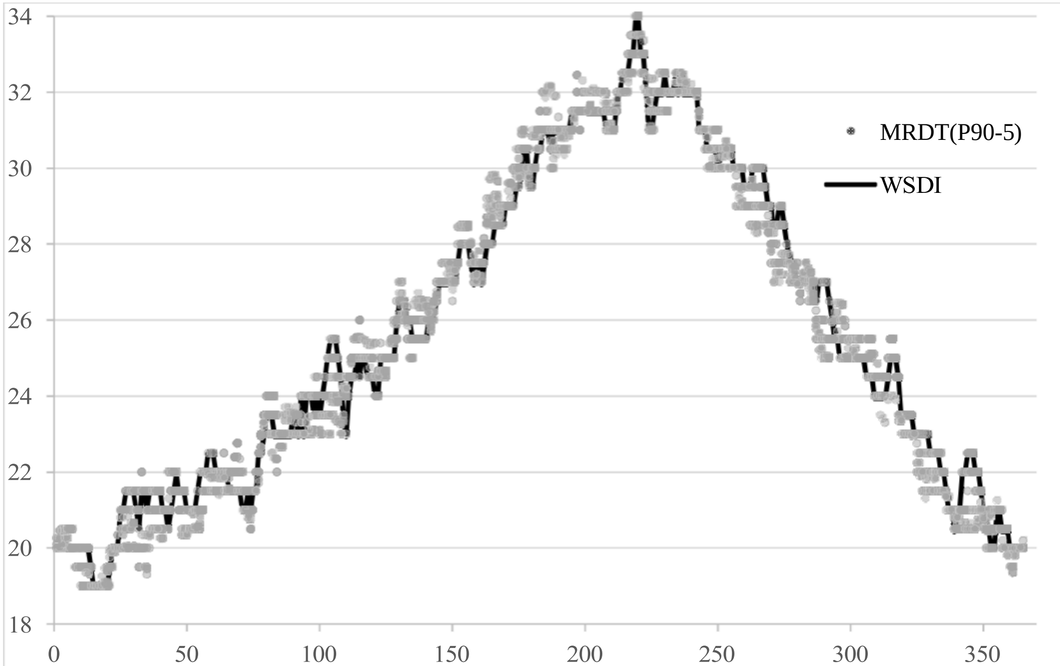


Figure A6. Daily thresholds for WSDI and MRDT(P90-5) during the period 2001-2016