


Review

Review of Biometeorology of Heatwaves and Warm Extremes in Europe

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Abstract: Numerous extreme heatwaves producing large impacts on human health, agriculture, water resources, energy demand, regional economies, and forest ecosystems occurred during the first twenty years of the 21st century. The present study strives to provide a systematic review of recent studies of warm biometeorological extremes in Europe. The main aim of this paper is to provide a methodical summary of the observed changes in warm extremes, duration, and variability in different parts of Europe. During the last decade, much attention has been paid to the negative impacts of heat and humidity on human health. Therefore, the human biometeorology is required to appraise the human thermal environment in a way that human thermoregulation is taken into account. In many European countries and regions, future heat exposure will indeed exceed critical levels, and a steep increase in biometeorological heatwaves and warm extremes are expected. The indices that take into account human energy balance along with weather conditions should be used to examine the impacts of extreme heatwaves on human health and should be used as a basis for the determination of acclimatization to high-heat-stress conditions. A detailed description of recent studies that have used biometeorological indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) for the estimation of warm extremes and their influence on human health is provided. Additionally, a short overview of the existence of the heat-health warning systems (HHWS), their conceptualization, and implementation across the European continent is considered, as well as the possibilities for further investigations and implementation of effective measures and programs that could reduce the adverse health impacts.

Keywords: heat stress; biometeorological indices; heatwaves; HHWS; Europe

1. Introduction

During the last 20 years, the magnitude and impact of heatwaves in Europe have increased substantially, thus raising concerns not only in the European continent but worldwide. Many studies have emphasized how important is the understanding of present changes, along with the prediction of future occurrences. The first twenty years of the 21st century have witnessed numerous extreme heatwaves producing large impacts on human health, agriculture, water resources, energy demand, regional economies, and forest ecosystems [1–3]. Heatwaves have devastating impacts on different systems and the first one to think of is the impact on human health. For example, during the most

intensive heatwaves of 2003 over Western Europe and 2010 over Russia more than 100,000 people died [4,5]. During these periods, 500 year long temperature records were broken over roughly 50% of European territory [6,7]. During the heatwave in 2003, France, Germany, Switzerland, Portugal, and the UK experienced the highest daily maximum temperatures [8–14]. In general, the recorded temperature anomalies were as high as 8 °C compared to the base period 1961–1990 [4].

Another heatwave hit Southeastern Europe, the Balkan Peninsula, and also part of Asia Minor in summer 2007 [15–18]. The extraordinary warm conditions were the primary cause for numerous excess deaths in several countries (Hungary, Romania, Bulgaria, Serbia, etc.) and caused problems in energy supply [17]. The 2010 Russian heatwave, due to its intensity, spatial extent, and duration was named mega-heatwave [1,19]. The heatwave persisted for more than 30 days, and 54,000 people died from heat exposure. The comparison between heatwaves in 2003 and 2010 showed that the latter was more extreme due to high-temperature anomalies as well as the area affected. The summer temperatures in 2010 were on average higher for 0.2 °C in Europe than in 2003. The area affected by extreme conditions was estimated to be larger than two million km², and the extreme temperatures lasted between 15- and 61-day averages [19]. The heatwave in August 2015 in Poland was characterized as a mega-heatwave, and it was defined as an event with at least 6 consecutive days when maximum air temperatures are above 30 °C with no more than 1 day declining below the established threshold from the beginning until the end of the extreme event. The authors stated that during the last 50 years, the frequency of mega-heatwaves is increasing [20,21].

Heatwaves have been given the name the “silent killers” [22] since they do not have an instantaneous effect on human health. Primary medical conditions are worsened when people are exposed to heatwaves for a longer period. Thus, these extreme weather conditions mainly affect the elderly, the young, and those that work outside. As it gets older the body’s hydration and temperature regulations are at high risk of not working properly. Additionally, young children and infants cannot articulate when they feel hot or thirsty so they do need special attention during hot weather. Similarly, some diseases lead to the body’s inability to cope with extreme heat, such as heart disease, diabetes, renal disease, and multiple sclerosis. Consequently, in these conditions, the body is disabled to function as it should and the body core temperature continues to rise. Sweating as a primal cooling mechanism cannot cool down the body and the risk of heatstroke—a serious medical condition that can result in organ failure and even death becomes incredibly high [22,23].

Since the human body can respond to environmental conditions and acclimatize to them, it is necessary to evaluate certain extreme events related to human sensation. Consequently, a complex approach to assessing an extreme climate event such as a heatwave must include a combination of weather elements that are related to the human sensation of heat [23–25]. In the present literature, there is a myriad of biometeorological indices [26,27] as well as the methods used to estimate the severity and intensity of individual extreme weather events [28]. As pointed out by Russo et al. [1], some heatwave indices use a fixed threshold of 5 °C above climatology, while others are based on a percentile-based threshold (Warm Spell Duration Index, Heat Wave Magnitude Index daily). For biometeorological heatwaves, some authors (e.g., [29]) used a fixed threshold of 35 °C for Physiological Equivalent Temperature (PET), while others (e.g., [25,30]) used percentile-based thresholds and applied the methodology of the Expert Team on Climate Change Detection and Indices (ETCCDI). Even though there is a necessity for using a unique index in studying the biometeorology of heatwaves, the methods for their identification and a unique definition are lacking. However, the common ground for all of them is that they are prolonged periods where temperatures are greatly higher than the previously defined normal. Modern studies employ the methods where the heatwave is defined as a prolonged event of more than three consecutive days, when air temperature exceeds a particular threshold. The most common threshold is above the upper tail of temperature distribution (90th or 95th percentile). The advantage of using a relative-based threshold over fixed ones is in the fact that their identification and measurements are possible across every location [28].

For biometeorological studies of heatwaves, it is of great importance to use a consistent framework for their identification and measuring as well as to use a biometeorological index that will be capable of best describing the human sensation of heat. Hence, the scientific community needs to work together to reach a consensus to diminish the overabundance of methods and indices used, plus to balance them with many sectors affected.

In this review, the current state of the scientific literature about bioclimatology of heatwaves is given. The following sections are themed around: application of biometeorological indices in a heatwave and studies of warm extremes in Europe; the short review of heat health warning systems in Europe, and ascertaining the possible adaptation to observed changes.

2. Application of Biometeorological Indices in Heatwave Studies in Europe

For more than 100 years, scientists have tried to develop thermal climate indices that will be able to tackle the complex problem of body-atmosphere heat exchange [26,27]. According to Parsons [31], thermal stress indices are divided into three categories based on their underlying principle. Indices based on heat balance equations are called rational indices and the calculations involve the heat balance equations. The second group is empirical indices, which are based on establishing equations from the physiological responses of human subjects. The third group of indices is direct indices that are based on direct measurements.

The indices from all three categories have been used to identify and measure heatwaves but only the widely used will be discussed further.

During the last decade, much attention has been paid to the negative impacts of heat and humidity on human health. The effect of so-called humid heatwaves is seen to extend beyond direct health outcomes to include large-scale economic impacts [19,24,32]. High relative humidity even with air temperatures lower than the optimum body core temperature (the human body will strive to keep a core temperature of about 37.5 °C) could lead to heat stress. When relative humidity increases, the temperatures do not need to be very high to induce heat stress and lead to mortality events [33]. Thus, some indices that take both temperature and humidity into consideration have recently been used to characterize and study heatwaves. The widely used are HUMIDEX, an index that combines air temperature and water vapor pressure [34,35], the Heat Index (HI) [24] Apparent Temperature (AT) [19,36], and Wet-Bulb Globe Temperature (WBGT) [23,37,38] and just recently Wet Bulb Temperature [24].

It has to be noted that previous works on environmental heat stress were developed with a global perspective [23,24,37,39–41] mainly focusing on densely populated areas (e.g., South-East Asia, Africa), but the detailed impact studies in Europe are scarce. Generally, the trends in heat humidity indices show a steeper increase than the air temperature and significant increases in the number of threshold exceedances over the latter half of the twentieth century [39,42]. Quantifying thermal comfort in 15 different regions around the world using WBGT, Willett and Sherwood [37] showed that positive historical trends (1973–2003) are present. Over the last four decades, WBGT increased along with the temperature. The model they presented indicates the increase in WBGT in all investigated regions except Southern Australia. For Europe, they showed that under the A1B scenario, both the temperature and WBGT will significantly increase leading to more pronounced heat extremes. Similarly, Casanueva et al. [43,44] indicated that heat stress levels shown with WBGT will amplify occupational risks in Europe in the future. They showed that daily summer maximum WBGT will increase by 1 to 4 °C by the end of the twenty-first century concerning the historical reference period. Additionally, changes in WBGT values across Europe will be more uniform than changes in air temperatures, but the increase in WBGT in Southern Europe and the Mediterranean will be less pronounced since the changes in relative humidity (RH) are projected to decrease. The overall conclusion of the study is that in the future the regions in Europe most affected by the changes in WBGT will be the ones that already have the same problems [44].

In addition to WBGT, recent studies employed standard wet bulb temperature (T_w) to characterize the dangerous combination of high temperature and humidity. The studies showed that even with wet-bulb temperatures between 29 and 31 °C during heatwaves, tens of thousands of deaths occur [40]. Additionally, physical labor becomes dangerous when the wet-bulb temperature reaches values above 35 °C, because when the body cannot be cooled by evapotranspiration and it accumulates heat. Thus, the value of 35 °C is considered to be the upper threshold of human tolerance to heat [38,40,45]. Mega heatwaves of 2003 and 2010 in Europe and Russia produced wet-bulb temperatures of approximately 28 °C [23]. Wet-bulb temperatures above 30 °C have been reported in scientific studies only several times although not in Europe but in Eastern Coastal India, Pakistan and Northwestern India, and the shores of the Red Sea, Gulf of California, and Southern Gulf of Mexico [23,46]. Generally, even under present global atmospheric conditions, high temperatures along with high humidity caused the death of many people in the 2015 heatwaves in India and Pakistan. It was estimated that more than 2500 excess deaths happen during the Indian heatwave with at least 700 in the megacity of Karachi and plenty more throughout the country [47]. Russo et al. [19] introduced the category of humid heatwaves and defined it as a heatwave with at least one of its days with Apparent Temperature (AT) higher than maximum daily temperatures. They used the newly developed Apparent Heat Wave Index (AHWI), calculated equivalently to the Heat Wave Magnitude Index daily (HWMId) [19]. The quantified humid heatwave showed that its magnitude and peak temperature have been amplified by higher relative humidity. Relative humidity has greatly augmented the heatwave magnitudes in some key regions during the last 40 years, such as the Midwestern and Eastern US, China, Northern Latin America, and Malaysia. The occurrence of dangerously intensive humid heatwaves is concentrated mainly in the regions where hot and humid air is being advected from surrounding water bodies such as tropical regions [19]. The apparent temperatures during most intensive heatwaves in Europe in 2003 and 2010 did not differ significantly from maximum air temperatures, and those heatwaves were not considered humid, such as the one that occurred in Shanghai in 2003 where high relative humidity played an important role in aggravating the negative impacts of the heatwave. Russo et al. [19] carried on their analysis and discussed the future occurrence of humid heatwaves. They concluded that at 1.5 °C and 2 °C global warming, the magnitude of humid heatwaves in densely populated areas is going to reach the levels higher than during the mega heatwave in Russia in 2010. Furthermore, the AHWI magnitude is going to be much higher than today's maximum value, with the highest AT reaching the levels beyond 55 °C, at least once in two years at 4 °C global warming.

The number of global studies of heatwaves in light of combined temperature and humidity is rising, but it is interesting to note that many studies are dealing with local or regional heatwaves from a biometeorological point of view. Evaluation of the extreme heatwave of 2003 in Naples (Southern Italy) was obtained using a HI. Historical discomfort conditions that affected the city from 1872 up to 2004 were evaluated using hourly meteorological data. The secular variation of HI over Naples during the 1872–2004 interval does not show any significant trend as well as the occurrence of extreme heatwaves, such as those recorded in 1950 and 2003. HI values in the city of Naples (Southern Italy) showed prolonged heat discomfort conditions during the second half of June 2003 and from the second half of July 2003 up to the first week of September 2003, resulting in the highest mortality rate for persons aged 75 years or more. During the 2003 summer, the heat stress was persistent even during the night [48].

Similarly, Unal et al. [49] used AT to define the heatwaves for the summer months (June–August) of 1965–2006 in Western Turkey. The numbers of hot days, heatwaves, and heatwave duration have increased during the observed period in the western part of Turkey. After 1998, the changes in extremes were more frequently observed, and the rate of change was larger during the last decade of the observed period. Analysis of regional distributions indicated a rising tendency of the number of heatwave events towards the southern latitudes.

The extreme heatwaves of 2003 and 2015 were analyzed for South-West Germany (Baden-Württemberg) using HUMIDEX. The study showed that even though the 2003 heatwave was longer and had higher maximum and minimum temperatures, the 2015 heatwave was amplified by higher air

humidity during day and night. The negative effects of these events were observed in higher excess summer mortality than the reference period 1971–2000. Additionally, regional climate models were used to investigate the future occurrences of heatwaves with similar characteristics as the ones in 2003 and 2015. The analysis showed that, under RCP4.5, even in the near future (2021–2050), a 2015-like heatwave is likely to occur about every other summer. Furthermore, for the far future (2070–2099), a distinct increase in heatwaves similar to 2015 is possible, with more than two per summer [35].

Using HUMIDEX to evaluate thermal conditions during four exceptionally hot summers in large cities in 1992, 1994, 2006, and 2010 and comparing them to mortality data concluded that excess mortality was elevated. In the investigated sites, on the hottest days the number of deaths was more than three times higher than for the reference period. The conclusions pointed out the dangers of excess mortality in warming climate [50].

Parsons [31] emphasized that six parameters for thermal stress estimation must be taken into account. They include thermal climate factors consisting of air temperature, humidity, air velocity, and heat radiation, and two individual factors that are comprised of metabolic rate and clothing. Thus, the human biometeorology is required to appraise the human thermal environment in a way that human thermoregulation is taken into account. Thus, in this way, it will produce and use the indices intimately connected to human thermal perception, stress, and strain. Therefore, the thermoregulatory models, as a mathematical representation of the human thermoregulation system, are required and biometeorological indices based on those models are essential for estimating the human thermal environment and stress. Staiger et al. [51] suggested the use of the Universal Thermal Climate Index (UTCI), Perceived Temperature (PT), Physiological Equivalent Temperature (PET), and Effective Temperature (ET). These indices should be used to examine the impacts of extreme heatwaves on human health and should be used as a basis for the determination of acclimatization to high-heat-stress conditions. Moreover, the indices should be recommended for use in future heat-health warning systems (HHWS) as well as for the improvement of present systems across Europe.

2.1. Universal Thermal Climate Index

Universal Thermal Climate Index (UTCI), developed by the European Cooperation in Science and Technology (COST) European Cooperation in Scientific and Technical Research (COST 730), represents an index based on human response-related thermo-physiological modelling with the help of a multisegmental, multilayered representation of the human body [52,53]. This model was coupled with a state-of-the-art clothing model that takes into consideration the behavioral adaptation of clothing insulation by the general urban population in response to actual environmental temperature. UTCI was derived conceptually as an equivalent temperature implying that for any combination of air temperature, wind, radiation, and humidity (stress), this index can be defined as the isothermal air temperature of the reference condition that would elicit the same dynamic response (strain) of the physiological model [54,55]. This approach is useful for predicting human thermal and regulatory responses in cold, cool, neutral, warm, and hot environments [52,53]. UTCI can be quantified using software such as RayMan and BioKlima [56]. The UTCI uses limit values to categorized thermal stress that ranges from “extreme cold stress” to “extreme heat stress” (Table 1) [57].

A study of global forecasts of the UTCI provided an overview of health hazards related to extremely high temperatures [58]. Predicting thermal hazards using UTCI is essential for developing international HHWS and disaster preparedness. The applicability of the index for such purposes was shown to be superior since the UTCI forecast could usefully predict the values for lead times up to 10 days [58]. The application of the UTCI to bioclimate research at a European scale was presented by Błażejczyk et al. [59]. The paper presents thermo-physiological principles of UTCI through some examples of its application to assess bioclimatic differentiation of Europe. A wide range of potential applications was identified. Analysis of mean monthly values of UTCI for January and July in selected European cities indicated that in both compared months the highest UTCI was observed for Athens (Greece) and Valencia (Spain), while in Scandinavian cities (Stockholm and Helsinki) the UTCI had

the lowest values. Low values were also noted for Łódź (Poland) and London (UK). During summer, strong heat stress was very frequently observed not only in the Mediterranean region but also in Budapest, with exceptions such as Ljubljana and Barcelona. In the Scandinavian cities and the cities under the frequent influence of maritime climate, the weak presence of strong heat stress was noted. During winter, the influence of the arctic air masses is manifested by the frequent occurrence of strong cold stress over Northern and Central Europe.

Table 1. Universal Thermal Climate Index (UTCI) Assessment Scale: UTCI is categorized in terms of thermal stress [57].

UTCI (°C)	Physiological Stress Level
<−40.1	Extreme cold stress
−40.0−−27.1	Very strong cold stress
−27.0−−13.1	Strong cold stress
−13.0−0.0	Moderate cold stress
0.1−9.0	Slight cold stress
9.1−26.0	No thermal stress
26.1−32.0	Moderate heat stress
32.1−38.0	Strong heat stress
38.1−46.0	Very strong heat stress
>46.1	Extreme heat stress

Jendritzky et al. [55] emphasized the necessity of the application of the UTCI thermal index in bioclimate studies. As highlighted by the authors, the application of the UTCI is intended to significantly enhance applications related to human health and wellbeing in the fields of public weather services, public health systems, precautionary planning, and climate impact research. Additionally, respective authors pointed out that utilization of the UTCI in the major fields of human biometeorology is highly applicable and of great importance, thus making the index more comparable and physiologically relevant.

In Europe, there is an evident latitudinal gradient in heat stress occurrences during summer months, and the UTCI values generally raise towards the south. This pattern, according to Di Napoli et al. [60], reveals the general connection between heat load and insolation. The application of UTCI for evaluation of heat stress and its effects on mortality was employed in numerous European countries [61–66]. However, the study on the pan European scale indicated that during the days with high UTCI values equivalent to a high degree of heat stress, the number of deaths and emergency patients increased. Additionally, the study of Di Napoli et al. [60] on the spatial extent of UTCI on the pan-European level revealed that there has been an increase in heat stress of 1 °C during the last 30 years. When they correlated the values of UTCI with mortality data, they observed that the number of deaths increased when UTCI values were higher than 26 and 32 °C.

2.1.1. Southern and Southeastern Europe

Nastos and Matzarakis [61] evaluated the grade of physiological stress and quantified the association between the daily mortality and daily values of the UTCI for the Athens region for the 10 years 1992–2001. The study revealed that mortality is in close relation to air temperature and UTCI. Additionally, statistically significant relationships on a given level ($p < 0.01$) are present between air temperature, UTCI, and mortality.

Assessment of bioclimatic conditions on Crete Island in Greece (Southern Europe) over 30 years (1975–2004) indicated that the estimated UTCI thermal comfort class presents higher frequencies and duration throughout the year compared to the respective PET classes, especially during the cold months. The UTCI values of extreme/very strong/strong cold stress and very strong heat stress were not observed for the majority of the analyzed stations excluding southern coastal stations, and displayed increasing and decreasing trends of strong heat stress, respectively. The UTCI values of extreme/very strong/strong cold stress and very strong heat stress (missing for the majority of the examined stations with the exceptions) showed increasing and decreasing trends of strong heat stress. In the region of

Crete Island, the time series of the annual number of days with mean daily extreme values of UTCI, as well as PET, did not present clear increasing or decreasing trends during the observed period [62].

The Eastern Mediterranean climate “hot spot” was investigated concerning heat-related risk and change in heat stress levels by Katavoutas and Founda [67]. They used the index that quantifies both the intensity and duration of the heatwave event and realized that during a nearly 60-year period, a total of 46 heatwaves occurred. The number of heat events was intensified after the late 1990s. Using the UTCI and HUMIDEX, it was observed that there was at least one thermal stress category between the extreme event and normal summer conditions. The striking results are connected to night-time heat stress conditions in urban areas that were strongly enhanced during pronounced heatwave episodes.

A different study by the same authors [68] that used simple (HI and HUMIDEX) and rational indices (PET, UTCI) revealed that heat stress conditions have become more intense during the last two decades. The 95th percentile of UTCI in the large urban area of the Eastern Mediterranean (Athens) was enlarged by 2.4 °C in the 2010s compared to the 1970s, which indicates the existence of extreme heat stress. The extreme values of UTCI indicate a steep growth of the very strong heat stress season by 4.3 days/decade. Additionally, exposure times per year when very strong heat stress conditions prevail are increasing by 0.3% per decade. For the last ten years, during night-time, the urban population has been exposed to significantly higher heat stress than in previous periods. The results point out that urban residents are under a noteworthy and increasing amount of heat stress.

Morabito et al. [69] identified the most effective thermal predictors of heat-related very-elderly mortality (people ≥ 75 years) for two cities located in different geographical contexts of central Italy. Direct multivariate indices showed the highest correlations with the UTCI and were identified as the best thermal predictors of heat-related mortality for both inland (Florence) and coastal (Livorno) cities. Thus, the UTCI was never identified as the best thermal predictor for the given case studies. Authors outlined that the use of direct multivariate indices (multivariate apparent temperature), which also account for the extra effect of wind speed and/or solar radiation, displayed the best fitting with all-cause, very-elderly mortality attributable to heat stress.

Even though heatwaves in 2003 and 2010 draw much attention to Western Europe and Russia, it is noteworthy to mention the particularly intensive heatwave of 2007 in South-East Europe. Pecelj et al. [70] noted that UTCI values at 14 h were as high as 48.4 °C in Novi Sad (Northern Serbia). The authors stated that due to the changes in air temperatures and the frequency of occurrence of extreme heatwave events, it can be expected that such high values of UTCI are likely to occur in the future.

2.1.2. Central and Western Europe

Assessment of urban thermal stress by UTCI in Poland was performed by Blazejczyk et al. [71]. A new approach to the study of the spatial variability of heat stress in urban areas was presented with the utilization of the UTCI. The spatial variability of UTCI at the local scale was studied using examples of urban areas in Warsaw with different sizes and geographical locations. A very high and significant heat stress gradient between downtown Warsaw and rural stations was observed.

Variability of human-biometeorological conditions in Gdańsk (Poland) was presented by Nidzgorska-Lencewicz [72]. The respective author investigated the characterization of temporal and spatial variability of thermal and air quality conditions within the area of Gdańsk with the use of UTCI and Common Air Quality Index (CAQI). Annually, the two UTCI classes that occur most often are no thermal stress and moderate cold stress. Comfortable and favorable thermal conditions of the city were observed during the warm half of the year (April–September). During the cold half of the year, cold stress was pronounced from October–March.

The analysis of UTCI variations for the 2015 and 2018 summer period was investigated and compared with the reference period of 1971–2018 for the region of Lower Silesia (Poland). During the most extreme heat events, the lowlands and the lower mountain zones experienced the highest heat stress classes, while in the highlands, “no thermal stress” classes existed [73].

Tomczyk and Owczarek [74] conducted a contemporary analysis of the occurrence of extreme heat stress in Poland using UTCI. The UTCI values were calculated based on daily data for 40 meteorological stations for the period 1966–2015. They used the UTCI values above 32 °C to characterize the extreme stress of humans. It is interesting to note that a statistically significant increase of 50% of the analyzed stations was observed, while at the other 50%, the tendency of a rising or no changes was detected. A major part of Poland’s territory was affected by conditions very strenuous for the organism with UTCI values higher than 40 °C after 1990. Similar changes in extreme values of UTCI were observed in regional studies in Poland [75], but also in other European countries—e.g., Hungary [76] or Romania [77], Serbia [70].

Future changes in human-biometeorological index classes for three regions of Luxembourg (Western-Central Europe) were investigated by Lokys et al. [78]. Assessment of the impact of climate change on human thermal comfort over the next century was performed with the usage of two human-biometeorological indices, PET, and UTCI for the period 1971–2098. The data used are from a multimodel ensemble of 12 Regional Climate Models and single Regional Climate Models (RCM) run with a spatial resolution of 1.3 km. The results of the study pointed out that cold stress levels will decrease significantly in the near future up to 2050, while the increase in heat stress turns statistically significant in the far future up to 2100. The result indicates the presence of a temporarily reduced overall thermal stress level. On the other hand, further increasing air temperatures will shift the thermal comfort towards the heat stress category. Additionally, for the future period in Western Europe (case study Luxembourg), cold stress levels will decrease significantly in the near future up to 2050 as a result of a temporarily reduced overall thermal stress level and further increasing air temperatures.

2.2. Physiologically Equivalent Temperature (PET)

Physiologically equivalent temperature (PET) [79] is based on the energy balance equation between a human body and the environment, and it is derived from the Munich Energy-Balance Model for Individuals (MEMI) [79,80]. During the last 30 years, PET has been widely used to explore the impact of oppressive heat or cold conditions on human health. PET is defined as the air temperature equivalent at which an average person (male, 35 years; 1.75 m, 75 kg) that is indoors, not active (work activity 80 W, heat resistance of clothing $I_{clo} = 0.9$, mean radiant temperature equal to air temperature ($T_{mrt} = T$), velocity 0.1 m/s, water vapor pressure 12 hPa) would feel the same as in real conditions. It is worth mentioning that Matzarakis et al. [80,81] produced the RayMan software package which calculates mean radiant temperature, necessary for quantification of thermal indices such as Predicted Mean Vote (PMV), PET, and Standard Effective Temperature (SET) values for given locations (e.g., Heraklion, Crete; Freiburg, South-West Germany). The values of PET are graded as an index for showing thermal sensation felt by humans [82] (Table 2).

Table 2. Physiologically equivalent temperature (PET) for different grades of thermal sensation and physiological stress on human beings [82].

PET (°C)	Thermal Sensation	Physiological Stress Level
<4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
>41.1	Very hot	Extreme heat stress

2.2.1. Western and Central Europe

Matzarakis et al. [83] analyzed the differences between thermal comfort in the city center of Strasbourg, and its vicinity by using PET. During the heatwave of 2003, the Strasbourg residents

experienced warmer conditions compared to other years. The temperatures were not extreme and did not cause severe heat stress. For both city centers, and the rural surrounding PET values were higher during the summer of 2003. It was concluded that in order to progress in the knowledge of thermal stress and human comfort, there is an increasing need for use and development of thermal indices that could be used in urban and rural surroundings alike.

Recently, two approaches were developed [84] to estimate the increases in mortality due to heat stress, with and without long-term adaptation in Vienna, Austria. They described the heat stress using PET that was calculated using the variables from two regional climate models based on the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios A1B and B1. According to scenarios, no significant changes were predicted until 2011–2040 compared to 1970–2000. An expected heat-related mortality of up to 129% would be reached in the following decades if the adaptation were absent. Still, with the long-term adaptation, the increase would be notable but not so pronounced.

Two complex approaches were used to assess the relationship between heat stress and mortality in the federal state of Vienna (Austria) in the period 1970–2007. The results revealed a significant impact of heat stress on human health, where the study pointed out that significantly higher sensitivity was observed for women compared to men. Over 38 years, some significant decreases in the sensitivity were observed, especially in the medium heat stress levels indicating active processes of long-term adaptation to the increasing heat stress [85].

For Freiburg (Germany), Matzarakis and Endler [86] evaluated recent thermal bioclimatic conditions as well as future ones using the A1B and B1 scenarios. It was stated that according to future climate scenarios, the days with extreme heat stress ($PET > 35\text{ }^{\circ}\text{C}$) will occur more frequently in the order of 5% (from 9.2% based on the reference period 1961–1990). It was also shown that the changes in reduction in heat stress would be much greater if the radiation fluxes were modified. This modification could be achieved by planting specific and relevant vegetation types that produce shade in summer and allow short wave radiation to reach the surface or the areas where humans spend their time in winter.

Matzarakis et al. [87] presented information on thermal comfort/stress conditions, as well as aesthetical and physical parameters for tourism climate potential in Western Europe (case study Luxembourg). The paper emphasized that most important bioclimate influences are connected with extreme events, indicating that in the future heat stress and sultriness will increase, while cold stress will experience a decrease in this part of Europe.

Junk et al. [88] analyzed the past and future changes in health-related meteorological variables across Luxembourg. The performed analysis indicated the presence of trends in the thermal index PET in the investigated area. The study pointed out that the number of frost days is declining by more than 40 days between the reference period (1961–1990) and the last decade of this century. Tropical nights which did not occur in the reference period rose to 11 events for the same time-span. The analysis revealed that PET values have a significant shift towards higher thermal stress levels for Luxembourg. It was found that the frequency, duration, and intensity of cold events will most probably decrease in a warming climate.

2.2.2. Northern Europe

The generalized additive models were used to examine the association of relative mortality to PET and air temperature in Finland (Northern Europe). Results indicated that during the two 21-year long sub-periods (1972–1992 and 1994–2014) relative mortality increased more in the hot than in the cold part of the thermal distribution. Among people aged 75 years and older, the increase was stronger, but it also had a positive tendency among individuals younger than 65 years. It was highlighted that the causality between relative mortality and cold extremes was negligible with the exception of individuals aged ≥ 75 years, during 1994–2014 [89].

2.2.3. Southern and Southeastern Europe

Matzarakis and Nastos [29] used the values of daily PET as well as the daily minimum air temperature to characterize heatwaves in Athens. The two parameters were used to emphasize the thermal stress during the day, but also the night-time discomfort. The results of the study indicated that there is an increase in the average duration of heatwaves throughout the investigated period 1955–2001. Furthermore, the acclimatization approach that was used to evaluate human adaptation to extreme thermal conditions showed that this method is better at estimating the heat stress and it could be used in urban planning measures as well as Urban Heat Island Reduction, especially during night-time.

In the study of Nastos and Matzarakis [61], the authors evaluated the grade of physiological stress and quantified the association between the daily mortality and daily values of PET for the wider region of Athens for the 10 years 1992–2001. Results obtained from this study indicated that the mortality was in close relation to the air temperature and PET, emphasizing those statistically significant relationships between air temperature, PET, and mortality exist on the same day.

Similarly to UTCI, Katavoutas and Founda [67] showed, using PET, that the Athens population has been exposed to a significant, increased risk of heat stress since the 1960s, which has been maximized in the last two decades. It was concluded that inhabitants of Athens are under extreme heat stress (for PET at values of 0.4%/decade), and the exposure has increased along with the additional time per year with extreme warm conditions.

Bleta et al. [62] assessed and analyzed the human bioclimatic conditions of Crete Island by applying two human thermal indices—PET and UTCI. They calculated PET and UTCI values from daily meteorological data for the 1975–2004 period. The results showed that the daily extreme PET values increased, but they could not find statistically significant values.

When analyzing the evolution of heatwaves in Madrid (Spain) and their impacts on human thermal comfort, Rasilla et al. [90] indicated that there was an evident increase in frequency and duration after 1980. Their findings are in good correlation with similar studies of heatwaves in the Iberian Peninsula and the Mediterranean region [91,92]. The cause for the increase in PET values and resulting heatwaves was the increase in global temperatures. The diurnal and nocturnal PET variations were also investigated, and it was concluded that extreme heat stress during the day was exuberated due to the lack of cooling winds [90].

Zaninović and Matzarakis [93] analyzed the relationship between heatwaves and mortality in Croatia during the 26 years from 1983 to 2008. The study revealed that higher values were observed for the continental part of Croatia than in the coastal region due to the refreshing influence of the sea daily. Additionally, it was revealed that an increase in mortality in both cold and warm parts of the scale was present but with higher frequency during the warm part.

Similarly, Basarin et al. [25] analyzed extreme bioclimate events in Novi Sad (Vojvodina, Northern Serbia, Southeastern Europe) during the period 1949–2012. The results showed that the number of days with temperatures above-defined thresholds rose and so has the number of heatwaves per year since 1981. Based on the presented results, it was concluded that the average duration of warm spells is increasing.

The regional analysis of extreme PET values for Vojvodina (Northern Serbia, Southeastern Europe) was presented by Basarin et al. [30]. To gain a better insight into the impacts of climate change on biometeorological conditions, the extreme values of PET were calculated based on the indices developed by the joint Commission for Climatology/Climate and Ocean: Variability, Predictability and Change/Joint Technical Commission for Oceanography and Marine Meteorology (CCI/CLIVAR/JCOMM) Expert Team (ET) on Climate Change Detection and Indices (ETCCDI; [94]). These indices are objective measurement and characterization of climate variability and change. These indices were developed to detect climate extremes covering a wide range of climates. Eleven PET indices based on Climate Variability and Predictability (CLIVAR) were used, and their main focus is on biometeorological change detection. The indices were created for air temperature and precipitation but were adapted for PET [30]. The significant increase in the frequency of warm conditions along with a significant decrease in the cold conditions dominates the whole area. The more pronounced

and higher frequency of warm biometeorological extreme conditions is most likely the prevailing factor in the warming in Vojvodina. The results showed that heatwaves are becoming more frequent and longer-lasting for the whole area. The heatwave of 2007 was particularly intense (Figure 1). National Hydro-meteorological Service of Serbia reported absolute maximum temperatures on the 23rd of July, reaching 44.9 °C [18]. The 2007 heatwave shows the highest PET values and the largest extension on the territory of Serbia. Similar conclusions were found in studies providing evidence that the anomalous 2007 heatwave exceeded the amplitude and spatial extent of the previous summer heatwaves. The heatwave in 2007 started in mid-July and lasted for 10 days at most places in Serbia. The PET values during the hottest part of the day as high as 55 °C (Figure 1). During the night-time, the temperatures were between 20 and 25 °C, which are still high and not enough to cool the environment. The latter confirms the severity of most of these heatwaves which have been characterized by the persistence of extremely high night-time temperatures [95].

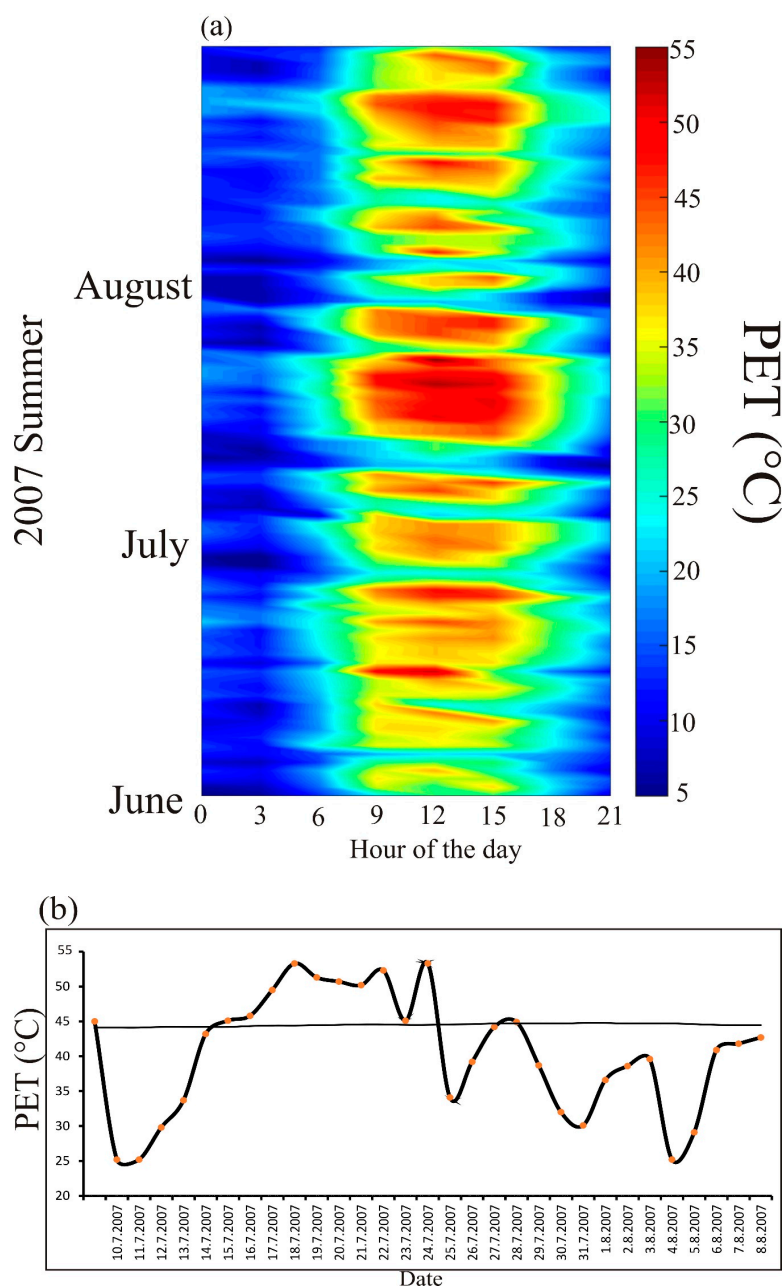


Figure 1. Cont.

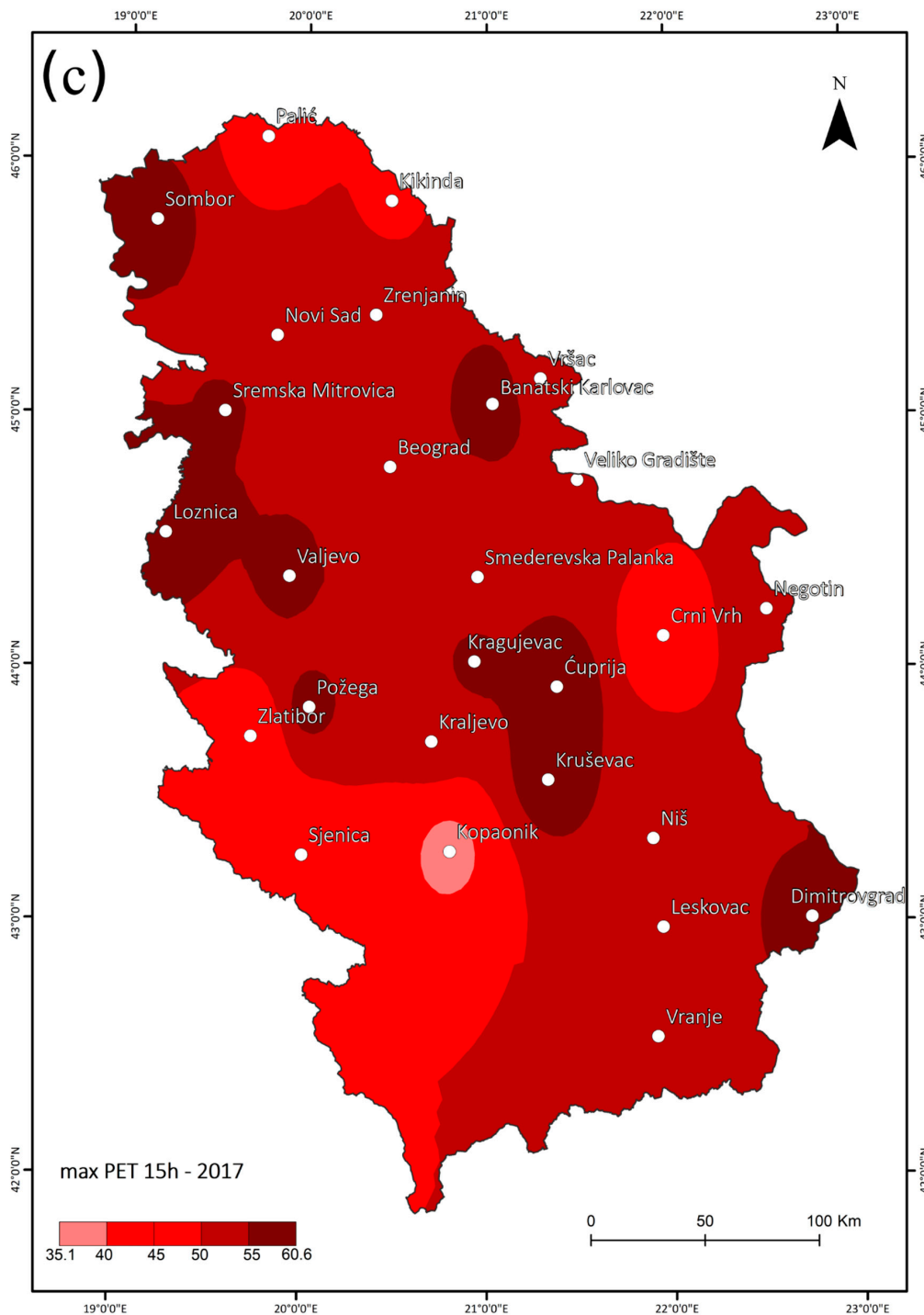


Figure 1. The highest PET values and the extension of the heatwave on the territory of Serbia. (a) Diurnal PET values recorded at Smederevska Palanka meteorological station (2007 heatwave is shown as highlighted part). (b) Maximum PET values during the heatwave at Smederevska Palanka meteorological station; the gray line shows 95th percentile threshold based on the 1981–2010 reference period. (c) Spatial distribution of maximum PET values recorded at 15.00 at all meteorological stations in Serbia [95].

The study of Stojićević et al. [96] presented the results of a detailed bioclimatological analysis of Banja Koviljača (northwestern part of Serbia, Southeastern Europe). The presented study analyzed the variations and trends of the PET for the period 1961–2014 on a seasonal and annual basis. In the future, the change in tourism season and recreation potential could change due to the increase in annual and seasonal values of PET. Hence, the number of days with PET values between 18 and 23 °C is decreasing every year by 0.22 days, and this decrease is statistically significant. Bioclimatological warm extremes exhibited statistically significant increasing trends, where the increase in the duration of heatwaves during the last 50 years pointed out that every year there are 0.44 more heatwaves.

Changes in the PET values for the future on a global basis indicate that the areas with extreme and uncomfortable thermal conditions and heat stress affections could be observed. In many regions of the world, especially the Mediterranean and North America, the changes in thermal stress will most likely outpace changes in air temperature. Thus, the major implications for the assessment of the health effects of climate change must be reconsidered. The effects of climate variability on human health and well-being have been underestimated in the past since most of the studies were based on air temperature rather than changes in PET [97]. The results of PET variation for winter and summer season for Northern Hemisphere based on emission scenarios (SRES) A1F and B1a period 2071–2100 were assessed and showed a strong increase in heat stress for many regions of the world. The areas most affected—e.g., the Mediterranean and western parts of North America—will likely experience changes in thermal perception, and those are expected to outpace the changes in air temperature.

It is highly likely that climate change will affect different parts of society and economy, but the negative effects on human health should be assessed using energy balance of the human body and the derived thermal index. Matzarakis [98] demonstrated the spatial distribution of PET values calculated using the standard SRES emission scenarios. These projections imply that human biometeorological conditions are going to become much worse in the future. Very popular summer tourism areas will be most affected by these changes. The extent extreme heat stress conditions (PET >35 °C) will cover significant portions of global mainland, especially the Northern Hemisphere [99].

3. Heat Health Warning Systems (HHWS)

The 2003 and 2010 severe heatwave events over Western Europe and Russia draw attention and necessity for the conceptualization and implementation of public health measures that would focus, almost exclusively, on heat health warning systems (HHWS). These systems use forecasts of high-risk weather conditions to provide public warnings in Europe [99]. HHWS is defined as a system that uses meteorological forecasts to initiate acute public health interventions designed to reduce heat stress impacts on human health during extreme weather conditions [43,100]. Once the temperature or other weather factors exceed certain thresholds, the HHWS is activated. These thresholds are called triggers, and the ideal setting of triggers enables efficient and coordinated emergency responses; effective communication; and, in the end, reduction in heat-related mortality and morbidity [43,101]. HHWS depend on certain thresholds that best describe human-health tolerance to extreme weather. For HHWS to be reliable, it is necessary to include several elements such as consistent meteorological forecasts; a thorough understanding of relationships between the thermal environment and how it impacts human health; effective and timely response measures as well as the involved stakeholders and decision-makers that have sufficient resources, capacities, knowledge, and political will to implement the response actions [100]. The utilization of modern HHWS is becoming more important and widely used, as these systems could save human lives. During recent heatwaves in Europe, it was observed that extreme temperature-related mortality indicated that in addition to economic wealth and technological development, adaptive capacity to climate change effects has to be enhanced [102].

Thus, many municipalities on a global basis have taken great interest in dealing with extreme heat conditions. These systems are becoming one of the key methods by which heat events are forecast and their effects are mitigated. Hence, regardless of the approach that is being used when creating an HHWS, several key considerations should be taken into account when correlating meteorological

parameters with human health response. Three of the most important factors are spatial variability, temporal variability, and persistence of the oppressive heat. HHWS should typically contain data on weather forecasts, assessments of relations between weather and human health, and a system of ranking alerts [43,100].

Some versions of heatwave warning systems used air temperature and exceedance of predefined thresholds of daily maximum temperatures for a given day. These thresholds are region specific and could not be uniform for all countries in Europe. On the other hand, some HHWS are based on a minimum duration of the heat event using different temperature-humidity indices or a combination of several meteorological parameters. During the 1990s, new synoptic methods emerged that identify air masses linked with high mortality rates. The greatest example is the ICARO system in Lisbon that uses the relationship between maximum temperature and mortality, and it issues a warning when the defined threshold is exceeded [103]. Similarly, The National Meteorological and Hydrological Service in Sweden issues a warning when thresholds based on a study by the Department of Public Health and Clinical Medicine of the University of Umeå are exceeded and rely on the relation between temperature and mortality [43]. Moreover, some systems integrate health observations as a goal to either advance the model of excess mortality (e.g., in Milan) or to confirm the negative effects of heatwave on human health (National Health Services—health advice and information service in the UK (NHS Direct)). Regardless of differences, the universal aim should be the identification of days associated with the greatest health effects associated with extreme weather conditions. The spatial distribution of the operational HHWS in Europe during 2009 and 2019 is given in Figures 2 and 3.

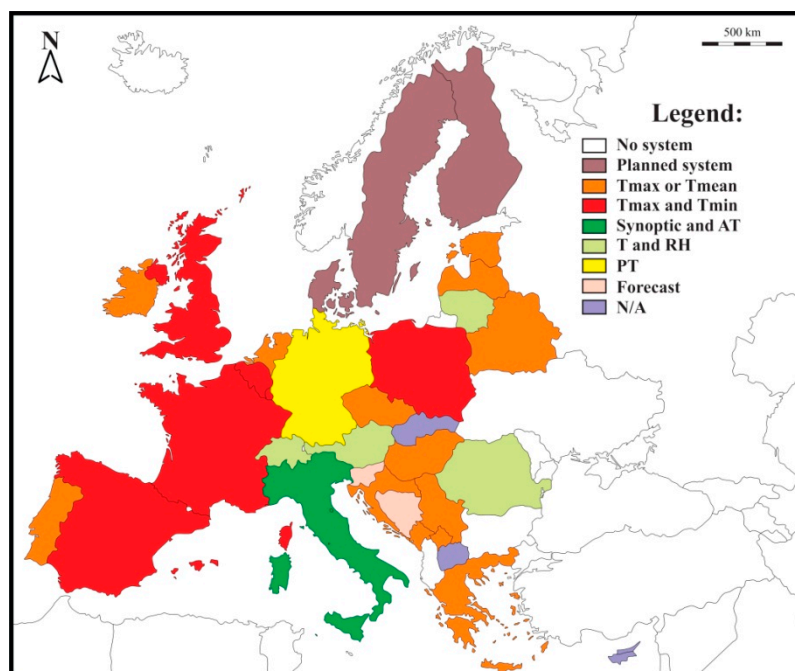


Figure 2. Heat-health warning systems (HHWS) in Europe during 2009. Taxonomy of operational HHWS in Europe—Tmax: maximum temperature; Tmean: mean temperature; Tmin: minimum temperature; AT: apparent temperature; T: Air temperature; RH: relative humidity; PT: perceived temperature. N/A: not known (modified after EURO HEAT project and [102]).

Examples of HHWS Based on Biometeorological Indices

HHWS must be based on a method for the prediction of health-relevant meteorological thresholds especially in data-sparse areas. When this scientific task is completed, it will help with the development and standardized implementation of HHWS at a European level [104]. As discussed, the HHWS are based on a single metric of temperature or a combination of several variables, and most countries issue

warnings that are based on maximum or mean temperatures. Other countries' HHWS in addition to maximum air temperature and humidity use a specific simple single index (e.g., HI). However, the most sophisticated systems issue warnings based on the combination of a thermal-stress indices (e.g., PT) and minimum temperatures such as in Germany and Austria. For most HHWS, the warnings are exclusively issued for warm conditions, but only in Germany PT is also used to measure cold stress [43]. In Germany, the heat warnings are generated automatically. When published, the warnings are adjusted and confirmed by a biometeorology forecaster. Preliminary studies indicate that there is a decrease in the heat related mortality and morbidity cases [105].



Heat Index:

- PT; Tmin
- Tmax; Tmin
- Teumul
- Tmax; Tmin
- Combination of Tmin and Tmax averaged over three days (BMI)
- Tmax; HI
- Tmean
- Tappmax and “air mass-based approach” in larger cities
- Tmax
- ÍCARO index
- Tmean; Tmax
- HI

Abbreviations:

- Tmax:** daily maximum temperature;
- Tmin:** daily minimum temperature;
- Teumul:** the sum of the difference between Tmax and 25°C for the 5 coming days (only the positive values are taken into account);
- PT:** perceived temperature (combination of temperature, radiation, wind, humidity);
- BMI:** Bio Meteorological Indicator;
- HI:** Heat Index;
- Tmean:** mean temperature;
- Tappmax:** maximum apparent temperature;
- ÍCARO index:** (number of expected deaths with the effect of heat (Yt) / number of expected deaths without the effect of heat).

Figure 3. HHWS in Europe in 2019 (modified after [43,106]).

Even though the Hellenic National Meteorological Service uses HHWS that issues the warning when defined thresholds of maximum temperatures are exceeded, the National Observatory of Athens operates a system based on PET and uses it to forecast the human-biometeorological conditions [107]. The Italian system uses maximum apparent temperature and is region-specific. Additionally, their model is based on air mass circulation enabling the further consideration of extreme warm conditions and the causes for their development [43]. Heat-budget models form the basis of HHWS in Germany and Austria and have a clear correlation with mortality.

4. Conclusions

The reviewed scientific papers, which studied the changes in biometeorological warm extremes, provided an extensive overview of significant fluctuations of these events for large parts of the European continent. In recent decades, there has been an evident increase in frequency, duration, and intensity of heatwaves that are determined using standard maximum temperature values but also those that are quantified as simple biometeorological indices (AT, HUMIDEX, HI). Furthermore, climate models suggest their intensification in the future. Thus, the more frequent and severe occurrences of heatwaves and mega heatwaves are anticipated under the future warmer climate, and their distribution will vary significantly. Moreover, the studies confirmed that the return period of those extreme events has declined and their frequency will increase in the parts of the globe that are already affected, but the mid-latitudes will also experience the intensification of humid heatwaves.

The use of heat budget modes and consequently complex biometeorological indices along with meteorological forecast data will provide a platform for future detection and attributions of biometeorological warm extremes. Further research is needed for additional adjustments of the complex biometeorological indices in order to better respond to the needs of society under global warming. For future scenarios, it can be observed that extreme biometeorological events will become more frequent in Europe, and due to the potential negative effects on human health, it is necessary to find the best mitigation strategies. Thus, the necessity for the conceptualization and implementation of the early warning systems is of great importance. Since the duration of extreme heat events is projected to become much longer and the intensity much stronger in the future along with the shortening of return periods, it is necessary to modify current and design new HHWS to take these changes into account. In the future, with accelerating changes in climate extremes, HHWS will have to evolve consequently, ensuring sustainability and continued efficacy. There are several very important challenges for adaptive management of HHWS such as updating the thresholds at which the warnings are issued. The thresholds will most likely be changes due to the acclimatization of the population to future extreme heat events, intensity, and duration. Additionally, the evolution of HHWS will have to take into account targeted risk communications and population profile changes, while the greater scientific knowledge is gathered about the relation between human health and atmospheric conditions [108]. Casanueva et al. [43] gave an extensive overview of recommendations for the design of future, as well as for the upgrading of existent, HHWS. In the scientific community, there has to be a consensus on how to integrate meteorological data into human thermal models as international standards subsequently to deliver more precise climate service tools and HHWS for individuals and society alike to better manage thermal stress-induced intensifying extreme climate events.

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