Theor Appl Climatol (2011) 105:99–106
DOI 10.1007/s00704-010-0379-3

ORIGINAL PAPER

Human-biometeorological assessment of heat waves in Athens

Andreas Matzarakis · Panagiotis T. Nastos

Received: 19 April 2010 / Accepted: 1 December 2010 / Published online: 15 December 2010

Abstract The goal of this study is the analysis of heat waves and their impact on humans, using human biometeorological indices, which are based on the energy balance of the human body. The implications for humans are not only described through the intensity of the heat waves, but also through their duration over consecutive days. Both intensity and duration were analyzed for the Greater Athens Area during the period 1955 to 2001. The analysis was carried out using the daily physiologically equivalent temperature and the daily minimum air temperature. Based on these two parameters, the results showed an increase in the average duration of heat waves. Furthermore, the use of the Gaussian filter revealed the intra-annual variation of heat stress conditions and their relevance to humans. The results could be used for the management of the negative consequences of heat waves in cities suffering from environmental pollution and also for climate impact studies.

1 Introduction

Heat waves, a phenomenon that is not only of interest for the scientific community, occur regularly in Greece and also in the Mediterranean and Western Europe (i.e., Baldi et al. 2006; Conte ad Colacino 1995; Thirion et al. 2005). In the last three decades, the study of heat waves in Greece using different methods of analysis has been very popular. Synoptical, climatological, and human-biometeorological methods were applied (Giles et al. 1990; Giles and Balafoutis 1990; Matzarakis and Mayer 1991; Prezerakos, 1989; Brikas et al. 2006; Fouillet et al. 2006; Katsouyanni et al. 1988; Nastos and Matzarakis 2008, Philandras et al. 2008; Founda and Giannakopoulos 2009).

However, the question on how a heat wave could be defined and what meteorological parameters or information on the impacts should be used to quantify them has not yet been addressed (Thirion et al. 2005; Fouillet et al. 2006; Koppe et al. 2004). Thus far the World Meteorological Organization has not put forward a universally agreed upon definition of heat waves (Koppe et al. 2004).

Heat wave is commonly defined as a period of abnormally and uncomfortably hot weather with high air humidity. Typically, a heat wave lasts for at least 2 days (Koppe et al. 2004).

Robinson (2001) describes a heat wave as an extended period of uncommonly high atmosphere-related heat stress, which causes temporary modifications in lifestyle habits and adverse health-related problems affecting communities. Thus, although a heat wave is a meteorological event, it cannot be assessed without reference to its impacts on humans. An analysis of weather elements should always include the assessment of the human sensation of heat. Appropriate thresholds must be established for this combined analysis, considering both daytime high and overnight low air temperature values. The thresholds should also relate to the normal climatic variability of the area, as well as the duration of the heat wave and its consequences on humans.

A variety of heat stress indices that relate atmospheric conditions to human heat sensations have already been developed (Fanger 1972; Koppe et al. 2004). Driscoll

A. Matzarakis
Meteorological Institute, Albert-Ludwigs-University of Freiburg, Freiburg, Germany

P. T. Nastos (✉)
Laboratory of Climatology and Atmospheric Environment, Faculty of Geology and Geoenvironment, University of Athens, Panepistimiopolis,
GR 157 84, Athens, Greece
e-mail: nastos@geol.uoa.gr

(1985) lists 11 independent indices, and since then, Kalkstein and Valimont (1986) and Höppe (1999) have proposed further analysis. One of the most widely used thermal indices is the physiologically equivalent temperature (PET), described in VDI (1998). Also popular are the perceived temperature (Tinz and Jendritzky 2003) and Out_SET* (Spagnolo and de Dear 2003). All thermal indices take into account the whole heat balance of the human body. This requires meteorological information about air temperature, air humidity, wind speed, as well as short- and long-wave radiation flux densities in addition to the non-meteorological components of fitness and activity level, clothing type, and physiological adaptation to a particular environment (Höppe 1993; VDI 1998).

The various indices combine individual components in a way that is appropriate for a particular meteorological application. For any long-term analysis of heat waves, however, an index that relies not only on synoptical routine observations is required (Robinson 2001).

In this analysis, we focus on PET (Höppe 1999; Matzarakis et al. 1999) and the daily minimum air temperature (T_{amin}) in order to analyze and quantify the heat waves in Greater Athens Area (GAA). The reason for taking PET is that it describes the effect of the thermal environment as a temperature value and can be quantified easier for non-specialists in this topic and it is based on the full human energy balance. For night time situation, air temperature corresponds very close to the PET value. Furthermore, an attempt was made to describe the short time or intra-annual adaptation of humans to the changing climate conditions. It is well known that the effect of thermoregulation is dominant in warm and hot conditions, while the behavioral regulation is more dominant in cold conditions (Khosla and Guntupalli 1999).

2 Methods and analysis

Daily meteorological data from the Hellinikon station for the period 1 Jan 1955 to 31 December 2001 were used in order to detect and quantify heat waves in Athens. Based on the climatic record of this station, which is located at the headquarters of the Hellenic National Weather Service, relevant meteorological parameters (mean, maximum and minimum air temperature, relative humidity, wind speed, and cloud cover) were utilized in the analysis. In order to describe and quantify heat waves using a human-biometeorological approach, the thermal index PET was calculated by the RayMan model (Höppe 1999; Matzarakis et al. 1999; 2007b; Matzarakis et al. 2010).

PET is defined as the physiologically equivalent temperature at any given place (outdoors or indoors). It is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism, 80 W of light activity, added to basic metabolism; heat resistance of clothing, 0.9 clo) is maintained with core and skin temperatures equal to those of a body in the assessed conditions (Mayer and Höppe 1987; VDI 1998; Höppe 1999). The classification of PET and the related physiological strain are given in Table 1.

The following assumptions are made for PET in the indoor reference climate:

- Mean radiant temperature equals air temperature ($T_{mrt}=T_a$).
- Air velocity (wind speed) is fixed at v=0.1 m/s.
- Water vapor pressure *VP* is set to 12 hPa (approximately, equivalent to a relative humidity of 50% at T_a=20°C).

The procedure for the calculation of PET contains the following steps:

- Calculation of the thermal conditions of the body with Munich Energy Balance Model for Individuals (MEMI) for a given combination of meteorological parameters.
- Insertion of the calculated values for mean skin temperature and core temperature into the model MEMI and solving the energy balance equation system for the air temperature T_a (with v=0.1 m/s, VP=12 hPa, and $T_{mrt}=T_a$).
- The resulting air temperature is equivalent to PET.

Compared to other thermal indices, which are also obtained from the human energy balance, e.g., the predicted mean vote PMV (Fanger 1972), PET offers the advantage of a widely known unit (degrees Celsius), which makes it more easy for regional or tourism planners to interpret the results. This also includes members of the public who might not be familiar with the human-biometeorological terminology (Matzarakis et al. 1999).

It is noteworthy that the VDI guideline 3787 part 2 "methods for the human-biometeorological evaluation of climate and air quality for urban and regional planning, part I:

Table 1 PET for different grades of thermal sensation and physiological stress on human beings (during standard conditions: heat transfer resistance of clothing, 0.9 clo; internal heat production, 80 W) (Matzarakis and Mayer, 1996)

PET (°C)	Thermal sensation	Physiological stress level
4	Very cold	Extreme cold stress
8	Cold	Strong cold stress
13	Cool	Moderate cold stress
18	Slightly cool	Slight cold stress
23	Comfortable	No thermal stress
29	Slightly warm	Slight heat stress
35	Warm	Moderate heat stress
41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

climate" (VDI 1998) recommends the application of PET for the evaluation of the thermal component of different climates. This further emphasizes the significance of PET. The VDI guideline is edited by the German Association of Engineers ("Verein Deutscher Ingenieure" (VDI)).

Our analysis was not solely based on meteorological values, but also included the quantification of climatological and human-biometeorological parameters over consecutive days with heat stress (Matzarakis and Mayer 1997).

The analysis was carried out for days with PET>35°C (Matzarakis and Mayer 1996) and T_{amin}>23.0°C (Nastos and Matzarakis 2008). Both criteria seem to adequately represent days with heat stress conditions during day and night.

Additionally, data on the human adaptation to intra-annual thermal perception variability was not available. Statistical filters were used instead to estimate the thermal perception of and heat stress for humans. Several studies indicate a different effect of heat waves in early summer compared to late summer. So, the impact of early heat waves on mortality is higher than the impact of heat waves of the same magnitude in late summer, a fact that can be explained by short-term adaptation processes. We used the HeRATE (Koppe and Jendritzky 2005) approach to allow this short-term adaptation. HeRATE modifies PET, in regard of thermal conditions in order to intensify earlier heat waves and reduces later ones.

In our analysis, in order to quantify, the short-time or intra-annual adaptation of humans to the thermal component of climate has been carried out. A twofold Gaussian filter of 41 days, which corresponds to a filter of 81 days, was applied. This one side filter has 30 significant filter weights (Schönwiese 1992; Koppe, 2005), which are in accordance with a time frame in which physiological changes in humans as a response to heat stress are observable. The 41 days of filter represents the variable part (short-time adaptation) that was applied to the daily PET and daily T_{amin} values. The PET values represent the upper limit of the thermal perception, and the T_{amin} represents the lower limit. The adapted values of $\mathrm{PET_a}$ and T_{amina} were calculated using the following formula. The formula expresses the constant part of thermal stress and a variable part which represents the short-time thermal adaptation.

$$\mathrm{PET_a} = limit + (\mathrm{PET_{41F}} - limit) \times 1/3 \text{ with limit of PET} = 30^\circ\mathrm{C} \text{ and PET} = 35^\circ\mathrm{C};$$

$$\mathrm{T_{amina}} = limit + (\mathrm{T_{amin41F}} - limit) \times 1/3 \text{ with limit of } \mathrm{T_{amin}} = 20^\circ\mathrm{C} \text{ and } \mathrm{T_{amin}} = 23^\circ\mathrm{C},$$

where $\mathrm{PET_a}$ is the PET value with short-time adaptation, $\mathrm{PET_{41F}}$ is the PET with Gaussian filter, and *limit* is the upper limit of PET. T_{amina} is the T_{amin} value with short time adaptation, $T_{amin41F}$ is the T_{amin} with Gaussian filter, and *limit* is the upper limit of T_{amin}.

As far as the trends of the maximum duration of heat waves and the number of heat waves (HW) within the year are concerned, the Mann–Kendall rank statistical method was applied on aforementioned time series (Mitchell et al. 1966; Sneyers, 1975; Chu et al. 1994). According to this criterion, every term x_i $(i=1,N)$ is compared to all terms following. If n_i is the number of terms which exceed x_i, then the sum (1) is computed and, in the process, the statistical term τ (2) is accessed. Then, this statistical term is compared to $(\tau)_t$ (3).

$$P = \sum_{i=1}^{N-1} n_t \tag{1}$$

$$\tau = \frac{4PN}{N(N-1)} - 1 \tag{2}$$

$$(\tau)_t = 0 \pm 1.96\sqrt{\frac{4N+10}{9N(N-1)}}, \tag{3}$$

where 1.96 is the value for t at the probability point in the Gaussian distribution for 95% significant level and for the two-tailed test.

3 Results

The following section is structured as follows: Firstly, results derived from the analysis of the mean bioclimatic conditions are given to provide an overview of the distribution of the bioclimatic conditions in the GAA. Next, we focus on consecutive days with heat stress, as single days with heat stress are commonly eliminated from this type of biometeorological study. The analysis was carried out for days with PET>35°C (Matzarakis and Mayer 1996) and T_{amin}>23.0°C (Nastos and Matzarakis 2008). Both criteria seem to adequately represent days with heat stress conditions during day and night. Additionally, data on the human adaptation to intra-annual thermal perception variability were not available. Statistical filters were used instead to estimate the thermal perception of and heat stress for humans.

3.1 Bioclimate diagram for Athens

We produced a bioclimate diagram for the PET-based analysis of the general bioclimate conditions. Ten-day frequencies of the daily PET values are illustrated for the period 1955 to 2001 (Fig. 1).

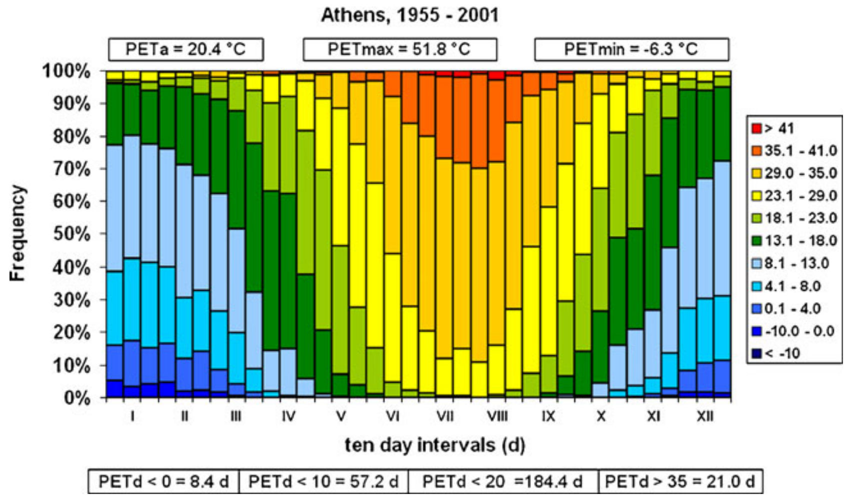

Fig. 1 Bioclimate diagram for Athens for the period 1955–2001

The thermal human-bioclimate conditions are expressed in percentages of the occurrence of classes for 10-day intervals. Figure 1 depicts that 50% of the days from the 8th dekas (middle of March) to the 34th dekas (end of November) are within the PET classes of 18°C and above. It has to be mentioned that the results shown in Fig. 1 are based on daily mean values of the meteorological variables. From the beginning of April until the end of October, extreme thermal stress (PET>35°C) can be observed for the study region. Figure 1 also presents mean and absolute maximum and minimum PET values as well as the frequencies of cold days (days with PET<10°C), days with thermal comfort (18°C<PET<23°C), and heat stress days (days with PET>35°C). This type of bioclimate diagram is a valuable tool for the assessment of the general thermal bioclimatic regime.

3.2 Consecutive days

We used consecutive days (three and more) in order to quantify the duration of heat waves and their impacts. For this purpose, we chose thresholds for PET and T_{amin}. From a variety of thresholds, we selected the days with PET≥35°C, as these are conditions with extreme heat stress (Matzarakis et al.; 1999), and T_{amin}≥23°C, which represents PET values of thermal neutrality (Nastos and Matzarakis 2008). The T_{amin} was used for the minimum temperature in a day. The number of consecutive days and the duration of each episode (heat waves) for PET≥35°C and T_{amin}≥23°C are shown in Figs. 2 and 3, respectively. There is no clear pattern for the number of consecutive days with respect to PET≥35°C, but a statistically significant (at confidence level 95%) increasing trend of the maximum duration of heat waves within the year (b=1.33 days/year, p=0.000) is observed since 1983. In addition, the number of heat waves (HW) within the year appears a statistically significant (at confidence level 95%) trend (b=0.26 HW/year, p=0.000), since 1983. Regarding the consecutive days with T_{amin}≥23°C, a statistically significant trend (at confidence level 95%) for the number of heat waves within the year (b=0.15 HW/year, p=0.048) appears since 1983, while there is no statistically significant trend of the maximum duration of heat waves within the year (b=0.07 days/year, p=0.344).

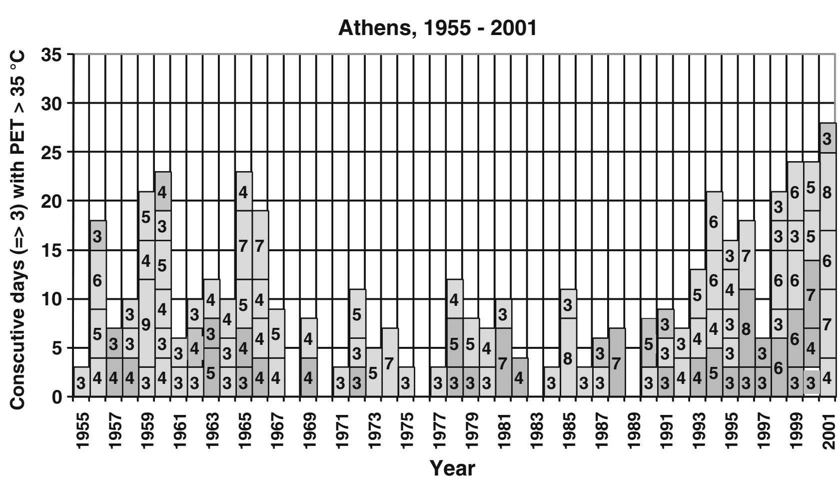

Fig. 2 Consecutive number of days with PET≥35°C for Hellenikon/Athens, during the period 1955–2001. The *number* in the *bars* indicates the duration in days of each episode

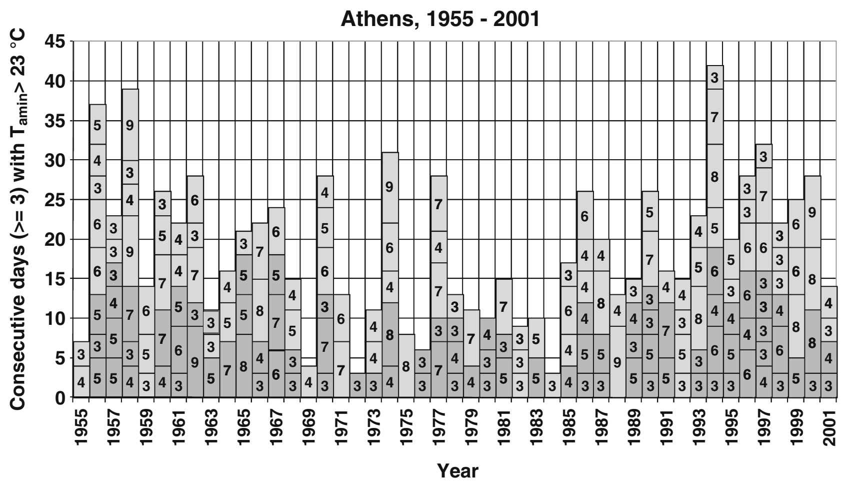

Fig. 3 Consecutive number of days with $T_{amin}\geq 23°C$ for Hellenikon/Athens, during the period 1955–2001. The *number* in the *bars* indicates the duration in days for each episode

3.3 Intra-annual thermal adaptation

As an example of the intra-annual thermal adaptation, we illustrate the most relevant years (strong heat waves) 1987 and 1988. These 2 years were selected because of the severe human health implications. Figures 4 and 5 show the thermal comfort and thermal stress conditions, taking into account human thermal adaptation.

Figure 4 depicts the intra-annual variability of the daily PET values, the Gaussian filtered PET-values (PET_{41F}), and the PET_a for the limit of 35°C (Heatwave35) and 30°C (Heatwave30), in Hellinikon/Athens, for the period 1987 to 1989. The courses of Heatwave35 and Heatwave30 show that there is a pattern describing the variability of the thermal adaptation. It can also be pictured as a “memory” of the thermal perception or heat stress in humans.

Besides, the intra-annual variability of the daily T_{amin} values, the Gaussian filtered T_{amin} values ($T_{amin41F}$) and the T_{amin} for the limit of 20°C ($T_{aminHeat20}$) and 23°C ($T_{aminHeat23}$) for 1987 to 1989 in Hellinikon/Athens are presented in Fig. 5. The courses of $T_{aminHeat20}$ and $T_{aminHeat23}$ are similar to those of Heatwave35 and Heatwave30 shown in Fig. 4.

4 Discussion

The use of single parameters or factors is not the only way of how the implications of heat waves on humans can be assessed. The present work uses the thermal indices and includes an analysis of consecutive days, as well as statistical filters to measure thermal adaptation. This represents a valuable step for the quantification of heat waves and heat stress, an issue that will become even more important in the future.

In spite of the absence of a heat wave definition, several methods are appropriate for analyzing and quantifying them. Thus, the analysis of heat waves can be carried out focusing either on air masses and weather type approaches or on human-biometeorological methods. An analysis, however, should include mean conditions, extremes, and frequencies for the quantification of the intensity and the

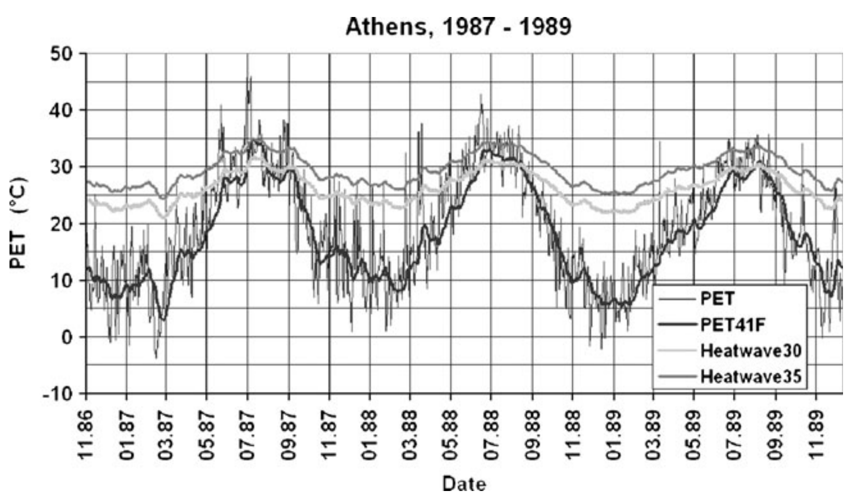

Fig. 4 Inter annual variability of thermal adaptation (PET original value, PET41F the Gaussian filtered, Heatwave30/35 with threshold of 30/35°C PET) based on PET for 1987 to 1989 in Athens

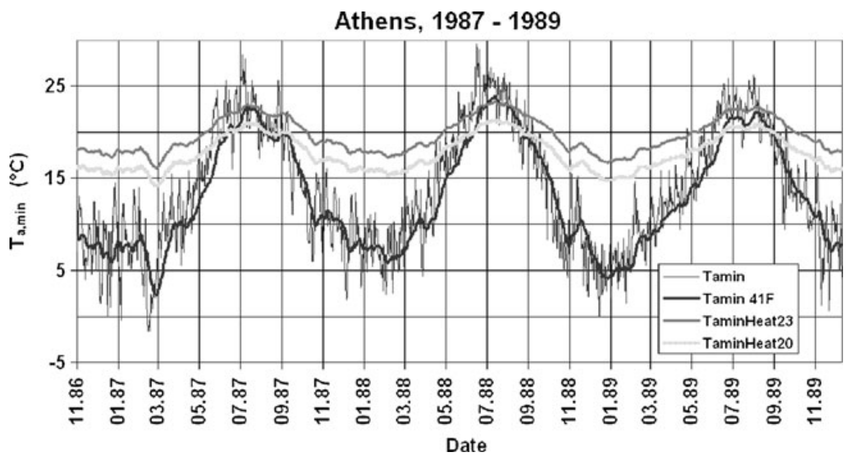

Fig. 5 Inter-annual variability of thermal adaptation (Tamin original value, Tamin41F the Gaussian filtered, TaminHeat20/23 with threshold of 20/23°C PET) based on minimum air temperature for 1987 to 1989 in Athens

duration. Besides, the analysis of consecutive days provides valuable details of heat waves and interpretations regarding relevant events.

Additionally, the thermal adaptation of humans can be included in both approaches using appropriate statistical methods, i.e., Gaussian filters and human-biometeorological threshold values.

Based on climate models, the analysis of climate change indicates that heat stress conditions will occur much more frequently in the future (IPCC 2007; Matzarakis et al. 2007a). The question of mitigation and adaptation is of vital importance for the Mediterranean and especially for the metropolitan areas, which are also suffering from problems related to urban climate. Philandras et al. (1999) studied the Urban Heat Island (UHI) in Athens and found that the urbanization effect refers mainly to the maximum air temperature (an increase ~2°C) and to the warmer seasons of the year. The minimum air temperature time series does not display any significant trend. The UHI is mainly attributed to the extensive building of Athens after the Second World War and the rapid increase of the population and the number of vehicles mainly after 1970. In London, the urban warming is strongest on summer nights when heat, which has been absorbed by buildings during daytime, is released (Lee 1992). Besides, in Kuwait City, a desert city but near the coast, the urban influence on maximum and minimum air temperature is almost negligible probably because of the similarities in the urban–rural landscape and the close proximity of the sea (Nasrallah et al. 1990).

Adaptation possibilities are required in the micro-scale level of cities, i.e., urban planning measures (green areas and air paths, roof greening, and facade greening) and UHI reduction, especially during night time (Matzarakis and Endler 2010). Human biometeorological information (i.e., PET or heat warning systems) is vital for the improvement of urban and environmental planning.

The findings of our analysis show that heat waves related to PET build an important and relevant possibility in the assessment of human thermal bioclimate. Furthermore, heat wave quantification based on consecutive days shows a significant increasing trend for the last 20 years of the twentieth century. For 2007, a study carried out by Founda and Giannakopoulos (2009) showed that a record value of 44.8°C was observed at Athens (National Observatory of Athens) on 26 June 2007 during the first and most intense heat wave that affected GAA. Concerning climate change conditions, Matzarakis et al. (2007a) showed that the PET conditions for 2070–2100 will be increased in the range of one and two thermal stress classes during winter, spring, and autumn and about two and higher classes of thermal stress during summer.

The intra-annual adaptation of the used thresholds PET>35°C for daytime (Matzarakis et al. 1999) and T_{amin}>23°C for night time (Nastos and Matzarakis, 2008) provides a better approach for the estimation of thermal perception of humans than simply indices based only on air temperature and humidity.

5 Conclusions

The analysis of the thermal human bioclimate, when applied to the present climate conditions, may reveal information, which can assist decision making on various levels, including health, tourism, and regional planning. Changes in the overall bioclimatic conditions for humans (here, PET has been used as an exhaustive indicator), with respect to heat stress events, are of great importance for the protection of the population especially in large agglomerations. In many regions of the Mediterranean Sea, the occurrence of stressful bioclimatic conditions (PET>35°C, extremely hot conditions for Europeans) to people will affect their health and well-being. Periods with PET> 35°C (for daytime) and T_{amin}>23°C (for nighttime) have increased especially in the last decade of the examined period. These periods are related to heat stress and heat waves, affecting several socio-economic branches. In addition, the changing thermal conditions will presumably lead to higher energy consumption (and higher emissions of greenhouse gases) as a result of the increased need for cooling. These needs will set regional and local authorities under pressure because of the increased energy demand and higher negative impacts due to climate.

Additional analyses, based on daily data from regional models, are required in order to describe future climate conditions and give information about extreme events for sensible and vulnerable areas and can be helpful in the development of adaptation strategies for public health.

Nevertheless, the information and results in their current form are satisfactory in order to address towards the main impacts of heat waves on human health.

Disciplines like meteorology, thermo-physiology, socio-ecology, and medicine should be included in the definition of heat waves. Existing heat warning systems sometime consider less specific local or regional information, i.e., land use and local wind systems. The recommendation for big cities and mega cities is to develop specific heat warning systems, which include urban climate factors. Also, little is yet known about the synergetic effects of extreme heat conditions, air pollution, and other environmental factors, like noise and UV radiation. Further research is needed to address this issue.

Acknowledgments Thanks to the Hellenic National Meteorological Service for providing the data from the Hellinikon station.

References

Baldi M, Dalu G, Maracchi G, Pasgui M, Cesanore F (2006) Heatwaves in the Mediterranean: a local feature or a larger-scale effect? Int J Climatol 26:1477–1487

Brikas DP, Karacostas TS, Pennas PJ, Flocas AA (2006) The role of the subtropical jeatstream during heatwave events over north-central Greece. Met Atmosp Phys 94:219–233

Chu PS, Yu ZP, Hastenrath S (1994) Detecting climate change concurrent with deforestation in the Amazon basin: which way has it gone? Bull Am Meteorol Soc 75:579–584

Conte M, Colacino M (1995) Heatwave in the central Mediterranean. Synoptic climatology. Il Nuovo Cimento 18C:295–304

Driscoll DM (1985) Human health. In: Houghton DD (ed) Handbook of applied meteorology. Wiley, New York, pp 778–814

Fanger PO (1972) Thermal comfort. McGraw-Hill, New York

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, Clavel J, Jougla E, Hémon D (2006) Excess mortality related to the August 2003 heatwave in France. Int Arch Occup Environm Health 80:16–24

Founda D, Giannakopoulos C (2009) The exceptionally hot summer of 2007 in Athens, Greece—a typical summer in the future climate? Glob Plan Change 67:227–236

Giles BD, Balafoutis C (1990) The Greek heatwaves of 1987 and 1988. Int J Climatol 10:505–517

Giles BD, Balafoutis C, Maheras P (1990) Too hot for comfort: the heat waves in Greece in 1987 and 1988. Int J Biometeorol 34:98–104

Höppe PR (1993) Heat balance modelling. Experientia 49:741–745

Höppe PR (1999) The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. Int J Biometeor 43:71–75

IPCC (2007) The physical science basis. Contribution of Working Group 1 to the fourth IPCC assessment report, chapter 11 regional climate projections. IPPC, Geneva

Kalkstein LS, Valimont KM (1986) An evaluation of summer discomfort in the United States using a relative climatological index. Bull Amer Meteor Soc 67:842–848

Katsouyanni K, Trichopoulos D, Zavitsanos X, Touloumi G (1988) The 1987 Athens heatwave. Lancet 2(8610):573

Khosla R, Guntupalli KK (1999) Heat related illness. Crit Care Clin 15:251–263

Koppe C (2005) Gesundheitsrelevante Bewertung von thermischer Belastung unter Berücksichtigung der kurzfristigen Anpassung der Bevölkerung an die lokalen Witterungsverhältnisse. Berichte des Deutschen Wetterdienstes Nr. 226

Koppe C, Jendritzky G (2005) Inclusion of short-term adaption to thermal stresses in a heat load warning procedure. Meteorol Z 14:271–278

Koppe C, Kovats S, Jendritzky G, Menne B (2004) Heat-Waves: Risks and Responses. Health and Global Environmental Change Series No 2, WHO, Copenhagen, Denmark.

Lee OD (1992) Urban warming? An analysis of recent trends in London's heat island. Weather 47:50–56

Matzarakis A, Mayer H (1991) The extreme heat wave in Athens in July 1987 from the point of view of human biometeorology. Atmos Env 25B:203–211

Matzarakis A, Mayer H (1996) Another kind of environmental stress: thermal stress. WHO Newsletter 18:7–10

Matzarakis A, Mayer H (1997) Heat stress in Greece. Int J Biometeorol 41:34–39

Matzarakis A, Endler C (2010) Adaptation of thermal bioclimate under climate change conditions—the example of physiologically equivalent temperature in Freiburg, Germany. Int J Biometeorol. doi:10.1007/s00484-009-0296-2

Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. Int J Biometeorol 43:76–84

Matzarakis A, Georgiadis T, Rossi F (2007a) Thermal bioclimate analysis for Europe and Italy. Il Nuovo Cimento C30:623–632

Matzarakis A, Rutz F, Mayer H (2007b) Modelling radiation fluxes in easy and complex environments—application of the RayMan model. Int J Biometeorol 51:323–334

Matzarakis A, Rutz F, Mayer H (2010) Modelling radiation fluxes in simple and complex environments—basics of the RayMan model. Int J Biometeorol 54:131–139

Mayer H, Höppe P (1987) Thermal comfort of man in different urban environments. Theor Appl Climatol 38:43–49

Mitchell JM, Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, Walléen CC (1966) Climatic Change. WMO Technical Note No 79.

Nasrallah HA, Brazel AJ, Balling RC (1990) Analysis of the Kuwait city urban heat island. Int J Climatol 10:401–405

Nastos P, Matzarakis A (2008) Variability of tropical days over Greece within the second half of the twentieth century. Theor Appl Climatol 93:75–89

Philandras CM, Metaxas DA, Nastos PT (1999) Climate variability and urbanization in Athens. Theor Appl Climatol 63:65–72

Philandras CM, Nastos PT, Repapis CC (2008) Air temperature variability and trends over Greece. Global Nest J 10(2):273–285

Prezerakos NG (1989) A contribution to the study of the extreme heat wave over the south Balkans in July 1987. Meteor Atmos Phys 41:261–271

Robinson PJ (2001) On the definition of heat waves. J Appl Meteorol 40:762–775

Schönwiese CD (1992) Praktische Statistik für Meteorologen und Geowissenschaftler. 2. Auflage, Berlin, Stuttgart, Gebrüder Borntraeger

Sneyers R (1975) Sur l' analyse statistique des series d'observations, Technical Note 143. WMO, Geneva

Spagnolo J, de Dear R (2003) A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Build Env 38:721–738

Thirion X, Debensason D, Delarozière JC, San Marco JL (2005) August 2003: reflections on a French summer disaster. Why were its medical consequences so serious? Are we sure to do better next time? J Conting Cris Manag 13:153–158

Tinz B, Jendritzky G (2003) Europa- und Weltkarten der gefühlten Temperatur, In: Chmielewski, F.-M., Foken, Th. (Ed.) Beiträge zur Klima- und Meeresforschung, Berlin und Bayreuth. 111–123

VDI (1998) Methods for the human-biometeorological assessment of climate and air hygiene for urban and regional planning. Part I: climate. VDI guideline 3787. Beuth, Berlin