Int J Biometeorol (1999) 43:76–84

ORIGINAL ARTICLE

Andreas Matzarakis · Helmut Mayer
Moses G. Iziomon

Applications of a universal thermal index: physiological equivalent temperature

Received: 7 April 1999 / Accepted: 26 May 1999

Abstract The physiological equivalent temperature, PET, is a thermal index derived from the human energy balance. It is well suited to the evaluation of the thermal component of different climates. As well as having a detailed physiological basis, PET is preferable to other thermal indexes like the predicted mean vote because of its unit (°C), which makes results more comprehensible to urban or regional planners, for example, who are not so familiar with modern human-biometeorological terminology. PET results can be presented graphically or as bioclimatic maps. Graphs mostly display the temporal behaviour of PET, whereas spatial distribution is specified in bioclimatic maps. In this article, some applications of PET are discussed. They relate to the evaluation of the urban heat island in cities in both temperate climates and warm climates at high altitude. The thermal component of the microclimate in the trunk space of a deciduous forest is also evaluated by PET. As an example of the spatial distribution of PET, a bioclimatic map for Greece in July (Mediterranean climate) is presented.

Key words Physiological equivalent temperature · Evaluation of the thermal component of different climates · Human biometeorology · Urban climate · Forest climate · Bioclimatic maps

Introduction

There are many tasks within the field of applied climatology, e.g. in urban or regional planning, as well as in tourism and environmental medicine, which require an evaluation of the thermal component of different climates. Consequently, a number of investigations in human biometeorology have been conducted that deal with the effects of the thermal environment on human beings. In the past, several thermal indexes based on meteorological parameters (such as effective temperature, equivalent temperature, heat stress index, or human comfort index) have often been used to evaluate the thermal component of different climates (e.g. Gonzales et al. 1974; Ayoade 1978; Yan and Oliver 1996; Veleva et al. 1997). Most of these indexes, however, have the major limitation that thermophysiological relevance is lacking (Mayer and Höppe 1987).

A. Matzarakis · H. Mayer (✉) · M. Iziomon
Meteorological Institute, University of Freiburg, Werderring 10, D-79085 Freiburg, Germany
e-mail: hmayer@uni-freiburg.de
Tel.: +49-761-203-3591, Fax: +49-761-203-3586

Physiological equivalent temperature, PET

There are now more popular thermal indexes with physiological relevance, as they are derived from the human energy balance (Höppe 1993; Taffé 1997). One of these is the physiological equivalent temperature (PET), discussed by Höppe (1999) in the preceding paper in this journal. Compared to other thermal indexes that are also obtained from the human energy balance, such as the predicted mean vote (PMV), PET has the advantage of a widely known unit (°C), which makes results more comprehensible to urban or regional planners, for example, who are not so familiar with modern human-biometeorological terminology.

Similar to the frequently used PMV index (Fanger 1972; Fanger et al. 1974; Jendritzky et al. 1990), PET is a universal index for characterising the thermal bioclimate. It also allows for the evaluation of thermal conditions in a physiologically significant manner. In the light of this, Matzarakis and Mayer (1996) related ranges of PMV for thermal perception and grade of physiological stress on human beings (Fanger 1972; Mayer 1993) to the corresponding PET ranges (Table 1), which are only valid for the assumed values of internal heat production and thermal resistance of the clothing.

To emphasise further the significance of PET, it is worth mentioning 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: climate” (VDI 1998), which is edited by the Ger-

Table 1 Ranges of the thermal indexes predicted mean vote (*PMV*) and physiological equivalent temperature (*PET*) for different grades of thermal perception by human beings and physiological stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to Jendritzky et al. 1990; Matzarakis and Mayer 1997)

PMV	PET (°C)	Thermal perception	Grade of physiological stress
		Very cold	Extreme cold stress
–3.5	4		
		Cold	Strong cold stress
–2.5	8		
		Cool	Moderate cold stress
–1.5	13		
		Slightly cool	Slight cold stress
–0.5	18		
		Comfortable	No thermal stress
0.5	23		
		Slightly warm	Slight heat stress
1.5	29		
		Warm	Moderate heat stress
2.5	35		
		Hot	Strong heat stress
3.5	41		
		Very hot	Extreme heat stress

man Association of Engineers (Verein Deutscher Ingenieure, VDI), recommends the application of PET for the evaluation of the thermal component of different climates.

It is necessary for the calculation of PET to determine all meteorological parameters important for the human energy balance at a human-biometeorologically significant height, e.g. 1.1 m above ground (the average height of a standing person's centre of gravity in Europe). Dominant meteorological parameters influencing the human energy balance include air temperature, vapour pressure, wind velocity and mean radiant temperature of the surroundings. Depending on the objectives of the evaluation, these meteorological parameters can be measured experimentally or calculated in a grid-net by numerical models.

Applications of PET

Examples of the application of PET to evaluate the thermal component of different climates are demonstrated below. In principle, PET results can be presented graphically in a temporal distribution for selected sites or in a spatial distribution as maps (e.g. bioclimate maps), which are very well suited for all kinds of planning tasks.

Cities in a temperate climate

Urban planning often requires the quantitative demonstration of the climatic effects of trees within street canyons. One example of such effects is the shading of direct solar radiation by the crown of trees. This reduces the demand for air-conditioning in residential buildings, especially in subtropical and tropical cities (Huang et al. 1987; Simpson and McPherson 1998; Summit and Sommer 1998).

Another effect is the reduction of thermal stress on humans within the crown's sphere of influence. This can be quantified by the use of PET, as the following case demonstrates. In the centre of Freiburg, a city with a population of about 200 000 residents in the south-west of Germany, an experimental study with a special mobile measuring system for human-biometeorological investigations was performed on a summer day (11 July 1996). As illustrated in Fig. 1, on a summer day the air temperature T_a was only about 1 K lower under the crown of the trees (chestnut) than in the conditions within a nearby non-tree-lined street canyon. The mean radiant temperature, T_{mrt}, however, was more strongly affected by the shade of the tree crowns, and showed values about 30 K lower within the tree-lined street canyon (Fig. 2). In Munich, Mayer (1993) found nearly the same reduction in T_{mrt} caused by the shading effect of poplar crowns on a hot summer day.

The most important meteorological factor influencing PET on summer days with weak wind velocity is T_{mrt} (Mayer and Matzarakis 1998). Therefore, PET indicates a decreasing thermal stress level for human beings in the daytime, when direct solar radiation is shaded by tree crowns (Fig. 3). The difference between PET values in unshaded and tree-shaded sites in Freiburg was then, on average, about 15 K.

The use of PET to evaluate the thermal component of different urban microclimates is also demonstrated here. Within the scope of the KLIWUS project (Mayer and Matzarakis 1997), measurements of the meteorological parameters that are necessary to calculate PET were performed in winter and summer 1989 in some urban microclimates in Munich. The same special mobile measuring system for human-biometeorological investigations was used as was later also employed in Freiburg. Consecutive measurements were taken at single points. These differed within the urban microclimates in sky-view factor and surface type. Figure 4 contains PET values at four nearby points measured on a summer day, which are taken from the comprehensive results of this project. There is a remarkable spatial variability of PET. If direct solar radiation is not shaded by tree crowns or buildings, PET values are comparatively high, and indicate a heat load of greater intensity for humans within that urban mircoclimate.

City in a warm high-altitude climate

Figure 5 provides an illustration of PET application in locations with different climatic conditions from those of Germany. It presents the diurnal variation of PET and T_{mrt} in the centre of a street canyon (8 m wide, no sidewalks) on a summer day in August. The street canyon is in Albuquerque (New Mexico, USA) which lies about

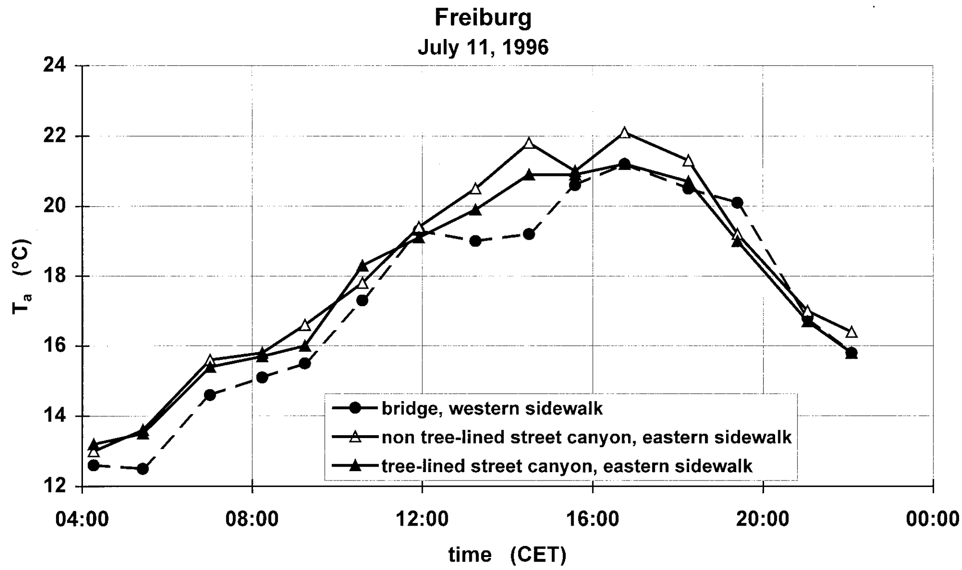

Fig. 1 Air temperature (T_a) at the human-biometeorologically significant height of 1.1 m above ground at three nearby urban structures in Freiburg (south-west Germany) on a summer day

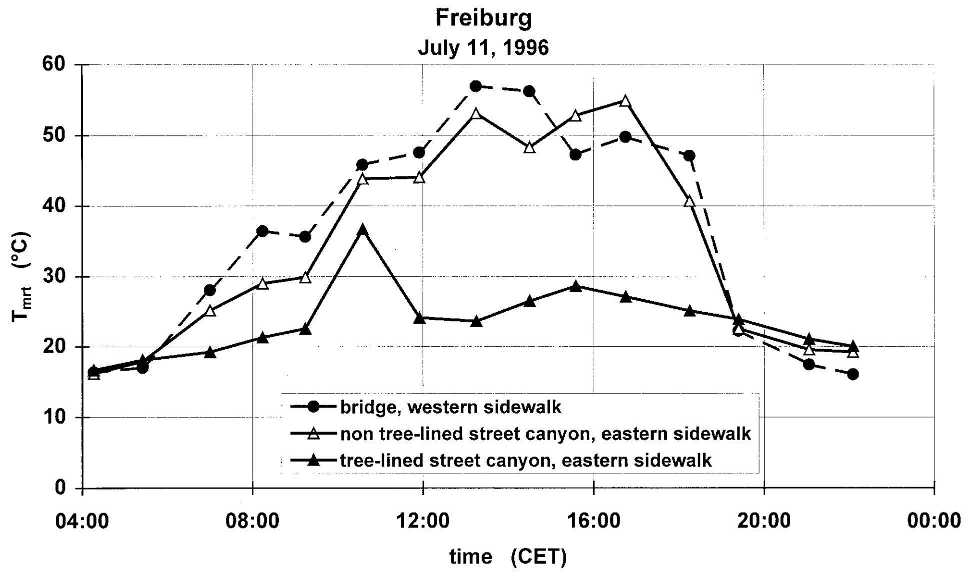

Fig. 2 Mean radiant temperature (T_{mrt}) at the human-biometeorologically significant height of 1.1 m above ground at three nearby urban structures in Freiburg (south-west Germany) on a summer day

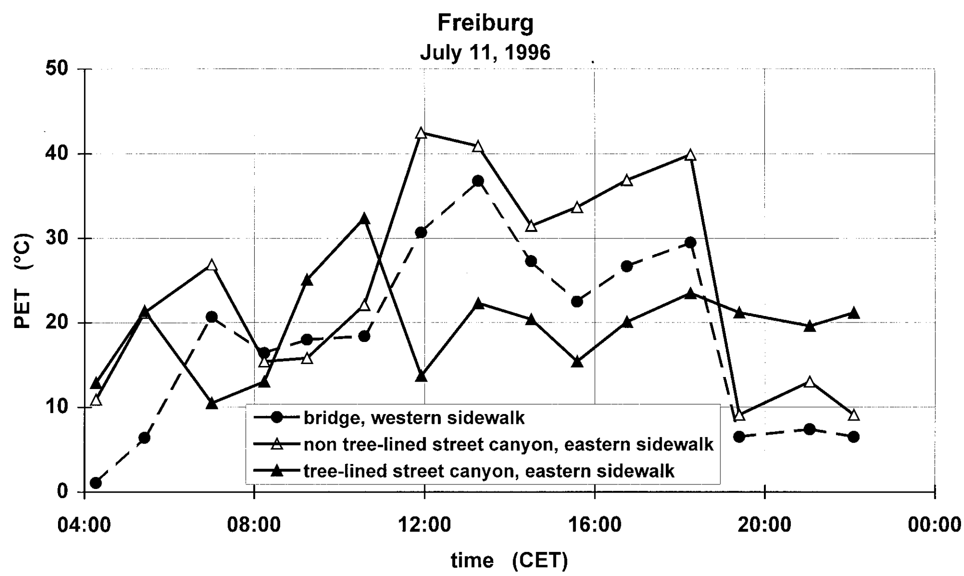

Fig. 3 Physiological equivalent temperature (*PET*) at the human-biometeorologically significant height of 1.1 m above ground at three nearby urban structures in Freiburg (south-west Germany) on a summer day

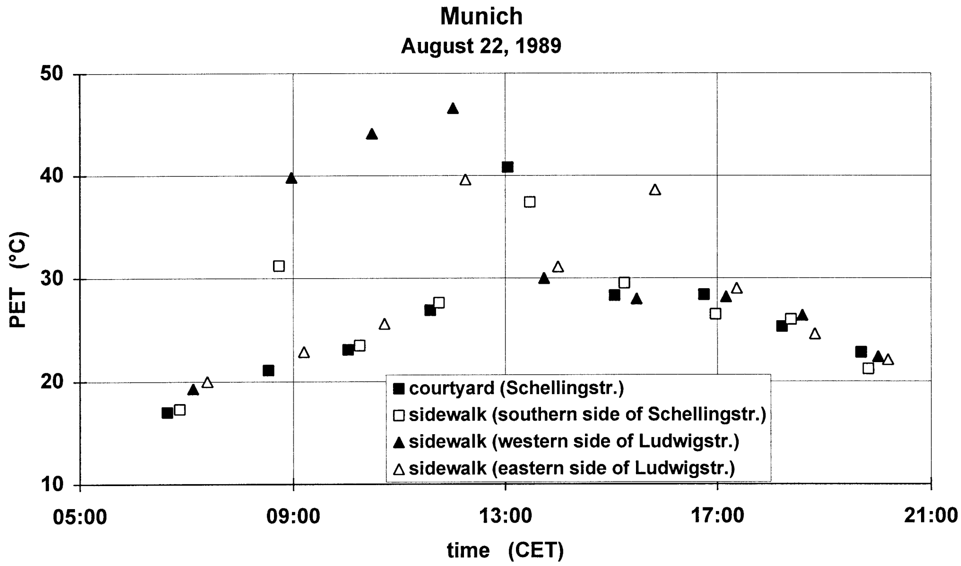

Fig. 4 Physiological equivalent temperature (*PET*) at the human-biometeorologically significant height of 1.1 m above ground at four nearby urban structures in Munich on a hot summer day

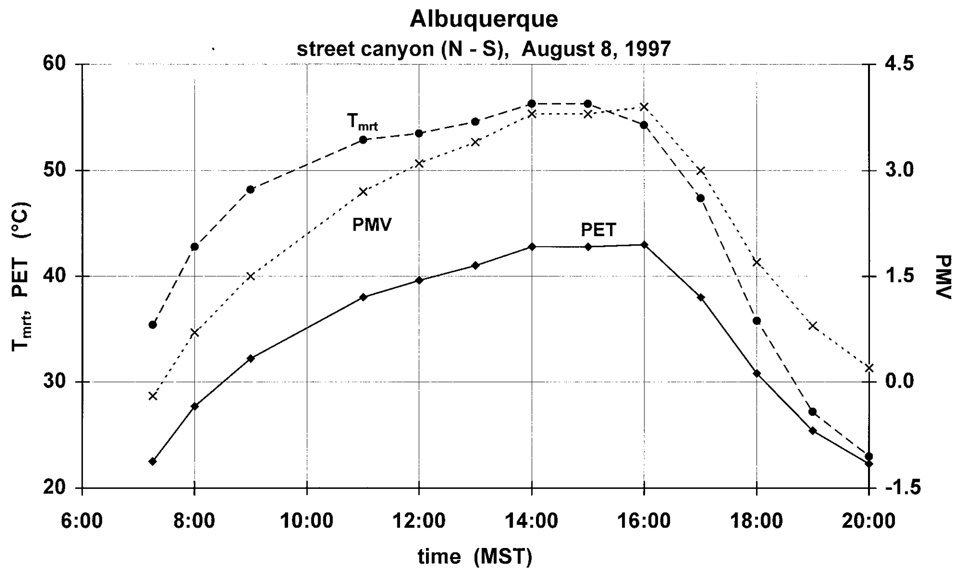

Fig. 5 Physiological equivalent temperature (*PET*), mean radiant temperature (T_{mrt}), and predicted mean vote (*PMV*) at the human-biometeorologically significant height of 1.1 m above ground in the centre of a street canyon formed by adobe-style houses in Albuquerque (N.M., USA) on a hot summer day

1500 m above sea level (asl) in the Rio Grande valley and is formed by adobe-style houses with a height of 4 m. The climatic conditions in August were characterised by high irradiation (due to a comparatively low turbidity of the atmosphere), high air temperature, low vapour pressure, and slight to moderate winds. The values for PET and the related thermal index, PMV, indicate extreme afternoon heat stress for humans. The highest PET values in Albuquerque correspond to the PET results for summer days in Freiburg and Munich. This is because the effect of higher irradiation on PET is almost compensated for by lower vapour pressure and higher wind velocity. The reduction of PET and PMV, which began at 1600 hours, was mainly caused by the influence of decreasing surface temperatures on T_{mrt} (Fig. 6).

Forest climate

The recreational function of forests plays an important role, especially when they are located within or in close proximity to cities (Mayer 1979; Mayer and Höppe 1984). Thermal conditions within the trunk space of forests constitute some of the physical factors that are responsible for the recreational value of forests.

PET has also been applied to evaluate the thermal component of the climate within a trunk space of a forest. This is illustrated by a case study carried out in summer 1995 in a 40-year-old deciduous forest (Mooswald) consisting of beech and oak trees near the western border of Freiburg (Mayer et al. 1997). As Fig. 7 shows, the differences in T_{mrt} between the open space (grassland outside of the forest) and the trunk space are greatest in the early afternoon, reaching about 30 K. During the night, however, T_{mrt} values are a little lower in the open space,

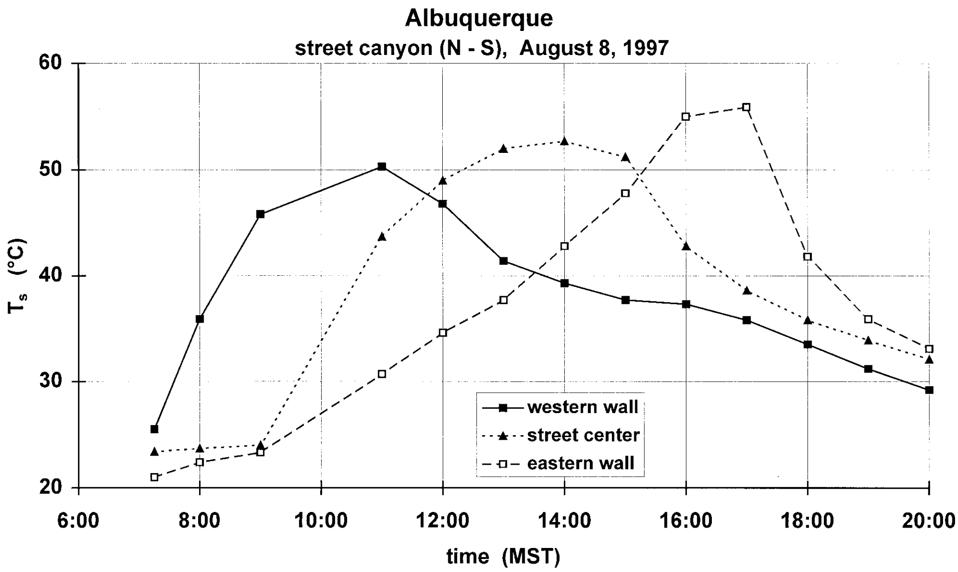

Fig. 6 Temperature (T_s) of different surfaces within an urban street canyon formed by adobe-style houses in Albuquerque (N.M., USA) on a hot summer day

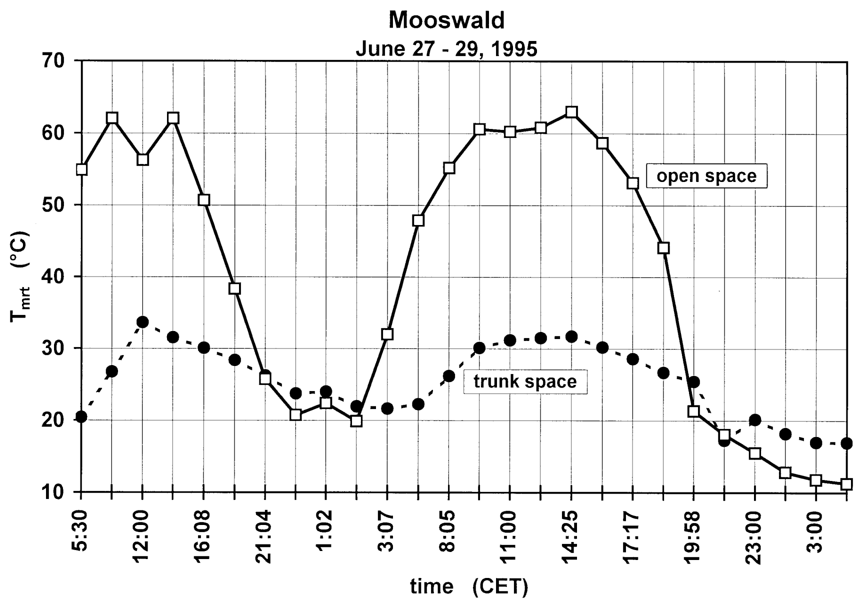

Fig. 7 Mean radiant temperature (T_{mrt}) on a warm summer day at the human-biometeorologically significant height of 1.1 m above ground within the trunk space of a deciduous forest (Mooswald) at the western border of Freiburg (south-west Germany) and out of the forest (*open space*)

which is caused by the lower long-wave radiation from the upper hemisphere.

T_{mrt} is the meteorological parameter that mostly influences PET on summer days (Mayer and Matzarakis 1998). Consequently, PET values indicate heat stresses of different intensity within the open space during the day, whereas no thermal stress or only a mild heat stress is typical for the trunk space (Fig. 8). Although this phenomenon has been qualitatively admitted for a long time, the application of PET now allows its quantification. During the night, PET values reveal a slightly stronger cold stress for human beings within the open space, since the additional downward long-wave radiation emitted from the canopy of the trees reduces the effective long-wave radiation within the trunk space, thus leading to slightly higher T_{mrt} values.

Mediterranean climate

The PET thermal index is suitable for the evaluation of the thermal environment not only in summer, but also throughout the year. As an example of such an application in a Mediterranean climate, Fig. 9 shows mean, highest and lowest PET values at 12 UTC per day at Athens airport (synoptic station Hellinikon) in Greece in the period 1980–1989. This kind of illustration provides good information on the variability of PET on each individual day of the year within the investigation period. The results in Fig. 9 show that different grades of cold stress (PET<18°C) occurred mostly from October to April. Mean PET values over 30°C, indicating at least moderate heat stress, were calculated from June to September, which is a period of 4 months. PET>30°C at noon, however, was also obtained on single days from

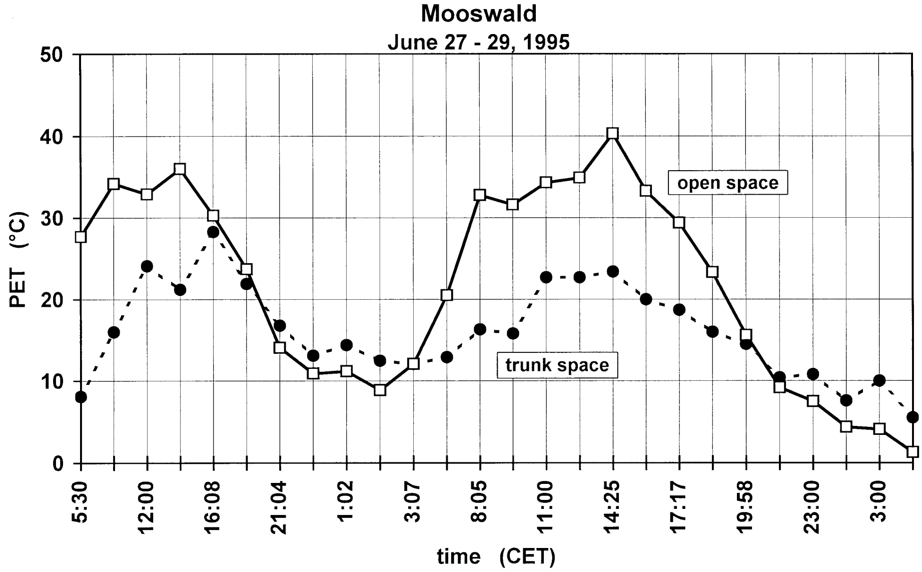

Fig. 8 Physiological equivalent temperature (*PET*) on a warm summer day at the human-biometeorologically significant height of 1.1 m above ground within the trunk space of a deciduous forest (Mooswald) at the western border of Freiburg (south-west Germany) and out of the forest (*open space*)

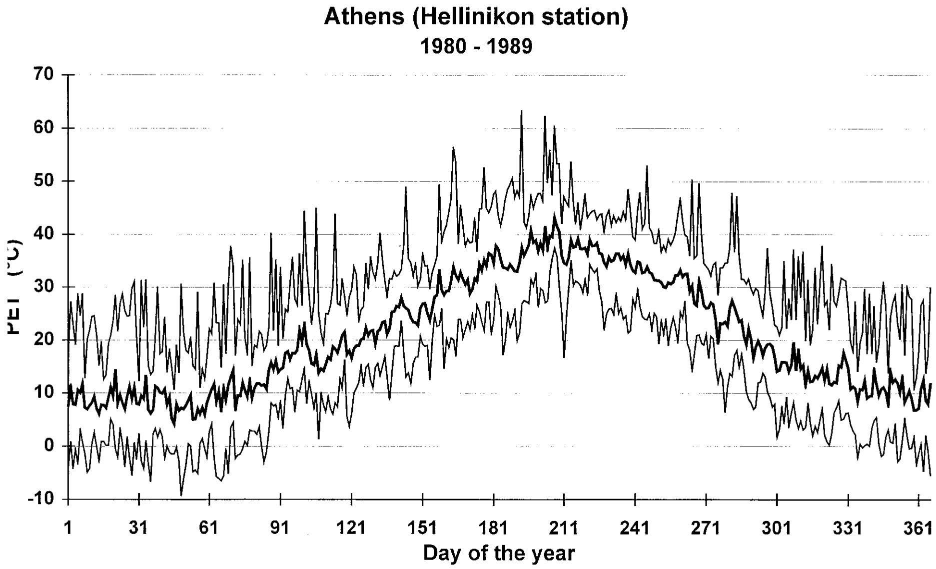

Fig. 9 Mean, highest and lowest values per day of physiological equivalent temperature (*PET*) at 12 UTC at Hellinikon station, Athens airport, for the years 1980–1989

February to May as well as from October to December. On some hot summer days from June to September, PET at 12 UTC was over 50°C, representing a pronounced thermal stress level in Athens that was much higher than at the other sites analysed here.

The results in Fig. 9, however, do not identify thermal loads on humans caused by heat waves, which are typical of Greece. This is because they can only be detected on the basis of the number of consecutive days with extreme heat stress for more than one station (Giles and Balafoutis 1990; Giles et al. 1990; Matzarakis and Mayer 1991, 1997). Therefore, the number of periods of consecutive days (at least 3 days) with PET values of 40°C or over at 12 UTC, indicating extreme heat stress, was calculated for 12 synoptic stations of the Greek Weather Service in the period 1980–1989. The results in Table 2 do not reveal a homogeneous distribution of heat waves in Greece. The average range of such episodes per year varies from less than one (island stations) to more than seven (stations in the interior of the county). The influence of topography and distance to the sea on the regional weather situation is responsible for the variation of heat waves observed in Greece.

The results given for the selected synoptic stations in Greece allow for a human-biometeorologically significant analysis of the varying thermal conditions at selected locations. There is also a need for spatial information on thermal stress level. Therefore bioclimatic maps have to be generated that display, for example, the spatial distribution of PET values. Individual PET values were charted on a map using a statistical model that also required topographical data. For this purpose, a digital relief model of Greece with a resolution of 1 min – equivalent to a resolution of 1.8 km×1.3 km for Athens – was developed (Matzarakis 1995). Topographical factors such as slope aspect and slope angle were derived from this map by use of geometric relationships.

Table 2 Number of periods of consecutive days (at least 3 days) with PET values of 40°C or higher (extreme heat stress) at selected stations (with elevations) of the Greek Weather Service for the years 1980–1989, *asl* above sea level

Station	Periods of high PET values in:										Total
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	
Larisa, Central Greece (73 m asl), continental	16	9	9	2	8	8	6	8	5	3	74
Florina, NW Greece (650 m asl), continental	11	13	7	8	9	5	5	8	7	2	75
Corfu, island in the Ionian Sea (4 m asl)	4	9	5	6	5	7	4	3	3	6	52
Samos, island in the Aegean Sea (2 m asl)	2	4	1	1	2	3	4	5	6	2	30
Hellinikon, airport of Athens (28 m asl), bay	4	2	1	0	1	2	1	3	4	1	19
Tripolis, middle of the Pellopones (644 m asl)	2	1	3	2	2	1	3	3	4	0	21
Alexandroupolis, coastal station (4 m asl) in NE Greece	3	3	2	0	0	1	1	2	4	0	16
Andravida, coastal station (17 m asl) at the western Pellopones	2	2	2	1	3	1	0	2	4	0	17
Mikra, coastal station (4 m asl) in N Greece near Thessaloniki	1	2	0	0	1	1	0	2	4	0	11
Limnos, island station (17 m asl) in the northern Aegean Sea with continental influence	0	0	1	0	1	1	0	2	2	0	7
Heraklion, in the south (37 m asl) of the island Kreta in the Aegean Sea	1	1	1	0	0	0	0	0	1	0	4
Rhodos, island station (4 m asl) in the Aegean Sea with influence by Asia Mino	0	1	0	0	0	0	0	1	1	0	3

By use of a multiple regression, a methodology was developed linking meteorological data from Greek synoptic stations that are necessary to calculate PET with geographical data, in order to generate a spatial distribution of PET values. They could thereby be calculated for each grid area as a function of latitude, shortest distance to the shore, elevation, slope aspect and slope angle, as well as the ratio of sea and land surface.

As an illustration of the resulting bioclimatic maps, Fig. 10 shows average values of PET at 12 UTC in July in Greece. Of all the summer months in Greece, July has the highest heat stress conditions for the population. PET values indicating no thermal stress are obtained for regions with elevations above 1200 m asl. Slight heat stress (PET values between 23°C and 29°C) is typical in this month for sites that are between 900 m and 1200 m asl. All regions below 600 m asl show high heat stress. There are comparatively large spatial differences between the areas with high heat stress. On the islands of the Aegean and Ionian Sea, the heat stress conditions are somewhat lower than those obtained in the interior parts of the country. Extreme heat stress is obtained for lower parts of Greece (e.g. in Thessaly and Macedonia, in the western part of Sterea Ellada, and in the southern part of Epirus) as well as for the coastal areas that are covered with land masses or closed gulfs. Most islands also fall into this category, although heat stress is much lower than in the mainland. This is due to the influence of cool, dry Etesian winds in the Aegean Sea and the development of regional wind systems in the Ionian Sea (Matzarakis 1995).

Conclusion

PET turns out to be very well suited to the human-biometeorological evaluation of the thermal component of different climates. It has its base in the energy balance of the human body and is therefore thermophysiologically significant and reproducible. Its unit (°C) makes it easily understood as an indicator of thermal stress. PET can be applied for the evaluation of different thermal environments such as the heat archipelago within cities, demonstrated here, or the flow of cold air, which is important in regional planning. Moreover, the consequences of a changed thermal environment caused by different planning variations can be quantified by use of PET. One example is the effect of different kinds of greenery or increasing green areas planted with trees. PET analysis can be applied widely and there are various possible ways of illustrating its results. Bioclimatic maps of whole cities can be generated by use of PET for application in urban

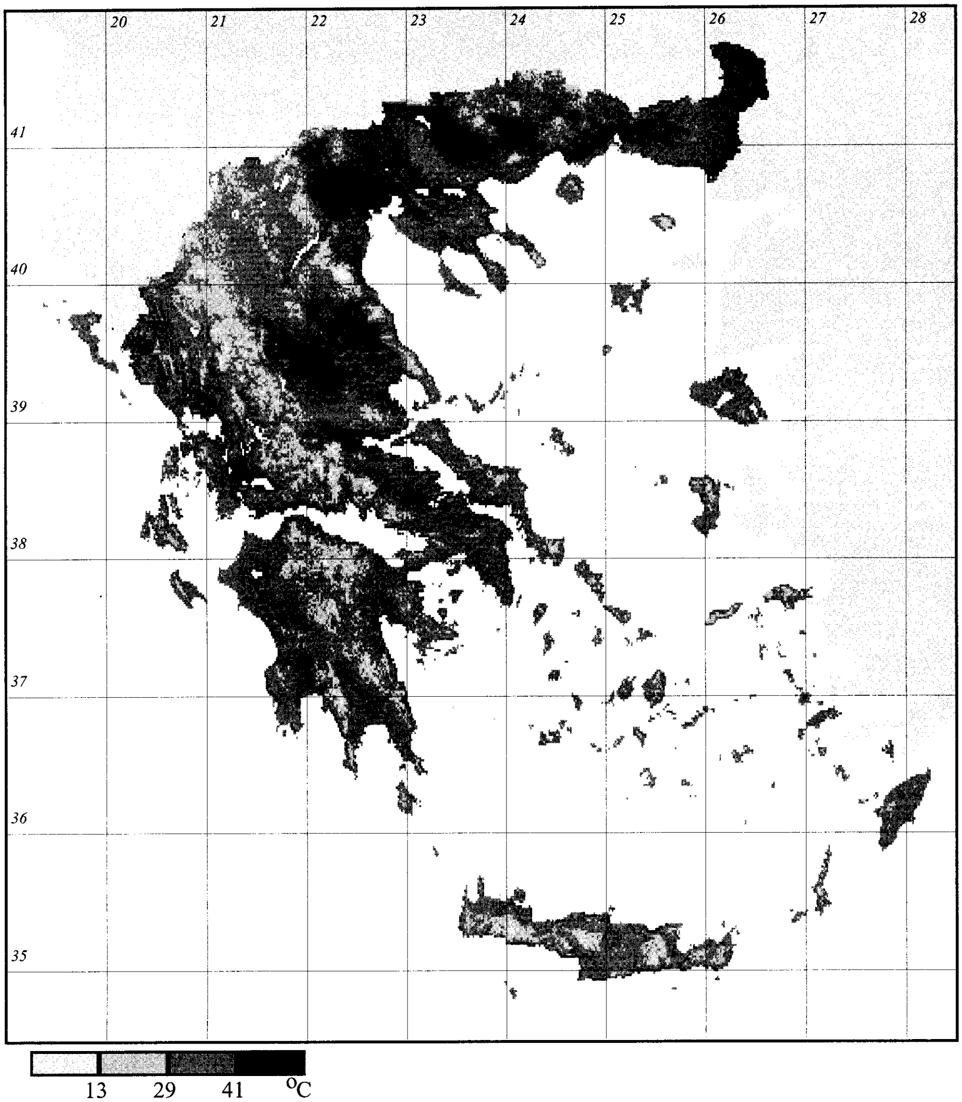

Fig. 10 Spatial distribution of mean daily values of the physiological equivalent temperature at 12 UTC in July in Greece

planning, as achieved by Grätz et al. (1994) as well as Jendritzky and Grätz (1998), with the help of PMV. They yielded a spatial resolution of 10 m×10 m for PMV values.

The ranges of PET for different grades of thermal stress in Table 1 were derived from analogous PMV ranges (VDI 1998) that are based on investigations by Fanger (1972). These ranges of PET depend on the assumed internal heat production and the thermal resistance of clothing. The question arises: are these PMV or PET ranges valid world-wide for humans? It is possible that the ranges for PMV and PET move to higher or lower values as our perception of the thermal environment or physiological processes changes and adaptation occurs. Special investigations are necessary to find a solution to this problem.

Acknowledgements The authors would like to express their special thanks to Miss Amy Doyle for checking the English version of this paper.

References

Ayoade JO (1978) Spatial and seasonal patterns of physiologic comfort in Nigeria. Arch Meteorol Geophys Bioklimatol Ser B 26:319–337

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

Fanger PO, Hojbjerre J, Thomsen JOB (1974) Thermal comfort conditions in the morning and in the evening. Int J Biometeor 18:16–22

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

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

Gonzalez RR, Nishi Y, Gagge AP (1974) Experimental evaluation of standard effective temperature: a new biometeorological index of man's thermal discomfort. Int J Biometeorol 18:1–15

Höppe PR (1993) Heat balance modelling. Experientia 49:741–746

Höppe PR (1999) The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol

Huang YJ, Akbari H, Taha H, Rosenfeld AH (1987) The potential of vegetation in reducing summer cooling loads in residential buildings. J Climate Appl Meteorol 26:1103–1116

Grätz A, Jendritzky G, Schmidt J, Brass S (1994) Stadtökologie. Die Bauverwaltung 3/94:122–126

Jendritzky G, Grätz A (1998) Human bioclimatological questions and solutions in applied urban climatology. In: Proceedings of the 2nd Japanese-German Meeting "Klimaanalyse für die Stadtplanung". Research Centre for Urban Safety and Security, Kobe University. Special report 1. pp 135–148

Jendritzky G, Menz H, Schirmer H, Schmidt-Kessen W (1990) Methodik zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima-Michel-Modell). Beitr Akad Raumforsch Landesplan 114

Matzarakis A (1995) Human-biometeorological assessment of the climate in Greece. (In Greek with extended summary in German) PhD Thesis, University Thessaloniki

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

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

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

Mayer H (1979) Forests as bioclimatic recreation areas. In: Proceedings of the WMO Symposium on Forest Meteorology, Ottawa 1978, pp 99–101

Mayer H (1993) Urban bioclimatology. Experientia 49:957–963

Mayer H, Höppe P (1984) Die Bedeutung des Waldes für die Erholung aus der Sicht der Humanbioklimatologie. Forstwiss Centralbl (Hamb) 103:125–131

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

Mayer H, Matzarakis A (1997) The urban heat island seen from the angle of human-biometeorology. In: Proceedings of the International Symposium on Monitoring and Management of the Urban Heat Island, Fujisawa, pp 84–95

Mayer H, Matzarakis A (1998) Human-biometeorological assessment of urban microclimates' thermal component. In: Proceedings 2nd Japanese-German Meeting "Klimaanalyse für die Stadtplanung". Research Centre for Urban Safety and Security, Kobe University. Special rep 1, pp 155–168

Mayer H, Matzarakis A, Linser S (1997) Thermischer Wirkungskomplex der Waldatmosphäre. Ann Meteorol 33:34–39

Simpson JR, McPherson EG (1998) Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. Atmos Environ 32:69–74

Summit J, Sommer R (1998) Urban tree-planting programs – a model for encouraging environmentally protective behavior. Atmos Environ 32:1–5

Taffé P (1997) A qualitative response model of thermal comfort. Build Environ 32:115–121

Veleva L, Pérez G, Acosta M (1997) Statistical analysis of the temperature-humidity complex and time of wetness of a tropical climate in the Yucatán peninsula in Mexico. Atmos Environ 31:773–776

VDI (1998) Methods for the human-biometeorological evaluation of climate and air quality for urban and regional planning. Part I: Climate. VDI guideline 3787. Part 2. Beuth, Berlin

Yan YY, Oliver JE (1996) The clo: a utilitarian unit to measure weather/climate comfort. Int J Climatol 16:1045–1056