Chapter 9
Physiological Equivalent Temperature as Indicator for Impacts of Climate Change on Thermal Comfort of Humans

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Abstract Using the measure of Physiologically Equivalent Temperature (PET) it is analysed how changes in the thermal environment can affect human well-being. Historical data used in this study have been assembled for the normal climate period 1961–1990 (CNTRL). Future conditions are calculated based on the period 2071–2100, for which simulated datasets are available, based on GCMs integrated with scenarios. The scenarios used here are the Intergovermental Panel on Climate Change (IPCC) second report on emission scenarios (SRES) A1F and B1A, which represent a worst and a moderate climate case. The results are shown for December, January and February (DJF, winter months in the northern hemisphere), and for June, July and August (JJA, summer months in the northern hemisphere). Areas with extreme and uncomfortable thermal conditions and heat stress affections can be identified. In many regions of the world, e.g. the Mediterranean and North America, changes in thermal perception by humans are shown to outpace changes in air temperature. This has major implications for the assessment of the health effects of climate change. It is highly likely that the effects of climate change on human health and well-being have been underestimated in past studies, because these were based on air temperature changes rather than changes in PET, which describes the effects of meteorological and thermo-physiological parameters.

Keywords Thermal comfort, physiologically Equivalent Temperature, Heat Stress

9.1 Introduction

Throughout the 21st century, air temperature will continue to rise, according to computer simulations performed with global circulation models (GCMs). In addition to air temperature, the output of these GCMs includes a range of climate variables,

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such as air humidity, wind speed and cloud cover. Based on these variables, further analysis of thermal comfort and the impacts of extreme heat conditions on humans can be undertaken.

Humans have always been aware that weather and climate affect their health and well being. Two thousand five hundred years ago, Hippocrates described regional differences of climate and their relationship to states of health. Fevers vary seasonally and so do people's moods and various psychological disturbances. Aches and pains in joints flare up in winter, while in summer heat waves debilitate and kill (World Meteorological Organisation 1999). Locations with extreme heat conditions may also result in health problems (e.g. caused by heat stress, UV-radiation, air pollution and heat strokes). Cause–effect relations between the atmospheric environment on the one hand, and human health and comfort on the other can be analysed with a human-biometeorological classification that takes into consideration:

- The thermal complex (comprises the meteorological elements which have a thermophysiological effect on humans)
- The air pollution complex (comprises solid, liquid and gaseous natural and anthropogenic air pollutants which have an effect on human health)
- The actinic complex (comprises the visible and ultraviolet spectrum of solar radiation which has a direct biological effect)

In this analysis, only the thermal complex is considered. It includes the meteorological factors air temperature, air humidity, and wind velocity, as well as short and long wave radiation, which affect humans thermo-physiologically in indoor and outdoor climates. This thermal complex is relevant to human health because of a close relationship between the thermoregulatory mechanisms and the circulatory system. Effects of the thermal environment of humans are best determined with the aid of thermal indices based on the energy balance of the human body (Verein Deutscher Ingenieure 1998). Common applications are PMV (Predicted Mean Vote) (Fanger 1972), PET (Physiologically Equivalent Temperature) (VDI 1998; Höppe 1999; Matzarakis et al. 1999), SET* (Standard Effective Temperature) (Gagge et al. 1986) or Outdoor Standard Effective Temperature (Out_SET*) (Spagnolo and de Dear 2003) and Perceived Temperature (Tinz and Jendritzky 2003). These well-documented thermal indices have varying foci, but are essentially different combinations of the same set of important meteorological and thermo-physiological parameters (Matzarakis 2001).

Unfortunately, data on several of these parameters, such as short and long wave radiation, are generally not available in climate records. As a result, climate assessments and thermal comfort studies have often resorted to the use of climate indices that do not include these key factors. For example, the Intergovermental Panel on Climate Change report (IPCC 2001) describes the effect of weather and climate on humans with a simple index based on a combination of air temperature and relative humidity. The exclusion of important meteorological (wind speed and radiation fluxes) and thermo-physiological (activity of humans and clothing) variables seriously diminishes the significance of the results. From synoptic, climatological and astronomical data, estimates for short and long wave radiation fluxes can be obtained (Verein Deutscher Ingenieure 1998; Matzarakis et al. 2000). These estimates are used in this paper to explore the effects of climate change for the thermal environment of humans around the world.

The objective of this article is twofold: (1) to give a brief overview of the assessment methods for human bioclimate and (2) to discuss some exemplary results indicating the current quality of human bioclimate at the end of the 21st century.

9.2 Data

Scenarios were used to determine the meteorological parameters needed to predict PET values. Future climatic conditions cannot be predicted with any degree of certainty, as several unpredictable factors are involved. Future socio-economical and technological developments will determine to a large extent the amount of human-induced emissions of greenhouse gases. To get a feeling for the range of possible climate conditions that may be common by the end of the century, a range of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) were used. IPCC undertook an exploration of the possible changes in socio-economical conditions and population (IPCC 2000, 2001), which resulted in a range of plausible scenarios (known as the SRES scenarios). From these, Greenhouse gases (GHG) emissions and atmospheric concentrations of greenhouse gases could be estimated, which in turn have been used to explore the response of the climate system. Among the four main SRES scenarios, the A1F and A2A represent cases of rapid climate change, while the B1A and B2A scenarios represent more moderate levels of change (Table 9.1).

The historical data that were used have been retrieved from the CRU CL 1.0 historical dataset, containing 0.5° 1961–1990 mean monthly gridded data, assembled by the Climatic Research Unit, University of East Anglia, Norwich, UK (New et al. 1999, 2000). The CRU CL 1.0 grid-based dataset is based on a dataset of 1961–1990 climatological normals, which was produced by numerous weather stations around the world. The station data were interpolated to obtain a 0.5° latitude × 0.5° long grid-based dataset, covering the entire landmass of the earth except Antarctica; ocean space is not included. From the historical data sets the mean monthly data of air temperature, relative humidity and wind speed of each grid of the globe have been used. For the calculation of the global radiation the mean monthly sunshine fraction has been manipulated to cloud cover. The way of production

Table 9.1 Description of used emission scenarios for PET-calculations

Scenario	Description
A1F	A world of rapid economic growth and rapid introductions of new and more efficient technologies
A2A	A very heterogenous world with an emphasis on family values and local traditions
B1A	A world of “dematerialization”and introduction of clean technologies
B2A	A world with an emphasis on local solutions to economic and environmental sustainability

of the grid data and their uncertainties of the climate variables are described in New et al. (1999). The mean radiant temperature of each grid of the globe has been calculated based on the possible global radiation and the mean monthly cloud cover by the RayMan model. The mean radiant temperature and the PET can be calculated in one run with the RayMan model based on input parameters (air temperature, relative humidity, wind speed and cloud cover).

The dataset of future climatic conditions was based on an integration of the Hadley Centre's HadCM3 model forced with the SRES emissions scenarios (Johns et al. 2003). The HadCM3 model produces gridded data with a spatial resolution of 2.5° latitude × 3.75° longitude, which is significantly coarser than that of the CRU 1.0 dataset. The used HadCM3 dataset consists of monthly averages for four time slices: 1961–1990, 2010–2039, 2040–2069, and 2070–2099. The uncertainties and difficulties of the climate projections data are described in Amelung (2006) and Hulme et al. (2002). All variables that were needed for the analysis of PET were available from the CRU 1.0 and HadCM3 datasets (air temperature, relative humidity and wind speed) or could be calculated from them (mean radiant temperature). The procedure of calculation of PET for the scenarios is the same as for the historical data sets.

9.3 Methods

Since the 1960s, heat balance models of the human body have become more and more accepted in the assessment of thermal comfort. The basis for these models is the human energy balance equation. One of the first and still very popular heat balance models is the comfort equation defined by Fanger (1972). Fanger introduced the thermal indices "Predicted Mean Vote" (PMV) and "Predicted Percentage Dissatisfied" (PPD) to help air-conditioning engineers create thermally comfortable indoor climates. Two decades later, Jendritzky et al. (1990) managed to make Fanger's approach applicable to outdoor conditions by assigning appropriate parameters to adjust the model the much more complex outdoor radiation conditions. This approach, which is also known as the "Klima Michel Model", is now increasingly being applied. Since this model was designed only to estimate an integral index for the thermal component of climate and not to represent a realistic description of thermal body conditions, it is able to work without the consideration of fundamental thermo-physiological regulatory processes. For example, in Fanger's approach the mean skin temperature and sweat rate are quantified as "comfort values", being only dependent on activity and not on climatic conditions (Höppe 1999).

More universally applicable models take into account all basic thermoregulatory processes, like the constriction or dilation of peripheral blood vessels and the physiological sweat rate (Höppe 1993, 1999). They enable the user to predict "real values" of thermal quantities of the body, i.e. skin temperature, core temperature, sweat rate or skin wetness. The Munich energy balance model for individuals" (MEMI) (Höppe 1993) is such a thermo-physiological heat balance model. It is the basis for the calculation of the physiologically equivalent temperature (PET).

In detail the MEMI model is based on the energy balance equation (9.1) for the human body:

$$M + W + R + C + E_{\mathrm{D}} + E_{\mathrm{Re}} + E_{\mathrm{Sw}} + S = 0 \tag{9.1}$$

Where, M the metabolic rate (internal energy production), W the physical work output, R the net radiation of the body, C the convective heat flow, E_{D} the latent heat flow to evaporate water diffusing through the skin (imperceptible perspiration), E_{Re} the sum of heat flows for heating and humidifying the inspired air, E_{Sw} the heat flow due to evaporation of sweat, and S the storage heat flow for heating or cooling the body mass. The individual terms in this equation have positive signs if they result in an energy gain for the body and negative signs in the case of an energy loss (M is always positive; W, E_{D} and E_{sw} are always negative). The unit of all heat flows is in Watt (Höppe 1999).

The individual heat flows in Eq. 9.1, are controlled by the following meteorological parameters (Verein Deutscher Ingenieure 1998; Höppe 1999):

– Air temperature: C, E_{Re}
– Air humidity: E_{D}, E_{Re}, E_{Sw}
– Wind velocity: C, E_{Sw}
– Mean radiant temperature: R

Thermo-physiological parameters are required in addition:

– Heat resistance of clothing (clo units)
– Activity of humans (in Watt)

The human body does not have any selective sensors for the perception of individual climatic parameters, but can only register (by thermoreceptors) and make a thermoregulatory response to the temperature (and any changes) of the skin and blood flow passing the hypothalamus (Höppe 1993, 1999). These temperatures, however, are influenced by the integrated effect of all climatic parameters, which are in some kind of interrelation, i.e. affect each other. In weather situations with less wind speed, for instance, the mean radiant temperature has roughly the same importance for the heat balance of the human body as the air temperature. At days with higher wind speeds, air temperature is more important than the mean radiant temperature because it dominates now the increased enhanced convective heat exchange. These interactions are only quantifiable in a realistic way by means of heat balance models (Verein Deutscher Ingenieure 1998; Höppe 1999).

PET is defined to be equivalent to the air temperature that is required to reproduce in a standardised indoor setting and for a standardised person the core and skin temperatures that are observed under the conditions being assessed (Verein Deutscher Ingenieure 1998; Höppe 1999). The standardised person is characterised by a work metabolism of 80 W of light activity, in addition to basic metabolism; and by 0.9 clo of heat resistance as a result of clothing.

The following assumptions are made for 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 vapour pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at T_a = 20°C).

The calculation of PET includes the following steps:

- Calculation of the thermal conditions of the body with 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 $T_{mrt} = T_a$).

Finally the resulting air temperature is equivalent to PET. PET allows the evaluation of thermal conditions in a physiologically significant manner, too. With respect to this, Matzarakis and Mayer (1996) transferred ranges of PMV for thermal perception and grade of physiological stress on human beings (Fanger 1972) into corresponding PET ranges (Table 9.2). They are valid only for the assumed values of internal heat production and thermal resistance of the clothing.

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

Table 9.2 Ranges of the 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 Matzarakis and Mayer 1996)

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

PET can be calculated with the radiation and bioclimate model RayMan, which is suitable for the calculation of the radiation fluxes and thermal indices a.e. PET in easy and complex environments (Matzarakis et al. 2000). RayMan includes the MEMI model and the calculation procedure for PET and is free available software.

9.4 Results

In order to have reference values for present climate conditions PET has been calculated from historical data sets. For climate projections have been used the scenarios results of HadCM3 model for the PET calculations.

The analyses have been carried out for two seasons and two time slices (i.e. intervals). The time segments represent seasons consisting of the combined months of December, January, and February, and the combined months of June, July, and August, coinciding with the winter and summer seasons in the northern hemisphere and the other way round in the southern hemisphere. Analysis has been carried out for the historical period 1961–1990 (CNTRL) and the future period 2071–2100. The PET values have been calculated with the RayMan model (Matzarakis et al. 2000).

Figure 9.1 shows the PET conditions for CNTRL (a, top) in the JJA season, and the expected changes according to the A1F scenario (b, middle panel) and the B1A scenario (c, bottom panel). The top panel can be taken as a proxy for actual bioclimatic conditions. A comparison of current and future conditions, projected by the scenarios, shows remarkable changes. The A1F projections show a shift towards warmer conditions in all regions of the world. Many parts of the world, including the Mediterranean and areas in North America show changes in PET values in excess of 10°C, which are much higher than the expected changes in air temperature for these regions. Especially in the Mediterranean and areas in North America the PET can increase more than 15°C, which corresponds to three levels of increased physiological strain for humans according to Table 9.2 classification. While PET values will increase in most areas, slight cooling will occur in a relatively small area around Gabon in Africa, and in a somewhat larger area around Burma and Thailand in Asia. As expected, the B1A projections show more moderate results, with PET conditions ranging between A1F and CNTRL. In some parts of the world (particularly in the southern hemisphere) the conditions will not change significantly and some small areas, i.e. Gabon will be have lower PET as the CNTRL conditions.

Figure 9.2a (top panel) shows the PET conditions for the DJF season. In the A1F projections, the DJF PET values will be higher than they are in the current CNTRL situation (see Fig. 9.2b, middle panel). This holds for all the world's regions, with the greatest changes occurring in the northern latitudes (sometimes in excess of 10°C) and the smallest changes taking place in the middle and lower latitudes. Analogous to the results from the JJA season, B1A projections indicate smaller changes in the DJF season than the A1F projections (Fig. 9.2c, bottom panel). Apart from the area close to the North Pole in which the level of change is

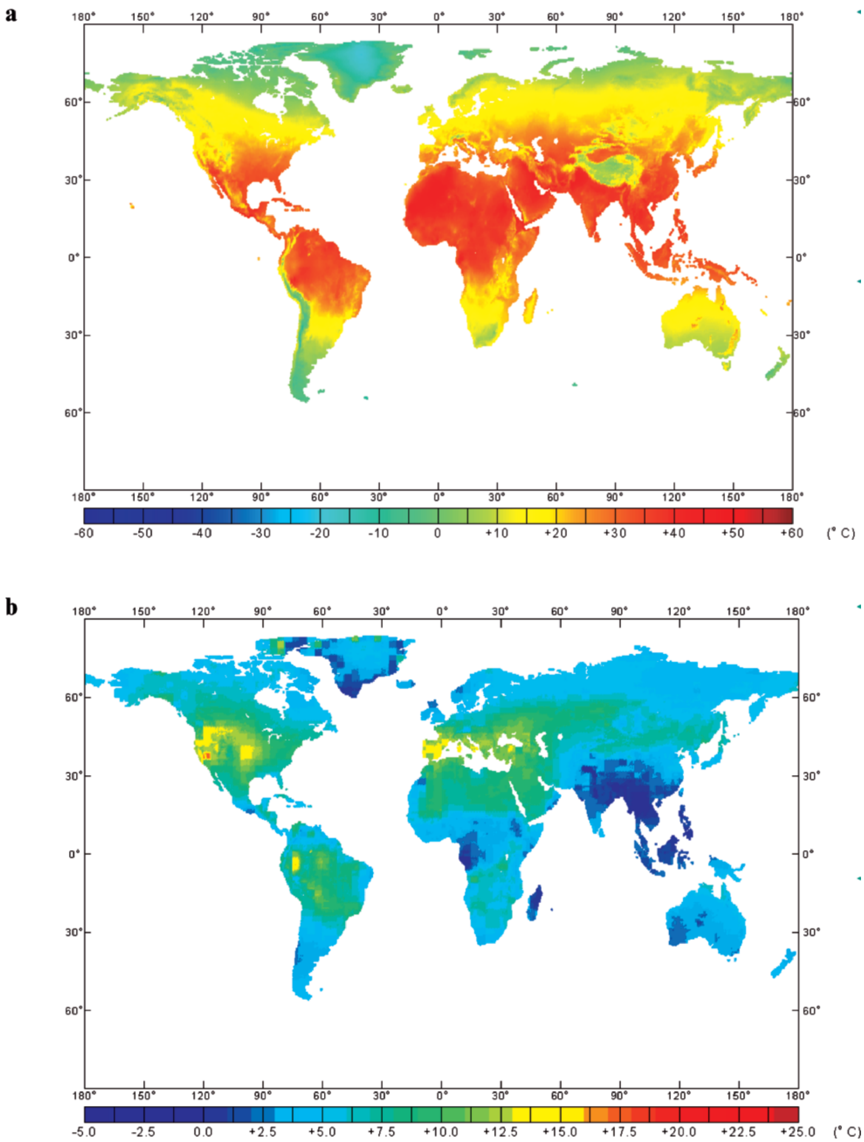


Fig. 9.1 (continued)

considerable, changes are moderate to small. A small area of West Africa will even experience slight cooling. In comparison to the maximum changes of PET the physiological strain value will be lower (more than one class) than the A1F projections, according to the classification of Table 9.2.

c

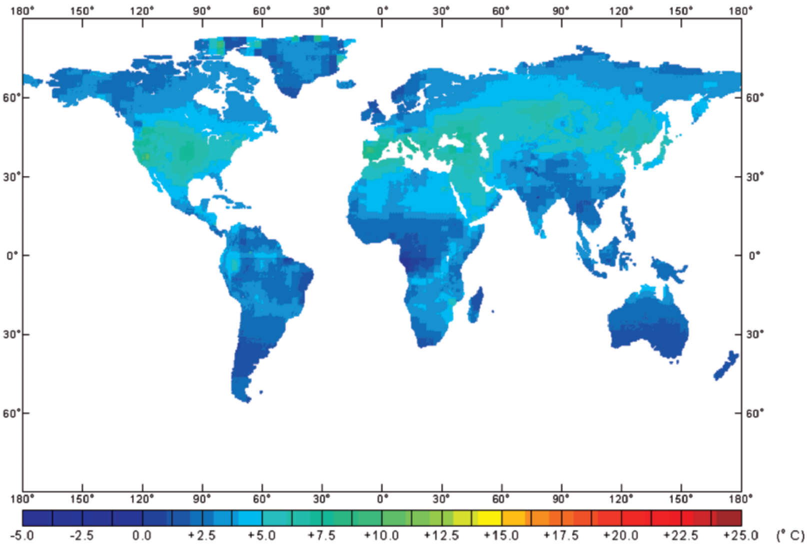


Fig. 9.1 (continued) Basic PET conditions (a) and differences between time slice (2070–2100) minus (1961–1990) for A1F (b) and B1A (c) for JJA (*see* Appendix 2)

a

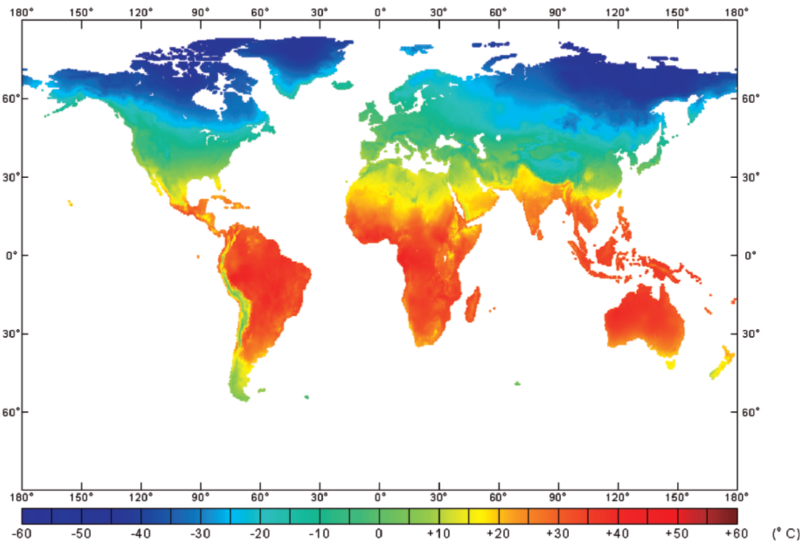
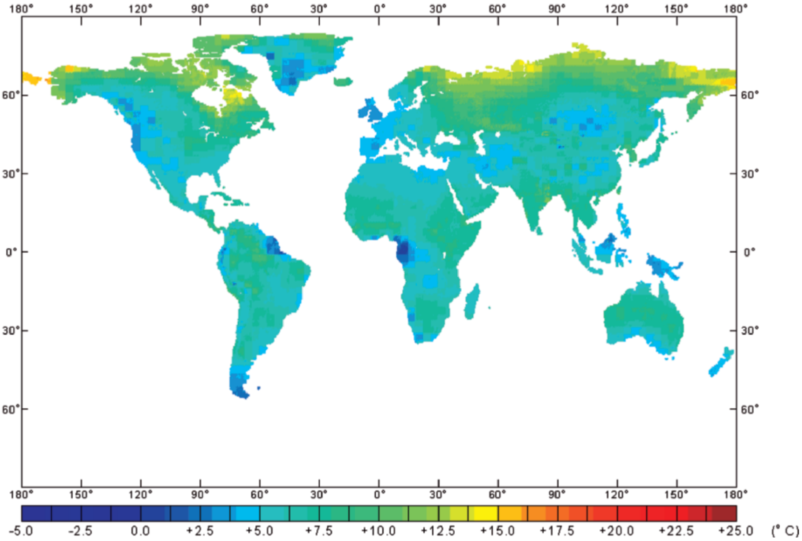


Fig. 9.2 (continued)

b



c

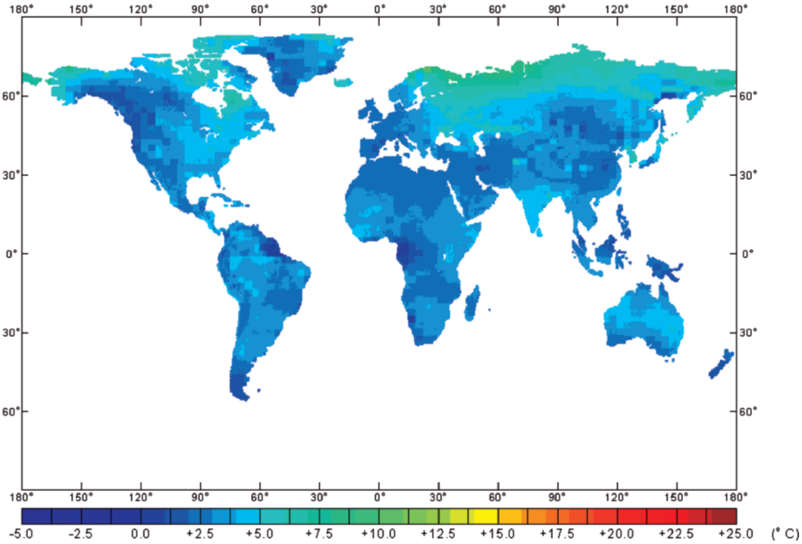


Fig. 9.2 (continued) Basic PET conditions (a) and differences between time slice (2070–2100) minus (1961–1990) for A1F (b) and B1A (c) for DJF (*see* Appendix 2)

9.5 Conclusions

The main conclusion from this paper is that the thermal consequences on humans of climate change should have been underestimated. Changes in the overall bioclimatic conditions for humans are expected to be considerably greater than changes in air temperature alone. Changes in non-temperature factors such as short and long wave radiation appear to reinforce the first-order effects of temperature change. In most regions of the world, the projected climate change will produce bioclimatic conditions that are more stressful (a PET of more than 35 means extreme hot conditions for Europeans) to people and affect their health and well being. Regions with PET >35°C will be increase compared to present bioclimatic conditions and the possibility of heat waves will also increase. In addition, the changed thermal conditions will lead to higher energy consumption (and higher emissions of greenhouse gases) as a result of the increased need for cooling.

The results presented in this paper have to be considered as a first approach. The analyses could be further elaborated by undertaking more detailed studies comparing different GCMs, including regional climate effects, extreme events (Heat waves) and expected future land use changes. It has to be mentioned that the uncertainties in the input data, which are included in the data derived from the climate scenarios have an influence in the thermal bioclimate conditions. These uncertainties a.e. an increase of air temperature of 2°C in thermal neutral conditions (air temperature 20°C) is associated with an increase of PET of 2.4°C.

Nevertheless, the information and results in their current form are already very likely to be assisting in decision making on various levels, including health, tourism and regional planning.

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