312: Development and application of assessment methods for thermal bioclimate conditions in Stuttgart

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Abstract

The complex region of Stuttgart, located in the south-westerly part of Germany, favours warm and humid climate accompanied by a low wind speed. Stuttgart lies in a Keuper sink and is surrounded by hills, a fact, which enforces the specific formation of these thermal and air quality conditions. The Urban Heat Island (UHI) of Stuttgart and its spatial distribution should be assessed using human-biometeorological methods. The most important and popular indices, Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) are applied and compared. The spatial variability of the thermal bioclimate in Stuttgart is mainly governed by differences mostly in wind speed. UTCI and PET show the largest differences in the very low and high ranges due to different scaling to thermal perception and clothing models. But also in the range of thermal response, they might differ by one range in the thermo-physiological assessment scale.

Keywords: thermal indices, urban bioclimate, RayMan, Stuttgart, Germany

1. Introduction

Artificial surfaces, anthropogenic production of heat and air pollution alter the urban atmosphere. Air and surface temperature alterations are the most obvious and characteristic phenomenon of the urban microclimate. The UHI intensity for a given urban location is defined as the difference between the air and surface temperature of the urban and a nearby rural reference site (Wilby 2003).

The urban climate shows spatial differences as a function of the surface structure influencing the aerodynamic surface structure and triggering changes in the radiation fluxes (Matzarakis 2001). The aim is to study these spatial differences of urban climate. As the city does not only alter the air temperature (Wilby 2003), but also wind speed (Oke 1973), air humidity (Mayer et al. 2003) and in general the energy budget, all these factors should be evaluated based on the effects of them on city dweller. First of all, the current intra-urban situation is evaluated and second, different available thermal indices are compared, third the influence of single meteorological parameters on thermal indices is analysed.

1.1 Study area

Stuttgart is the fourth largest metropolitan region of Germany and had a population of 0.6 million in 2008. Stuttgart is spread across several hills, valleys and parks (Figure 1). The city centre, called Stuttgarter Kessel (cauldron) lies in a Keuper sink and is surrounded by hills. Besides of that greater Stuttgart is one of the warmest regions in Germany. Its location favours warmer and humid climate than in the surrounding rural side. As the metropolitan region lies in the lee of the Black Forest it has less precipitation compared to other regions in Germany. As Stuttgart is the most important city for industry, education, culture and policy in the south-western part of Germany, the city and its population attained growth. Those city dwellers suffer not only from strong UHI, but also from strong air pollution caused by weather conditions connected with a low wind speed.

Compared to other cities the low wind speed is a unique feature in Stuttgart.

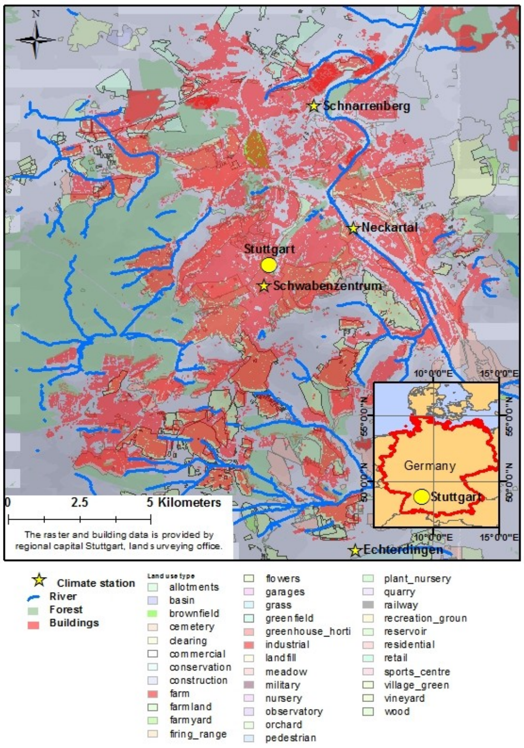

Fig 1. Map of Stuttgart in the south-westerly part of Germany.

The investigation of the UHI for the purpose of / on behalf of city planners has to focus on the thermal perception of humans, wherefore air temperature, wind speed, air humidity and radiation has to be taken into account. This can be done by using thermal indices as the Physiologically Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), Standard Effective Temperature (SET*) or Perceived Temperature (PT).
The aim of this paper is to compare different methods determining the thermal comfort of the population and its spatial variation. The most used thermal indices based on the human energy budget PET, UTCI, SET* and PT are compared and correlated with the meteorological parameter wind speed, air temperature, air humidity and mean radiant temperature.

1.2 Frame project

The aim of the transnational cooperation project, within the Central Europe Programme „Development and application of mitigation and adaptation strategies and measures for counteracting the global urban heat island (UHI) phenomenon“ is to investigate and quantify methods for prevention, adaptation and mitigation of natural and man-made risks, arising from the urban heat island.

2. Methods

2.1 Data

Four measuring stations are located in Stuttgart, Neckartal (Neckar valley), Schwabenzentrum (city centre), Schnarrenberg and Hohenheim (suburb). The rural reference station is located at the airport in Leinfelden-Echterdingen (371 m asl). The measuring station in Schwabenzentrum, located in the city centre on the top of a 25 m high house, is a background measuring station at an altitude of 250 m asl. The horizontal distance between the rural and urban climate stations is around 11 -12 km.

Table 1: Coordinates and altitude (asl) above sea level of the measuring devices

Climate Station	Lat (N)	Long (E).	Altitude
Neckartal	48:47	09:13	224 m
Schwabenzentrum	48:46	09:10	250 m
Schnarrenberg	48:50	09:12	314 m
Hohenheim	48:42	09:02	405 m
Echterdingen	48:41	09:14	371 m

As human beings experience the integral effect of meteorological parameters (air temperature, air humidity, wind speed, and radiation fluxes), the bioclimate of Stuttgart is assessed using thermal indices.

2.2 Physiologically Equivalent Temperature

PET is based on the energy balance of humans (Mayer and Höppe 1987, Matzarakis et al., 1999) in terms of the Munich Energy Balance Model for Individuals (Höppe 1983, 1993). PET is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperature equal of those being assessed. For the indoor reference climate is assumed that the mean radiant temperature (T_{mrt}) corresponds to the air temperature (T_a), wind speed (v) is 0.1 m/s and the water vapour pressure (VP) is 12.5 hPa with a metabolic rate of 80 W of light activity, added to the basic metabolism and the heat resistance of clothing is 0.9 clo. For a man sitting indoor under the above mentioned conditions the thermal comfort is described by a PET of 18-23°C (Table 1). PET has the advantage to be in the unit degree Celsius (°C), which makes it more comprehensible for e.g. urban planners (Höppe 1999). Therefore, the German Association of Engineers recommends the application of PET for the evaluation of the thermal component (VDI 1998).
PET is calculated using the model RayMan (Matzarakis et al., 2007, 2010). The wind speed is calculated for the height of 1.1 m, the human centre of gravity using following equation (Kuttler 2000):

$$WS_{1.1}=WS_h\cdot(1.1/h)^{\alpha}$$

where WS_h is the wind speed (ms^{-1}) at a height of h=10 m, α is an empirical exponent $\alpha=0.12\cdot z_0+0.18$, depending on the roughness length z_0.

2.3 The Universal Thermal Climate Index

UTCI follows the concept of an equivalent temperature. The meteorological conditions are compared to a reference environment, which has 50% relative humidity, calm air and the mean radiant temperature being equal to the air temperature (Jendritzky et al. 2012). The UTCI equivalent temperature for a given meteorological condition is defined as the air temperature of the reference environment that produces the same physiological stress (strain). These dynamic physiological reactions are multidimensional (core temperature, sweat rate, skin hydration, etc. at different exposure times).
As a one-dimensional representation of the model responses therefore UTCI stress index was calculated as strain on a principal component analysis (Bröde et al 2009). The thermal stress can thus be evaluated over a 10-point scale of "extreme heat stress" to "extreme cold stress". UTCI values between 18 and 26ºC may comply closely with the definition of the “thermal comfort zone” supplied in the *Glossary of Terms for Thermal Physiology* (2003).

2.4 Perceived Temperature

PT is an equivalent temperature based on the heat budget of the human body considering the integral effect of air temperature, air humidity, mean radiant temperature and wind velocity (Staiger et al. 1997). The perceived temperature is calculated using the Klima-Michel-Model of the German Meteorological Service (DWD, Jendritzky et al. 1979, 1990), which is based on the comfort equation by Fanger (1972). The Klima-Michel-Model translates PMV to outdoor applications using measuring or forecast data to calculate the mean radiant temperature. PT is expressed in degree Celsius.

2.5 Standard Effective Temperature

SET* is based on a dynamic two node model of the human temperature regulation (Gagge et al. 1986). A transient energy balance states that the rate of heat storage is equal to the net heat gain minus the heat loss. The standard effective temperature is defined as the equivalent temperature of a hypothetical isothermal environment at 50% relative humidity in which a human subject wearing clothes, standardized for activity concerned, would have the same heat stress (skin temperature) and thermoregulatory strain (skin wetness) he would have in the actual test environment (Gagge et al. 1986).

3. Results

PET is compared between four stations and the rural reference climate station during 2003 (Fig. 2).

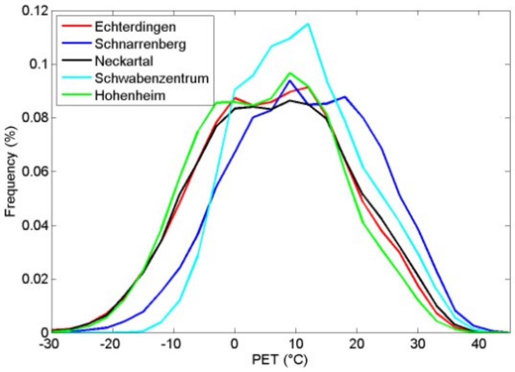

Fig 2. Frequencies of PET for the rural reference station Echterdingen (red) and the urban stations in Stuttgart Schnarrenberg (blue), Schwabenzentrum (cyan), Neckartal (black) and Hohenheim (green). Based on meteorological data (1 h mean values) for 2003.

The most frequent PET range measured in Echterdingen is between -2.5 to 2.5°C and in Stuttgart between 2.5 to 7.5°C. The minimal range of PET in Echterdingen is around 5°C lower than in Stuttgart. The maximum is 5°C higher in Stuttgart Schwabenzentrum compared to the rural reference station and 10°C in Stuttgart Neckartal. In Stuttgart, PET is not only in average but also during the extreme events two comfort ranges higher, which is, especially during heat waves, an issue. Factors for this difference between rural and urban station are the difference of altitude, but also the urban heat island and especially the lower wind speed in Stuttgart. As the Neckar valley is known for its low wind speed, this is the cause for higher PET values in Neckartal than in Schwabenzentrum. However, the daily maxima during heat periods are often higher in Schwabenzentrum than in Neckartal. This can be explained by the surface type. While in the city centre around the climate station the area is sealed with less vegetation, the climate station Neckartal is located next to the river Neckar and is rather surrounded by green areas.

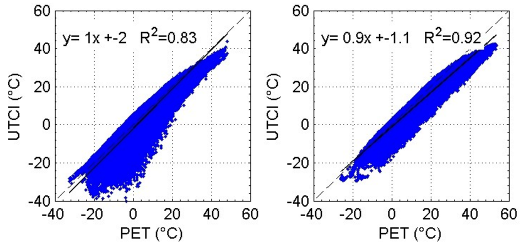

Fig 3. Scatterplot of PET vs. UTCI for the rural reference station Echterdingen (right) and the urban station Stuttgart- Schwabenzentrum (left) on the basis of hourly data from 1987-2010.

Figure 3 shows a comparison of PET and UTCI at the rural site (Echterdingen (Fig. 3, right) and in Stuttgart (Fig. 3, left). Largest differences occur below UTCI of -20°C and above 35°C the data is also skewed. UTCI has lower temperature during very cold periods, as the UTCI scale differs from the one of PET especially in this temperature range. PET leans rather to heat stress than UTCI due to the defined clothing, while UTCI has integrated an acclimatised clothing model. In Echterdingen the difference between UTCI and PET is larger than in the city of Stuttgart. This might be caused by the stronger wind speed in the rural area and colder temperatures.
The perceived temperature PT (Staiger et al. 1996), Standard Effective Temperature SET* (Gagge et al. 1986) and PET are very similar (Table 2), but show a slight bias under warm conditions.

Table 2: Comparison of the most frequent used thermal indices, which are based on the human-energy balance.

Thermal Indices	PET	UTCI	PT	SET*
PET		0.83	0.97	0.99
UTCI	0.83		0.84	0.85
PT	0.97	0.84		0.97
SET*	0.99	0.85	0.97	

PET and SET* have the strongest correlation with t_{mrt} while UTCI and PT correlate stronger with air temperature. Wind speed has the strongest influence on UTCI, but does not feature significantly in Stuttgart (Table 3)

Table 3: Comparison of the most frequent used thermal indices and meteorological parameter air temperature t_a, vapour pressure VP, wind speed v and mean radiant temperature t_{mrt}

Thermal Indices	t_a	VP	v	t_{mrt}
PET	0.90	0.56	0.01	0.91
UTCI	0.81	0.63	0.07	0.61
PT	0.95	0.65	0.01	0.82
SET*	0.87	0.58	0.01	0.90

4. Conclusion

We can conclude that the thermal bioclimate and the meteorological parameters show a highly spatial variability. The difference between city center and rural reference station is largest in winter and becomes smaller in very warm season. The intra-urban variability can be explained by the elevation and position of the climate station. Very low wind velocity is the feature, which distinct Stuttgart from other cities and significantly alters the thermal bioclimate and in Stuttgart.

The differences between UTCI and PET are particularly large during very cold and very warm weather, because an acclimatised clothing model is integrated in the calculation of the UTCI, while for the calculation of PET the clothing is defined. However, PET is wider used and is good for comparison of different cities. PET and SET* depend strongest with T_{mrt}, while UTCI and PT have the strongest correlation with T_a.

6. Acknowledgements

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