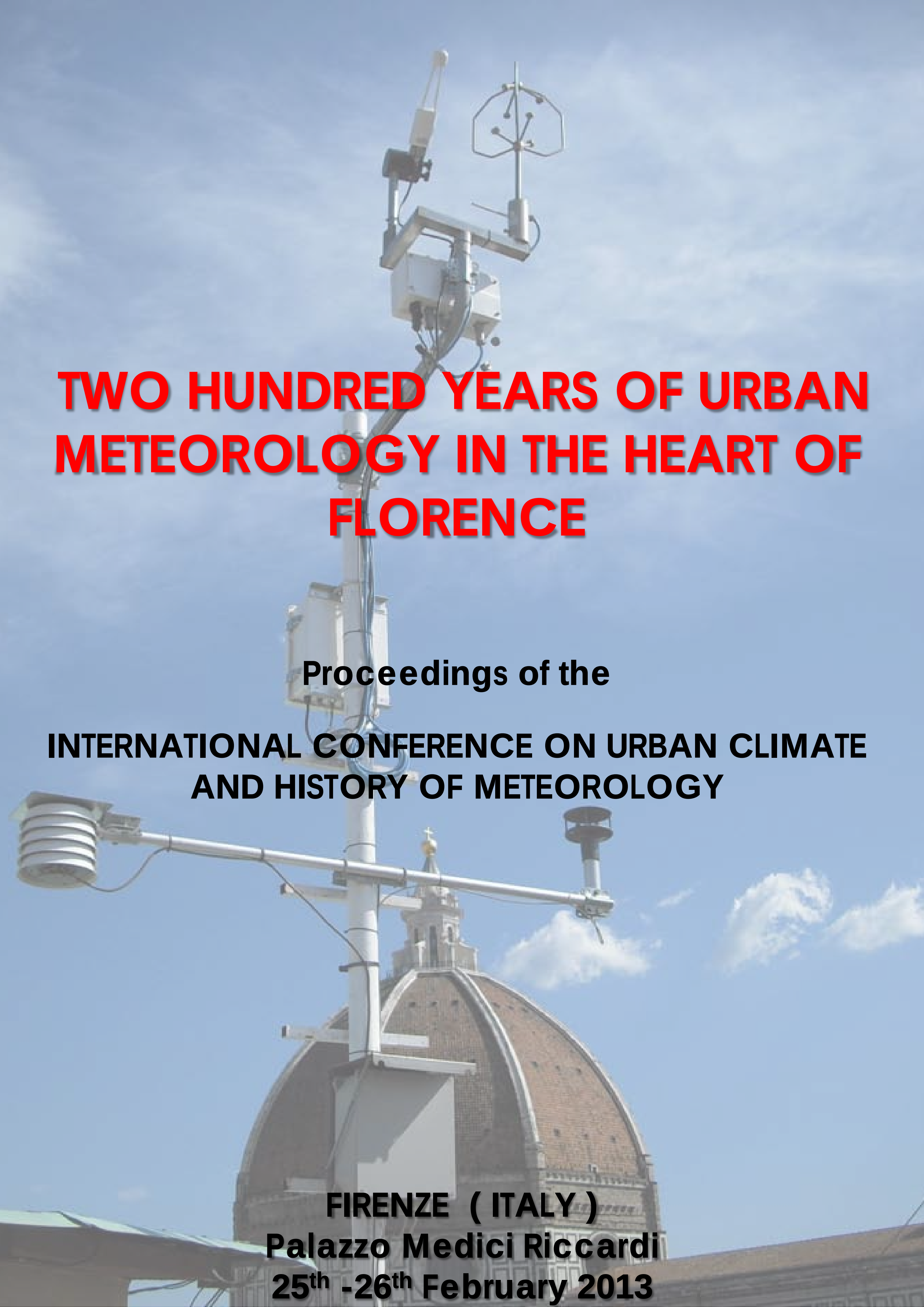

TWO HUNDRED YEARS OF URBAN METEOROLOGY IN THE HEART OF FLORENCE

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THE DILEMMA IN THERMAL COMFORT ESTIMATIONS IN URBAN AREAS

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Summary

Current quantifications of the thermal environment are based on the human energy balance and the derived thermal indices (i.e. Physiologically Equivalent Temperature or Universal Thermal Climate Index). The advantage of these indices based on the human energy balance is the possibility of their application to environments ranging from cold to hot conditions. One advantage of the thermal indices is the output from human energy balance calculations is terms of a temperature and easy understandable by non-specialists in human biometeorology. Another advantage is that most of the thermal indices require the same meteorological input data (air temperature, air humidity, wind speed and mean radiant temperature) and thermo-physiological information (activity and heat transfer of clothing covering skin surface). Meteorological parameters contain pronounced variability in the spatial and temporal dimension. In addition, the input parameters vary with measurement height and different transfer techniques into appropriate input conditions of thermal indices. Several examples for this influence of input parameters and their variability on thermal indices in urban structures are shown.

Keywords: thermal indices, physiologically equivalent temperature, universal thermal climate index, measurements, modelling

INTRODUCTION

Modern human biometeorological methods are based on the human energy balance of the human body and extracted thermal indices can describe the effects of the thermal environment on humans (Mayer 1993). The result of a thermal index is mostly given as a temperature (e.g. Physiologically Equivalent Temperature (PET) or Universal Thermal Climate Index (UTCI)), which is easier acceptable and understandable by applied sciences (Höppe 1999, Matzarakis 2006, Matzarakis and Amelung 2008). In order to derive a specific result about the influence of the thermal environment, the human energy balance has to be solved with meteorological data and thermo-physiological information. The thermo-physiological data can be summarized in terms of clothing and activity. They are well quantified in several studies and can be used as standard for several studies in order to have comparable conditions (e.g. VDI 1998). The meteorological data required are air temperature, air humidity (relative humidity or vapour pressure), wind speed and the synthetically human-biometeorological quantification of the short- and long wave radiation fluxes in terms of the mean radiant temperature (VDI 1998, Matzarakis et al. 2007).

The availability and accuracy of meteorological data is the first step to be done in order to quantify thermal comfort or stress issues. From the data required usually air temperature and air humidity are avail-able at most from synoptic or climatological networks (Matzarakis 2006). Wind is usually included in synoptic observations and measured at 10 m height a.g.l. and has to be reduced for the human weighting center of 1.1 m a.g.l for the most thermal indices. The wind information from climatological or synoptic networks has to be also transformed from wind force to wind velocity. It has to be mentioned that at most the wind has a large variability in the spatial dimension and is also modified by regional and local climatological factors, e.g. land and sea breezes. Finally, the mean radiant temperature, which is

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difficult to be quantified due to atmospheric influences firstly by clouds and other meteorological compounds as vapour pressure or particles (Matzarakis et al. 2010). In addition, the influences of topography or urban morphology modify not only wind but also radiation properties in the meso- and micro-scale (Lin et al. 2010). The data measured is based on different kind of instruments and are accompanied with different resolutions, quality and accuracy. Therefore the challenge is often not the used method but the required and available data in the spatial and temporal dimension (Matzarakis 2001, 2010).

All this parameters or factors fitted in human energy balance models delivers a specific thermal index, which describes in an appropriate manner the thermal environment and can be used for several applications from global to micro scale issues (Matzarakis 2006, 2007, Matzarakis and Amelung 2008, Scott et al. 2009).

METHODS

The effect of the thermal environment on humans, can be described by thermal indices, which are based on the human energy balance and are appropriate for the description of the effects of climate not only for cold but also for warm conditions (Fanger 1972; Gagge et al. 1996; Matzarakis 2007; Spagnolo and de Dear 2003, Jendritzky et al., 2012, Staiger et al., 2012). Two of the most popular physiological thermal indices derived from the human energy balance (Höppe 1993) the Physiologically Equivalent Temperature (PET) (Mayer and Höppe, 1987, Höppe, 1999, Matzarakis et al., 1999) and Universal Thermal Climate Index (UTCI) are chosen. PET is defined as the physiological equivalent temperature at any given place (outdoors or indoors), equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (with light activity (80 W) and heat resistance of clothing (0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed (VDI 1998, Höppe 1999).

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 procedure for the calculation of PET contains the following steps (Höppe 1984, 1999):

- 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 Ta (with v =0.1 m/s, VP = 12 hPa and Tmrt = Ta).
- The resulting air temperature is equivalent to PET.

Compared to other thermal indices, which are likewise obtained from the human energy balance, e.g., the predicted mean vote (PMV), PET offers the advantage of a widely known unit (degrees Celsius), which makes results more comprehensible to regional or tourism planners, who may not be so familiar with the modern human-biometeorological terminology (Matzarakis et al. 1999). Similar to the frequently used PMV index (Fanger 1972; Matzarakis and Mayer 1997), PET is one of the universal indices to characterise the thermal bioclimate. It allows the evaluation of thermal conditions in a physiologically significant manner. 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; Mayer 1993) into corresponding PET ranges. They are valid only for the assumed values of internal heat production and thermal resistance of the clothing (Matzarakis and Mayer, 1996) and are applied very often.

The UTCI is defined as the air temperature of the reference condition causing the same model response as the actual condition. Thus, UTCI is the air temperature, which would produce under reference conditions the same thermal strain as in the actual thermal environment. Both, meteorological and non-meteorological (metabolic rate and thermal resistance of clothing) reference conditions were defined:

- Wind speed (v) of 0.5 m/s at 10 m height (approximately 0.3 m/s in 1.1 m),
- Mean radiant temperature (Tmrt) equal to air temperature and,
- Vapour pressure (VP) that represent relative humidity of 50%; at high air temperatures (>29 ºC) the reference humidity was taken constant at 20 hPa.
- Representative activity to be that of a person walking with a speed of v = 4 km/h (1.1 m/s). This provides a metabolic rate of 2.3 met (135 W/m²).

The adjustment of clothing insulation is a powerful behavioral response to changing climatic conditions. Thereby, the philosophy for UTCI was to consider seasonal clothing adaptation habits of Europeans based on available data from field surveys in order to obtain a realistic representation of this behavioral action that notably affects the human perception on the outdoor climate.

For applications the categorization of the different values of UTCI in terms of thermal stress is required (Błażejczyk et al., 2010). The present approach looks at responses for the reference conditions and deducts load (i.e. heat or cold stress) caused by physiological response of an organism at actual environmental conditions. It can be noted that with respect to the averaged dynamic thermal sensation UTCI values between 18 and 26 °C may comply closely with the definition of the “thermal comfort zone” supplied in the Glossary of Terms for Thermal Physiology (International Union of Physiological Sciences - Thermal Commission, 2003) as: “The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period”.

The thermal environment expressed in terms of PET or UTCI can be calculated by the radiation and energy balance model RayMan (Matzarakis et al. 2007, 2010). For the assessment of thermal comfort issues the meteorological information needed has to be adjusted and cannot be taken directly from a meteorological station or measurement network. The needed parameters (air temperature, air humidity, and wind speed) have to be converted to the gravity center of the human body (1.1 m). More complicated is the mean radiant temperature, which has to be calculated or simulated.

Table 1. Human-biometeorological parameters in their spatial and temporal dimension required for the quantification of thermal comfort.

Parameter	**Spatial**	**Temporal**
Air temperature	Medium	High
Vapour pressure	Medium	High
Wind speed	Large	Medium
Mean radiant temperature (short- and long-wave radiation)	Large	Large
Activity	None	High
Clothing	None	Medium

In addition the input parameters have a temporal and spatial variability (Table 1), which has a huge influence on thermal indices and has to be considered in the assessment and quantification of thermal comfort issues. Table 1 shows

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the spatial and temporal variability of the input parameters. So, for a diurnal quantification of thermal comfort the input parameters have to be known and be available considering their daily variability. In complex areas, wind speed and mean radiant temperature have the highest variability and are modified by surroundings and obstacles. Many measurements are performed without the required quality and appropriateness, i.e. excluding artificial ventilation or without radiation shield in air temperature leading to errors in the results.

The aim of this paper is therefore to show the effects and difficulties in the assessment of the input parameters and the differences in the used thermal indices. This was done by making adjustments in the input parameters, mostly in wind speed and mean radiant temperature.

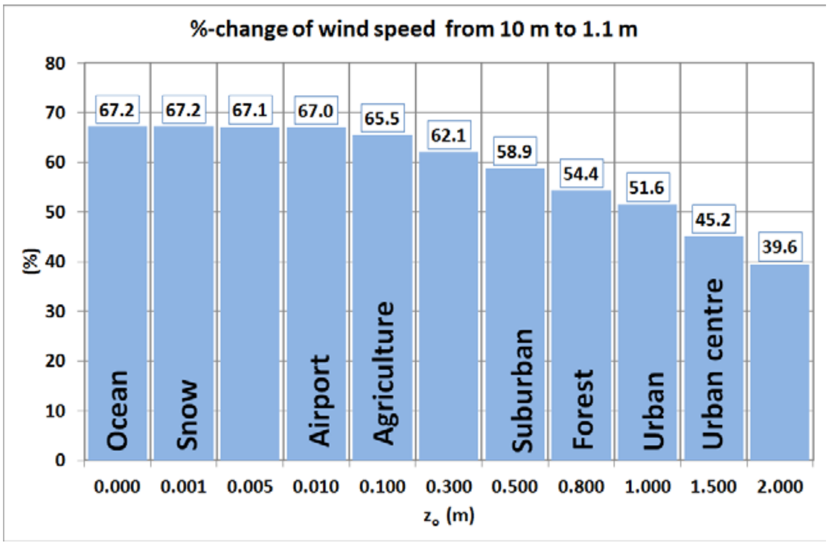
RESULTS AND EXAMPLES

Based on the mentioned and described methods, emphasis has to be given in the parameters required as input. The possibilities and limitations of the applied thermal indices and on the way derived results are presented. Focus on the results and exampled is given here on the factors, which have the highest influence and variability.

Input parameters

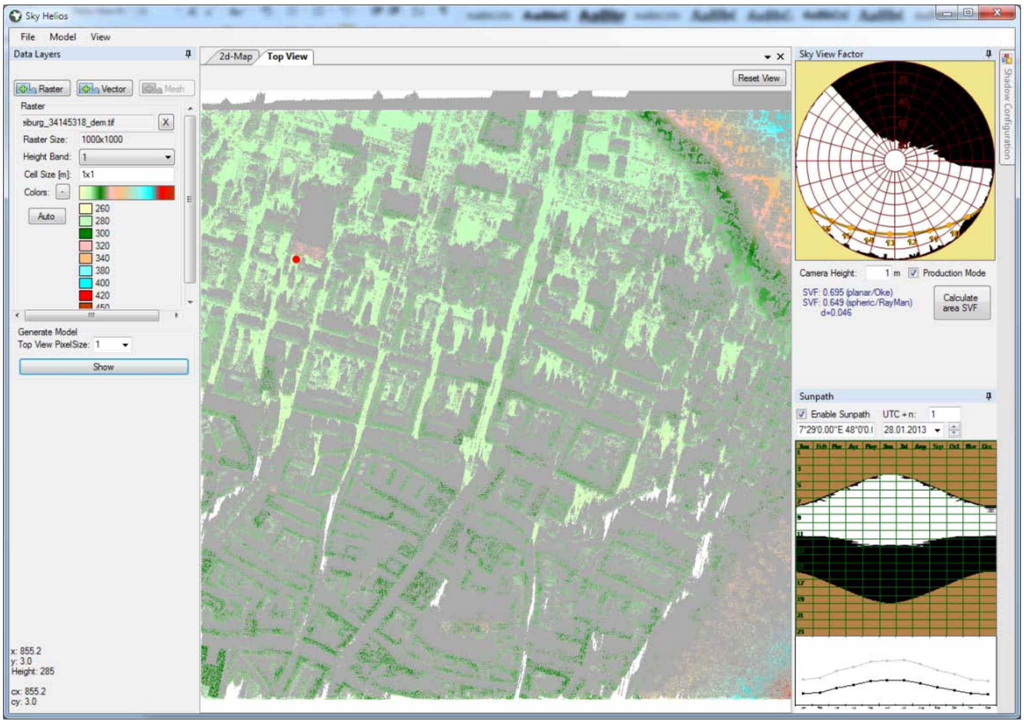
The primary concern about the input parameters is their accuracy. Meteorological measurement guidelines have to be followed first in order to have appropriate data sets. Second, for human-biometeorological thermal indices (e.g. PET and UTCI) the simulations are performed at a height, which is the center of gravity of the human body (1.1 m). However, meteorological parameters are measured and obtained at different heights. Air temperature and air humidity are usually measured at 1.5 m or 2 m above the ground. Global radiation is measured at least at a height of 2 m, in order to reduce the effects of albedo and the souroundings. Standard observations of wind are done at a minimum height of 6 m and mostly at 10 m. This is valid for standard measurements station like synop and climate station, which are located mostly on flat areas and airports. Concerning the adjustment of measurement heights and application for human-biometeorological application the input parameters have to be adjusted.

Figure 1: Changes (in %) of wind speed from originally 10 m height to human-biometeorological height of 1.1 m for different roughness lengths.



Variation of wind speed is usually high and depends mostly on the surroundings and the related roughness length of the obstacles. The wind adjustment to 1.1 m is of relevant importance and the reduction can be to 40 to 60 % of the wind at 10 m (Fig. 1) for the adjustment of wind speed in urban areas. Appropriate knowledge of roughness lengths is required. The simulation and calculation of wind can be performed with micro scale models (like ENVI-met) (Bruse and Fleer, 1998) or by known equations for the wind profile (Matzarakis et al. 2009). In most of simulations, limitation exists, which have to be addressed. The wind profile equations are difficult to apply in urban areas and micro scale models (mostly prognostic) have the limitation of long running time and are complex for application.

Figure 2: SkyHelios Screenshot and estimation of SkyView Factor.



The input parameter with the highest temporal and spatial variability is the mean radiant temperature (T_{mrt}), which is a synthesis of the short and long wave radiation fluxes and it describes the effect of radiation as a single value. T_{mrt} is not only dependent on atmospheric factors and radiation fluxes but also on the modification of the radiation fluxes by urban morphology. The variability of radiation fluxes is even higher than for wind speed. For studies in urban areas the measurement of principle factors affecting T_{mrt} is possible and then the calculation of T_{mrt} (Höppe, 1992, VDI, 1998). In addition T_{mrt} and affecting factor (i.e. Sky View Factor) can be estimated (Fig. 2) by several micro scale models provide (Matzarakis et al., 2007, 2010; Lindberg et al., 2008, Bruse and Fleer, 1998). Several studies have addressed modifications and variability and factors affecting T_{mrt} in simple and complex environments (Matzarakis et al., 2007, 2010, Lin, 2009, Lin et al., 2010, 2012). It has to be pointed out that T_{mrt} has the highest variability in temporal terms and also in different urban structures especially during day time.

Recently many researchers have started to focus on the variability and modifications of wind speed and Tmrt in urban structures and the effects of them on thermal indices (Herrmann and Matzarakis, 2012, Fröhlich and Matzarakis, 2013, Matzarakis and Endler, 2010).

Thermal Indices

As mentioned in the input parameters, the large variability can be found in wind speed. Concerning wind speed effect on thermal indices, it has to be mentioned that mostly wind has a cooling effect. Except, when air temperature is higher are skin temperature has not anymore a cooling but the heat exchange is positive (increased) for the surface of humans. This can be seen from Fig. 3, where different wind speeds and the relationship between air temperature and PET are visualized. For air temperature and PET lower than 35 °C a cooling effect and higher than 35 °C and increasing effect on PET. For UTCI (right figure) it can be seen also that the effect of wind speed in cooler regimes even is higher than PET.

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Figure 3: Effect of wind speed on PET and UTCI based on different air temperature levels (Ta) for 1 to 20 m/s.

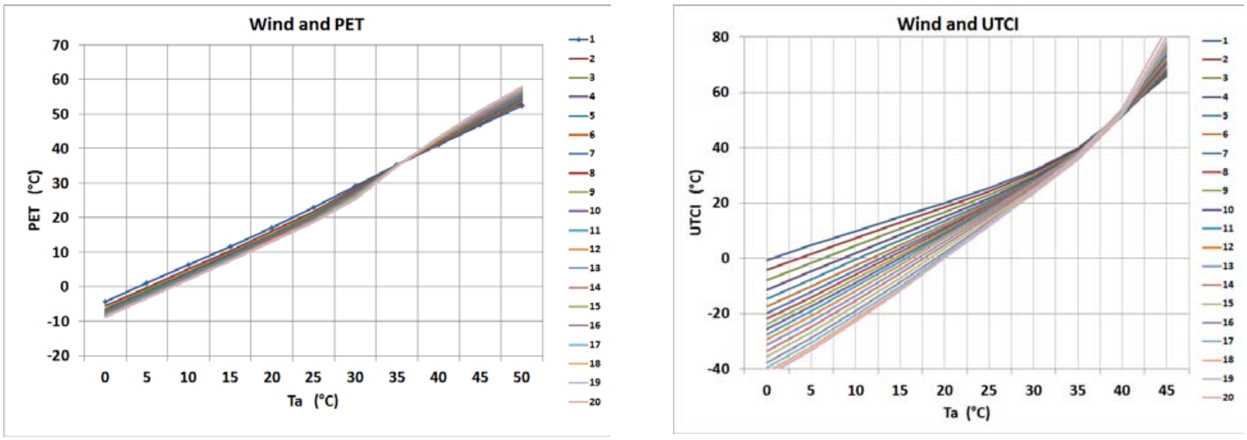
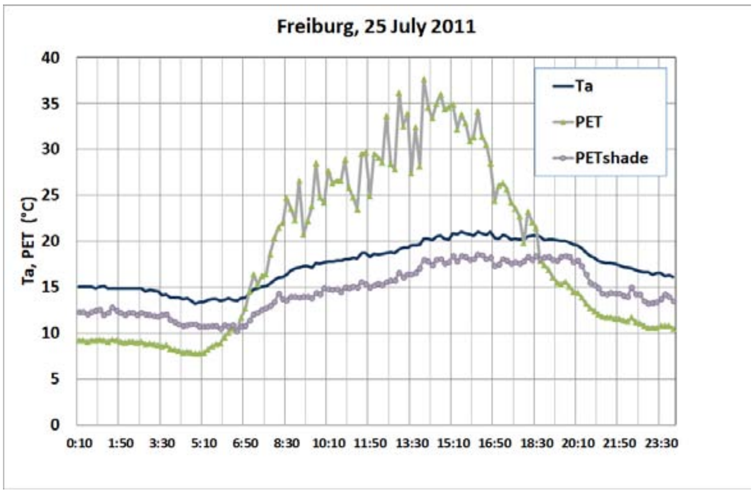


Figure 4: Temporal variability of air temperature (T_a), PET and PET is shade for a typical day (light cloudy and moderate windy) in Freiburg.



For radiation fluxes (expressed here in terms of T_{mrt}), it can be seen for the example of Fig. 4, that Tmrt has the highest influence on PET. It can be also seen that the difference between PET and Ta is during the day much higher up to 15 °C in the specific case. In addition, it can be seen that PET during the night is lower than air temperature.

In general it is obvious that PET has a much higher daily variability than air temperature (Fig. 4).

Presentation Of Results

Usually results for thermal comfort issues are presented in terms of mean condition or daily patterns. Based on the data used in different time resolution for single points the possibility of considering presentation possibilities of frequencies of occurrence based on thermal perception ranges and thresholds has to be discussed. A recent possibility can be the frequency diagrams which include specific ranges of PET or UTCI and can represent the overall assessment of background conditions of PET or other thermal indices (i.e. Lin and Matzarakis, 2008, Herrmann and Matzarakis, 2012, Fröhlich and Matzarakis, 2013). The presentation of results based on frequency diagrams has the advantage that more information is included than monthly means and represents all classes from cold to hot conditions and are easier to be applied and understood by planers and authorities.

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Another important factor builds the mapping issue because of the demand and application in planning. Planners prefer detailed information on the spatial behaviour of the human-biometeorological conditions for the decision-making (Matzarakis et al., 2008). To provide spatial information on the thermal bioclimate, numerical or statistical models can be applied. Here, has to be mentioned that urban climate maps are mostly produced as a case study and do not deliver information for the overall assessment of thermal conditions and the mobility of urban dweller including time to stay indoor and outdoor should be included and considered.

DISCUSSION AND CONCLUSION

The examples shown, indicate that there are difficulties and deficiencies in the quantification of thermal comfort. First of all the data used has to be accurate and in an appropriate way. Mean daily data cannot accurately and precise reproduce the thermal conditions during the day.

As mentioned before, there are two major factors that can mostly affect the assessment of thermal comfort: a) the input data with their accuracy and variability and b) the method used for the quantification (VDI 1998). The methods used rely on the human energy balance in steady state conditions and assess the thermal environment by solving the human energy balance for long period while considering the change in the meteorological conditions in the temporal scale. This assumption is used for different reasons, primarily because of the calculation time. In addition the way of presentation of results is important and has to be in an easily understandable way. Limitations and defficiencies has to be expressed and quantified.

A third important factor and often not considered is the mobility of humans and the frequency of use of a specific space. Dwellers have a high mobility during the day and, depending on the time of day they spend their time, due to several reasons, in- and outdoors. This makes an assessment of their thermal comfort conditions difficult, because the periods of stay have to be known. Another issue is quantifying from another point of view, the use of different spaces (i.e., parks, indoor and outdoor). A first approach, concerning this issue, is described as affect analysis, is given in the integral climate analysis for Freiburg (Röckle et al., 2003, Matzarakis et al., 2008).

Thermal comfort assessment performed in the past had some deficiencies, which can be reduced with modern techniques and possibilities. This requires reliable spatial and temporal data, which are relevant as input data for thermal indices. The periods of use of different land use areas and periods of stay indoor (also in cars and bus) and their appropriate representation of their climate are required and is of great relevance in the thermal comfort quantification.

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