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Estimation of human-biometeorological conditions in south west Germany for the assessment of mitigation and adaptation potential

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1. Introduction

Human thermal perception is influenced by the sum of several meteorological parameters (Höppe 1993, Fiala et al. 2012, Jendritzky et al. 2012, Blazejczyk et al. 2012). The parameters showing the strongest impact on thermal conditions, especially during summer conditions, are the various radiation fluxes, as well as the local wind speed. Both are strongly dependent on the surrounding environment. In urban environments, they are mostly driven by the urban morphology. Therefore, they can be modified by urban planning (e.g. Ketterer and Matzarakis 2014; Fröhlich and Matzarakis 2013).

The impact of the individual meteorological parameters on thermal bioclimate can be best estimated by applying thermal indices. The best known indices are based on the energy balance of the human body or on energy flux models, e.g. the Perceived Temperature (PT) (Staiger et al. 2012), the Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012) or the Physiologically Equivalent Temperature (PET) (Mayer and Höppe 1987, Höppe 1999, Matzarakis et al. 1999). To assess thermal stress for humans, the results can be evaluated using the thermal stress classifications, that are available for different indices and regions (e.g. the thermal perception classification for central Europe by Matzarakis and Mayer (1996)).

2. Data and Method

This study consists of two parts. In the first part future bioclimatic conditions are estimated and presented in easy and comprehensive graphs. In the second part, the sensitivity of three commonly used thermal indices to the most important meteorological input parameters is analyzed. For both parts, the city of Freiburg, Southwest Germany is selected as an example.

2.1 Estimation of future conditions

The regional model REMO (Jacob et al. 2001, 2007) is a three-dimensional, hydrostatic atmospheric circulation model. It considers non-linear interference of relevant physical processes. Subscale processes are parameterized physically (Jacob et al. 2001, 2007). The dataset applied has a resolution of 0.088° (approximately 10 km) in space (horizontal) and of 1 hour in time. It covers the years 1970 to 2100.

For the analysis, data for the corresponding grid cells was extracted for three time series. The cover the years 1970 to 2000 (addressed as “now”), a future scenario “2035” consisting of the years 2020 to 2050, and a second future scenario for the far future called “2085” including the years 2070 to 2100. The data was modified according to average differences of the “now” dataset to measured data provided by the German Weather Service (DWD), that are described in the subsection below. Finally, PET was calculated using the RayMan model (Matzarakis et al. 2007, 2010). Results were classified according to the thermal perception classification for central Europe by Matzarakis and Mayer (1996) (refer to tab. 1).

Tab. 1: Thermal stress classes for human beings (with an iactivity of 80 W and a heat transfer resistance of the clothing of 0.9 clo (clothing value)) modified after Matzarakis and Mayer (1996).

PET	Thermal Perception	Grade of physical stress
< 4	Very cold	Extreme cold stress
4 – 8	Cold	Strong cold stress
8 – 13	Cool	Moderate cold stress
13 – 18	Slightly cool	Slight cold stress
18 – 23	Comfortable	No thermal stress
23 – 29	Slightly warm	Slight heat stress
29 – 35	Warm	Moderate heat stress
35 – 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Results are presented as stacked barplots comparing the three time periods. To give a better insight on the changes in thermal conditions, results are also presented for day and night separately (fig. 1). As changes are not homogeneous throughout the year, the period with the strongest changes, the summer months June, July and August, are also analyzed separately (fig. 2).

2.2 Sensitivity of thermal indices

The sensitivity of the thermal indices Perceived Temperature (PT), Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) was tested. All three of them are calculated from the same four meteorological input parameters air temperature (T_a), relative humidity (RH), wind speed (v), and mean radiant Temperature (T_{mrt}) and claim to be globally applicable.

PT is an equivalent temperature based on a complete energy budget model of the human body, the “Klima-Michel Model” (Fanger 1972). PT is designed for staying outdoors and is defined as the air temperature of a reference environment in which the thermal perception would be the same as in the actual environment (Staiger et al. 2012). PT includes an auto-adjusting clothing insulation model. Thermal assessment in PT is based on a modification of the predicted mean vote (PMV) index (Fanger 1972; Staiger et al. 2012).

Like PT, UTCI is an equivalent temperature. It is based on a heat transfer model. The outdoors meteorological conditions are compared to a indoors reference environment. For UTCI, the indoors setting is 50 % relative humidity, calm air and a mean radiant temperature equal to air temperature (Jendritzky et al. 2012). The clothing insulation in UTCI is also dynamic. To speed up the calculation, UTCI is determined using a regression formula (Fiala et al. 2012).

PET follows the concept of an equivalent temperature and is based on a simplified version of the “Munich Energy Balance Model for Individuals ” (MEMI) (Höppe 1993). It is defined as “the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed” (Höppe 1999) (Mayer and Höppe 1987; Matzarakis et al. 1999). In contrast to PT and UTCI, its clothing insulation model is static. In the field of human thermal comfort PET is currently one of the most commonly applied indices (e.g. in Matzarakis and Mayer (1996), Matzarakis et al. (1999, 2009), Lin et al. (2010, 2013), Lopes et al. (2011), Muthers et al. (2010), Hwang et al. (2011), Nastos and Matzarakis (2012), Ketterer et al. (2013), and Fröhlich and Matzarakis (2013)).

The sensitivity analysis is based on modification of single parameters in long-term meteorological records. For this study, records obtained at the official meteorological station for Freiburg operated by the German Weather Service (DWD) have been used. They cover the period 1981-01-01 to 2013-10-20 in hourly resolution. Using this dataset, several modified copies were created including one the following modifications each:

- air temperature +/- 2 K
- wind speed +/- 2 m/s
- mean radiant Temperature $T_{mrt}' = T_a$ (shade); $T_{mrt}' = 0.5 * T_a + 0.5 * T_{mrt}$ (half shade); $T_{mrt}' = T_{mrt}$ (sun)

The three indices were calculated for each of the datasets using the RayMan model and compared to the results of the original one. To facilitate the comparison, results were presented as Beanplots (Kampstra 2008, figs. 3-5). Each dataset is presented as one bean with its title on the x-axis. The wider a bean at a given temperature on the y-axis, the more results were counted to equal this temperature (Kampstra 2008).

3. Results

The results are presented in two subsections analogue to the Data and Method section. The first subsection will present the results from the estimation of the future conditions. The second subsection will deal with the results from the sensitivity analysis.

3.1 Estimation of future conditions

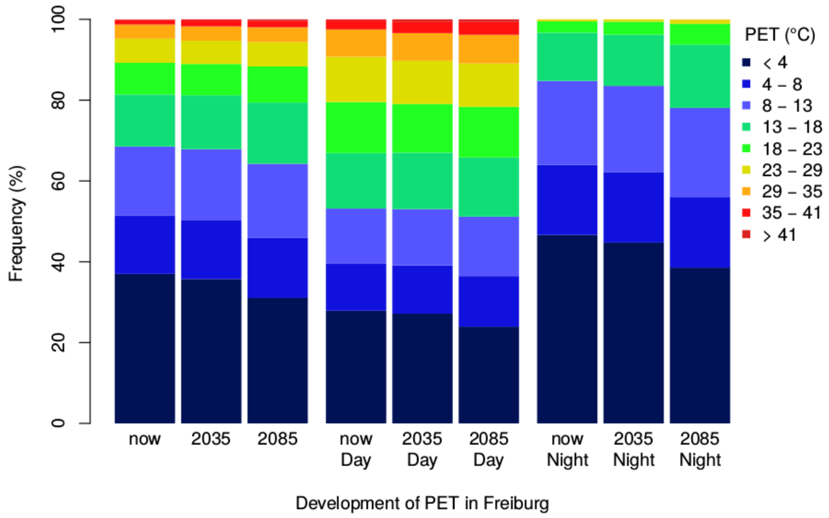

Fig. 1 Comparison of the thermal bioclimate in Freiburg of the current state ("now") with the two future scenarios for the years 2020 - 2050 ("2035") and 2070 - 2100 ("2085") for the whole year. Results are presented for all hours combined, as well as for daytime (7 - 18 LST) and night time (19 - 6 LST) separately.

For the dataset representing the current conditions ("now") the class of PET < 4°C is the most common one representing extreme cold stress in 37.0 % of the hours in the dataset. This fraction decreases to 35.7 % in the 2035 and further to 31.0 % in the 2085 dataset. At the same time, the classes of 35 - 41°C and > 41°C together only represent 1.2 % of the hours in the now dataset. For the future dataset this fraction increases to 1.8 % for the 2035 and to 1.9 % for the 2085 dataset. This trend becomes more clear if the dataset is separated into day and night hours. The classes representing cold stress are way more frequent during the night hours than at daytime while the two classes with PET > 35°C are occurring almost exclusively at daytime. However, also at night time, the warmer classes become more frequent in the future datasets.

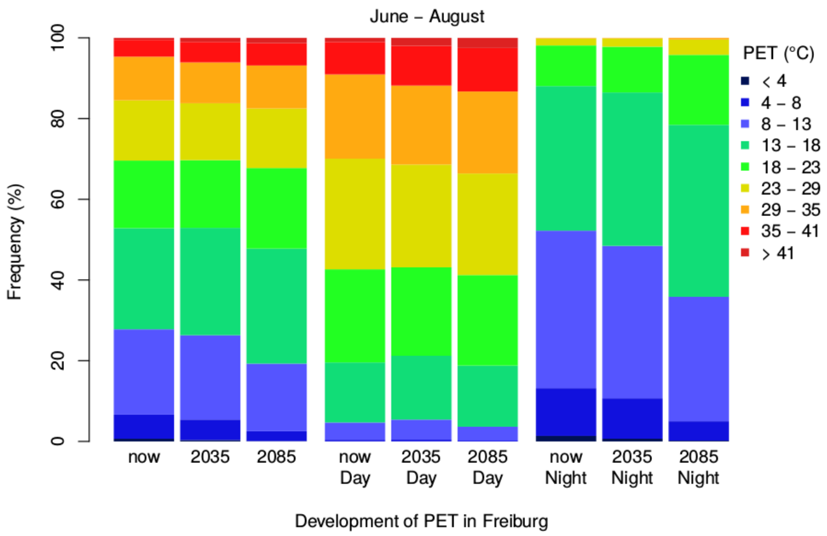

Fig. 2 Comparison of the thermal bioclimate in Freiburg during the summer months (June to August) of the current state ("now") with the two future scenarios for the years 2020 - 2050 ("2035") and 2070 - 2100 ("2085") for the whole year. Results are presented for all hours combined, as well as for daytime (7 - 18 LST) and night time (19 - 6 LST) separately.

Focusing on the summer months June to August (fig. 2) the class PET < 4°C does almost not occur at all. It's frequency exceeds 1 % (1.37 %) for the now dataset at night time only. For the future datasets, a trend towards warmer classes can be seen. At daytime, the frequency of the classes > 35°C is increased from 9.1 % (now) to 11.8 % for the 2035 and further to 13.3 % for the 2085 dataset.

3.2 Sensitivity of thermal indices

The thermal indices PT, UTCI and PET have been tested to assess their sensitivity to the meteorological parameters T_a, v, and T_{mrt}.

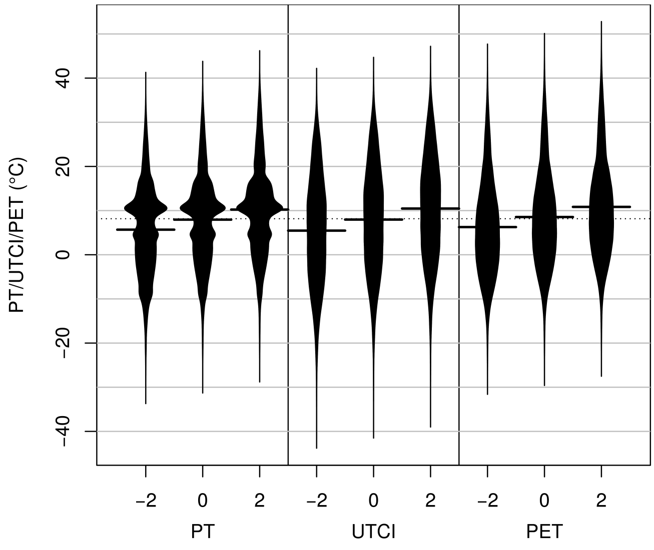

Fig. 3 Distribution of PT (left), UTCI (centre) and PET (right) calculated with modified air temperature (T_a) for the moderate conditions in Freiburg, Southwest Germany. For each index, the distribution of the results is plotted as three beans (Kampstra 2008) for a dataset with T_a reduced by 2°C (left), the default dataset (centre) and a dataset with T_a increased by 2°C (right).

Comparing the bean plots for the three indices based on the default dataset (the central one of each index's section, fig. 3) it can be seen, that the indices very well agree in their mean values (black lines). Their extreme values, as well as the shape of their distribution is, however, quite different. While UTCI and PET show a smooth and even distribution, that for PT is irregular for the same input data.

Generally all the three indices agree very well in their response to the modification in the input T_a. To the modifications of + / - 2 K in input T_a, they respond by approximately the same amount in their results. Only for PT also the distribution changes along with modified input T_a.

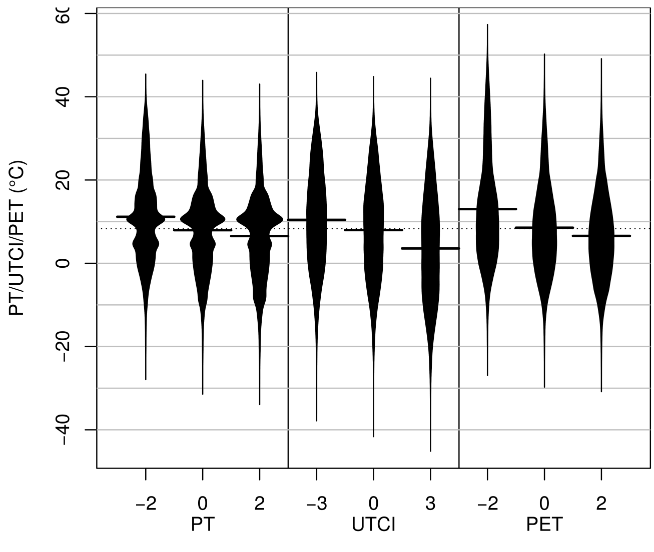

Fig. 4 Distribution of PT (left), UTCI (centre) and PET (right) calculated with modified wind speed (v) for the moderate conditions in Freiburg, Southwest Germany. For each index, the distribution of the results is plotted as three beans (Kampstra 2008) for a dataset with v reduced by 2 m/s (left), the default dataset (centre) and a dataset with v increased by 2 m/s (right).

Comparison of the results for the modified wind speed by + / - 2 m/s show that the indices again agree in the trend in their response (fig. 4). The indices furthermore agree on that a change of 2 m/s in input wind speed has a stronger impact on thermal comfort than one of 2°C in input air temperature. However, the amount of the changes in the results is different for each index. PET seems to respond stronger to a reduction of wind speed while UTCI is modified stronger by an increase in wind speed.

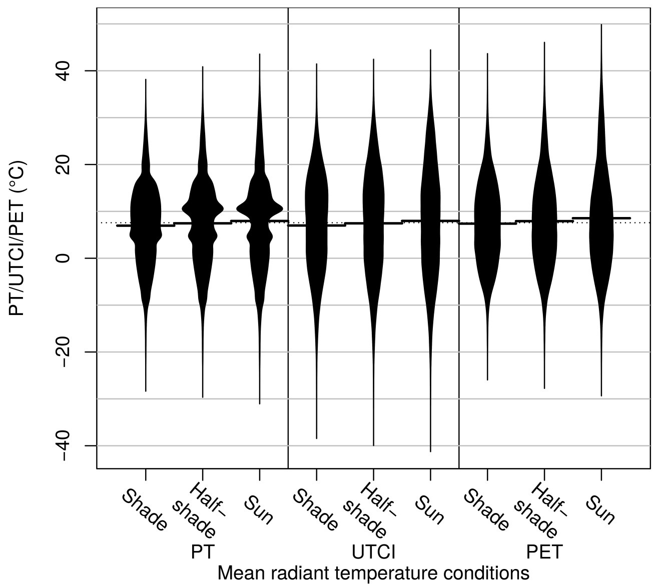

Fig. 5 Distribution of PT (left), UTCI (centre) and PET (right) calculated with modified mean radiant temperature (T_{mrt}') for the moderate conditions in Freiburg, Southwest Germany. For each index, the distribution of the results is plotted as three beans (Kampstra 2008) for a dataset with $T_{mrt}' = T_a$ (shade, left), $T_{mrt}' = 0.5 * T_a + 0.5 * T_{mrt}$ (50 % shade, centre) and $T_{mrt}' = T_{mrt}$ (sun, right).

A whole different pattern of results is shown by the indices if T_{mrt} is modified (fig. 5). While the mean values are only reduced slightly for the shaded conditions, the extremes are reduced and more results are counted in the thermally neutral area for all indices.

4. Discussion and Conclusions

The estimation of future conditions shows in general, that the frequencies of occurrence of classes representing higher PET is increased for the future datasets, while those for classes representing lower PET are reduced. This is in good agreement to a previous work by Matzarakis and Endler (2010), who predict an increase in days with PET > 35°C of 5.5 % for Freiburg comparing the periods 1961 - 1990 and 2071 - 2100. At the same time they find the percentage of days with PET < 0°C decreased by 12.6 % (Matzarakis and Endler 2010).

Due to the separate consideration of day- and nighttime also the conclusion can be drawn, that the trend towards higher classes is stronger at daytime, but still present at nighttime. The trend is found to be even stronger for the summer months June to August. It can therefore be concluded, that hotter conditions are predicted by REMO in general, but especially for daytime during summer.

The sensitivity analysis of the three thermal indices PT, UTCI and PET reveals certain shortcomings in the three indices. For PT, this is the overall distribution of the results. UTCI can not be calculated for some data, as it has a very narrow range of valid input conditions. All three indices show the same trend responding to the modified T_a input (Fig. 3). Their mean values are modified by almost the input T_a modification. This is surprising, as Blazejczyk et al. (2012) state, that they would expect PT and PET to be closer related to T_a than UTCI. On the other hand it is in good agreement to the results of a sensitivity study performed for the hot and dry conditions in Doha (Fröhlich and Matzarakis 2015). While for UTCI and PET the distributions are just offset by the modification in input T_a, there seems to be no offset in the distribution of PT. The distribution of PT results rather changes its shape.

The indices showed a slightly stronger response to the modifications in input wind speed than to those in input air temperature. For UTCI it has to be noted, that unlike PT and PET, the index needs input wind speed in 10 m height. The input wind speed therefore had to be extrapolated to 10 m for the UTCI calculations. Due to the calculation by a regression formula, the range of valid input conditions for UTCI is rather narrow. This holds especially for wind speed, where values in range of 0.5 m/s to 17.0 m/s can be used. However, there was quite some values lower than 0.5 m/s in the input dataset, that had to be excluded for UTCI. This becomes worse in the dataset with reduced v by 2 m/s, what should be considered interpreting the results for UTCI. Generally, the results agree well to a validation study by Blazejczyk et al. (2012), who found that UTCI responds much stronger to the effect of wind cooling than PET.

The results for the analysis of the sensitivity against T_{mrt} shows that T_{mrt} strongly influences the indices both in the cold and in the warm area. This is also in good agreement with findings by Fröhlich and Matzarakis (2015). As T_{mrt} is also easy to modify, it is considered the most important parameter to influence thermal comfort in urban areas by urban planning.

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