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A quantitative sensitivity analysis on the behaviour of common thermal indices under hot and windy conditions in Doha, Qatar

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Abstract Human thermal perception is best described through thermal indices. The most popular thermal indices applied in human bioclimatology are the perceived temperature (PT), the Universal Thermal Climate Index (UTCI), and the physiologically equivalent temperature (PET). They are analysed focusing on their sensitivity to single meteorological input parameters under the hot and windy meteorological conditions observed in Doha, Qatar. It can be noted, that the results for the three indices are distributed quite differently. Furthermore, they respond quite differently to modifications in the input conditions. All of them show particular limitations and shortcomings that have to be considered and discussed. While the results for PT are unevenly distributed, UTCI shows limitations concerning the input data accepted. PET seems to respond insufficiently to changes in vapour pressure. The indices should therefore be improved to be valid for several kinds of climates.

1 Introduction

Humans do not have receptors to sense the air temperature (T_a). The temperature humans feel and have to

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deal with is a summary of their thermal environmental conditions, represented by the temperature of the skin and the blood in the hypothalamus (Höppe 1993), as well as their current demand for cooling or heating (Fiala et al. 2012). Thermal perception or thermal stress can therefore not be expressed by a single parameter like T_a (Höppe 1993; Jendritzky et al. 2012; Blazejczyk et al. 2012), but only by human energy balance or heat flux models expressing all energy gains and losses of the body (e.g. Munich Energy Balance Model for Individuals (MEMI)) (Höppe 1984; Jendritzky et al. 2012). One of the greatest sources of energy are the radiation fluxes. Together with the air temperature as a background, they can be summarized in one parameter, the mean radiant temperature (T_{mrt}) (Höppe 1993). Based on the human energy balance and T_{mrt}, several thermal indices have been developed representing the thermal sensation of humans. The most popular indices are the perceived temperature (PT) (Staiger et al. 2012), the Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012; Havenith et al. 2012; Fiala et al. 2012), and the physiologically equivalent temperature (PET) (Mayer and Höppe 1987; Höppe 1993; 1999). Thermal indices are usually considered to be globally applicable (Matzarakis et al. 1999; Jendritzky et al. 2012). They are used in studies for places all over the world (Matzarakis and Mayer 1996; Lin et al. 2010). For the moderate climate of Freiburg, Southwest Germany, they are found to be well correlated (Blazejczyk et al. 2012). However, their behaviour in different climates, e.g. in hot and windy climates like in Qatar, has been rarely studied. The aim of this study is therefore to show the indices applicability and reliability in hot and windy conditions by analysing their distribution and sensitivity

under the given conditions based on the modification of a real data set.

2 Methodology and data

2.1 Location and data

For this study, a set of data for a location with hot and dry climate has been analysed to calculate the three thermal indices PT, UTCI and PET. Several runs have been performed with different modified parameters to study the indices response.

The location that has been chosen for the analysis is the city of Doha. Doha is located in the east of the peninsula covered by the state of Qatar. Data recorded at the Doha Airport Climate Station and provided by Ogimet (www.ogimet.com) was used as input data for this study. The geographic position of the recording station is 25° 15′ N, 51° 34′ E at an elevation of 11 m above sea level. The records cover the period between March 1999 and January 2014 in 3-h resolution. Wind speed was altitude corrected to 1.1 m for the calculations of PT and PET by an approach used in Matzarakis et al. (2009). An overview over the meteorological conditions at Doha is given in Table 1.

2.2 Thermal indices

Thermal perception of humans is based on a huge quantity of parameters and therefore can not be described through single meteorological parameters, e.g. air temperature (T_a) (Höppe 1993; Jendritzky et al. 2012; Blazejczyk et al. 2012). To approximate human thermal perception, thermal indices have been developed. Most of them follow the approach of an equivalent temperature and are based on a human energy balance or heat flux models. One of the most important input parameters for all of these indices is the mean radiant temperature (T_{mrt}), summarizing the

Table 1 Summary of the applied input data parameters recorded at the Doha Airport Station and the T_{mrt} input calculated from this data

Parameter	Min	1st Qu.	Median	Mean	3rd Qu.	Max	Missing data
T_a (°C)	1.4	22.0	29.0	28.3	34.0	59.1	1794 (4.34 %)
VP (hPa)	1.4	13.8	18.7	20.4	25.6	46.4	1816 (4.39 %)
RH (%)	4.7	38.2	56.2	54.3	71.0	100.0	1895 (4.58 %)
cc (1/8)	0	0	0	1.2	2	8	1690 (4.09 %)
v (m/s)	0.0	2.6	4.6	4.9	6.5	63.5	1697 (4.10 %)
T_{mrt} (°C)	−3.2	17.6	25.8	30.2	43.1	66.8	1919 (4.64 %)

The records cover the period from March 1999 to January 2014. The table shows the default input that was modified to analyse the indices response

different radiation fluxes. T_{mrt} is defined as the temperature of a perfect black and equal surrounding environment, which leads to the same energy balance as the current environment (VDI-Kommission Reinhaltung der Luft 1988; Fanger 1972). As the three thermal indices analysed in this study are equivalent temperatures, they use °C as unit, facilitating interpretation by people with less knowledge in the field of human biometeorology.

Perceived temperature The perceived temperature (PT) is an equivalent temperature based on the "Klima-Michel Model", an energy balance model for humans. It is designed for people 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 contains a clothing model, that is automatically adapted to the meteorological conditions (Staiger et al. 2012). Thermal assessment in PT is based on a modification of the predicted mean vote (PMV) index (Fanger 1972; Staiger et al. 2012).

Universal Thermal Climate Index Universal Thermal Climate Index (UTCI) also follows the concept of an equivalent temperature. The meteorological conditions are compared to a reference environment with 50 % relative humidity, calm air and T_{mrt} being equal to T_a (Jendritzky et al. 2012). UTCI is defined as "the isothermal air temperature of the reference condition that would elicit the same dynamic response (strain) of the physiological model" (Jendritzky et al. 2012). UTCI includes a clothing model that automatically adapts to the current conditions (Havenith et al. 2012). UTCI is calculated using a regression formula on the basis of a heat transfer model (Fiala et al. 2012). Therefore, it has a very narrow range for the input parameters it accepts. Limitations for the Doha input due to the restriction for T_a of −50 to +50 °C, as well as for the valid range of wind speed ranging from 0.5 to 17 m/s, are to be expected. To meet these criteria, only 93.5 % of the Doha input data could be used for the assessment. Other uncertainty is to be expected due to vapour pressure of the reference environment, which is limited to 20 hPa (Jendritzky et al. 2012). For Doha, VP of 20 hPa is exceeded in 41.98 % of all readings (compare to Table 1).

Physiologically equivalent temperature A regularly used index for the assessment of human thermal comfort is the physiological equivalent temperature (PET). 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). PET is based on a simplification

of the human energy balance model "Munich Energy Balance Model for Individuals" (MEMI) (Höppe 1984). One of the most important determining factors of PET is the mean radiant temperature (T_{mrt}) (Herrmann and Matzarakis 2012). PET is currently one of the most commonly used indices for human thermal comfort (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)).

2.3 RayMan

The RayMan model was applied for calculating the thermal comfort conditions using the three indices. RayMan is a micro-scale model developed at the Chair for Meteorology and Climatology of the Albert-Ludwigs-University Freiburg to calculate radiation fluxes in simple and complex environments (Matzarakis et al. 2007; 2010). This allows the calculation of T_{mrt}, which is an important input parameter in the calculation of thermal biometeorological indices like PT, UTCI and PET.

2.4 Thermal stress classes

To make the results more obvious, results for all three indices were classified into nine classes of thermal perception (Table 2) (Matzarakis and Mayer 1996) originally defined for PET in Central Europe. Since the assessment scale was defined for moderate conditions regularly occurring in central Europe and for PET only, it does not give reliable information about thermal perception. It is used anyway as it helps visualising and comparing the results for the indices, as thermal sensation was not analysed in this study. For productive studies, there are also perception

Table 2 Thermal sensation classes for human beings in Central Europe (with an internal heat production of 80 W and a heat transfer resistance of the clothing of 0.9 clo (clothing value)) modified after Matzarakis and Mayer (1996)

PET (°C)	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

classes for PT (Staiger et al. 2012) and UTCI (Blazejczyk et al. 2013; International Union of Physiological Sciences–Thermal Commission 2003) with differing classes, as well as classifications for other regions (e.g. Lin et al. (2013)).

2.5 Input modifications

Results were not only analysed for the default input data (Table 1), but also for modified datasets to show the impact of the different parameters. The indices were calculated and evaluated for additional 16 datasets with modified T_a of ±1 and ±2 K, modified wind speed (v) of ±1 and ±2 m/s, modified vapour pressure (VP) of ±2.5 and ±5 hPa. Additionally, four input data sets with modified T_{mrt} (T_{mrt}') were calculated as follows: one with $T_{mrt}' = T_a$ ("shaded"), $T_{mrt}' = 75\,\%T_a + 25\,\%T_{mrt}$, $T_{mrt}' = 50\,\%T_a + 50\,\%T_{mrt}$ ("half-shaded"), and $T_{mrt}' = 25\,\%T_a + 75\,\%T_{mrt}$.

3 Results

The distribution of each of the calculated indices PT, UTCI and PET under different modified input conditions is shown by Figs. 1, 2, 3, 4, 5, 6, and 7. Each index is shown as a "bean" (Kampstra 2008) for each set of data, in order to visualize the frequency of a given result, together with the overall distribution. The width of a bean thereby represents the frequency. The black lines indicate the mean value for one bean. The dotted line gives the overall mean to better set the beans in relation.

Comparing the beans for the three indices based on the default data set (e.g. the ones with a T_a modification of 0 °C in Fig. 1) it can be seen that the mean values for the three indices are quite similar. However, the distribution of the result is very different for the single indices. PT (Fig. 1, left) shows a high frequency for results below 18 °C and low frequent results for the range from 18 to 20 °C. UTCI (Fig. 1, centre) calculates a lower minimum value than the other two indices. Except for the low minimum, it shows the smoothest distribution of the three indices. The bean for PET (Fig. 1, right) shows a weak narrowing around 22 to 24 °C. PET also calculates the largest maximum value of all three indices with 69 °C.

The frequencies of the different thermal sensation classes for PT, UTCI and PET in Doha are shown by Figs. 3, 2, 6, and 8. They are plotted to allow for an overview over the consequences of the modified distributions (Figs. 1, 4, 5 and 7). Looking at the frequencies for the classes, first of all, the hot and dry conditions in Doha become obvious by the high frequencies of classes of 29 °C and above (46.0 % PT, 41.6 % UTCI and 40.8 % PET) in the default data set, indicating heat stress to humans that are not adapted to hot conditions.

Air temperature Going into detail, first of all, the indices sensitivity to T_a is analysed. In average, PT responds to a change in input T_a by 2 °C with a shift by almost 3 °C in the direction of the modification (Fig. 1, left). The distribution of the results for PT shows some changes with the modifications as well. While the narrowing between 18 and 20 °C stays persistent, frequencies between 10 to 12 °C are increased by decreasing T_a and decreased by increasing T_a, respectively. The distribution of results for PT higher than 12 °C seems to remain the same, except to offset by the difference in the mean value.

The results calculated for UTCI also show a shift in the mean values of almost 3 °C by a modification of the input air temperature of 2 °C in either direction. The distribution thereby almost stays the same (Fig. 1, center), but seems to be offset by the mean value. Also, the maximum values calculated for UTCI show a much stronger response (around 10 °C) compared to the results for the default data set.

The distribution of the results for PET (Fig. 1, right) seems to stay pretty much the same, but only to offset by approximately 3 °C due to a modification of the input air temperature by 2 °C. Unlike for PT and UTCI, also the narrowings in the distribution are offset. Regarding the consequences of the modified distribution of the results for the different indices, the results have been organised using the assessment classes (see Table 2). For PT (Fig. 3, left), a
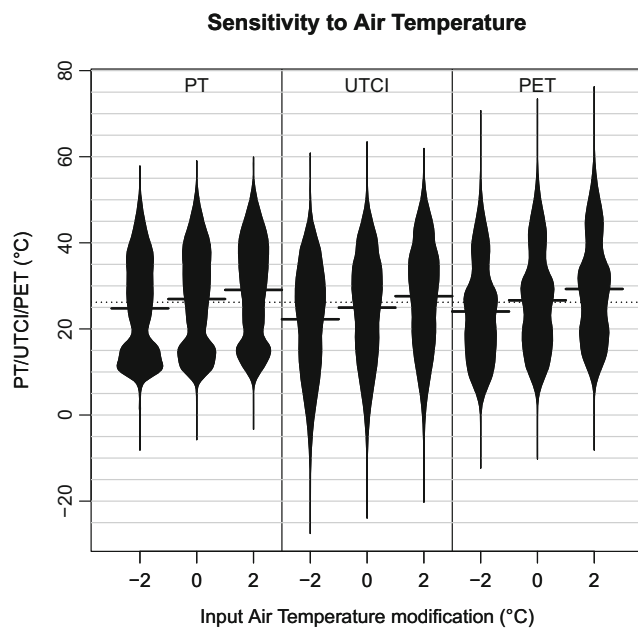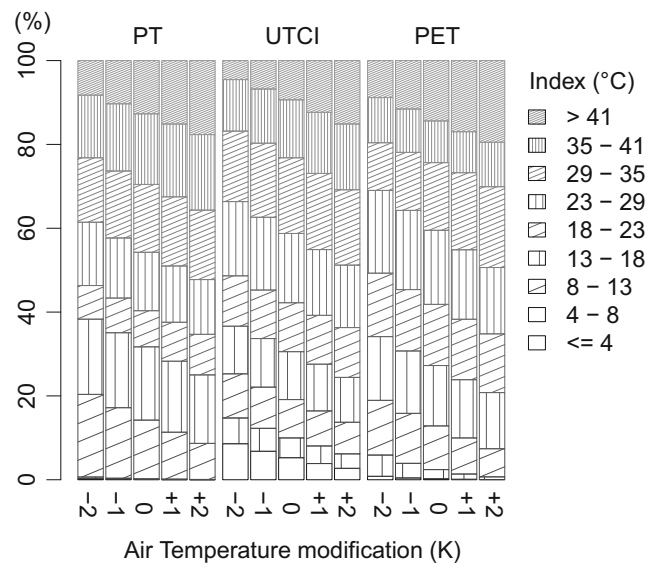

Fig. 2 Frequencies of thermal sensation classes (Table 2) of results for PT (*left*), UTCI (*centre*) and PET (*right*). The frequencies for input data sets with modified air temperature (T_a) are compared. The modification in the input T_a for each *bar* is given by the caption

strong sensitivity to T_a can be observed. The frequency of classes representing PT of 35 °C and more is decreased by 6.4 % due to a decreased input T_a of 2 °C, and increased by 6.1 % due to increased input T_a, respectively.

Like PT, UTCI is strongly influenced by T_a under hot and dry conditions (Fig. 3, center). While the frequency of the classes of 35 °C and more is smaller for UTCI than for PT; also, the impact of the input modification is a little weaker (the fraction of results $\geq$35 °C is 23.5 % in the default data set, 6.5 % less (17.0 %) in the T_a −2 K and 7.6 % larger (31.1 %) in the T_a + 2 K dataset). UTCI also calculates the lowest values among the three indices. Even for the input data set with increased T_a by 2 °C, the class of lower than 4 °C still occurs in the results (2.6 %).

PET shows the weakest impact on the distribution of thermal stress classes among the three indices (Fig. 3, right). The increase or decrease of T_a by 2 °C in the input data causes the classes of 35 °C and above, representing strong heat stress, to occur 5.9 % more, or 4.7 % less frequently, respectively.

Wind speed The different indices sensitivity to wind speed under hot and dry conditions is more different than T_a (Fig. 4). Generally, all indices show the same trend of lower absolute results along with higher wind speed. PT is found to be less sensitive to the changes in wind speed than the other two indices. The general distribution of the results thereby seems to remain the same below 18 °C, while the upper part of the bean, representing all results larger than
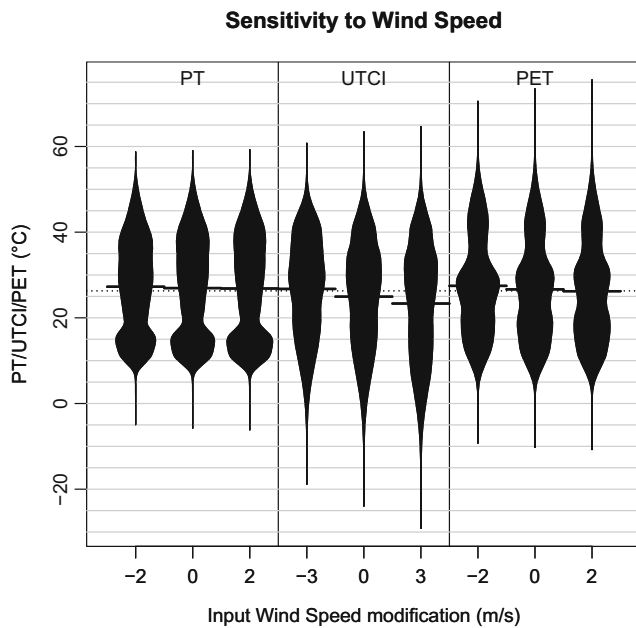

Fig. 1 Distribution of PT (*left*), UTCI (*centre*) and PET (*right*) calculated with modified air temperature (T_a) for the hot and dry conditions in Doha. For each index, the distribution of the results is plotted as three beans (Kampstra 2008) for a dataset with T_a reduced by 2 °C (*left*), the default dataset (*centre*) and a dataset with T_a increased by 2 °C (*right*)

Sensitivity to Wind Speed

Fig. 3 Distribution of PT (*left*), UTCI (*centre*) and PET (*right*) calculated with modified wind speed (v) for the hot and dry conditions in Doha. 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*). As UTCI requires the incident wind speed in 10-m height, the modifications have been extrapolated to 10 m according to Havenith et al.'s (2012) Eq. 14 to meet those for the other two indices at 1.1 m

20 °C, appears vertically stretched for the increased wind speed dataset.

UTCI is the most sensitive to wind speed among the three indices. However, also for UTCI, results are only influenced moderately by the modification of wind speed by 2 m/s (at 1.1-m height) (Fig. 4, centre). In average, the response is limited to less than 2 K due to the input modification in either direction. While the upper part of the bean almost stays the same, the distribution is stretched vertically in the lower part due to a increase in wind speed by 2 m/s and squeezed due to a decrease by the same amount. The minimum value therefore shows the strongest response of almost 3 °C in either direction.

In average, results for PET seem less influenced by the modification in the input wind speed than those for UTCI (Fig. 4, right). However, the influence is stronger than on those for PT. In contrast to the results for UTCI, the maximum results for PET show the greatest impact by the modifications, while the minimum values almost stay the same. Also, the narrowing at approximately 30 to 38 °C seems to not be affected.

The different modification of the distribution of the results for the three indices can also be seen in the thermal sensation classifications. For PT, a slight increase in the frequency for hot classes can be seen if the input wind velocity
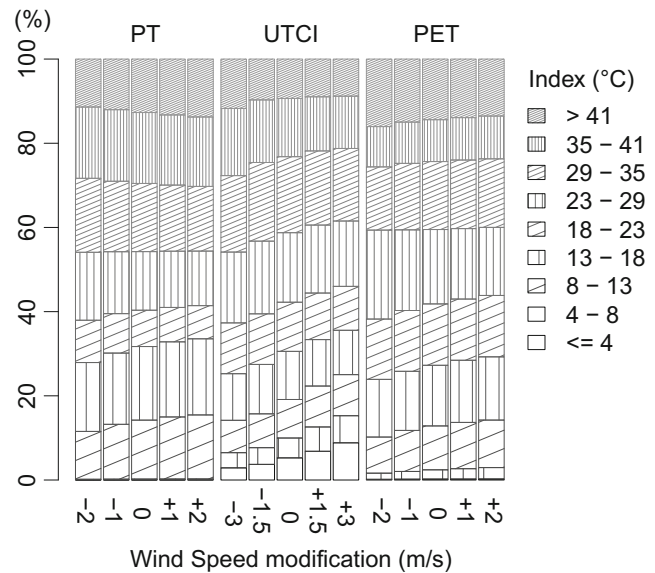

Fig. 4 Frequencies of thermal sensation classes (Table 2) of results for PT (*left*), UTCI (*centre*) and PET (*right*). The frequencies for input data sets with modified wind speed (v) are compared. The modification in the input v for each *bar* is given by the caption

is increased (Fig. 2, left). E.g., the class with PT >41 °C has a probability of 12.7 % in the unmodified dataset. For the increased wind speed by 2 m/s, this probability rises to 13.8 %. For the decreased wind speed by 2 m/s, it is decreased to 11.4 %. On the other hand, also the frequency for cold classes increases with increasing wind velocity, e.g. the class with PT of 8–13 °C has a probability of 14.0 % in the unmodified dataset. For the increased wind speed by 2 m/s, this probability rises to 15.2 %. For the decreased wind speed by 2 m/s, it is decreased to 11.4 %. However, all the changes are lesser than 5 %.

A stronger modification can be seen for the classes calculated for UTCI (Fig. 2, centre). Other than for PT, the wind speed modifications rather cause a shift in the frequency of the classes, only changing the frequencies for the hot and cold classes a lot. Only the most upper class seems to be less affected. A decrease in the input wind speed thereby causes an increase in the frequencies for classes indicating heat stress (the class with UTCI >41 °C is increased from 9.4 % in the default dataset to 11.7 % in the dataset with reduced wind speed by 3 m/s), while an increase in the input wind speed decreases the frequencies for those classes (UTCI >41 °C is decreased to 8.8 % for wind speed increased by 3 m/s). For the lower classes, the modifications are way stronger (e.g. for the class ≤4 °C, default = 5.3 %, −3 m/s = 2.9 %, +3 m/s = 8.8 %). This is most likely due to wind strongly increasing cold stress for low T_a.

The frequencies for the thermal sensation classes calculated for PET (Fig. 2, right) generally show the same trend as those for UTCI due to the modified input wind speed.

For both indices, the decreased wind speed shows a stronger impact than the increased one. Yet, the impact is weaker for PET than for UTCI, e.g. the class with PET >41 °C has a probability of 14.4 % in the unmodified dataset. For the increased wind speed by 2 m/s, this probability declines slightly to 13.5 %. For the decreased wind speed by 2 m/s, it is increased to 16.0 %.

Vapour pressure To analyse the indices sensitivity to VP, the input vapour pressure was modified by increasing it by 5 hPa and decreasing it by the same amount. Results show, that the indices response is quite different (Fig. 5). While PT seems to be quite sensitive to VP, PET does not appear to be very much affected. Generally, the upper parts of the PT beans appear to be more affected than the parts below 20 °C, which show little response for all indices. PT responds with decreased results of almost 1 °C in average, if input VP is decreased by 5 hPa (Fig. 5, left). The response of PT to increased VP is an increase of approximately 2 °C in average (+5 hPa = +1.8 °C, −5 hPa = −1.77 °C in average).

UTCI in average shows a similar response, but little weaker than PT (Fig. 5, centre). In average, UTCI is modified by about 1 °C due to the changes in the input VP (1.1 °C in average in either direction). Like for PT, the upper part of the distribution shows a stronger response than the lower part.
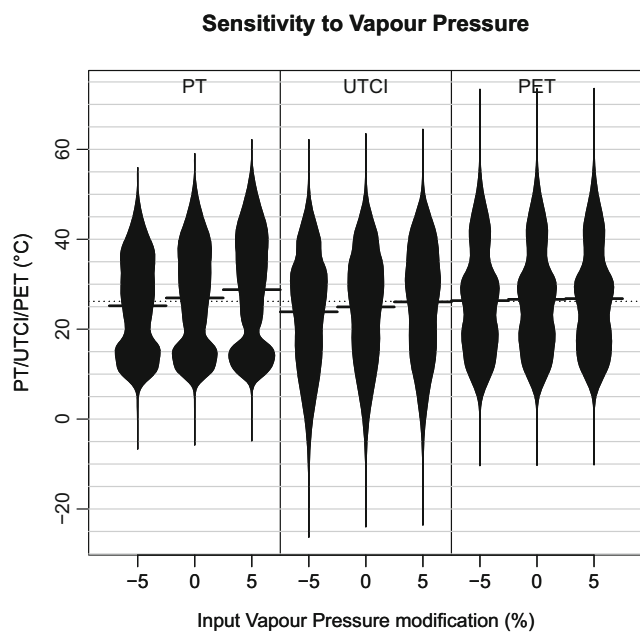
For PET, however, there only seems to be a response to the decreased VP (Fig. 5, right). This decreases PET by less than 0.4 °C. For the data set with increased VP, only little changes in PET were observed (+5 hPa = +0.1 °C in average).

This trend is also shown by the distribution of the thermal sensation classes. While PT shows a strong response to the changes in VP (Fig. 6, left), these changes are a little smaller for UTCI (Fig. 6, centre), while PET hardly seems to respond (Fig. 6, right), e.g. for PT, the class >41 °C has a probability of 12.7 % in the default dataset. If VP is reduced by 5 hPa, its probability decreases to 6.7 %, while it is increased to 20.3 % for the dataset with increased VP by 5 hPa. For UTCI these values are much closer together (default = 9.4 %, +5 hPa = 11.7 %, −5 hPa = 7.9 %) while PET hardly responds (default = 14.4 %, +5 hPa = 14.6 %, −5 hPa = 13.9 %).

Mean radiant temperature The indices sensitivity to the mean radiant temperature (T_{mrt}) was analysed by forcing $T_{mrt}' = T_a$ (causing totally shaded conditions) compared to different fractions of part-shading (e.g. $T_{mrt}' = 0.25 \, T_a + 0.75 \, T_{mrt}$ for one fourth shade) and the default input without shading. As the data set covers day and night time, the average values of the calculated indices don't show much difference between sun and shade (Fig. 7). However, mostly the upper and lower part of the distribution is modified for all indices. Probability for very high and very low values is decreased in the case of $T_{mrt}' = T_a$ for all indices. The minimum values therefore are higher, while the maximum
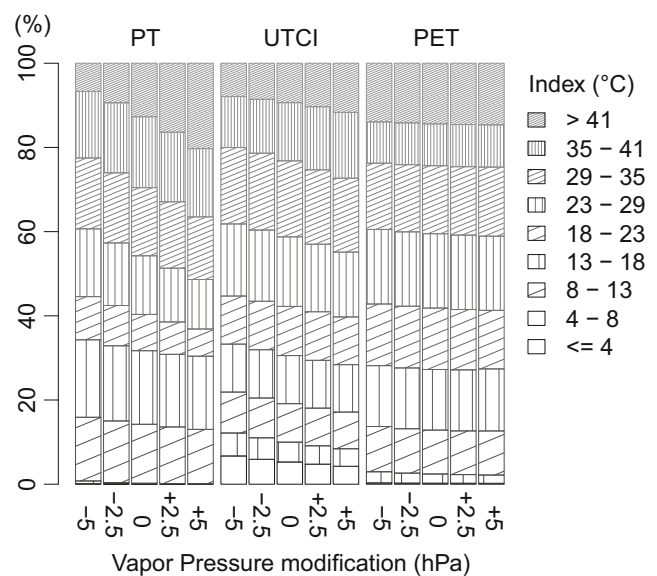

Fig. 5 Distribution of PT (*left*), UTCI (*centre*) and PET (*right*) calculated with modified vapour pressure (VP) for the hot and dry conditions in Doha. For each index, the distribution of the results is plotted as three beans (Kampstra 2008) for a dataset with VP reduced by 5 hPa (*left*), the default dataset (*centre*) and a dataset with VP increased by 5 hPa (*right*)

Fig. 6 Frequencies of thermal sensation classes (Table 2) of results for PT (*left*), UTCI (*centre*) and PET (*right*). The frequencies for input data sets with modified vapour pressure (VP) are compared. The modification in the input VP for each *bar* is given by the caption
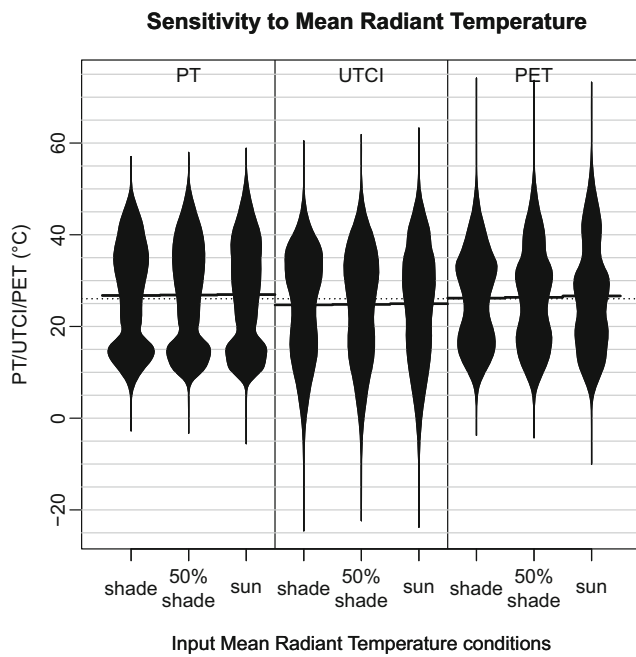
Sensitivity to Mean Radiant Temperature

Fig. 7 Distribution of PT (*left*), UTCI (*centre*) and PET (*right*) calculated with modified mean radiant temperature (T_{mrt}') for the hot and dry conditions in Doha. 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*)

values are lower in the shade. However, the differences are quite small. For PT, the minimum value is only increased by 2.8 °C in the shade. The UTCI minimum is lower anyway
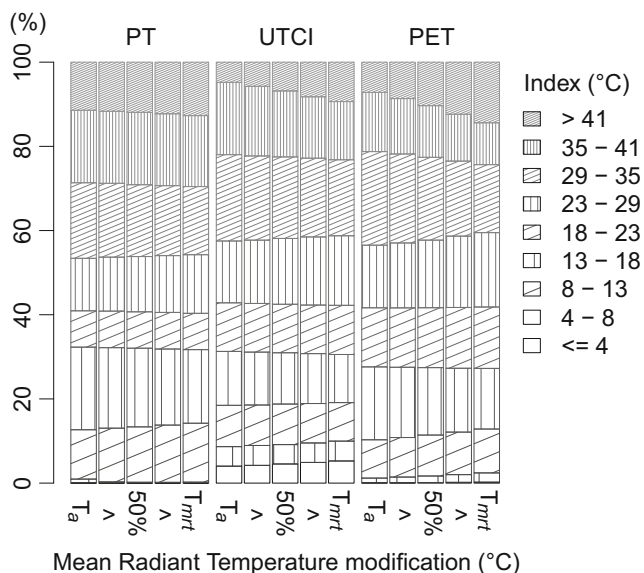

Fig. 8 Frequencies of thermal sensation classes (Table 2) of results for PT (*left*), UTCI (*centre*) and PET (*right*). The frequencies for input data sets with modified mean radiant temperature (T_{mrt}') are compared. The modified input T_{mrt}' for each *bar* is given by the caption

and shows a decrease in the minimum value by 0.8 °C. Like for PT, the minimum value for PET is increased by 6.3 °C in the shade. The maximum values are even less modified. For all three indices, maximum values are decreased slightly within 2 °C in shade.

Little more difference can be seen in the distribution of thermal sensation classes between sunny and shaded conditions (Fig. 8). PT responds very little to T_{mrt} (Fig. 8, left). The strongest difference between PT for shaded and non-shaded conditions can be found for the probability for the lower classes, e.g. the probability for the class 8–13 °C is 14.0 % in the default dataset (sunny) and reduced to 11.7 % for the shaded conditions. Nevertheless, these differences seem to be quite small. UTCI appears to be stronger driven by T_{mrt} (Fig. 8, centre). The frequency for the class of 41 °C and larger is decreased by almost 5 % (from 9.4 to 4.8 %) in the shade ($T_{mrt}' = T_a$). Also, the class for 4 °C and below is slightly less frequent in the shade (reduced from 5.3 % in the sun to 4.0 % in the shade). PET shows the strongest response to the modifications in input T_{mrt} (Fig. 8, right). The class of 41 °C and above is decreased by about 7 % under shaded conditions (sun = 14.4 %, shade = 7.2 %). For PET, the frequency of the class of 4–8 °C is reduced slightly by 1.1 % in the shade (from 2.2 % in the sun to 1.1 % in the shade).

4 Discussion and conclusions

For the hot and windy conditions in Doha, the thermal indices PT, UTCI and PET show different results for the default input conditions. The results for PT appear to be very unevenly distributed. Especially the high frequencies for results between 10 and 18 °C, as well as the neck between 18 and 20 °C, seems to be highly implausible. Both might be caused by the automatically adapting clothing model. The distributions of UTCI and PET are smoother and do agree better in their general shape. They are therefore considered to represent the human perception more reliably for hot and windy conditions.

The sensitivity of all indices to T_a seems to be quite strong in the results. However, the modifications of ±1 and ±2 K are very strong compared to those of the other parameters. This has to be considered while interpreting the impact of T_a. Regarding UTCI, it has furthermore to be considered, that the limit for input T_a of 50 °C was exceeded several times, causing the results to be based on less data on the upper side of the distribution only.

For the variation in the input wind speed, it has to be considered that UTCI requires incident wind speed in 10-m height, while PT and PET require the incident wind speed in the target height of 1.1 m. The modifications therefore had to be extrapolated to 10 m according to Havenith et al. ([2012], Eq. 14) to result in the same impact at a

height of 1.1 m; as for the other two indices. It also has to be considered, that through restrictions in the input wind conditions (refer to Section 2.2) the analysis of UTCI is based on less data than the other two indices. In contrast to UTCI and PET, PT calculates a reduction in the frequencies for hotter classes due to an decrease in wind speed.

For all the indices, it should be considered, that increased wind speed can lead to hotter or cooler sensations depending on the air temperature. As mainly the overall distribution of the results is analysed, this alternating effect of cooling and heating might decrease the influence of wind speed visible in the results.

PT seems to respond nicely to the changes in VP. For UTCI, the limit of 20 hPa for the reference vapour pressure will cause some uncertainties for hot climates, as it is likely to be regularly exceeded there. PET shows only very weak response to the modifications in VP.

The calculations for the modifications in the input conditions for T_{mrt} show that they affect the distribution of the results both in the upper, as well as in the lower part. The reduction in the upper part is mostly due to decreased incident shortwave radiation at daytime, while the decreased long wave radiation fluxes at night time cause lower frequencies of very low values. The average values almost stay the same. All indices therefore predict more comfortable conditions in the shade ($T_{mrt}' = T_a$). This makes T_{mrt} one of the most promising input variables for countermeasures against thermal stress, especially in hot climate. While this trend can be seen in the results for all three indices, it is much weaker in the results for PT than in those for the other two indices.

All in all, PT seems to be sensitive to T_a and VP. The impact of v and T_{mrt} seems to be quite low. Also, the distribution of the results appears to be strange in general. UTCI seems to respond nicely to modifications of all the parameters. However, due to the regression applied in the calculations, it is limited to moderate meteorological conditions. It also tends to calculate very low values. PET is found to lack sensitivity to VP.

As PT, UTCI and PET respond quite differently to the modifications in the input conditions showing particular weaknesses, those should be well known to select the most appropriate index for the specific requirements in productive use. Finally, the indices should be improved to be applicable for all climates worldwide.

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