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Assessment of predicted versus measured thermal comfort and optimal comfort ranges in the outdoor environment in the temperate climate of Glasgow, UK

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Abstract

In a warming world the risk of overheating is significant in temperate climate areas such as Glasgow, UK where adaptation to overheating is low. An easy-to-use thermal comfort evaluation is therefore a necessary first step towards developing effective coping mechanisms. In this study we explore the effectiveness of Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) and Physiologically Equivalent Temperature (PET), together with air temperature in mimicking actual thermal sensation votes of street users obtained in 2011 in Glasgow City Centre. The PMV/PPD indices developed for controlled indoors show a surprising similarity to actual thermal sensation votes derived from outdoor surveys, than the PET developed specifically for the outdoors. The method of calculation of mean radiant temperature (T_{mrt}) is key to improved performance of PET, with fish-eye lens photographs improving its performance. The results also show air temperature (T_a) alone has nearly equal predictive power of the actual thermal sensation. A preliminary comfort range for Glasgow is also derived and its limitations are explored.

Keywords: Environmental comfort; Comfort ranges; Thermal comfort; PMV; PET

Practical applications

The strong relation between thermal sensation votes and T_a enables future thermal comfort studies to predict the thermal comfort using easy-to-access T_a only. A current thermal comfort study in Glasgow aiming at developing a link between urban morphology and T_a is already using this strong relation to predict outdoor thermal comfort in the city centre. This helps to establish a correlation between these three factors.

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1 Introduction and background

The determination of the thermal comfort and thermal stress in outdoor environments, both in an effective and a practical way, is known to be one of the most important applications in human biometeorology¹. Thermal stress negatively influences health in different ways. Apart from the reduction of general wellbeing, heat stress also reduces health and productive efficiency.^{2,3} Moreover heat stress might be associated with the decrease in use of outdoor space⁴. Besides, as studies on the impact of heat waves show, a link between morbidity/mortality and heat stress exists^{1,4}. This was evident in the 2003 heat wave in Central Europe that led to 14,800 additional deaths due to heat stress.⁴ Given the lack of adaptation to hot conditions in temperate climates such risks exist even at relatively lower temperatures. For example, the threshold temperatures beyond which heat-related mortality rises significantly is $> 32^{\circ}\text{C}$ in the equatorial regions, but cities such as London and Stockholm exhibit much lower thresholds (21-23 $^{\circ}\text{C}$)⁵.

Cities form a complex structure and modify atmospheric conditions in the urban canopy layer. One of the best known phenomena is the urban heat island (UHI) which increases heat stress especially in warm periods. The intensity of the UHI varies according to form, material and density of the urban structure¹. Three different methods to minimize the influence of severe heat on urban dwellers exist⁶: implementation of heat warning systems, individual adaptation of citizens by clothing and behaviour and urban planning strategies.

In order to reduce thermal stress pre-emptively, especially in light of overheating risk associated with future climate change exacerbated by the UHI effect^{7,8} biometeorology needs to provide information for adapting urban structures to decrease heat stress¹. A reliable

assessment of the thermal comfort of the population in complex urban structures based on actual thermal comfort surveys is a necessary first step in this regard.

A common practice to estimate thermal comfort is to use rational thermal indices, which are based on the human body energy balance and are said to be universally applicable.¹ However, the adaptive comfort theory⁹ continues to challenge this notion, and posits that comfort is a function of the thermal context and exhibits significant spatial and temporal variations. Nevertheless, several different thermal indices continue to be used for the assessment of the thermal comfort conditions. The present work focuses on Fanger's Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) according to ISO 7730¹⁰ as well as the Physiologically Equivalent Temperature (PET)¹¹. PMV/PPD indices were originally developed for indoor environments. The PMV predicts the mean value of the votes of a large group of persons based on the human body heat balance and is arranged in a seven-point thermal sensation scale (hot, warm, slightly warm, neutral, slightly cool, cool and cold). The PPD establishes a quantitative prediction of the percentage of thermally dissatisfied people, representing those who voted hot, warm, cool or cold in scale of PMV thermal sensation. The PMV value is taken into account to calculate the PPD¹⁰. PET index¹¹ on the other hand, is expressed in °C and is defined as the equivalent temperature to the air temperature in which, for a given situation, the thermal balance of a person remains the same, with the same core and skin temperatures as in the original situation.

The calculations of these indices are complex, requiring several relevant meteorological parameters that influence the heat balance: air temperature (T_a), relative humidity (RH), wind velocity (V_{wind}) and mean radiant temperature (T_{mrt}). While T_a and RH are commonly measured, T_{mrt} and V_{wind} are infrequently measured (with significant exceptions^{13, 14, 15}) and

secondary data, especially site specific urban data, is hard to obtain^{11,12}. The modelling of necessary input parameters for calculating thermal indices is an easier way to generate necessary thermal comfort input data¹². Other more complex and costly methods include measurement campaigns¹⁶ which, nevertheless, supply more precise data¹¹.

Given the acclimatisation of population to local conditions it is imperative that contextually relevant thermal comfort estimations are carried out for each locality. An easy-to-use and low cost method to do so will greatly facilitate rapid estimation of the thermal comfort consequences of urban development options. It will also help identify the likely thermal comfort effects of a changing climate more readily, thus helping planners and designers prepare more robust adaptive options.

This study provides a basis for future thermal comfort studies in temperate climate outdoors based on models and measurement campaigns, by investigating the relationship between (1) the actual thermal sensation of Glaswegian population, derived from an outdoor survey campaign conducted previously in Glasgow City Centre, Glasgow, UK,^{17,18} and T_a and (2) the relationship between the actual thermal sensation and calculated PMV and (3) the relationship between the actual thermal sensation and modelled PMV. Thus, this study forms a basis for the evaluation of future model outputs and measurement campaigns. Besides, (4) an adjustment of the equation for the calculation of the Predicted Percentage of Dissatisfied (PPD) was conducted.

The accuracy of the PMV/PPD/PET indices depends on the quality of the input data.

Towards this end, the paper also explores (5) the effectiveness of the Sky View Factor (SVF, which indicates which part of the sky can be seen from a specific point in the street at the height of pedestrians) on the ability of calculated indices to better mimic actual thermal sensation votes of outdoor users.

2 Study area

Measurements and outdoor comfort surveys were conducted in the city centre of Glasgow, Scotland, UK (55°51'N, 04°12'W) in a pedestrian area which extended from Sauchiehall Street to Argyle Street and covered parts of Buchanan Street forming the shape of a “Z” as shown in Figure 1. Measurement campaign lasted between March and July 2011 and included 19 outdoor surveys under a wide range of air temperatures, wind conditions and solar angles and heights but mostly under clear-sky conditions. Weather conditions during the measurement period are shown as box plots in Figure 2. Monitored climatic variables (air temperature, relative humidity, wind speed and direction, global horizontal solar radiation and globe temperature) are according to ISO 7726¹⁹. Measurements were taken at five second intervals and averaged over a minute. Each campaign spanned up to three hours (typically from 10am to 1pm). Instrumentation included a Davis Vantage Pro2 weather station equipped with a three cup anemometer (at approximately 1.5 m height), air temperature and humidity sensors at 1.1 m, silicon pyranometer at 1.4 m. and a globe thermometer. Details of the equipment and their ranges are given in Table 1 and in previous works¹⁷.

(Figure 1a and 1b here)

(Table 1 here)

(Figure 2 here)

The climate of Glasgow is Cfb according to Köppen-Geigers climate classification that states that the climate is temperate and mild due to strong maritime influence. Average maximum T_a does not exceed 20°C, with at least five months presenting an average above 10°C.

Precipitation is high (annual average = 1300 mm) and spread evenly throughout the year²⁰. Sunshine is typically low (annual average = 1348 hrs) with only 3 months (May, June and July) having a monthly average > 150 hrs/month. Wind speed is moderate (annual average speed at 10m above ground = 7.7 knots [3.96 m/s], with below annual average speeds during the summer months = 5.6 knots [2.88 m/s]).²⁰

Six measurement locations within the pedestrian street area shown in Figure 1b were selected for outdoor comfort surveys and climate measurement. Sky view factor (SVF), street orientation, urban canyon geometry and street type (street junction or squares) were used as criteria for the selection of the measurement locations. The urban characteristics of the monitoring sites are shown in Table 2. A FC-E8 fisheye lens coupled to a digital camera was used for sky view photos and polar photo, black and white mask and the SVF's were derived from RayMan Pro, a public domain software developed by Andreas Matzarakis.²¹

(Table 2 here)

3 Method

A three step process was employed by the present study. First, a pedestrian area in Glasgow City Centre as detailed in Section 2 was selected and a field work comprising of micrometeorological measurements and thermal comfort surveys were administered. The second step generated the input files necessary to calculate comfort indices and the Mean Radiant Temperature (T_{mrt}). Finally, the third step carried out comparisons of actual thermal sensation against measured PMV/PPD/PET.

3.1 Thermal comfort fieldwork

Measurement of air temperature (T_a), wind speed (V_{wind}), relative humidity (RH) and globe temperature (T_g) were conducted at about 1m above ground which reflects the centre of the human body, which is necessary to calculate the thermal index according to the human energy balance²¹. Climate measurements employed a Davis Vantage Pro2 weather station and an additional globe thermometer (consisting of a 40 mm diameter flat grey painted table tennis ball with an enclosed temperature probe [Tinytag-TGP-4500 with external temperature probe], attached to the tripod at 1.1 m height) which together provided all variables needed for the calculation of T_{mrt} ^{17,18}. Resolution and operational ranges of the equipment are shown in Table 1. Weather conditions during the measurement period are shown as box plots in Figure 2 and details of the solar radiation profiles on survey dates are shown in Figure 3.

Each fieldwork campaign lasted for 3 hours (usually between 10 a.m. and 1 p.m. local time). T_{mrt} was calculated according to ISO 7726¹⁹, using Equation 1, for forced convection, taking into account: measured globe temperature (T_g), wind speed (V_{wind}), air temperature (T_a), and globe's emissivity (ϵ_g) and diameter (D). In Equation 1 the convective heat loss of the globe depends on size, material, colour and shape of the globe²² as well as on the geographical latitude²⁸. Preferably the formula should be calibrated with three-dimensional measurements of short and long-wave radiation fluxes at the site but this would require sophisticated and expensive equipment³².

$$T_{MRT} = \left\{ (T_g + 273)^4 + \frac{1.1 \times 10^8 \times V_{wind}^{0.6}}{\epsilon_g \times D^{0.4}} \times (T_g - T_a) \right\}^{\frac{1}{4}} - 273 \quad (\text{Equation 1})$$

(Figure 3)

3.2 Outdoor comfort surveys

In addition to the climate measurements a comfort questionnaire was created according to ISO 10551²³ (see Appendix A). The first part of the questionnaire consisted of personal questions including length of residency in Glasgow that accounts for the acclimatisation. Besides, information regarding the time spent outdoors, prior to the interview, was recorded. The second part consisted of symmetrical seven-point with two-pole scale, ranging from -3 cold over 0 neutral to +3 hot, used for assessing the respondent's thermal sensation and thermal preference.

After data cleansing (i.e. removal of surveys from those residing in Glasgow for less than 6 months; pregnant women, construction workers and others likely to have high metabolic rates), the sample consisted of thermal sensation and thermal preference votes under which the largest concentration of data lies in summer due to more stable conditions. Further narrowing of data samples was arranged to accord for the time spent outdoors. A residency of at least 15 minutes outdoors was used as a criterion as recommended by ANSI/ASHRAE²⁴ for indoor thermal comfort assessments, since calculations with IMEM (Instationary Munich Energy-Based Model)²⁵ suggest that the thermal adaptation, especially to cold, needs to be taken into account. The sample consisted of 61 % male and 39 % female votes and covered an age range from 12-86 years old. The average number of votes at each measurement site counted 100 ± 14 . Total sample size after data cleansing consisted of 573 thermal sensation votes.

3.3 Assessment of thermal indices

The thermal indices used in this survey are PMV, PPD and PET. PMV is based on the same seven-point thermal sensation scale as the outdoor comfort survey, thus allowing a comparison of surveyed thermal sensation votes against calculated thermal PMV values¹⁰.

PMV was calculated using RayMan Pro^{12,26} software (www.mif.uni-freiburg.de/RayMan) and two different calculations were made using different input parameters. The first calculation included location, date, time, T_a , V_{wind} , RH and measured T_{mrt} as input parameters (This is termed as $PMV_{measured}$); the second calculation used the same input parameters except for T_{mrt} . Instead of T_{mrt} , sky view photos of each thermal comfort survey location and global horizontal solar radiation data, derived from the Glasgow Caledonian University reference station (distance to measurement locations = between 0.5 – 1.1km) to account for cloud conditions, were used as input variables. In this case, T_{mrt} , which is necessary to calculate PMV values, was simulated by RayMan Pro ($PMV_{calculated}$). The motivation was to explore whether a simpler method than using globe thermometers could provide equally robust results. For personal input parameters the default values in RayMan Pro were used for both calculations (male, 35 years, 1.75 m, 75 kg). Furthermore an estimated metabolic rate of 295 W was used (walking at 4 km / h on level ground, in agreement with the survey assumptions) and a clothing level of 1.55 (based on average values for surveys conducted during Mar-May 2011) for the colder periods and 0.75 (based on average values for Jun-Jul 2011 surveys) for the warmer periods was used.

As PMV only predicts the mean votes of a large group of people, the individual thermal sensation might differ from the calculated mean¹⁰. Thus, the calculation of the percentage of people who are dissatisfied (PPD) under the current climate conditions, i.e. who feel too cold or too warm, is useful¹⁰. The thresholds for satisfaction with the thermal comfort were taken to be -0.5 and +0.5²¹. Thus thermal discomfort can be due to heat (thermal sensation votes exceed +0.5) and due to cold (thermal sensation votes undershoot -0.5). PPD can be derived from PMV / thermal sensation votes as shown in Equation 2 according to ISO 7730¹⁰.

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad (\text{Equation 2})^{10}$$

In order to test the applicability of T_a , T_{mrt} and PMV as predictors of the outdoor thermal sensation of the Glaswegian population, the thermal sensation votes from the outdoor comfort surveys were matched to the measured climate data and to the calculated indices. The applicability of T_a , T_{mrt} and PMV (measured and calculated) to predict the thermal sensation of Glaswegian population was tested using binned data. Bin width and number of bins varied according to the individual variable. The parameters of the binned data used for the computation of the regression equation are shown in Table 3. For each bin, the mean thermal sensation was calculated according to the thermal sensation votes and compared to the T_a and PMV data.

(Table 3 here)

3.4 Statistical Tests

Statistical tests were conducted using the R Project for Statistical Computing²⁷. For the analysis of the relation of predicted versus measured thermal sensation data, simple linear regression equations were calculated and the coefficients of determination were assessed. The correlation between different indices was tested using Pearson's r values. Besides, an analysis of variance (ANOVA) was conducted to test which variable (T_a , T_{mrt} , V_{wind} , or RH) explains most of the variance in the thermal sensation data and is thus most suitable to predict thermal sensation votes in Glasgow.

Optimal comfort ranges for Glasgow were derived using the regression equations and a thermal comfort zone from -0.5 to +0.5²¹. For the calculation of the actual Percentage of Dissatisfied (PPD) the thermal sensation for each T_a / PMV bin was predicted using the regression equations shown in Figures 4 and 5. From the predicted thermal sensation data, the amount of dissatisfied people (i.e. outlying the comfort zone from -0.5 to +0.5), was calculated and compared against the computed PPD, which is derived from equation 2,

setting the predicted thermal sensation data as PMV. The original equation (equation 2) to compute PPD was then optimized to better fit the measured PPD. This was achieved by minimising the sum of squares between the actual PPD and the corresponding computed PPD values.

4 Results and Discussion

4.1 Comparison of thermal sensation votes against T_a / PMV

The comparison between the actual thermal sensation votes against T_a and the predicted thermal sensation (Table 4) for both scenarios, i.e. for calculated and measured PMV, shows weak correlations for raw data but higher correlation for binned data, although both binned and raw data show significant results ($p \ll 0.05$) (Table 5). While higher correlation to binned data is to be expected the very high values in Table 4 indicate that PMV based on measured input data are highly accurate and, in combination with the regression equation, can be used for the prediction of the thermal comfort in outdoor settings of a temperate climate city.

An analysis of variance (ANOVA) shows that T_a ($R^2 = 86.2\%$) explains a larger amount of the variance in the thermal sensation votes than T_{mrt} . Both measured T_{mrt} ($R^2 = 59.8\%$) and calculated T_{mrt} ($R^2 = 68.9\%$) show weaker correlations than T_a .

(Table 4 here)

However, when intending to carry out future thermal comfort studies in Glasgow, e.g. for examination of the influence of urban geometry on the thermal comfort, it is unpractical, expensive and time consuming to measure all necessary input variables at each measurement site and for different hours of a day and climate configurations.

(Figure 4 here)

Predicted PMV values using fisheye photos and global horizontal solar radiation data as input variables show a good relation, too, as shown in Figure 4. With a $R^2 > 99\%$ the comparison of calculated PMV against thermal sensation votes is nearly identical to the measured PMV. However, the calculated PMV tends to slightly over predict cool sensation and under-predict warm sensation than the measured PMV, although both are higher than the actual thermal sensation. Nevertheless, PMV results derived from RayMan Pro with simulated T_{mrt} data exhibit a close match to actual thermal sensation in Glasgow.

While the match between PMV and measured thermal sensation is very good, PMV itself is difficult to calculate given the importance of wind and T_{mrt} at local scale. If wind data at street level cannot be accessed, the regression equation between T_a and the thermal sensation can be used, too, showing a R^2 of 86.2 % (Figure 5). Since T_a is easy to measure and widely included as part of many measurement campaigns, this close relationship is valuable to estimate thermal sensation during clear sky and moderate wind speed conditions, even though its performance is somewhat poorer than PMV.

The lower outlier at the 10°C T_a bin (Figure 5) is due to three very negative (-2 and -3) thermal sensation votes from the surveys in March 2011 which influence the mean thermal sensation. The second outlier at the 11°C T_a bin is strongly influenced by one thermal sensation vote of +2 which causes a relatively high mean thermal sensation. It should be noted that the thermal sensation of each individual is different and only the mean thermal sensation of a large group of people corresponds to the observed weather conditions.

(Figure 5 here)

4.2 'Optimal' comfort ranges

The range of air temperature corresponding to satisfactory thermal environment (i.e. $-0.5 < \text{thermal sensation} < +0.5$) in Glasgow is 11.6-16.2°C (Table 5). This corresponds to a measured PMV range of +0.3 to +1.6 while calculated PMV ranges from -0.1 to +2.0. This indicates that Glaswegian population considers what would otherwise be considered as 'cool' temperatures (11.6-16.2°C) as 'comfortable' while slightly warmer conditions are considered as 'warmer than neutral.' Given the low annual average T_a in Glasgow (8.9°C)²⁰, this provides indirect evidence to the theory of adaptive thermal comfort⁹ from a cold adaptation point of view. Nevertheless it is worth pointing out that only in five months of the year the outdoor temperature would fall within the 11.6-16.2°C range, indicating cold stress in the outdoors is clearly a significant problem. This is further accentuated by the PPD data which is discussed in Section 4.5 below.

(Table 5 here)

4.3 Quality of predicted T_{mrt} using RayMan Pro

The comparison of measured T_{mrt} against predicted T_{mrt} shows a weak correlation ($R^2 = 23.4\%$, $p < 0.05$) (see Figure 6). Differences between measured and calculated T_{mrt} ($\Delta T_{mrt} = \text{measured } T_{mrt} - \text{calculated } T_{mrt}$) are large (ranging from -34.3 to +34.8). The mean measured T_{mrt} (22.3°C) is lower than the mean calculated T_{mrt} (25.2°C) suggesting that RayMan overestimates T_{mrt} data. Larger differences ($\Delta T_{mrt} > 10^\circ\text{C}$) typically occurred between 10:00 – 11:00 a.m. local time. Given the low sun angles, this result is similar to Thorsson *et al.*²⁸. However, two caveats are in order: global horizontal solar radiation was not measured at the thermal comfort survey sites but at a reference station located 0.5-1.1 km away (thus, there could be differences in the amount of cloud cover, which strongly influences T_{mrt}).

Furthermore, given our focus on clear days, global radiation in the street canyons could have been overestimated due to reflected shortwave radiation.

(Figure 6 here)

Given the lack of comparable solar radiation data, it is difficult to justify the second caveat above. However, the effect of differences in cloud cover could be tested by considering a 25-minute moving average T_{mrt} , which improved the coefficient of determination ($R^2 = 35.9\%$).

4.4 Comparison of calculated against measured PMV / PET

Figure 7a shows a comparison of measured and calculated PMV. Raw data show a very high correlation ($R^2 = 70\%$), although the correlation between measured and calculated T_{mrt} , which is one of the input variables, is weak. The same comparison was also conducted for Physiological Equivalent Temperature (PET) index (Figure 7b). These two indices were calculated using sky view photos and global horizontal solar radiation data as input.

(Figure 7 a/b here)

The coefficient of determination between PET calculated with measured T_{mrt} vs. simulated T_{mrt} ($R^2 = 66.7\%$) is weaker than the PMV correlation. However, correlation would be even better if individual clothing values are used.

The correlation between the thermal sensation votes and PET were conducted in previous studies^{17,18} where a good correlation was found ($R^2 = 91\%$); however this was weaker than PMV.

4.5 Predicted Percentage of Dissatisfied - PPD

In order to estimate the amount of dissatisfied, PPD was calculated and the goodness of fit of the original PPD regression equation for the Glasgow area was tested. The predicted PPD, shown in Table 6, was calculated and compared to the actual percentage of dissatisfied (see Figure 8).

(Table 6 here)

(Figure 8 here)

The relationship between actual and computed PPD against the predicted thermal sensation votes for each of the T_a / PMV bins show that the neutral zone ($TS = 0$) for the theoretical PPD is below the minimum of the actual PPD. The thermal sensation vote for each T_a / PMV bin shows greater variation (i.e. there are larger amount of dissatisfied) which is indicative of a greater diversity of thermal sensation in the outdoors. Based on this, the regression equation for the calculation of PPD (Equation 2) can empirically be adjusted to fit the actual percentage of dissatisfied, which generates the formula for adjusted PPD (PPD*) presented in Table 7.

(Table 7 here)

5 Conclusions

The regression equations of the actual thermal sensation votes against T_a , measured PMV and calculated PMV show excellent results. This indicates that PMV and T_a data can be used for the prediction of outdoor thermal sensation, although clearly T_a is a weaker, albeit easy-to-obtain substitution. In the case of Glasgow's outdoors PMV data show even better relations than PET data¹⁷, which recommends the use of PMV for further studies. However, it should

be kept in mind that we had excluded thermal sensation votes from persons not exposed to the outdoor conditions for a sufficiently long enough time as well as those not resident in the city. These factors may explain the better fit between thermal sensation and PMV, contrary to other studies in similar temperate climate cities^{14,15}. Furthermore the measured PMV values were in a range similar to the actual sensation votes, which was not the case in the studies referred to above.

It should be further noted that these regression equations cannot be used in different climate regions since the acclimatization of the population needs to be considered. Furthermore, the use of T_a as a predictor of the thermal sensation needs to be handled carefully. As our work has shown, rational thermal comfort indices clearly perform better while air temperature could provide an early indication of likely thermal comfort in the outdoors. In regions where V_{wind} is low, T_{mrt} is a dominating factor and the correlation between T_a and the thermal sensation becomes weaker²⁹. Additionally, that fact that thermal comfort in the outdoors is further influenced by psychological adaptation^{13, 14} too needs to be taken into account.

The ‘optimal’ PET comfort range for Glasgow (9-18°C)¹⁷ is clearly below the suggested thermal comfort range from 18°C to 23°C²¹. The comparison of PET against thermal sensation votes in Glasgow shows a high correlation ($R^2 = 91\%$)¹⁸ and thus is useful for the prediction of thermal comfort. Although PET is a commonly used index for the prediction of the thermal conditions of an outdoor environment^{21,28,29,30,31} our results suggest that both measured and calculated PMV are more consistent with the actual thermal sensation votes in Glasgow which recommends the use of PMV index for future investigations of the thermal sensation. However, it should be kept in mind that the above “comfort” zone is valid for outdoor clothing and activity.

Given the low annual average temperature in the city, comfort ranges of T_a indicate that heat stress and cold stress occur throughout the year whereas thermal discomfort due to cold is more frequent (annual mean temperature undershoots lower comfort threshold). However, the changing climate may lead to increased heat stress in the future.⁷

Additionally it is shown that the results for PMV attained by RayMan Pro using (1) measured input data (PMV_{measured}) and (2) fisheye photographs and site-specific global radiation data ($PMV_{\text{calculated}}$) both closely mimic actual thermal sensation. Thus, future thermal comfort studies can be conducted using RayMan Pro in combination with the adjusted regression equations for thermal comfort. Besides, thermal discomfort due to heat or cold can be assessed using the suggested optimal thermal comfort range for PMV / T_a (Table 5).

Several studies mention that T_{mrt} is the climate variable which influences the human energy balance the most^{16, 29} and thus shows the strongest correlation with thermal sensation votes. In contrast to those findings, our results show a better fit for T_a data. As Höpfe¹¹ points out, T_a becomes more dominant in windy conditions as it is the case in Glasgow, because T_a bestrides the convective heat exchange. This explains the better fit of thermal sensation votes against T_a data compared to T_{mrt} data and enables planners and urban designers to estimate the thermal sensation by means of easy-to-access T_a data. However, as other studies^{16, 29} suggest, in different climate conditions, this close relationship between T_a and thermal sensation votes might not be valid and T_{mrt} dominates the thermal sensation. Furthermore, it is important to keep in mind that T_a itself cannot be directly influenced by urban design. However, given its widespread use and greater popular awareness, T_a is a useful medium in which to express the likely thermal comfort implications of design options.

PPD results for Glasgow indicates the presence of a large amount of dissatisfied for a predicted thermal sensation of “0” compared to computed PPD (Fig. 7). This demonstrates

the greater diversity of the thermal sensation of the Glaswegian population and the adjusted PPD (PPD*) should be considered for further studies. Such works could explore outdoor design strategies that could decrease the percentage of dissatisfied in Glasgow to increase the comfort conditions in this cold temperate climate.

For further studies which examine the thermal comfort in urban areas in windy temperate climate conditions, the close link between the thermal sensation and T_a , will especially be useful, since it enables planners and architects to assess thermal comfort data by easy-to-access T_a data. Therefore, future studies that require a lot of measurement sites, e.g. studies which aim at finding a link between urban morphology and thermal comfort, can be carried out easily.

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Appendix:

Comfort questionnaire (based on ISO 10551)

Date:

Time:

Part 1: background and personal information

Gender (**circle it**): Male Female

Age:

Weight: Height:

Time of residency (Glasgow or UK, **circle it**): less than 6 months more than 6 months

Time spent outdoors (**minutes**):

Part 2: current clothing garments (clothing ensembles as in ISO 9920, refer to Table Annex A)

Part 3: How do you feel at this precise moment?

(-3) cold

(-2) cool

(-1) slightly cool

(0) neutral

(+1) slightly warm

(+2) warm

(+3) hot

Part 4: Please state how you would prefer to be now:

(+3) much warmer

(+2) warmer

(+1) a little warmer

(0) neither warmer nor cooler

(-1) a little cooler

(-2) cooler

(-3) much cooler

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Table 1 Equipment characteristics

Sensor	Resolution	Measurement range	Accuracy
Air temperature	0.1 °C or 1 °C (user-selectable)	-25° to +85 °C	±0.5 °C above 20 °F (-7 °C)
Relative Humidity	1 %	1 to 100 %	±3 % (0-90 %). ±4 % (90-100 %)
Air velocity	0.4 m/s	1 to 80 m/s	±1 m/s
Wind direction	22.5°	0-360°	±3°
Solar radiation	1 W/m ²	0 to 1800 W/m ²	±5 %

Table 2 Characteristics of the thermal sensation measurement sites

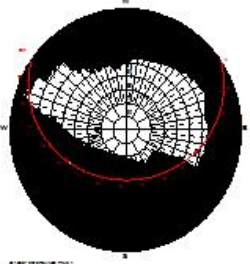
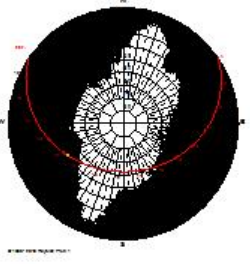
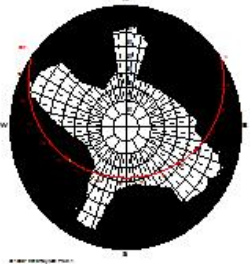
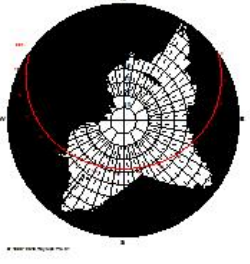
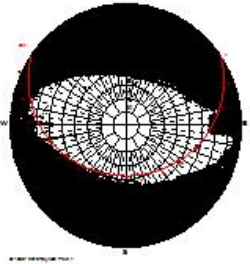
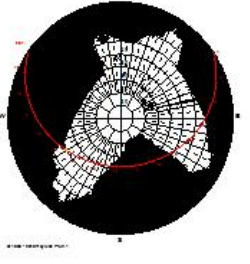
Code, location and SVF	Fisheye photo	Code, location and SVF	Fisheye photo
<p>Point 1 55°51'50.06" N 4°15'10.17" W SVF = 0.287</p>		<p>Point 2 55°51'33.48" N 4°15'16.40" W SVF = 0.278</p>	
<p>Point 3 55°51'27.93" N 4°15'4.74" W SVF = 0.337</p>		<p>Point 4 55°51'43.14" N 4°15'13.14" W SVF = 0.309</p>	
<p>Point 5 55°51'52.66" N 4°15'23.11" W SVF = 0.313</p>		<p>Point 6 55°51'39.65" N 4°15'14.02" W SVF = 0.318</p>	

Table 3 Bins used for computing the regression equations

	Bin width	Number of bins	Minimum bin	Maximum bin
T _a	1 (°C)	14	8 (°C)	21 (°C)
T _{mrt} measured	2 (°C)	25	10 (°C)	50 (°C)
T _{mrt} calculated	2 (°C)	27	8 (°C)	52 (°C)
PMV measured	1	7	-3	+3
PMV calculated	1	8	-3	+4

Table 4 Performance of calculated and measured indices against actual thermal sensation

	Raw Data			Binned data		
	R ²	Pearsons r	p-value	R ²	Pearsons r	p-value
TS ~ T _a	20 %	0.45	<< 0.05	86.2 %	0.93	<< 0.05
TS ~ T _{mrt} measured	9.5 %	0.31	<< 0.05	59.8 %	0.77	<< 0.05
TS ~ T _{mrt} calculated	5.6 %	0.24	<< 0.05	68.9 %	0.83	<< 0.05
TS ~ PMV _{measured}	18.0 %	0.42	<< 0.05	99.3 %	0.996	<< 0.05
TS ~ PMV _{calculated}	10.9 %	0.33	<< 0.05	99.4 %	0.997	<< 0.05

Table 5 ‘Optimal’ thermal comfort ($-0.5 < \text{thermal sensation} < +0.5$) ranges

	Lower threshold (TS = -0.5)	Upper threshold (TS = +0.5)
Measured PMV	+0.3	+1.6
Calculated PMV (RayMan)	-0.1	+2.0
Measured T_{mrt} (°C)	+10.3	+30.9
Calculated T_{mrt} (°C)	+7.6	+33.2
T_{a} (°C)	+11.6	+16.2

Table 6 Actual and adjusted PPD for Glasgow and the corresponding PMV / T_a bins

PMV bin	Actual PPD (%)	PPD* (adjusted) (%)	Thermal sensation (TS)
Measured PMV			$TS = -0.76176 + 0.79569 * PMV$
-3	NA	99.9	-3.1
-2	NA	94.1	-2.4
-1	NA	59.1	-1.6
±0	31.4	33.9	-0.8
+1	30.9	30.6	0.0
+2	37.1	34.9	+0.8
+3	62.5	62.6	+1.6
Calculated PMV[†]			$TS = -0.45433 + 0.48456 * PMV$
-3	NA	69.3	-1.9
-2	NA	59.8	-1.4
-1	NA	45.0	-0.9
±0	20.0	30.5	-0.5
+1	32.8	24.9	0
+2	30.4	32.0	+0.5
+3	52.5	47.0	+1.0
T_a (°C)			$TS = -2.92597 + 0.21188 * T_a$
8	47.4	49.5	-1.2
9	35.7	35.4	-1.0
10	50.0	31.1	-0.8
11	16.7	29.5	-0.6
12	35.5	30.1	-0.4
13	31.8	31.1	-0.2
14	31.7	31.4	0
15	29.9	30.8	+0.3
16	29.0	29.8	+0.5
17	21.1	29.8	+0.7
18	39.4	32.9	+0.9
19	38.1	41.3	+1.1
20	47.6	55.5	+1.3
21	80.0	72.7	+1.5

Notes

[†] – Equations only valid in the range from TS = ~ -2 to ~ +2 (which corresponds to the range of thermal sensation calculations)

Table 7 Adjusted regression equations for PPD

Original PPD equation (ISO 7730) ¹⁰	$PPD = 100 - 95 * \exp(-0.03353 * PMV^4 - 0.2179 * PMV^2)$	Equation 2	-
Best-fit for T_a	$PPD^* = 100 - 69 * \exp(-0.2411 * TS^4 + 0.1636 * TS^2)$	Equation 3	$R^2 = 75.7 \%$
Best fit for measured PMV	$PPD^* = 100 - 69 * \exp(-0.0727 * TS^4 - 0.0414 * TS^2)$	Equation 4	$R^2 = 98.7 \%$
Best-fit for calculated PMV	$PPD^* = 100 - 68 * \exp(-0.9544 * TS^4 + 0.5855 * TS^2)$	Equation 5	$R^2 = 84.7 \%$



Figure 1a Glasgow city centre map

Source: Google Earth



Figure 1b Thermal comfort survey sites

Source: Google Earth

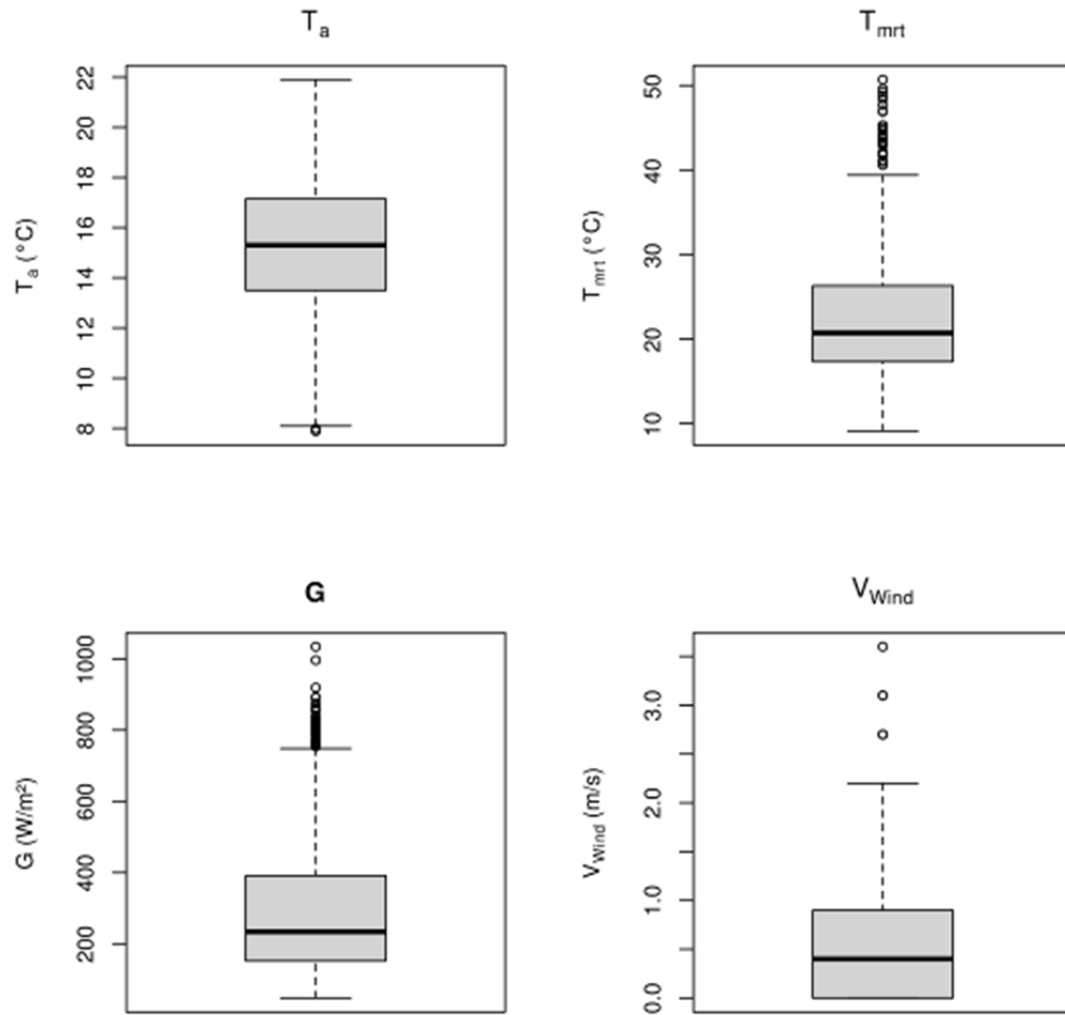


Figure 2 Weather conditions during the measurement period

Note:

Boxplots of air temperature (T_a) (top left), mean radiant temperature (T_{mrt}) (top right), global horizontal solar radiation (G) (bottom left) and wind velocity (V_{wind}) (bottom right) for the measurement campaigns between March and July 2011 in the Glasgow city centre. The solid black line is the median and the dashed line shows the mean; the lower and upper edge of the box are first and third quartile; the error bars show extreme values which are within 1.5 times the Inter quartile range (IQR); the dots show extreme values beyond 1.5 IQR.

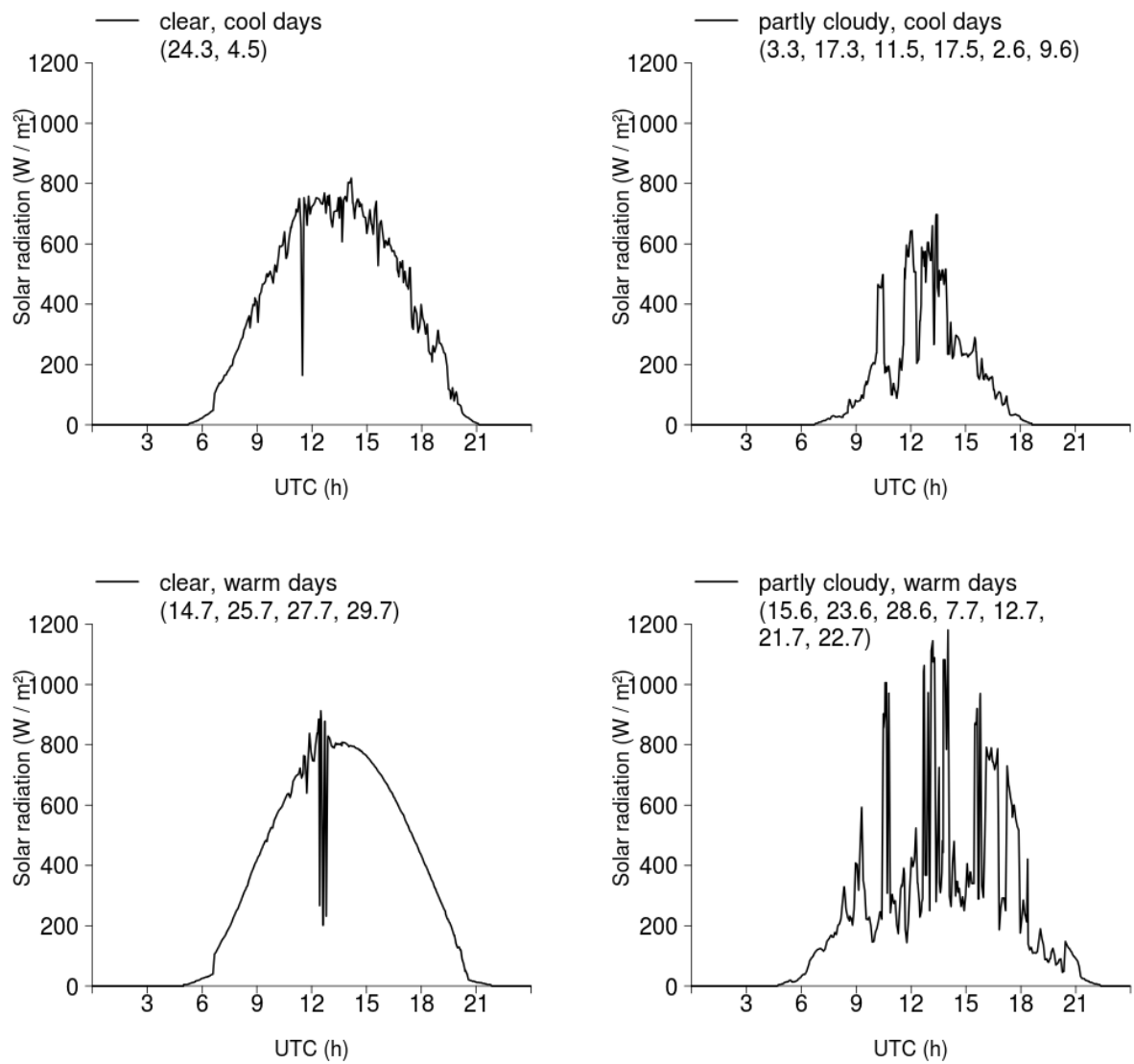


Figure 3 Typical solar radiation profiles on the survey days

Note:

Figures in parenthesis indicate the thermal comfort survey dates in date.month format

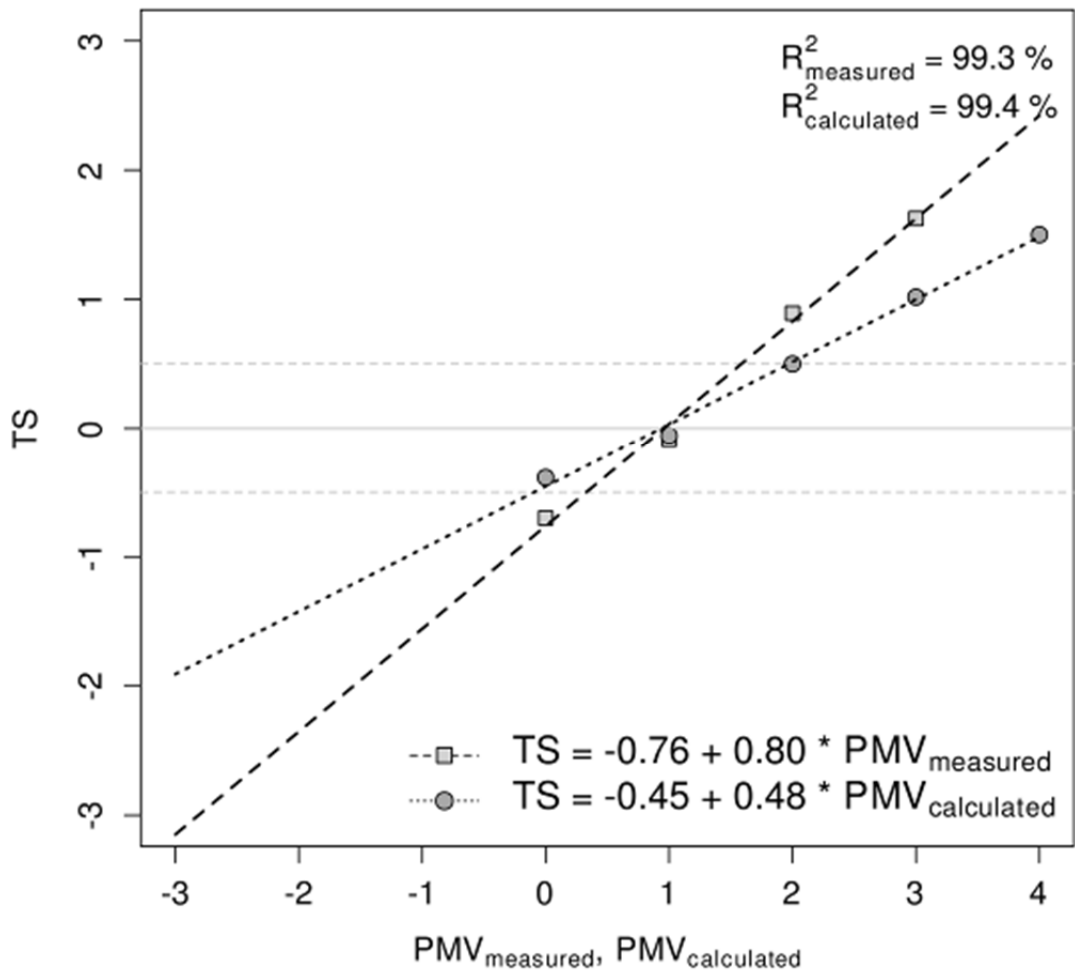


Figure 4 Mean thermal sensation votes against calculated (RayMan) and measured PMV

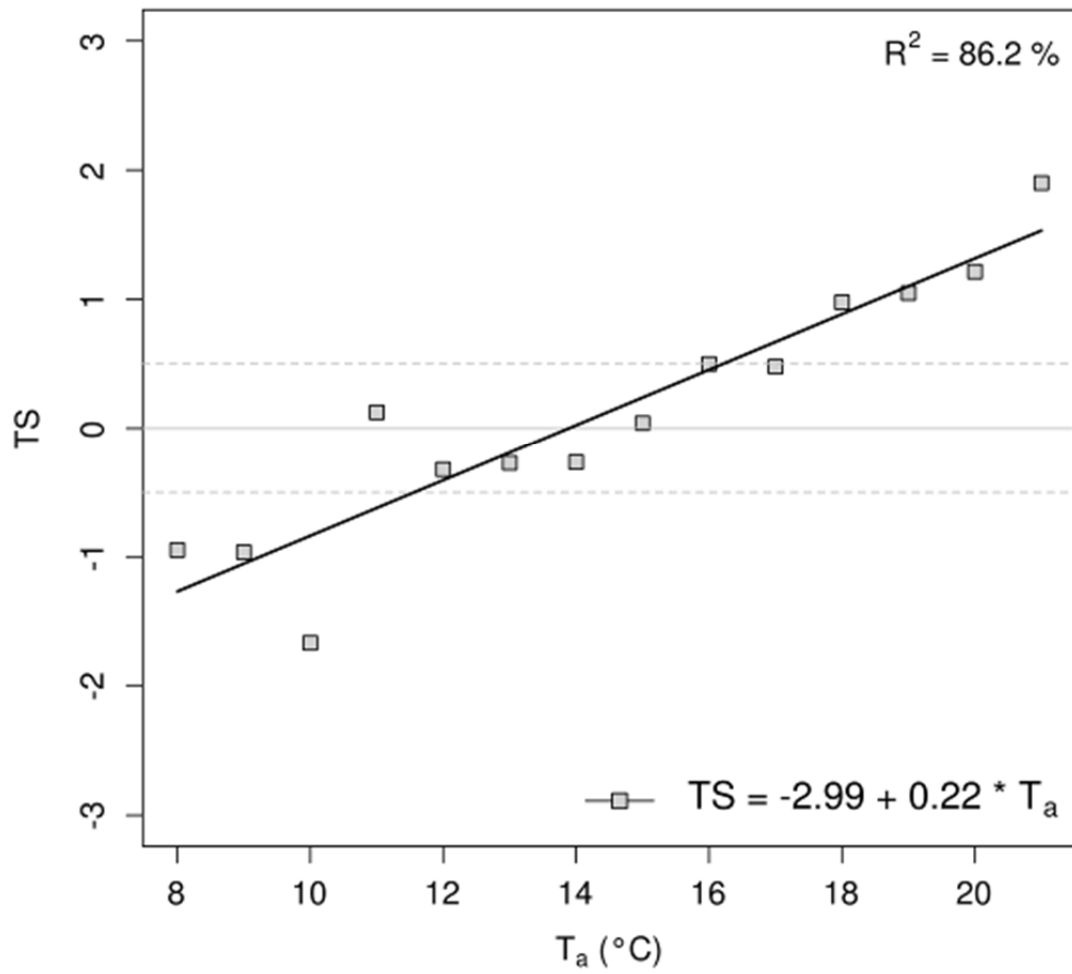


Figure 5 Mean thermal sensation votes and binned T_a classes for Glasgow

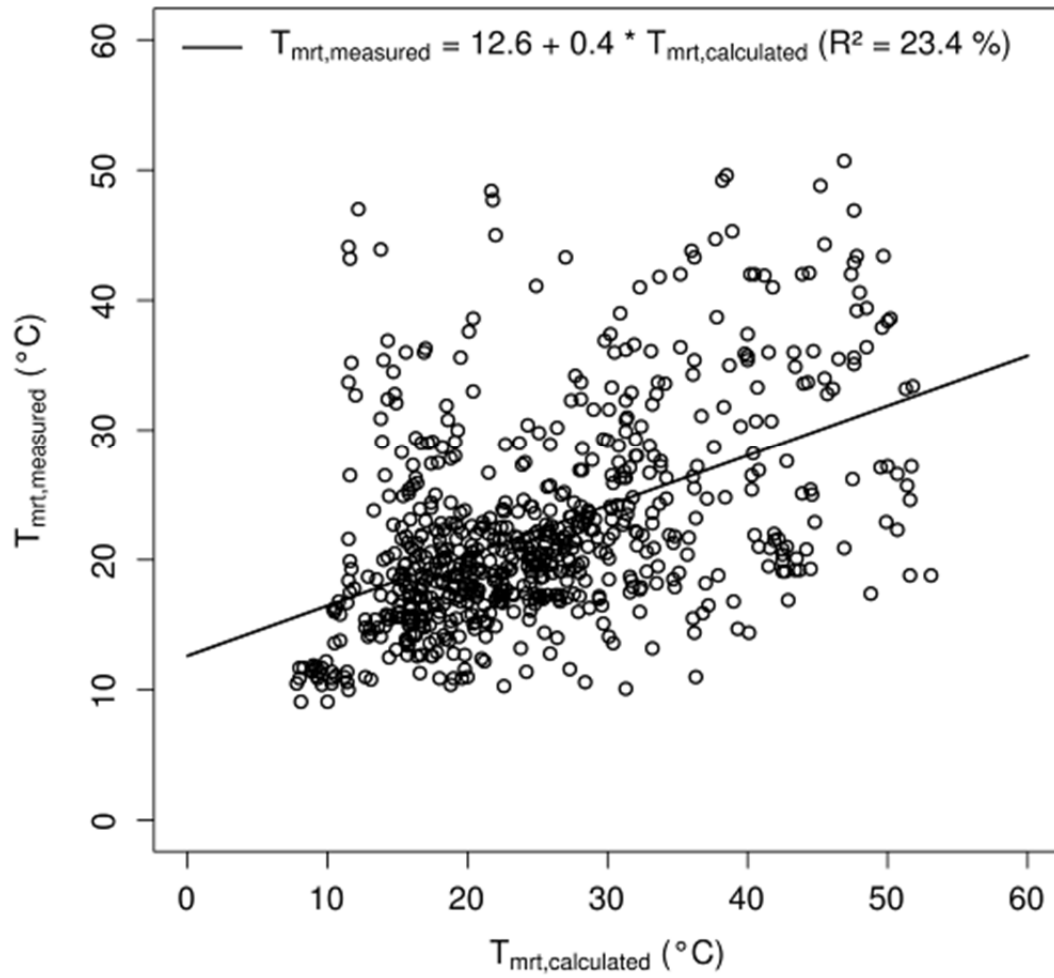


Figure 6 Measured T_{mrt} data and predicted T_{mrt} data using RayMan for Glasgow

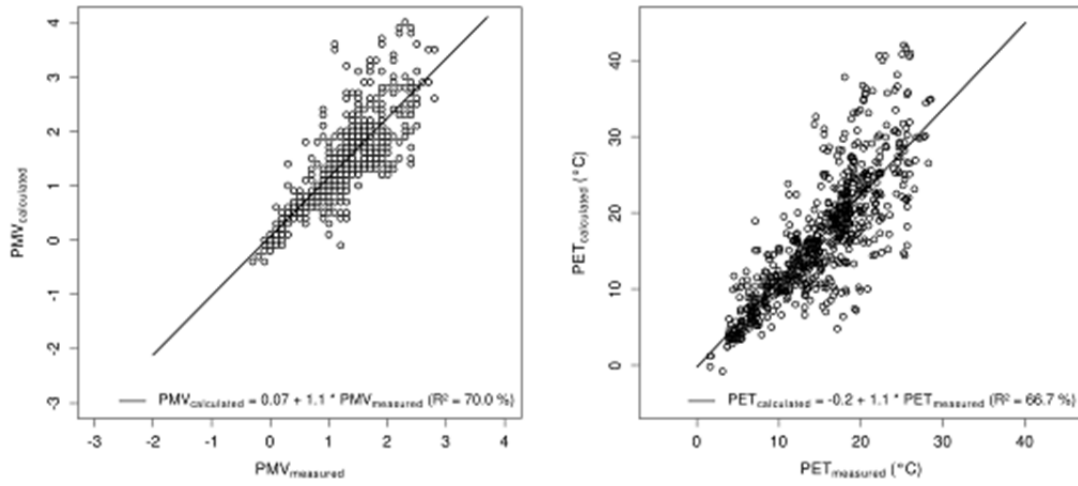


Figure 7 Correlation between measured and calculated (a) PMV and (b) PET for Glasgow

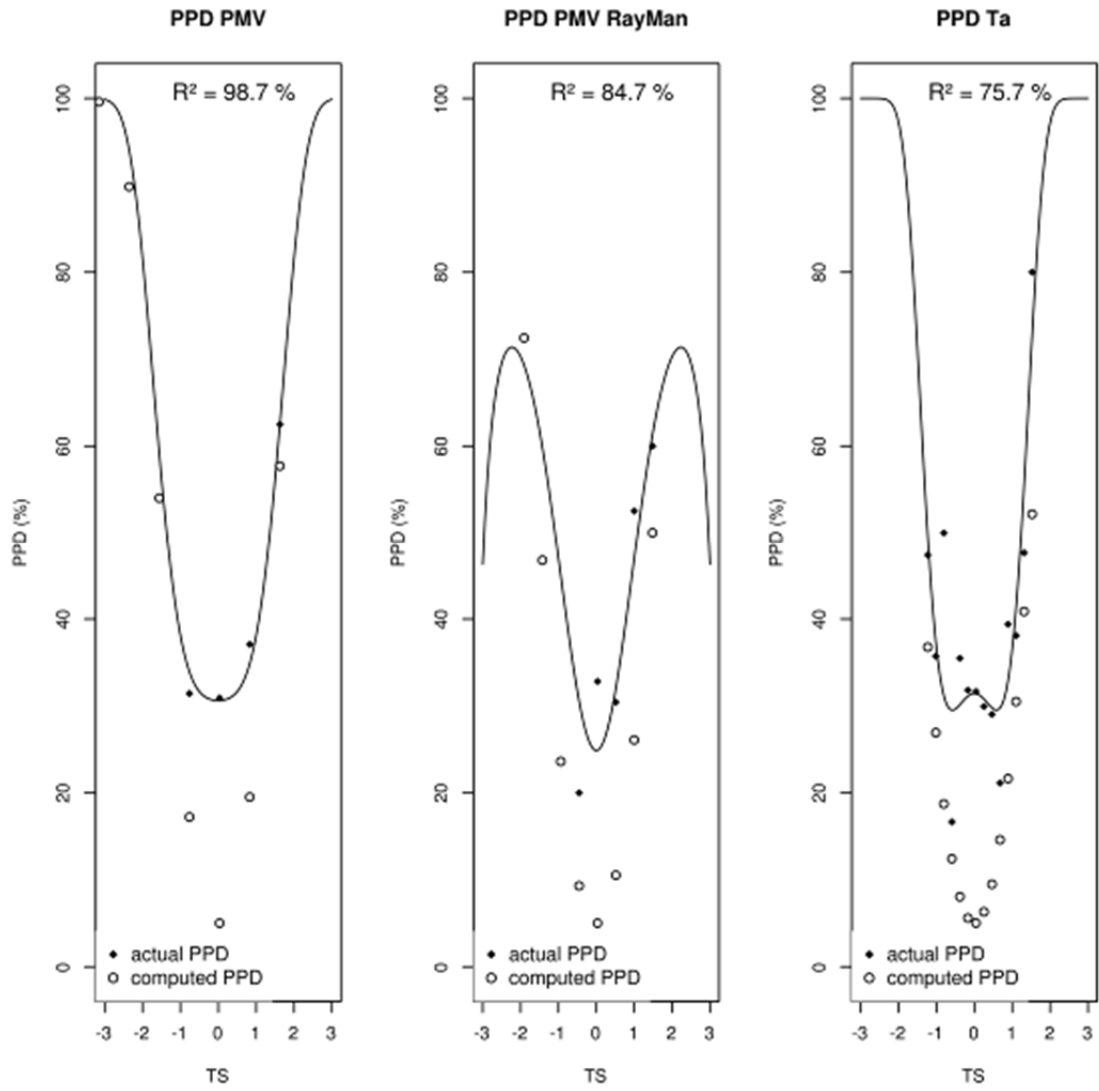


Figure 8 Actual and computed PPD for Glasgow. The parabola shows the adjusted PPD* regression parabola (equations are provided in table PPD*).