

Urban heat island and differences in outdoor comfort levels in Glasgow, UK

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Abstract From extensive outdoor comfort campaigns, preliminary outdoor comfort ranges have been defined for the local population of Glasgow, UK, in terms of two thermal indices: ‘Temperature Humidity Sun Wind’ (THSW) and ‘Physiological Equivalent Temperature’ (PET). A series of measurements and surveys was carried out from winter through summer 2011 during 19 monitoring campaigns. For data collection, a Davis Vantage Pro2 weather station was used, which was equipped with temperature and humidity sensors, cup anemometer with wind vane, silicon pyranometer and globe thermometer. From concurrent measurements using two weather stations, one located close to the city core and another located at a rural setting, approximately at a 15-km distance from the urban area of Glasgow, comparisons were made with regard to thermal comfort levels and to urban–rural temperature differences for different periods of the year. It was found that the two

selected thermal indices (THSW and PET) closely correlate to the actual thermal sensation of respondents. Moreover, results show that the urban site will have fewer days of cold discomfort, more days of ‘neutral’ thermal sensation and slightly higher warm discomfort. The most frequent urban heat island intensity was found to be around 3° C, whereas the fraction of cooling to heating degree-hours for a T_{base} of 65 °F was approximately 1/12th.

1 Introduction

The consideration of outdoor thermal environment as a critical linchpin in the design of public spaces can be seen as one of the major applications of human biometeorology (Vanos et al. 2010). Modifications to urban form are able to promote improved outdoor thermal conditions that positively influence the use of open spaces. Depending on the background climatic conditions shaded or sunlit open areas resulting from carefully manipulated urban geometry leads to greater pedestrian use of urban spaces, contributing at least partially to their attractiveness. Furthermore, the outdoor thermal conditions may have an indirect effect on indoor environments, interfering with indoor thermal comfort or enhancing/reducing energy loads for heating/cooling in buildings. An ability to link urban geometry to outdoor comfort could thus contribute to planners’ and designers’ ability to create better urban places.

A number of studies carried out in the field of outdoor thermal comfort have attempted to explore the links between thermal comfort and urban planning variables, particularly with regard to the influence of urban canyons on outdoor comfort and energy consumption in buildings (Ali-Toudert and Mayer 2006; Johansson 2006; Johansson and Emmanuel 2006; Williamson et al. 2009) and to the effect of sky view factor and other morphological attributes on

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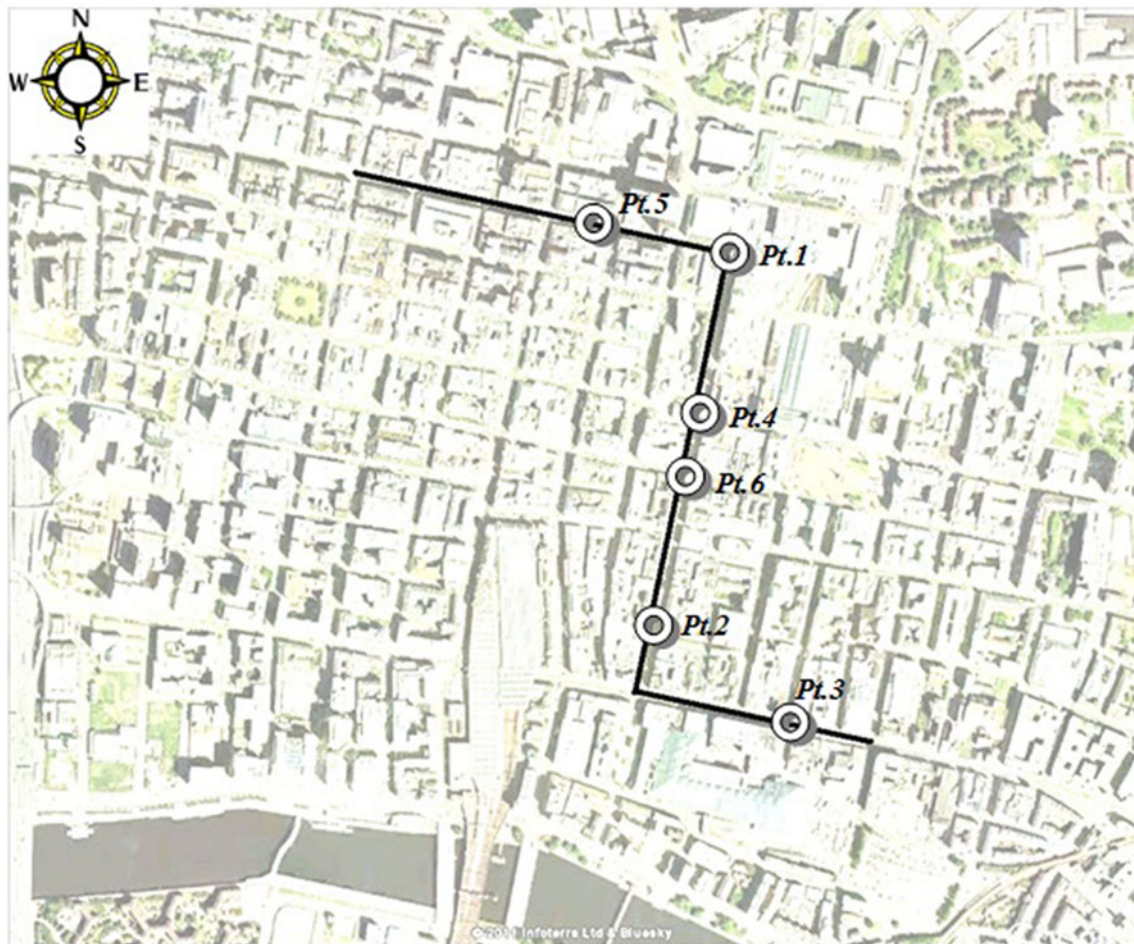


Fig. 1 Monitoring points along the pedestrian area

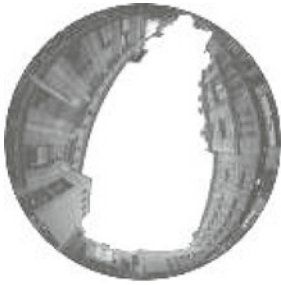

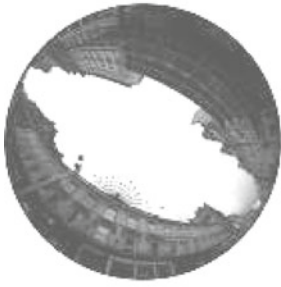



pedestrian comfort (Upmanis and Chen 1999; Unger 2004; Svensson 2004; Souza 2007; Pearlmutter and Krüger 2007; Krüger et al. 2011). Indices such as the ‘Physiological Equivalent Temperature’ (PET) have been used for planning purposes and for tracing urban design guidelines (Erell et al. 2011; VDI 1998). More recent papers (Thorsson et al. 2010; Kolokotroni et al. 2012) attempted to predict future consequences of densely built urban settings on the urban heat island (UHI) effect based on climate change projections.

However, as pointed out by Erell et al. (2011), in complex real-life situations, behaviour patterns tend to be adapted to climatic conditions to which people are mostly exposed to. This factor is in agreement with the adaptive comfort approach. Applying this concept to intermediate and outdoor spaces requires the conduction of field studies, which could identify more adequately desired exposure conditions and delineate adaptive opportunities (Nicol et al. 2012).

The purpose of the paper is to present a feasible method of assessing local thermal preferences for allowing calibration of optimal ranges of thermal comfort

indices in order to use the calibrated indices as additional tools in UHI analyses. The present paper is part of a broader research initiative focused on the understanding of the UHI effect and possibilities to enhance urban resilience to local and global climate change in the city of Glasgow, UK. In this paper, two independent data series from two interrelated studies are used for analysis: data from outdoor comfort surveys, conducted from March through the end of July 2011, and weather data collected with standard weather stations at two different locations within and outside the city of Glasgow. The purpose of the paper is two-fold: (1) to summarize the results of the outdoor comfort surveys, proposing a preliminary outdoor comfort range from thermal sensation votes obtained from the administration of 763 questionnaires to street users in Glasgow’s main pedestrian area and (2) to evaluate the effects on the urban heat island and on thermal comfort of the urban area of Glasgow. The quantification of thermal comfort employed the ‘Temperature Humidity Sun Wind’ (THSW) index and the PET index, which is presently

Table 1 Characteristics of monitoring points

Code, location and description	Sky View (fish-eye image)	Code, location and description	Sky View (fish-eye image)
Point 1 (CS-1,6,12,19): Corner between Buchanan Street and Sauchiehall Street, opposite Royal Concert Hall – location with wind channelling effect (SVF = 0.41)		Point 4 (CS-4,9,15): Nelson Mandela Place (SVF = 0.39)	
Point 2 (CS-2,7,14): Middle of regular urban canyon on Buchanan Street (SVF = 0.38)		Point 5 (CS-5,10,17): Middle of regular urban canyon on Sauchiehall Street (SVF = 0.39)	
Point 3 (CS-3,13,18): Crossroads between Argyle Street and Miller Street (SVF = 0.48)		Point 6 (CS-8,11,16): Crossroads between pedestrianized Buchanan Street and motorized Saint Vincent Street (SVF = 0.45)	

adopted in outdoor comfort evaluations under various climatic conditions.

2 Outdoor comfort surveys

According to Koeppen–Geiger's climate classification, the climate of Glasgow (55°51'N, 04°12'W) is Cfb temperate climate, especially mild due to strong maritime influences. With significant precipitation in all seasons (average annual precipitation=1,100 mm), the average maximum temperatures in the warmest months (July and August) remain below 20 °C, but with at least 5 months averaging above 10 °C (UK Met Office 2011).

The outdoor thermal comfort study was conducted in the pedestrian area of downtown Glasgow, a stretch of approximately 1.5 km long, between Argyle Street and Sauchiehall Street, covering most of the Buchanan Street, in the shape of a 'Z' (Fig. 1). Within this area, six locations were selected

for conducting surveys related to the thermal perception of the urban environment. Criteria for selection of the monitoring points were the following: street orientation, sky view factor,¹ urban canyon geometry and street type (crossings and squares). Table 1 shows the features of each of the six monitoring points.

The microclimate measurements and the field surveys were carried out between March and July 2011, over 19 outdoor survey campaigns, covering a wide range of weather types, typically under clear-sky conditions. Climatic variables (air temperature and humidity, wind speed and direction, solar radiation and globe temperature) were monitored according to ISO 7726 (1998) standards. Each measurement/survey campaign spanned up to 3 h (typically

¹ For the determination of the SVF, fisheye images at each monitoring point were generated using a fisheye lens FC-E8 coupled to a Nikon CoolPix 4500 digital camera. From the fisheye images, the SVF was calculated using Rayman, a public domain software, developed by Andreas Matzarakis (<http://www.mif.uni-freiburg.de/RayMan/>).



Fig. 2 'Mobile' weather station (Davis Vantage Pro2) with grey globe thermometer, at Point 1

from 10 am to 1 pm, local time). Climate measurements employed a Davis Vantage Pro2 weather station (Fig. 2), equipped with a three-cup anemometer (at approximately 1.5 m above ground), air temperature and humidity sensors at 1.1 m above ground and a silicon pyranometer at 1.4 m. Additionally, a globe thermometer was prepared for assessing the mean radiant temperature (T_{mrt}), which consisted of a grey sphere (11 mm in diameter) with an enclosed temperature data logger (Tinytag-TGP-4500), attached to the tripod at 1.1 m above ground. Resolution and operational ranges of the equipment are shown in Table 2. Data from all sensors were registered by a logger and recorded every 5 s and averaged over 5 min. This sampling time was necessary to offset the response time of the globe thermometer (Nikolopoulou et al. 1999), though it was constrained by the setup time of about 5 min prior to each monitoring campaign. T_{mrt} was calculated according to (ISO 7726 1998) for forced convection (Eq. 1) from the measured globe temperature (T_g), wind speed (V_a), air temperature (T_a), and globe's emissivity (ε_g) and diameter (D).

$$T_{mrt} = \left\{ (T_g + 273)^4 + \left[\frac{(1.1 \times 10^8 \times V_a^{0.6})}{(\varepsilon_g \times D^{0.4})} \right] \times (T_g - T_a) \right\}^{\frac{1}{4}} - 273 \quad (1)$$

Ambient temperatures measured during the campaigns ranged between 7.9 and 21.9 °C, with a corresponding relative humidity range of 28–77 %, while the mean radiant temperature range was 9.6–48.5 °C and the wind speed range was 0–3.6 m/s.

A comfort questionnaire was tailored according to the recommendations of ISO 10551 (1995). The first part of the questionnaire consisted of items related to gender, age, height, weight, clothing insulation (a look-up table with typical clothing garments was used²), time of residency in Glasgow (to account for the acclimatisation factor) and information regarding the estimated time spent outdoors prior to the interview. The second part of the questionnaire consisted of two symmetrical seven-point two-pole scales ranging from $-3 = \text{'cold'}$ over $0 = \text{'neutral'}$ to $+3 = \text{'hot'}$, used for assessing the respondent's thermal perception and preference. Metabolic rate was assumed to be 2.8 Met for all respondents (walking at 4 km/h on level ground). The time of residency was used as a criterion of exclusion, when less than 6 months. The time of the interview was then matched to the 5-min average of all relevant comfort variables (T_a , RH, V_a , T_{mrt}).

The sample consists of 567³ thermal sensation/preference responses, after data cleansing (not accounting for non residents, pregnant women, construction workers with higher metabolic rate etc.). Due to more frequent clear-sky conditions in summer, the largest concentration of data lies within this season. The time spent outdoors was used as a relevant parameter for narrowing the sample further as it is a controversial issue in outdoor comfort surveys. From calculations with Instationary Munich Energy-Based Model, Höpfe (2002) suggests that the thermal adaptation to cold is much slower than to heat, meaning that it would take several hours, if ever, until a person is fully acclimatized under cold conditions. Considering the very low probability of finding substantial amount of individuals which were exposed to outdoor conditions for longer periods, particularly when using 'volunteers' (passers-by), a residency of at least 15 min outdoors was adopted as a criterion for the 'time spent outdoors' factor. This is the minimum space residency recommended by ANSI/ASHRAE Standard 55 (2004) for indoor thermal comfort evaluations taking into account the concept of thermal adaptation. The sample consisted of 61 % males and 39 % females, with an age range 12–86 years.

Data collection at each of the six monitoring points took place on three sessions, so that a fairly even distribution of respondents at each point could be achieved to account for the diversity of street users. Although the locations were not very far from each other, visible differences in street users (social and educational) at each point were evident. The

² Table A.1, Annex A, ISO 9920 (2007)

³ Accounting for a population of approximately 600,000 inhabitants (Glasgow), with a margin of error of 5 %, confidence level 95 % and response distribution of 33 % (comfort, discomfort due to cold or discomfort due to heat), a minimum of 340 respondents would be required.

Table 2 Equipment characteristics

Sensor	Resolution	Measurement range	Accuracy
Air temperature	0.1 or 1 °C (user-selectable)	-40 to +65 °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 1,800 W/m ²	±5 %
Air temperature (Tinytag TGP-4500)	0.01 °C	-25 to +85 °C	±0.45 °C

relevance of psychological and context-related factors in outdoor surveys has been stressed by some authors (Nikolopoulou and Steemers 2003; Spagnolo and de Dear 2003). An additional campaign was carried out at point 1, so as to bring the average the number of respondents at each point to 100 ± 14 .

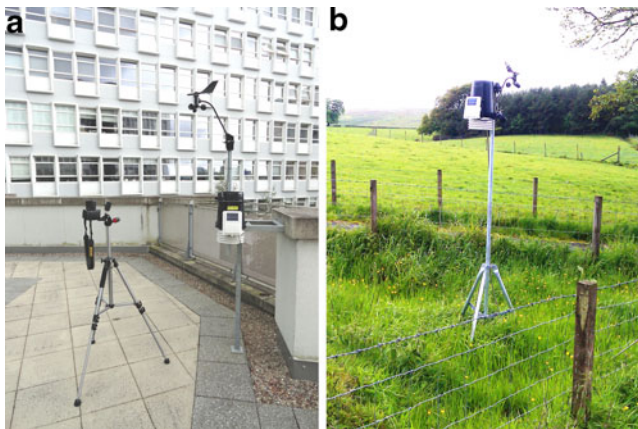
3 Assessment of thermal indices

Two thermal indices were used for comparisons with the field data (thermal sensation votes): the THSW index and the PET index. The THSW index uses humidity and temperature to calculate an apparent temperature, expressed in degree Celsius, incorporating the heating effect of solar radiation and the cooling effect of wind on perceived temperature (Steadman 1984). This index was used for comparisons as it is part of the output data of the WeatherLink software, which is the Davis VantagePro2 interface used for downloading data.

The PET index, expressed in degree Celsius, is defined by Höppe (1999) as the equivalent temperature to the air temperature in which, for a typical internal situation, the thermal balance of the human does not change,

considering the same core and skin temperatures as in the original situation. The PET index has been frequently used as a reasonable predictor of thermal comfort/discomfort conditions in outdoor spaces (Mayer and Höppe 1987; Matzarakis et al. 1999; Svensson et al. 2003; Ali-Toudert and Mayer 2006; Thorsson et al. 2004). Furthermore, PET is one of the indicators used by German standards in urban and regional planning (VDI 1998). The Rayman software version 2.0 (1999–2007) was used for PET calculations.

Whereas THSW is an output Davis VantagePro2 weather stations, data have to be post-processed for PET calculations. The input parameters for assessing PET were location, time of day and year, air temperature, humidity, wind speed and the mean radiant temperature. The personal input variables were assumed to be that of an average man or woman⁴ (matching the respondent, with his/her corresponding clothing insulation) with a metabolic rate of 2.8 Met, in agreement with the survey assumptions. The applicability of both indices as predictors of thermal sensation under the monitored climate conditions was tested by binning thermal sensation data for each degree in both scales (THSW and PET), according to data grouping suggested by de Dear and Fountain (1994).

**Fig. 3** Weather station at **a** city centre and **b** rural location

4 Stationary weather stations

The two other weather stations used for analysing the impact of the urban area on thermal comfort/discomfort levels were of the same kind (Davis VantagePro2, both equipped with solar radiation sensors) as the ‘mobile’ station used during the outdoor comfort campaigns. The ‘urban’ weather station (Fig. 3a) was sited on the rooftop of a low-rise building on the central city campus of

⁴ According to ISO 8996, an average man is 30 years old, weighs 70 kg and is 1.75 m tall; the average woman is 30 years old, weighs 60 kg and is 1.70 m tall.



Fig. 4 Panoramic view of the urban weather station

Glasgow Caledonian University and was set up in February 2011. The rooftop is approximately 6 m from the street level, originally planned as a recreational green roof of the main campus library. The weather station is thus flanked by taller buildings all around, but open to the south side (Fig. 4). The fish-eye image of the monitoring location yielded a sky view factor (SVF) of 0.51. According to a local land cover/land use/building cover classification developed by Stewart

and Oke (2009), this site could be classified as ‘open set high rise’ of the local climate zone (LCZ). LCZs are defined based on characteristic geometry and land cover that generates a unique near-surface climate under calm, clear skies. These include vegetative fraction, building/tree height and spacing, soil moisture and anthropogenic heat flux. The LCZ class attributed to the urban station represents typical urban locations, with some of the common characteristics found in such areas: compact

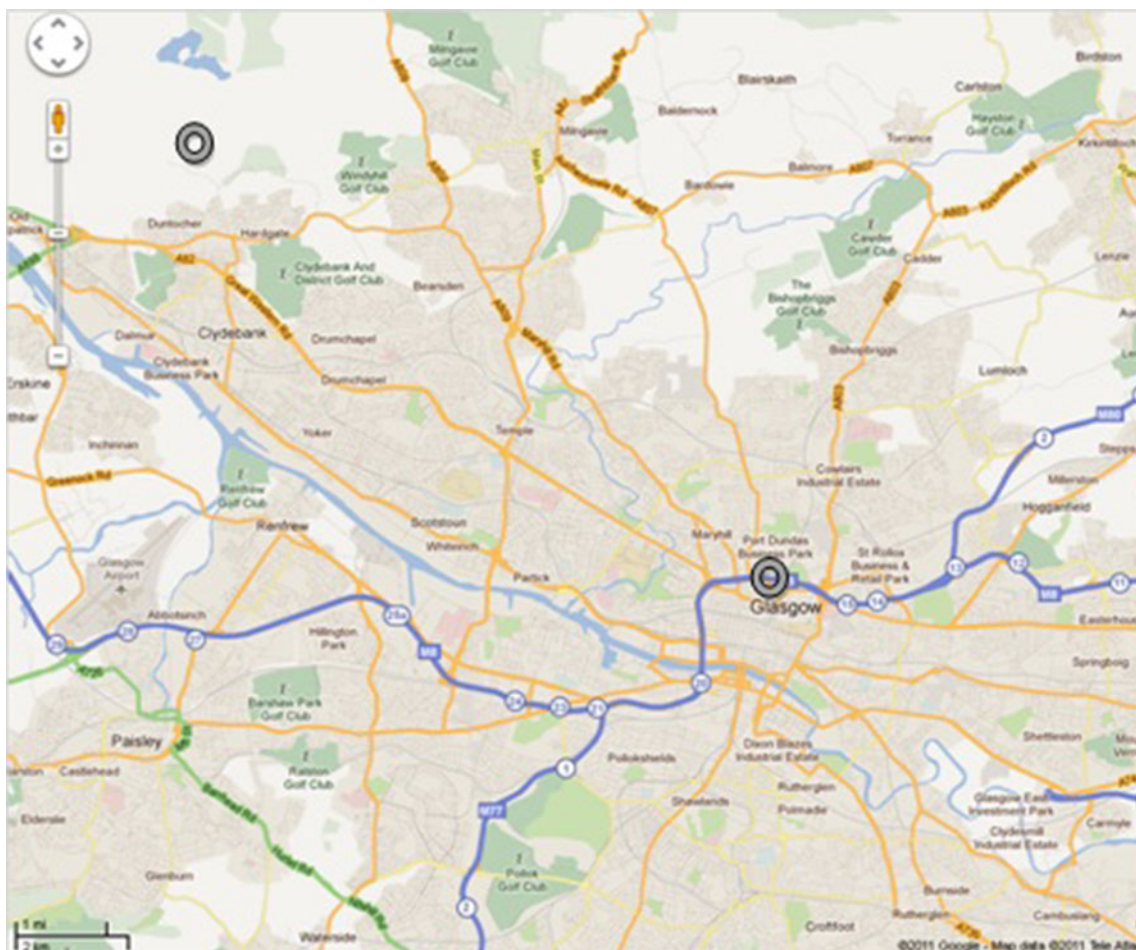
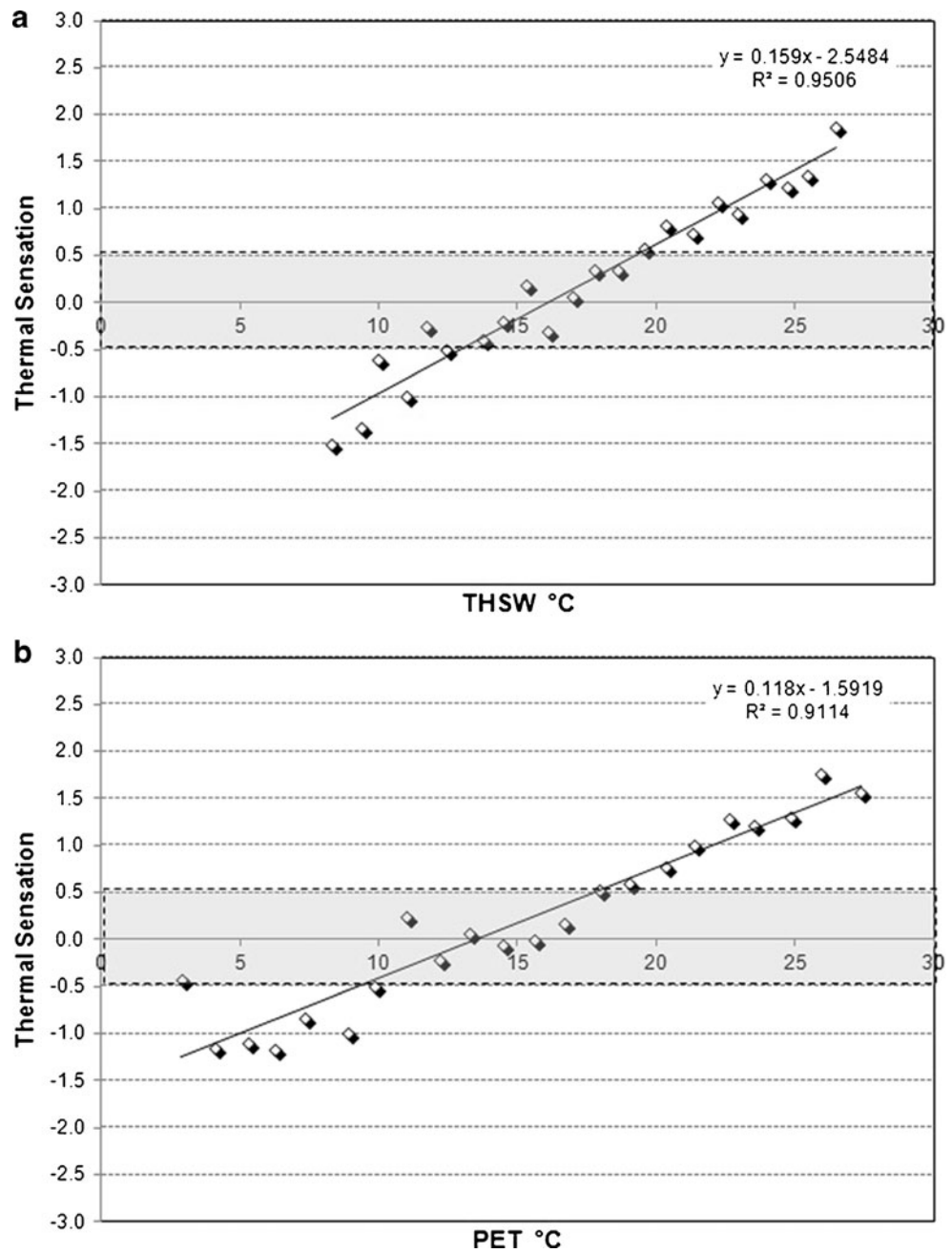


Fig. 5 Location of urban and rural weather stations

Fig. 6 Correlations between binned thermal sensation and thermal indices: **a** mean thermal sensation versus THSW and **b** mean thermal sensation versus PET



skyline of mid- and high-rise buildings, surface cover mostly paved, buildings of dense, solid construction, high space heating/cooling demand and heavy traffic flow (Stewart and Oke 2009). Local coordinates for this site were 55°52'1.66"N, 4°15'1.01"W.

The rural weather station (Fig. 3b) was located at Cochno Farm, a 350-ha farm located approximately 15 km from the reference station. The SVF at this site was assumed to be close to 1 and the LCZ class for the site was 'low plant cover' (local coordinates: 55°56' 20.74"N, 4°24'40.83"W). Figure 5 shows the locations of both weather stations.

5 Comfort ranges for THSW and PET in Glasgow

Comparisons between actual thermal sensation votes against predicted thermal sensation (TS), expressed either as THSW or PET degrees, were based on binned data in each scale. For a 7.9–26.8 °C range, 19 bins would be required for 1° bins in the THSW scale; for the 2.3–27.7 °C range, 25 bins would be required in the PET scale. A compromise number of 22 bins were adopted for both scales, corresponding either to 0.9 °C THSW or to 1.2 °C PET. Weak correlations were found for the raw (unbinned) data ($r^2=0.45$) between the thermal indices and the actual thermal sensation. For the

Table 3 Optimal ranges for PET and THSW

THSW bin (°C)	PPD* (adjusted)	Thermal sensation= 0.159x- 2.5484	PET bin (°C)	PPD* (adjusted)	Thermal sensation= 0.116x- 1.5919
8.3	56	-1.2	2.9	29	-1.2
9.4	50	-1.1	4.1	44	-1.1
10.0	32	-1.0	5.3	43	-1.0
11.0	41	-0.8	6.2	45	-0.9
11.7	28	-0.7	7.4	35	-0.7
13.0	31	-0.5	9.0	40	-0.5
13.8	29	-0.4	9.9	30	-0.4
14.4	28	-0.3	11.0	28	-0.3
15.3	28	-0.1	12.2	28	-0.2
16.1	28	0.0	13.3	27	0.0
17.0	27	0.2	14.4	27	0.1
17.7	29	0.3	15.6	27	0.3
18.6	29	0.4	16.7	27	0.4
19.0	32	0.5	18.0	30	0.5
20.4	37	0.7	19.0	31	0.7
21.3	35	0.8	20.3	34	0.8
22.2	43	1.0	21.4	40	0.9
22.9	39	1.1	22.6	49	1.1
23.9	50	1.3	23.5	46	1.2
24.7	47	1.4	24.8	49	1.3
25.4	51	1.5	25.9	68	1.5
26.4	67	1.7	27.4	61	1.6

binned data, correlations were high ($r^2=0.95$, $r^2=0.91$, for THSW and PET, respectively) and significant ($p \gg 0.05$ for both) (Fig. 6).

The correlation between both indices is relatively high for the raw data ($r^2=0.75$) and virtually perfect for the binned data ($r^2=0.9995$ —to be regarded with caution, as the binned TS data are not equal), suggesting that both indices are comparable. As THSW exhibits a higher correlation to actual TS data and has less mean bias (maximum bias was 0.4 of thermal vote for THSW and 0.8 for PET), besides the fact that it can be directly assessed from the weather station output file, such index has a great advantage when compared to PET.

Figure 6 presents the regression equation to define comfort zones for THSW and PET. The comfort range (Table 3) was determined from using the regression equation on the assumption that the predicted thermal sensation within the range of -0.5 to $+0.5$ should correspond to ‘comfortable, no thermal stress’ as suggested by Matzarakis et al. (1999).

Another analysis procedure was used from the weather and thermal sensation survey data in terms of the concept of the predicted percentage of dissatisfied (PPD). According to ISO 7730 (1994), which defines the methods for assessment of

thermal comfort in conditioned, indoor thermal environments, while the proposed thermal index predicted mean vote (PMV) merely predicts the mean value of the thermal votes of a large group of people exposed to a given thermal environment, it could be useful to predict the number of people most likely to experience thermal discomfort under such circumstances. Such standard proposes the use of PPD for a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. As PMV is based on the same seven-point thermal scale used in our surveys and as PPD can be numerically determined from PMV from a regression equation, the goodness of fit of the original PPD formulae was tested here. For each THSW or PET bin, the percentage of people below or above a given threshold in the seven-point scale used for assessing the actual thermal sensation can be determined. According to the procedure shown in ISO 7730 (1994), thermal comfort corresponds to the range between -1 (slightly cold) to $+1$ (slightly warm)⁵ of actual thermal perception; thus, discomfort can be due to heat, when the binned thermal sensation is either $+2$ or $+3$ and due to cold, when -2 or -3 . Figures 7a, b show the relationship between PPD and the mean thermal sensation for each THSW/PET bin. The same graphs also show the theoretical PPD calculated according to ISO 7730 (1994) (binned thermal sensation).

Results indicate that the minimum PPD for a neutral thermal sensation (TS=0) for THSW and PET bins in Glasgow is well above the minimum calculated PPD, which can be explained by the greater diversity of declared thermal sensations for a given bin. The polynomial equation in Fig. 7 can be substituted by empirical adjustments to the original PPD formula, yielding the formulae shown on Table 4.

The equations in Table 4 were applied to the thermal sensation data to calculate the adjusted PPD (PPD*), shown against the corresponding binned THSW/PET data in Table 3. The ‘optimal’ ranges for PET and THSW (i.e. corresponding to $-0.5 \leq TS \leq +0.5$) are italicized. Table 3 indicates that the comfort ranges in Glasgow are 13–19 °C (THSW) and 9–18 °C (PET). Thermal discomfort due to cold or heat can be assumed to be THSW or PET values below or above these ranges, respectively.

6 Temperature and comfort levels in and outside the urban area of Glasgow

The procedure adopted for assessing the impact of the urban area on local temperature and on comfort/discomfort

⁵ Table 2 of ISO 7730 shows three possible thresholds for the definition of the acceptable percentage of persons in thermal discomfort: TS=0; $-1 \leq TS \leq +1$; $-2 \leq TS \leq +2$, the choice lying with the second threshold. Thus, comfortable conditions correspond to a maximum of 10 % dissatisfied.

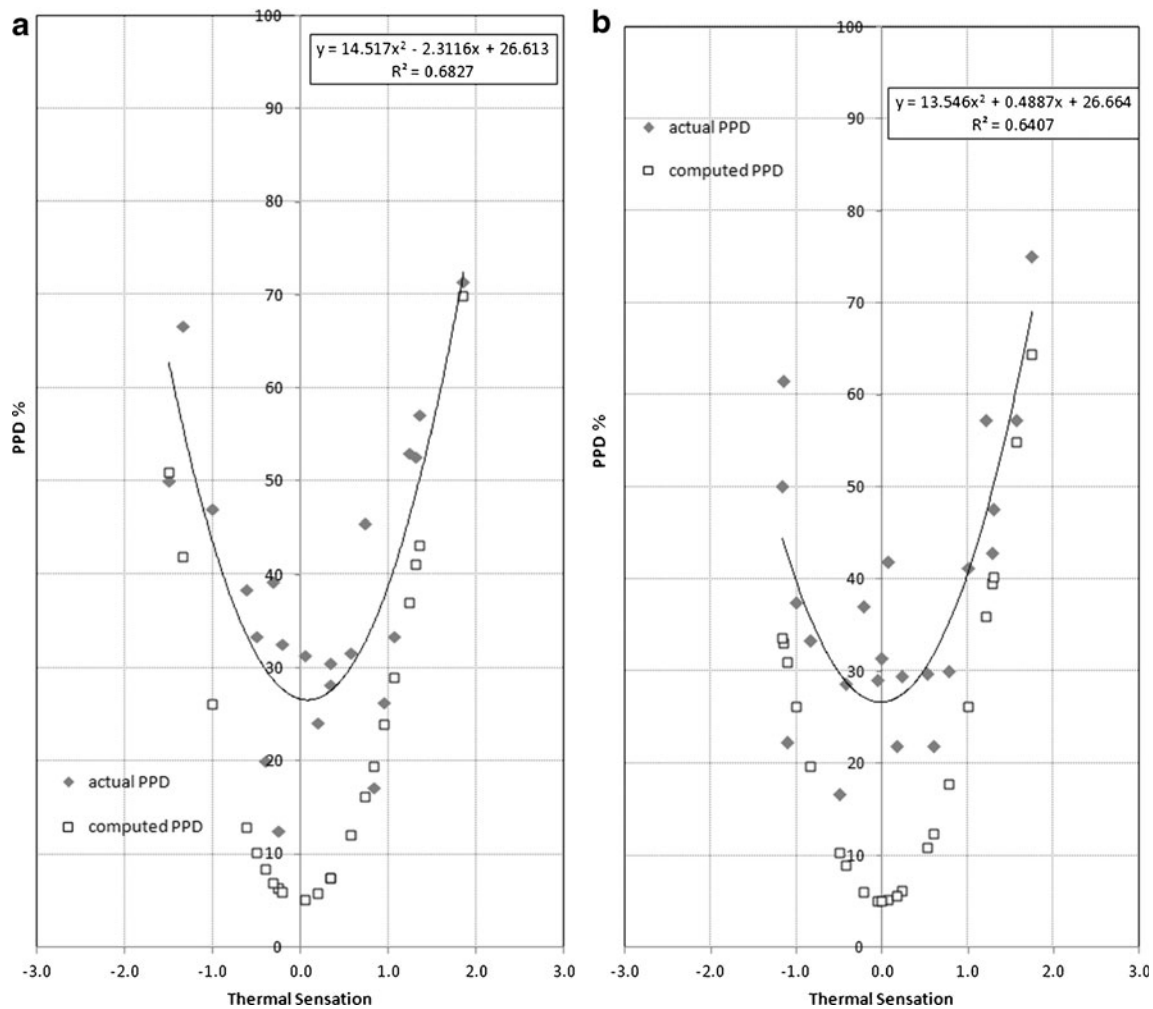


Fig. 7 Computed and actual PPD for binned data: **a** for THSW and **b** for PET

conditions relative to a rural location (stationary weather station at Cochno Farm) was based on the following steps:

- Analysis of climatic and THSW data directly read from the output data file of the two stationary weather stations
- Calculation of PET for the data collected at both locations with the Rayman software
- Data comparison for the whole period of measurements and for colder and warmer periods

For the PET calculations at the rural site, since the stationary stations were not equipped with a globe thermometer, global solar radiation data in watts per square metre and the SVF were used as input data to Rayman for estimating

the resulting mean radiant temperature. A comparison made by Thorsson et al. (2007) between three different methods to calculate mean radiant temperature indicated that the method used by Rayman underestimated the actual T_{mrt} in Göteborg, Sweden, which is located at similar latitude. Thus, we attributed the highest SVF possible to the rural site to account for this limitation. For the urban site, the actual SVF (Fig. 8), which was previously determined in Rayman from a fish-eye picture taken at the spot, was fed into Rayman to account for radiant heat exchanges due to local urban geometry in PET calculations.

Thus, the input parameters for assessing the T_{mrt} and PET were location, time of day and year, air temperature,

Table 4 Best-fit PPD equations for each comfort index

Original PPD equation (ISO 7730 1994)	$PPD = 100 - 95 \times \text{EXP}(-0.03353 \times TS^4 - 0.2179 \times TS^2)$	Eq. 2	–
Best-fit PPD for THSW	$PPD = 100 - 73 \times \text{EXP}(-0.01 \times TS^4 - 0.2 \times TS^2)$	Eq. 3	$r^2 = 0.82$
Best-fit for PET	$PPD = 100 - 74 \times \text{EXP}(-0.04 \times TS^4 - 0.15 \times TS^2)$	Eq. 4	$r^2 = 0.80$

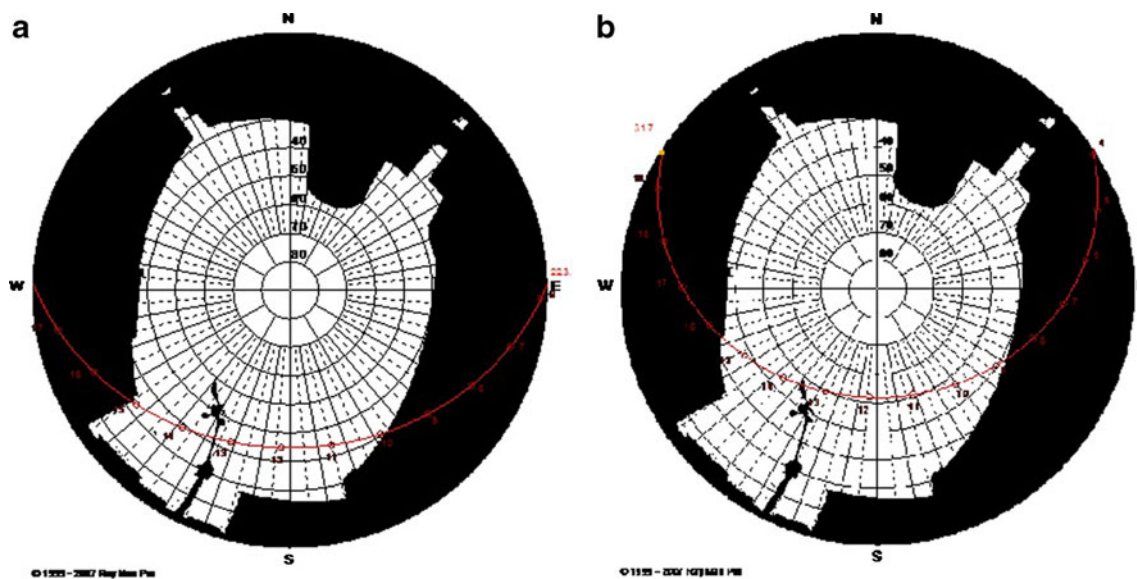


Fig. 8 Fish eye image of the urban weather station overlapped by solar path on 22.03.2011 (a) and on 01.08.2011 (b)

humidity, wind speed, global radiation and the SVF, to account for the effect of local obstructions. Albedo, Bowen ratio and the ratio of diffuse and global radiation were assumed to be Rayman's default values. The personal input variables were assumed to be that of an average man⁶ with varying clothing level (1.55 clo for the colder period and 0.75 clo for the warmer period) and a metabolic rate of 2.8 Met (or 295 W, walking at 4 km/h on the level, in agreement with the survey assumptions).

Figure 9 shows average daily ambient temperatures at the urban and rural locations. Two periods can be discerned: a colder period from 23 March 2011 to 31 May 2011 and a warmer period from 1 June 2011 to 1 August 2011.

Figure 10 shows the frequency distribution of daytime (maximum) and night time (minimum) temperature differences between urban and rural locations. The differences are more pronounced and more varied at night (daily minima) than during daytime. No significant cool island effect is observed for the urban location during daytime periods, and this is clearly shown in Fig. 11, which depicts two clear-sky days in the warm and cold periods. A possible reason for the absence of the cool island effect in this particular location is given by solar exposure: Although the urban site has a lower sky-view due to the surrounding buildings, there is a great 'openness' to the south (ref. fish-eye image of Fig. 8 with solar paths corresponding to the start and end dates of the monitoring).

Overall differences between both sites are presented in Table 5. The pattern of behaviour for the differences observed is consistent with what would be expected in urban

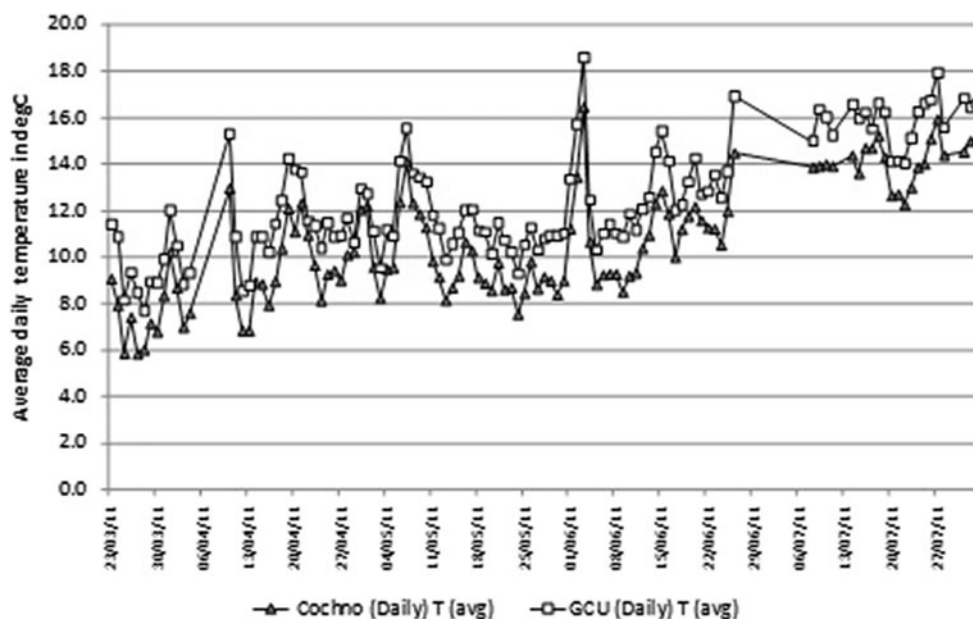
areas, with an overall increase in air temperature and corresponding decrease in relative humidity, lower wind speed and solar global radiation levels, due to higher surface roughness and to obstructions of the sky dome. As a result, there is a noticeable increase in mean radiant temperature in the city in each period.

Average differences between the urban and the rural stationary weather stations are presented in terms of: percent variations in thermal comfort/discomfort due to cold and heat (i.e. above or below the comfort thresholds for THSW (13–19 °C) and PET (9–18 °C)), predicted thermal sensation and percentage of dissatisfied (PPD*), for each period of analysis (Table 6). In addition, the mean index value is shown for PET and THSW with the respective coefficient of variation (CV) and average swings. CV is defined as the ratio of the standard deviation to the mean, here expressed as a percent.

Differences between the rural site and the urban locations are statistically significant ($p \lll 0.05$) and consistently positive with regard to thermal sensation and negative regarding PPD*. Although differences in predicted thermal sensation are relatively small (all below one thermal vote), the percent variations for the whole data set ('all data') suggest for THSW as well as for PET a larger variation in thermal discomfort due to cold (negative) than in heat stress (positive). This means that the urban site benefits from less cold with a slight increase in heat stress, however with a proportionately larger increase in comfort. Furthermore, a comparison of results between the cold and the warm periods shows that in summer, there is greater increase in terms of comfort, with the urban site exhibiting more comfortable conditions.

⁶ According to ISO 8996, an average man is 30 years old, weighs 70 kg and is 1.75 tall.

Fig. 9 Daily average ambient temperature for urban and rural locations



With respect to differences between both thermal indices, all urban–rural changes are exacerbated in PET results:

1. Coefficients of variation are significantly higher for PET than for THSW, meaning that a larger dispersion takes place in PET estimates. The predicted PET values fluctuate within a range which is quite below and a little above the preferable PET values of 9–18 °C (Table 6, average daily minima/maxima) at the urban site, whereas the upper limit is only reached in summer at the rural site. THSW fluctuations are much less pronounced and closer to preferable conditions (13–19 °C in the THSW scale) and exhibit a different pattern: The upper limit of THSW 19 °C is reached and surpassed at both locations.
2. The percent changes in cold/heat stress and comfort for each period are substantially higher for PET, ranging from 2 to about 22 times higher than those of THSW.
3. The ‘increase of heat stress to reduction of cold stress’ ratio is very different for both indices: for the ‘all data’ series: 0.11 for THSW and 0.32 for PET.

A possible explanation for the diverging patterns observed in the percentage of time in cold and heat stress for both indices could be attributed to assumptions behind the calculation of T_{mrt} from SVF estimates and solar global radiation for each site, considering that the T_{mrt} has a strong effect on PET estimates. Thus, the initial SVF for the rural site, assumed to be 1, was changed to a lower SVF of 0.8 which corresponds to the LCZ class ‘Sparsely Built’ (<http://www.geog.ubc.ca/urbanflux/resources/lcz.pdf>).

Still, the reductions in those percentages were not substantial (Table 6).

In order to verify T_{mrt} calculations from Rayman, the procedure of using SVF and measured global solar

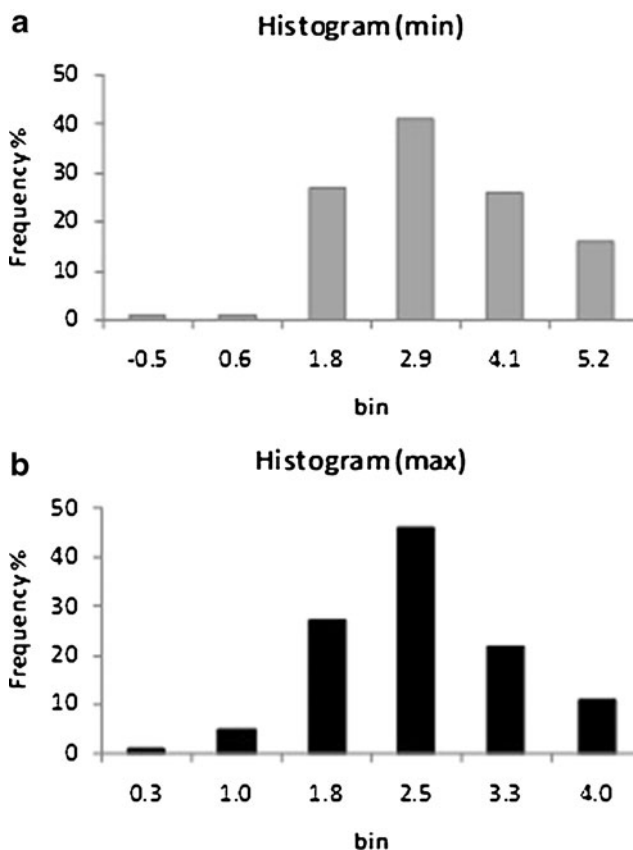


Fig. 10 Frequency histograms for **a** daily minimum temperature differences and **b** daily maximum temperature differences

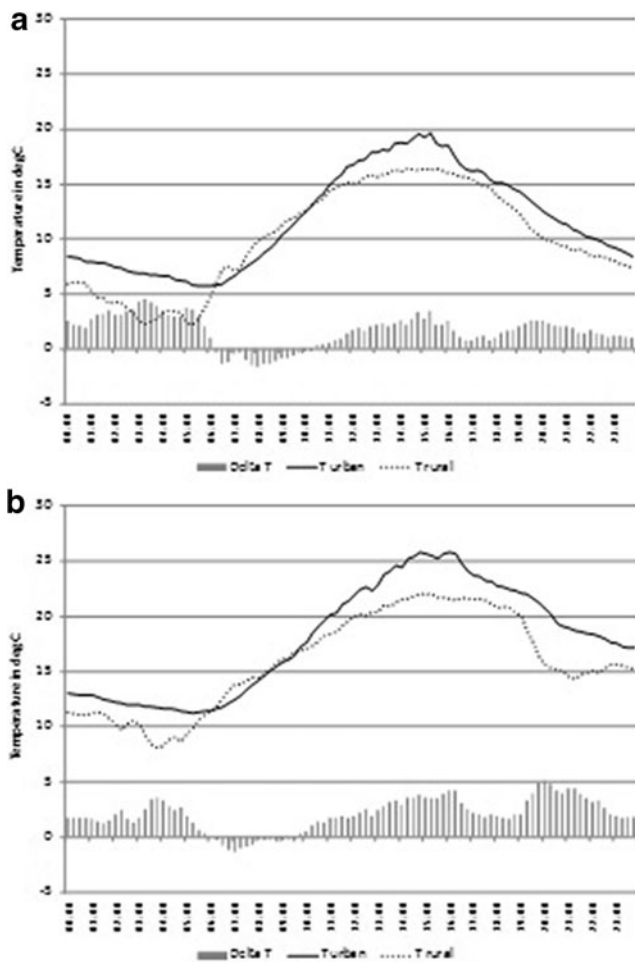


Fig. 11 Hourly profile for a clear-sky day during **a** the colder period and **b** the warmer period

radiation as input parameters for Rayman calculations was adopted for the six locations where outdoor comfort surveys took place (Table 2). Large differences were found between measured and predicted T_{mrt} (Fig. 12), yielding unrealistic estimated T_{mrt} values for the highest global solar radiation data measured in the city.

7 Discussion

Our results indicate the following:

1. The predicted thermal sensation by THSW and PET indices matches well with observed thermal responses in Glasgow.
2. The ‘optimal’ ranges for thermal comfort conditions in Glasgow are lower than those suggested by literature for the PET index.
3. There is considerable difference in estimated thermal sensation between an urban and a rural site in Glasgow: The urban site has a smaller fraction of time in ‘cold discomfort’ and a longer ‘comfort’ fraction than the rural site. This was true throughout the measurement period and for the two indices evaluated.
4. PET results with regard to urban–rural thermal comfort differences seem to be overrated in comparison to THSW and to observed UHI trends.

The relatively small data sample for the winter period (less than 10 % of the sample with ambient temperature below 10 °C) means further data collection is needed in order to investigate in more detail the effect of colder conditions on human thermal response in Glasgow. However, it was possible to devise a preliminary definition of optimal ranges for THSW and PET. In the case of PET, our range diverges considerably from the limits proposed by Matzarakis and Mayer (1996), which suggest a PET range of 18–23 °C as ‘no thermal stress’. As the optimal range found in this study is considerably lower, it is suggested that future studies using PET as an indicator of human thermal perception should seek local adjustments of the ranges proposed by Matzarakis and Mayer (1996) to reflect local realities.

The application of the derived TS and PPD equations (for THSW and PET) to measured conditions in different locations can be used as additional information to standard UHI analyses. Particularly with respect to the THSW index, establishing comfort ranges for a given region can be useful when performing data analyses from Davis Vantage

Table 5 Average differences in air temperature and humidity, wind speed, solar radiation and predicted mean radiant temperature (urban versus rural)

Period	Urban					Rural				
	T_a avg (°C)	RH avg (%)	V avg (m/x)	SR (daily total) (W/m ²)	T_{mrt} avg (°C) ^a	T_a avg (°C)	RH avg (%)	V avg (m/x)	SR (daily total) (W/m ²)	T_{mrt} avg (°C) ^a
All data	12.9	74	0.8	10,997	35.8	10.5	83	1.6	15,106	21.5
Colder period	11.5	74	1.0	10,488	35.0	9.1	82	1.9	13,999	20.3
Warmer period	14.8	75	0.6	11,685	36.8	12.4	84	1.3	16,606	23.0

^a Calculated with Rayman

Table 6 Average index value, coefficient of variation and average daily swings; thermal comfort/discomfort variations; differences in predicted thermal sensation and adjusted PPD* between the urban

and the rural location (for THSW and PET calculated from the consideration of the sky view factor for the rural site 1 and 0.8, respectively)

Period	Avg index value (°C) (urban)/CV (%)	Avg index value (°C) (rural)/CV (%)	Avg daily Min/Max (°C) (urban)	Avg daily Min/Max (°C) (rural)	Urban–rural % cold discomfort	Urban–rural % heat discomfort	Urban–rural % comfort	Diff TS _{u-r}	Diff PPD* _{u-r}
THSW									
All data	12.3/40	10.7/50	7.4/21.9	4.3/19.2	-7.5	0.8	6.7	0.3	-6
Colder period	10.7/40	8.8/60	5.8/21.0	2.6/17.7	-5.3	0.9	4.3	0.3	-8
Warmer period	14.5/30	13.2/40	9.6/23.0	6.7/21.3	-10.5	0.6	9.9	0.2	-4
PET (SVF_{rural}=1)									
All data	11.6/70	6.0/120	2.8/37.3	-2.9/17.9	-26.6	8.6	18.0	0.7	-9
Colder period	9.5/80	4.3/150	1.8/33.7	-3.6/15.2	-21.7	5.2	16.5	0.6	-12
Warmer period	14.4/60	8.2/90	4.0/42.2	-2.1/21.5	-33.1	13.2	19.9	0.7	-5
PET (SVF_{rural}=0.8)									
All data	11.6/70	6.4/111	2.8/37.3	-2.5/18.5	-24.7	8.3	16.4	0.6	-8
Colder period	9.5/80	4.8/135	1.8/33.7	-3.2/16.2	-20.7	4.7	16.0	0.6	-10
Warmer period	14.4/60	8.6/86	4.0/42.2	-1.6/21.6	-30.1	13.1	17.0	0.7	-4

Pro2 weather stations. With regard to PET, in particular, adjusted comfort ranges can be useful when assessing the impact of different urban layouts in Glasgow and in cities with similar climatic conditions. Our conclusions could also assist the prediction of outdoor thermal conditions resulting from the manipulation of the urban geometry in such cities.

The overall decrease in degree-hours for a base temperature of 65 °F (18 °C) in the urban area was for the ‘all data’ series 209 °C h for heating and the increase in cooling demand was only 18 °C h. As a result, only a small fraction (0.09 or about 1/12th) of the savings in heating leads to an increase in cooling demand. A similarity to such an estimate is found for THSW but not for PET results. It is suggested that T_{mrt} results from Rayman using as input data global solar radiation and fish-eye images do not correspond to actual figures from the locations analysed and thus affect PET calculations. Thorsson et al. (2007) used three different methods to assess T_{mrt} in an open space at a similar high latitude location and found that Rayman underestimates T_{mrt} during the night time period whereas performing fairly well during the day. Our T_{mrt} data for more constrained urban conditions (SVF ranging 0.38–0.48) show large discrepancies for such locations, with an overestimation of T_{mrt} in Rayman during daytime.

THSW readings, by their turn, are automatically calculated by Weather Link, the embedded software in Davis Vantage Pro2 stations provided with solar radiation sensors and are in this respect more reliable (no post-processing, calculated exclusively from weather data). Kolokotroni et al. (2012) show that, in the case of London, the existence of an UHI may not be necessarily detrimental: Energy savings

on heating are followed by only marginal increases in cooling demand, particularly in the case of heating dominated buildings. Running computer simulations based on the Canyon Ambient Temperature (CAT) model for different aspect ratios (H/W factor) of urban canyons in Glasgow, Williamson et al. (2009) found a maximum UHI intensity during summer ranging 2.5–4.6° (from shallow to narrow canyons). The maximum UHI intensity found for an aspect ratio of 1 (which corresponds to an SVF of approximately 0.4 for regular street canyons) roughly matches the most frequent night time temperature differences between urban and rural locations found in our study (Fig. 10a). The derived effect on

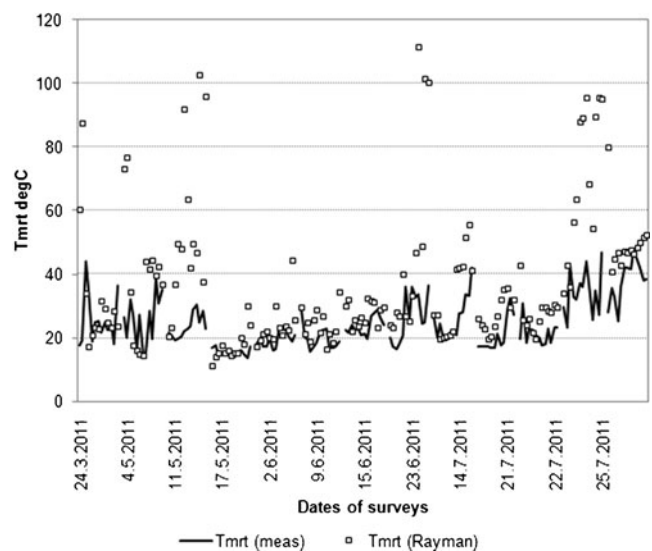


Fig. 12 Differences between measured (5-min averaged) and predicted (Rayman) T_{mrt} for the six survey locations

air-conditioning loads from simulations with EnerWin of a standard office building located in Glasgow yielded a cooling-to-heating relationship of 0.11 for open spaces (annual energy budget for $H/W=0$ or base climate file) and of 0.13 for urban areas with similar aspect ratio to our study. These figures bear some resemblance with the ‘increase of heat stress to reduction of cold stress’ ratio found for THSW in the ‘all data’ series and to the heating/cooling degree-hours relationship shown above.

Thus, the broader lesson from our results corroborates these findings, pointing to the benefit of densification in cold, temperate cities in reducing cold stress while leading only marginally to an increase in heat stress. Such results corroborate the findings of Thorsson et al. (2010), which showed that densely built structures are able to mitigate extreme swings in T_{mrt} , while improving outdoor comfort conditions both in summer and in winter. Indeed, Table 5 suggests that there is a benefit in both seasons (in our case, the colder and warmer periods) in terms of overall increase in comfort/decrease in discomfort levels in urban areas. It should be noted that our urban location was at a disadvantage concerning thermal gains from direct radiation. A comparison of historic data gathered at weather stations from the British Atmospheric Data Centre (<http://badc.nerc.ac.uk>) during a 12-year period from 1974 to 1985 showed some instances of the cool island effects in a weather station more centrally located compared to a weather station in the outskirts, with an offset of almost one degree in the ‘rural’ site with respect to the average daily temperature fluctuation for both sites (Emmanuel and Krüger 2012). More ‘typical’ urban locations, which cause overshadowing during daytime, would possibly have smaller or negative heat island effects during the day and thus alleviate heat stress.

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